2002-01-2681

# Engine Oil Effects on the Friction and Emissions of a Light-Duty, 2.2L Direct - Injection - Diesel Engine

# Part 1- Engine Test Results

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## ABSTRACT

The effects of lubricating oil on friction and engine-out emissions in a light-duty 2.2L compression ignition direct injection (CIDI) engine were investigated. A matrix of test oils varying in viscosity (SAE 5W-20 to 10W-40), friction modifier (FM) level and chemistry (MoDTC and organic FM), and basestock chemistry (mineral and synthetic) was investigated. Tests were run in an engine dynamometer according to a simulated, steady state FTP-75 procedure. Low viscosity oils and high levels of organic FM showed benefits in terms of fuel economy, but there were no significant effects observed with the oils with low MoDTC concentration on engine friction run in this program.

No significant oil effects were observed on the gaseous emissions of the engine. PM emissions were analyzed for organic solubles and insolubles. The organic soluble fraction was further analyzed for the oil and fuel soluble portions. The oil fraction of the PM emissions was found to account for approximately half of the total PM emissions for the simulated FTP-75 test. Synthetic oils showed lower oil concentrations in the soluble organic fraction (SOF). Lower viscosity oils yielded less lubricating oil in the SOF than high viscosity ones, but the total PM was the lowest for the SAE 5W-30 oil. The concentration of unburned fuel in SOF was found to be lower for mineral oils. For a few PM samples analysis for the presence of toxics was performed and the results are discussed.

## INTRODUCTION

The increasing popularity of large passenger cars, “sport utility vehicles” and trucks compounded by the growth in vehicle miles traveled (VMT) has led to an increase in overall fleet fuel consumption in the US. Diesel engines could be a fuel-efficient alternative to power large and heavy vehicles and thus could reduce fuel consumption. However, future stringent emissions regulations require a significant reduction of emissions of oxides of nitrogen (NOx) and particulate matter (PM) for diesel engines. NOx emissions are directly linked to the combustion temperatures in the engine. PM emissions also strongly depend on combustion patterns, but literature suggests that there is also a major contribution of lubricating oil to PM tailpipe emissions [1]. In recent years, diesel exhaust emissions, particularly NOx and PM, have been reduced significantly. High-pressure injection systems along with advanced engine controls have allowed for a significant reduction of pollutants, particularly PM. Additionally, the use of exhaust gas recirculation (EGR) was proven very effective in reducing NOx. Nevertheless, in order to meet future emissions standards, further reductions will be required.

Considerable research on lube oil effects has been documented in the literature. The work can be summarized in basically two main areas; lube oil effects on exhaust emissions and lube oil effects on friction/fuel economy. Research on PM emissions is reported rather sparsely, and the documented results are sometimes contradictory.

- Froelund et al. [2] investigated lube oil effects on regulated exhaust emissions for three different oils and two fuels. The test engine was a light duty DI-diesel engine. A reduction of PM emissions for higher viscosity synthetic oils was found. However, fuel effects were found to have a greater impact on PM emissions than lube oil.

- Jefferd et al. [3] conducted a study using one semi-synthetic oil and two full synthetic ones on a heavy-duty diesel engine. These tests revealed a 20% benefit for PM emissions with the semi-synthetic oil over its full synthetic counterparts.

- Manni et al. [4] reported no significant lube oil effects on total PM emissions for a light-duty diesel engine, but stated that lower viscosity oils tend to show lower lube oil contribution but higher unburned fuel in the soluble organic fraction of PM.

- Inoue et al. [5] reported that reducing oil leakages in the engine could reduce the lube oil fraction of PM emissions.

- Manni et al [6] investigated effects of three different oils on emissions of a single cylinder DI-diesel engine operating close to full load. Based on these results, a reduced viscosity prototype oil was blended that allowed the engine to operate at a higher air/fuel rate at constant load and thereby reduced PM by 22% and NOx by 10%.

The effects of lube oil viscosity on engine friction have been studied extensively and are well documented in the literature. Results in this area are much more coherent than results for PM emissions; commonly lower viscosity oils yield lower engine friction.

- Manni et al. [4] reported a significant gain in fuel economy, particularly in urban driving cycles, for lower viscosity oils.

- Tseregounis et al. [7] investigated effects of oil viscosity and different friction modifiers for three different gasoline engines and reported benefits for lower viscosity oils and friction modifiers.

PM emissions are commonly measured using a dilution system to simulate ambient conditions. Several researchers [8, 9, and 10] pointed out that the way exhaust gas is sampled and diluted has a significant impact on mass and composition of the measured PM. Particularly, dilution ratios, sampling temperatures and gas residence times in the sampling device must be nearly constant throughout all tests in order to reduce measurement variability. Considering the varying exhaust gas conditions for different engine loads, this poses a challenge to measure PM emissions accurately and with reasonable repeatability. Furthermore, combustion in diesel engines is inherently less stable than in SI engines. The introduction of EGR adds an additional source of variability. The current low emissions levels combined with the high sensitivity of the dilution systems and unstable operation of diesel engines pose a considerable challenge to detect the small differences in PM emissions attributable to lube oil at a statistically significant level.

The previously cited studies adjusted the injected mass of fuel in order to maintain constant engine-out torque for all engine oils, which might eventually result in different combustion conditions for different oils. Since combustion patterns strongly affect PM emissions [1], the injected mass of fuel for this study was kept constant throughout all tests in an effort to maintain similar combustion patterns for all oils.

The present study was conducted within the framework of the General Motors Collaborative Research Lab (GM CRL) at the University of Michigan, and aims to provide a comprehensive investigation of the effects of lubricating oil, referred to as “lube oil” in this paper, on engine friction performance and engine-out emissions for a light-duty, state of the art, direct injection 2.2L diesel engine.

## EXPERIMENTAL SETUP

### TEST ENGINE SPECIFICATIONS

The tests were conducted in a 4-cylinder inline, direct injected, turbo charged Opel 2.2 liter engine. The test engine features a cylinder head with 4 valves per cylinder, which are driven by a single camshaft. The engine’s piston skirts are coated with molybdenum. A Bosch VP44 Radial Piston Distribution pump carries out the fuel injection. Other technical features are swirl control and cooled EGR. A list of technical specifications is given in table 1 below:

Table 1 Test Engine Specifications

| **Technical Data:** | |
|---|---|
| Displacement: | 2,171 ccm |
| Cylinders: | 4 / in line |
| Bore: | 84 mm |
| Stroke: | 98 mm |
| Compression ratio: | 18.5 : 1 |
| Rated Power | 85 kW @ 4300 rpm |
| Rated Torque: | 260 Nm /1900-2500 rpm |
| Factory Oil Type: | SAE 10W-30 mineral Opel # B 040 1042 |
| Engine controller: | Bosch EDC 15, ETK 3.1 |

TEST CELL SETUP

The engine was attached to a General Electric DC-dynamometer, capable of absorbing 200 hp @ 6000rpm. A Dyno-Loc IV digital dyno controller by Dyne Systems Corp. controlled the dynamometer. The engine's glow plugs were removed and the holes modified to accept water-cooled Kistler 6041-A pressure transducers.

Furthermore, the following support systems were designed and used for the tests:

Engine cooling system

The conventional thermostat was removed and replaced by a two-loop system. The outer control loop simulates an idealized radiator utilizing a PID controlled tube-in-shell heat exchanger. The inner loop contains an analog three-way valve, which is attached to a stepper motor. This system controls the coolant temperature to the inlet of the engine by mixing hot engine coolant with cold coolant from the outer loop. This combination allowed maintaining coolant temperatures within +/- 1.5º C of the set point for all tests.

Oil Conditioning System

A dual stage tube-in-shell heat exchanger and an electric oil heater carried out the temperature conditioning of the engine oil. The engine's standard European cartridge filter was modified to allow for the oil to be pumped from the engine to the 3 kW heater and on to the heat exchanger. Finally the oil was routed through an automotive oil filter and returned to the engine block. All lines and devices were insulated to minimize uncontrolled heat losses of the oil. The oil temperatures were monitored at the inlet and outlet of the engine block. The heat exchanger and the electric heater were controlled by dual stage PID controllers, which are capable of "learning" the dynamics of the system. Fluctuations of the oil temperature could also be kept within +/-1.5º C. The oil system's total volume was about 8 liters and it was operated using the engine's conventional oil pump.

Overall Engine Friction Measurements

The pressure transducer signals were processed using a LabView based program developed at U of M. This software references the sampled cylinder pressure data of approximately 500 individual engine cycles to the ambient pressure and, upon phasing the data for the thermodynamic loss angle, integrates the pressure history with respect to the relative piston location with a 1° crank angle (CA) resolution. The result is the calculated internal work, which is expressed in terms of "indicated mean effective pressure (IMEP)". Overall friction could then be calculated as the difference between IMEP and the flywheel work, which is expressed as "brake mean effective pressure (BMEP)". The result, expressed as "friction mean effective pressure (FMEP)", can be written as:

$$FMEP = IMEP - BMEP \qquad (1)$$

In order to minimize parasitic loads associated with the engine's accessory drive, the alternator, power steering pump, air-conditioning compressor and stock belt tensioner were removed and replaced by a new belt and custom designed tensioner bracket.

