

Evaluation of Exhaust Emissions from Elizabeth River Ferries

Final Report



Presented to:

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Executive Summary

Hampton Roads Transit Authority in Norfolk, Virginia, owns and operates a pair of similar passenger ferries on the Elizabeth River between Norfolk and Portsmouth VA. Several years ago one of the ferries was converted from diesel to natural gas fueled engines. The ferries were the *James C Echols*, which is powered by twin Caterpillar 3406_G natural gas engines and the *Elizabeth River II*, powered by twin Detroit Diesel 671 diesel fueled engines. This project was undertaken to perform in-use emissions testing to determine environmental benefits of ferry conversion to CNG, and to compare the operating economics of the two vessels. Sponsors of the program included United States Coast Guard, Hampton Roads Transit, Norfolk by Boat, U.S. Department of Energy, U.S. Maritime Administration, U.S. Environmental Protection Agency, Lyons Shipyard and NAVSEA.

The project was designed to measure exhaust emissions under two separate sets of conditions. (1) Under constant engine speed conditions (idle, 40%, 60%, 80%, 100%) in order to duplicate as far as possible the ISO test protocol, and (2) under transient conditions, where emissions were averaged over one complete circuit of the ferry route (1.37 miles). The parameters measured were: particulate mass, gaseous emission analysis, NO_x, CO, CO₂, THC, fuel mass flow rate, intake air & exhaust flow rates, shaft speed/torque and air temperature, pressure, and humidity. All the data was recorded in real time and later reduced to industry standard units such as grams of NO_x per horsepower-hour. One additional ad-hoc experiment was performed whereby one of the gas engines was operated under lean-burn conditions.

A secondary goal was to compare the results from West Virginia University's portable laboratory grade testing equipment to a new EPA portable exhaust emissions instrument specially designed for measuring emissions from off-road vehicles. Throughout the tests, the project followed the ISO and the CFR standards/specifications for measurement and precision.

Overview of Results

Stated broadly, the test results indicated that the natural gas engine emissions were significantly lower in particulate matter (10-100x), 2-3x higher in CO and THC and roughly equal in NO_x. Emissions results for CO and NO_x from the natural gas fired ferry were expected to be significantly lower than the diesel fueled ferry. The hydrocarbon emissions were dominated by methane, which is not a reactive gas. The poor gaseous emissions performance of natural gas ferries was due to poor control of the engine fuel-air ratio. According to the operator, the gas vessel conversion was the first variable speed application of what had been a constant speed generator engine and it is apparent that the system was not capable of maintaining control over a wide range of variable speed operating conditions.

Recommendations

The natural gas engines were running significantly richer than optimum. An ad-hoc attempt to adjust the fuel-air ratio resulted in a significant reduction in emissions at one point (almost zero NO_x) but also in a dramatic reduction in power. It is suggested that a properly designed air-gas mixer with

oxygen sensor and closed loop controls could significantly improve emissions, while maintaining adequate horsepower.

It is expected that a modern electronically controlled diesel engine operating on ultra low sulfur diesel fuel (less than 15 ppm S) and fitted with an exhaust PM after-treatment system will have PM emission levels equivalent to that of a natural gas fueled engine. Also, SOx emissions from natural gas-fueled engines would be lower than those from diesel-fueled engines. However, use of low sulfur fuel would also lower SOx emissions.

Conclusions

The primary lessons to be drawn from these tests are that

- Careful consideration must be given to design when installing new technology.
- Some level of initial emissions testing is critical, particularly on new technology applications.
- Proper instrumentation must also be provided to permit the operator to assure that the engine is properly adjusted and is performing in accordance with design parameters.

Summary of Data

Compared to diesel, gas engine emissions were found to have: 10-100x lower particulates, 2-3x higher CO, and approximately the same NOx. In general, the emission results from this study showed that the THC emissions from the natural gas-powered ferry are ~2.5 times higher than the diesel-powered ferry. The CO emissions are generally lower for the diesel-powered ferry, except for the 100% speed point. NOx is generally lower for the diesel-powered ferry, except at the 40% speed point. The natural gas ferry has significantly lower PM emissions, as expected.

