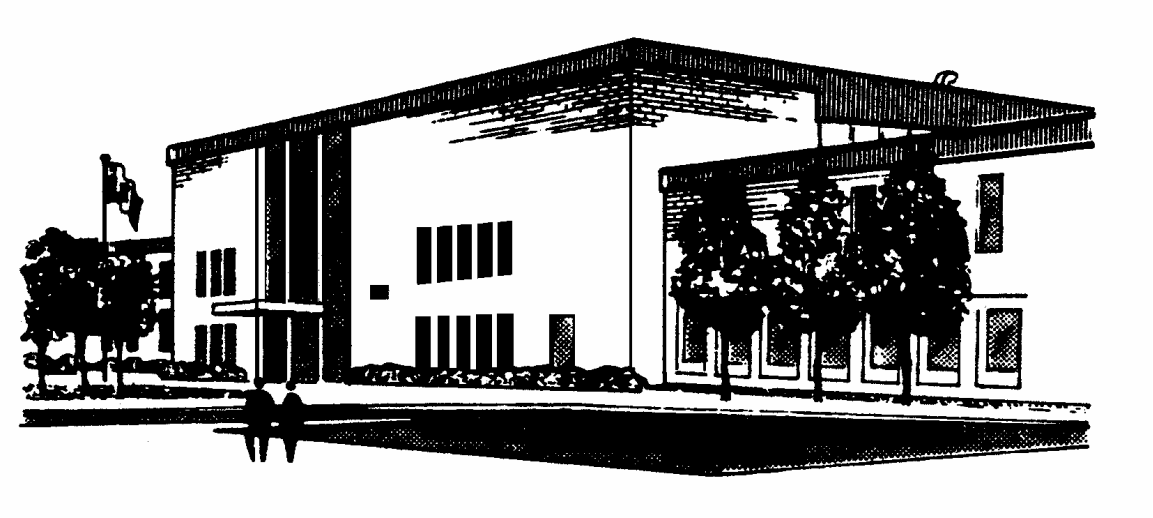
# Investigation of Potential Exhaust Emissions Reductions using Biodiesel Blends in a Conventional Diesel Engine



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# Summary

The Emissions Research and Measurement Division (ERMD) of Environment Canada tested a light duty diesel truck on a chassis dynamometer over the four-phase Federal Test Procedure (FTP). The vehicle was tested at two temperatures using a commercially available low sulfur diesel fuel (LSD) and LSD blended with 10%, 20%, and 30% soybean oil methyl ester.

Samples of dilute exhaust were obtained using a constant volume sampling system and mass emission rates for the following emissions were determined:

- criteria emissions (CO, $NO_x$, THC) and $CO_2$
- methane and non-methane organic compounds,
- methyl and ethyl esters of soybean oil,
- carbonyl compounds,
- total particulate matter (TPM)

This vehicle also provided a first attempt at collecting emissions samples for the more detailed characterization of emissions under the PERD[1] funded project "Determination of the concentration, composition and sources of airborne carbonaceous particles in Canada". The following emissions were determined as part of this project:

- $PM_{2.5}$ mass emissions,
- particle phase ions,
- particle phase organic and elemental carbon
- vapour phase organic acids
- vapour phase and particle bound polycyclic aromatic hydrocarbons (PAH), polycyclic aromatic sulphur heterocycles (PASH), and nitro polycyclic aromatic hydrocarbons ($NO_2$-PAH), and
- particle phase alkanes and biomarker compounds.

The use of biodiesel blends resulted in the following statistically significant (95% confidence) changes in emissions over the base fuel:

  - B10 gives a statistically significant decrease in $NO_X$ emissions (4.5%) and THC emissions (10-20%) over the base fuel at the standard test temperature.
  - B20 gives a statistically significant decrease in THC emissions (hot start only 34%) over the base fuel at the standard test temperature. $NO_X$ emissions remain essentially unchanged.
  - B30 gives a statistically significant decrease in THC emissions (27-37%) over the base fuel at the standard test temperature.
  - B20 gives a statistically significant increase (20%) in $CO_2$ emissions in the cold temperature cold start test as compared to the base fuel.

No statistically significant differences in TPM emissions were observed among the fuels. Increases in acrolein, PAH and $NO_2$-PAH emissions were observed with the biodiesel blends as compared to the base fuel, though there was insufficient data for statistical significance tests.

[1] PERD (Program on Energy Research and Development) is a joint program sponsored by Natural Resources Canada, Environment Canada and Health Canada with the goal of supporting federal government research activities in the area of effective, efficient use of energy resources.

Operation at cold ambient temperatures generally results in increased emissions regardless of the fuel used. The increase is greatest on cold start. Once the engine and emission control system have reached operating temperature, very little difference in emissions is observed.

Emissions of vapour phase organic acids were measured and emission rates of formic, acetic and glycolic acid were found at levels similar to the non-methane hydrocarbon emissions.

For the standard temperature tests, organic carbon accounts for approximately 55% of the particle mass while elemental carbon accounts for approximately 40% of the mass. Particle phase ions (ammonium, sulphate and nitrate) comprise a tiny fraction of the total mass. For the cold temperature tests, the organic carbon fraction increases to approximately 80% of the mass. It is suspected that lubricating oil contributes significantly to the increase observed at cold temperature. This hypothesis is supported by the significant increase in both the n-alkane and petroleum biomarker emission rates and a shift in the n-alkane distribution to lower carbon number.

The two methods for determining organic and elemental carbon composition (TOR and TOT) compare well for total carbon. The two methods differ in their distributions of organic and elemental carbon – largely due to the difference in approach for accounting for pyrolized carbon.

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# 1. Introduction

Due to more stringent diesel tailpipe emission regulations around the world, technology for reducing toxic emissions continues to evolve. Improvements in engine and combustion design, oxidation catalysts, particulate traps and alternate fuel technology have provided significant reductions in exhaust emissions. Characteristics of the diesel engine such as high efficiency, durability, reliability and low operating costs have traditionally made it a mainstay of the heavy-duty truck and bus vehicle industry. Recently, the diesel engine has begun to attain a growing share of the light duty market as well. However, with the increase in diesel vehicle sales there is a proportional increase in fuel consumption and emissions.

Fuel quality and composition have exhibited significant effects on diesel exhaust emissions. Biodiesel is defined as the mono alkyl esters of long chain fatty acids derived from renewable lipid feed stocks, such as vegetable oils and animal fats for use in compression ignition (diesel) engines. The methyl soyate biodiesel, derived from soybean oil, is an alternative fuel used in neat form, or as a blending agent with petroleum based diesel in order to reduce emissions of unburned hydrocarbons, carbon monoxide and particulate matter.

In this study, the Emissions Research and Measurement Division of Environment Canada conducted an investigation of potential exhaust emission reductions on a light duty diesel truck that was operated on a commercial low sulphur diesel fuel, and various percentage blends of the base diesel with methyl soyate at two different operating temperatures.

The following emissions were determined:

- criteria emissions (CO, $NO_x$, THC) and $CO_2$
- methane and non-methane organic compounds,
- methyl and ethyl esters of soybean oil,
- carbonyl compounds,
- total particulate matter (TPM)

This vehicle also provided a first attempt at collecting emissions samples for the more detailed characterization of emissions under the PERD[2] funded project "Determination of the concentration, composition and sources of airborne carbonaceous particles in Canada". The following emissions were determined as part of this project:

- $PM_{2.5}$ mass emissions,
- particle phase ions,
- particle phase organic and elemental carbon
- vapour phase organic acids
- vapour phase and particle bound polycyclic aromatic hydrocarbons (PAH), polycyclic aromatic sulphur heterocycles (PASH), and nitro polycyclic aromatic hydrocarbons ($NO_2$-PAH), and
- particle phase alkanes and biomarker compounds.

The vehicle was tested on a chassis dynamometer over the four-phase Federal Test Procedure (FTP). The vehicle was tested at two temperatures using a commercially available low sulfur diesel fuel (LSD) and LSD blended with 10%, 20%, and 30% soybean oil methyl ester.

[2] PERD (Program on Energy Research and Development) is a joint program sponsored by Natural Resources Canada, Environment Canada and Health Canada with the goal of supporting federal government research activities in the area of effective, efficient use of energy resources.

# 2. Experimental Methods

## 2.1 Vehicle Description

The test vehicle was a 1998 Dodge Ram 2500 4X4 P/U equipped with a 5.9 Litre 24-valve Cummins Turbo Diesel engine with two-way oxidation catalyst and had accumulated 8759 kilometers prior to the project. The vehicle specifications are summarized in Table 1.

**Table 1. Vehicle specifications.**

| | |
|---|---|
| Engine Type | 4-cycle in-line 6-cylinder |
| Aspiration | Turbocharged, charge air cooled |
| Bore and Stroke | 4.02 in. x 4.72 in. |
| Displacement | 5.9 Litre (359 $in.^3$) |
| Compression Ratio | 16.3:1 |
| Peak Torque | 420 lb-ft (from 1600 to 2700 rpm) |
| Advertised Power | 215 hp @ 2700 rpm |
| Governed Speed | 3200 rpm |
| Inertia Weight | 6128 lbs. |
| Road Load Horsepower | 16.0 |

## 2.2 Test Fuel

The baseline fuel used in the program was a commercially available low sulfur diesel (<0.05 %), and various percentage blends of methyl soyate (methyl ester of soybean oil) were blended with this fuel. The soyate blending agent was provided by the Ontario Soybean Growers Marketing Association. Standard temperature testing was conducted with 10%, 20%, and 30%, by volume, mixtures of the methyl soyate with the baseline diesel fuel. Each time a fuel blend was prepared, a sample of the fuel was collected for laboratory analysis. The analysis provided fuel blend density, fuel fraction carbon, hydrogen, oxygen, and additional fuel parameters. The test fuel specifications are summarized in Table 2.

**Table 2. Test fuel specifications**

| Specification | Low Sulfur Diesel | B10 | B20 | B30 |
|---|---|---|---|---|
| Wt. % Carbon | 86.6 | 86.1 | 85.2 | 84.6 |
| Wt. % Hydrogen | 13.2 | 13.2 | 12.9 | 12.8 |
| Wt. % Oxygen | 0 | 0.7 | 1.9 | 2.6 |
| Density ($kg/m^3$) | 841.0 | 845.4 | 852.9 | 854.1 |
| Trace $N_2$ (ng/ul) | 72.8 | - | - | - |
| Wt. % Sulfur | 0.049 | - | - | - |
| Cetane Number | 44.4 | - | - | - |

## 2.3 Chassis Dynamometer

The chassis dynamometer is a 60.96 cm diameter single roll electric dynamometer. The inertia and road load were simulated by a direct current motor with a fully regenerative power converter. This system has the capability of testing vehicles with inertia weight of up to 5000 kilograms and road load setting of up to 37.3 kilowatts. In this project the vehicle was tested at an inertia setting of 2780 kilograms and a road load at 80 kilometres per hour of 11.92 kilowatts.

## 2.4 Test Cycles

The driving cycle used for this project was the LA-4 Driving Schedule. This cycle is comprised of the first two phases of the Urban Dynamometer Driving Schedule (UDDS), which is used for certification of new vehicles. Each test incorporated two consecutive repeats of the LA-4 cycle, a cold start and a hot start, with a ten-minute soak between repeats.

The LA-4 test cycle is separated into two sampling phases. The first phase is called the Transient phase and includes the engine crank followed by 505 seconds of driving at an average speed of 41 km/h, covering a distance of 6.2 km. The second phase is called the Stabilized phase immediately follows the first and is 865 seconds in duration with an average speed of 25.7 km/h. At the conclusion of this phase the vehicle and sampling systems are turned off for a ten-minute soak period. After the soak, the vehicle and sampling systems are restarted and the second LA-4 cycle repeated. This four-phase test sequence provided a complete UDDS test cycle as well as an additional fourth sample phase. The first two phases collectively are referred to as the cold start portion and the last two phases are referred to as the hot start portion. A speed versus time plot of the LA-4 test cycle is presented in Figure 1.

The 4-phase FTP is an earlier version of the current 3-phase Urban Dynamometer Driving Schedule (UDDS) cycle, the emissions certification driving cycle used in Canada and the U.S. The fourth phase was dropped from the UDDS as the emissions obtained during that phase were nearly identical to the second phase. This phase was retained for the current testing program as it made collecting samples to obtain a composite emission rate possible. Emission rates for the UDDS and the 4-phase FTP tests are usually quoted as a composite or weighted average over the three or four phases. The composite emission rate for both tests is mathematically identical, just the weighting factors for the phases are different to account for the deleted fourth phase in the UDDS. Retaining this phase allowed samples to be collected over the cold start and hot start portions that could be weighted to obtain the desired composite emission rate. This calculation is illustrated below. Equation 1 shows the 4-phase composite emission rate calculation for a given species and Equation 2 shows the 3-phase composite emission rate calculation. Since the driving cycle for phase 2 and phase 4 are identical and emission rates for phases 2 and 4 were found to be not significantly different, it is obvious how Equation 1 can be written as Equation 2.

$$FTP_{4comp} = 0.43\left(\frac{m_1 + m_2}{d_1 + d_2}\right) + 0.57\left(\frac{m_3 + m_4}{d_3 + d_4}\right) \qquad \text{Equation 1}$$

$$FTP_{3comp} = 0.43\left(\frac{m_1 + m_2}{d_1 + d_2}\right) + 0.57\left(\frac{m_2 + m_3}{d_2 + d_3}\right) \qquad \text{Equation 2}$$

where $m_i$ = mass of a given compound emitted per phase $i$

$d_i$ = distance travelled in phase $i$

The mass of a given compound emitted per phase is given by Equation 3.

$$m_i = V_i * D * \left(C_{si} - C_{ai}\left(1 - \frac{1}{DF_i}\right)\right) \qquad \text{Equation 3}$$

where $V_i$ = total dilute exhaust volume of phase i

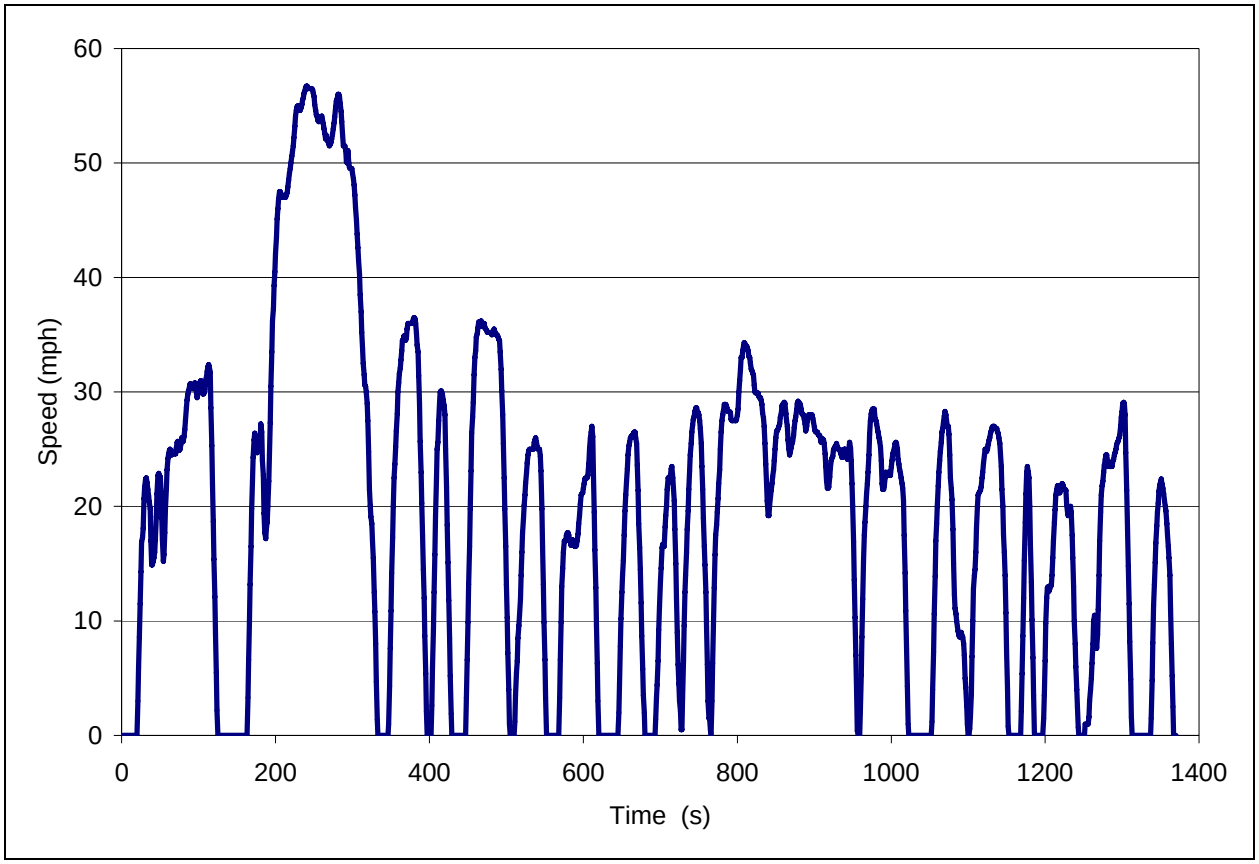
$D$ = density of species

$C_{si}$ = dilute exhaust concentration of species, phase i (ppm)

$C_{ai}$ = dilution air concentration of species, phase i (ppm)

$DF_i$ = dilution factor of phase i

**Figure 1. LA-4 Driving Test Cycle**




## *2.5 Sampling Methodology*

### 2.5.1 Sampling System and Sample Collection

All of the exhaust produced by the vehicle was collected and diluted using a total exhaust dilution constant volume sampling (CVS) system. The total dilute exhaust volume flow rate was 750 scfm (21 237 L/min). The dilution air was taken from the test cell and was conditioned by removing particulate matter using a HEPA filter resulting in a particle removal efficiency of 99.9%. The organic composition of the dilution air was reduced and stabilized by passing it through a bed of activated carbon.

### 2.5.2 Volatile and Semi-volatile Organic Compounds

The detailed hydrocarbon analysis of diesel exhaust requires two separate samples to be collected. Dilute exhaust was drawn through a Tenax adsorbent tube (SKC 226-35-03, two sections 100 mg/50 mg separated with glass wool) to collect hydrocarbons from $C_7$-$C_{26}$ (SvNMHC). The sample not retained by the Tenax tube was collected in a Tedlar bag for analysis of methane and $C_2$-$C_{12}$ hydrocarbons (NMHC). This methodology was used as it allows for analysis of the full $C_1$-$C_{26}$ range of hydrocarbons. A set of hydrocarbon samples was collected during the cold start portion and another set was collected during the hot start portion. One dilution air sample was collected over both the cold start and hot start portions. An SvNMHC sample was not required for the dilution air as the air was conditioned through activated carbon as described previously.

The NMHC and SvNMHC samples were drawn from the dilution tunnel through 3/8" OD probe and 1/4" Teflon line using a diaphragm pump. An electronic mass flow controller was used to provide a constant sample flow rate of 0.5 L/min.

### 2.5.3 Methyl Esters

Methyl esters were determined from the same Tenax sample and analysis as SvNMHCs.

### 2.5.4 Carbonyl Compounds

Carbonyl compounds were sampled by passing dilute exhaust through a 2,4-dinitrophenylhydrazine (2,4-DNPH) coated Sep-Pak silica cartridge. The carbonyl compounds selectively react with the 2,4-DNPH to form hydrazones that are retained on the cartridge.

One dilute exhaust carbonyl sample was collected during each of the four phases of the FTP. Dilution air carbonyl samples were also collected, one for the cold start portion and another for the hot start portion.

The carbonyl samples were drawn from the dilution tunnel through a 3/8" OD probe and 1/4" Teflon line using a diaphragm pump. An electronic mass flow controller was used to provide a constant sample flow rate of 1.0 L/min.

### 2.5.5 Total Particulate Matter

Dilute exhaust was drawn through a stainless steel ½" OD probe inserted into the tunnel along the axis of the flow. The dilute exhaust was drawn from the tunnel through the sample media by a rotary vane pump at a flow rate of 40 L/min controlled using an electronic mass flow controller.

Total particulate mass samples were collected by drawing dilute exhaust through a 70 mm diameter Pallflex filter (type T60A20) held in the single stainless steel holder upstream of the polyurethane foam plugs (PUFs). This filter served a dual purpose: the filter sample was used for total particulate matter mass determination and then was analysed for PAH, PASH, and $NO_2$-PAH.

### 2.5.6 PAH, PASH, and $NO_2$-PAH

The material used to make the PUFs was #1032 density polyurethane foam. The PUFs were cleaned by Soxhlet extraction with methanol and cyclohexane. Two PUFs were placed in each of the stainless steel sleeves ready for sampling. The PUFs were not removed from their stainless steel sleeves until returned to the analytical laboratory. The PUF sleeves were stored wrapped in aluminum foil and sealed in zip-seal bags. As the $NO_2$-PAH compounds are ultraviolet light sensitive, the filters and PUFs were handled very quickly in near darkness.

The overall dimensions of the pair of PUFs were 75 mm diameter by 150 mm long and separated from the filter by approximately 100 mm. This distance was allowed for the flow to expand to the full diameter of the PUF plug. The PUF canister, used to house the PUF sleeve, was manufactured from aluminum but all sample-wetted surfaces within the canister were either stainless steel or Teflon.

The sample media used to obtain a sample for PAH, PASH, and $NO_2$-PAH analysis consisted of a single 70 mm diameter Pallflex filter (type T60A20) to obtain the particle phase sample and backed up with a PUF sleeve to obtain the vapour phase sample. Two filter samples were collected per test, one filter during the cold start portion and another during the hot start portion, while only one PUF sleeve was used to collect the gas-phase sample over both cold start and hot start portions. This sampling strategy results in an "average" rather than a "composite" emission rate.

### 2.5.7 $PM_{2.5}$

Two-stage filter packs with 2.5 μm cyclones and flow straighteners were used to collect $PM_{2.5}$ samples on various filter media. Table 3 summarizes the particulate matter samples that were collected. Two ½" OD probes were inserted into the dilution tunnel along the axis of flow to collect the dilute exhaust. Each probe was fitted with a flow splitter that directed dilute exhaust to two 2.5 μm diameter cut cyclones. The

cyclones were equipped with flow straighteners and filter packs for sample collection. One set of filters was used to collect dilution air samples over the 4 phases.

**Table 3: Filter media used to collect $PM_{2.5}$ samples**

| Source | Media | Sample |
|---|---|---|
| Dilute Exhaust | Teflon<br>Carbonate coated cellulose | Mass, anions and cations<br>$SO_2$ |
| | Quartz<br>KOH coated quartz | Alkane and biomarker analysis<br>Vapour phase organic acids |
| | Quartz<br>Citric acid coated cellulose | Alkane and biomarker analysis<br>$NH_3$ |
| | Quartz<br>Quartz | OC/EC<br>OC/EC |
| Dilution air | Teflon<br>Carbonate coated cellulose | Mass, anions and cations<br>$SO_2$ |
| | Quartz<br>KOH coated quartz | Alkane and biomarker analysis<br>Vapour phase organic acids |
| | Quartz<br>Citric acid coated cellulose | OC/EC<br>$NH_3$ |

$PM_{2.5}$ samples were collected on Teflon membrane filters (Gelman Teflo R2PJ047, 2μm pore size, 47 mm diameter). These Teflon filters were used for gravimetric determinations and anions and cations analyses.

Situated behind the Teflon filter was a Carbonate coated cellulose filter used to collect samples for $SO_2$.

Quartz fibre filters (Pallflex 2500 QAT-UP, 47 mm diameter, pre-fired to 900°C for 3 hours to remove all carbon) were used for organic and elemental carbon (OC/EC) analyses. Two quartz filters were used in series, the first filter collected the particulate matter sample, the second filter was used to measure the amount of carbon desorbed from the first filter during sample collection and the amount of carbon adsorbed to the filter media from the gas phase. A selection of these filters were analyzed by two methods.

Two quartz filters, pre-cleaned as described above, were used to collect sample for alkane and biomarker analysis. One quartz filter had downstream from it a citric acid coated filter to determine $NH_3$ emissions. The other quartz filter had downstream from it a potassium hydroxide (KOH) coated quartz filter to collect sample for vapour phase organic acid determination.

# 3. Analytical Methods

## *3.1 Methane and Non-methane Hydrocarbon Compound Analyses*

Approximately 165 non-methane hydrocarbon compounds were determined using a Hewlett Packard 5890 Series II gas chromatograph with a flame ionization detector. An Entech M7000 cryogenic concentrator was used for sample concentration and introduction. The analytical conditions are summarized in Table 4. Data was acquired using the Hewlett Packard GC-ChemStation (Windows NT) software. The analytical method was calibrated using external standards on a per component basis. The hydrocarbon gas phase standards used were prepared in-house using a permeation tube gas standard generator (Kin-Tek Laboratories, LaMarque, Texas).

The detection limits for this set of analytical conditions is approximately 0.5 ng/L in the dilute exhaust or 0.03 mg/mile.

**Table 4. Analytical conditions for volatile hydrocarbon analysis**

| | |
|---|---|
| Column | HP1 50m x 0.32 mm x 1 μm film<br>Column head pressure 80 kPa |
| Oven Program | -50°C hold 5 min, 10°C/min to 50°C,<br>5°C /min to 200 °C, hold 2 min. |
| Detector | FID, 300 °C |
| Sample Concentration | 50 mL on glass bead/Tenax trap<br>microscale purge and trap mode. |

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 was determined and confirmation of the $C_2$ and $C_3$ hydrocarbons was accomplished by simple gas loop injection onto a capillary column. The sample loop was flushed with sample, the pressure inside the loop allowed to equilibrate to ambient conditions and the contents of the loop were injected directly onto the capillary column. A Hewlett Packard 5890 Series II gas chromatograph equipped with a gas sampling valve and a flame ionization detector was used for the analysis. Data was acquired using the Hewlett Packard GC-ChemStation (Windows NT) software. The analytical conditions are summarized in Table 5. The detection limit for methane using this method is approximately 10 ng/L in the dilute exhaust or 0.6 mg/mile.

**Table 5. Analytical conditions for light hydrocarbon analysis**

| | |
|---|---|
| Column | GS-Q 30 m x 0.53 mm<br>column head pressure 9 psig |
| Oven Program | 40°C hold 1.1 min, 25 °C/min 130 °C hold 7.3 min |
| Detector | FID, 180 °C |
| Sample | 0.25 mL sample loop,<br>sample valve at 100 °C |

The list of target analytes for the complete analysis, indicating co-eluting compounds, is given in Appendix 1.

## *3.2 Semi-volatile Non-methane Hydrocarbon Compound Analysis*

For analysis of the semi-volatile non-methane hydrocarbons (SvNMHC), the Tenax adsorbent was removed from the glass sampling tube and the adsorbed hydrocarbons were solvent extracted using high purity pentane (Caledon Laboratories). Solvent desorption was accomplished by placing the Tenax material in a 3.7 mL vial, pipetting 2.0 mL pentane into the vial and shaking vigorously for a few minutes. The desorption was complete in a few minutes and recovery has been determined from separate studies to be nearly complete for hydrocarbons up to $C_{26}$. An aliquot of this pentane extract was analysed by GC-FID. Standards were prepared from commercially available petroleum product standards (PIANO analysis standards from Supelco Canada). A Hewlett Packard 5890 Series II gas chromatograph with a flame ionization detector and HP 7673 autoinjector with the nanolitre injection volume option was used for the analysis. The analytical conditions are summarized in Table 6. Data was acquired using the Hewlett Packard GC-ChemStation (Windows NT) software.

A large number of peaks appear in the chromatogram between the normal paraffins from $C_{12}$-$C_{26}$ which were not identified. These peaks were not reported.

Detection limits for the hydrocarbons in the pentane extract were approximately 20 ng/mL which corresponds to 3.5 ng/L in the dilute exhaust or 0.2 mg/mile

**Table 6. Analytical conditions for semi-volatile hydrocarbon analysis**

| | |
|---|---|
| Column | DB1 60 m x 0.25 mm x 0.25 μm film<br>column head pressure 165 kPa |
| Oven Program | 35°C hold 5 min, 2 °C/min to 275 °C,<br>hold 5 min |
| Detector | FID 300 °C |
| Sample | 0.5μL injection volume<br>splitless inlet 250 °C |

## *3.3 Carbonyl Compound Analysis*

Carbonyl cartridges were prepared by the ERMD and contained approximately 2 mg 2,4-DNPH. Carbonyl compounds selectively react with the 2,4-DNPH forming hydrazones which are retained on the cartridge. 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 DOS 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 prepared in-house from the pure carbonyl compounds and purified 2,4-DNPH. 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.

Details of the analytical conditions are given in Table 3. Detection limits for this method are 0.04-0.06 μg/mL of hydrazone in the extract or 0.08 – 0.3 mg/mile.

**Table 3: Analytical conditions for carbonyl analysis**

| | |
|---|---|
| Column | 2 of ODS Hypersil 3 μm packing 100 mm x 2.1 mm.<br>10 mm guard column of same material. |
| Gradient | 62.5% MeOH/$H_2O$<br>to 65% MeOH at 12.5 min, hold to 15 min.<br>to 82.5% MeOH at 30 min<br>column flush at 100% MeOH for 5 min<br>equilibration at initial conditions for 5 min<br>oven temperature 40°C<br>flow rate 0.25 mL/min, injection volume 2.5 μL |
| Detector | signal at 370 nm; bandwidth 30 nm<br>reference at 550 nm; bandwidth 60 nm |

Lot blanks were analyzed using the same procedure as the samples to determine blank contamination levels. Samples were then corrected for blank levels as required. Emission rates were also corrected for dilution air levels.

## 3.4 Particulate Matter Mass Determination

### 3.4.1 TPM

Total particulate mass was determined gravimetrically by weighing humidity and temperature equilibrated conditioned filters before and after sampling. Filters were conditioned in a dessicator for a minimum of 16 hours before each mass determination. A Mettler AE240 semi-micro balance was used for all mass measurements. After the final weighing, the filters were stored in polystyrene petri dishes, sealed with paraffin wax strips, wrapped in aluminum foil, placed in plastic zip-seal bags, and then stored in a freezer until submitted for PAH, PASH, and $NO_2$-PAH analyses.

### 3.4.2 $PM_{2.5}$

The Teflon membrane filters were humidity and temperature equilibrated for a minimum of 16 hours before gravimetric determinations were performed. A Mettler MT5 microbalance, with a resolution of 0.001 mg, was used. Filter masses were determined as an average of two consecutive measurements, within 0.002 mg of one another, for each of the initial and final mass measurements.

## 3.5 PAH, PASH, and $NO_2$-PAH Analyses

The filter and PUF samples were analysed for PAH, PASH and $NO_2$PAH by the Analysis and Air Quality Division (AAQD) of Environment Canada using their standard method as summarized below. PASH and PANH methods were also developed by AAQD. The methods for analysis of PASH is described in detail in "Status Report on Method Development for the Analysis of Polycyclic Aromatic Heterocycles with Sulphur and/or Nitrogen" and "Status Report – II (July 99 to June 00) on Method Development for the Analysis of Polycyclic Aromatic Heterocycles with Sulphur and/or Nitrogen." The method is briefly summarized below.

It is known that generally, the heavier PAH compounds are associated with particulate material and that the lighter PAH compounds are in the vapour phase. For this study, samples were submitted as two filters and a PUF and treated as one sample. As the distribution of PAH between the vapour phase and particle bound phase is dependent on sampling conditions such as flow rate, pressure drop across the filter, temperature of the dilute exhaust when it is sampled, differentiating between vapour phase and particle phase PAH using this type of sample is not possible.

The filters were folded twice and placed in between two PUFs inside a large (500 mL) pre-cleaned Soxhlet apparatus. The surface of the top foam plug was spiked with PAH and $NO_2$PAH surrogates before extraction. Sample was extracted with dichloromethane at a rate of 3-5 cycles/hour for 16-20 hours. During the extraction and concentration, the florescent lights were off to minimize degradaton of the $NO_2$PAH. The raw extract was concentrated to approximately 3 to 5 mL by rotary evaporation and then filtered through anhydrous sodium sulphate. The concentrated dichloromethane extract was exchanged to cyclohexane by adding 30 mL of cyclohexane and reducing to approximately 3 to 5 mL by rotary evaporation. The extract was made up to 10 mL and split in half, one half for PAH and PASH, the other half for $NO_2$-PAH.

PAH and PASH Cleanup: an open glass column (25 cm x 1.5 cm ID), filled with approximately 6 g 5% deactivated silica gel and topped with approximately 1 g sodium sulphate, was conditioned with 10 mL of cyclohexane. When the cyclohexane drained to bed level, the sample extract was quantitatively transferred onto the column with approximately 5 mL of cyclohexane rinses. The column was eluted with 10 mL cyclohexane and the eluate archived. This fraction contains non-polar compounds. The PAH and PASH were then eluted with 15-mL of 1:1 cyclohexane/acetone into a calibrated centrifuge tube. The extract was concentrated to approximately 0.4 mL by nitrogen blow-down. After adding 50 μL internal standard, the extract was made up to 0.5 mL for GC/MS analysis.

The final extract was analysed for PAH by GC/MS under the operating conditions summarized in Table 7. The detection limit for the analytical method is 5-10 ng per sample. Table 9 summarises the target analytes and the surrogates used for monitoring sample recovery for this method.

**Table 7. PAH analytical conditions**

| | |
|---|---|
| Instrument | HP 5890 Series II GC interfaced directly to HP 5970 MSD. |
| Injection | 1 μL, on-column |
| Column | 30 m DB-5 fused silica, 0.25 mm ID and 0.25 μm film thickness |
| Oven Program | 90°C for 1 min, to 200°C at 20 °C/min, to 210°C at 3 °C/min, then to 280°C at 5 °C/min and hold for 15 min |
| Detection Mode | Electron Impact (EI), Selected Ion Monitoring (SIM);<br>Scan time 1 s or less, dwell time 50-100 ms/ion<br>A minimum of two characteristic ions per compound are monitored. |

**Table 8. PASH analytical conditions**

| | |
|---|---|
| Instrument | HP 5890 Series II GC interfaced directly to HP 5970 MSD. |
| Injection | 1 μL, cool on-column |
| Column | 30 m DB-XLB fused silica, 0.25 mm ID and 0.25 μm film thickness |
| Oven Program | 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);<br>One-step acquisition of 17 ions, dwell time 50 ms/ion<br>A minimum of two characteristic ions per compound are monitored. |

**Table 9. Target analytes and surrogates for PAH analytical method**

| | |
|---|---|
| Acenaphthalene (AL) | Perylene (PER) |
| Acenaphthene (AE) | 3-Me-Cholanthrene (MCH) |
| Fluorene (FL) | Indeno(1,2,3-cd)pyrene (IP) |
| 2-Methylfluorene (MFL) | Dibenz(ah)anthracene (D(ah)A) |
| Phenanthrene (PHE) | Benzo(b)chrysene (B(b)C) |
| Anthracene (AN) | Benzo(ghi)perylene (B(ghi)P) |
| Flouranthene (FLT) | Anthanthrene (ANT) |
| Pyrene (PY) | |
| Benzo(a)fluorene (B(a)FL) | Surrogates: |
| Benzo(b)flourene (B(b)FL) | $d_{10}$-Acenaphthalene |
| 1-Me-Pyrene (MPY) | $d_{10}$-Anthracene |
| Benzo(ghi)fluoranthene (B(ghi)F) | $d_{10}$-Pyrene |
| Benz(a)anthracene (B(a)A) | $d_{12}$-Benzo(a)Anthracene |
| Triphenylene (Tri) | $d_{12}$-Benzo(a)Pyrene |
| Chrysene (C) | $d_{14}$-Dibenzo(ah)Anthracene |
| 7-methylbenz(a)anthracene (MB(a)A) | $d_{12}$-Benzo(ghi)Perylene |
| Benzo(b)fluoranthene (B(b)FLT) | |
| Benzo(k)fluoranthene (B(k)FLT) | Internal Standard: |
| Benzo(e)pyrene (B(e)P) | $d_{10}$-Fluoranthene |
| Benzo(a)pyrene (B(a)P) | |

**Table 10. Target analytes and surrogates for PASH analytical method.**

| PASH | Acronym |
|---|---|
| thionaphthene | Thionaphthene |
| dibenzothiophene | DBT |
| naphtho(2,1-b)thiophene | N(2,1b)T |
| 2-methyldibenzothiophene | 2-MDBT |
| 8-methylnaphtho(2,1-b)thiophene | 8-MN(2,1b)T |
| 5-methylnaphtho(2,1-b)thiophene | 5-MN(2,1b)T |
| 4,6-dimethyldibenzothiophene | 4,6-DMDBT |
| 1,8-dimethyldibenzothiophene | 1,8-DMDBT |
| 1,3-dimethyldibenzothiophene | 1,3-DMDBT |
| phenanthro(4,3-b)thiophene | Pa(4,3b)T |
| phenanthro(3,4-b)thiophene | Pa(3,4b)T |
| phenanthro(2,1-b)thiophene | Pa(2,1b)T |
| phenanthro(2,3-b)thiophene | Pa(2,3b)T |
| anthra(2,3-b)thiophene | A(2,3b)T |
| 10-methylbenzo(b)naphtho(2,1-d)thiophene | 10-MBbN(2,1d)T |
| 2-methylbenzo(b)naphtho(2,1-d)thiophene | 2-MBbN(2,1d)T |
| 8-methylbenzo(b)naphtho(1,2-d)thiophene | 8-MBbN(1,2d)T |
| 5-methylbenzo(b)naphtho(2,1-d)thiophene | 5-MBbN(2,1d)T |
| 6-methylbenzo(b)naphtho(2,1-d)thiophene | 6-MBbN(2,1d)T |
| 8-methylbenzo(b)naphtho(2,3-d)thiophene | 8-MBbN(2,3d)T |
| 11-methylbenzo(b)naphtho(2,3-d)thiophene | 11-MBbN(2,3d)T |

$NO_2$PAH Cleanup: The other half extract was filtered through a 0.45 μm PTFE filter before being blown down to dryness and re-dissolved in 1 mL DMSO. Aliphatic compounds were removed by liquid-liquid extraction with hexane (1 mL x 3). The DMSO solution was diluted with 3 mL water and extracted 3 times with 3 mL cyclohexane. The cyclohexane extract was concentrated and fractionated on a HPLC silica column. The $NO_2$PAH were eluted with 45% DCM in hexane. This fraction was blown-down to dryness and reconstituted with 50 μL Recovery Standard before the GC-HRMS analysis.