EMISSIONS MEASUREMENT INSTRUMENTATION

Analyzers for Gaseous Emissions

Gaseous emissions were measured using Horiba instruments. A list of analyzers for the individual species concentrations can be found in the table below:

Table 2 Analyzers for Gaseous emissions

| | |
|---|---|
| Oxygen ($O_2$) | Magneto Pneumatic with condenser microphone |
| Oxides of nitrogen ($NO_x$) | Chemiluminescent analyzer |
| Carbon Dioxide ($CO_2$) | Non Dispersive Infrared Analyzer |
| Carbon Monoxide (CO) | Non Dispersive Infrared Analyzer |
| Total Hydrocarbons (THC) | Heated Flame Ionization Detector |

The emissions analyzers were rebuilt and recalibrated for the appropriate ranges by Horiba immediately before the beginning of the experiments.

Particulate Matter (PM) Emissions

A partial flow, single stage dilution tunnel was used to sample PM in the exhaust gas. The exhaust gas was sampled downstream of the turbo charger in the center of the tailpipe in order to capture flowing exhaust gas without wall deposits. The exhaust gas was routed into the tunnel through a Venturi nozzle where it was mixed with clean compressed air, which was heated in order to maintain an overall gas temperature of 52 deg C at the filter face. The $CO_2$ concentration in the diluted exhaust gas was measured and compared with the raw $CO_2$ concentration. The actual dilution ratio could then be determined as:

$$DR = \frac{[CO_2]_{raw} - [CO_2]_{ambient}}{[CO_2]_{dil} - [CO_2]_{ambient}} \qquad (2)$$

A controlled flow with a known volume was then directed across an EMFAB 47mm filter. The filter media is borosilicate micro fibers bonded with PTFE. The filters were weighed using a Mettler UMT-2 microbalance in a class 1000 clean room. The sampling times were chosen to keep the accumulated mass approximately constant for all filters. This was done to avoid errors induced by non-linearity of the scale during the weighing procedure.

Chemical Analysis of PM Samples

The filters were analyzed chemically by AVL List GmbH in Austria to determine the insoluble organic fraction (ISOF) and the soluble organic fraction (SOF). The SOF was then subdivided into a lubricating oil fraction and an unburned fuel fraction. The following description gives a brief outline of the method. Detailed information can be found in the literature [11, 12]. A sample of test fuel was distilled to remove the volatile fraction of the fuel < C14. Fuel- oil samples, so called "calibration blends", were prepared with the test fuel and each test oil, with the proportion of fuel to oil shifting in increments of 10%. Once these calibration blends were established, distillation curves for these blends were generated using a gas chromatograph. The SOF of the PM loaded filters was extracted with the Soxhlet technique using dichloromethane, and a distillation curve of the extracted SOF was created. The oil and fuel content of the SOF was then determined by comparing the boiling curves of the SOF to the calibration boiling curves.

## ENGINE OILS AND PROPERTIES

A total of twelve lubricants was blended for this study. A set of four baseline formulations was blended to comply with necessary viscometric requirements of the 5W-20, 5W-30 (mineral base), 5W-30 (synthetic base), and 10W-40 fluids. Table 3 reports physical characteristics of the base fluids.

Table 3 Base Fluids

| **Viscosity Grade** | **5W-20** | **5W-30** | **5W-30** | **10W-40** |
|---|---|---|---|---|
| **Oil Type** | **Synthetic** | **Synthetic** | **Mineral** | **Mineral** |
| 100°C Kin. Vis. (cSt) | 8.91 | 10.90 | 11.08 | 14.70 |
| 40°C Kin. Vic. (cSt) | 52.38 | 65.88 | 65.78 | 97.97 |
| Viscosity Index | 150 | 157 | 161 | 156 |
| HTHS Vis. at 150 °C, $10^{-6}s^{-1}$ (cP) | 2.71 | 3.16 | 3.22 | 4.05 |
| Volatility | | | | |
| NOACK (%) | 5.8 | 6.0 | 20.6 | 13.3 |
| Simulated Distillation (%) | 1.9 | 2.0 | 14.3 | 7.0 |
| D4684 MRV-TP1 | | | | |
| Temperature (°C) | -35 | -35 | -35 | -30 |
| Viscosity (cPs) | 8,400 | 10,100 | 29,600 | 28,200 |
| Yield Stress | None | None | None | None |
| D5293 CCS | | | | |
| -25°C (cPs) | 2,340 | 2,570 | 3,160 | - |
| -20°C (cPs) | - | - | - | 3,050 |
| % Sulfated Ash | 1.20 | 1.20 | 1.20 | 1.20 |
| Total Base # | 9.75 | 9.75 | 9.75 | 9.75 |

The additive package remained constant in all blends and represented a technology approved to meet API SH/CF and ACEA A3/B3-98 qualifications. Specifically, sulphated ash level was designed to be 1.2 mass %, calcium level was 0.30 mass %, phosphorous level was 0.09 mass %, and zinc level was 0.10 mass %. None of the baseline oils contained any friction modifier technology.

Additionally, eight fluids were formulated using two types of friction modifying technology: organic (ashless) type and molybdenum dithiocarbamate (MoDTC). Four fluids were blended using organic (ashless) chemistry at levels of 1 mass % (high, HO) or 0.25 mass % (low, LO). Another four fluids contained MoDTC at levels of 750 ppm (high, HM) or 250 ppm (low, LM).

Test Matrix

The design strategy shown in Table 4 was constructed to assess statistically the effects of friction modifier type (MoDTC, Organic) and amount (250 ppm to 750 ppm and 0.25% to 1.0%, respectively), viscosity grade (5W-20, 5W-30 and 10W-40) and base oil type (full synthetic, mineral). Five runs were also done on the 5W-30 mineral oil (reference) and 3 runs on oils without friction modifier.

The run order of the oil samples can be found in Table I in the APPENDIX.

Table 4 Design Matrix 1/2 $4x2^2$

| | No FM | Organic | Organic | Mo-DTC | Mo-DTC |
|---|---|---|---|---|---|
| | | Low 0.25% | High 1% | Low 250ppm | High 750ppm |
| 5W-20 (synth) | X | | X | X | |
| 5W-30 (min) | X | X | | | X |
| 5W-30 (synth) | X | X | | | X |
| 10W-40 (min) | X | | X | X | |

## TEST FUEL PROPERTIES

The test fuel used was commercially available AMOCO Premier Diesel fuel, not winterized. A summary of the fuel's chemical properties is given in the table below.

Table 5 Test Fuel Specifications

| **Contents** | **Specification** |
|---|---|
| Sulfur | 500 ppm |
| Cetane Number | 50 |
| Distillation 90% | 600 |
| 95% | 659 |
| Flash Point | 54.4 °C (130 °F) |
| Naphthalene | 1% |
| Xylene | 1% |

## DESIGN OF EXPERIMENT AND TEST PROCEDURE

### Engine Operating Points

Test points were chosen to match the operating points for a similar size engine during a simulated FTP-75 cycle. The operating points were developed at GM R&D for a powertrain comprising a 2.56L DI engine with a 5 speed manual transmission and a vehicle weight of 1588 kg. For details see reference [13].

Figure 1 shows these FTP points under the test engine's maximum speed-load curve. A summary of the points can be found in table 6:

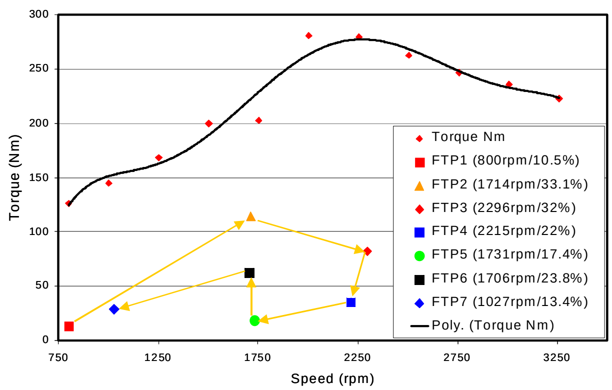


Figure 1 Simulated FTP points and full load behavior

Figure 2 shows the running times for the individual operating points of this simulated FTP cycle. The total test time was 1264 seconds. This time map was used to weigh experimental results from individual operating points according to their fraction of the total test time. It should be cautioned that the simulated FTP is not equivalent to an actual federal test procedure. All transient effects are omitted from the calculated FTP values in the procedure described here.