The transient test results between the two ferries showed that the natural gas ferry required ~30% more work to perform the test than the diesel ferry. Both ferries covered the same distance of ~1.37 miles. The brake specific THC mass emissions from the natural gas-powered ferry (1.51 g/bhp-hr) were 2.5 times that of the diesel ferry (0.6 g/bhp-hr). The brake specific CO mass emissions for the natural gas-powered ferry (13.7 g/bhp-hr) were 2.6 times that of the diesel ferry (5.2 g/bhp-hr). The brake specific NOx mass emissions from the natural gas-powered ferry (25.5 g/bhp-hr) were 10 percent higher than that of the diesel ferry (23.0 g/bhp-hr). The brake specific PM results show that the diesel-powered ferry (0.50 g/bhp-hr) was emitting 50 times greater than the natural gas-powered ferry (0.01 g/bhp-hr). The brake specific fuel consumption (bsFC) results show that the natural gas-powered ferry (274 g/bhp-hr) and the diesel ferry (270 g/bhp-hr) were equivalent in fuel consumption.

The idle point data for the diesel ferry port engine showed significantly higher mass emissions rates for THC, CO, CO₂, NOx, and fuel consumption rates than the starboard side engine. This may be attributed to over fueling at the idle point as alluded to in the oil analysis for this engine as shown in Figure 25. However, the concentration levels of THC, CO, CO₂, and NOx were equivalent for both engines but the measured fuel rate was approximately four times higher for the port engine than the

starboard engine, leading to a higher (or lower) calculated mass rate for the port (or starboard) engine. This is borne out in Equation (1) or (2) where the emission mass rate was linearly proportional to the fuel mass rate. Thus, if the idle data was incorrect for one of these engines, then the resulting mass emission rate (or brake-specific) was incorrect. No other data points appeared to have a discrepancy in the fuel measurement; care must be exercised in interpreting the idle data for the diesel engines.

The over fueling reference in the port-side oil analysis, Figure 25, of the diesel ferry's port engine was supported by higher mass rate and brake-specific mass emissions for this engine compared to the starboard engine. Generally, the emissions measured during the steady state and transient tests from the port engine were higher than those measured for the starboard engine.

The CO emission levels for the natural gas ferry' port engine were significantly higher than that of the starboard engine as shown in Figure 6. and Figure 12 for the 40% point. This may be attributed to incomplete combustion condition, as supported by the lower exhaust temperature in Figure 4 this steady-state point. However, the THC emissions in Figure 5 and Figure 11 were not significantly different between the two engines.

The results from an additional set of tests for the natural gas ferry's port engine are shown in Table 5. This test was performed in an ad hoc manner to examine the effects on emissions from adjusting the natural gas carburetor to a leaner setting. The test consisted of operating the engine at the three points as shown in the figure. The engine was operated at each point for approximately five minutes; the data from the last 60 seconds of each set point were averaged for the results shown in the table. The NOx data for Point 1 was negative, no errors in the NOx data collection could be found for this point. This observation merits further investigation following a well laid out test plan. All four engines were checked for proper operation and tuning prior to the emissions test. As set up, the natural gas engines were running very rich. An attempt to adjust air-fuel ratios after initial testing resulted in a dramatic drop in emissions at higher powers but also resulted in a significant loss of available power.

This data indicates that the emissions performance of the natural gas engines is well below optimum, and that the problem lies with poor control of the air-fuel mixture under different operation conditions. It is not clear that the installed air/gas mixer is capable of maintaining an air-fuel ratio that will provide low emissions and sufficient power over the operational range. It should be noted that this application was among the first variable speed marine installations of this engine. It is believed that provision of a modified air/fuel mixing system with closed loop oxygen controls could provide significant improvements in emissions while maintaining acceptable power.

Based on the actual fuel costs of 72 cents per 137.33 cu ft for natural gas and 65 cents per gallon of diesel, the fuel cost per circuit computes to an average of \$1.64 for the natural gas ferry and \$0.81 for the diesel ferry.