The final extract was analysed for $NO_2$PAH by high resolution gas chromatography/ high resolution mass spectrometry (HRGC/HRMS) under the operating conditions summarized in Table 11. The detection limit for the analytical method is approximately 10-100 pg per sample for mono-nitrated species and approximately 40-100 pg per sample for dinitro species. Table 12 summarises the target analytes and the surrogates used for monitoring sample recovery for this method.

**Table 11. $NO_2$PAH analytical conditions**

| | |
|---|---|
| Instrument | HP 5890 Series II GC |
| Injection | Splitless, 280°C |
| Column | 30 m DB-5 fused silica, 0.25 mm ID and 0.25 μm film thickness |
| Oven Program | 90°C for 1 min, to 200°C at 20 °C/min, hold 1 min., 10 °C/min to 290 °C, hold 13 min |
| Mass Spectrometer | AutoSpec Q / 10,000 Resolution |
| Ionisation Mode | NCI using UHP methane as reagent gas, Selected Ion Recording<br>Source pressure: 2-4 x $10^{-5}$ torr<br>Source temperature: 260 °C |

**Table 12. Target analytes and surrogates for $NO_2PAH$ analytical method**

| | |
|---|---|
| 2-nitrofluorene | 1,3-dinitropyrene |
| 9-nitroanthracene | 1,6-dinitropyrene |
| 2-nitroanthracene | 1,8-dinitropyrene |
| 9-nitrophenanthrene | 7-nitro-12-methylbenzo(a)anthracene) |
| 2-nitrofluoranthene | 12-ethyl-6-nitrochrysene |
| 3-nitrofluoranthene | |
| 4-nitropyrene | Surrogates: |
| 1-nitropyrene | 9-nitrofluorene-$d_9$ |
| 2-nitropyrene | 3-nitrofluoranthene-$d_9$ |
| 7-nitrobenz(a)anthracene | 9-nitroanthracene-$d_9$ |
| 6-nitrochrysene | 1-nitropyrene-$d_9$ |
| 1-nitrobenzo(e)pyrene | 6-nitropyrene-$d_9$ |
| 6-nitrobenzo(a)pyrene | 6-nitrochrysene-$d_{11}$ |
| 4-nitrobenzo(e)pyrene | 6-nitrobenzo(a)pyrene-$d_{11}$ |
| 3-nitrobenzo(e)pyrene | |
| 3-nitrobenzo(a)pyrene | Recovery Standard: |
| 1-nitrobenzo(a)pyrene | 2-nitrodibenzodioxin-$d_7$ |
| 2-nitrobenzo(a)pyrene | |
| 9-nitrodibenzo(a,c)anthracene | |

## *3.6 Organic and Elemental Carbon*

$PM_{2.5}$ samples collected on quartz filters were submitted for organic and elemental carbon analysis to two laboratories. Selected filters were cut in half and were analyzed using the Thermal/Optical Reflective (TOR) method at the Desert Research Institute, Reno, Nevada. All of the filters were analyzed using the Thermal Optical Transmittance (TOT) method (also known as NIOSH Method 5040) at the Mining and Mineral Sciences Laboratories, Natural Resources Canada, Sudbury, Ontario.

For the TOR Method, a 0.5 $cm^2$ punch is taken from each filter sample. This filter punch is heated sequentially at temperatures of 120, 250, 450 and 550 °C in a pure helium atmosphere to evolve volatile carbon. The sample is heated further to 550, 700 and 800 °C in a 2% oxygen in helium atmosphere. The carbon dioxide evolved is converted to methane that is quantified using a flame ionisation detector. The reflectance from the deposit side of the filter is monitored throughout the analysis. This reflectance decreases during the volatilization in a helium atmosphere owing to the pyrolysis of organic material. When oxygen is added, the reflectance 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 reflectance has been attained. The definitions of organic fractions OC1, OC2, OC3, OC4 and elemental carbon fractions EC1, EC2, and EC3 are operational (i.e. based on analysis temperature program) rather than fundamental. This does not matter in source apportionment studies provided that both source and ambient samples are analysed in the same way. The TOR method has been used in a majority of source apportionment studies in the U.S.[1] and in Canada[2]. There is interest in Canada to adopt the TOT method for determining organic and elemental carbon as an instrument is now commercially available.

For the TOT method, a 1.5 $cm^2$ punch is taken from each filter sample. This filter punch is heated sequentially at temperatures of 300, 600 and 900 °C in a pure helium atmosphere to evolve volatile carbon. The sample is cooled to 600 °C, the atmosphere is changed to 2% oxygen in helium and the sample is heated further at 600, 750 and 940 °C. The carbon dioxide evolved is converted to methane that 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.

## 3.7 Ions and Organic Acids

After gravimetric determinations, the Teflon membrane filters were 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 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 acids. Both ion chromatography methods used suppressed conductivity detection while the capillary electrophoresis method used indirect UV detection at 214 nm[3]. Table 13 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 10 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 for sulphate ion by isocratic ion chromatography with suppressed conductivity detection. The detection limit for this method is approximately 0.17 mg/mile.

The citric acid coated filters were extracted into 10 mL deionised water and ultrasonicated for 30 minutes. The extracts were analysed for ammonium ion by isocratic ion chromatography with suppressed conductivity detection. The detection limit for this method is approximately 0.02 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[3]. Table 14 summarises the complete suite of organic acids determined using this method and their respective detection limits.

**Table 13. Particle phase organic and inorganic ions and their detection limits (mg/mile).**

| Particle Phase Anions | | | Particle Phase Inorganic Cations | | |
|---|---|---|---|---|---|
| | DL | QL | | DL | QL |
| Fluoride | 0.003 | 0.015 | Lithium | 0.006 | 0.021 |
| Acetate | 0.045 | 0.145 | Sodium | 0.027 | 0.089 |
| Propionate | 0.081 | 0.273 | Ammonium | 0.027 | 0.092 |
| Formate | 0.021 | 0.071 | Potassium | 0.057 | 0.193 |
| MSA | 0.057 | 0.187 | Rubidium | 0.126 | 0.418 |
| Chloride | 0.021 | 0.065 | Cesium | 0.075 | 0.243 |
| Nitrite | 0.006 | 0.021 | Magnesium | 0.015 | 0.050 |
| Bromide | 0.012 | 0.039 | Manganese | 0.045 | 0.151 |
| Nitrate | 0.006 | 0.021 | Strontium | 0.069 | 0.225 |
| Sulphate | 0.033 | 0.119 | | | |
| Oxalate | 0.021 | 0.068 | | | |
| Phosphate | 0.012 | 0.039 | | | |

**Table 14. Gas phase organic acids and their detection limits (mg/mile).**

| | Ion Chromatography | | Capillary Electrophoresis | |
|---|---|---|---|---|
| | DL | QL | DL | QL |
| malonic | 0.016 | 0.055 | 0.216 | 0.714 |
| formic | 0.014 | 0.047 | 0.114 | 0.377 |
| glycolic | 0.030 | 0.097 | 0.199 | 0.653 |
| acetic | 0.030 | 0.097 | 0.122 | 0.403 |
| lactic | | | 0.199 | 0.653 |
| propionic | 0.054 | 0.182 | 0.081 | 0.266 |
| benzoic | | | 0.199 | 0.653 |
| succinic | 0.034 | 0.109 | 0.182 | 0.602 |
| glutaric | | | 0.186 | 0.616 |
| oxalic | | | 0.193 | 0.639 |

## *3.8 Alkanes and Biomarkers*

Quartz filters were submitted for analyses of alkanes and biomarkers to the CANMET Energy Technology Centre of Natural Resources Canada. The analytical methodology can be found in their reports entitled "Determination of the Concentration, Composition and Sources of Airborne Carbonaceous Particles in Canada. Analytical Methodologies for Determination of Paraffins and Biomarkers. Phase 1" and "Phase 2." The method is briefly summarized below.

The goal of the method development work was to establish a sample extraction and cleanup procedure that would allow analysis of non-polar compounds, the suite of PAH compounds and polar compounds from a single sample. This study is the first attempt at implementing the combined procedure on a set of samples. The results for the non-polar alkanes and biomarkers are reported. The fractions generated containing the suite of PAH compounds and the polar compounds were used in further method development studies and quantitative results are not available.

The filters were received in polystyrene petri dishes, sealed with parafilm, wrapped in aluminum foil and sealed in plastic bags. They were stored in the freezer (<-20°C) prior to analysis.

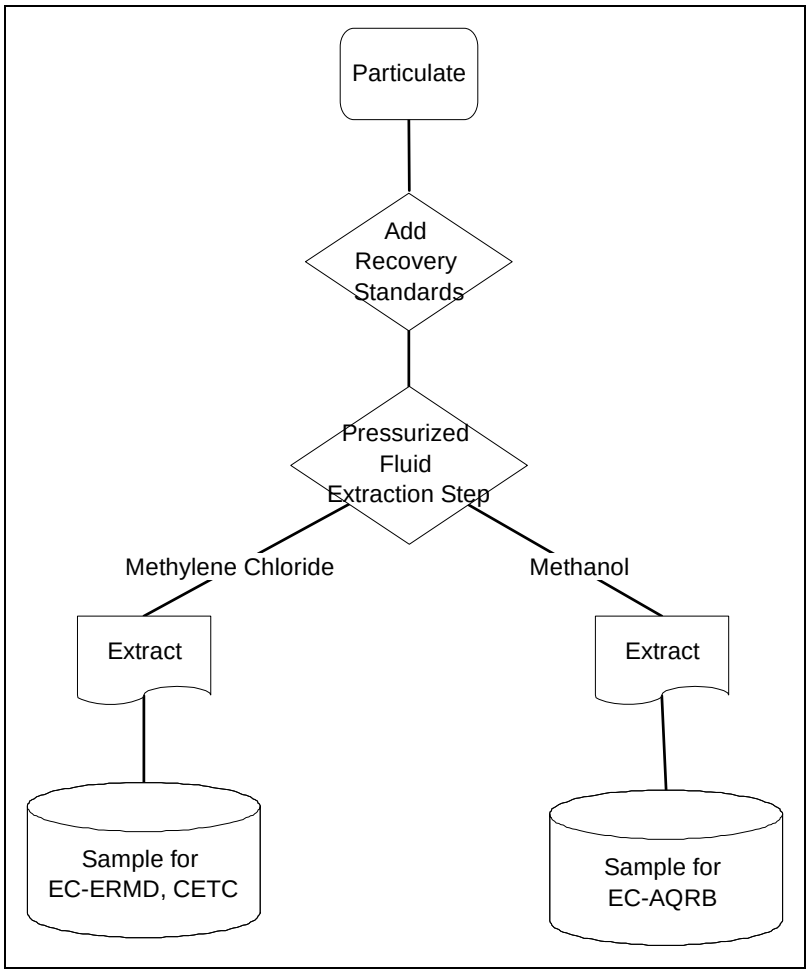
Distilled chromatographic grade solvents including acetone, cyclohexane, toluene, dichloromethane (DCM) and methanol were used without further purification. Silica gel (100-200 mesh, pore size 150Å, pore 1.2$cm^3$/g, active surface 320 $m^2$/g), as purchased from Aldrich (Milwaukee, WI) was used. The silica is placed into a large chromatographic column and eluted with 2 volumes of methanol followed by 2 volumes of DCM. The silica is transferred to a large beaker and allowed to air dry overnight. Next, the silica is dried in an oven at 75°C for several hours then activated at 250°C for 24 hours and stored at this temperature until use. Deactivated silica is prepared by adding 5 % water to activated silica (w/w) and shaking vigorously until no clumps are observed.

Aliphatic standards, deuterotetracosane, and 5-α-androstane were obtained from Chiron Laboratories (Trondheim, Norway), Chromatographic Specialties, Ultra Scientific/VWR and Aldrich (Milwaukee, WI). The alkylcyclohexane, sterane and hopane standards were purchased from Chiron Laboratories (Trondheim, Norway). Deuterotetracosane, 5-α-androstane and β,β-hopane were used as internal recovery standards.

ASE OPERATIONAL CONDITIONS

In Figure 2, the particulate-loaded filters are placed in the extraction cell of the pressurized solvent extractor ASE 200 from DIONEX (hereafter referred to as ASE) after being spiked with appropriate alkane, biomarker and PAH recovery standards. The filters are extracted sequentially with DCM followed by methanol.

**Figure 2. ASE extraction scheme**



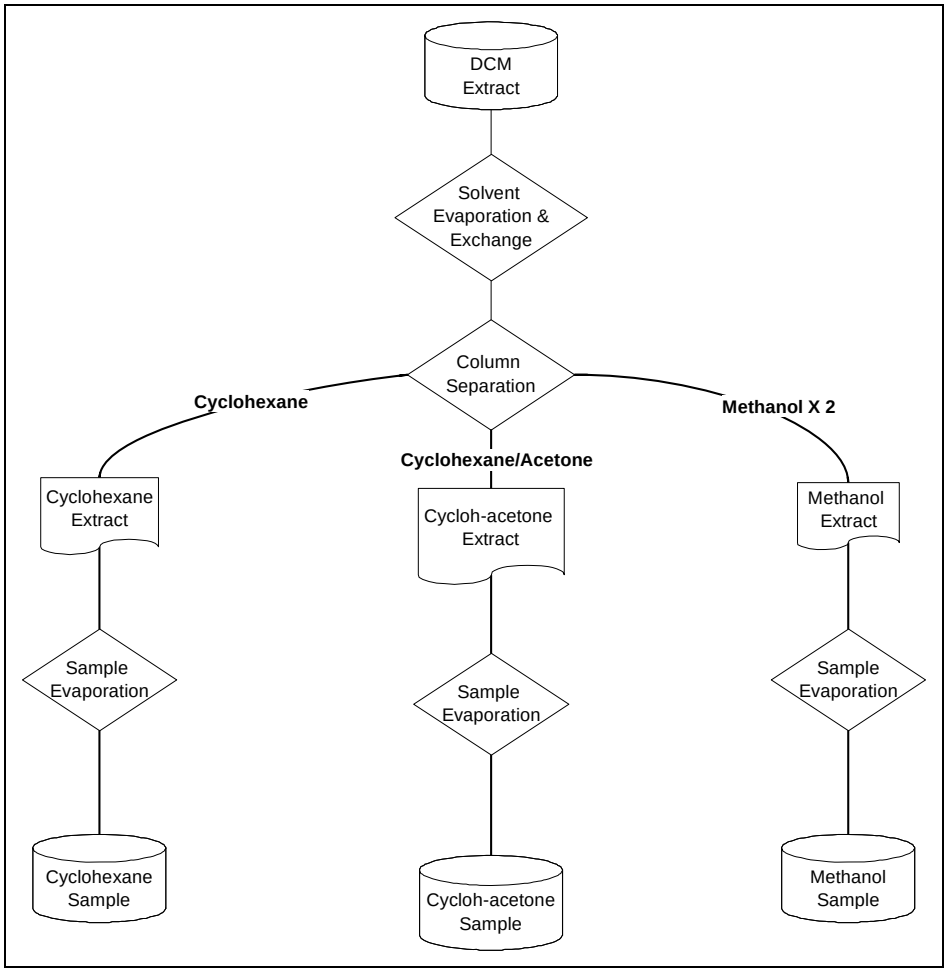

The DCM extract is solvent exchanged to cyclohexane and concentrated to less than 0.5mL in an automated solvent evaporator from Zymark.

CHROMATOGRAPHIC COLUMN SEPARATION

Figure 3 shows the solvent separation scheme used for all the samples analyzed in this phase. In this scheme, approximately 5 g of 5% $H_2O$ deactivated silica are 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 pre-cleaned sodium sulphate. Before each fractionation step, the sample vial was rinsed with ~1-2 mL of the appropriate solvent.

Each cyclohexane fraction was concentrated to 1 mL or less using the Zymark automated solvent evaporator. When necessary, these fractions were further concentrated to a preinjection volume of 0.1-1.0 mL using nitrogen blowdown in a precalibrated vial or Kuderna-Danish concentrator.

**Figure 3. Separation scheme - column chromatography of DCM extracts**




GAS CHROMATOGRAPHY-MASS SPECTROMETRY

The analysis for alkanes, pristane, phytane and biomarker compounds was performed on an HP 6890GC equipped with a 5972a or 5973 mass selective detector (MSD). System control and data acquisition were achieved with an HP MS Chemstation (Windows95 or Windows NT series). Instrumental and measurement parameters were described in detail in the previous report.

The MSD was operated in scan mode to obtain spectral data for identification of components and in the selected ion monitoring mode (SIM) for quantitative analysis of target compounds:

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

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.

# 4. Results and Discussion

Exhaust emission tests were conducted on a light duty truck over a four phase FTP cycle consisting of two LA-4 driving cycles using low sulphur diesel fuel and various biodiesel blends. The following section provides the summarized results of this testing while the complete body of results is contained in Appendix 1.

## *4.1 Criteria Emissions*

The average mass emission rates of the criteria emissions (CO, $NO_X$, THC), $CO_2$, and fuel consumption with the standard deviation (*in italics*) obtained for each fuel at standard temperature and cold temperature are presented in Table 15 and Table 16. Emission rates over the entire cold start and hot start tests were calculated and are compared in Figure 4. The fuel consumption obtained over the cold start and hot start tests are compared in Figure 5.

**Table 15. Emission rates (g/mile) and fuel consumption (L/100 km) at standard temperature (24°C)**

| Fuel | Test Cycle | | CO | $CO_2$ | $NO_X$ | THC | FC (L/100 km) |
|---|---|---|---|---|---|---|---|
| LSD | Cold Start | Phase 1 | 1.42 | 599 | 7.67 | 0.105 | 13.98 |
| | | | *0.02* | *5* | *0.15* | *0.006* | *0.11* |
| | | Phase 2 | 1.21 | 619 | 7.69 | 0.139 | 14.45 |
| | | | *0.07* | *2* | *0.11* | *0.008* | *0.06* |
| | Hot Start | Phase 1 | 0.88 | 522 | 5.75 | 0.086 | 12.18 |
| | | | *0.03* | *2* | *0.10* | *0.012* | *0.06* |
| | | Phase 2 | 1.12 | 594 | 7.39 | 0.140 | 13.85 |
| | | | *0.03* | *5* | *0.09* | *0.008* | *0.11* |
| B10 | Cold Start | Phase 1 | 1.51 | 583 | 7.31 | 0.105 | 13.59 |
| | | | *0.07* | *9* | *0.06* | *0.003* | *0.18* |
| | | Phase 2 | 1.26 | 653 | 7.32 | 0.116 | 15.19 |
| | | | *0.04* | *63* | *0.11* | *0.004* | *1.44* |
| | Hot Start | Phase 1 | 0.88 | 515 | 5.52 | 0.073 | 11.97 |
| | | | *0.04* | *14* | *0.05* | *0.008* | *0.29* |
| | | Phase 2 | 1.16 | 572 | 7.05 | 0.111 | 13.31 |
| | | | *0.03* | *27* | *0.04* | *0.009* | *0.63* |
| B20 | Cold Start | Phase 1 | 1.52 | 606 | 7.66 | 0.093 | 14.01 |
| | | | *0.07* | *4* | *0.15* | *0.009* | *0.05* |
| | | Phase 2 | 1.17 | 616 | 7.49 | 0.112 | 14.22 |
| | | | *0.04* | *6* | *0.10* | *0.047* | *0.21* |
| | Hot Start | Phase 1 | 0.84 | 528 | 5.72 | 0.061 | 12.19 |
| | | | *0.04* | *9* | *0.08* | *0.006* | *0.22* |
| | | Phase 2 | 1.09 | 600 | 7.25 | 0.089 | 13.86 |
| | | | *0.06* | *5* | *0.03* | *0.012* | *0.15* |
| B30 | Cold Start | Phase 1 | 1.44 | 589 | 7.64 | 0.088 | 13.61 |
| | | | *0.01* | *11* | *0.19* | *0.003* | *0.38* |
| | | Phase 2 | 1.10 | 617 | 7.58 | 0.090 | 14.24 |
| | | | *0.01* | *14* | *0.05* | *0.011* | *0.18* |
| | Hot Start | Phase 1 | 0.81 | 521 | 5.70 | 0.057 | 12.01 |
| | | | *0.02* | *9* | *0.13* | *0.004* | *0.31* |
| | | Phase 2 | 1.02 | 593 | 7.29 | 0.086 | 13.67 |
| | | | *0.02* | *3* | *0.11* | *0.003* | *0.20* |

**Table 16. Emission rates (g/mile) and fuel consumption (L/100 km) at cold temperature (0°C)**

| Fuel | Test Cycle | | CO | $CO_2$ | $NO_X$ | THC | FC (L/100 km) |
|---|---|---|---|---|---|---|---|
| LSD | Cold Start | Phase 1 | 2.21 | 660 | 11.55 | 0.213 | 15.44 |
| | | Phase 2 | 2.42 | 564 | 7.68 | 0.224 | 13.23 |
| | Hot Start | Phase 1 | 1.19<br>*0.05* | 511<br>*81* | 5.79<br>*0.46* | 0.112<br>*0.009* | 11.93<br>*1.88* |
| | | Phase 2 | 1.57<br>*0.02* | 581<br>*84* | 7.34<br>*0.75* | 0.173<br>*0.011* | 13.59<br>*1.96* |
| B20 | Cold Start | Phase 1 | 2.36<br>*0.43* | 784<br>*11* | 11.72<br>*0.47* | 0.262<br>*0.147* | 18.16<br>*0.02* |
| | | Phase 2 | 1.86<br>*0.01* | 687<br>*9* | 8.61<br>*0.15* | 0.165<br>*0.035* | 15.89<br>*0.43* |
| | Hot Start | Phase 1 | 1.10<br>*0.02* | 595<br>*4* | 6.53<br>*0.10* | 0.101<br>*0.026* | 13.75<br>*0.29* |
| | | Phase 2 | 1.47<br>*0.03* | 656<br>*18* | 8.06<br>*0.33* | 0.137<br>*0.036* | 15.18<br>*0.63* |

In general, very small changes were observed at the test temperature of 24°C as the biodiesel blend increased. The most dramatic change was observed in the THC emissions where a steady decrease in emission rate was observed as the biodiesel blend increased. As the THC analyzer is calibrated with propane and is intended to respond to hydrocarbons ($C_xH_y$), if the composition of the exhaust changes significantly – such as an increase in oxygen-containing hydrocarbons that have a different response at the analyzer than propane does – the analyzer may be underestimating the true organic carbon emission rate. The organic carbon composition of the gas phase emissions must be fully characterized to substantiate this possible explanation.

The emissions measured at the cold test temperature (0°C) were greater than those measured at the standard test temperature (24°C), especially during the cold start portion of the test. The fuel consumption was also substantially greater at the cold test temperature.

**Figure 4. Comparison of cold start and hot start criteria emissions at the two test temperatures.**

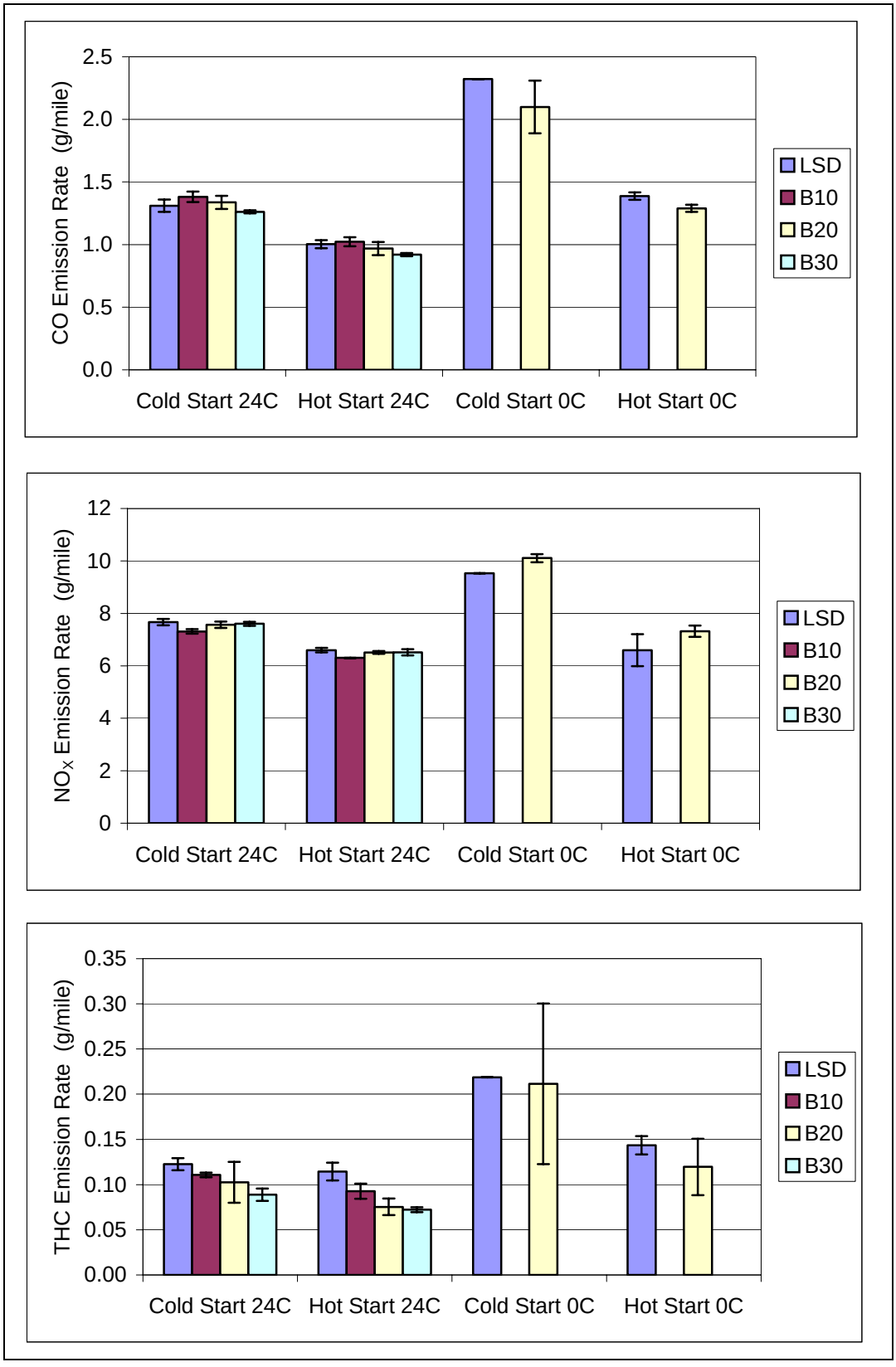


**Figure 5. Comparison of fuel consumption obtained for the test fuels at both test temperatures.**

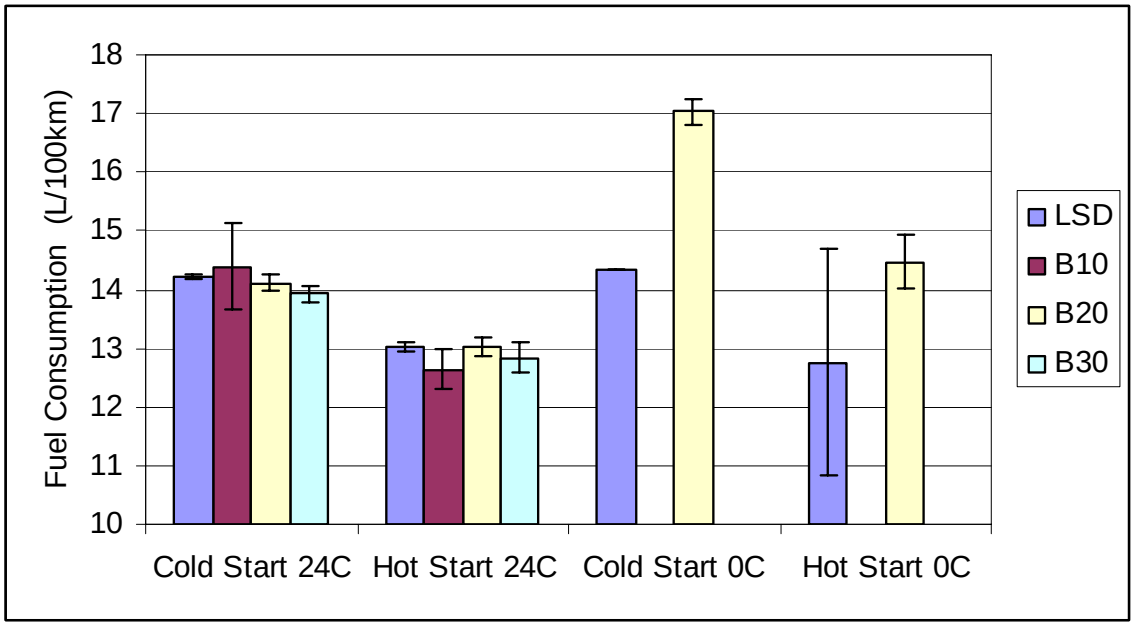
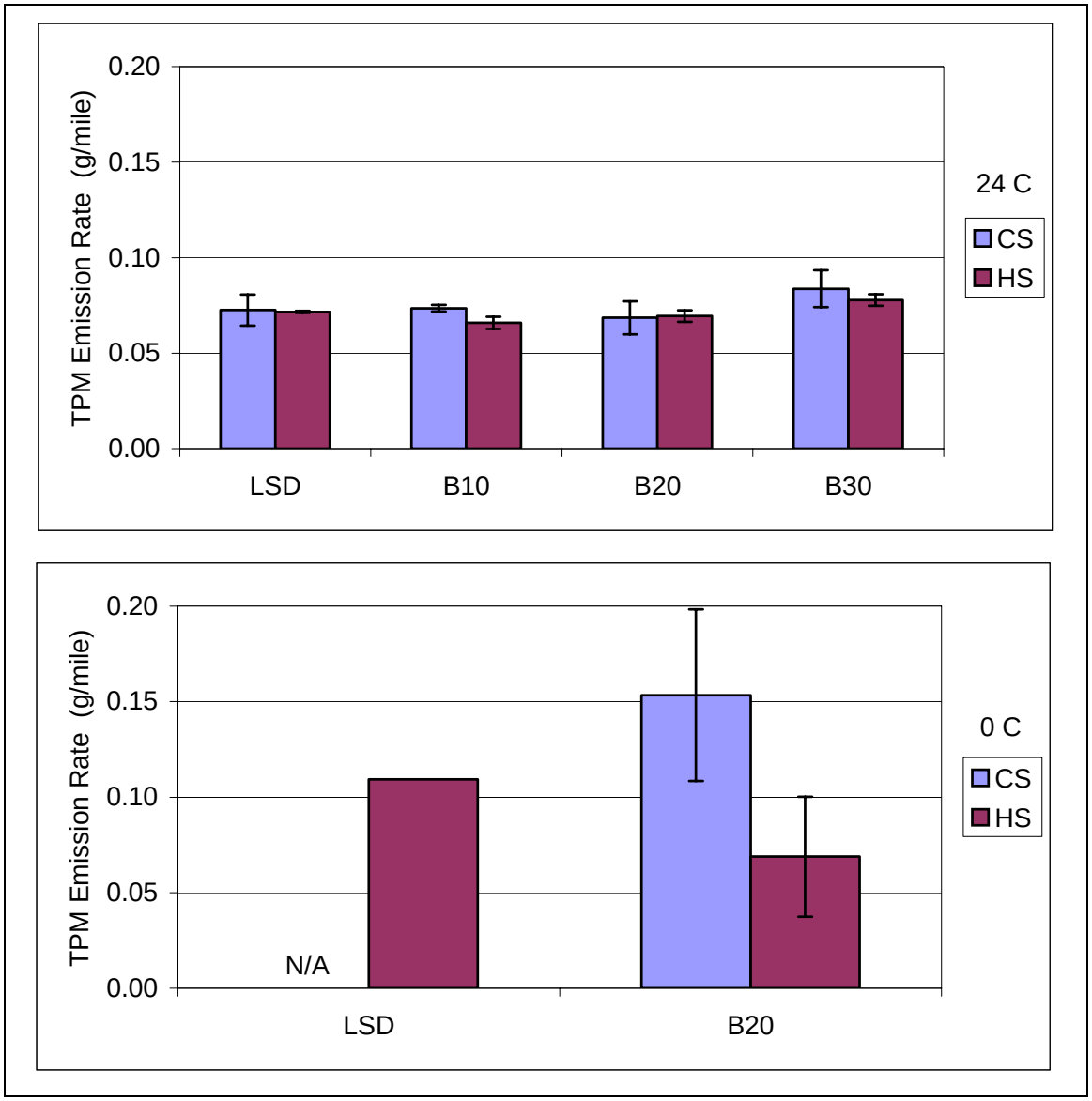



Table 17 presents the mass emission rates of total particulate matter (TPM) retained on the Pallflex 70 mm T60A20 filter that was placed upstream of the PUF. These results are compared in Figure 6. Cold start emissions were generally greater than the hot start emissions at both test temperatures. The cold temperature TPM emission rates were substantially greater than the standard temperature emission rates.

**Table 17. Summary of TPM emission rates (g/mile).**

| | Cold Start | | Hot Start | |
|---|---|---|---|---|
| **24 °C** | **avg** | **stdev** | **avg** | **stdev** |
| LSD | 0.073 | 0.008 | 0.072 | 0.001 |
| B10 | 0.073 | 0.002 | 0.066 | 0.003 |
| B20 | 0.068 | 0.009 | 0.069 | 0.003 |
| B30 | 0.084 | 0.010 | 0.078 | 0.003 |
| **0 °C** | | | | |
| LSD | N/A | | 0.109 | (1 sample) |
| B20 | 0.153 | 0.045 | 0.069 | 0.031 |

**Figure 6. Comparison of TPM emission rates.**




Analysis of variance (ANOVA) was conducted on the gaseous criteria emissions and TPM emissions to determine whether the observed changes were significant. Table 18 through Table 21 show the results of the ANOVA comparing the emissions from each of the biodiesel blends to the emissions from base low sulphur diesel fuel. Those changes that are indicated as statistically significant are so at the 95% confidence interval.

- B10 gives a statistically significant decrease in $NO_X$ emissions (4.5%) and THC emissions (10-20%) over the base fuel at the standard test temperature.
- B20 gives a statistically significant decrease in THC emissions (hot start only 34%) over the base fuel at the standard test temperature. $NO_X$ emissions remain essentially unchanged.
- B30 gives a statistically significant decrease in THC emissions (27-37%) over the base fuel at the standard test temperature.