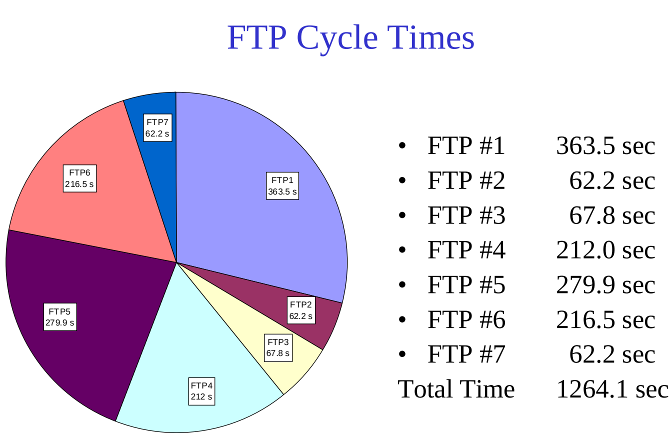


Figure 2 Simulated FTP Cycle Times

Table 6 Simulated FTP Operating Points

| FTP # | Speed | IMEPnet | Run Time | Speed / Load |
|---|---|---|---|---|
| | (rpm) | (bar) | (sec) | |
| **1** | 800 | 1.81 | 363.5 | low/low |
| **2** | 1714 | 7.93 | 62.2 | mid/high |
| **3** | 2296 | 6.33 | 67.8 | high/high |
| **4** | 2215 | 3.3 | 212.0 | high/low |
| **5** | 1731 | 2.26 | 279.9 | mid/low |
| **6** | 1706 | 4.72 | 216.5 | mid/mid |
| **7** | 1027 | 2.6 | 62.2 | low/low |

These operating points were repeated with each oil of the oil matrix. The engine load was controlled using a conventional acceleration potentiometer ("*gas pedal*"). The injected mass of fuel for each FTP point was kept constant throughout all oils to isolate the potential effects of lubricating oil on PM emissions as well as possible.

### Oil Changing Procedure

In order to conduct testing of all oils with a maximum of accuracy and repeatability, a standardized procedure for changing and conditioning the oil was developed. Before the engine was charged with new oil, it was purged with a low viscosity, high detergent oil, referred to as "flush oil" in this paper, as is common practice in the auto/oil industry to remove any memory from the engine of previous oils that may have contained surface active additives. The engine was operated at two different speed/load combinations, to allow flushing of the engine for all friction regimes. These points were 1100 rpm, 20% of full load and 2300 rpm, 30% of full load respectively, the engine was operated at both points for 15 minutes, then a repetition with 10 minutes at each point was carried out.

After flushing the engine with flush oil, the engine was filled with the new test oil and the flushing procedure, as outlined, was repeated to purge the remaining flush oil out of the system. This first charge of test oil was then drained again and the engine was refilled with a fresh charge of test oil before beginning the tests.

### Oil Break-In

The lubricants to be tested were new and unconditioned. Due to the distillation process used in the manufacturing of lubricants, fresh oil contains a relatively volatile fraction that usually evaporates during the first hours of operation of new oils (e.g. reference [2]). Since this study featured also a chemical analysis, the oil had to be conditioned in order to remove this initial volatility and to provide highest possible repeatability.

Upon filling the engine with new oil, the oil was conditioned in a 6-step process:

- Motoring warm up of the engine, 1 minute
- Warm up at 1500 rpm, 30% of full load, 30 minutes
- Stabilization of engine parameters at 2500 rpm, 70% of full load, 15 minutes
- Upon stabilization, conditioning of oil, 2500 rpm, 70% of full load, 4 hours
- Cool down, 2000 rpm, motoring, 2 min
- Cool down, 1100 rpm, motoring, 1 min

During the conditioning of the engine, the friction mean effective pressure (FMEP) was determined every 20 minutes to monitor possible break in effects during this period, however, no significant changes in friction were observed.

Testing Procedure

The total time for a complete test of one oil without change, flush and break-in took approximately nine hours. The testing procedure was conducted as follows:

- Warm up and calibration of emission analyzers
- Warm up of engine for 1 hour
- Testing according to schedule in the appendix. The engine was stabilized for 20 minutes at each FTP point (30 minutes for FTP point 1) before data was taken.
- For each FTP point, two PM filters were loaded according to the timetable in table 4.
- Six sets of high-speed data for each FTP point, each of which averaged 87 engine cycles, were taken to determine IMEP.
- Time resolved data was sampled continuously throughout the entire testing procedure

A set of cylinder pressure data, which averaged 87 individual engine cycles, was taken at the end of each test with the engine motoring, to monitor the validity of the pressure data.

## RESULTS AND ANALYSIS

ENGINE DYNO TESTING

Effects of Temperature and Humidity

The engine tests were conducted at the University of Michigan, where air conditioned test cells are currently not available. In order to minimize temperature effects, the test cell was heated to 90 deg F (~32.4 deg C). However, the changing level of heat rejected from the engine at the various FTP points could not be balanced properly in the test cell, and the ambient temperature fluctuated between 88 deg - 96 deg F (31.5 deg - 35.5 deg C). Thus, a correlation between temperature and FMEP was used to correct the test results.

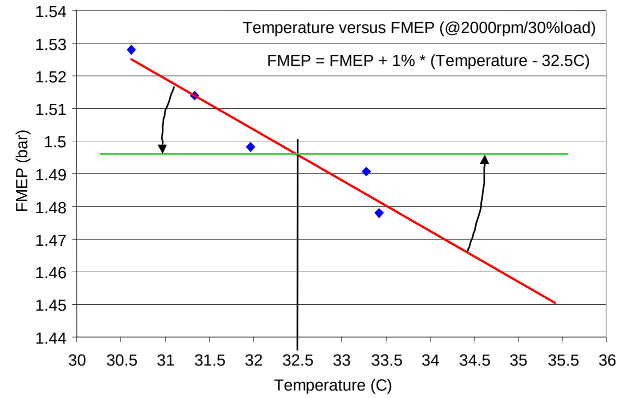


Figure 4 Adjustment for Temperature Correlation

Figure 4 shows the effect of ambient temperature on FMEP during break-in at 2000 rpm and 30% load. Tests for a range of speed/load combinations were conducted at various test cell temperatures. The relationship between ambient temperature and FMEP was then approximated for all tests using the following linear expression:

$$FMEP_{corr} = FMEP + 1\% * [T_{ambient} - 32.5] \quad (3)$$

Humidity affects primarily NOx emissions. To take these effects into account, the Federal Register [14] requires that measured NOx concentrations are multiplied by the following NOx Humidity Correction Factor (NHCF) when reporting NOx emissions:

$$NHCF = 1/(1 - \alpha * (abs.\ Humidity - 10.71)) \quad (4)$$

with $\alpha = 0.0329$ and *abs. Humidity*=g/kg dry air.

It was found empirically that this factor overcompensates for the effects of humidity. As NOx emissions were expected to be the same for all tests with the reference oil, all differences were attributed primarily to changes in humidity, which were sought to be factored out. Thus, NHCF was adjusted with an empirical constant $\beta$ to achieve constant NOx emissions for all tests with reference oils. The adjusted NHCF was expressed as:

$$NHCF_{corr} = 1/(1 - \frac{\alpha}{\beta} * (abs.\ Humidity - 10.71)) \quad (5)$$

with $\beta = 2.5$.

## Baseline Variations

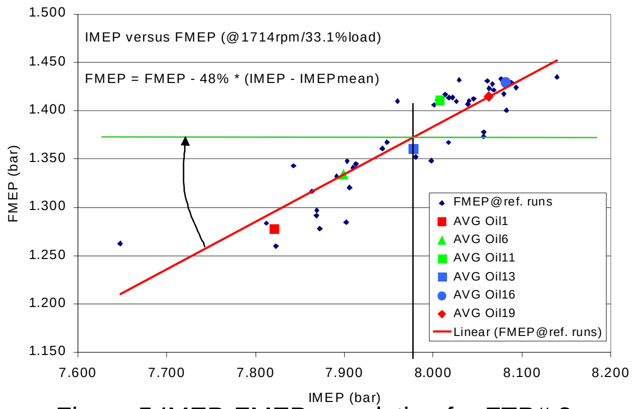


Figure 5 IMEP-FMEP correlation for FTP# 2

In addition to ambient temperature, other factors may affect the engine's friction performance. Increasing engine wear and decreasing functionality of engine components (e.g. EGR valve characteristics) throughout the tests are also known to influence the measured friction. Thus from results of the reference oil tests, a correlation was developed that takes these drift effects into account. As can be seen in Figure 5, this correlation is based on a linear relationship between FMEP and IMEP. FMEP data of all oils were plotted against the corresponding IMEP values for all individual operating points. Figure 5 shows the procedure for FTP # 2.