Introduction

In-use exhaust emissions tests were performed on two Hampton Road Transit Authority passenger ferryboats. The James C. Echols craft, as tested, was powered by two Caterpillar 3406 engines operating on compressed natural gas, while the Elizabeth River II was powered by two Detroit Diesel

engines operating on diesel fuel. The purpose of this testing was to determine the differences in exhaust mass emissions from the two crafts while they were operated over similar test conditions. Gaseous emissions (CO₂, CO, NO_x, THC) and particulate matter emissions (PM) data were collected. The test engine specifications are listed in Table 1. All emissions tests were performed on the Elizabeth River near the cities of Norfolk and Portsmouth, VA. Representatives from the Hampton Roads Transit Authority provided and operated the ferryboats, while West Virginia University (WVU) provided and operated the emissions measurement equipment. The computed results of the four sets of emissions tests are presented in this report.



James E. Echols
(Natural gas fueled-ferry)



Elizabeth River II
(Diesel-fueled ferry)

Many organizations lent their support to this research effort. USCG provided the primary funding for the project and provided the air flow meter. MARAD managed the project and subcontracted Dr. Tom Fox for engine instrumentation, logistics, and on-site management. Hampton Roads Transit Authority and Norfolk by Boat provided access to the ferries, crewing and general support. Instrument installation was performed at Lyon shipyards. DOE funded WVU who provided the gaseous emissions and PM sampling and measurement, data acquisition and recording systems and generated the final report. The US EPA provided their SPOT system, the US Navy (NAVSEA Philadelphia) instrumented each prop shaft to provide real time shaft speed and torque, and MARAD managed the project and furnished a Micro Motion fuel mass flow measurement system. With the exception of the US EPA SPOT data, all data were recorded and maintained by WVU through either electronic means and/or field custody logs.

Table 1 Test engines specifications.

Ferry	James C. Echols		Elizabeth River II	
Engine Manufacturer	Caterpillar		Detroit Diesel Corporation	
Engine	Port	Starboard	Port	Starboard
Engine Model	3406	3406	671	671
Model Year	1982	1982	1986	1986
Engine I.D.	4FDOO770	4FDOO771	6A82689	6A7518
Displacement (cu. in.)	893	893	426	426
Power Rating (hp)	215	215	172@1800 RPM	172@1800 RPM
Configuration	Inline 6	Inline 6	Inline 6	Inline 6
Bore (in.) x Stroke (in.)	5.4 x 6.5	5.4 x 6.5	4.25 x 5	4.25 x 5
Induction	Naturally Aspirated	Naturally Aspirated	Super Charged	Super Charged
Fuel Type	CNG	CNG	Diesel	Diesel
Engine Strokes per Cycle	4	4	2	2
Injection	Direct	Direct	Direct	Direct

Objective

The objective of this study was to measure engine emissions of oxides of nitrogen (NO_x), total particulate matter (TPM), carbon monoxide (CO), carbon dioxide (CO₂), oxygen (O₂), and total hydrocarbon (THC). For this testing, West Virginia University designed and developed a raw emissions sampling system, based on recommendations provided by Title 40 CFR 86, Title 40 CFR 89, Title 40 CFR 92, Title 40 CFR 94, ISO8178, and SAE J177 [1-6], where applicable.

Overview of Exhaust Emissions Measurement System

The following section is included in order to outline the equipment and the procedures used for the evaluation of the ferryboat engine exhaust emissions. Due to space limitations and the nature of in-use emissions testing, special attention was paid to the selection of the analytical equipment. WVU designed and developed a raw exhaust emissions sampling and measurement system that would provide the highest possible accuracy while following the requirements set forth in Title 40 CFR 86, Title 40 CFR 89, Title 40 CFR 92, Title 40 CFR 94, ISO8178, and SAE J177 [1-6], where applicable. In particular, analyzers and transducers were selected that would provide the required accuracy specified in the above documents and not be influenced by the vibration of the ferry found during the in-use testing.