- B20 gives a statistically significant increase (20%) in $CO_2$ emissions in the cold temperature cold start test as compared to the base fuel.

Table 22 and Table 23 show the results of the ANOVA on the test temperature effect.

- CO, $NO_X$ and THC emissions were greater at cold temperature than at standard temperature for the base fuel. The $CO_2$ emissions were essentially unchanged.
- CO, $CO_2$, $NO_X$ and THC emissions were greater at cold temperature than at standard temperature for the B20 blend. The TPM emissions on the cold temperature cold start were more than double that at standard temperature, but due to the large variation in the cold temperature results, the difference was not statistically significant.

**Table 18. ANOVA results comparing LSD and B10 emissions at 24 °C.**

| Test | | LSD | B10 | %change | Pvalue | Significant |
|---|---|---|---|---|---|---|
| Cold Start | CO | 1.31 | 1.38 | 5.4 | 0.129 | No |
| Hot Start | | 1.00 | 1.02 | 2.0 | 0.514 | No |
| Cold Start | $CO_2$ | 609 | 619 | 1.6 | 0.640 | No |
| Hot Start | | 559 | 544 | -2.7 | 0.170 | No |
| Cold Start | $NO_X$ | 7.67 | 7.31 | -4.7 | 0.013 | Yes |
| Hot Start | | 6.60 | 6.30 | -4.5 | 0.004 | Yes |
| Cold Start | THC | 0.12 | 0.11 | -9.7 | 0.047 | Yes |
| Hot Start | | 0.11 | 0.09 | -19.0 | 0.045 | Yes |
| Cold Start | TPM | 0.073 | 0.073 | 1.3 | 0.856 | No |
| Hot Start | | 0.072 | 0.066 | -7.9 | 0.121 | No |

**Table 19. ANOVA results comparing LSD and B20 emissions at 24 °C.**

| Test | | LSD | B20 | %change | Pvalue | Significant |
|---|---|---|---|---|---|---|
| Cold Start | CO | 1.31 | 1.34 | 2.0 | 0.505 | No |
| Hot Start | | 1.00 | 0.97 | -3.4 | 0.348 | No |
| Cold Start | $CO_2$ | 609 | 611 | 0.3 | 0.446 | No |
| Hot Start | | 559 | 565 | 1.0 | 0.166 | No |
| Cold Start | $NO_X$ | 7.67 | 7.57 | -1.4 | 0.276 | No |
| Hot Start | | 6.60 | 6.51 | -1.4 | 0.111 | No |
| Cold Start | THC | 0.12 | 0.10 | -16.4 | 0.196 | No |
| Hot Start | | 0.11 | 0.08 | -34.1 | 0.001 | Yes |
| Cold Start | TPM | 0.073 | 0.068 | -5.6 | 0.676 | No |
| Hot Start | | 0.072 | 0.069 | -3.1 | 0.417 | No |

**Table 20. ANOVA results comparing LSD and B30 emissions at 24 °C.**

| Test | | LSD | B30 | %change | Pvalue | Significant |
|---|---|---|---|---|---|---|
| Cold Start | CO | 1.31 | 1.26 | -3.7 | 0.175 | No |
| Hot Start | | 1.00 | 0.92 | -8.3 | 0.014 | Yes |
| Cold Start | $CO_2$ | 609 | 603 | -0.9 | 0.092 | No |
| Hot Start | | 559 | 557 | -0.3 | 0.685 | No |
| Cold Start | $NO_X$ | 7.67 | 7.60 | -0.9 | 0.457 | No |
| Hot Start | | 6.60 | 6.52 | -1.3 | 0.383 | No |
| Cold Start | THC | 0.12 | 0.09 | -27.5 | 0.004 | Yes |
| Hot Start | | 0.11 | 0.07 | -36.9 | 0.002 | Yes |
| Cold Start | TPM | 0.073 | 0.084 | 15.4 | 0.275 | No |
| Hot Start | | 0.072 | 0.078 | 8.6 | 0.072 | No |

**Table 21. ANOVA results comparing LSD and B20 emissions at 0 °C.**

| Test | | LSD | B20 | %change | Pvalue | Significant |
|---|---|---|---|---|---|---|
| Cold Start | CO | 2.32 | 2.10 | -9.6 | 0.545 | No |
| Hot Start | | 1.39 | 1.29 | -7.0 | 0.078 | No |
| Cold Start | $CO_2$ | 610 | 733 | 20.2 | 0.008 | Yes |
| Hot Start | | 547 | 627 | 14.5 | 0.310 | No |
| Cold Start | $NO_X$ | 9.53 | 10.11 | 6.1 | 0.204 | No |
| Hot Start | | 6.59 | 7.32 | 11.0 | 0.253 | No |
| Cold Start | THC | 0.22 | 0.21 | -3.2 | 0.959 | No |
| Hot Start | | 0.14 | 0.12 | -16.7 | 0.411 | No |

* insufficient TPM data for ANOVA.

**Table 22. ANOVA results comparing LSD emissions at 24 °C and 0°C.**

| Test | | 24 C | 0 C | %change | Pvalue | Significant |
|---|---|---|---|---|---|---|
| Cold Start | CO | 1.31 | 2.32 | 77.2 | 0.003 | Yes |
| Hot Start | | 1.00 | 1.39 | 38.3 | 0.001 | Yes |
| Cold Start | $CO_2$ | 609 | 610 | 0.2 | 0.520 | No |
| Hot Start | | 559 | 547 | -2.1 | 0.801 | No |
| Cold Start | $NO_X$ | 7.67 | 9.53 | 24.2 | 0.006 | Yes |
| Hot Start | | 6.60 | 6.59 | -0.1 | 0.984 | No |
| Cold Start | THC | 0.12 | 0.22 | 78.4 | 0.007 | Yes |
| Hot Start | | 0.11 | 0.14 | 25.4 | 0.050 | Yes |

* insufficient TPM data for ANOVA.

**Table 23. ANOVA results comparing B20 emissions at 24 °C and 0°C.**

| Test | | 24 C | 0 C | %change | Pvalue | Significant |
|---|---|---|---|---|---|---|
| Cold Start | CO | 1.34 | 2.10 | 57.0 | 0.000 | Yes |
| Hot Start | | 0.97 | 1.29 | 33.1 | 0.001 | Yes |
| Cold Start | $CO_2$ | 611 | 733 | 20.1 | 0.000 | Yes |
| Hot Start | | 565 | 627 | 10.9 | 0.000 | Yes |
| Cold Start | $NO_X$ | 7.57 | 10.11 | 33.6 | 0.000 | Yes |
| Hot Start | | 6.51 | 7.32 | 12.4 | 0.000 | Yes |
| Cold Start | THC | 0.10 | 0.21 | 106.5 | 0.033 | Yes |
| Hot Start | | 0.08 | 0.12 | 58.6 | 0.022 | Yes |
| Cold Start | TPM | 0.068 | 0.153 | 124.0 | 0.120 | No |
| Hot Start | | 0.069 | 0.069 | -0.8 | 0.983 | No |

## *4.2 Methane and Non-methane Hydrocarbons*

Methane and non-methane hydrocarbons were determined were determined for the cold start and hot start tests. Hydrocarbon profiles for the cold start and hot start tests at both temperatures are shown in Figure 7 and Figure 8. The complete dataset is given in Appendix 1, along with the compound names that correspond to the identifier numbers shown in the figures. As is typical of diesel emissions, the methane emission rate was very low, often reported as zero when the dilution air concentration was subtracted. The hydrocarbon emissions are dominated by light compounds ($<C_3$). For standard temperature tests, the light hydrocarbons account for between 30% and 40% of the total named hydrocarbon emissions while for the cold temperature tests, this increases to 50%. The total named hydrocarbons account for 40% to 80% of the total hydrocarbons determined by the test cell analyzer. This is largely due to the method not identifying a significant fraction of the semivolatile material. Only the straight chain hydrocarbons are determined above $C_{12}$.

The cold start emissions are greater than the hot start emissions at both test temperatures. Cold temperature operation causes an increase in emissions for both the cold start and hot start tests. The profiles of the $C_3$+

hydrocarbons don't change substantially with test cycle or with test temperature, only the magnitude changes.

**Figure 7. Comparison of cold start and hot start emission profiles for the LSD tests.**

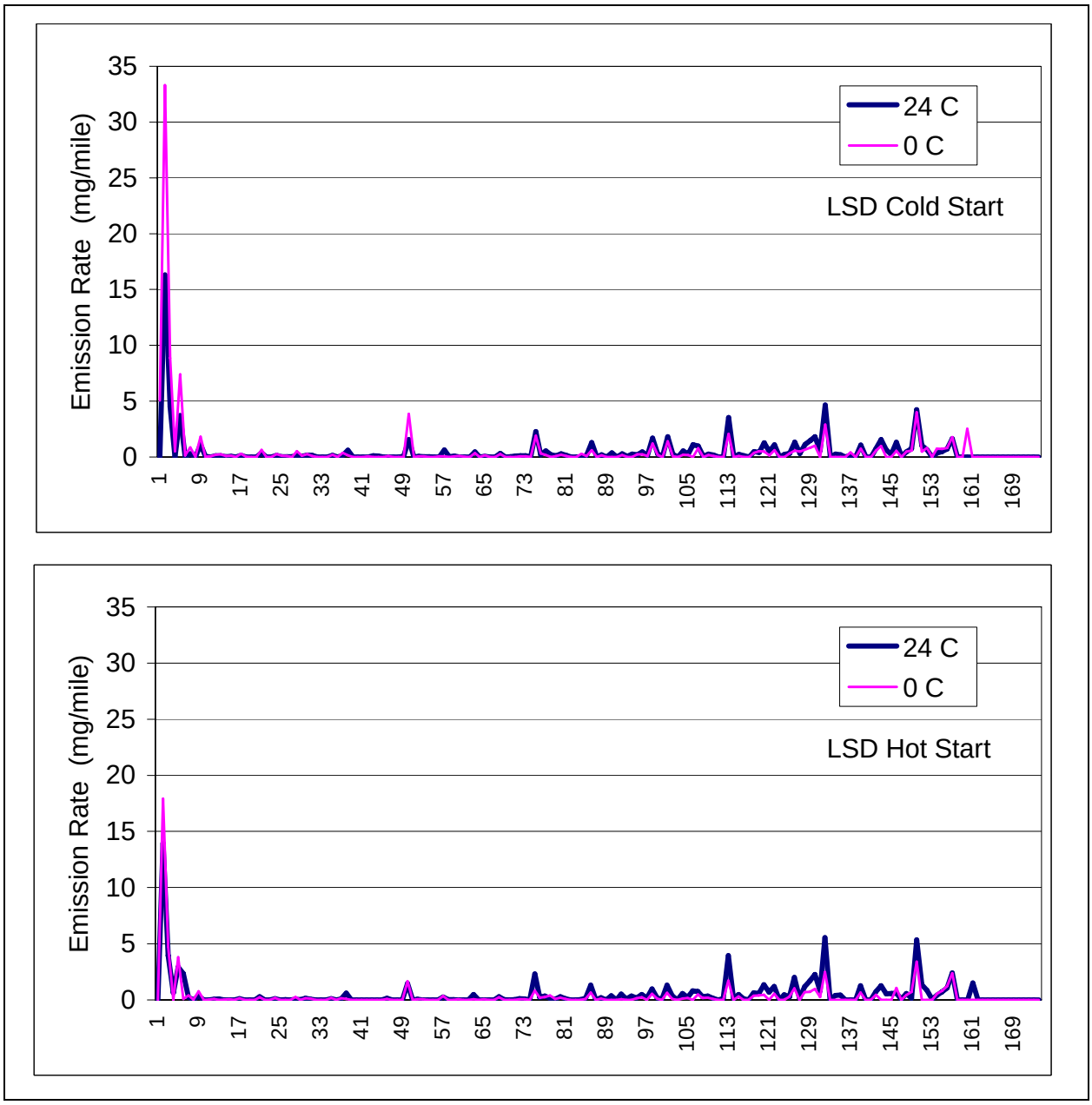
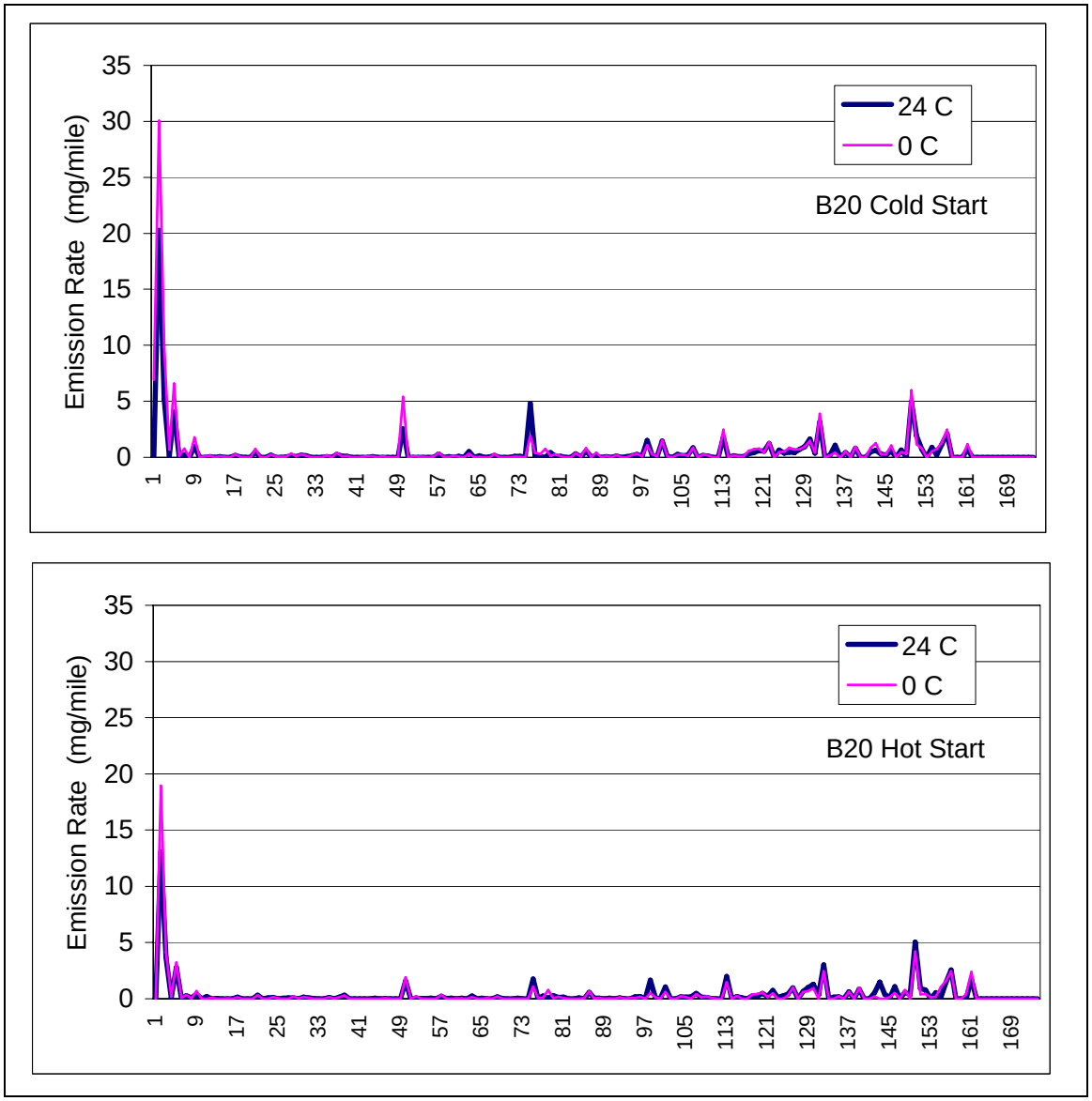


**Figure 8. Comparison of cold start and hot start emission profiles for the B20 tests.**



## 4.3 Methyl Esters

The biodiesel blend used in this study was a methyl ester of soybean oil. A sample of the neat ester was diluted with pentane analysed using the same method as the SvNMHC samples to determine where in the chromatogram the ester compounds would appear. The chromatogram of the neat material is shown in Figure 9. The ester compounds were identified as given in Table 24. The low sulphur diesel fuel and the B30 biodiesel blend were diluted and analyzed in the same way and the resulting chromatograms are shown in Figure 10 and Figure 11. The classic straight chain hydrocarbon pattern of diesel fuel is readily apparent in these two figures. None of the ester compounds were found in the vapour phase dilute exhaust samples. Due to their low volatility, it is likely that if they survived the combustion process, they would be found in the particle phase. These compounds were not determined in the particle phase.

**Figure 9. Chromatogram of the neat soybean methyl ester.**

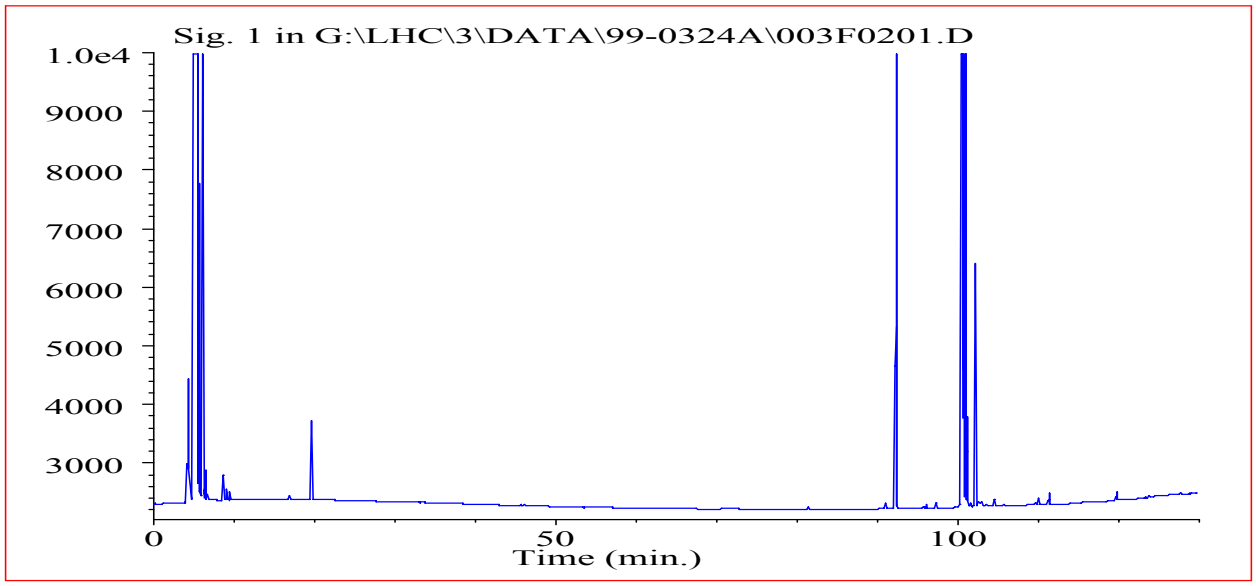



**Figure 10. Chromatogram of the low sulphur diesel fuel.**

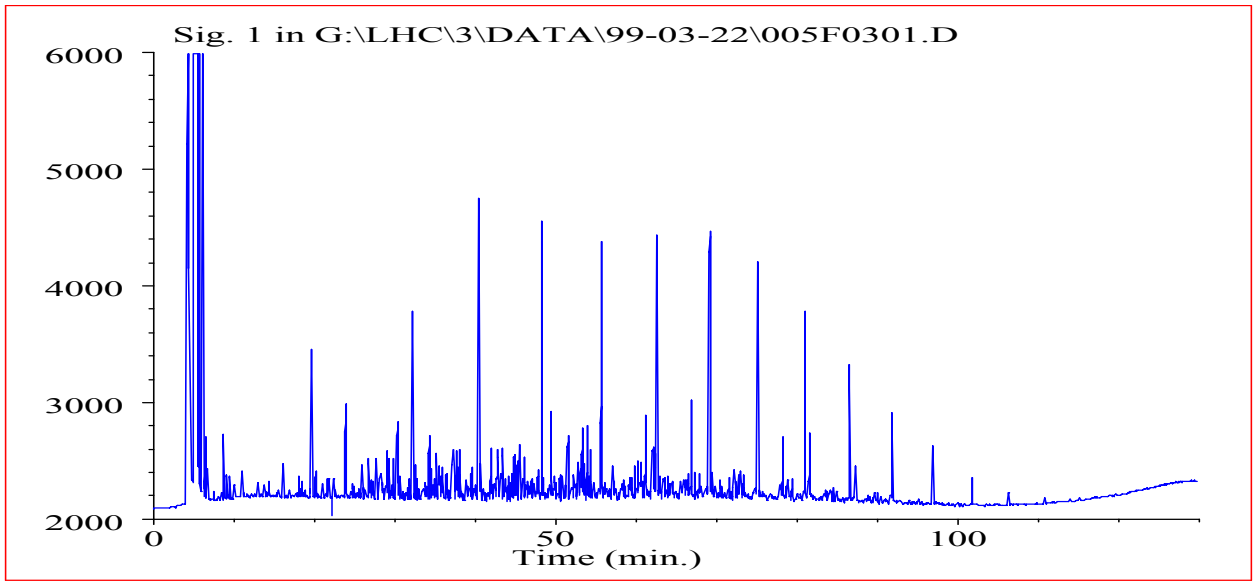


**Figure 11. Chromatogram of the B30 biodiesel blend.**

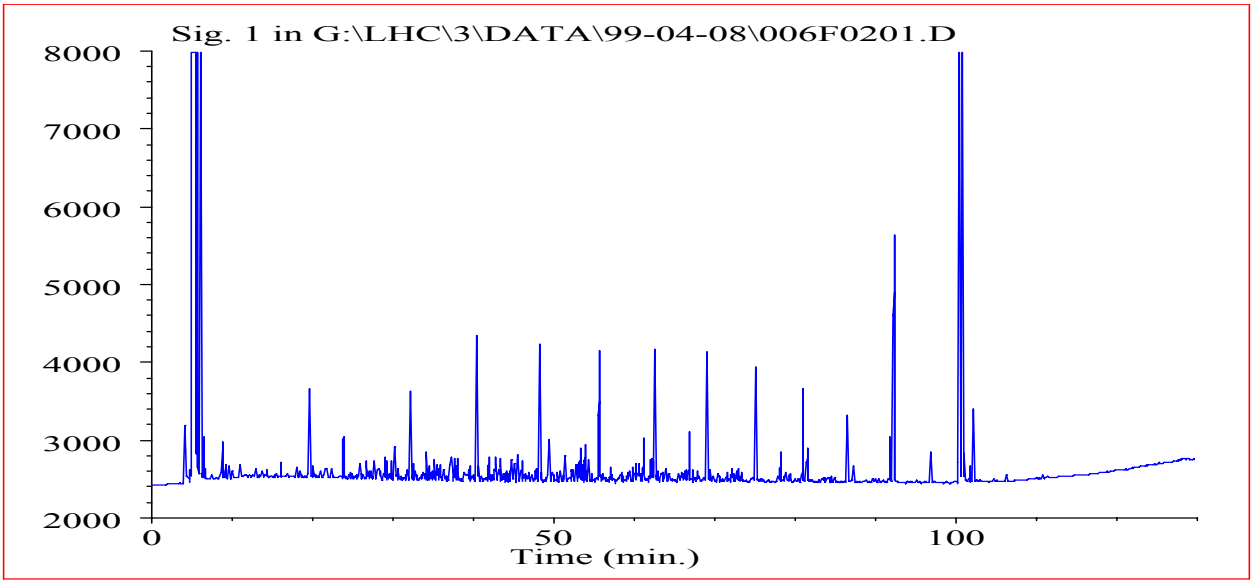



**Table 24. Peak identification for Figure 9.**

| Ester | Retention Time (min) |
|---|---|
| Palmitic acid methyl ester (C16:0) | 92.65 |
| Linoleic acid methyl ester (C18:2) | 100.86 |
| Linolenic acid methyl ester (C18:3) | 100.99 |
| Oleic acid methyl ester (C18:1) | 101.24 |
| Stearic acid methyl ester (C18:0) | 102.57 |
| Eicosenonic acid methyl ester (C20:1) | 110.43 |
| Arachidic acid methyl ester (C20:0) | 111.69 |
| Behenic acid methyl ester (C22:0) | 120.13 |
| Lignoceric acid methyl ester (C24:0) | 128.17 |

## *4.4 Carbonyls*

Carbonyl compounds were determined on the cold start and hot start tests. The complete set of results are tabulated in Appendix 1. The average cold start and hot start results for each fuel at standard temperature are shown in Figure 12 and the cold temperature results are shown in Figure 13. The cold start emission rates are generally greater than the hot start emission rates at both test temperatures. The cold temperature cold start emissions are greater than the standard temperature cold start emissions while the hot start emissions at both test temperatures are very similar. There are no significant changes in the formaldehyde and acetaldehyde emissions with changes in the test fuel, but acrolein emissions are greater (100-300%) on the biodiesel blends than they are on the base fuel. There is insufficient data to determine whether these increases are statistically significant. The vehicle is equipped with an oxidation catalyst, so changes in engine-out emissions will not be apparent from measured tailpipe emissions. Many questions remain unanswered such as:

- Are engine out emissions of formaldehyde and acetaldehyde greater with the biodiesel blends but the catalyst is effective in reducing them to levels seen with the base fuel?

- Is the engine out emission rate of acrolein greater with the biodiesel blends and the catalyst ineffective in reducing the level to that seen with the base fuel?
- Is acrolein formed over the catalyst from other combustion products of the biodiesel blends?

**Figure 12. Comparison of carbonyl compound emission rates at standard temperature.**

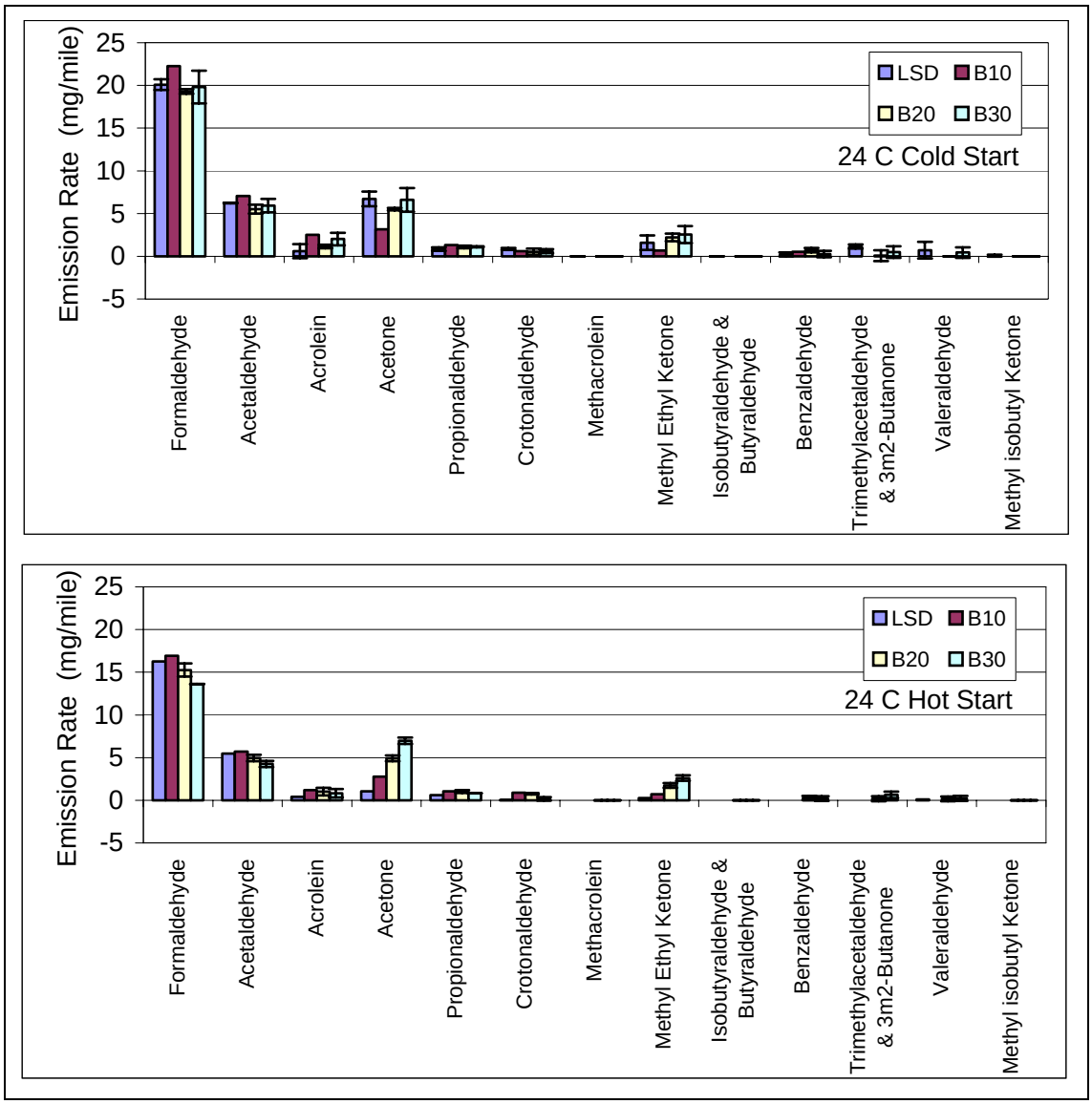
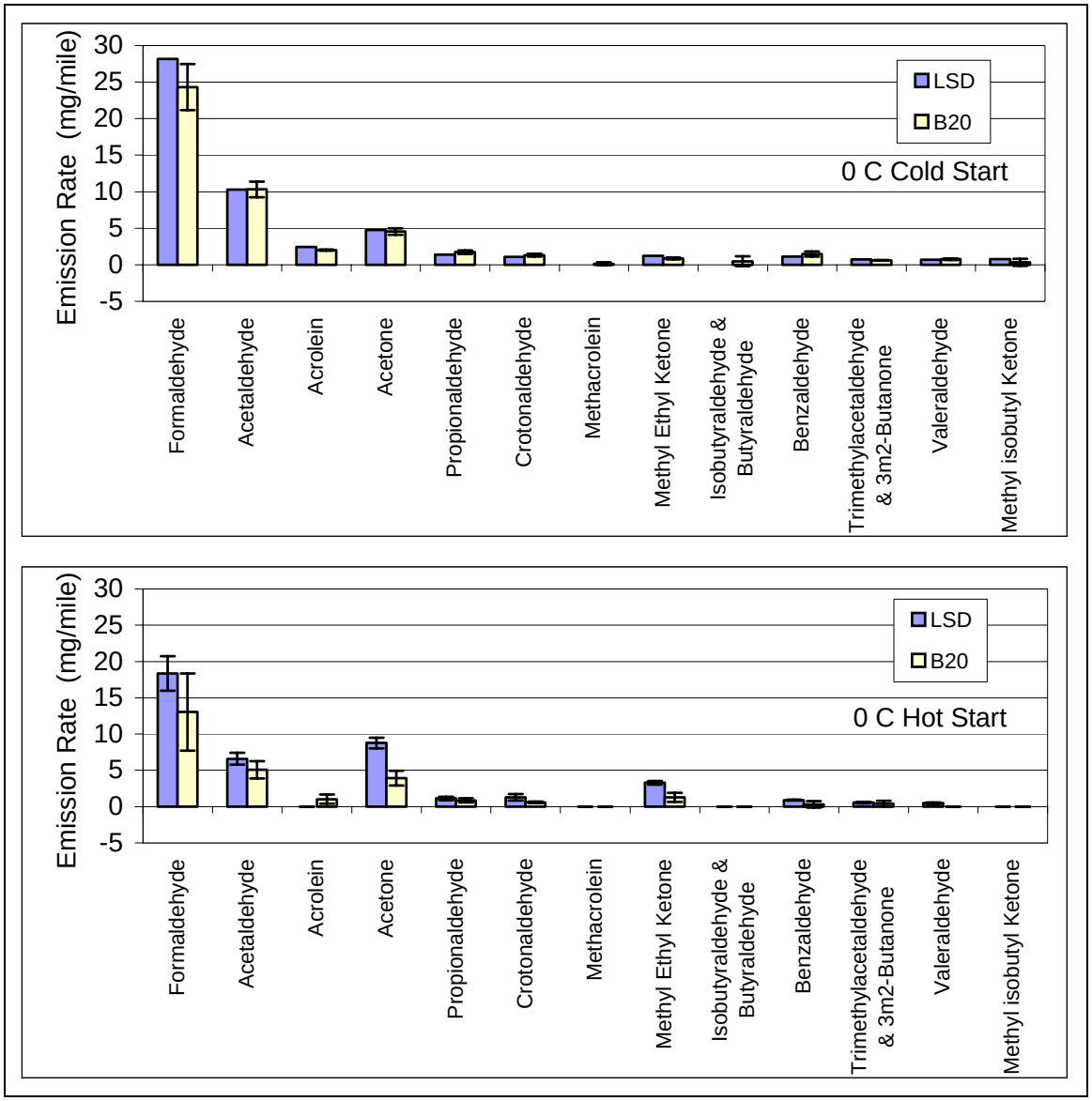


**Figure 13. Comparison of carbonyl compound emission rates at cold temperature.**



## 4.5 PAH, PASH and $NO_2$-PAH

Emission rates for PAH, PASH and NO2-PAH are tabulated in Appendix 1. Figure 14, Figure 15 and Figure 16 present the mass emission rate (μg/mi) of PAH, PASH, and $NO_2$PAH compounds, respectively. The PAH results are shown on two panels due to the large difference in emission rates of the lighter compounds as compared to the heavier compounds. The first panel shows species that are more volatile, thus found predominantly in the vapour phase. The second panel shows species that are largely particle bound. Samples of the dilution air were not collected for PAH, PASH, and $NO_2$-PAH analysis, so the reported results are not corrected for dilution air concentrations. The PAH and $NO_2$-PAH analytical results were corrected for surrogate recovery which provides upper limits of the emission rates. PASH results are not corrected for surrogate recovery. The general trend observed is that PAH and $NO_2$-PAH emissions tend to increase with the use of biodiesel blends, but the increase does not seem to directly correlate with the blend level. The PASH emission rates do not change with fuel. It is suspected that these compounds arise largely from the lubricating oil, not the fuel.