The mean IMEP for each FTP point was determined using the following expression:

$$IMEP_{mean} = \frac{1}{36} * \sum_{i=1}^{36} IMEP(referenceOil_i) \quad (6)$$

A linear best-fit line through all data points was then established and it was used as the corrected baseline for all reports. All data reported in the next section was thus compensated for variations in temperature, humidity and baseline drifting.

## TEST RESULTS

### Friction

This section will provide an overview of the friction results. Detailed analysis will be given in the statistical analysis section.

Figure 6 shows friction results for the entire cycle weighted according to the cycle times as shown in Figure 2 for the simulated FTP cycle. The dark bars indicate the reference runs with the base oil.

The synthetic oils (oil 2, 7, 9, 14, 15) tend to have lower FMEP than the mineral oils. Oil viscosity effects behaved as expected; higher viscosity yielded higher FMEP. A rather surprising trend was noticed for oils with MoDTC FM. This friction modifier did not show significant benefits at both concentration levels compared to the same oils without MoDTC FM (compare oils 2 & 10, oils 5 & 12, oils 7 & 9). These results are particularly surprising since additives containing molybdenum are reported to be effective in reducing friction in several publications [7, 15, 16 and 17]. However, these publications refer to tests with SI engines. Several possibilities could explain this lack of effectiveness of MoDTC FM for the present study: First, the piston skirts of the test engine are coated with molybdenum. Secondly, the different operational characteristics of SI engines and light-duty CIDI engines might cause differences in the boundary lubrication regimes that may respond differently to Mo FM. Another explanation could be some interaction between the MoDTC and PM contamination in the engine oil. These possibilities will be investigated in future tests. However, all FMEP measurements containing MoDTC friction modifier have a larger standard deviation (2.23-2.41%) compared with the oils without MoDTC FM (1.06%-1.73%).

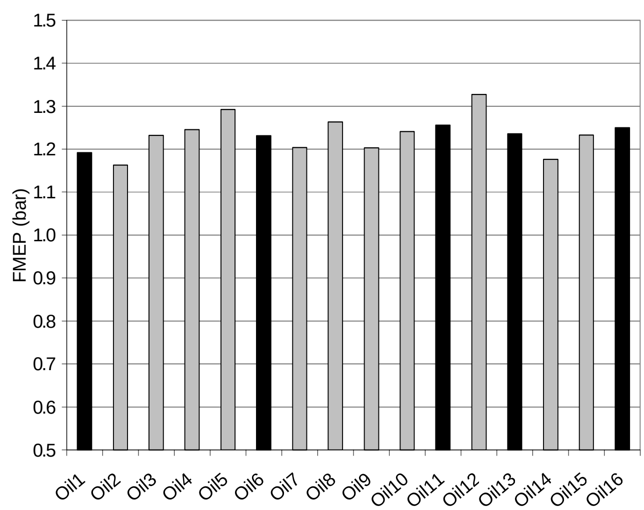


Figure 6 Avg FMEP Weighted by Cycle Time

Results for organic friction modifiers showed inconsistent trends. Blends with high levels (1%) of organic FM did show benefits compared to the same oils without FM (compare oils 3 & 5, oils 9 & 14). Blends with low levels (0.25%) of organic FM did not show significantly lower friction than the base oils (compare oils 4 & 16, oils 2 & 15).

Again, it is noted that the test matrix, as shown in Table 4, was constructed to assess and isolate several effects using statistical methods. Comparisons performed between blends with different concentrations of organic FM and MoDTC FM (low versus high) provided the required boundary information. Comparison of similar concentrations (i.e. low versus low) of each oil blend would not have provided the necessary boundary information, and thus were not conducted in this study.

## Standard Deviation of the Results

For diesel engines, combustion variability is inherently larger than that for gasoline engines, and it strongly depends on the engine load. Since the FMEP is load dependent, its variability will also be larger for diesel engines and will change with load. Table 7 provides a list of the standard deviations for the individual operating points.

Table 7 Standard Deviation for Reference Oil

| | Standard Deviation Abs. (+/- bar) | Standard Deviation Percent (+/- %) |
|---|---|---|
| FTP 1 | 0.0232 | 2.41 |
| FTP 2 | 0.0150 | 1.10 |
| FTP 3 | 0.0313 | 1.97 |
| FTP 4 | 0.0330 | 2.23 |
| FTP 5 | 0.1370 | 1.06 |
| FTP 6 | 0.0224 | 1.73 |
| FTP 7 | 0.0174 | 1.65 |
| FTP Avg | 0.0223 | 1.74 |

Due to the rather high standard deviation, a statistical analysis was conducted to verify the significance of the results. These results are presented in the statistical analysis section.

## EMISSIONS RESULTS

The chosen operating strategy for these tests did not yield significant differences in gaseous emissions for different oils. Thus the main emphasis here will be put on the effects of different oil viscosities and oil blends on PM emissions. All emissions are reported as specific emissions, using emissions index (EI-XX) in grams of emissions XX per kg fuel:

$$EI_{xx} = XX * \left[ \frac{MW_{xx}}{MW_{fuel} * [CO + CO_2 + 3 * C_3H_{3y}]} \right] * 1000$$

## Gaseous Emissions

Of all 4 emissions species that were measured, CO, $CO_2$ and Oxygen concentrations in the exhaust did not vary noticeably. The only species that did change over the tests was NOx. One reason was changes in ambient humidity. However another reason was assumed to be combustion and hardware variability. The test engine features an EGR system. Slight changes of the EGR valve may result in small variations of the EGR rate, which will have an immediate impact on NOx emissions. Also combustion variability will affect the formation of thermal NOx during combustion. However, test results also indicated that the oil viscosity in the journal bearing of the turbo charger affected the efficiency of the turbo charger. This resulted in different levels of boost pressure, which might be another factor for variations of NOx emissions. These boost pressure effects were somewhat unexpected and the experimental setup was

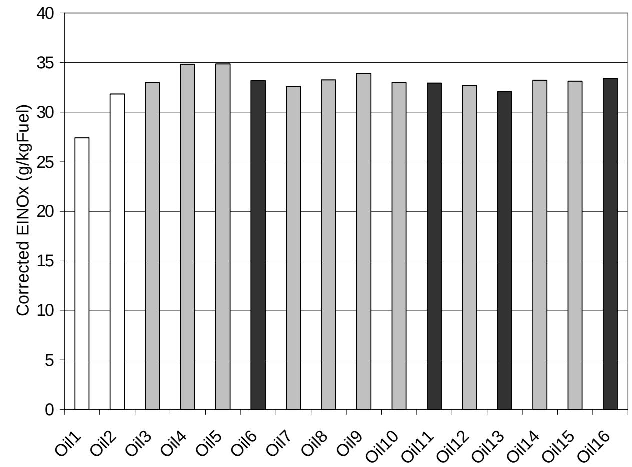


Figure 7 Corrected EI-NOx for FTP 2

not designed to capture this trend accurately. Thus for this report, effects of boost pressure on NOx emissions were factored out using the IMEP-drift correction.

Figure 7 shows the normalized NOx results for the FTP 2 point, which has the highest load among the FTP points. The dark bars again indicate results for the reference oils. Results for oils 1 and 2 are too low due to a HC measurement failure, which was used to calculate the emissions index (EI [g/kg fuel]), and were only reported for completeness. The results reveal no clear trend for oil effects on NOx emissions. The same was true for other gaseous emissions.

## PM Emissions

The characteristics of PM emissions strongly depend on the sampling conditions and the dilution ratio in the dilution tunnel. [10] In order to minimize potential variations, the dilution tunnel was set up in a way that all tests could be run without any changes to the hardware. However, the dilution ratios were different for the individual FTP points. Figure 8 shows the dilution ratios that were achieved for each FTP point:

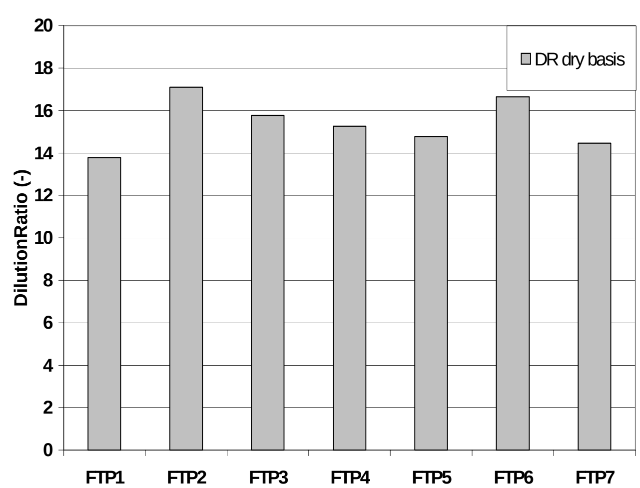


Figure 8 Dilution Ratio on Dry Basis for FTP Points

PM results are reported in grams emitted during the total FTP cycle. The individual points are weighed according to the timetable given in Figure 6. As the combustion process primarily affects the insoluble organic fraction, the main focus in this oil study was to investigate the results for the soluble organic fraction (SOF). All results are plotted in the designed running order as found in Table I in the appendix. However, since tests for oils 4 and 8 had to repeated, the displayed results for these two oils were obtained last.