A. Particulate Sampling System

The primary goal of engine emissions testing was to determine the effects that exhaust constituents have on the environment. In order to simulate “real world” conditions and to produce accurate particulate matter measurements, it was necessary to simulate the dilution process that occurs when hot exhaust gases mix with ambient air. The effects of this exhaust gas dilution are threefold. The primary reason for dilution is to allow any in-use exhaust-air interactions to take place, but it also quenches post-cylinder combustion reactions and lowers the exhaust gas dew point, thus inhibiting condensation.

The dilution tunnel used for this research was of a partial-flow design, where a measured amount of exhaust gas emitted by the test engine was routed into the tunnel and mixed with a regulated amount of HEPA-filtered, conditioned dilution air in order to achieve desired dilution ratios. The system was mass-flow controller based, but uses conditioned, time-aligned raw and dilute CO₂ tunnel concentrations to infer dilution ratios and exhaust sample inlet flow rates. The dilution tunnel, which was approximately 2 inches in diameter and 24 inches in length, was constructed with stainless steel to prevent oxidation contamination and degradation. The dilution air supply was provided by a rotary-vane pump, and was HEPA-filtered and cooled - to remove water as well as maintain near-ambient temperatures. The exhaust gases entered the tunnel at its centerline and passed through a mixing orifice plate that was close-coupled to the divergent tunnel entrance. The orifice plate creates turbulence in the flow path that promotes thorough mixing, and tunnel flow rates were maintained sufficiently high so as to promote the fully-developed, blunt-shaped turbulent flow profile, which reduces the sensitivity of the sample probe placement. The full tunnel flow stream was pulled through a stainless steel filter holder, which contains two Pallflex 70mm diameter Model T60A20 fluorocarbon-coated glass micro-fiber filters. Two filters, a primary and a secondary filter, were used in the filter holder to extract the maximum amount of PM from the sample stream for analysis. The diluted sample stream was maintained at temperatures below 125°F, measured at the inlet of the PM filter holder. The purpose of this was to keep the face of the particulate sampling filter at a sufficiently low temperature so as to prevent any damage, and to prevent the stripping of volatile components that would normally condense upon the filter surface.

Sierra mass flow controllers provided flow rate control of the total flow and dilution air based on computer voltage outputs determined from the raw and dilute CO₂ concentrations. The mass flow controllers are routinely recalibrated by the manufacturer and additionally checked with Merriam Instruments laminar flow elements. As mentioned before, the deduction of the dilution ratio was provided through the measurement of dilute and raw CO₂ concentrations in the dilution tunnel. Exhaust sample flow rate into the tunnel was inferred from this dilution ratio along with the total mass flow rate measured with the mass flow controller.

The sample filter collected the particulate matter from the diluted exhaust to enable the determination of the amount of PM emitted by the engine during a test cycle with a gravimetric analysis. The PM collected consists primarily of elemental carbon as well as sulfates, the soluble organic fractions (SOF), engine wear metals and bound water. The sample filters were conditioned in an environmentally controlled chamber to 70°F and 50% relative humidity, in compliance with requirements of CFR Parts 86 and 89 [1, 2], and weighed before and after sample collection using a Cahn C-32 microbalance. However, for this research effort, the filters were pre-weighed at the Engine and Emissions Research Laboratory (EERL) at WVU and shipped to the test site in individually

labeled petri dishes. After the filters were used, they were shipped back to the EERL and reconditioned and the final weight was recorded. The required times set forth in CFR Parts 86 and 89 [1, 2] were not followed. However, previous experience with PM gravimetric analyses performed at remote sites indicates minimal, if any, variations due to non-standard PM conditioning constraints.