**Figure 14: Comparison of mass emission rates of PAHs.**

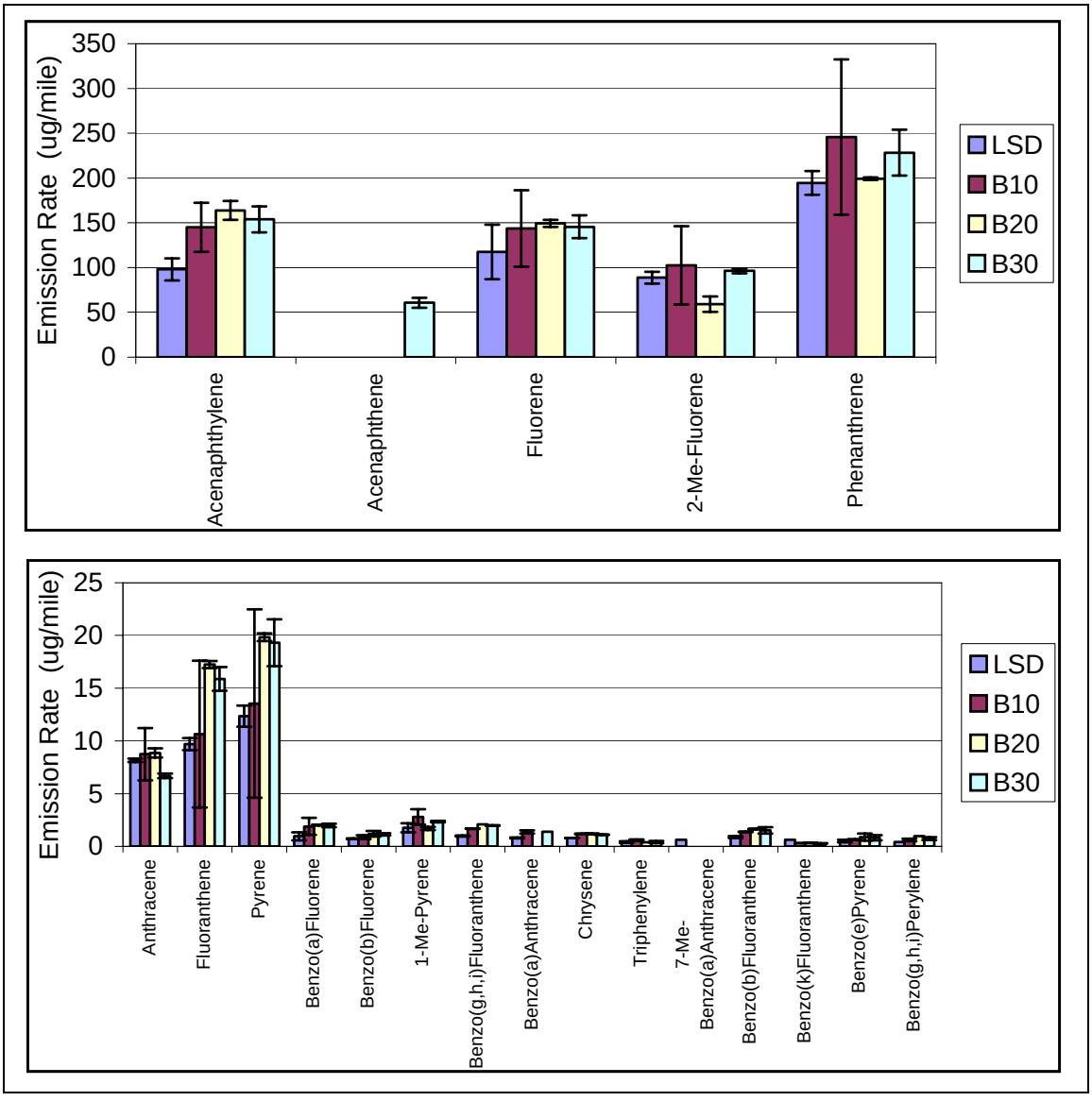


**Figure 15: Comparison of mass emission rates of PASHs.**

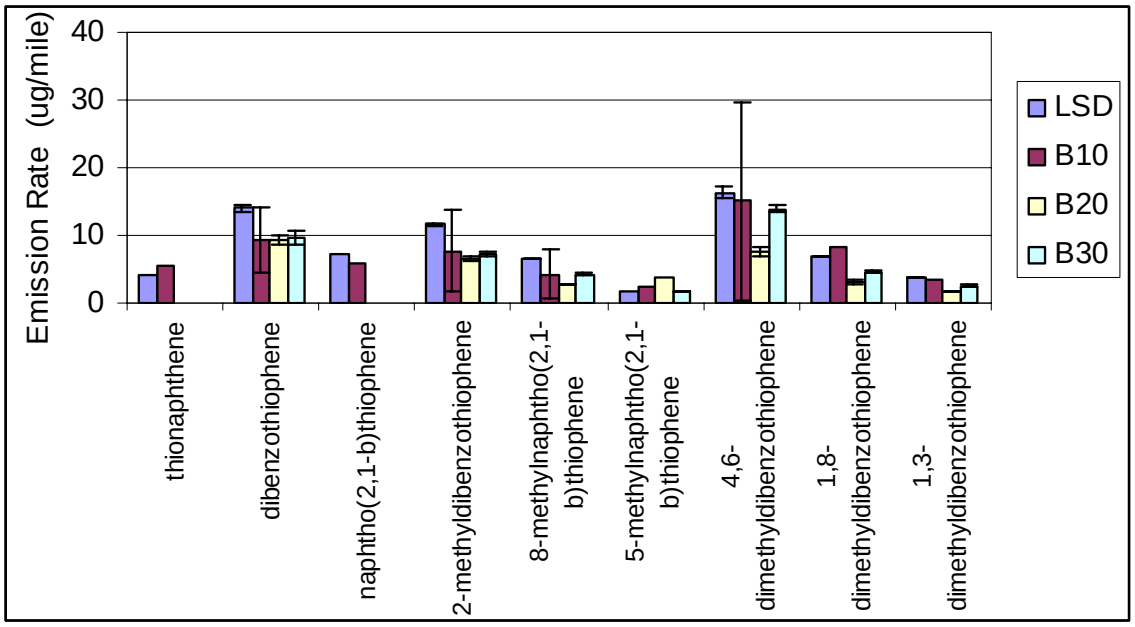
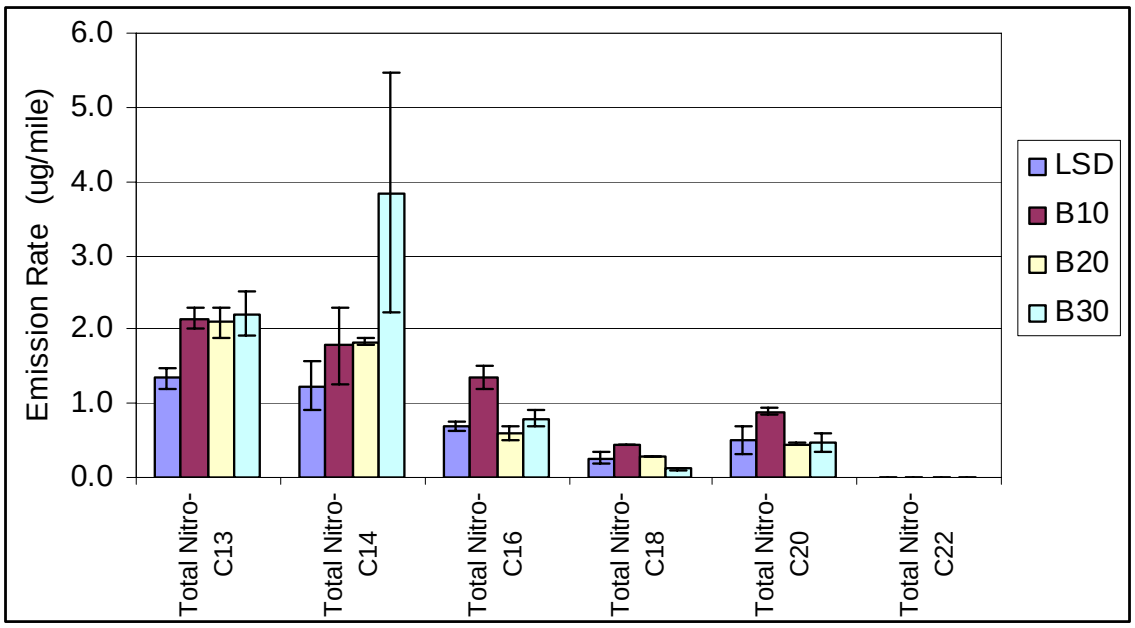



**Figure 16: Comparison of mass emission rates of $NO_2$PAHs.**



## 4.6 $PM_{2.5}$

For regulatory purposes, particulate matter emissions are sampled as total particulate matter (TPM). There is no size selection imposed on the sample stream before it is drawn through the filter media during sample collection. For use in source apportionment studies, particulate matter emissions are sampled using a cyclone to obtain either $PM_{10}$ or $PM_{2.5}$ samples. This is done to facilitate comparison to the $PM_{10}$ and $PM_{2.5}$ ambient air samples that are routinely collected.

In the present study $PM_{2.5}$ cyclones were used. The combustion particles in freshly diluted vehicle exhaust are all smaller than 1 μm in diameter. The observed differences between TPM and $PM_{2.5}$ mass emission rates determined in this study are due to several factors. The first factor is the CVS used to dilute the raw exhaust. Over time, a layer of particulate matter accumulates on the inner surfaces of the system and particles are re-entrained in the exhaust sample. These particles are much larger than exhaust particles and can contribute significantly to the mass of a TPM sample. These particles are removed from the $PM_{2.5}$ sample stream by the cyclone. The second factor is the different filter media used for the two samples. The TPM samples are collected on Teflon coated glass fibre filters (Pallflex T60A20) while the $PM_{2.5}$ samples collected for mass emission rate determination are collected on Teflon membrane filters (Gelman Teflo 2 μm pore size). The membrane filters have a much higher efficiency for smaller particles than do the Teflon coated glass fibre filters. The Teflon coated glass fibre filters also show some adsorption of vapour phase organic material while the Teflon membrane filters do not. The third factor is similar in some ways to the first in that any particles generated from the exhaust system (rust, catalyst attrition) are also excluded from the $PM_{2.5}$ sample but remain as part of the TPM sample.

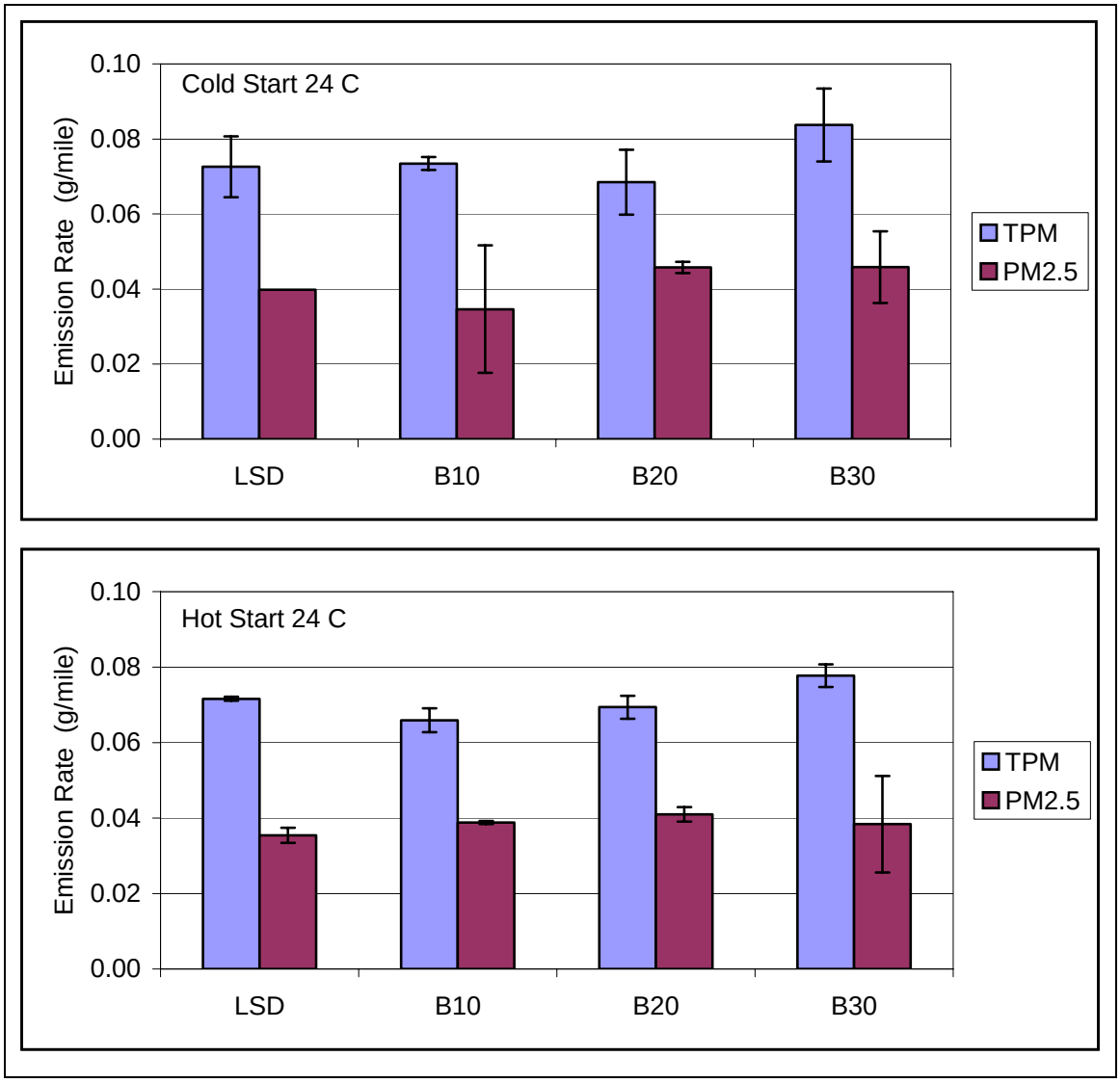
### 4.6.1 Mass

Table 25 presents the mass emission rates of particulate matter less than 2.5 μm diameter retained on the 47 mm diameter Teflon membrane filters. A comparison of the $PM_{2.5}$ emission rates and the TPM emission rates is shown in Figure 17. The measured $PM_{2.5}$ emission rates are approximately 45% lower than the measured TPM emission rates. This difference seems large in the context of the possible reasons given above.

**Table 25. Summary of $PM_{2.5}$ emission rates (g/mile).**

| | Cold Start | | Hot Start | |
|---|---|---|---|---|
| **24°C** | **avg** | **stdev** | **avg** | **stdev** |
| LSD | 0.040 | (1 sample) | 0.035 | 0.002 |
| B10 | 0.035 | 0.013 | 0.039 | 0.003 |
| B20 | 0.046 | 0.001 | 0.041 | 0.002 |
| B30 | 0.046 | 0.010 | 0.038 | 0.013 |
| **0°C** | | | | |
| LSD | 0.128 | (1 sample) | 0.088 | 0.013 |
| B20 | 0.142 | 0.022 | 0.100 | 0.012 |

**Figure 17. Comparison of TPM and $PM_{2.5}$ emission rates.**




## 4.6.2 Organic and Elemental Carbon

Samples of particulate matter ($PM_{2.5}$) were collected on pre-fired quartz filters for analysis of organic and elemental carbon by two different methods – Thermal Optical Transmittance (TOT) and Thermal Optical Reflectance (TOR). The TOT technique is used in the NIOSH 5040 method for determining elemental carbon in occupational health studies while the TOR technique is used by the Desert Research Institute (DRI) and has found application in a large number of U.S. ambient air studies. All samples were submitted for analysis by the TOT method. Selected samples were submitted for analysis by the TOR method for comparison.

Two filters were collected in series to allow for correction of organic carbon adsorbed by the filter media from the gas phase. The results presented below have been corrected for adsorbed organic carbon by subtracting the amount organic carbon found on the secondary quartz filter from the amount found on the primary quartz filter. This correction method is the one used in ambient air studies, but may be inadequate for vehicle emission studies as the organic carbon concentration in the gas phase is much greater than found

in ambient air samples. The magnitude of the correction is on average 32% of the uncorrected organic carbon amount.

Emission rates for organic, elemental and total carbon as determined by both methods are presented in Appendix 1. The total carbon emission rate as determined by the TOT method is compared to both the TPM and the $PM_{2.5}$ mass emission rates in Figure 18. For nearly all the standard temperature samples, the total carbon emission rate is equal to or greater than the measured $PM_{2.5}$ mass emission rate. This is not possible since the carbon analysis does not include any of the hydrogen bonded to the organic carbon. The $PM_{2.5}$ mass includes other particle phase species such as sulphate and ash (metal oxides). This is evidence that the organic carbon correction is insufficient for vehicle emission samples. The last two data points in the figure are for the cold temperature tests on B20. It appears that there may be substantial material that is not carbonaceous in these samples.

**Figure 18. Comparison of total $PM_{2.5}$ carbon to $PM_{2.5}$ mass.**

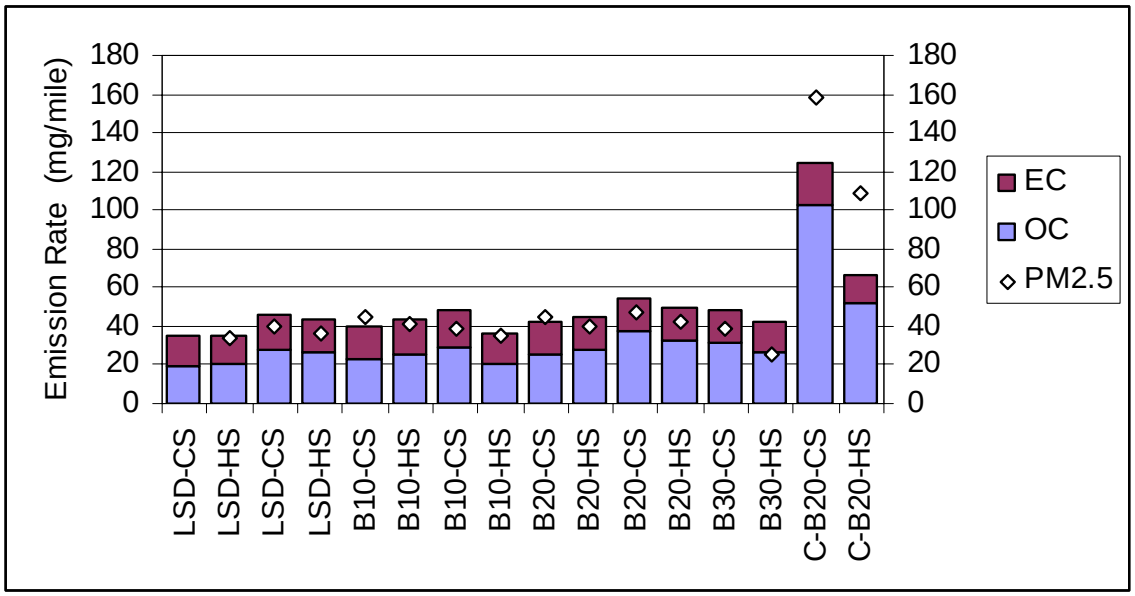



Figure 19 shows the change in distribution of carbon in $PM_{2.5}$ samples with change in fuel and test temperature. There appears to be a very slight increase in organic carbon content at standard temperature with the use of biodiesel fuels. A significant increase in organic carbon content appears with a decrease in test temperature. This might suggest the need for cold temperature vehicle emission profiles when using winter ambient air samples in source apportionment work.

Figure 20 shows a comparison of the results for organic, elemental and total carbon obtained by the two methods. The TOT method tends to give organic carbon results about 14% greater and elemental carbon results about 16% lower than the TOR method. The overall difference in total carbon results from the two methods is less than 2.5%, well within the measurement uncertainties of the two methods. The difference in the distribution of organic and elemental carbon between the two methods results from the manner in which the correction for pyrolized carbon is accomplished. Since neither method is an absolute measurement, an assessment for which method is correct cannot be done. Therefore it is important to ensure that when conducting source apportionment work, the emission source profiles and the ambient air receptor profiles are developed from data that is obtained from the same method whenever possible.

**Figure 19. Distribution of carbon in $PM_{2.5}$ samples.**

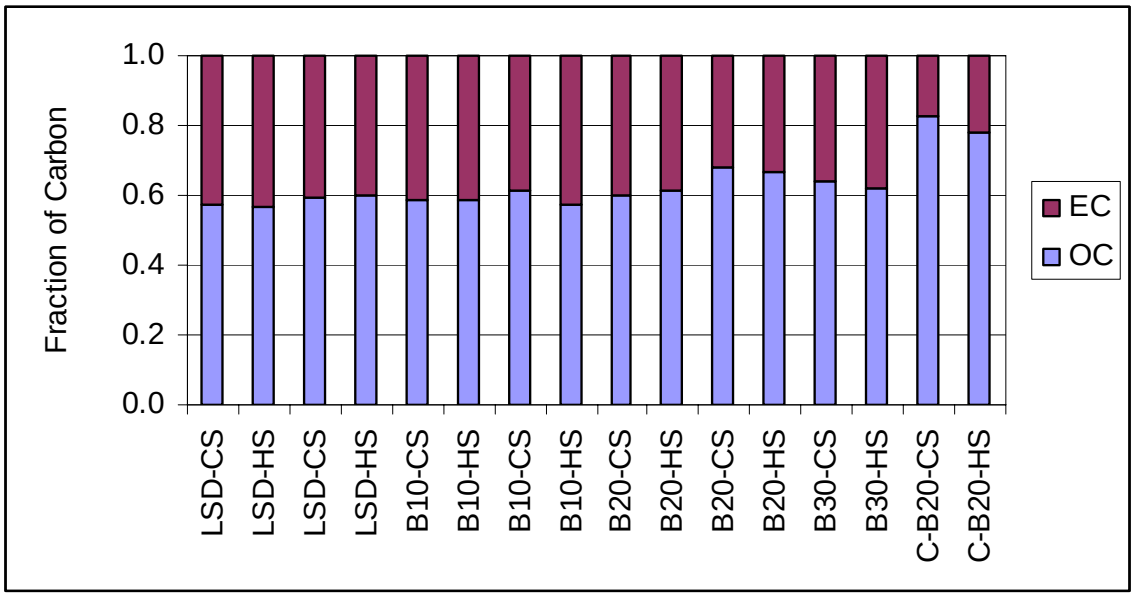
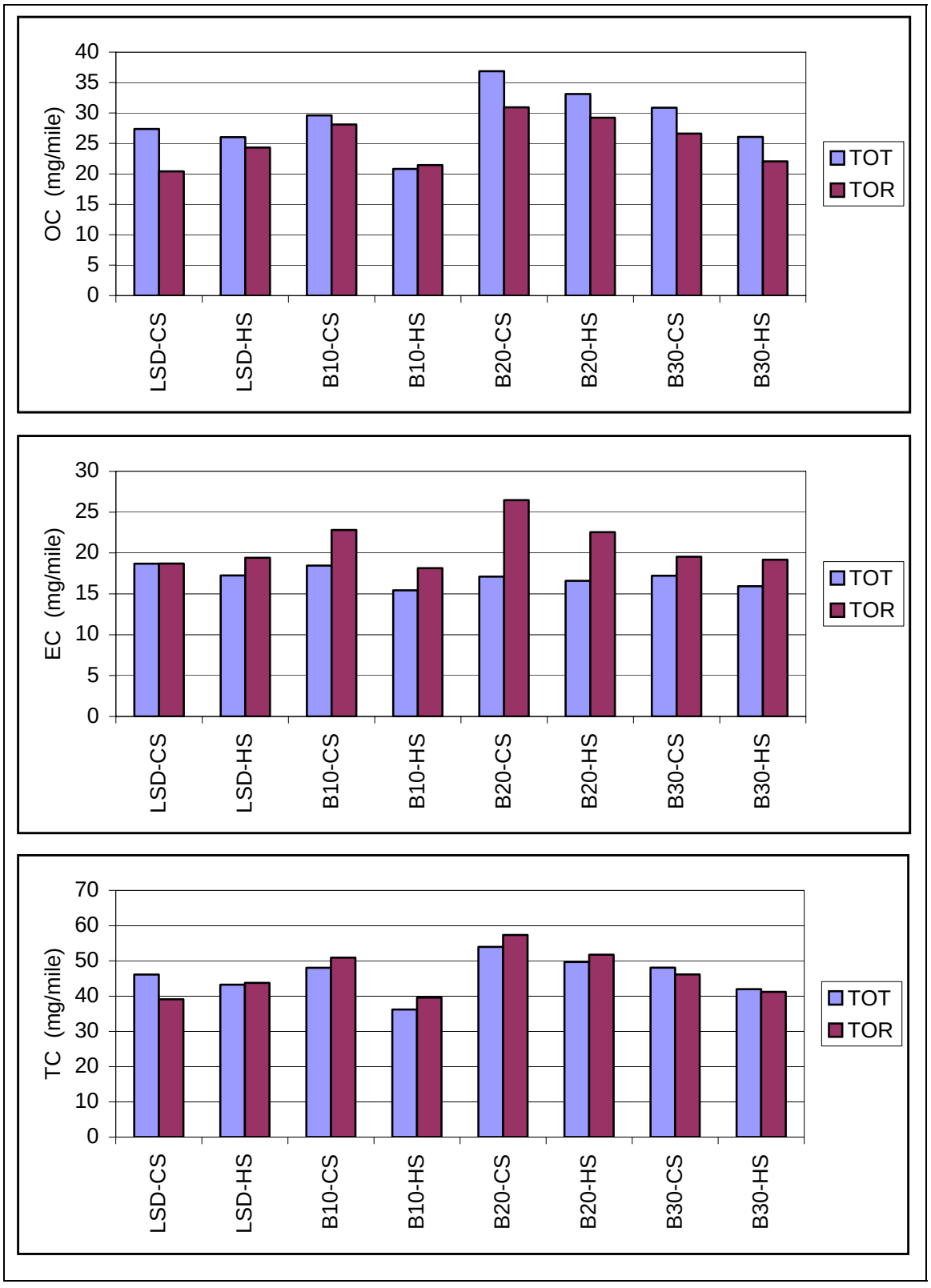


**Figure 20. Comparison of TOR and TOT methods for determining organic and elemental carbon in $PM_{2.5}$ samples.**



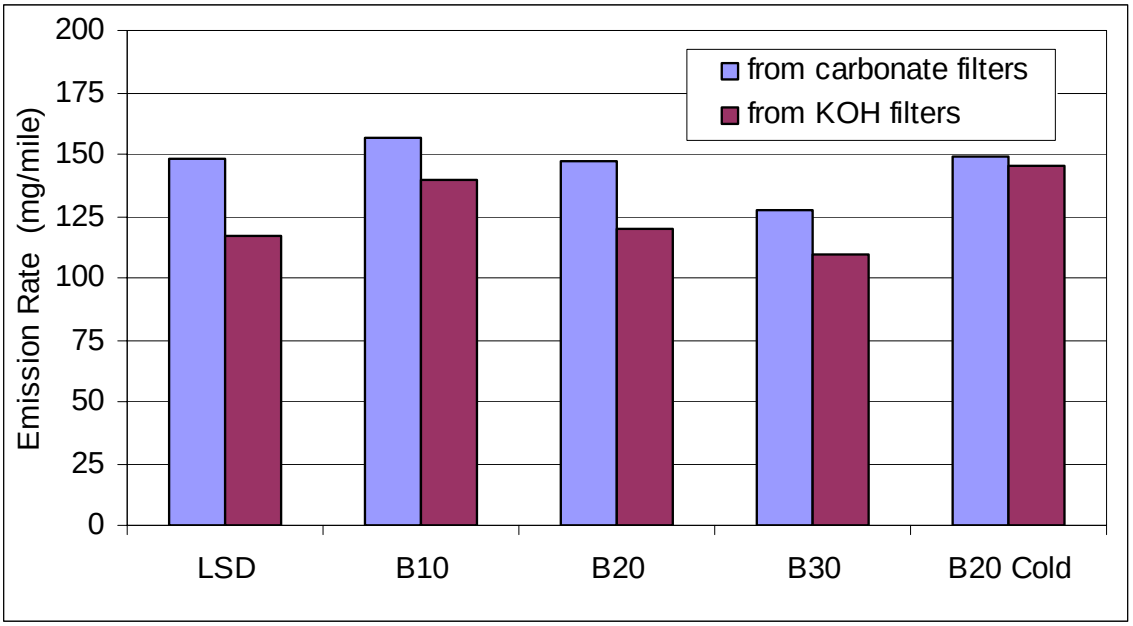
### 4.6.3 Aerosol Precursors

To simplify the discussion of aerosol precursor emissions, the FTP composite emission rates will be used. The FTP composite emission rate is a weighted average of the cold start and hot start emission rates. The complete set of emission rates is given in Appendix 1.

Sulphur dioxide ($SO_2$) is determined from potassium carbonate coated filters. The KOH coated filters used to determine organic acids also shows some capacity for capturing $SO_2$, though the sampling efficiency appears to be lower than the carbonate filters.

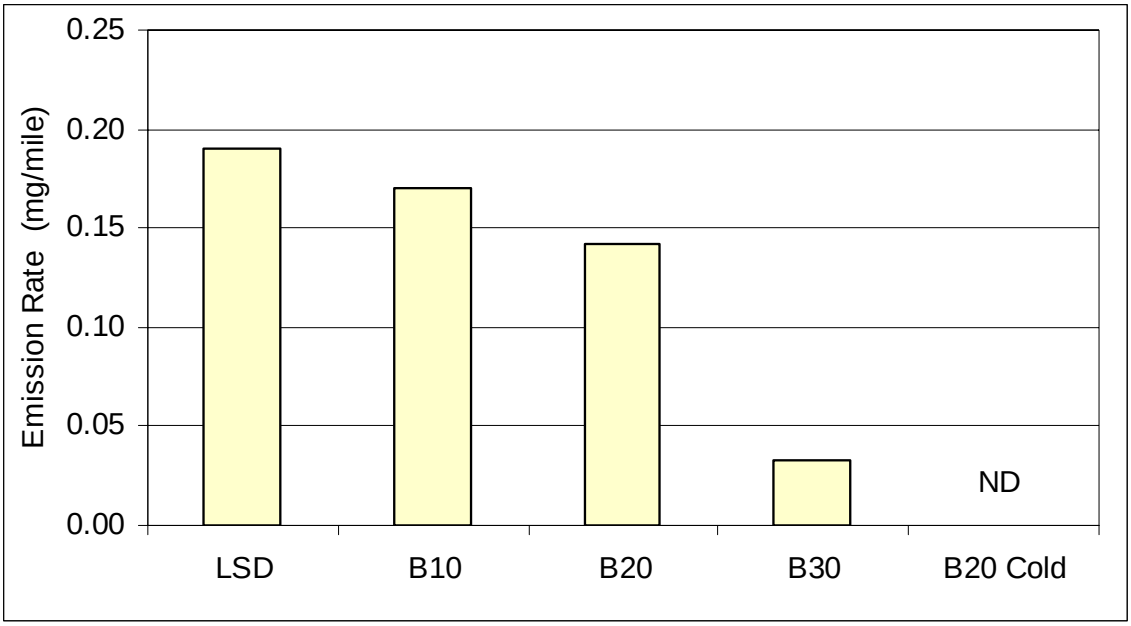
Sulphur dioxide when emitted into the atmosphere undergoes further oxidation to $SO_3$, which then reacts with water vapour to form sulphuric acid. The sulphuric acid is neutralized by ammonia to form particle phase ammonium sulphate. Figure 21 shows the measured $SO_2$ emission rates. A pattern similar to the fuel consumption results shown in Figure 5 is observed where a slight increase is seen in changing from the base fuel to B10 then a consistent decrease with increasing fuel blend. $SO_2$ emissions arise from the fuel sulphur as well as burning lubricating oil. Since the sulphur contents of the blends were not determined, it is not possible to determine whether the increase in $SO_2$ emissions results from the fuel or from an increase in oil consumption.

**Figure 21. Comparison of $SO_2$ emissions (mg/mile FTP Composite).**




Ammonia ($NH_3$) is determined using citric acid coated filters. The efficiency of the reaction depends on there being sufficient water present on the filter. It appears from the results shown in Figure 22 that the filters were slowly drying out as the study ran. These results are not considered reliable.

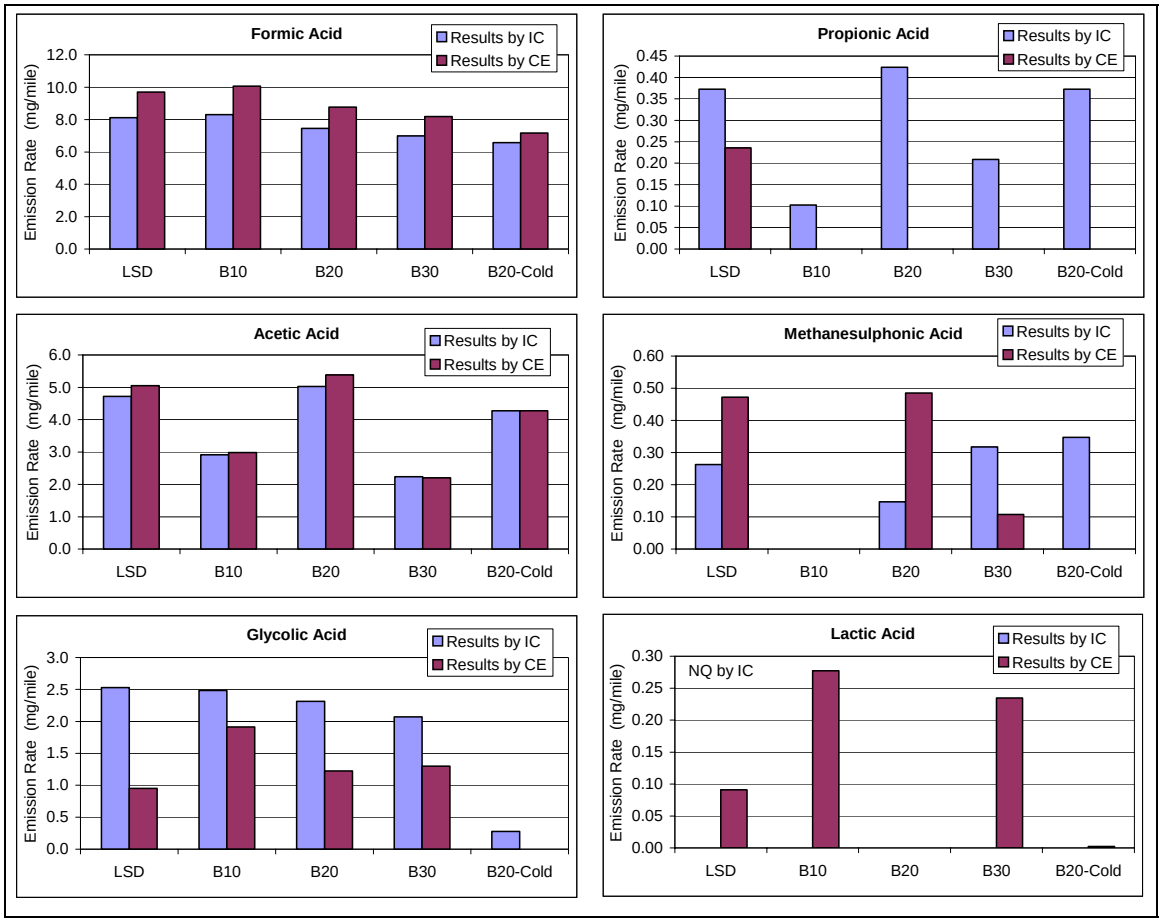
**Figure 22. Comparison of $NH_3$ emissions (mg/mile FTP Composite) showing sampling difficulties. See text for details.**




Vapour phase organic acids were determined on KOH coated quartz filters. This study represents the first attempt at determining organic acids in vehicle exhaust. The samples were analyzed by two different methods to confirm the identity of the acids and to cover a range of concentrations. The IC method has better detection limits than the CE method, but the CE method is able to detect a wider range of compounds. Emission rates for those compounds detected in the vehicle exhaust are shown in Figure 23. Emission rates of organic acids are of the same order of magnitude as the non-methane hydrocarbons. Formic, acetic and glycolic acids are the most predominant of the acids measured. The acetic acid emission rate appears somewhat erratic as the fuel changes while the formic and glycolic acid emissions appear to decrease with increasing biodiesel blend.

For high concentrations, the results from the two methods agree well. The difference in detection limits between the two methods is seen for glycolic, propionic and methanesulphonic acids.