Figure 9 shows the total PM mass emitted over the simulated cycle. The standard deviation for the reference oil runs (runs 1, 6, 11, 13, 16) was found to be in the same order of magnitude as measured differences between oils. Also, it has to be mentioned that for oil 9, the results are somewhat out of line due to excessive ambient humidity on the day this test was taken. Thus no compelling conclusions could be made based on results for total PM.

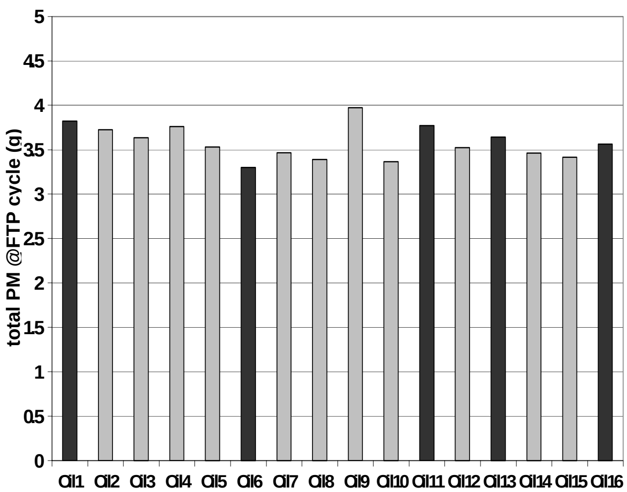


Figure 9 Total PM (g) for FTP cycle

Results for SOF were split into Lube oil in SOF, and unburned fuel in SOF. Results for the Lube oil in SOF are reported in Figure 10. This plot indicates that synthetic oils (2, 7, 9, 10, 14, 15) yield lower lube oil contents in the SOF. Also, low viscosity oils (7, 9, 14) tend to show lower lube oil concentrations in SOF than high viscosity oils (oil 5, 12). These results are consistent with findings reported by Manni et al. [4] but disagree with results by Froelund et al. [2]. However, unlike for the present study, in both referenced studies the engines' operating parameters were altered to account for changing friction losses with different oils. Such changes constitute different combustion patterns for different oils, which are known to have a direct impact on the formation and appearance of particulates. As the present study was striving to maintain constant combustion conditions for all oils, a direct comparison of the PM chemistry of the previous results with results of the present study may have only limited validity.

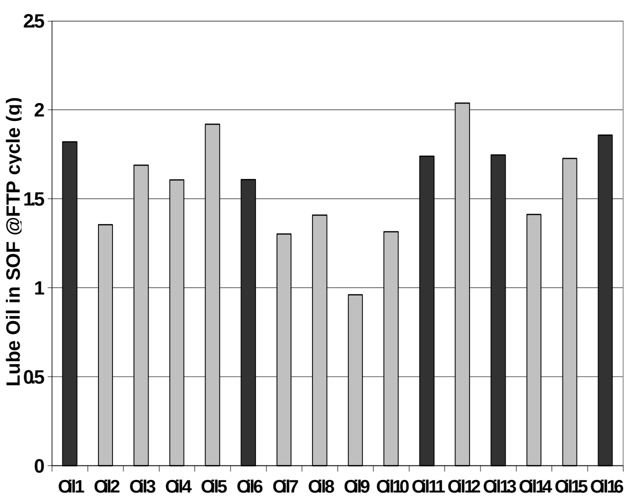


Figure 10 Lube Oil in SOF for FTP Cycle

A comparison of Figures 9 and 10 shows that for the simulated FTP-75 cycle, the lube oil content of the SOF accounts for about half of the total emitted PM mass.

Results for unburned fuel in SOF are shown in Figure 11. Data for synthetic oils (oils 2, 7, 9, 10, 14, 15) indicate higher fractions of unburned fuel in the SOF. This phenomenon is somewhat unexpected but agrees with findings reported by Manni et al. [4]. This trend was also consistent throughout all tests. Again, it has to be mentioned that results for oil 9 are likely to be affected by excessive humidity on the test day.

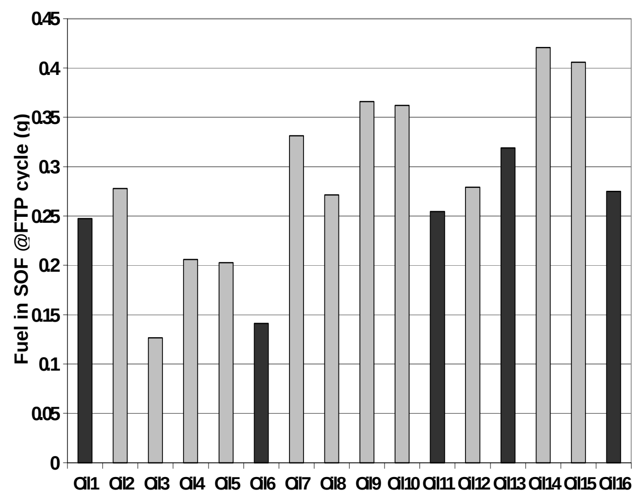


Figure 11 Unburned Fuel in SOF for FTP Cycle

A comparison of Figures 10 and 11 seems to show an inverse trend for concentrations of lube oil and unburned fuel in SOF. This phenomenon can currently not be explained cohesively. It could be a result of systematic or random errors arising during the sampling or analyzing process. Another reason could be a different interaction between oil film and unburned fuel in the cylinder due to viscosity or chemistry effects. This issue requires more research to obtain a more fundamental understanding of oil effects on PM. Furthermore, the suitability of currently available measurement techniques for such experiments with the low current emissions levels needs to be taken into consideration.

STATISTICAL ANALYSIS

Of the several responses measured in this study, the ones showing the greatest statistical significance and which will be included in this discussion are: Fuel Economy as measured by Fuel Consumption (g/kWh) and Emissions as measured by EI-Particulates (g/kg Fuel) and Soluble Organic Fraction (g/kg Fuel). Of special note, however, is that NOx showed no response to any of the variables under study. The data were initially evaluated using a Bayesian Variable Assessment [18] program that assesses the relative activity of independent variables on a response of interest. Functionally, the BVA program fits all possible single order models to a dataset and determines the probabilities that the variables measured impact the response in question. Practically, it allows researchers to determine if a particular variable is important or not, as well as the direction of its influence.

Once the influence of a variable was identified as statistically significant, the specific nature of the significance was determined and is displayed here via Box Plots that show the average response and a least significant difference interval. When bars overlap, those levels of the independent variable are not significantly different; however, when the bars do not overlap we can say that we are 95% confident there are real differences between the associated levels of the factor. All information given in the following discussion is based on real differences of the test data and not derived from generalized trends.

In the plots and discussion that follow, the superior performance of 5W oils in fuel consumption, soluble organic fraction and particulates will be discussed. Also, differences between full synthetic and mineral oils on soluble organic fraction and the superior performance of the organic friction modifier over MoDTC on fuel consumption will be outlined. For ease of discussion, the seven FTP regimes were characterized as a combination of low, mid or high speed and low, mid or high load as detailed in Table 6.

Fuel Economy versus Viscosity Grade

For low speed and low load and mid speed and mid load cycles, the 5W-30 oils outperform the 5W-20 and the 10W-40 oils on Fuel Consumption (g/kWh). The data presented is for the 1706 rpm; 23.8% load; however, similar results were found for 800 rpm; 10.5% load and 1027 rpm; 13.4% load.

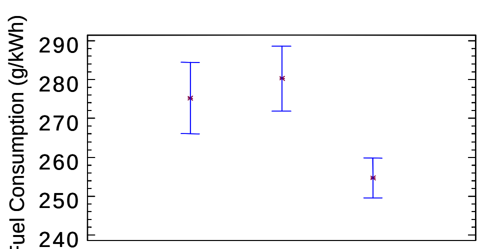


Figure 12 Fuel Economy vs. Viscosity, FTP #6

Fuel Economy versus Base Oils

For the mid speed and mid load cycle (1706 rpm; 23.8% load), the full synthetic base oil displays lower fuel consumption (g/kWh) than the mineral reference oil. This was the only regime in which the full synthetic was found to outperform the mineral oil.