B. Gaseous Emission Sampling System

The gaseous sampling system originated with insulated, stainless-steel sample probes that were mounted in the raw exhaust stacks and close-coupled with heated filter assemblies and heated sampling lines. The multi-hole, stainless-steel probes were designed according to the recommendations included in CFR 40 Part 89, Subpart E [2]. The wall temperatures of the filter assembly and the heated sample transport lines are electrically heated and maintained at a temperature of $375^{\circ} \pm 10^{\circ}\text{F}$ using electronic temperature controllers. This temperature set point, prescribed by CFR 40, Parts 86 and 89 [1, 2], prevents the high molecular weight hydrocarbons from condensing in the sample line. The heated sample lines transport the exhaust sample to the gaseous emissions sample conditioning system. This system incorporates yet another heated filter assembly, a heated-head pump, a redundant external NO_2 converter, flow control devices, and a sample moisture control system. The flow rate controllers were implemented to provide a constant, pulsation-damped sample for the NDIR and HCLD analyzers, since sample pressure fluctuations can compromise measurement accuracy. The sample humidity control was used to prevent the interference effects of water – a common problem for both NDIR and HCLD devices.

C. Exhaust Gas Analyzers

The gas analysis bench houses four major analyzer components: THC analyzer, CO analyzer, CO_2 analyzer, and two NO_x analyzers, one of which was operated in NO only mode. A brief description of each analyzer and its components as well as theory of operation is included in this section. The gas analyzers used meet or exceed the recommendations set forth in CFR 40 Part 86, Subpart N and Part 89, Subpart D [1, 2].

Oxides of Nitrogen Analyzer

The NO/ NO_x analyzers used for testing were California Analytical Model 400 Heated Chemiluminescent Detectors (HCLD). Each of the analyzers is capable of detecting the concentration of NO or NO and NO_2 together, which is commonly referred to as NO_x . An additional external converter, Horiba COM11, was used to facilitate optimal NO_2 conversion efficiencies. When measurement of NO is desired, the sample NO is converted into NO_2 by gas-phase oxidation with molecular ozone (O_3). During this reaction, about 10% of the NO_2 becomes electrically excited, followed by an immediate return to the non-excited state. This phenomenon is known as photon emission. A photon detector, or multiplier tube, is used to detect the photon emission quantity, which is proportional to the amount of NO present in the sample. For the detection of NO_x , the sample is first passed through a NO_2 converter that converts the NO_2 into NO, which is then measured with the principle described previously. Therefore, in the NO_x detection mode, total analyzer response would determine the amount of NO present in the original sample, as well as the NO created through the dissociation of NO_2 in the converter. The mode of operation is determined by the converter bypass switch on the front panel of the analyzer. A NO_x efficiency tester, designed and operated according to the procedures set forth in CFR 40 Part 86, Subpart N [1], was used to ensure that the converter in the

Model 400 analyzer was operating optimally. For the testing, one of the CAI Model 400 analyzers was operated in NO mode, while the other was operated in the NO_x mode. With these simultaneous measurements inferences could then be made regarding the levels of NO₂ produced by the engines that were tested. An HCLD analyzer is inherently linear by nature, but the linearized response was validated through calibration curves that were generated before each testing session began. These calibration curves were generated by using a capillary-flow gas divider and component gases mixtures that are traceable to the standards set forth by the National Institute of Standards and Technology (NIST).

Hydrocarbon Analyzer

The hydrocarbon analyzer used was a Rosemount Model 402 Heated Flame Ionization Detector (HFID) analyzer. Counting of the elemental carbon atoms in the sample is used to determine the amount of hydrocarbon levels in the exhaust stream. The sample gas flow is regulated and flows through a hydrogen/helium-fueled flame that produces ions that are collected with polarized electrodes. The absorption of these ions by electrodes produces a current flow in the analyzer's measurement circuitry, which is quantified and related to the number of carbon atoms contained in the sample. An HFID analyzer is inherently linear by nature, but the linearized response was validated through calibration curves that were generated before each testing session began. These calibration curves were generated by using a capillary-flow gas divider and component gases mixtures which are traceable to the standards set forth by the NIST.