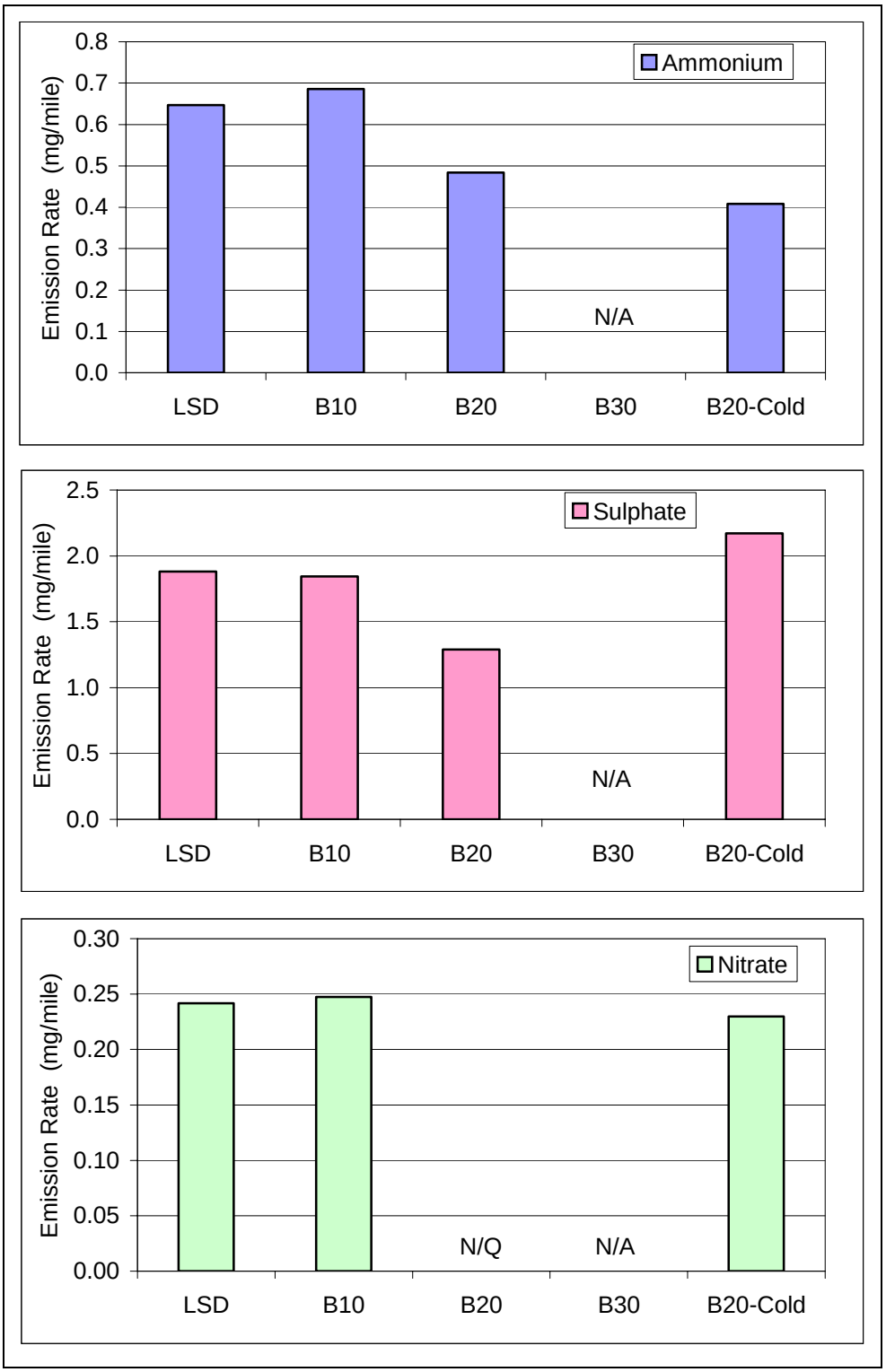
**Figure 23. Comparison of vapour phase organic acid emissions (FTP composite mg/mile).**




## 4.6.4 Particle Phase Ions

Particle phase ions were determined by IC from the Teflon membrane filters. These ionic species form a very small fraction of the $PM_{2.5}$ mass. The emission rates of the major ions found in the particulate matter samples are shown in Figure 24. The complete data set is given in Appendix 1.

**Figure 24: Mass emission rates for particle phase ion collected on Teflon filters (mg/mile FTP composite),**



### 4.6.5 Alkanes and Biomarkers

Particle phase n-alkanes and petroleum biomarker compounds were determined in selected samples. These compounds are useful in source apportionment studies. In total, these compounds account for only a few percent of the total organic carbon content of the particulate matter samples. The complete data sets for these compounds are presented in Appendix 1.

The n-alkane compositions are compared for each of the test fuels in Figure 25 while the effect of test temperature on measured n-alkane compositions is shown in Figure 26. The same pattern as observed with organic carbon composition is seen in these results, with a slight increase in emission rate in changing from the base fuel to B10, followed by a decrease in emission rate with increasing biodiesel blend. A shift in the peak of the n-alkane distribution is also seen between the cold start and hot start emissions. The hot start emissions tend to peak one carbon number greater than the cold start emissions. The effect of test temperature is dramatic in the n-alkane composition. The cold temperature emission rates are much greater than the standard temperature emission rates and a shift is also seen in the peak of the n-alkane distribution with the cold temperature distribution showing a peak one carbon number lower than the standard temperature distribution. These compounds appear in the emissions both from the fuel and from the lubricating oil. The shift in the peak of the distributions may be a result of the change in relative importance of the fuel versus the lubricating oil as the source under different operating conditions.

The petroleum biomarker compositions are compared for each of the test fuels in Figure 27 while the effect of test temperature on measured petroleum biomarker compositions is shown in Figure 28. Note the low emission rates of these compounds. Again, an increase in emission rate is seen with the change in fuel from the base fuel to B10. Thereafter, the emission rates appear constant with the change in biodiesel blend. It is thought that these compounds appear in the emissions as a result of burning lubricating oil rather than from the fuel, since the boiling points of these compounds put them outside the distillation range of the fuel.

The sample from the base fuel test (Jan. 13/99) was from the test with the lower of the two TPM emission rates. This may explain the increase observed in changing from the base fuel to B10.

**Figure 25. Comparison of particle phase n-alkane compositions for the test fuels.**

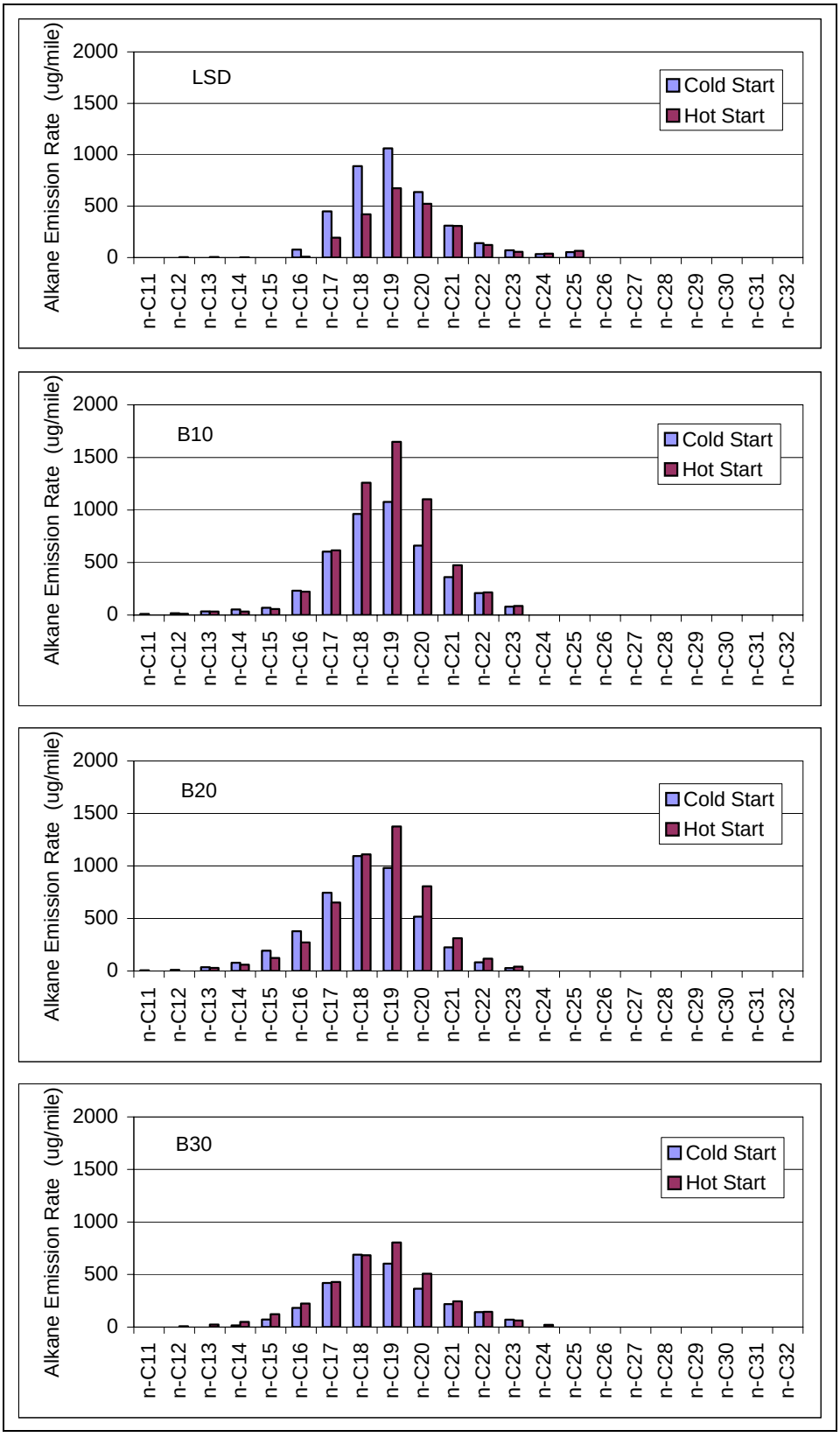


**Figure 26. Effect of test temperature on particle phase n-alkane composition.**

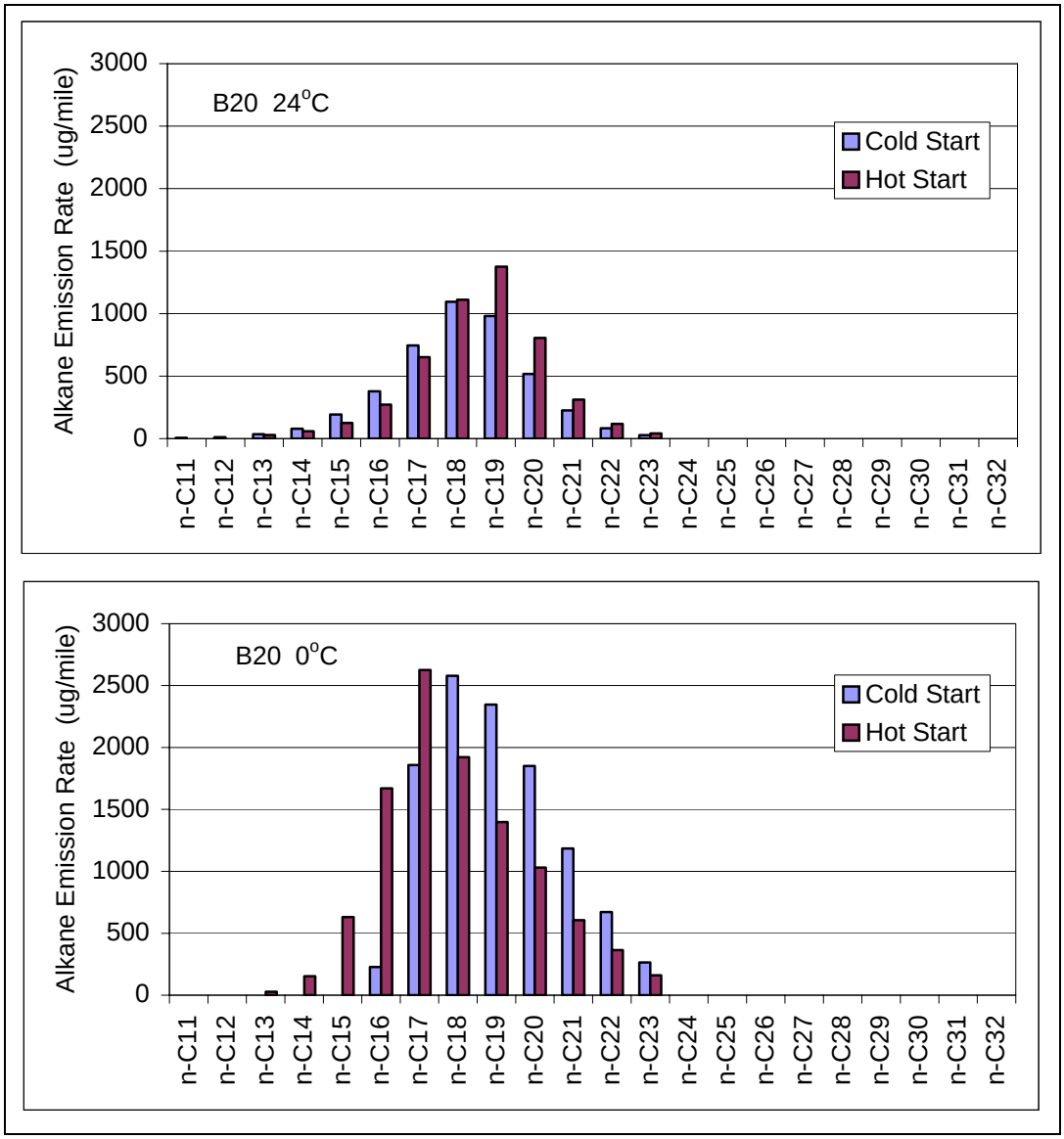


**Figure 27. Comparison of particle phase biomarker compound compositions for the test fuels.**

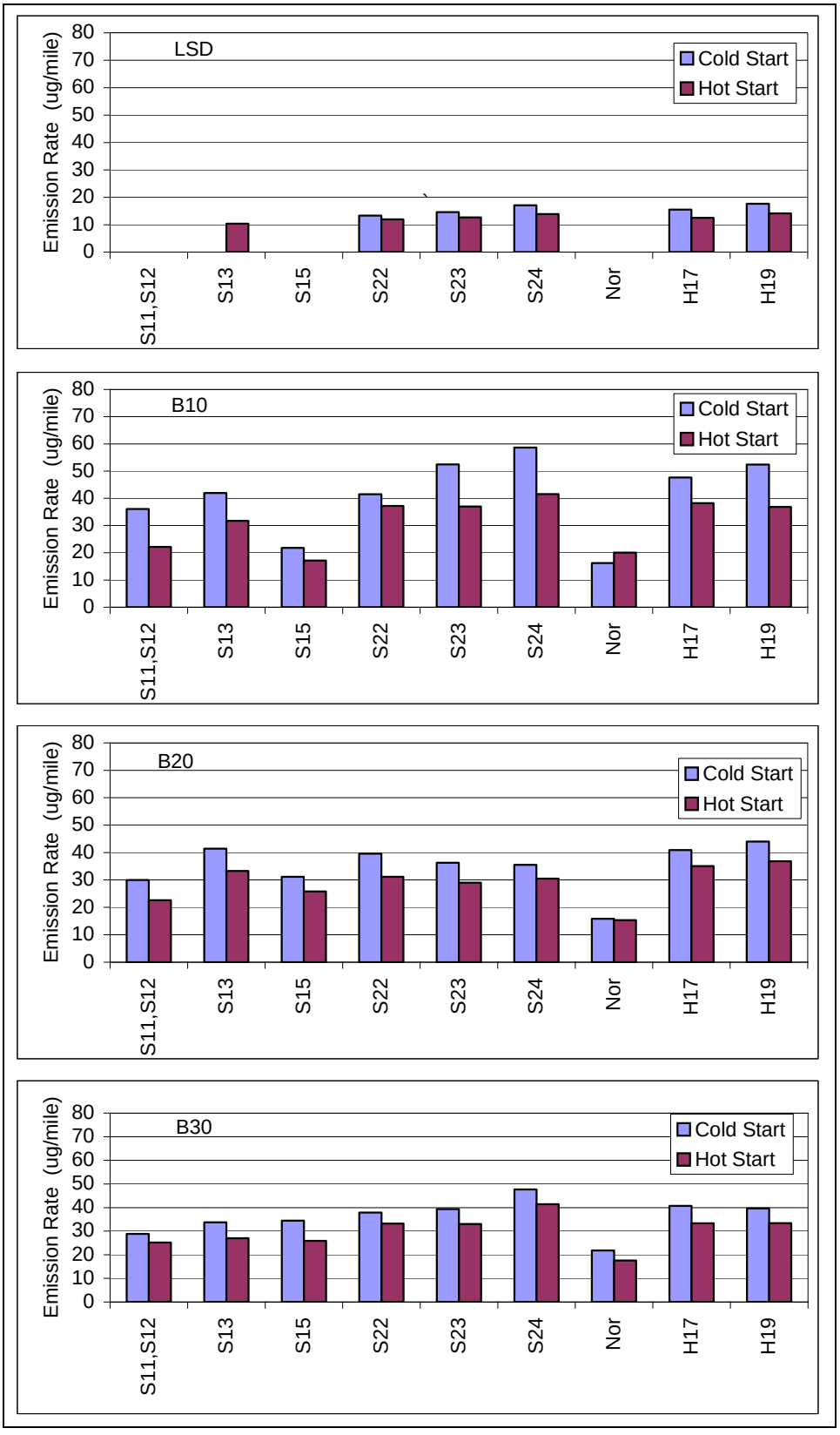
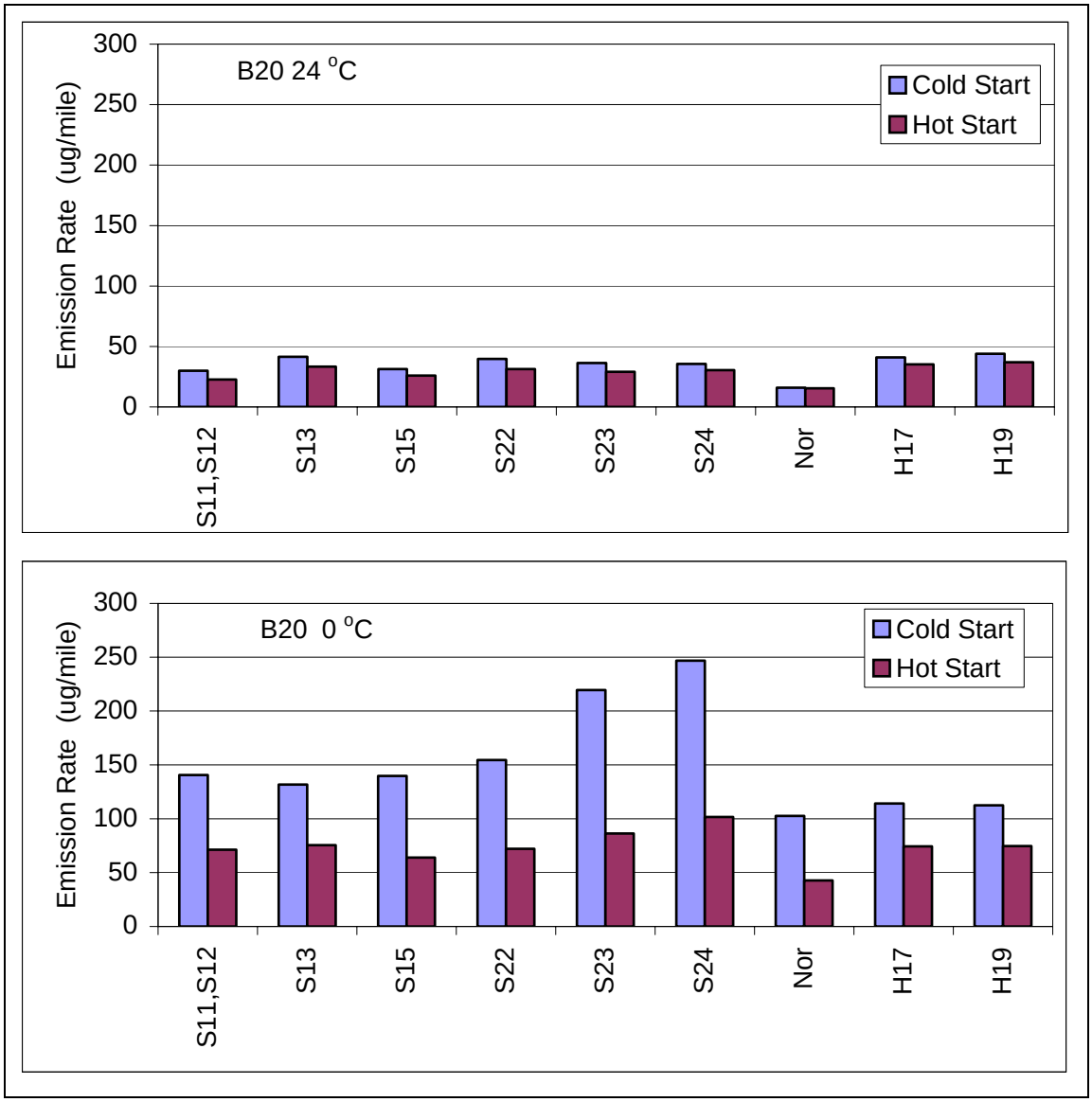


**Figure 28. Effect of test temperature on particle phase petroleum biomarker composition.**



# 5. Conclusions

The use of biodiesel blends resulted in the following statistically significant (95% confidence) changes in emissions over the base fuel:

- B10 gives a statistically significant decrease in $NO_X$ emissions (4.5%) and THC emissions (10-20%) over the base fuel at the standard test temperature.
- B20 gives a statistically significant decrease in THC emissions (hot start only 34%) over the base fuel at the standard test temperature. $NO_X$ emissions remain essentially unchanged.
- B30 gives a statistically significant decrease in THC emissions (27-37%) over the base fuel at the standard test temperature.
- B20 gives a statistically significant increase (20%) in $CO_2$ emissions in the cold temperature cold start test as compared to the base fuel.

No statistically significant differences in TPM emissions were observed among the fuels. Increases in acrolein, PAH and $NO_2$-PAH emissions were observed with the biodiesel blends as compared to the base fuel, though there was insufficient data for statistical significance tests.

Operation at cold ambient temperatures generally results in increased emissions regardless of the fuel used. The increase is greatest on cold start. Once the engine and emission control system have reached operating temperature, very little difference in emissions is observed.

Emissions of vapour phase organic acids were measured and emission rates of formic, acetic and glycolic acid were found at levels similar to the non-methane hydrocarbon emissions.

For the standard temperature tests, organic carbon accounts for approximately 55% of the particle mass while elemental carbon accounts for approximately 40% of the mass. Particle phase ions (ammonium, sulphate and nitrate) comprise a tiny fraction of the total mass. For the cold temperature tests, the organic carbon fraction increases to approximately 80% of the mass. It is suspected that lubricating oil contributes significantly to the increase observed at cold temperature. This hypothesis is supported by the significant increase in both the n-alkane and petroleum biomarker emission rates and a shift in the n-alkane distribution to lower carbon number.

The two methods for determining organic and elemental carbon composition (TOR and TOT) compare well for total carbon. The two methods differ in their distributions of organic and elemental carbon – largely due to the difference in approach for accounting for pyrolized carbon.

The attempt made to measure ammonia emissions was not successful due to sample collection problems. The citric acid coated filters require moisture in the filter for the reaction to occur. It is thought that the filters slowly dried out over the course of the study resulting in a steadily decreasing trend in ammonia emission rates. A change in the filter preparation and storage procedures will be necessary.

# Appendix 1

**Mass emission rates of hydrocarbon compounds (mg/mi)**

| Test Date | January 13/99 | | | January 15/99 | | | January 18/99 | | | February 2/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Low Sulfur Diesel | | | Low Sulfur Diesel | | | Biodiesel 10 % | | | Biodiesel 10% | | |
| Temperature (°C) | 22.9 | | | 22.6 | | | 24.1 | | | 24.3 | | |
| | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| methane | | | | | | | 0.34 | | 0.15 | | | |
| ethylene | 16.12 | 12.06 | 13.81 | 16.50 | 13.90 | 15.02 | 19.21 | 13.53 | 15.97 | 18.98 | 13.88 | 16.07 |
| acetylene | 4.21 | 3.88 | 4.02 | 4.74 | 4.04 | 4.34 | 4.92 | 4.08 | 4.44 | 5.81 | 4.02 | 4.79 |
| ethane | | 2.47 | 1.41 | | 0.43 | 0.24 | 0.27 | | 0.12 | 0.26 | | 0.11 |
| propylene | 4.39 | | 1.89 | 3.86 | | 1.66 | 4.41 | | 1.89 | 6.88 | | 2.96 |
| propane | 0.02 | 46.94 | 26.76 | 0.03 | | 0.01 | | | | 0.01 | 0.08 | 0.05 |
| propyne | | | | | | | | | | 2.85 | | 1.23 |
| isobutane | | | | | 0.16 | 0.09 | | 0.09 | 0.05 | | | |
| isobutene/1-butene | 1.56 | | 0.67 | 0.71 | | 0.31 | 0.95 | | 0.41 | 1.95 | | 0.84 |
| 13-butadiene | 0.10 | | 0.04 | | | | | | | | | |
| n-butane | | | | | 0.29 | 0.16 | | 0.06 | 0.04 | | | |
| t2-butene | 0.18 | 0.02 | 0.09 | 0.10 | | 0.04 | 0.11 | | 0.05 | 0.07 | | 0.03 |
| 22-dm-propane | 0.13 | | 0.06 | 0.11 | | 0.05 | 0.11 | | 0.05 | 0.11 | | 0.05 |
| 1-butyne | | | | | | | | | | 0.06 | | 0.02 |
| c2-butene | 0.09 | 0.04 | 0.06 | 0.01 | | 0.00 | 0.05 | | 0.02 | | | |
| 12-butadiene | | | | | | | | | | | | |
| 3m1-butene | 0.15 | | 0.06 | 0.16 | | 0.07 | | 0.12 | 0.07 | 0.12 | | 0.05 |
| 2m-butane | | | | 0.00 | 0.52 | 0.30 | 0.00 | 0.24 | 0.14 | | | |
| 14-pentadiene | | | | | | | | | | | | |
| 2-butyne | | | | | | | | | | | | |
| 1-pentene | 0.32 | | 0.14 | 0.40 | | 0.17 | 0.50 | | 0.22 | 0.38 | | 0.16 |
| 2m1-butene | 0.03 | | 0.02 | | | | | | | | | |
| n-pentane | | 0.04 | 0.02 | | 0.08 | 0.05 | 0.01 | 0.04 | 0.03 | | | |
| 2m-13-butadiene | 0.13 | | 0.06 | 0.17 | | 0.07 | 0.04 | | 0.02 | 0.13 | | 0.06 |
| t2-pentene | 0.08 | | 0.04 | 0.05 | | 0.02 | 0.09 | | 0.04 | | | |
| c2-pentene | | | | | | | | | | | | |
| 2m2-butene | | | | 0.07 | | 0.03 | | 0.08 | 0.05 | | | |
| 22-dm-butane | 0.13 | | 0.06 | 0.17 | | 0.07 | 0.29 | | 0.13 | | | |
| cyclopentene | | | | 0.06 | | 0.03 | 0.08 | | 0.03 | 0.02 | | 0.01 |
| 4m1 & 3m1-pentene | 0.10 | | 0.04 | 0.20 | | 0.09 | 0.14 | | 0.06 | 0.05 | | 0.02 |
| cyclopentane | 0.16 | | 0.07 | 0.18 | | 0.08 | 0.13 | 0.02 | 0.07 | 0.11 | | 0.05 |
| 23-dm-butane | | 0.06 | 0.04 | 0.01 | 0.02 | 0.01 | | 0.03 | 0.02 | | | |
| c/t-4m2-pentene | | | | | | | | | | | | |
| 2m-pentane | | | | 0.01 | 0.02 | 0.01 | 0.02 | 0.06 | 0.04 | | | |
| 3m-pentane | 0.07 | 0.14 | 0.11 | 0.15 | 0.01 | 0.07 | 0.05 | 0.11 | 0.08 | | | |
| 2m1-pentene | | | | | | | | | | | | |
| 1-hexene | 0.11 | | 0.05 | 0.17 | | 0.07 | 0.28 | | 0.12 | 0.18 | | 0.08 |
| n-hexane | 1.10 | 1.02 | 1.06 | 0.13 | 0.19 | 0.16 | 0.15 | 0.17 | 0.16 | | 0.19 | 0.11 |
| c/t-3-hexene | | | | | | | | | | | | |
| t2-hexene | | | | | | | | | | | | |
| 2m2-pentene | | | | | | | | | | | | |
| t-3m2-pentene | | | | | | | | | | | | |
| c2-hexene | | | | 0.26 | 0.45 | 0.36 | 0.40 | 0.62 | 0.52 | | | |
| c-3m2-pentene | 0.07 | | 0.03 | 0.12 | | 0.05 | 0.24 | | 0.10 | | | |
| 22-dm-pentane | | | | | | | | | | | | |
| m-cyclopentane | 0.01 | 0.26 | 0.15 | 0.02 | 0.01 | 0.01 | 0.04 | 0.03 | 0.03 | | 0.06 | 0.04 |
| 24-dm-pentane | | 0.01 | 0.00 | 0.01 | 0.01 | 0.01 | 0.00 | | 0.00 | | 0.01 | 0.01 |
| 223-tm-butane | | | | | | | | | | | | |
| 1m-cyclopentene | 0.11 | | 0.05 | | | | | | | | | |
| benzene | 1.79 | 1.70 | 1.74 | 1.34 | 1.24 | 1.29 | 2.24 | 1.64 | 1.90 | 2.22 | 1.62 | 1.88 |
| 33-dm-pentane | | | | | | | 0.22 | | 0.10 | | | |
| cyclohexane | 0.04 | 0.04 | 0.04 | 0.06 | 0.08 | 0.07 | 0.05 | 0.06 | 0.06 | | 0.05 | 0.03 |
| 2m-hexane | 9.03 | 8.76 | 8.88 | 0.04 | 0.25 | 0.16 | 1.57 | 0.05 | 0.70 | | 1.09 | 0.62 |
| 23-dm-pentane | 0.02 | 0.00 | 0.01 | 0.03 | 0.01 | 0.02 | 0.05 | 0.04 | 0.04 | | 0.03 | 0.02 |
| 11-dm-cyP | | | | | | | | 0.15 | 0.09 | 0.00 | | 0.00 |
| cyclohexene | | | | | | | | | | 0.09 | | 0.04 |
| 3m-hexane | 0.06 | | 0.03 | 0.06 | 0.04 | 0.05 | 0.60 | 0.05 | 0.28 | | 0.16 | 0.09 |

| Test Date | January 13/99 | | | January 15/99 | | | January 18/99 | | | February 2/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Low Sulfur Diesel | | | Low Sulfur Diesel | | | Biodiesel 10 % | | | Biodiesel 10% | | |
| Temperature (°C) | 22.9 | | | 22.6 | | | 24.1 | | | 24.3 | | |
| | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| c-13-dm-cyP | | | | | 0.05 | 0.03 | 0.06 | 0.05 | 0.06 | | 0.02 | 0.01 |
| 3e-pentane/t-13-dm-cyP | 0.08 | 0.00 | 0.04 | 0.08 | 0.08 | 0.08 | 0.09 | 0.07 | 0.08 | | 0.02 | 0.01 |
| t-12-dm-cyP | 6.08 | 5.30 | 5.64 | 1.13 | 1.46 | 1.32 | 2.84 | 1.59 | 2.13 | 4.93 | 5.54 | 5.27 |
| 224-tm-pentane/1-heptene | | | | 0.11 | 0.05 | 0.08 | | | | | 0.28 | 0.16 |
| t3-heptene | | | | | | | | | | | | |
| n-heptane | 0.74 | 0.73 | 0.73 | 0.32 | 0.25 | 0.28 | 0.54 | 0.44 | 0.48 | 0.22 | 0.27 | 0.25 |
| c3-heptane | | | | | | | | | | | | |
| t2-heptene | | | | 0.12 | | 0.05 | 0.10 | 0.05 | 0.07 | 0.03 | | 0.01 |
| c2-heptene | | | | | | | | | | | | |
| 22-dm-hexane | | | | | | | | | | | | |
| m-cyH/c12-dm-cyP/113-tm-cyP | 0.28 | 0.24 | 0.26 | 0.32 | 0.32 | 0.32 | 0.25 | 0.22 | 0.23 | 0.07 | 0.19 | 0.14 |
| 12-dm-cyH | 0.10 | 0.03 | 0.06 | | | | | | | | | |
| 25-dm-hexane/e-cyP | 0.03 | | 0.01 | 0.04 | 0.02 | 0.03 | 0.03 | 0.00 | 0.01 | | 0.05 | 0.03 |
| 24-dm-hexane/223-tm-pentane | 0.12 | 0.04 | 0.07 | 0.08 | | 0.04 | 0.05 | | 0.02 | | 0.14 | 0.08 |
| 33-dm-hexane/ctc124-tm-cyP | 0.10 | 0.12 | 0.11 | 0.12 | 0.08 | 0.10 | 0.08 | 0.08 | 0.08 | 0.03 | 0.11 | 0.07 |
| ctc123-tm-cyP | 0.09 | 0.08 | 0.09 | 0.13 | 0.06 | 0.09 | 0.09 | 0.07 | 0.08 | 0.01 | 0.09 | 0.05 |
| 234-tm-pentane | | 0.01 | 0.01 | 0.07 | | 0.03 | 0.01 | 0.00 | 0.00 | | 0.07 | 0.04 |
| toluene/233-tm-pentane | 2.29 | 2.94 | 2.66 | 2.25 | 1.67 | 1.92 | 2.32 | 2.01 | 2.15 | 2.02 | 2.29 | 2.18 |
| 23-dm-hexane/2m3e-pentane/112-tm-cyP | 0.07 | 0.38 | 0.24 | 0.22 | 0.08 | 0.14 | 0.14 | 0.03 | 0.08 | 0.19 | 0.22 | 0.21 |
| 2m-heptane | 0.30 | 0.40 | 0.36 | 0.45 | 0.29 | 0.36 | | | | 0.00 | 0.23 | 0.13 |
| 4m-C7/3m3e-C5/34-dm-C7/1m-cyH | 0.35 | | 0.15 | 0.48 | 0.30 | 0.38 | 0.45 | 0.31 | 0.37 | 0.07 | 0.37 | 0.24 |
| 3m-heptane | 0.03 | | 0.01 | 0.13 | 0.11 | 0.12 | 0.45 | 0.39 | 0.42 | | 0.00 | 0.00 |
| 3e-hexane/c-13-dm-cyH/cct-124-tm-cyP | 0.17 | 0.30 | 0.24 | 0.30 | 0.32 | 0.31 | 0.12 | 0.16 | 0.15 | 0.21 | 0.18 | 0.19 |
| t-14-dm-cyH | 0.23 | 0.11 | 0.16 | 0.13 | 0.14 | 0.13 | 0.26 | 0.23 | 0.24 | 0.06 | 0.12 | 0.09 |
| 225-tm-hexane | 0.09 | | 0.04 | | 0.07 | 0.04 | 0.14 | 0.11 | 0.13 | | | |
| 11-dm-cyH | | | | | | | | | | | | |
| 1-octene | | | | 0.07 | | 0.03 | 0.07 | 0.11 | 0.09 | 0.38 | | 0.16 |
| 224-tm-hexane/11em-cyP | 0.10 | 0.13 | 0.12 | 0.17 | 0.15 | 0.16 | | | | 0.14 | 0.12 | 0.13 |
| n-octane/t12-dm-cyH | 1.56 | 1.47 | 1.51 | 1.09 | 1.24 | 1.18 | 0.81 | 0.79 | 0.80 | 0.60 | 0.82 | 0.73 |
| t2-octene | 0.17 | | 0.07 | | | | 0.17 | 0.16 | 0.17 | | | |
| ccc-123-tm-cyP | 0.06 | 0.20 | 0.14 | 0.20 | 0.20 | 0.20 | | | | 0.02 | 0.13 | 0.08 |
| 244-tm-hexane/ip-cyP | | | | | | | | | | | | |
| c2-octene | 0.87 | 0.71 | 0.78 | | 0.02 | 0.01 | 0.19 | 0.13 | 0.15 | | | |
| 235-tm-hexane | | | | | | | | | | | | |
| 44&22&26-dm-heptane/c12-dm-cyH | 0.08 | 0.29 | 0.20 | 0.34 | 0.34 | 0.34 | 0.21 | | 0.09 | | | |
| 24-dm-heptane | | 0.38 | 0.22 | 0.11 | 0.10 | 0.10 | | | | 0.01 | | 0.00 |
| np-cyP/ccc-135-tm-cyH/e-cyH | 0.14 | | 0.06 | 0.54 | 0.70 | 0.63 | | 0.17 | 0.10 | 0.23 | 0.21 | 0.22 |
| 25-dm-heptane | 0.36 | 0.17 | 0.25 | 0.21 | 0.20 | 0.20 | 0.28 | 0.23 | 0.25 | 0.13 | 0.27 | 0.21 |
| 33-dm-heptane | 0.43 | 0.48 | 0.46 | 0.52 | 0.52 | 0.52 | 0.27 | 0.25 | 0.26 | 0.17 | 0.13 | 0.15 |
| 114-tm-cyH | 0.13 | 0.17 | 0.15 | 0.18 | 0.17 | 0.17 | 0.09 | 0.09 | 0.09 | 0.29 | 0.25 | 0.27 |
| e-benzene | 1.99 | 0.92 | 1.38 | 1.52 | 1.02 | 1.24 | 1.34 | 1.21 | 1.27 | 0.66 | 0.44 | 0.54 |
| cct124-tm-cyH | 28.85 | 29.55 | 29.25 | 4.13 | 5.03 | 4.64 | 7.80 | 4.85 | 6.12 | 5.83 | 8.50 | 7.35 |
| 35-dm-heptane | | | | 0.20 | | 0.08 | 0.09 | | 0.04 | 0.21 | | 0.09 |
| m&p-xylene/23-dm-heptane | 0.99 | 1.52 | 1.29 | 1.62 | 1.57 | 1.59 | 0.82 | 0.52 | 0.65 | 1.44 | 1.43 | 1.43 |
| 34-dm-heptane/4m-octane | | | | 0.47 | 0.39 | 0.42 | | | | | | |
| 4e-heptane | | | | | | | | | | | | |
| 2m-octane/246-tm-hexane | 0.17 | 0.13 | 0.15 | 0.85 | 0.65 | 0.73 | 0.17 | | 0.07 | 0.44 | | 0.19 |
| ctc-124-tm-cyH | 0.22 | 0.24 | 0.23 | 0.29 | 0.26 | 0.27 | 0.29 | 0.18 | 0.23 | 0.26 | 0.33 | 0.30 |
| 3m-octane/33-de-C5/3e-C7 | 1.22 | 1.32 | 1.28 | 1.17 | 0.80 | 0.96 | 0.47 | 0.53 | 0.51 | 0.50 | | 0.21 |
| o-xylene | 1.18 | 1.28 | 1.24 | 1.06 | 1.09 | 1.08 | 0.93 | 0.95 | 0.95 | 0.69 | 0.84 | 0.78 |
| 112-tm-cyH | 0.20 | | 0.09 | | | | 0.20 | | 0.09 | | 0.09 | 0.05 |
| 1-nonene | 0.06 | | 0.02 | 0.37 | | 0.16 | 0.20 | | 0.09 | 0.10 | | 0.04 |