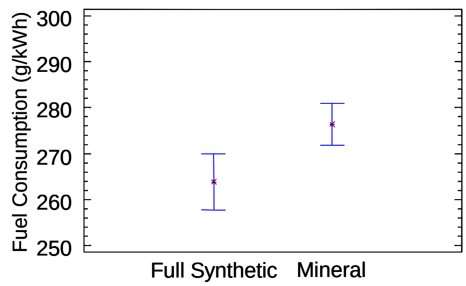


Figure 13 Fuel Economy vs. Base Oil, FTP #6

Fuel Economy versus Friction Modifiers

With the high speed and load (2296 rpm; 32% load), mid speed and load cycles (1706 rpm; 23.8% load), and low speed and load cycles (800 rpm; 10.5% load), as well as across all cycles (Total FTP), the blends with 1% organic friction modifier demonstrated significantly lower fuel consumption than the high MoDTC friction modifier. The Fuel Consumption (g/kWh) data shown in Figure 14 below are for the 800 rpm; 10.5% load cycle.

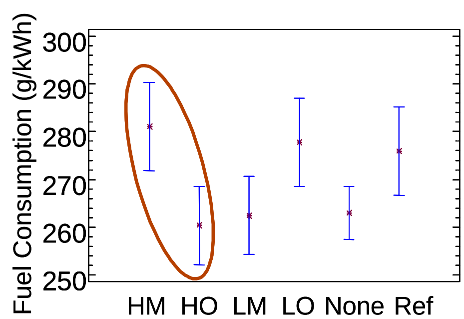


Figure 14 Fuel Economy vs. Friction Modifier FTP #1

Emissions versus Viscosity Grade

Results for the emissions data were not nearly as strong as those found for the fuel economy and only a few speed/load cycles showed any response to the factors under study. The most frequent cycle element associated with significant results is high speed.

For high speed and load (2296 rpm; 32% load), the 5W-30 oils produced significantly fewer particulates (g/kg Fuel) than either the 5W-20 or the 10W-40 oils. However, for SOF (g/kg Fuel), the 5W-20 oils outperform the other two viscosity grades.

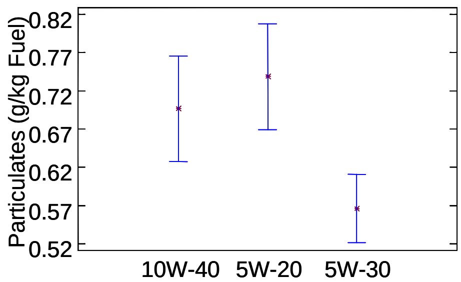


Figure 15 Total PM, FTP #2

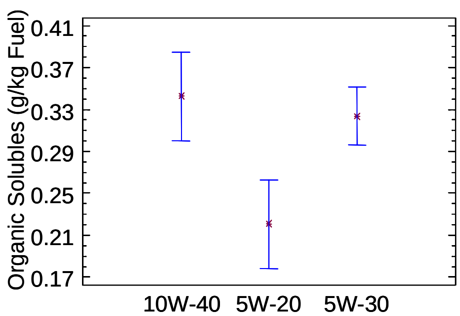


Figure 16 Soluble Organic Fraction, FTP #2

The full synthetic oils were significantly lower on SOF (g/kg Fuel) than the mineral oils for the mid speed/high load cycle (1714 rpm; 33.1% load).

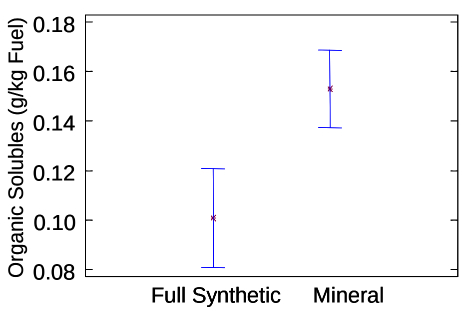


Figure 17 Soluble Organic Fraction, FTP# 2

Blends with 1% organic and 250 ppm MoDTC produce significantly fewer particulates than no FM and the reference oil in the high speed and load cycle (2296 rpm; 32%). However, for the high speed/ low load cycle (2215 rpm; 22% load), blends with no friction modifier, 0.25% organic and 750 ppm MoDTC are all significantly lower on SOF (g/kg Fuel) than the 250ppm MoDTC blends.

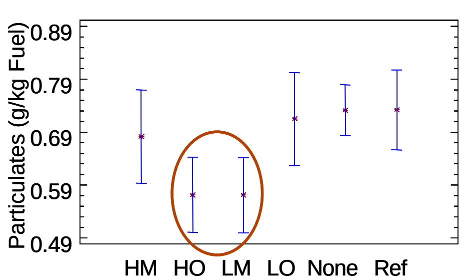


Figure 18 Total PM, FTP #3

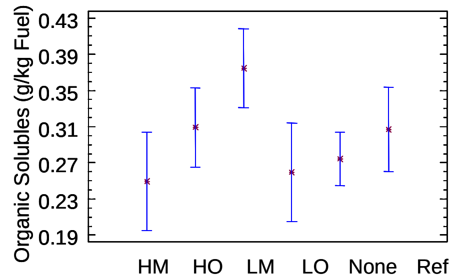


Figure 19 Soluble Organic Fraction, FTP# 3

## PARTICULATE MATTER ANALYSIS

### Toxics Analysis

The Environmental Protection Agency identified 21 compounds emitted from motor vehicles that are known or suspected to cause cancer or other serious health effects. This Mobile Source Air Toxics (MSAT) list includes various volatile organic compounds (VOCs) and metals, as well as diesel particulate matter and diesel exhaust organic gases. The MSAT list is found in Table II in the appendix. Many of the MSATs are gaseous. This test program did not address the measurement of any of the gaseous toxics. The filter collection of exhaust particulate matter (PM) described above was primarily aimed at determining PM mass emission rates. The type of filters used was not appropriate for subsequent analysis of the collected PM for trace metals by X-ray fluorescence. They were, however, adequate for the analysis of semi-volatile organic compounds (SVOC), conducted at the Desert Research Institute. The test program filters were separated according to the test oil viscosity and basestock chemistry into four groups: 5W-20 synthetic, 5W-30 mineral, 5W-30 synthetic and 10W-40 mineral. Each group of filters was then composited to produce a sample for the group. The filters were extracted in dichloromethane and the reduced extracts were analyzed by GC/MS in the selected ion monitoring mode for 76 individual SVOCs. The list of 76 SVOCs measured in the analysis and the average ratio of the measured emission rate and the uncertainty are found in Table III in the appendix. The compounds are listed in their gas chromatography elution order or in order of decreasing vapor pressure. The ratio can be used to judge the precision of the measurement. The generally lower ratios for the first third of the list – up to flourene – are to be expected since these are the gaseous and lower molecular weight semi-volatiles and were not captured on the filter samples to a large degree. The ratios increase with decreasing vapor pressure indicating greater precision in the measurements of the remaining semi-volatiles up to chrysene and the predominantly particle phase compounds from chrysene through coronene.

Results and Significance of Observed Effects

The individual emission rates, total by lubricant category and percent of total PM emission rates for the four composited samples are contained in Table IV. As can be seen the emission rates are very low- individually at levels of µg/kg fuel. The individual and total emissions rates vary little by lubricant category. The highest rates were observed for the compounds from acenaphthenequinone through benzanthrone, but the overall profile is strikingly similar for the four lubricant categories.

The percent of the total particulate matter collected that was identified as SVOC was also consistent for the four categories, ranging from 0.119 – 0.146 %. These results are lower, but in reasonable agreement with particle bound SVOC emission rates observed by Tang, et al.[19] who found fractions ranging from 0.1 – 5.5 % of the total PM mass for heavy duty diesels over two test schedules. Similarly, for a fleet of older gasoline vehicles, including a number of high particle emitters, Sagebiel, et al [20]. reported filter bound fractions of 1.0 and 0.98% for the entire fleet and the high emitters, respectively. In summary, the results obtained for particle bound SVOCs in this study are similar to other reports in the literature. However, this study could not address the greater issue of gas phase SVOC emissions. It has been reported that the particle bound fraction accounts for only 2.5% of the SVOCs emitted by vehicles [20].

## SUMMARY AND CONCLUSIONS

DYNO TESTING RESULTS

Engine Friction

- Twelve different oils were tested. Base oil viscosity seems to have a stronger effect on FMEP than friction modifiers.
- In the engine tests, synthetic oils yielded lower friction than mineral oils of the same viscosity grade.
- High levels of organic friction modifier reduced engine friction more effectively than high levels of MoDTC friction modifier.
- Lowest friction results were obtained for a full synthetic 5W-20 oil with 1% organic friction modifier.
- By changing from the oil with the highest friction to the one with the best results, the overall engine friction for the simulated FTP 75 cycle was reduced by 0.15 bar, which corresponds to an improvement of 10%.

Particulate Matter

- A comparison of twelve different oils, each tested at the same engine load, did not reveal statistically significant differences in terms of emissions of total PM mass.
- For the simulated FTP 75 cycle, the lube oil fraction of particulates was found to account for approximately half of the engine's total PM emissions.
- No clear oil effect could be identified for the insoluble organic fraction.
- Low viscosity oils indicated a smaller lube oil fraction in PM.