Carbon Monoxide/Carbon Dioxide Analyzers

Gaseous constituents of CO and CO₂ were measured with a California Analytical, Inc. Model 300, three-component, non-dispersive infrared (NDIR) gas analyzer. NDIR analyzers operate using the principle of selective infrared light absorption – where a particular gas will absorb a certain wavelength of light within the infrared spectrum, while the other spectral wavelengths are able to transmit through the gas. The analyzer detects the amount of infrared energy able to pass through the sample gas and uses it in the determination of the concentration of the measured absorbent gas in the sample stream. An NDIR analyzer is inherently non-linear by nature, so linear calibrated curves were generated for the analyzers before each testing session began. These calibration curves were generated by using a capillary-flow gas divider and component gases mixtures which are traceable to the standards set forth by the NIST.

Bag Sampling

In addition to being sampled by the analyzers during the test, a portion of the raw exhaust was collected in 3-liter Tedlar bags that were stored in black plastic storage bags for post-test speciation of total hydrocarbon results.

D. Fuel Flow Rate

Continuous direct fuel flow measurement was provided by Micro Motion, using two CMF025 flow meters with RFT9739D4SUA transmitters. Two units were incorporated into the testing. The two units were installed on the James C. Echols ferry, one for each engine. The same two units were used for the diesel-powered Elizabeth River Ferry II ferry. However, for the diesel-powered engines both units were used on the engine under test; one for the supply side and one for the return side. Personnel

from Micro Motion provided the unit and support to interface the units into the WVU DAQ. The WVU DAQ recorded redundant signals for each unit, one was a frequency-generated signal and the other was a current-generated signal. The calibration constants for each signal were entered into the WVU DAQ program and verified through signals generated from a laptop with software from Micro Motion.

E. Intake and Exhaust Flow Rates

Three different means were used to measure the intake and exhaust flow rates through the engine. The first method was provided by Tom Fox using a hood located in the passenger area and connected to the intake with a flexible duct. This system required that the intake flow rate data be manually recorded by WVU into field logs and later transcribed into an Excel file for processing. The second method was an AnnubarTM provided by WVU and located in the exhaust stream just downstream of the exhaust manifold. The absolute pressure, differential pressure, and exhaust temperatures were recorded and stored with the WVU DAQ. These transducers were calibrated at WVU prior to the testing and the calibration checked at the test site. The third method was a proprietary unit integral to the SPOT system provided by the US EPA and installed in the exhaust outlet at the end of the stack. The data from this system was provided to WVU.

F. Shaft Speed/Torque

Prop shaft speed and torque was measured using Binsfeld's Model BT9000 transmitter and RD9000 receiver. Personnel from the US Navy installed the unit on each prop shaft of the engine under test. An rf signal was transmitted from the shaft in the engine compartment area to the receiver located on the lower deck seating area of the ferry. The signals from the receiver were connected into the WVU DAQ. The calibration constants for the speed and torque were entered into the WVU DAQ program and the torque was checked with a shunt calibration. The calibration of shaft speed was confirmed with the wheelhouse engine speed display and transmission gear ratio.

G. Additional Signals

Additional signals included the ambient pressure, temperature, and humidity. These signals were recorded and stored into the WVU DAQ. These transducers were calibrated at WVU prior to the testing and the calibration checked at the test site.

H. Instrumentation Control/Data Acquisition

Data acquisition was controlled with software developed by WVU. National Instruments E-series data acquisition boards with a minimum 12-bit resolution were used along with rack-mounted signal conditioning units (Analog Devices Model 3B). All data were recorded in raw voltage form at a minimum of 5 Hz and later converted to the proper engineering units with a reduction program developed in-house at WVU. The analog channels collected for the gaseous emissions, shaft speed and torque, and fuel flow measurement are shown in Table 2 along with the abbreviated name. In addition, GPS data was recorded and stored to disk at 1 Hz.

Table 2 Analog DAQ channels collected by WVU.