| Test Date | January 13/99 | | | January 15/99 | | | January 18/99 | | | February 2/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Low Sulfur Diesel | | | Low Sulfur Diesel | | | Biodiesel 10 % | | | Biodiesel 10% | | |
| Temperature (°C) | 22.9 | | | 22.6 | | | 24.1 | | | 24.3 | | |
| | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| t3-nonene | 0.04 | 0.28 | 0.18 | 0.20 | 0.41 | 0.32 | 0.22 | 0.17 | 0.20 | 0.24 | 0.18 | 0.20 |
| ib-cyP | | 0.04 | 0.03 | | | | 0.10 | | 0.04 | | 0.20 | 0.11 |
| c3-nonene | | | | | | | | 0.22 | 0.12 | 0.26 | | 0.11 |
| n-nonane | 3.62 | 3.99 | 3.83 | 3.44 | 3.45 | 3.45 | 2.47 | 2.52 | 2.50 | 1.83 | 1.70 | 1.76 |
| t2-nonene | | 0.09 | 0.05 | | 0.18 | 0.10 | | | | 0.20 | | 0.08 |
| c2-nonene | 0.28 | 0.09 | 0.17 | 0.15 | 0.13 | 0.14 | 0.35 | | 0.15 | | | |
| ip-benzene | | 0.52 | 0.29 | 0.14 | 0.14 | 0.14 | | 0.36 | 0.21 | 0.44 | 0.40 | 0.42 |
| 22-dm-octane | | 0.08 | 0.04 | | 0.13 | 0.07 | | | | | | |
| ip-cyH | 0.24 | | 0.10 | 0.64 | 0.71 | 0.68 | 0.41 | | 0.18 | 0.39 | 0.42 | 0.40 |
| nb-cyP | 0.13 | 0.31 | 0.23 | 0.66 | 0.77 | 0.72 | 0.50 | 0.27 | 0.37 | 0.12 | 0.50 | 0.33 |
| 33-dm-octane | 1.27 | 1.56 | 1.44 | 1.27 | 1.24 | 1.25 | 0.56 | 0.68 | 0.63 | 0.67 | 0.35 | 0.49 |
| n-propylbenzene | 0.23 | 0.73 | 0.51 | 1.11 | 0.78 | 0.92 | 0.34 | 0.67 | 0.53 | 0.55 | 0.60 | 0.58 |
| 3e-toluene | 1.10 | 1.19 | 1.15 | 1.24 | 1.45 | 1.36 | 1.93 | 0.25 | 0.98 | 0.70 | 0.49 | 0.58 |
| 23-dm-octane | | | | | | | | | | | | |
| 4e-toluene | | 0.37 | 0.21 | 0.22 | 0.56 | 0.41 | 0.53 | 0.28 | 0.39 | | 0.14 | 0.08 |
| 135-tm-benzene | 0.38 | 0.20 | 0.28 | 0.64 | 0.39 | 0.50 | 0.47 | 0.35 | 0.40 | 0.06 | 0.26 | 0.17 |
| 2m-nonane | 1.58 | 1.54 | 1.56 | 1.10 | 1.19 | 1.15 | 0.82 | 1.26 | 1.07 | 0.17 | 0.56 | 0.39 |
| 3e-octane | | | | | 0.27 | 0.16 | 0.48 | | 0.21 | 0.30 | | 0.13 |
| 3m-nonane | 1.16 | 1.30 | 1.24 | 1.01 | 1.84 | 1.48 | 1.02 | 0.67 | 0.82 | 0.73 | 0.55 | 0.63 |
| 2e-toluene | 1.49 | 2.31 | 1.96 | 1.44 | 1.56 | 1.51 | 1.01 | 1.11 | 1.07 | 0.70 | 1.76 | 1.30 |
| 124-tm-benz/tb-benz/1-decene | 1.89 | 2.19 | 2.06 | 1.86 | 2.62 | 2.30 | 1.36 | 1.48 | 1.43 | 0.99 | 1.14 | 1.08 |
| 1b-cyH | 0.52 | 0.53 | 0.52 | 0.52 | 0.65 | 0.59 | 0.42 | 0.34 | 0.37 | 0.42 | | 0.18 |
| n-decane | 5.01 | 6.23 | 5.70 | 4.30 | 5.30 | 4.87 | 3.35 | 3.73 | 3.57 | 3.18 | 2.83 | 2.98 |
| ib-benzene | | | | | | | | | | | | |
| sb-benzene | | 0.31 | 0.18 | 0.43 | 0.46 | 0.45 | | | | 0.36 | | 0.15 |
| 3-ip-toluene | | 0.45 | 0.26 | 0.17 | 0.40 | 0.30 | 0.42 | 0.37 | 0.39 | 0.74 | | 0.32 |
| 123-tm-benzene | 0.09 | | 0.04 | | | | | | | | | |
| 4-ip-toluene | | | | | 0.65 | 0.37 | | | | 0.25 | | 0.11 |
| indan | | | | | | | | | | | | |
| 2-ip-toluene | 1.19 | 1.41 | 1.32 | 0.94 | 1.08 | 1.02 | 0.94 | 0.84 | 0.88 | 0.92 | 0.74 | 0.82 |
| 13-de-benzene | | | | | | | | | | | | |
| 14-de-benzene | | | | | | | | | | | | |
| 3-np-toluene | 0.46 | 0.71 | 0.60 | 1.06 | 0.79 | 0.90 | 0.72 | 0.72 | 0.72 | 0.73 | 0.71 | 0.72 |
| 4-np-toluene/nb-benz/13dm5e-benzene | 1.12 | 1.30 | 1.22 | 2.34 | 1.25 | 1.71 | 1.34 | 0.84 | 1.06 | 0.62 | | 0.27 |
| 12de-benzene | 0.46 | 0.59 | 0.54 | 0.78 | 0.52 | 0.63 | 0.54 | 0.39 | 0.46 | | 0.75 | 0.43 |
| 2-np-toluene | | 0.45 | 0.26 | 0.44 | 0.43 | 0.43 | | 0.37 | 0.21 | | | |
| 14dm-2e-benzene | 0.97 | 0.56 | 0.74 | 0.81 | 0.64 | 0.71 | 1.58 | 2.17 | 1.92 | 1.28 | 1.01 | 1.12 |
| 13dm-4e-benzene | | | | | | | | | | | | |
| 12dm-4e-benzene | 0.69 | 0.48 | 0.57 | 0.37 | 0.45 | 0.41 | 0.46 | 0.44 | 0.45 | 0.53 | 0.42 | 0.46 |
| 13dm-2e-benzene | | 0.30 | 0.17 | 0.78 | 0.92 | 0.86 | | | | 0.92 | 0.75 | 0.82 |
| n-undecane/12-dm-3e-&1245-ttm-benzene | 3.70 | 5.16 | 4.53 | 4.61 | 5.65 | 5.21 | 4.20 | 4.71 | 4.49 | 4.35 | 3.99 | 4.15 |
| 2mb-benzene | 0.87 | 1.41 | 1.18 | 0.77 | 1.09 | 0.95 | 2.61 | 0.90 | 1.63 | 2.46 | | 1.06 |
| tb-2m-benzene | 0.59 | 0.83 | 0.72 | 0.72 | 0.89 | 0.82 | 0.80 | 0.53 | 0.64 | 0.91 | 0.91 | 0.91 |
| 1234-ttm-benzene | | | | | | | | | | | | |
| npentyl-benzene | | 0.57 | 0.33 | | 0.53 | 0.30 | 0.88 | 0.61 | 0.72 | 0.60 | 0.53 | 0.56 |
| tb-35dm-benzene | | | | | 0.53 | 0.30 | 0.44 | 0.48 | 0.46 | 0.40 | 0.42 | 0.41 |
| tb-4e-benzene | | 0.42 | 0.24 | 0.46 | 0.85 | 0.68 | 0.49 | 0.80 | 0.67 | 0.46 | 0.49 | 0.48 |
| n-dodecane | 1.19 | 2.23 | 1.78 | 1.87 | 2.56 | 2.26 | 1.73 | 2.59 | 2.22 | 2.21 | 2.43 | 2.33 |
| 135-TE-BENZENE | | | | | | | | | | | | |
| 124-TE-BENZENE | | | | | | | | | | | | |
| N-HEXYLBENZENE | | | | | | | | | | | | |
| N-C13 | | 1.44 | 0.82 | | 1.57 | 0.90 | 1.31 | 1.96 | 1.68 | 1.32 | 1.91 | 1.66 |
| N-C14 | | | | | | | | | | | 0.36 | 0.20 |
| N-C15 | | | | | | | | | | | | |
| N-C16 | | | | | | | | | | | | |
| N-C17 | | | | | 0.46 | 0.26 | | 0.60 | 0.34 | | | |
| N-C18 | | | | | | | | | | | | |
| N-C19 | | | | | | | | | | | | |
| N-C20 | | | | | | | | | | | | |
| N-C21 | | | | | | | | | | | | |
| N-C22 | | | | | | | | | | | | |
| N-C23 | | | | | | | | | | | | |
| N-C24 | | | | | | | | | | | | |

| Test Date | January 13/99 | | | January 15/99 | | | January 18/99 | | | February 2/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Low Sulfur Diesel | | | Low Sulfur Diesel | | | Biodiesel 10 % | | | Biodiesel 10% | | |
| Temperature (°C) | 22.9 | | | 22.6 | | | 24.1 | | | 24.3 | | |
| | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| N-C25 | 112.03 | 72.14 | 89.29 | | | | | | | 38.85 | | 16.70 |
| N-C26 | 1.31 | | 0.56 | | | | | | | 3.10 | | 1.33 |

| Test Date | February 4/99 | | | February 8/99 | | | January 26/99 | | | January 27/99 | | | January 28/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Biodiesel 20% | | | Biodiesel 20% | | | Biodiesel 30 % | | | Biodiesel 30 % | | | Biodiesel 30 % | | |
| Temperature (°C) | 24.2 | | | 24.1 | | | 23.2 | | | 24.8 | | | 24.7 | | |
| | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| methane | | | | | | | | | | | 0.45 | 0.26 | | | |
| ethylene | 21.87 | 15.95 | 18.50 | 19.03 | 11.49 | 14.73 | 15.43 | 13.68 | 14.43 | 17.98 | 12.04 | 14.59 | 19.80 | 12.77 | 15.79 |
| acetylene | 6.04 | 3.92 | 4.83 | 4.54 | 3.81 | 4.12 | 3.72 | 4.32 | 4.06 | 4.66 | 4.70 | 4.68 | 4.64 | 4.51 | 4.57 |
| ethane | | | | 0.26 | | 0.11 | | | | 0.33 | | 0.14 | 0.34 | | 0.15 |
| propylene | 4.26 | | 1.83 | 6.86 | | 2.95 | 6.34 | | 2.72 | 3.73 | | 1.61 | 4.34 | | 1.86 |
| propane | | | | | 0.86 | 0.49 | 0.03 | | 0.01 | 0.11 | 0.35 | 0.25 | 0.05 | | 0.02 |
| propyne | 2.11 | | 0.91 | | | | | | | | | | | | |
| isobutane | | | | | 0.79 | 0.45 | 0.01 | | 0.01 | 0.01 | 0.02 | 0.02 | 0.06 | 0.45 | 0.28 |
| isobutene/1-butene | | | | 0.77 | | 0.33 | 0.75 | | 0.32 | 1.07 | | 0.46 | 1.03 | | 0.44 |
| 13-butadiene | | | | 0.06 | | 0.02 | | | | 0.15 | | 0.07 | | | |
| n-butane | | | | | 1.30 | 0.74 | | | | 0.01 | 0.15 | 0.09 | 0.16 | 0.49 | 0.35 |
| t2-butene | | | | 0.01 | | 0.00 | | 0.02 | 0.01 | 0.13 | | 0.06 | 0.15 | | 0.07 |
| 22-dm-propane | | | | 0.13 | | 0.06 | | 0.07 | 0.04 | 0.09 | | 0.04 | 0.10 | | 0.04 |
| 1-butyne | | | | 0.05 | | 0.02 | | | | | | | | | |
| c2-butene | | | | | | | | 0.06 | 0.04 | 0.11 | | 0.05 | 0.11 | | 0.05 |
| 12-butadiene | | | | | | | | | | | | | | | |
| 3m1-butene | | | | 0.16 | | 0.07 | 0.12 | | 0.05 | 0.14 | | 0.06 | 0.22 | | 0.09 |
| 2m-butane | | | | 0.06 | 1.15 | 0.68 | | | | 0.09 | 0.17 | 0.14 | 0.68 | 0.97 | 0.85 |
| 14-pentadiene | | | | | 0.18 | 0.10 | | | | | | | | | |
| 2-butyne | | | | | | | | | | | | | | | |
| 1-pentene | | | | 0.44 | | 0.19 | 0.41 | | 0.18 | 0.48 | | 0.21 | 0.54 | | 0.23 |
| 2m1-butene | | | | | | | | | | 0.08 | | 0.03 | | | |
| n-pentane | | | | 0.00 | 0.16 | 0.09 | 0.03 | | 0.01 | 0.06 | | 0.03 | 0.15 | 0.13 | 0.14 |
| 2m-13-butadiene | | | | 0.24 | | 0.10 | 0.19 | | 0.08 | 0.16 | | 0.07 | 0.18 | | 0.08 |
| t2-pentene | | | | | 0.01 | 0.00 | 0.08 | 0.03 | 0.05 | 0.08 | | 0.03 | 0.09 | | 0.04 |
| c2-pentene | | | | | | | | | | | | | | | |
| 2m2-butene | | | | | 0.06 | 0.03 | 0.07 | | 0.03 | 0.06 | | 0.03 | | 0.06 | 0.03 |
| 22-dm-butane | | | | 0.24 | | 0.10 | 0.09 | | 0.04 | 0.25 | | 0.11 | 0.20 | | 0.09 |
| cyclopentene | | | | | | | 0.05 | 0.02 | 0.03 | 0.07 | | 0.03 | 0.09 | | 0.04 |
| 4m1 & 3m1-pentene | | | | 0.17 | | 0.07 | 0.13 | | 0.06 | 0.10 | | 0.04 | 0.12 | | 0.05 |
| cyclopentane | | | | 0.27 | | 0.12 | 0.06 | 0.01 | 0.03 | 0.06 | 0.05 | 0.05 | 0.06 | 0.12 | 0.09 |
| 23-dm-butane | | | | 0.01 | 0.05 | 0.03 | | | | | 0.01 | 0.01 | 0.04 | 0.01 | 0.03 |
| c/t-4m2-pentene | | | | | | | | | | | | | | | |
| 2m-pentane | | | | 0.00 | 0.09 | 0.05 | | | | 0.02 | 0.01 | 0.02 | 0.08 | 0.03 | 0.05 |
| 3m-pentane | | | | 0.13 | 0.01 | 0.07 | 0.06 | | 0.02 | 0.12 | | 0.05 | 0.14 | 0.03 | 0.08 |
| 2m1-pentene | | | | | | | | | | | | | | | |
| 1-hexene | | | | 0.28 | | 0.12 | 0.20 | | 0.09 | 0.25 | | 0.11 | 0.30 | | 0.13 |
| n-hexane | 0.39 | 0.29 | 0.34 | 0.11 | 0.34 | 0.24 | 0.19 | 0.15 | 0.17 | 0.18 | 0.21 | 0.20 | 0.30 | 0.22 | 0.25 |
| c/t-3-hexene | | | | 0.12 | | 0.05 | 0.12 | | 0.05 | 0.08 | | 0.03 | 0.13 | 0.08 | 0.10 |
| t2-hexene | | | | | | | | | | | | | | | |
| 2m2-pentene | | | | | | | | | | | | | | | |
| t-3m2-pentene | | | | | | | | | | | | | | | |
| c2-hexene | | | | | | | | | | | | | | 0.32 | 0.18 |
| c-3m2-pentene | | | | 0.10 | 0.10 | 0.10 | | | | | | | 0.14 | | 0.06 |
| 22-dm-pentane | | | | | | | | | | | | | | | |
| m-cyclopentane | | | | 0.01 | 0.00 | 0.01 | 0.05 | 0.02 | 0.03 | 0.04 | 0.03 | 0.03 | 0.06 | 0.05 | 0.05 |
| 24-dm-pentane | | | | | 0.02 | 0.01 | | | | 0.01 | | 0.00 | 0.02 | 0.01 | 0.01 |
| 223-tm-butane | | | | | | | | | | | | | | | |
| 1m-cyclopentene | | | | | | | | | | | | | | | |
| benzene | 2.02 | 1.25 | 1.58 | 2.54 | 1.68 | 2.05 | 2.14 | 1.71 | 1.90 | 2.49 | 1.67 | 2.02 | 2.71 | 1.85 | 2.22 |
| 33-dm-pentane | | | | | | | | | | | | | 0.16 | | 0.07 |
| cyclohexane | | | | 0.02 | 0.04 | 0.03 | 0.03 | 0.02 | 0.03 | 0.03 | 0.04 | 0.03 | 0.03 | 0.04 | 0.04 |
| 2m-hexane | | | | 0.02 | 0.02 | 0.02 | 0.13 | 0.96 | 0.60 | 0.81 | 2.31 | 1.66 | 0.58 | 0.56 | 0.57 |
| 23-dm-pentane | | | | 0.01 | 0.01 | 0.01 | 0.00 | 0.00 | 0.00 | 0.08 | 0.06 | 0.07 | 0.03 | 0.03 | 0.03 |
| 11-dm-cyP cyclohexene | | | | | | | | | | 0.10 | | 0.04 | | | |
| 3m-hexane | 0.46 | 0.46 | 0.46 | 0.04 | 0.02 | 0.03 | 0.01 | 0.03 | 0.02 | 0.06 | 0.06 | 0.06 | 0.04 | 0.05 | 0.04 |
| c-13-dm-cyP | | | | 0.31 | | 0.13 | | | | | | | | | |

| Test Date | February 4/99 | | | February 8/99 | | | January 26/99 | | | January 27/99 | | | January 28/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Biodiesel 20% | | | Biodiesel 20% | | | Biodiesel 30 % | | | Biodiesel 30 % | | | Biodiesel 30 % | | |
| Temperature (°C) | 24.2 | | | 24.1 | | | 23.2 | | | 24.8 | | | 24.7 | | |
| | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| 3e-pentane/t-13-dm-cyP | | | | 0.08 | 0.07 | 0.07 | 0.07 | | 0.03 | | | | 0.06 | | 0.03 |
| t-12-dm-cyP | | 0.80 | 0.46 | 0.35 | 0.68 | 0.54 | 2.00 | 2.02 | 2.01 | 2.31 | 3.91 | 3.22 | 2.59 | 2.17 | 2.35 |
| 224-tm-pentane/1-heptene | 1.34 | | 0.58 | 0.16 | | 0.07 | | | | 0.10 | | 0.04 | 0.39 | 0.43 | 0.41 |
| t3-heptene | | | | | | | | | | | | | | | |
| n-heptane | 0.61 | 0.60 | 0.60 | 0.50 | | 0.22 | 0.28 | | 0.12 | 0.58 | 0.21 | 0.37 | 0.08 | | 0.04 |
| c3-heptane | | | | | | | | | | | | | | | |
| t2-heptene | | | | 0.20 | 0.11 | 0.15 | | | | | | | 0.06 | | 0.03 |
| c2-heptene | | | | | | | | | | | | | | | |
| 22-dm-hexane | 0.07 | | 0.03 | | | | | | | | | | | | |
| m-cyH/c12-dm-cyP/113-tm-cyP | | | | 0.22 | 0.19 | 0.20 | 0.14 | 0.13 | 0.14 | 0.19 | 0.14 | 0.16 | 0.17 | 0.18 | 0.17 |
| 12-dm-cyH | | | | | | | | | | | | | | | |
| 25-dm-hexane/e-cyP | 0.23 | | 0.10 | 0.02 | 0.00 | 0.01 | | 0.02 | 0.01 | 0.07 | | 0.03 | 0.05 | 0.06 | 0.05 |
| 24-dm-hexane/223-tm-pentane | | | | 0.01 | | 0.00 | | 0.06 | 0.03 | 0.06 | 0.00 | 0.03 | 0.10 | 0.11 | 0.10 |
| 33-dm-hexane/ctc124-tm-cyP | | | | 0.07 | 0.08 | 0.07 | | | | | | | | | |
| ctc123-tm-cyP | | | | 0.07 | | 0.03 | | | | | | | | | |
| 234-tm-pentane | | | | 0.05 | | 0.02 | | | | 0.02 | | 0.01 | 0.09 | 0.11 | 0.10 |
| toluene/233-tm-pentane | 13.11 | 1.39 | 6.43 | 1.79 | 2.03 | 1.93 | 2.58 | 1.62 | 2.03 | 1.88 | 1.51 | 1.67 | 2.78 | 2.46 | 2.60 |
| 23-dm-hexane/2m3e-pentane/112-tm-cyP | | | | 0.12 | 0.07 | 0.09 | 0.17 | 0.02 | 0.09 | 0.24 | 0.11 | 0.17 | 0.21 | 0.19 | 0.20 |
| 2m-heptane | | | | 0.18 | 0.53 | 0.38 | | | | 0.30 | 0.22 | 0.26 | | | |
| 4m-C7/3m3e-C5/34-dm-C7/1m-cyH | | | | | | | 0.76 | 0.60 | 0.67 | 0.33 | 0.39 | 0.36 | 0.94 | 0.85 | 0.89 |
| 3m-heptane | 0.23 | | 0.10 | 0.31 | 0.08 | 0.18 | | | | 0.12 | 0.09 | 0.10 | 0.11 | | 0.05 |
| 3e-hexane/c-13-dm-cyH/cct-124-tm-cyP | | | | 0.16 | 0.19 | 0.18 | | | | 0.15 | 0.10 | 0.12 | | 0.09 | 0.05 |
| t-14-dm-cyH | | | | | 0.08 | 0.04 | 0.11 | 0.14 | 0.13 | | | | 0.11 | 0.14 | 0.13 |
| 225-tm-hexane | | | | | | | | 0.07 | 0.04 | | | | | | |
| 11-dm-cyH | | | | | | | | | | 0.08 | | 0.03 | | | |
| 1-octene | 0.33 | | 0.14 | | | | 0.09 | | 0.04 | | | | | | |
| 224-tm-hexane/11em-cyP | | | | 0.08 | | 0.04 | | | | 0.09 | 0.07 | 0.08 | 0.07 | | 0.03 |
| n-octane/t12-dm-cyH | 0.50 | 0.50 | 0.50 | 0.71 | 0.71 | 0.71 | 0.55 | 0.44 | 0.49 | 0.47 | 0.53 | 0.51 | 0.82 | 0.52 | 0.65 |
| t2-octene | | | | | | | 0.11 | 0.12 | 0.11 | | | | 0.14 | 0.11 | 0.12 |
| ccc-123-tm-cyP | | | | 0.19 | 0.12 | 0.15 | | | | 0.10 | 0.09 | 0.10 | | | |
| 244-tm-hexane/ip-cyP | | | | | | | | | | | | | | | |
| c2-octene | | | | | | | | 0.34 | 0.19 | | 0.08 | 0.05 | 0.09 | 0.12 | 0.10 |
| 235-tm-hexane | | | | | | | | | | | | | | | |
| 44&22&26-dm-heptane/c12-dm-cyH | | | | 0.24 | | 0.10 | | | | 0.09 | 0.11 | 0.10 | | | |
| 24-dm-heptane | | | | | | | | | | | | | | | |
| np-cyP/ccc-135-tm-cyH/e-cyH | | | | | | | 0.09 | 0.13 | 0.11 | | | | 0.10 | 0.10 | 0.10 |
| 25-dm-heptane | | | | 0.34 | 0.22 | 0.28 | 0.15 | 0.19 | 0.17 | 0.10 | 0.14 | 0.12 | 0.14 | 0.12 | 0.13 |
| 33-dm-heptane | | | | 0.17 | | 0.07 | 0.15 | 0.19 | 0.17 | 0.14 | 0.15 | 0.15 | | 0.14 | 0.08 |
| 114-tm-cyH | | | | 0.36 | 0.22 | 0.28 | | | | | | | 0.16 | | 0.07 |
| e-benzene | 0.79 | 0.45 | 0.60 | 0.67 | 0.66 | 0.66 | 0.94 | 1.18 | 1.08 | 1.04 | 0.32 | 0.63 | 0.14 | 0.86 | 0.55 |

| Test Date | February 4/99 | | | February 8/99 | | | January 26/99 | | | January 27/99 | | | January 28/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Biodiesel 20% | | | Biodiesel 20% | | | Biodiesel 30 % | | | Biodiesel 30 % | | | Biodiesel 30 % | | |
| Temperature (°C) | 24.2 | | | 24.1 | | | 23.2 | | | 24.8 | | | 24.7 | | |
| | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| cct124-tm-cyH | 1.94 | 1.86 | 1.89 | 3.53 | 3.21 | 3.35 | 6.44 | 6.68 | 6.58 | 6.99 | 11.23 | 9.41 | 7.08 | 6.36 | 6.67 |
| 35-dm-heptane | | | | 0.23 | | 0.10 | | | | | | | 0.15 | | 0.07 |
| m&p-xylene/23-dm-heptane | 1.16 | 0.87 | 0.99 | 1.88 | 1.53 | 1.68 | 0.64 | 0.25 | 0.42 | 0.55 | 0.33 | 0.42 | 0.63 | 0.35 | 0.47 |
| 34-dm-heptane/4m-octane | | | | 0.16 | | 0.07 | | | | | | | | | |
| 4e-heptane | | | | | | | | | | | | | | | |
| 2m-octane/246-tm-hexane | | | | 0.26 | 0.29 | 0.28 | 0.22 | | 0.09 | 0.14 | 0.16 | 0.15 | 0.18 | | 0.08 |
| ctc-124-tm-cyH | | | | 0.22 | 0.17 | 0.19 | 0.19 | 0.15 | 0.17 | 0.09 | 0.08 | 0.09 | 0.14 | 0.20 | 0.17 |
| 3m-octane/33-de-C5/3e-C7 | 0.41 | 0.33 | 0.37 | | | | | | | | | | | | |
| o-xylene | 0.89 | 0.33 | 0.57 | 0.82 | 0.71 | 0.76 | 0.50 | 0.54 | 0.52 | 0.63 | 0.49 | 0.55 | 0.67 | 0.62 | 0.64 |
| 112-tm-cyH | | | | | 0.21 | 0.12 | 0.12 | | 0.05 | | 0.12 | 0.07 | | | |
| 1-nonene | | | | 0.23 | | 0.10 | 0.09 | | 0.04 | 0.09 | | 0.04 | 0.12 | | 0.05 |
| t3-nonene | | | | 0.15 | | 0.06 | 0.11 | 0.10 | 0.11 | 0.12 | | 0.05 | 0.17 | 0.11 | 0.13 |
| ib-cyP | | | | | | | | 0.12 | 0.07 | | | | | 0.13 | 0.07 |
| c3-nonene | | | | | | | | | | | | | | | |
| n-nonane | 1.36 | 2.28 | 1.88 | 2.19 | 1.87 | 2.00 | 1.33 | 1.20 | 1.26 | 1.35 | 1.39 | 1.37 | 1.46 | 1.37 | 1.41 |
| t2-nonene | | | | | | | | | | | | | | | |
| c2-nonene | | | | 0.11 | 0.25 | 0.19 | 0.18 | | 0.08 | 0.19 | 0.16 | 0.17 | 0.19 | | 0.08 |
| ip-benzene | | | | | | | | 0.22 | 0.13 | | | | | 0.23 | 0.13 |
| 22-dm-octane | | | | 0.13 | | 0.05 | | | | | | | | | |
| ip-cyH | | | | 0.49 | 0.38 | 0.42 | 0.19 | 0.24 | 0.22 | 0.23 | 0.21 | 0.22 | 0.25 | 0.28 | 0.27 |
| nb-cyP | | | | 0.75 | 0.24 | 0.46 | 0.17 | 0.28 | 0.23 | 0.21 | 0.20 | 0.20 | 0.27 | 0.20 | 0.23 |
| 33-dm-octane | 0.69 | 0.65 | 0.67 | 0.52 | 0.53 | 0.53 | 0.46 | 0.62 | 0.55 | 0.44 | 0.38 | 0.41 | 0.52 | 0.66 | 0.60 |
| n-propylbenzene | 0.58 | 0.40 | 0.48 | 0.75 | 0.13 | 0.40 | 0.06 | | 0.02 | 0.26 | | 0.11 | 0.27 | | 0.12 |
| 3e-toluene | 1.87 | 1.23 | 1.50 | 0.97 | 0.73 | 0.83 | 0.68 | 0.28 | 0.45 | 0.99 | 0.11 | 0.49 | 1.22 | 0.29 | 0.69 |
| 23-dm-octane | | | | | | | | | | | | | | | |
| 4e-toluene | 1.02 | 0.64 | 0.80 | 0.47 | | 0.20 | 0.10 | | 0.04 | | | | 0.36 | | 0.16 |
| 135-tm-benzene | 0.70 | 0.97 | 0.85 | 0.09 | 0.05 | 0.07 | 0.35 | 0.33 | 0.34 | 0.26 | 0.27 | 0.27 | 0.32 | 0.38 | 0.35 |
| 2m-nonane | 0.62 | 0.72 | 0.67 | 0.60 | 0.74 | 0.68 | 0.37 | 0.48 | 0.44 | 0.40 | 0.53 | 0.48 | 0.54 | 0.53 | 0.54 |
| 3e-octane | | | | 0.74 | 0.47 | 0.59 | | | | 0.22 | | 0.09 | 0.32 | | 0.14 |
| 3m-nonane | 0.70 | 0.66 | 0.68 | 0.72 | 0.64 | 0.68 | 1.15 | 0.79 | 0.95 | 0.42 | 0.70 | 0.58 | 0.45 | 0.82 | 0.66 |
| 2e-toluene | 1.32 | 1.08 | 1.18 | 0.83 | 0.92 | 0.88 | 0.76 | 0.64 | 0.69 | 0.81 | 0.59 | 0.68 | 0.65 | 0.60 | 0.62 |
| 124-tm-benz/tb-benz/1-decene | 2.71 | 2.12 | 2.37 | 1.22 | 1.08 | 1.14 | 0.89 | 1.15 | 1.04 | 0.91 | 0.96 | 0.94 | 0.80 | 1.11 | 0.98 |
| 1b-cyH | 0.38 | 0.45 | 0.42 | 0.39 | | 0.17 | | | | 0.32 | | 0.14 | | | |
| n-decane | 3.16 | 3.22 | 3.19 | 3.09 | 3.01 | 3.05 | 2.40 | 2.97 | 2.73 | 2.47 | 2.39 | 2.42 | 2.89 | 2.80 | 2.84 |
| ib-benzene | | | | | | | | | | | | | | | |
| sb-benzene | 0.38 | 0.31 | 0.34 | | | | | | | | | | | | |
| 3-ip-toluene | 0.49 | 0.35 | 0.41 | 1.70 | | 0.73 | | 0.32 | 0.18 | 1.04 | | 0.45 | 0.75 | | 0.32 |
| 123-tm-benzene | | | | | | | 1.38 | 0.70 | 0.99 | | | | | 0.29 | 0.17 |
| 4-ip-toluene | 0.64 | 0.54 | 0.58 | 0.36 | 0.72 | 0.56 | | | | | | | | | |
| indan | | | | | | | | | | | 0.44 | 0.25 | | | |
| 2-ip-toluene | 0.78 | 0.80 | 0.80 | 0.84 | 0.89 | 0.87 | 0.58 | 0.64 | 0.61 | 0.61 | 0.59 | 0.59 | 0.61 | 0.68 | 0.65 |
| 13-de-benzene | | | | | | | | | | | | | | | |
| 14-de-benzene | | | | | | | | | | | | | | | |
| 3-np-toluene | 0.22 | 0.40 | 0.32 | 0.87 | 0.70 | 0.77 | 0.60 | 0.59 | 0.59 | 0.76 | 0.53 | 0.63 | 0.46 | 0.67 | 0.58 |
| 4-np-toluene/nb-benz/13dm5e-benzene | 1.38 | 2.22 | 1.86 | | 0.75 | 0.43 | | | | | | | | | |
| 12de-benzene | 0.58 | 0.73 | 0.66 | | | | | | | | | | | | |
| 2-np-toluene | 0.39 | | 0.17 | | | | | | | | | | | | |
| 14dm-2e-benzene | 0.61 | 1.20 | 0.94 | 0.54 | 0.94 | 0.77 | 0.87 | 0.56 | 0.69 | 0.54 | 0.48 | 0.50 | 0.74 | 0.64 | 0.69 |
| 13dm-4e-benzene | | | | | | | | | | | | | | | |
| 12dm-4e-benzene | 0.50 | 0.57 | 0.54 | 0.80 | 0.45 | 0.60 | 0.64 | | 0.27 | 0.70 | 0.67 | 0.69 | 0.35 | 0.43 | 0.39 |
| 13dm-2e-benzene | 0.77 | 0.92 | 0.85 | | 2.68 | 1.53 | | 0.69 | 0.39 | 0.61 | | 0.26 | 0.56 | | 0.24 |
| n-undecane/12-dm-3e-&1245-ttm-benzene | 5.34 | 5.68 | 5.54 | 4.50 | 4.54 | 4.52 | 3.41 | 3.87 | 3.67 | 3.88 | 3.67 | 3.76 | 3.29 | 3.73 | 3.54 |