STATISTICAL ANALYSIS AND SIGNIFICANCE

Friction

- The 5W-30 oils outperform the 10W-40 oil on fuel economy as measured by fuel consumption (g/kwh).

Particulate Matter

- Full synthetic oils are significantly lower on lube oil in SOF.
- The 5W-30 oils outperform the 10W-40 oil on PM
- The 5W-20 oil outperforms the 10W-40 oil on SOF (g/kg Fuel)

PARTICULATE MATTER TOXICS ANALYSIS

- Particle bound SVOCs emission rates were determined to be in the range of 5.4 x 10-4 to 6.65 x 10-4 g/kg fuel. This represents an average of only 0.13% of the total PM mass emission rate.
- These emission rates are low and comparable to other literature reports.
- The emissions varied little between the four lubricant categories: 5W-20 synthetic, 5W-30 mineral, 5W-30 synthetic and 10W-40 mineral.
- However, since this work characterized the particle bound SVOC only, future work should also include collection and measurement of the gas phase emissions.

## ACKNOWLEDGMENTS

The authors would like to thank AVL North America Inc in Plymouth, MI and AVL List Gmbh in Graz, Austria for generously contributing the chemical analyses to this study that provided this work with more insight.

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**APPENDIX**

Table I, Running Order for Oils

| Run # | FM Type | FM Level | Viscosity Grade | Base Oil Type |
|---|---|---|---|---|
| | | | | |
| **1** | Reference Oil: 5W-30 Mineral | | | |
| **2** | None | None | 5W-30 | Synthetic |
| **3** | Organic | 1% | 10W-40 | Mineral |
| **4** | Organic | 0.25% | 5W-30 | Mineral |
| **5** | None | None | 10W-40 | Mineral |
| **6** | Reference Oil: 5W-30 Mineral | | | |
| **7** | MoDTC | 250 ppm | 5W-20 | Synthetic |
| **8** | MoDTC | 750 ppm | 5W-30 | Mineral |
| **9** | None | | 5W-20 | Synthetic |
| **10** | MoDTC | 750 ppm | 5W-30 | Synthetic |
| **11** | Reference Oil: 5W-30 Mineral | | | |
| **12** | MoDTC | 250 ppm | 10W-40 | Mineral |
| **13** | Reference Oil: 5W-30 Mineral | | | |
| **14** | Organic | 1% | 5W-20 | Synthetic |
| **15** | Organic | 0.25% | 5W-30 | Synthetic |
| **16** | Reference Oil: 5W-30 Mineral | | | |

Table II, List of Mobile Source Air Toxics (MSAT)

| | | | | | |
|---|---|---|---|---|---|
| Acetaldehyde | gas | Styrene | gas | Dioxins/Furans | particle |
| Formaldehyde | gas | Toluene | gas | Arsenic[3] | particle |
| Benzene | gas | Xylene | gas | Lead[3] | particle |
| 1,3-Butadiene | gas | Ethylbenzene | gas | Nickel[3] | particle |
| MTBE | gas | Naphthalene | gas | Chromium[3] | particle |
| Acrolein | gas | n-Hexane | gas | Manganese[3] | particle |
| POM1 | gas | DPM + DEOG2 | g + p | Mercury[3] | particle |

[1]Polycyclic Organic Matter includes organic compounds with more than one benzene ring and which have boiling points > 100$^{o}$ C.
[2]Diesel Particulate Matter and Diesel Exhaust Organic Gases.
[3]The entire group of compounds for each individual metal is included.

Table III, Measured SVOC Compounds

| no. | compound | Avg. Ratio Meas/Uncer | no. | compound | Avg. Ratio Meas/Uncer |
|---|---|---|---|---|---|
| 1 | Naphthalene | 2.76 | 39 | Anthrone | 7.66 |
| 2 | 2-methylnaphthalene | 1.95 | 40 | Anthraquinone | 4.37 |
| 3 | 1-methylnaphthalene | 1.55 | 41 | 3,6-dimethylphenanthrene | 7.75 |
| 4 | Biphenyl | 2.58 | 42 | A-dimethylphenanthrene | 8.38 |
| 5 | 1+2ethylnaphthalene | 3.42 | 43 | B-dimethylphenanthrene | 4.83 |
| 6 | 2,6+2,7-dimethylnaphthalene | 0.92 | 44 | C-dimethylphenanthrene | 9.76 |
| 7 | 1,3+1,6+1,7dimethylnaphth | 1.13 | 45 | 1,7-dimethylphenanthrene | 8.55 |
| 8 | 1,4+1,5+2,3-dimethylnaphth | 0.47 | 46 | D-dimethylphenanthrene | 5.28 |
| 9 | 1,2-dimethylnaphthalene | 0.17 | 47 | E-dimethylphenanthrene | 7.73 |
| 10 | 2-Methylbiphenyl | 0.88 | 48 | Anthracene | 2.51 |
| 11 | 3-Methylbiphenyl | 1.37 | 49 | 9-methylanthracene | 0.83 |
| 12 | 4-Methylbiphenyl | 2.68 | 50 | Fluoranthene | 6.42 |
| 13 | Dibenzofuran | 3.03 | 51 | Pyrene | 9.57 |
| 14 | A-trimethylnaphthalene | 1.49 | 52 | 9-Anthraaldehyde | 7.36 |
| 15 | 1-ethyl-2-methylnaphthalene | 2.30 | 53 | Retene | 2.26 |
| 16 | B-trimethylnaphthalene | 2.01 | 54 | Benzonaphthothiophene | 7.22 |
| 17 | C-trimethylnaphthalene | 1.88 | 55 | B-MePy/MeFl | 6.49 |
| 18 | 2-ethyl-1-methylnaphthalene | 0.50 | 56 | C-MePy/MeFl | 1.30 |
| 19 | E-trimethylnaphthalene | 1.44 | 57 | D-MePy/MeFl | 9.76 |
| 20 | F-trimethylnaphthalene | 2.19 | 58 | 4-methylpyrene | 9.62 |
| 21 | 2,3,5+I-trimethylnaphthalene | 1.59 | 59 | 1-methylpyrene | 8.07 |
| 22 | 2,4,5-trimethylnaphthalene | 1.19 | 60 | Benzo(c)phenanthrene | 3.48 |
| 23 | 1,4,5-trimethylnaphthalene | 1.94 | 61 | Benz(a)anthracene | 3.28 |
| 24 | Acenaphthylene | 0.22 | 62 | 7-methylbenz(a)anthracene | 0.78 |
| 25 | Acenaphthene | 0.86 | 63 | Chrysene | 4.34 |
| 26 | Fluorene | 0.89 | 64 | Benzanthrone | 6.70 |
| 27 | Phenanthrene | 4.08 | 65 | Benz(a)anthracene-7,12-dione | 2.55 |
| 28 | A-methylfluorene | 2.68 | 66 | 5+6-methylchrysene | 1.69 |
| 29 | 1-methylfluorene | 2.89 | 67 | 1,4-chrysenequinone | 0.00 |
| 30 | B-methylfluorene | 1.06 | 68 | Benzo(b+j+k)fluoranthene | 2.93 |
| 31 | Xanthone | 1.07 | 69 | 7-methylbenzo(a)pyrene | 0.54 |
| 32 | Acenaphthenequinone | 4.54 | 70 | BeP | 3.10 |
| 33 | Perinaphthenone | 9.88 | 71 | Perylene | 3.70 |
| 34 | A-methylphenanthrene | 7.83 | 72 | BaP | 2.35 |
| 35 | 2-methylphenanthrene | 8.10 | 73 | Indeno[123-cd]pyrene | 2.12 |
| 36 | B-methylphenanthrene | 2.08 | 74 | Benzo(ghi)perylene | 1.79 |
| 37 | C-methylphenanthrene | 7.69 | 75 | Dibenzo(ah+ac)anthracene | 0.33 |
| 38 | 1-methylphenanthrene | 8.11 | 76 | Coronene | 0.00 |