Description	Name	Source
Cold Junction Temperature	anlCJC	WVU
THC	anlHC_1	WVU
CO	anlCO_1	WVU
High CO ₂	anlCO2_2	WVU
NOx	anlNOx_1	WVU
NO	anlNOx_2	WVU
Annubar Absolute Pressure	anlAnnAP	WVU
Annubar Differential Pressure	anlAnnDP	WVU
Ambient Absolute Pressure	anlAmbAP	WVU
Ambient Relative Humidity	anlAmbRH	WVU
Ambient Temperature	anlAmbTemp	WVU
Prop Shaft Torque	anlShftTorque	US Navy
Prop Shaft Speed	anlShftSpeed	US Navy
Fuel Rate from Meter 1 (Frequency)	anlFuelRate1a	Micro Motion
Fuel Rate from Meter 1 (Current)	anlFuelRate1b	Micro Motion
Fuel Rate from Meter 2 (Frequency)	anlFuelRate2a	Micro Motion
Fuel Rate from Meter 2 (Current)	anlFuelRate2b	Micro Motion
Annubar Exhaust Temperature	anlAnnTempPre	WVU

Ferryboat Test Cycle

Steady-state engine set points and transient runs were utilized for the emissions testing. All testing was performed on the Elizabeth River. For the steady state tests, nominal engine speeds of 40, 60, 80, and 100% of rated power and idle were selected as operating points. A single repeat was performed at each engine set point. Due to the nature of in-use testing, it was nearly impossible to vary the load on the engine (or engines); the load applied to the engine was a function of the requirements set forth by the ferry operation (passenger loading, wind, current direction, speed, etc.). Therefore, the loading on the engine(s) could vary from set point-to-set point since no effort was made to reproduce the exact path of the ferry for each set point. The data collection procedure consisted of operating the ferry at a constant engine speed for a short duration (~ five minutes). After the emissions had stabilized, data collection commenced. The duration of the data collection was dependant upon the PM filter loading. For the natural gas-powered ferry, fifteen to twenty minutes was required for the runs whereas only about five minutes were required for the diesel-powered ferry. The test times were varied according to the expected filter loading.

The transient tests consisted of operating the ferry through a simulated passenger run operating between three ports. Only the portside engines of the James C. Echols and the Elizabeth River Ferry II ferries were evaluated for transient operation due to time limitations. A single repeat was performed for each of these two engines. At each port the ferry was stopped for approximately five minutes with the engine operating to simulate the loading and unloading of passengers. All data were recorded continuously for these tests from the start of the idle period to the last port stop.

Data Reduction Methodology

Since the research performed was the in-use emissions evaluation from the four engines in the two ferries, there are no specific standards governing the testing. However, the data reduction procedures outlined in Title 40 CFR 86, Title 40 CFR 89, Title 40 CFR 92, Title 40 CFR 94, ISO8178, and SAE J177 were followed, where applicable, in the experimental setup and data evaluation [1-6]. The computation of the mass emissions emitted from the natural gas-fueled and diesel-fueled engines in the ferries can be determined from the sources listed above. Generally, knowledge of the intake air flow rate and fuel flow rate (or exhaust flow rate) and the concentration level of the exhaust constituents are required. However, the three methods used to measure the intake or exhaust flow rate were deemed unsuitable for this work. In this study, the fuel flow rate measurement was assumed to be a more accurate measurement than any of the air flow measurements, permitting the implementation of the procedures outlined in Title 40 CFR 92 as the primary calculation method for the gaseous mass emission rate [3]. WVU has successfully employed an averaging pitot tube, the Annubar™, for exhaust flow rate measurements from on-highway vehicles. While, WVU was not scheduled to collect exhaust flow rate data in this study, they did install their exhaust flow rate measurement system on the engine stacks and collected data. This system was in addition to the SPOT that was provided by the US EPA. It was clear that the range of the differential pressure transducer for the Annubar-based system was not optimum.

Steady State Test Reduction Method

The mass rate of each exhaust constituent was determined from the measured concentration levels of the exhaust and the measured fuel mass rate as defined in Title 40 CFR 92 [3]. The data from the last 60 seconds of each steady-state point were averaged and used for the gaseous emission analysis. For PM, the entire duration of the sampling period was used for the determination of the TPM. The emission mass rate may be calculated using the concentration levels reported on a wet basis

$$\dot{M}_i = \frac{\dot{M}_f * C_{i,w} * MW_i}{(12.011 + 1.008 * \alpha) * (C_{CO_2,w} + C_{CO,w} + C_{HC,w})} \quad (1)$$

or reported on a dry basis

$$\dot{M}_i = \frac{\dot{M}_f * C_{i,d} * MW_i}{(12.011 + 1.008 * \alpha) * (C_{CO_2,d} + C_{CO,d} + C_{HC,d})} \quad (2)$$