| Test Date | February 4/99 | | | February 8/99 | | | January 26/99 | | | January 27/99 | | | January 28/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Biodiesel 20% | | | Biodiesel 20% | | | Biodiesel 30 % | | | Biodiesel 30 % | | | Biodiesel 30 % | | |
| Temperature (°C) | 24.2 | | | 24.1 | | | 23.2 | | | 24.8 | | | 24.7 | | |
| | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| 2mb-benzene | 1.26 | 1.21 | 1.23 | 2.62 | 0.91 | 1.64 | 1.06 | 1.56 | 1.34 | 1.85 | 0.35 | 1.00 | 1.87 | 2.02 | 1.95 |
| tb-2m-benzene | 0.80 | 0.89 | 0.85 | 0.68 | 0.68 | 0.68 | 0.68 | 0.55 | 0.61 | 0.85 | 0.24 | 0.50 | 0.73 | 0.72 | 0.72 |
| 1234-ttm-benzene | | | | | | | | | | | 1.02 | 0.58 | | | |
| npentyl-benzene | | | | 0.76 | 0.13 | 0.40 | | 0.67 | 0.38 | 1.24 | | 0.53 | 0.36 | | 0.16 |
| tb-35dm-benzene | 0.61 | 0.46 | 0.53 | 0.37 | | 0.16 | 0.73 | 0.48 | 0.59 | 0.28 | | 0.12 | 0.63 | 0.61 | 0.62 |
| tb-4e-benzene | 1.10 | 0.84 | 0.95 | 0.47 | 0.45 | 0.46 | 0.45 | 0.42 | 0.43 | 0.64 | 0.66 | 0.65 | 0.33 | 0.41 | 0.37 |
| n-dodecane | 2.27 | 3.16 | 2.78 | 1.76 | 1.96 | 1.87 | 1.88 | 2.38 | 2.17 | 2.33 | 2.14 | 2.22 | 2.36 | 2.50 | 2.44 |
| 135-TE-BENZENE | | | | | | | | | | | | | | | |
| 124-TE-BENZENE | | | | | | | | | | | | | | | |
| N-HEXYLBENZENE | | | | | | | | | | | | | | | |
| N-C13 | 1.44 | 2.01 | 1.77 | | 1.46 | 0.83 | 1.37 | 1.94 | 1.70 | 2.41 | 1.77 | 2.04 | 1.04 | 1.85 | 1.50 |
| N-C14 | | | | | | | | | | | | | | | |
| N-C15 | | | | | | | | | | | | | | | |
| N-C16 | | | | | | | | | | | | | | | |
| N-C17 | | | | | | | | | | | | | | 1.10 | 0.63 |
| N-C18 | | | | | | | | | | | | | | | |
| N-C19 | | | | | | | | | | | | | | | |
| N-C20 | | | | | | | | | | | | | | | |
| N-C21 | | | | | | | | | | | | | | | |
| N-C22 | 1.99 | 1.84 | 1.91 | | | | | | | | | | | | |
| N-C23 | | | | | | | | | | | | | | | |
| N-C24 | | | | | | | | | | | | | | | |
| N-C25 | | | | | | | | | | | | | | | |
| N-C26 | | 1.36 | 0.77 | | | | | | | | | | | | |

| Test Date | February 16/99 | | | February 17/99 | | | February 18/99 | | | February 19/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Low Sulphur Diesel | | | Low Sulfur Diesel | | | Biodiesel 20% | | | Biodiesel 20% | | |
| Temperature (°C) | 0.5 | | | 0 | | | 0 | | | 0 | | |
| | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| methane | 5.07 | | 2.18 | n/a | | n/a | 12.13 | | 5.21 | 1.69 | | 0.73 |
| ethylene | 33.30 | 17.92 | 24.53 | n/a | 16.06 | n/a | 32.97 | 17.25 | 24.01 | 27.15 | 20.62 | 23.43 |
| acetylene | 8.85 | 4.71 | 6.49 | n/a | 4.51 | n/a | 10.36 | 4.89 | 7.24 | 9.33 | 3.38 | 5.94 |
| ethane | 0.53 | | 0.23 | n/a | 0.54 | n/a | 0.83 | | 0.35 | 0.56 | | 0.24 |
| propylene | 9.68 | | 4.16 | n/a | 4.52 | n/a | 10.99 | | 4.73 | 9.14 | | 3.93 |
| propane | 0.13 | 0.10 | 0.11 | n/a | 0.91 | n/a | 0.20 | | 0.09 | 0.10 | 0.12 | 0.11 |
| propyne | | | | n/a | | n/a | | | | | | |
| isobutane | 0.15 | | 0.07 | n/a | 0.10 | n/a | | 0.04 | 0.02 | 0.02 | 0.02 | 0.02 |
| isobutene/1-butene | 1.78 | | 0.77 | n/a | 0.89 | n/a | 1.99 | | 0.85 | 1.58 | | 0.68 |
| 13-butadiene | | | | n/a | | n/a | | | | | | |
| n-butane | 0.05 | | 0.02 | n/a | 0.12 | n/a | 0.09 | 0.08 | 0.08 | 0.12 | 0.00 | 0.05 |
| t2-butene | 0.20 | | 0.09 | n/a | 0.10 | n/a | 0.10 | | 0.04 | 0.14 | | 0.06 |
| 22-dm-propane | 0.21 | | 0.09 | n/a | 0.10 | n/a | 0.25 | | 0.11 | 0.18 | | 0.08 |
| 1-butyne | 0.07 | | 0.03 | n/a | | n/a | 0.08 | | 0.03 | 0.09 | | 0.04 |
| c2-butene | | | | n/a | | n/a | | 0.05 | 0.03 | 0.07 | | 0.03 |
| 12-butadiene | | | | n/a | | n/a | | | | | | |
| 3m1-butene | 0.28 | | 0.12 | n/a | 0.12 | n/a | 0.26 | | 0.11 | 0.23 | 0.00 | 0.10 |
| 2m-butane | | 0.06 | 0.03 | n/a | 0.13 | n/a | 0.05 | | 0.02 | 0.04 | 0.01 | 0.03 |
| 14-pentadiene | 0.42 | | 0.18 | n/a | 0.22 | n/a | 0.42 | | 0.18 | 0.40 | | 0.17 |
| 2-butyne | | | | n/a | 0.49 | n/a | | | | | | |
| 1-pentene | 0.68 | | 0.29 | n/a | 0.33 | n/a | 0.83 | | 0.36 | 0.73 | | 0.31 |
| 2m1-butene | | | | n/a | | n/a | | | | | | |
| n-pentane | 0.01 | 0.00 | 0.01 | n/a | 0.06 | n/a | | 0.02 | 0.01 | 0.06 | | 0.03 |
| 2m-13-butadiene | 0.25 | | 0.11 | n/a | 0.17 | n/a | 0.26 | | 0.11 | 0.23 | | 0.10 |
| t2-pentene | 0.12 | | 0.05 | n/a | | n/a | | | | 0.11 | | 0.05 |
| c2-pentene | 0.07 | | 0.03 | n/a | | n/a | | | | | | |
| 2m2-butene | | | | n/a | | n/a | 0.06 | | 0.03 | 0.06 | | 0.03 |
| 22-dm-butane | 0.51 | | 0.22 | n/a | 0.19 | n/a | 0.36 | | 0.16 | 0.33 | | 0.14 |
| cyclopentene | 0.11 | | 0.05 | n/a | | n/a | | | | 0.11 | | 0.05 |
| 4m1 & 3m1-pentene | 0.17 | | 0.07 | n/a | 0.08 | n/a | 0.17 | | 0.07 | 0.14 | | 0.06 |
| cyclopentane | 0.10 | 0.00 | 0.04 | n/a | 0.20 | n/a | 0.16 | | 0.07 | 0.15 | | 0.06 |
| 23-dm-butane | | | | n/a | | n/a | | | | | | |
| c/t-4m2-pentene | | | | n/a | | n/a | | | | | | |
| 2m-pentane | 0.09 | | 0.04 | n/a | 0.08 | n/a | 0.33 | | 0.14 | 0.08 | 0.01 | 0.04 |
| 3m-pentane | 0.20 | | 0.09 | n/a | 0.14 | n/a | 0.13 | 0.02 | 0.07 | 0.18 | | 0.08 |
| 2m1-pentene | | | | n/a | | n/a | | | | | | |
| 1-hexene | 0.36 | | 0.16 | n/a | 0.12 | n/a | 0.45 | | 0.19 | 0.36 | | 0.16 |
| n-hexane | 0.20 | 0.09 | 0.13 | n/a | 0.06 | n/a | 0.09 | 0.31 | 0.21 | 0.07 | 0.24 | 0.17 |
| c/t-3-hexene | | | | n/a | | n/a | 0.15 | | 0.07 | 0.10 | | 0.04 |
| t2-hexene | | | | n/a | | n/a | | | | | | |
| 2m2-pentene | | | | n/a | | n/a | | | | | | |
| t-3m2-pentene | 0.07 | | 0.03 | n/a | | n/a | | | | | | |
| c2-hexene | | | | n/a | | n/a | 0.17 | | 0.07 | | | |
| c-3m2-pentene | | | | n/a | 0.06 | n/a | 0.11 | | 0.05 | | 0.12 | 0.07 |
| 22-dm-pentane | | | | n/a | | n/a | | | | | | |
| m-cyclopentane | 0.08 | 0.08 | 0.08 | n/a | 0.07 | n/a | 0.11 | 0.07 | 0.09 | 0.09 | 0.07 | 0.08 |
| 24-dm-pentane | | | | n/a | | n/a | | | | | | |
| 223-tm-butane | | | | n/a | | n/a | | | | | | |
| 1m-cyclopentene | | | | n/a | | n/a | | | | | | |
| benzene | 3.86 | 1.67 | 2.61 | n/a | 0.47 | n/a | 6.22 | 1.95 | 3.78 | 4.58 | 1.88 | 3.04 |
| 33-dm-pentane | | | | n/a | | n/a | | | | | | |
| cyclohexane | 0.07 | 0.06 | 0.07 | n/a | 0.07 | n/a | 0.10 | 0.35 | 0.24 | 0.05 | 0.12 | 0.09 |
| 2m-hexane | | | | n/a | 0.09 | n/a | 0.09 | 0.02 | 0.05 | 0.05 | | 0.02 |
| 23-dm-pentane | | | | n/a | | n/a | 0.05 | | 0.02 | | | |
| 11-dm-cyP | | | | n/a | | n/a | | | | | | |
| cyclohexene | 0.07 | | 0.03 | n/a | | n/a | 0.06 | | 0.02 | 0.05 | | 0.02 |
| 3m-hexane | 0.06 | 0.06 | 0.06 | n/a | 0.06 | n/a | 0.06 | 0.12 | 0.10 | 0.07 | 0.06 | 0.06 |
| c-13-dm-cyP | | | | n/a | | n/a | 0.07 | | 0.03 | | | |
| 3e-pentane/t-13-dm-cyP | | | | n/a | | n/a | 0.07 | | 0.03 | | | |
| t-12-dm-cyP | 1.25 | 1.01 | 1.11 | n/a | 0.06 | n/a | 1.39 | 1.48 | 1.44 | 1.91 | 1.12 | 1.46 |
| 224-tm-pentane/1-heptene | 0.04 | 0.00 | 0.02 | n/a | 0.08 | n/a | 0.05 | 0.06 | 0.05 | 0.08 | | 0.04 |
| t3-heptene | | | | n/a | | n/a | | | | | | |
| n-heptane | 0.08 | | 0.03 | n/a | 0.10 | n/a | 0.57 | | 0.25 | 0.07 | 0.29 | 0.20 |
| c3-heptane | | | | n/a | | n/a | | | | | | |

| Test Date | February 16/99 | | | February 17/99 | | | February 18/99 | | | February 19/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Low Sulphur Diesel | | | Low Sulfur Diesel | | | Biodiesel 20% | | | Biodiesel 20% | | |
| Temperature (°C) | 0.5 | | | 0 | | | 0 | | | 0 | | |
| | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| t2-heptene | 0.18 | 0.05 | 0.10 | n/a | 0.11 | n/a | 0.03 | | 0.01 | | | |
| c2-heptene | | 0.77 | 0.44 | n/a | | n/a | | | | 0.29 | 0.12 | 0.19 |
| 22-dm-hexane | | | | n/a | | n/a | | | | | | |
| m-cyH/c12-dm-cyP/113-tm-cyP | 0.25 | 0.23 | 0.24 | n/a | 0.23 | n/a | 0.37 | 0.21 | 0.28 | 0.22 | 0.22 | 0.22 |
| 12-dm-cyH | | | | n/a | | n/a | | | | | | |
| 25-dm-hexane/e-cyP | | | | n/a | | n/a | | | | | | |
| 24-dm-hexane/223-tm-pentane | | | | n/a | | n/a | | | | | | |
| 33-dm-hexane/ctc124-tm-cyP | | 0.07 | 0.04 | n/a | | n/a | 0.09 | | 0.04 | | | |
| ctc123-tm-cyP | | | | n/a | | n/a | 0.07 | | 0.03 | | | |
| 234-tm-pentane | | | | n/a | | n/a | | | | | | |
| toluene/233-tm-pentane | 1.89 | 0.83 | 1.29 | n/a | 0.25 | n/a | 2.08 | 1.10 | 1.52 | 1.78 | 1.05 | 1.37 |
| 23-dm-hexane/2m3e-pentane/112-tm-cyP | 0.32 | 0.19 | 0.24 | n/a | 0.34 | n/a | 0.54 | 0.19 | 0.34 | 0.25 | | 0.11 |
| 2m-heptane | 0.18 | 0.27 | 0.23 | n/a | 0.27 | n/a | 0.38 | 0.14 | 0.25 | 0.16 | | 0.07 |
| 4m-C7/3m3e-C5/34-dm-C7/1m-cyH | | 0.39 | 0.22 | n/a | 0.58 | n/a | 0.81 | 0.57 | 0.67 | 0.58 | | 0.25 |
| 3m-heptane | 0.09 | 0.09 | 0.09 | n/a | 0.16 | n/a | 0.19 | | 0.08 | 0.07 | 0.09 | 0.08 |
| 3e-hexane/c-13-dm-cyH/cct-124-tm-cyP | 0.21 | 0.19 | 0.20 | n/a | 0.17 | n/a | 0.31 | 0.16 | 0.23 | 0.18 | 0.17 | 0.17 |
| t-14-dm-cyH | 0.10 | 0.09 | 0.09 | n/a | 0.07 | n/a | 0.12 | 0.07 | 0.09 | | | |
| 225-tm-hexane | | | | n/a | | n/a | | | | | | |
| 11-dm-cyH | | | | n/a | | n/a | | | | | | |
| 1-octene | 0.29 | | 0.12 | n/a | | n/a | 0.40 | | 0.17 | 0.32 | | 0.14 |
| 224-tm-hexane/11em-cyP | 0.09 | 0.08 | 0.08 | n/a | 0.07 | n/a | 0.10 | | 0.04 | | 0.09 | 0.05 |
| n-octane/t12-dm-cyH | 0.61 | 0.66 | 0.64 | n/a | 0.15 | n/a | 0.90 | 0.65 | 0.76 | 0.73 | 0.64 | 0.68 |
| t2-octene | | | | n/a | | n/a | | | | | | |
| ccc-123-tm-cyP | 0.14 | 0.12 | 0.13 | n/a | 0.12 | n/a | 0.21 | 0.09 | 0.14 | 0.63 | 0.10 | 0.33 |
| 244-tm-hexane/ip-cyP | | | | n/a | | n/a | | | | | | |
| c2-octene | | | | n/a | | n/a | | 0.08 | 0.04 | 0.23 | | 0.10 |
| 235-tm-hexane | | | | n/a | | n/a | | | | | | |
| 44&22&26-dm-heptane/c12-dm-cyH | 0.17 | | 0.07 | n/a | 0.18 | n/a | | 0.12 | 0.07 | 0.13 | | 0.06 |
| 24-dm-heptane | | | | n/a | | n/a | | | | | | |
| np-cyP/ccc-135-tm-cyH/e-cyH | | 0.14 | 0.08 | n/a | | n/a | 0.26 | | 0.11 | | 0.12 | 0.07 |
| 25-dm-heptane | 0.23 | 0.14 | 0.18 | n/a | 0.22 | n/a | 0.40 | 0.13 | 0.25 | 0.20 | 0.15 | 0.17 |
| 33-dm-heptane | | | | n/a | 0.23 | n/a | 0.19 | | 0.08 | 0.23 | | 0.10 |
| 114-tm-cyH | 0.23 | 0.21 | 0.22 | n/a | | n/a | 0.39 | 0.18 | 0.27 | | 0.17 | 0.10 |
| e-benzene | 0.74 | | 0.32 | n/a | | n/a | 0.61 | | 0.26 | 0.32 | | 0.14 |
| cct124-tm-cyH | 4.21 | 2.91 | 3.47 | n/a | 0.16 | n/a | 4.31 | 6.20 | 5.39 | 4.69 | 4.63 | 4.65 |
| 35-dm-heptane | 0.09 | | 0.04 | n/a | | n/a | | | | | | |
| m&p-xylene/23-dm-heptane | 0.83 | 0.63 | 0.72 | n/a | 0.30 | n/a | 1.02 | 0.43 | 0.68 | 0.93 | 0.67 | 0.78 |
| 34-dm-heptane/4m-octane | | | | n/a | | n/a | 0.29 | | 0.13 | | | |
| 4e-heptane | | | | n/a | | n/a | | | | | | |
| 2m-octane/246-tm-hexane | | | | n/a | 0.27 | n/a | 0.16 | | 0.07 | 0.39 | | 0.17 |
| ctc-124-tm-cyH | 0.27 | 0.22 | 0.24 | n/a | 0.15 | n/a | 0.20 | 0.21 | 0.20 | 0.06 | 0.32 | 0.21 |
| 3m-octane/33-de-C5/3e-C7 | | | | n/a | | n/a | 0.53 | | 0.23 | | | |
| o-xylene | 0.80 | 0.73 | 0.76 | n/a | 0.24 | n/a | 1.13 | 0.64 | 0.85 | 0.69 | 0.57 | 0.62 |
| 112-tm-cyH | 0.16 | | 0.07 | n/a | | n/a | | | | | | |
| 1-nonene | 0.16 | | 0.07 | n/a | 0.15 | n/a | 0.43 | | 0.19 | 0.13 | | 0.05 |
| t3-nonene | 0.19 | 0.17 | 0.18 | n/a | 0.09 | n/a | 0.22 | 0.14 | 0.17 | 0.15 | 0.14 | 0.15 |
| ib-cyP | | 0.20 | 0.11 | n/a | | n/a | | 0.18 | 0.10 | | | |
| c3-nonene | | | | n/a | | n/a | | | | | 0.20 | 0.11 |
| n-nonane | 2.06 | 1.73 | 1.87 | n/a | 0.23 | n/a | 3.00 | 1.51 | 2.15 | 1.92 | 1.47 | 1.67 |
| t2-nonene | | | | n/a | | n/a | | | | | | |
| c2-nonene | 0.28 | | 0.12 | n/a | 0.23 | n/a | 0.13 | | 0.05 | 0.22 | | 0.10 |
| ip-benzene | | 0.38 | 0.22 | n/a | | n/a | 0.22 | 0.28 | 0.26 | | 0.37 | 0.21 |
| 22-dm-octane | | | | n/a | | n/a | | | | | | |

| Test Date | February 16/99 | | | February 17/99 | | | February 18/99 | | | February 19/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Low Sulphur Diesel | | | Low Sulfur Diesel | | | Biodiesel 20% | | | Biodiesel 20% | | |
| Temperature (°C) | 0.5 | | | 0 | | | 0 | | | 0 | | |
| | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| ip-cyH | 0.37 | 0.38 | 0.38 | n/a | 0.34 | n/a | 0.81 | 0.34 | 0.54 | 0.32 | 0.38 | 0.35 |
| nb-cyP | 0.53 | 0.40 | 0.45 | n/a | 0.27 | n/a | 1.15 | 0.43 | 0.74 | 0.27 | 0.43 | 0.36 |
| 33-dm-octane | 0.48 | 0.44 | 0.46 | n/a | | n/a | 0.94 | 0.52 | 0.70 | 0.59 | 0.54 | 0.56 |
| n-propylbenzene | 0.27 | 0.17 | 0.22 | n/a | 0.37 | n/a | 0.93 | 0.13 | 0.47 | 0.41 | 0.17 | 0.27 |
| 3e-toluene | 0.50 | 1.38 | 1.00 | n/a | | n/a | 0.15 | 1.29 | 0.80 | 1.33 | 0.80 | 1.03 |
| 23-dm-octane | | | | n/a | | n/a | | | | | | |
| 4e-toluene | | | | n/a | | n/a | 0.57 | | 0.24 | | | |
| 135-tm-benzene | 0.32 | 0.30 | 0.31 | n/a | | n/a | 1.04 | 0.27 | 0.60 | 0.37 | 0.24 | 0.29 |
| 2m-nonane | 0.58 | 0.51 | 0.54 | n/a | | n/a | 0.90 | 0.57 | 0.71 | 0.61 | 0.54 | 0.57 |
| 3e-octane | 0.48 | 0.51 | 0.50 | n/a | 0.40 | n/a | 0.18 | | 0.08 | 0.35 | | 0.15 |
| 3m-nonane | 0.65 | 0.67 | 0.66 | n/a | | n/a | 1.76 | 0.62 | 1.11 | 0.66 | 0.59 | 0.62 |
| 2e-toluene | 0.82 | 0.72 | 0.77 | n/a | | n/a | 1.15 | 1.20 | 1.18 | 0.74 | 0.62 | 0.67 |
| 124-tm-benz/tb-benz/1-decene | 1.00 | 0.53 | 0.73 | n/a | 0.22 | n/a | 1.92 | 0.96 | 1.37 | 0.85 | 0.90 | 0.88 |
| 1b-cyH | | | | n/a | | n/a | 0.66 | | 0.28 | | 0.45 | 0.26 |
| n-decane | 2.90 | 2.48 | 2.66 | n/a | 0.30 | n/a | 4.78 | 2.64 | 3.56 | 3.09 | 2.23 | 2.60 |
| ib-benzene | | 0.33 | 0.19 | n/a | | n/a | 0.29 | | 0.13 | | | |
| sb-benzene | | | | n/a | | n/a | 0.32 | | 0.14 | | | |
| 3-ip-toluene | 1.71 | | 0.73 | n/a | 0.93 | n/a | 0.49 | 0.43 | 0.45 | 1.25 | | 0.54 |
| 123-tm-benzene | | | | n/a | | n/a | | | | | | |
| 4-ip-toluene | | | | n/a | | n/a | 0.92 | 0.13 | 0.47 | 0.49 | 0.82 | 0.68 |
| indan | | | | n/a | | n/a | | | | | | |
| 2-ip-toluene | 0.75 | 0.65 | 0.69 | n/a | | n/a | 1.10 | 0.82 | 0.94 | 0.79 | 1.12 | 0.98 |
| 13-de-benzene | | | | n/a | | n/a | | | | | | |
| 14-de-benzene | | | | n/a | | n/a | | | | | | |
| 3-np-toluene | 0.58 | 0.47 | 0.52 | n/a | | n/a | 0.85 | 0.41 | 0.60 | 0.88 | | 0.38 |
| 4-np-toluene/nb-benz/13dm5e-benzene | 0.99 | | 0.43 | n/a | | n/a | 1.50 | 0.50 | 0.93 | 1.02 | | 0.44 |
| 12de-benzene | | | | n/a | | n/a | 0.54 | | 0.23 | | | |
| 2-np-toluene | | | | n/a | | n/a | 0.52 | | 0.23 | | | |
| 14dm-2e-benzene | 0.55 | 1.07 | 0.85 | n/a | | n/a | 1.13 | 0.53 | 0.79 | 0.98 | 0.47 | 0.69 |
| 13dm-4e-benzene | | | | n/a | | n/a | | | | | | |
| 12dm-4e-benzene | 0.49 | 0.76 | 0.64 | n/a | | n/a | 0.51 | 0.75 | 0.65 | 0.42 | 0.78 | 0.63 |
| 13dm-2e-benzene | 0.57 | 1.10 | 0.87 | n/a | | n/a | 1.18 | | 0.51 | | | |
| n-undecane/12-dm-3e-&1245-ttm-benzene | 4.00 | 3.40 | 3.66 | n/a | 0.27 | n/a | 8.08 | 5.10 | 6.38 | 3.87 | 3.29 | 3.54 |
| 2mb-benzene | 2.94 | | 1.26 | n/a | 2.18 | n/a | 4.17 | 0.81 | 2.25 | 4.19 | | 1.80 |
| tb-2m-benzene | 0.79 | | 0.34 | n/a | | n/a | 0.65 | 0.86 | 0.77 | 0.96 | | 0.41 |
| 1234-ttm-benzene | | | | n/a | | n/a | 0.32 | | 0.14 | | | |
| npentyl-benzene | 0.52 | 0.56 | 0.55 | n/a | | n/a | 0.54 | 0.60 | 0.57 | | | |
| tb-35dm-benzene | 0.29 | | 0.12 | n/a | | n/a | 1.28 | 0.58 | 0.88 | | | |
| tb-4e-benzene | 0.43 | 0.54 | 0.49 | n/a | | n/a | 1.75 | 0.79 | 1.20 | 0.29 | 0.79 | 0.58 |
| n-dodecane | 1.60 | 2.38 | 2.05 | n/a | | n/a | 3.40 | 2.35 | 2.80 | 1.33 | 2.56 | 2.03 |
| 135-TE-BENZENE | | | | n/a | | n/a | | | | | | |
| 124-TE-BENZENE | | | | n/a | | n/a | | | | | | |
| N-HEXYLBENZENE | | | | n/a | | n/a | | | | | | |
| N-C13 | | | | n/a | | n/a | 2.33 | 3.03 | 2.73 | | 1.77 | 1.01 |
| N-C14 | | | | n/a | | n/a | | | | | | |
| N-C15 | | | | n/a | | n/a | 0.83 | | 0.35 | | | |
| N-C16 | | | | n/a | | n/a | | | | | | |
| N-C17 | | | | n/a | | n/a | | | | | | |
| N-C18 | | | | n/a | | n/a | | | | | | |
| N-C19 | | | | n/a | | n/a | | | | | | |
| N-C20 | | | | n/a | | n/a | | | | | | |
| N-C21 | | | | n/a | | n/a | | | | | | |
| N-C22 | | | | n/a | | n/a | | | | | | |
| N-C23 | | | | n/a | | n/a | | | | | | |
| N-C24 | | | | n/a | | n/a | | | | | | |
| N-C25 | | | | n/a | | n/a | | | | | | |
| N-C26 | | | | n/a | | n/a | | | | | | |

**Mass emission rates of carbonyl compounds (mg/mi)**

| Test Date | January 13/99 | | | January 15/99 | | | January 18/99 | | | February 2/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Low Sulfur Diesel | | | Low Sulfur Diesel | | | Biodiesel 10 % | | | Biodiesel 10% | | |
| Temperature (°C) | 22.9 | | | 22.6 | | | 24.1 | | | 24.3 | | |
| | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| Formaldehyde | 19.65 | 2.49 | 9.87 | 20.55 | 16.24 | 18.09 | 22.27 | 16.92 | 19.22 | 0.15 | 3.23 | 1.91 |
| Acetaldehyde | 6.20 | 0.72 | 3.08 | 6.24 | 5.46 | 5.80 | 7.06 | 5.71 | 6.29 | | 1.06 | 0.49 |
| 2-3 butandione | | | | | | | | | | | | |
| Acrolein | | | | 1.18 | 0.40 | 0.74 | 2.52 | 1.19 | 1.76 | | | |
| Acetone | 7.31 | 3.58 | 5.18 | 6.09 | 1.06 | 3.22 | 3.14 | 2.76 | 2.92 | 3.18 | 5.48 | 4.49 |
| Propionaldehyde | 0.70 | | 0.30 | 1.00 | 0.60 | 0.77 | 1.29 | 1.05 | 1.16 | | | |
| Methoxyacetone | | | | | | | | | | | | |
| Crotonaldehyde | 0.95 | | 0.41 | 0.77 | 0.02 | 0.35 | 0.58 | 0.89 | 0.76 | | | |
| Methyl Vinyl Ketone | | | | | | | | | | | | |
| Methacrolein | | | | | | | | | | | | |
| Methyl Ethyl Ketone | 0.98 | 1.38 | 1.21 | 2.17 | 0.27 | 1.09 | 0.67 | 0.70 | 0.69 | 2.00 | 2.51 | 2.29 |
| Isobutyraldehyde & Butyraldehyde | | | | | | | | | | | | |
| Benzaldehyde | 0.05 | | 0.02 | 0.38 | | 0.16 | 0.50 | | 0.22 | | | |
| Isovaleraldehyde | | | | | | | | | | | | |
| Trimethylacetaldehyde & 3m2-Butanone | 0.96 | 0.55 | 0.72 | 1.31 | | 0.56 | | | | 0.43 | | 0.18 |
| Valeraldehyde | 1.38 | | 0.59 | | 0.10 | 0.06 | | | | | | |
| Acetophenone | | | | | | | | | | | | |
| o-Tolualdehyde | | | | | | | | | | | | |
| m&p-Tolualdehyde | | | | | | | | | | | | |
| Methyl isobutyl Ketone | 0.16 | | 0.07 | | | | | | | | | |
| Pinacolone | | | | | | | | | | | | |
| Hexanaldehyde | | | | | | | | | | | | |

| Test Date | February 3/99 | | | February 4/99 | | | February 8/99 | | |
|---|---|---|---|---|---|---|---|---|---|
| Fuel | Biodiesel 20% | | | Biodiesel 20% | | | Biodiesel 20% | | |
| Temperature (°C) | 23.6 | | | 24.2 | | | 24.1 | | |
| | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| Formaldehyde | 19.11 | 15.90 | 17.28 | 2.89 | 15.48 | 10.07 | 19.48 | 14.39 | 16.58 |
| Acetaldehyde | 5.13 | 5.12 | 5.12 | 1.08 | 5.21 | 3.43 | 5.88 | 4.53 | 5.11 |
| 2-3 butandione | | | | | | | | | |
| Acrolein | 1.29 | 1.33 | 1.31 | | 1.20 | 0.68 | 1.00 | 0.47 | 0.70 |
| Acetone | 5.63 | 5.24 | 5.41 | 5.50 | 4.57 | 4.97 | 5.42 | 4.90 | 5.12 |
| Propionaldehyde | 0.98 | 1.14 | 1.07 | | 1.07 | 0.61 | 1.18 | 0.82 | 0.97 |
| Methoxyacetone | | | | | | | | | |
| Crotonaldehyde | 0.28 | 0.87 | 0.62 | | 0.72 | 0.41 | 0.78 | 0.71 | 0.74 |
| Methyl Vinyl Ketone | | | | | | | | | |
| Methacrolein | | | | | | | | | |
| Methyl Ethyl Ketone | 1.90 | 1.75 | 1.81 | 2.37 | 2.00 | 2.16 | 2.51 | 1.46 | 1.91 |
| Isobutyraldehyde & Butyraldehyde | | | | | | | | | |
| Benzaldehyde | 0.89 | 0.40 | 0.61 | | | | 0.51 | 0.45 | 0.48 |
| Isovaleraldehyde | | | | | | | | | |
| Trimethylacetaldehyde & 3m2-Butanone | | 0.53 | 0.13 | 0.39 | | 0.17 | 0.52 | | 0.22 |
| Valeraldehyde | | 0.50 | 0.28 | | | | | | |
| Acetophenone | | | | | | | | | |
| o-Tolualdehyde | | | | | | | | | |
| m&p-Tolualdehyde | | | | | | | | | |
| Methyl isobutyl Ketone | | | | | | | | | |
| Pinacolone | | | | | | | | | |
| Hexanaldehyde | 0.43 | | 0.18 | | | | | | |

| Test Date | January 26/99 | | | January 27/99 | | | January 28/99 | | |
|---|---|---|---|---|---|---|---|---|---|
| Fuel | Biodiesel 30 % | | | Biodiesel 30 % | | | Biodiesel 30 % | | |
| Temperature (°C) | 23.2 | | | 24.8 | | | 24.7 | | |
| | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| Formaldehyde | 21.18 | 13.58 | 16.85 | | 8.36 | 4.62 | 18.45 | 13.62 | 15.70 |
| Acetaldehyde | 6.47 | 4.00 | 5.06 | | 2.75 | 1.44 | 5.36 | 4.51 | 4.88 |
| 2-3 butandione | | | | | | | | | |
| Acrolein | 2.53 | 0.48 | 1.36 | | | | 1.50 | 1.16 | 1.31 |
| Acetone | 5.62 | 7.24 | 6.54 | 5.12 | 4.35 | 4.68 | 7.57 | 6.72 | 7.08 |
| Propionaldehyde | 1.14 | 0.81 | 0.95 | | 0.35 | 0.20 | 1.07 | 0.82 | 0.93 |
| Methoxyacetone | | | | | | | | | |
| Crotonaldehyde | 0.76 | 0.29 | 0.50 | | | | 0.45 | | 0.19 |
| Methyl Vinyl Ketone | | | | | | | | | |
| Methacrolein | | | | | | | | | |
| Methyl Ethyl Ketone | 1.84 | 2.82 | 2.40 | 2.33 | 1.84 | 2.05 | 3.25 | 2.38 | 2.75 |
| Isobutyraldehyde & Butyraldehyde | | | | | | | | | |
| Benzaldehyde | 0.53 | | 0.23 | | | | | 0.39 | 0.22 |
| Isovaleraldehyde | | | | | | | | | |
| Trimethylacetaldehyde & 3m2-Butanone | 0.96 | 0.88 | 0.92 | | 0.43 | 0.25 | | 0.37 | 0.21 |
| Valeraldehyde | 0.85 | | 0.37 | | | | | 0.42 | 0.24 |
| Acetophenone | | | | | | | | | |
| o-Tolualdehyde | | | | | | | | | |
| m&p-Tolualdehyde | | | | | | | | | |
| Methyl isobutyl Ketone | | | | | | | | | |
| Pinacolone | | | | | | | | | |
| Hexanaldehyde | | | | | | | | | |

| Test Date | February 16/99 | | | February 17/99 | | | February 18/99 | | | February 19/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Low Sulphur Diesel | | | Low Sulfur Diesel | | | Biodiesel 20% | | | Biodiesel 20% | | |
| Temperature (°C) | 0.5 | | | 0 | | | 0 | | | 0 | | |
| | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| Formaldehyde | 28.16 | 20.02 | 23.52 | n/a | 16.67 | n/a | 26.52 | 9.28 | 16.69 | 22.07 | 16.80 | 19.06 |
| Acetaldehyde | 10.29 | 7.16 | 8.50 | n/a | 6.01 | n/a | 11.08 | 4.22 | 7.17 | 9.56 | 5.89 | 7.47 |
| 2-3 butandione | | | | n/a | | n/a | | | | 0.46 | | 0.20 |
| Acrolein | 2.43 | | 1.04 | n/a | | n/a | 1.93 | 0.57 | 1.15 | 2.06 | 1.46 | 1.72 |
| Acetone | 4.78 | 9.26 | 7.33 | n/a | 8.24 | n/a | 4.86 | 4.63 | 4.73 | 4.24 | 3.19 | 3.64 |
| Propionaldehyde | 1.39 | 1.29 | 1.33 | n/a | 0.94 | n/a | 1.90 | 0.62 | 1.17 | 1.57 | 1.03 | 1.26 |
| Methoxyacetone | | | | n/a | | n/a | | | | | | |
| Crotonaldehyde | 1.09 | 1.56 | 1.36 | n/a | 0.95 | n/a | 1.46 | 0.49 | 0.91 | 1.19 | 0.67 | 0.89 |
| Methyl Vinyl Ketone | | | | n/a | | n/a | | | | | | |
| Methacrolein | | | | n/a | | n/a | 0.29 | | 0.12 | | | |
| Methyl Ethyl Ketone | 1.20 | 3.12 | 2.30 | n/a | 3.45 | n/a | 0.79 | 1.69 | 1.30 | 0.96 | 0.82 | 0.88 |
| Isobutyraldehyde & Butyraldehyde | | | | n/a | | n/a | 0.98 | | 0.42 | | | |
| Benzaldehyde | 1.12 | 0.85 | 0.96 | n/a | 0.93 | n/a | 1.25 | | 0.54 | 1.72 | 0.59 | 1.08 |
| Isovaleraldehyde | | | | n/a | | n/a | | | | | | |
| Trimethylacetaldehyde & 3m2-Butanone | 0.72 | 0.63 | 0.67 | n/a | 0.47 | n/a | 0.57 | 0.65 | 0.62 | 0.62 | 0.13 | 0.34 |
| Valeraldehyde | 0.68 | 0.53 | 0.60 | n/a | 0.38 | n/a | 0.85 | | 0.37 | 0.68 | | 0.29 |
| Acetophenone | | | | n/a | | n/a | | | | | | |
| o-Tolualdehyde | | | | n/a | | n/a | | | | | | |
| m&p-Tolualdehyde | | | | n/a | | n/a | | | | | | |
| Methyl isobutyl Ketone | 0.78 | | 0.33 | n/a | | n/a | 0.67 | | 0.29 | | | |
| Pinacolone | | | | n/a | 0.43 | n/a | | | | | | |
| Hexanaldehyde | | | | n/a | | n/a | 0.48 | | 0.21 | | | |