Table IV, Emission rates (g/kg fuel) of individual SVOC compounds by lubricant category

| **Compound** | **10W-40 mineral** | **5W-30 mineral** | **5W-20 synthetic** | **5W-30 synthetic** |
|---|---|---|---|---|
| Naphthalene | 4.42E-06 | 1.49E-06 | 7.83E-07 | 1.09E-06 |
| 2-methylnaphthalene | 4.90E-06 | 3.16E-06 | 2.54E-06 | 3.85E-06 |
| 1-methylnaphthalene | 2.03E-06 | 6.08E-07 | 1.27E-06 | 9.09E-07 |
| Biphenyl | 2.22E-06 | 1.08E-06 | 1.65E-06 | 2.09E-06 |
| 1+2ethylnaphthalene | 1.18E-06 | 1.30E-06 | 1.44E-06 | 2.37E-06 |
| 2,6+2,7-dimethylnaphthalene | 1.72E-06 | 1.99E-06 | 3.29E-06 | 1.84E-06 |
| 1,3+1,6+1,7dimethylnaphth | 2.91E-06 | 2.83E-06 | 5.31E-06 | 3.91E-06 |
| 1,4+1,5+2,3-dimethylnaphth | 1.93E-06 | 1.74E-06 | 1.71E-06 | 2.28E-06 |
| 1,2-dimethylnaphthalene | 3.47E-07 | 3.18E-07 | 4.52E-07 | 8.20E-07 |
| 2-Methylbiphenyl | 1.31E-06 | 1.37E-06 | 3.13E-07 | 8.56E-07 |
| 3-Methylbiphenyl | 6.04E-06 | 4.46E-06 | 1.97E-06 | 3.37E-06 |
| 4-Methylbiphenyl | 2.45E-06 | 1.69E-06 | 1.76E-06 | 1.23E-06 |
| Dibenzofuran | 1.54E-06 | 1.44E-06 | 2.23E-06 | 1.85E-06 |
| A-trimethylnaphthalene | 8.10E-07 | 9.91E-07 | 8.70E-07 | 7.49E-07 |
| 1-ethyl-2-methylnaphthalene | 1.77E-06 | 3.16E-06 | 3.48E-06 | 3.28E-06 |
| B-trimethylnaphthalene | 9.26E-07 | 1.18E-06 | 1.29E-06 | 9.63E-07 |
| C-trimethylnaphthalene | 9.26E-07 | 7.86E-07 | 1.08E-06 | 9.27E-07 |
| 2-ethyl-1-methylnaphthalene | 2.31E-07 | 2.06E-07 | 1.04E-07 | 4.99E-07 |
| E-trimethylnaphthalene | 6.94E-07 | 7.86E-07 | 1.08E-06 | 9.63E-07 |
| F-trimethylnaphthalene | 7.33E-07 | 1.08E-06 | 8.70E-07 | 0.00E+00 |
| 2,3,5+I-trimethylnaphthalene | 7.71E-07 | 1.16E-06 | 1.01E-06 | 6.78E-07 |
| 2,4,5-trimethylnaphthalene | 6.56E-07 | 4.68E-07 | 5.57E-07 | 0.00E+00 |
| 1,4,5-trimethylnaphthalene | 0.00E+00 | 6.64E-07 | 7.48E-07 | 8.02E-07 |
| Acenaphthylene | 1.12E-06 | 3.93E-07 | 6.26E-07 | 4.28E-07 |
| Acenaphthene | 4.94E-06 | 1.12E-06 | 7.31E-07 | 8.92E-07 |
| Fluorene | 2.18E-06 | 1.69E-06 | 5.74E-07 | 5.17E-07 |
| Phenanthrene | 6.00E-06 | 1.16E-05 | 1.16E-05 | 9.11E-06 |
| A-methylfluorene | 8.87E-07 | 9.91E-07 | 9.75E-07 | 1.39E-06 |
| 1-methylfluorene | 1.18E-06 | 1.52E-06 | 1.51E-06 | 1.09E-06 |
| B-methylfluorene | 7.33E-07 | 4.30E-07 | 5.22E-07 | 4.99E-07 |
| Xanthone | 1.54E-07 | 5.05E-07 | 0.00E+00 | 5.35E-07 |
| Acenaphthenequinone | 1.25E-05 | 8.64E-06 | 1.09E-05 | 1.48E-05 |
| Perinaphthenone | 6.67E-05 | 7.96E-05 | 7.82E-05 | 6.97E-05 |
| A-methylphenanthrene | 1.03E-05 | 1.28E-05 | 1.52E-05 | 1.49E-05 |
| 2-methylphenanthrene | 1.18E-05 | 1.78E-05 | 1.75E-05 | 1.21E-05 |
| B-methylphenanthrene | 1.06E-06 | 9.82E-07 | 9.92E-07 | 1.05E-06 |
| C-methylphenanthrene | 5.88E-06 | 9.14E-06 | 9.21E-06 | 6.44E-06 |
| 1-methylphenanthrene | 4.88E-06 | 8.16E-06 | 7.19E-06 | 5.83E-06 |
| Anthrone | 2.84E-05 | 3.47E-05 | 3.79E-05 | 3.15E-05 |
| Anthraquinone | 4.05E-06 | 5.69E-06 | 5.71E-06 | 4.24E-06 |
| 3,6-dimethylphenanthrene | 8.91E-06 | 1.15E-05 | 1.23E-05 | 8.38E-06 |

| Compound | 10W-40 | 5W-30 | 5W-20 | 5W-30 |
|---|---|---|---|---|
| | mineral | mineral | synthetic | synthetic |
| A-dimethylphenanthrene | 1.22E-05 | 1.81E-05 | 1.81E-05 | 1.42E-05 |
| B-dimethylphenanthrene | 7.25E-06 | 1.21E-05 | 1.27E-05 | 7.99E-06 |
| C-dimethylphenanthrene | 2.64E-05 | 3.95E-05 | 3.79E-05 | 2.81E-05 |
| 1,7-dimethylphenanthrene | 7.98E-06 | 1.07E-05 | 1.17E-05 | 8.99E-06 |
| D-dimethylphenanthrene | 1.46E-05 | 1.98E-05 | 2.13E-05 | 1.59E-05 |
| E-dimethylphenanthrene | 1.12E-05 | 0.00E+00 | 1.56E-05 | 0.00E+00 |
| Anthracene | 9.26E-07 | 1.48E-06 | 1.43E-06 | 1.82E-06 |
| 9-methylanthracene | 3.66E-07 | 2.34E-07 | 1.22E-07 | 5.88E-07 |
| Fluoranthene | 8.25E-06 | 9.54E-06 | 9.78E-06 | 8.10E-06 |
| Pyrene | 2.78E-05 | 3.57E-05 | 3.83E-05 | 3.06E-05 |
| 9-Anthraaldehyde | 5.79E-06 | 3.50E-06 | 7.66E-06 | 6.03E-06 |
| Retene | 2.62E-06 | 1.83E-06 | 2.85E-06 | 2.14E-06 |
| Benzonaphthothiophene | 2.83E-05 | 2.59E-05 | 1.92E-05 | 1.64E-05 |
| B-MePy/MeFl | 1.21E-05 | 1.30E-05 | 1.27E-05 | 1.19E-05 |
| C-MePy/MeFl | 1.62E-06 | 3.03E-06 | 9.75E-07 | 5.71E-07 |
| D-MePy/MeFl | 3.63E-05 | 4.31E-05 | 4.43E-05 | 3.48E-05 |
| 4-methylpyrene | 3.85E-05 | 4.53E-05 | 4.80E-05 | 3.83E-05 |
| 1-methylpyrene | 2.61E-05 | 2.92E-05 | 3.17E-05 | 2.35E-05 |
| Benzo(c)phenanthrene | 1.54E-06 | 2.26E-06 | 1.88E-06 | 1.25E-06 |
| Benz(a)anthracene | 5.25E-06 | 6.83E-06 | 7.13E-06 | 6.74E-06 |
| 7-methylbenz(a)anthracene | 6.56E-07 | 3.18E-07 | 4.87E-07 | 1.07E-07 |
| Chrysene | 2.05E-05 | 1.96E-05 | 1.98E-05 | 1.55E-05 |
| Benzanthrone | 3.06E-05 | 3.19E-05 | 3.07E-05 | 2.72E-05 |
| 1,4-chrysenequinone | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| Benzo(b+j+k)fluoranthene | 5.52E-06 | 4.55E-06 | 2.05E-06 | 5.14E-06 |
| 7-methylbenzo(a)pyrene | 0.00E+00 | 2.43E-07 | 3.13E-07 | 0.00E+00 |
| BeP | 6.33E-06 | 2.94E-06 | 5.92E-06 | 4.96E-06 |
| Perylene | 2.16E-06 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| BaP | 2.64E-06 | 3.83E-06 | 3.99E-06 | 2.76E-06 |
| Indeno[123-cd]pyrene | 2.20E-06 | 2.36E-06 | 2.75E-06 | 2.71E-06 |
| Benzo(ghi)perylene | 3.24E-06 | 4.75E-06 | 4.45E-06 | 4.39E-06 |
| Dibenzo(ah+ac)anthracene | 2.70E-07 | 3.18E-07 | 1.53E-06 | 8.92E-07 |
| Coronene | 0.00E+00 | 0.00E+00 | 0.00E+00 | 0.00E+00 |
| **Total SVOC g/kg fuel** | **5.67E-04** | **6.34E-04** | **6.65E-04** | **5.44E-04** |
| **% of Total Particulate Matter** | **0.119** | **0.131** | **0.146** | **0.132** |