**Mass emission rates of TPM (g/mi)**

| Test Date | Fuel | Temperature (°C) | Cold Start | Hot Start | Composite |
|---|---|---|---|---|---|
| January 13/99 | Low Sulphur Diesel | 22.9 | 0.067 | 0.071 | 0.069 |
| January 14/99 | Low Sulphur Diesel | 22.8 | 0.078 | 0.072 | 0.075 |
| January 18/99 | Biodiesel 10 % | 24.1 | 0.071 | 0.067 | 0.069 |
| January 19/99 | Biodiesel 10 % | 24.9 | 0.074 | 0.062 | 0.067 |
| February 2/99 | Biodiesel 10% | 24.3 | 0.076 | 0.069 | 0.072 |
| January 20/99 | Biodiesel 20 % | 24.4 | 0.075 | 0.067 | 0.070 |
| January 21/99 | Biodiesel 20 % | 24.6 | 0.062 | 0.072 | 0.068 |
| January 26/99 | Biodiesel 30 % | 23.2 | 0.095 | 0.081 | 0.087 |
| January 27/99 | Biodiesel 30 % | 24.8 | 0.079 | 0.077 | 0.078 |
| January 28/99 | Biodiesel 30 % | 24.7 | 0.077 | 0.075 | 0.076 |
| February 17/99 | Low Sulphur Diesel | 0 | n/a | 0.109 | n/a |
| February 18/99 | Biodiesel 20% | 0 | 0.185 | 0.091 | 0.132 |
| February 19/99 | Biodiesel 20% | 0 | 0.122 | 0.047 | 0.079 |

**Mass emission rates of $PM_{2.5}$ (g/mi)**

| Test Date | Fuel | Temperature (°C) | Cold Start | Hot Start | Composite |
|---|---|---|---|---|---|
| January 13/99 | Low Sulphur Diesel | 24 | n/a | 0.034 | n/a |
| January 14/99 | Low Sulphur Diesel | 24 | 0.040 | 0.037 | 0.038 |
| January 18/99 | Biodiesel 10 % | 24 | 0.021 | 0.040 | 0.032 |
| January 19/99 | Biodiesel 10 % | 24 | 0.045 | 0.041 | 0.042 |
| February 2/99 | Biodiesel 10% | 24 | 0.039 | 0.036 | 0.037 |
| January 20/99 | Biodiesel 20 % | 24 | 0.045 | 0.040 | 0.042 |
| January 21/99 | Biodiesel 20 % | 24 | 0.047 | 0.042 | 0.044 |
| January 26/99 | Biodiesel 30 % | 24 | n/a | 0.050 | n/a |
| January 27/99 | Biodiesel 30 % | 24 | 0.053 | 0.040 | 0.045 |
| January 28/99 | Biodiesel 30 % | 24 | 0.039 | 0.025 | 0.031 |
| February 16/99 | Low Sulphur Diesel | 0 | 0.128 | 0.079 | 0.100 |
| February 17/99 | Low Sulphur Diesel | 0 | n/a | 0.097 | n/a |
| February 18/99 | Biodiesel 20% | 0 | 0.158 | 0.108 | 0.130 |
| February 19/99 | Biodiesel 20% | 0 | 0.127 | 0.091 | 0.106 |

**Mass emission rates of organic, elemental and total carbon (mg/mi) as determined by two analytical methods (TOT and TOR).**

| | | | *TOT* | *TOR* |
|---|---|---|---|---|
| Test Date | January 13/99 | **Cold Start** | | |
| Fuel | Low Sulphur Diesel | Organic Carbon | 19.80 | |
| Temperature (C) | 24 | Elemental Carbon | 14.88 | |
| | | Total Carbon | 34.67 | |
| | | **Hot Start** | | |
| | | Organic Carbon | 20.09 | |
| | | Elemental Carbon | 15.31 | |
| | | Total Carbon | 35.39 | |
| | | **Composite** | | |
| | | Organic Carbon | 19.96 | |
| | | Elemental Carbon | 15.12 | |
| | | Total Carbon | 35.08 | |
| Test Date | January 14/99 | **Cold Start** | | |
| Fuel | Low Sulphur Diesel | Organic Carbon | 27.38 | 20.41 |
| Temperature (C) | 24 | Elemental Carbon | 18.70 | 18.71 |
| | | Total Carbon | 46.14 | 39.10 |
| | | **Hot Start** | | |
| | | Organic Carbon | 26.03 | 24.32 |
| | | Elemental Carbon | 17.25 | 19.41 |
| | | Total Carbon | 43.28 | 43.75 |
| | | **Composite** | | |
| | | Organic Carbon | 26.61 | 22.64 |
| | | Elemental Carbon | 17.87 | 19.11 |
| | | Total Carbon | 44.51 | 41.75 |
| Test Date | January 19/99 | **Cold Start** | | |
| Fuel | Biodiesel 10 % | Organic Carbon | 23.38 | |
| Temperature (C) | 24 | Elemental Carbon | 16.69 | |
| | | Total Carbon | 40.07 | |
| | | **Hot Start** | | |
| | | Organic Carbon | 25.27 | |
| | | Elemental Carbon | 17.87 | |
| | | Total Carbon | 43.14 | |
| | | **Composite** | | |
| | | Organic Carbon | 24.45 | |
| | | Elemental Carbon | 17.36 | |
| | | Total Carbon | 41.82 | |
| Test Date | February 2/99 | **Cold Start** | | |
| Fuel | Biodiesel 10% | Organic Carbon | 29.59 | 28.11 |
| Temperature (C) | 24 | Elemental Carbon | 18.46 | 22.81 |
| | | Total Carbon | 48.06 | 50.92 |
| | | **Hot Start** | | |
| | | Organic Carbon | 20.81 | 21.44 |
| | | Elemental Carbon | 15.43 | 18.14 |
| | | Total Carbon | 36.24 | 39.60 |
| | | **Composite** | | |
| | | Organic Carbon | 24.58 | 24.31 |
| | | Elemental Carbon | 16.73 | 20.15 |
| | | Total Carbon | 41.32 | 44.47 |
| Test Date | January 20/99 | **Cold Start** | | |
| Fuel | Biodiesel 20 % | Organic Carbon | 24.98 | |

| | | | *TOT* | *TOR* |
|---|---|---|---|---|
| Temperature (C) | 24 | Elemental Carbon | 16.75 | |
| | | Total Carbon | 41.72 | |
| | | **Hot Start** | | |
| | | Organic Carbon | 27.82 | |
| | | Elemental Carbon | 17.43 | |
| | | Total Carbon | 45.25 | |
| | | **Composite** | | |
| | | Organic Carbon | 26.60 | |
| | | Elemental Carbon | 17.14 | |
| | | Total Carbon | 43.73 | |
| Test Date | January 21/99 | **Cold Start** | | |
| Fuel | Biodiesel 20% | Organic Carbon | 36.89 | 30.93 |
| Temperature (C) | 24 | Elemental Carbon | 17.10 | 26.46 |
| | | Total Carbon | 53.99 | 57.36 |
| | | **Hot Start** | | |
| | | Organic Carbon | 33.12 | 29.23 |
| | | Elemental Carbon | 16.60 | 22.55 |
| | | Total Carbon | 49.72 | 51.78 |
| | | **Composite** | | |
| | | Organic Carbon | 34.74 | 29.96 |
| | | Elemental Carbon | 16.82 | 24.23 |
| | | Total Carbon | 51.56 | 54.18 |
| Test Date | January 27/99 | **Cold Start** | | |
| Fuel | Biodiesel 30 % | Organic Carbon | n/a | |
| Temperature (C) | 24 | Elemental Carbon | n/a | |
| | | Total Carbon | n/a | |
| | | **Hot Start** | | |
| | | Organic Carbon | n/a | |
| | | Elemental Carbon | n/a | |
| | | Total Carbon | n/a | |
| | | **Composite** | | |
| | | Organic Carbon | n/a | |
| | | Elemental Carbon | n/a | |
| | | Total Carbon | n/a | |
| Test Date | January 28/99 | **Cold Start** | | |
| Fuel | Biodiesel 30% | Organic Carbon | 30.86 | 26.63 |
| Temperature (C) | 24 | Elemental Carbon | 17.22 | 19.55 |
| | | Total Carbon | 48.08 | 46.18 |
| | | **Hot Start** | | |
| | | Organic Carbon | 26.06 | 22.05 |
| | | Elemental Carbon | 15.93 | 19.17 |
| | | Total Carbon | 42.00 | 41.22 |
| | | **Composite** | | |
| | | Organic Carbon | 28.12 | 24.02 |
| | | Elemental Carbon | 16.49 | 19.33 |
| | | Total Carbon | 44.61 | 43.35 |
| Test Date | February 18/99 | **Cold Start** | | |
| Fuel | Biodiesel 20% | Organic Carbon | 103.25 | |
| Temperature (C) | 0 | Elemental Carbon | 21.27 | |
| | | Total Carbon | 125.37 | |
| | | **Hot Start** | | |
| | | Organic Carbon | 52.04 | |
| | | Elemental Carbon | 14.88 | |
| | | Total Carbon | 67.00 | |
| | | **Composite** | | |

| | | | *TOT* | *TOR* |
|---|---|---|---|---|
| | | Organic Carbon | 74.06 | |
| | | Elemental Carbon | 17.63 | |
| | | Total Carbon | 92.10 | |
| Test Date | February 19/99 | **Cold Start** | | |
| Fuel | Biodiesel 20% | Organic Carbon | n/a | n/a |
| Temperature (C) | 0 | Elemental Carbon | n/a | n/a |
| | | Total Carbon | n/a | n/a |
| | | **Hot Start** | | |
| | | Organic Carbon | n/a | n/a |
| | | Elemental Carbon | n/a | n/a |
| | | Total Carbon | n/a | n/a |
| | | **Composite** | | |
| | | Organic Carbon | n/a | n/a |
| | | Elemental Carbon | n/a | n/a |
| | | Total Carbon | n/a | n/a |

**Mass emission rates of $SO_2$ and $NH_3$ (mg/mile).**

| **Test Date** | **Fuel** | **Temperature (°C)** | | **$SO_2$** | | **$NH_3$** |
|---|---|---|---|---|---|---|
| | | | | **Carbonate** | **KOH** | **Citric** |
| January 14/99 | Low Sulphur Diesel | 24 | Cold Start | 161 | 138 | 0.25 |
| | | | Hot Start | 137 | 99 | 0.14 |
| | | | Composite | 147 | 115 | 0.19 |
| February 2/99 | Biodiesel 10% | 24 | Cold Start | 166 | 149 | 0.12 |
| | | | Hot Start | 147 | 132 | 0.22 |
| | | | Composite | 155 | 139 | 0.17 |
| January 21/99 | Biodiesel 20% | 24 | Cold Start | 145 | 122 | 0.11 |
| | | | Hot Start | 148 | 118 | 0.17 |
| | | | Composite | 147 | 120 | 0.14 |
| January 28/99 | Biodiesel 30% | 24 | Cold Start | 135 | 112 | 0.07 |
| | | | Hot Start | 121 | 108 | 0.00 |
| | | | Composite | 127 | 109 | 0.03 |
| February 18/99 | Biodiesel 20% | 0 | Cold Start | 129 | 144 | 0.00 |
| | | | Hot Start | 166 | 146 | 0.00 |
| | | | Composite | 150 | 145 | 0.00 |

**Mass emission rates of particle phase ions collected on Teflon filters (mg/mi).**

| Test Date | January 14/99 | | | February 2/99 | | | January 21/99 | | | January 28/99 | | | February 18/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Low Sulphur Diesel | | | Biodiesel 10% | | | Biodiesel 20% | | | Biodiesel 30% | | | Biodiesel 20% | | |
| Temperature (C) | 24 | | | 24 | | | 24 | | | 24 | | | 0 | | |
| (mg/mi) | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| Fluoride | | | | | | | | | | n/a | | n/a | | | |
| Acetate | | | | | | | | | | n/a | | n/a | | | |
| Propionate | | | | | | | | | | n/a | | n/a | | | |
| Formate | | | | 0.05 | 0.20 | 0.14 | | | | n/a | | n/a | | | |
| MSA | | | | | | | | | | n/a | | n/a | | | |
| Chloride | | 0.04 | 0.02 | 0.11 | 0.07 | 0.08 | 0.07 | 0.06 | 0.07 | n/a | | n/a | | 0.07 | 0.04 |
| Nitrite | | | | | 0.02 | 0.01 | | | | n/a | | n/a | 0.00 | | 0.00 |
| Bromide | | | | | | | | | | n/a | | n/a | | | |
| Nitrate | 0.21 | 0.27 | 0.24 | 0.25 | 0.25 | 0.25 | | | | n/a | 0.22 | n/a | 0.25 | 0.21 | 0.23 |
| Sulphate | 2.04 | 1.74 | 1.87 | 2.10 | 1.62 | 1.82 | 1.40 | 1.19 | 1.28 | n/a | 1.48 | n/a | 2.49 | 1.89 | 2.15 |
| Oxalate | | | | | | | | | | n/a | | n/a | | | |
| Phosphate | 0.09 | 0.11 | 0.10 | 0.12 | 0.08 | 0.10 | | 0.14 | 0.08 | n/a | 0.11 | n/a | 0.11 | 0.09 | 0.10 |
| Lithium | | | | | | | | | | n/a | | n/a | | | |
| Sodium | | | | | | | 0.05 | 0.01 | 0.03 | n/a | | n/a | | 0.05 | 0.03 |
| Ammonium | 0.70 | 0.60 | 0.64 | 0.72 | 0.66 | 0.68 | 0.48 | 0.49 | 0.48 | n/a | 0.52 | n/a | 0.46 | 0.36 | 0.40 |
| Potassium | | | | 0.46 | 0.58 | 0.53 | | 0.44 | 0.25 | n/a | | n/a | | | |
| Rubidium | | | | | | | | | | n/a | | n/a | | | |
| Cesium | | | | | | | | | | n/a | | n/a | | | |
| Magnesium | | | | 0.05 | | 0.02 | 0.12 | 0.03 | 0.07 | n/a | 0.04 | n/a | | 0.07 | 0.04 |
| Manganese | | | | | | | | | | n/a | | n/a | | | |
| Strontium | | | | | | | | | | n/a | | n/a | | | |

missing values indicates compound determined but not detected. n/a indicates data not available.

**Mass emission rates of vapour phase acids collected on KOH coated filters as determined by ion chromatography (mg/mi).**

| Test Date | January 14/99 | | | February 2/99 | | | January 21/99 | | | January 28/99 | | | February 18/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Low Sulphur Diesel | | | Biodiesel 10% | | | Biodiesel 20% | | | Biodiesel 30% | | | Biodiesel 20% | | |
| Temperature (C) | 24 | | | 24 | | | 24 | | | 24 | | | 0 | | |
| (mg/mile) | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| Glycolic | 2.81 | 2.28 | 2.51 | 2.89 | 2.12 | 2.45 | 2.48 | 2.17 | 2.30 | 2.28 | 1.88 | 2.06 | 0.38 | 0.19 | 0.27 |
| Acetic | 5.99 | 3.59 | 4.62 | 3.34 | 2.54 | 2.88 | 5.48 | 4.62 | 4.99 | 3.03 | 1.54 | 2.18 | 4.74 | 3.86 | 4.24 |
| Propionic | 0.56 | 0.20 | 0.36 | 0.22 | | 0.09 | 0.52 | 0.34 | 0.42 | 0.44 | | 0.19 | 0.38 | 0.36 | 0.37 |
| Formic | 9.64 | 6.77 | 8.00 | 9.73 | 7.06 | 8.20 | 8.70 | 6.34 | 7.36 | 7.89 | 6.20 | 6.92 | 7.35 | 5.89 | 6.52 |
| MSA | 0.32 | 0.21 | 0.26 | | | | 0.18 | 0.12 | 0.14 | 0.36 | 0.28 | 0.31 | 0.40 | 0.30 | 0.34 |
| Pyruvic | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q |
| Glyoxylic | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q |
| *Nitrite (NO) | 84.84 | 29.17 | 53.11 | 35.46 | 29.15 | 31.86 | 57.40 | 64.19 | 61.27 | 38.56 | 28.79 | 32.99 | 58.45 | 54.84 | 56.39 |
| *Nitrate ($NO_2$) | 59.63 | 29.50 | 42.46 | 35.90 | 28.00 | 31.40 | 42.31 | 43.78 | 43.15 | 35.39 | 31.09 | 32.94 | 114.03 | 78.26 | 93.64 |
| Glutaric | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q |
| Succinic | | | | | | | | | | | | | | | |
| Malonic | | | | | | | | | | | | | | | |
| Suberic | | | | | | | | | | | | | | | |
| *Sulphate ($SO_2$) | 206.30 | 148.10 | 173.13 | 223.15 | 197.88 | 208.74 | 183.10 | 177.27 | 179.78 | 167.46 | 161.20 | 163.89 | 215.38 | 219.32 | 217.62 |
| Oxalic | | | | | | | | | | | | | | | |
| Azelaic | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q |
| Phthalic | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q |
| Lactic | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q |
| Benzoic | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q |

*acid gases

missing values indicates compound determined but not detected. n/a indicates data not available. n/q indicates compound not determined by the method.

**Mass emission rates of vapour phase acids collected on KOH coated filters as determined by capillary electrophoresis (mg/mi).**

| Test Date | January 14/99 | | | February 2/99 | | | January 21/99 | | | January 28/99 | | | February 18/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Low Sulphur Diesel | | | Biodiesel 10% | | | Biodiesel 20% | | | Biodiesel 30% | | | Biodiesel 20% | | |
| Temperature (C) | 24 | | | 24 | | | 24 | | | 24 | | | 0 | | |
| | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite | Cold Start | Hot Start | Composite |
| Glycolic | 1.07 | 0.84 | 0.94 | 2.30 | 1.57 | 1.88 | 1.33 | 1.13 | 1.21 | 1.53 | 1.10 | 1.28 | | | |
| Acetic | 6.71 | 3.58 | 4.92 | 3.51 | 2.53 | 2.95 | 6.09 | 4.76 | 5.33 | 3.03 | 1.48 | 2.14 | 4.97 | 3.65 | 4.22 |
| Propionic | 0.50 | | 0.22 | | | | | | | | | | | | |
| Formic | 11.76 | 7.86 | 9.54 | 11.97 | 8.39 | 9.93 | 10.36 | 7.36 | 8.65 | 9.10 | 7.37 | 8.12 | 8.38 | 6.09 | 7.07 |
| MSA | 0.48 | 0.47 | 0.47 | | | | 0.54 | 0.44 | 0.48 | 0.23 | | 0.10 | | | |
| Pyruvic | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q |
| Glyoxylic | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q |
| *Nitrite (NO) | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q |
| *Nitrate ($NO_2$) | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q |
| Glutaric | | | | | | | | | | | | | | | |
| Succinic | | | | | | | | | | | | | | | |
| Malonic | | | | | | | | | | | | | | | |
| Suberic | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q |
| *Sulphate ($SO_2$) | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q |
| Oxalic | n/a | 12.07 | 6.88 | n/a | 2.91 | 1.66 | 3.12 | n/a | n/a | 5.51 | 9.71 | 7.90 | n/a | n/a | n/a |
| Azelaic | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q |
| Phthalic | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q | n/q |
| Lactic | 0.19 | | 0.08 | 0.33 | 0.23 | 0.27 | | | | 0.05 | 0.40 | 0.25 | 0.00 | | 0.00 |
| Benzoic | | | | | | | 0.12 | | 0.05 | | | | | | |

*acid gases

missing values indicates compound determined but not detected. n/a indicates data not available. n/q indicates compound not determined by the method.

**Mass emission rates of PAH compounds (μg/mi)**

| Date | 13-Jan-99 | 14-Jan-99 | 19-Jan-99 | 2-Feb-99 | 20-Jan-99 | 21-Jan-99 | 27-Jan-99 | 28-Jan-99 |
|---|---|---|---|---|---|---|---|---|
| **Fuel** | **LSD-1** | **LSD-2** | **B10-1** | **B10-2** | **B20-1** | **B20-2** | **B30-1** | **B30-2** |
| Acenaphthylene | 89.1 | 107 | 164 | 126 | 156 | 171 | 164 | 144 |
| Acenaphthene | <ql | <ql | <ql | <ql | <ql | <ql | 64.7 | 56.8 |
| Fluorene | 95.9 | 139 | 113 | 174 | 147 | 152 | 137 | 155 |
| 2-Me-Fluorene | 93.5 | 84.1 | 71.5 | 133 | 65.1 | 53.0 | 98.0 | 94.4 |
| Phenanthrene | 185 | 204 | 184 | 307 | 200 | 198 | 246 | 210 |
| Anthracene | 8.0 | 8.3 | 7.0 | 10.5 | 9.1 | 8.6 | 6.8 | 6.5 |
| Fluoranthene | 9.3 | 10.1 | 5.7 | 15.6 | 17.6 | 16.9 | 16.7 | 15.1 |
| Pyrene | 11.6 | 13.1 | 7.2 | 19.9 | 20.1 | 19.6 | 20.9 | 17.8 |
| Benzo(a)Fluorene | 0.68 | 1.24 | 1.33 | 2.47 | 2.29 | 1.77 | 1.88 | 2.12 |
| Benzo(b)Fluorene | 0.74 | 0.71 | 0.76 | 1.01 | 1.16 | 1.22 | 1.22 | 1.08 |
| 1-Me-Pyrene | 1.46 | 2.07 | 2.27 | 3.31 | 1.89 | 1.53 | 2.41 | 2.31 |
| Benzo(g,h,i)Fluoranthene | 0.96 | 1.02 | 1.67 | 1.70 | 2.19 | 1.97 | 1.99 | 1.96 |
| Benzo(a)Anthracene | 0.84 | 0.77 | 1.48 | 1.25 | <ql | <ql | <ql | 1.39 |
| Chrysene | 0.79 | 0.79 | 1.17 | 1.22 | 1.13 | 1.27 | 1.11 | 1.12 |
| Triphenylene | 0.47 | 0.36 | 0.64 | 0.54 | 0.40 | 0.37 | 0.32 | 0.47 |
| 7-Me-Benzo(a)Anthracene | 0.63 | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| Benzo(b)Fluoranthene | 0.82 | 0.94 | 1.39 | 1.36 | 1.67 | 1.63 | 1.72 | 1.30 |
| Benzo(k)Fluoranthene | 0.63 | <ql | <ql | 0.34 | 0.31 | 0.33 | 0.27 | 0.30 |
| Benzo(e)Pyrene | 0.44 | 0.61 | 0.67 | 0.62 | 0.90 | 0.87 | 1.00 | 0.65 |
| Benzo(a)Pyrene | <ql | <ql | <ql | <ql | 0.42 | 0.37 | 0.32 | 0.30 |
| Perylene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| 2-Me-Cholanthrene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| Indeno(1,2,3-cd)Pyrene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| Dibenzo(a,c)&(a,h)Anthracene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| Benzo(b)Chrysene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| Benzo(g,h,i)Perylene | <ql | 0.42 | 0.70 | 0.53 | 1.22 | 0.73 | 0.84 | 0.65 |
| Anthanthrene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |

<ql indicates below detection limit

**Mass emission rates of PASH compounds (μg/mi)**

| Date | 13-Jan-99 | 14-Jan-99 | 19-Jan-99 | 2-Feb-99 | 20-Jan-99 | 21-Jan-99 | 27-Jan-99 | 28-Jan-99 |
|---|---|---|---|---|---|---|---|---|
| **Fuel** | **LSD-1** | **LSD-2** | **B10-1** | **B10-2** | **B20-1** | **B20-2** | **B30-1** | **B30-2** |
| thionaphthene | 4.20 | <ql | 5.45 | <ql | <ql | <ql | <ql | <ql |
| dibenzothiophene | 13.7 | 14.5 | 5.80 | 12.6 | 9.64 | 8.67 | 10.3 | 8.98 |
| naphtho(2,1-b)thiophene | 7.36 | <ql | 5.80 | <ql | <ql | <ql | <ql | <ql |
| 2-methyldibenzothiophene | 11.6 | 11.6 | 3.41 | 11.9 | 6.89 | 6.24 | 7.53 | 6.91 |
| 8-methylnaphtho(2,1-b)thiophene | 6.66 | 6.70 | 1.70 | 6.80 | 2.76 | 2.77 | 4.45 | 4.14 |
| 5-methylnaphtho(2,1-b)thiophene | <ql | 1.76 | <ql | 2.38 | 3.79 | <ql | 1.71 | 1.73 |
| 4,6-dimethyldibenzothiophene | 15.8 | 16.9 | 4.77 | 25.5 | 7.92 | 6.94 | 14.4 | 13.5 |
| 1,8-dimethyldibenzothiophene | 7.01 | 7.06 | <ql | 8.16 | 3.44 | 2.77 | 4.79 | 4.49 |
| 1,3-dimethyldibenzothiophene | 3.85 | 3.88 | <ql | 3.40 | 1.72 | 1.73 | 2.74 | 2.42 |
| phenanthro(4,3-b)thiophene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| phenanthro(3,4-b)thiophene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| phenanthro(2,1-b)thiophene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| phenanthro(2,3-b)thiophene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| anthra(2,3-b)thiophene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| 10-methylbenzo(b)naphtho(2,1-d)thiophene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| 2-methylbenzo(b)naphtho(2,1-d)thiophene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| 8-methylbenzo(b)naphtho(1,2-d)thiophene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| 5-methylbenzo(b)naphtho(2,1-d)thiophene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| 6-methylbenzo(b)naphtho(2,1-d)thiophene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| 8-methylbenzo(b)naphtho(2,3-d)thiophene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| 11-methylbenzo(b)naphtho(2,3-d)thiophene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |

<ql indicates below detection limit

**Mass emission rates of $NO_2$PAH compounds (μg/mi)**

| Date | 13-Jan-99 | 14-Jan-99 | 19-Jan-99 | 2-Feb-99 | 20-Jan-99 | 21-Jan-99 | 27-Jan-99 | 28-Jan-99 |
|---|---|---|---|---|---|---|---|---|
| **Fuel** | **LSD-1** | **LSD-2** | **B10-1** | **B10-2** | **B20-1** | **B20-2** | **B30-1** | **B30-2** |
| 2- Nitrofluorene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| **Total Nitro-C13** | 1.44 | 1.25 | 2.05 | 2.24 | 1.95 | 2.24 | 2.42 | 2.00 |
| 9-Nitroanthracene | 0.53 | 0.64 | 0.49 | 1.01 | 0.89 | 0.92 | 1.03 | 0.81 |
| 2-Nitroanthracene | <ql | 0.01 | NDR | <ql | <ql | <ql | <ql | <ql |
| 9-Nitrophenanthrene | <ql | 0.02 | NDR | <ql | NDR | NDR | <ql | 0.20 |
| **Total Nitro-C14** | 1.00 | 1.48 | 1.42 | 2.15 | 1.81 | 1.86 | 4.99 | 2.70 |
| 2-Nitrofluoranthene | 0.04 | 0.02 | 0.02 | 0.03 | 0.01 | 0.02 | 0.02 | 0.01 |
| 3-Nitorfluoranthene | <ql | <ql | <ql | <ql | <ql | <ql | 0.01 | 0.01 |
| 4-Nitropyrene | 0.03 | <ql | 0.03 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| 1-Nitropyrene | 0.59 | 0.72 | 1.37 | 1.18 | 0.51 | 0.62 | 0.82 | 0.67 |
| 2-Nitropyrene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| **Total Nitro-C16** | 0.66 | 0.74 | 1.46 | 1.24 | 0.54 | 0.66 | 0.87 | 0.73 |
| 7-Nitrobenz(a)anthracene | 0.07 | 0.12 | 0.17 | 0.15 | 0.09 | 0.09 | 0.06 | 0.04 |
| 6-Nitrochrysene | 0.01 | 0.01 | <ql | 0.02 | <ql | <ql | 0.01 | 0.00 |
| **Total Nitro-C18** | 0.21 | 0.31 | 0.44 | 0.45 | 0.29 | 0.29 | 0.13 | 0.10 |
| 1-Nitrobenzo(e)pyrene | 0.04 | <ql | <ql | 0.05 | <ql | <ql | <ql | <ql |
| 6-Nitrobenzo(a)pyrene | 0.21 | 0.39 | 0.73 | 0.67 | 0.37 | 0.42 | 0.40 | 0.28 |
| 4-Nitrobenzo(e)pyrene | 0.03 | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| 3-Nitrobenzo(e)pyrene | 0.04 | 0.04 | 0.03 | 0.06 | 0.01 | 0.02 | 0.02 | 0.01 |
| 3-Nitrobenzo(a)pyrene | 0.03 | <ql | <ql | <ql | <ql | <ql | <ql | 0.01 |
| 1-Nitrobenzo(a)pyrene | <ql | <ql | <ql | 0.06 | <ql | <ql | 0.01 | 0.01 |
| 2-Nitrobenzo(a)pyrene | 0.03 | <ql | <ql | <ql | <ql | <ql | 0.02 | 0.01 |
| **Total Nitro-C20** | 0.38 | 0.65 | 0.85 | 0.92 | 0.43 | 0.46 | 0.56 | 0.37 |
| 9-Nitrodibenzo(a,c)anthracene | <ql | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| **Total Nitro-C22** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1,3-Dinitropyrene | 0.03 | <ql | 0.01 | 0.02 | 0.01 | <ql | <ql | <ql |
| 1,6-Dinitropyrene | 0.09 | 0.06 | 0.03 | 0.04 | 0.02 | <ql | 0.01 | <ql |
| 1,8-Dinitropyrene | 0.14 | 0.05 | 0.03 | NDR | 0.02 | <ql | 0.01 | <ql |
| 7-Nitro-12-Methylbenzo(a)anthracene | 0.03 | <ql | <ql | <ql | <ql | <ql | <ql | <ql |
| 12-Ethyl-6-Nitrochrysene | 0.04 | <ql | <ql | 0.08 | <ql | <ql | <ql | <ql |

<ql indicates below detection limit

NDR indicates not detected due to incorrect isotope ratio

**Mass emission rates of particle bound n-alkanes (μg/mi).**

| Test Date | January 13/99 | | | January 19/99 | | | January 20/99 | | | January 27/99 | | | February 18/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fuel | Low Sulphur Diesel | | | Biodiesel 10 % | | | Biodiesel 20 % | | | Biodiesel 30 % | | | Biodiesel 20% | | |
| Temperature (C) | 24 | | | 24 | | | 24 | | | 24 | | | 0 | | |
| Alkanes (ug/mile) | Cold Start | Hot Start | Comp | Cold Start | Hot Start | Comp | Cold Start | Hot Start | Comp | Cold Start | Hot Start | Comp | Cold Start | Hot Start | Comp |
| n-C11 | | | | 11 | | 4.6 | 6.7 | | 2.9 | | | | | | |
| n-C12 | | 3.1 | 1.8 | 17 | 11 | 14 | 11 | | 4.8 | | 7.8 | 4.4 | | | |
| n-C13 | | 5.2 | 3.0 | 34 | 34 | 34 | 36 | 30 | 33 | | 23 | 13 | | 27 | 15 |
| n-C14 | | 2.1 | 1.2 | 54 | 34 | 43 | 79 | 60 | 68 | 15 | 49 | 35 | | 152 | 87 |
| n-C15 | | | | 69 | 58 | 63 | 193 | 125 | 154 | 72 | 123 | 101 | | 631 | 360 |
| n-C16 | 78 | 7.6 | 38 | 233 | 223 | 227 | 379 | 272 | 318 | 183 | 223 | 206 | 228 | 1669 | 1049 |
| n-C17 | 449 | 193 | 303 | 604 | 616 | 611 | 746 | 652 | 693 | 419 | 428 | 424 | 1858 | 2625 | 2295 |
| n-C18 | 888 | 421 | 622 | 962 | 1260 | 1132 | 1095 | 1111 | 1105 | 689 | 683 | 685 | 2580 | 1920 | 2204 |
| n-C19 | 1062 | 673 | 840 | 1078 | 1649 | 1403 | 981 | 1375 | 1206 | 604 | 804 | 718 | 2346 | 1397 | 1805 |
| n-C20 | 638 | 522 | 572 | 660 | 1102 | 912 | 517 | 806 | 682 | 366 | 508 | 447 | 1851 | 1031 | 1384 |
| n-C21 | 310 | 307 | 308 | 362 | 475 | 426 | 225 | 312 | 275 | 219 | 244 | 233 | 1184 | 605 | 854 |
| n-C22 | 139 | 122 | 130 | 209 | 216 | 213 | 83 | 117 | 102 | 142 | 144 | 143 | 671 | 363 | 495 |
| n-C23 | 70 | 55 | 61 | 80 | 88 | 84 | 29 | 42 | 36 | 70 | 63 | 66 | 263 | 160 | 204 |
| n-C24 | 34 | 38 | 36 | | | | | | | | 21 | 12 | | | |
| n-C25 | 53 | 65 | 60 | | | | | | | | | | | | |
| n-C26 | | | | | | | | | | | | | | | |
| n-C27 | | | | | | | | | | | | | | | |
| n-C28 | | | | | | | | | | | | | | | |
| n-C29 | | | | | | | | | | | | | | | |
| n-C30 | | | | | | | | | | | | | | | |
| n-C31 | | | | | | | | | | | | | | | |
| n-C32 | | | | | | | | | | | | | | | |
| | Cold Start | Hot Start | Dilution Air | Cold Start | Hot Start | Dilution Air | Cold Start | Hot Start | Dilution Air | Cold Start | Hot Start | Dilution Air | Cold Start | Hot Start | Dilution Air |
| CPI | 1.08 | 1.06 | 1.18 | 1.05 | 1.03 | 1.08 | 1.02 | 1.07 | 1.08 | 1.00 | 1.02 | 0.95 | 1.05 | 1.06 | n/a |

**Mass emission rates of petroleum biomarker compounds (μg/mi).**

| | Test Date | January 13/99 | | | January 19/99 | | | January 20/99 | | | January 27/99 | | | February 18/99 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fuel | Low Sulphur Diesel | | | Biodiesel 10 % | | | Biodiesel 20 % | | | Biodiesel 30 % | | | Biodiesel 20% | | |
| | Temperature (C) | 24 | | | 24 | | | 24 | | | 24 | | | 0 | | |
| ID | | Cold Start | Hot Start | Comp | Cold Start | Hot Start | Comp | Cold Start | Hot Start | Comp | Cold Start | Hot Start | Comp | Cold Start | Hot Start | Comp |
| S11,S12 | 20R-Baa-cholestane, 20S-aaa-cholestane | | | | 36.0 | 22.2 | 28.1 | 30.0 | 22.6 | 25.7 | 28.9 | 25.2 | 26.8 | 141 | 71.3 | 101 |
| S13 | 20R-aBB-cholestane | | 10.4 | 5.9 | 42.0 | 31.7 | 36.1 | 41.4 | 33.3 | 36.8 | 33.8 | 27.0 | 29.9 | 132 | 75.5 | 99.7 |
| S15 | 20R-aaa-cholestane | | | | 21.8 | 17.2 | 19.2 | 31.2 | 25.8 | 28.1 | 34.5 | 25.9 | 29.6 | 140 | 64.0 | 96.6 |
| S22 | 20S-aaa-stigmastane | 13.3 | 11.9 | 12.5 | 41.5 | 37.2 | 39.0 | 39.6 | 31.2 | 34.8 | 37.9 | 33.2 | 35.2 | 155 | 72.1 | 108 |
| S23 | 20R-aBB-stigmastane | 14.6 | 12.7 | 13.5 | 52.5 | 37.0 | 43.6 | 36.3 | 29.0 | 32.1 | 39.4 | 33.0 | 35.8 | 219 | 86.3 | 144 |
| S24 | 20S-aBB-stigmastane | 17.1 | 13.9 | 15.3 | 58.6 | 41.5 | 48.9 | 35.5 | 30.5 | 32.7 | 47.7 | 41.4 | 44.1 | 247 | 102 | 164 |
| Nor | Trisnorhopane | | | | 16.2 | 20.1 | 18.4 | 15.9 | 15.4 | 15.6 | 21.8 | 17.5 | 19.4 | 103 | 42.6 | 68.5 |
| H17 | Norhopane | 15.5 | 12.6 | 13.8 | 47.7 | 38.2 | 42.3 | 40.9 | 35.1 | 37.6 | 40.7 | 33.4 | 36.5 | 114 | 74.4 | 91.5 |
| H19 | aB-hopane | 17.7 | 14.1 | 15.6 | 52.4 | 36.8 | 43.5 | 44.0 | 36.8 | 39.9 | 39.7 | 33.4 | 36.1 | 112 | 74.7 | 90.9 |

# References

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[2] Dr. J. Brook, Environment Canada, Atmospheric Environment Service; personal communication, April 1998.
[3] Dabek-Zlotorzynska, E., Piechowski, M., McGrath, M., Lai, E.P.C.; Chromatographia, (2000), submitted.