The molecular weight of each constituent is shown in Table 3. The dry and wet concentration levels are related by

$$C_{i,d} = K_w * C_{i,w} \quad (3)$$

where the correction factor is given as

$$K_w = 1 + D_{H_2O} \quad (4)$$

The value of D_{H_2O} can be determined from an iterative process or using an approximate solution. An approximate solution used in this analysis and is given by:

$$D_{H_2O} = \left[\frac{\alpha * (C_{CO_2,d} + C_{CO,d})}{2} + Y * DVOL_{Ratio} \right] * \left[\frac{1}{1 + \frac{C_{CO,d}}{K * C_{CO_2,d}}} \right], \quad (5)$$

where

$$DVOL_{Ratio} = 1 - \left(\frac{\alpha}{4} \right) * C_{CO_2,d} - \left(\frac{\alpha}{4} + 0.5 \right) * C_{CO,d}. \quad (6)$$

The constituents of CO, CO₂, and NO_x were measured dry and THC was measured wet. Equation (2) was used for calculating the mass emission rate. Therefore, the measured concentration of THC is converted to a dry basis for the calculations by

$$C_{THC,d} = K_w * C_{THC,w}. \quad (7)$$

Table 3 Molecular weight of each exhaust constituent.

Constituent i	MW
THC	$(12.011 + 1.008 * \alpha)$
CO	28.01
CO ₂	44.01
NO _x *	46.01
NMHC	$(12.011 + 1.008 * \alpha)$

* NO_x MW based on NO₂

The concentration level of the nonmethane hydrocarbons may be calculated on a wet basis

$$C_{NMHC,w} = C_{THC,w} - r_{CH_4} * C_{CH_4,w} \quad (8)$$

or on a dry basis

$$C_{NMHC,d} = C_{THC,d} - r_{CH_4} * C_{CH_4,d}. \quad (9)$$

The concentration level of methane for each test was analyzed from a bag sample by means of Gas Chromatography on a wet basis and then converted to a dry basis via equation (7).

The mass emission rate of NO_x is corrected for ambient temperature and humidity according to procedure outlined in Title 40 CFR 89 [2].

The particulate matter mass rate was determined from knowledge of the partial flow dilution tunnel dilution ratio, particulate filter net mass, integrated flow across the filter during the test, and the average exhaust flow rate. The particulate matter mass rate is analogous to that given in ISO8178 [5] and is given by

$$\dot{M}_{PM} = \frac{m_{net} * \dot{Q}_{Exh}}{Q_{SecTun}} \quad (10)$$

The flow across the filter is determined from integrating the measured flow through the mass flow controller on the mini dilution tunnel. The net filter mass is the sum of the PM loading on the primary and secondary filter. The average exhaust flow rate can be determined from the measured in-field methods (Tom Fox (intake + fuel), EPA Spot (exhaust), or WVU (exhaust)) or from the measured exhaust constituents and fuel flow rate. For this analysis, it was determined that the most accurate method would be from the measured exhaust constituents and fuel flow rate approach and is determined from the approach shown in Ferguson and Kirkpatrick [7].

The average exhaust volumetric flow rate over the PM collection phase was determined from the equivalence ratio, stoichiometric air-to-fuel ratio, and fuel flow measurement. The exhaust volumetric flow rate is given as

$$\dot{Q}_{Exh} = \rho * \dot{M}_{Exh} \quad (11)$$

where the exhaust mass rate is given as

$$\dot{M}_{Exh} = \dot{M}_{intake} + \dot{M}_{fuel} \quad (12)$$

The fuel flow rate was measured. The intake mass flow rate is given as

$$\dot{M}_{intake} = \frac{\left(\frac{A}{F}\right)_{stoich}}{\phi} \dot{M}_{fuel} \quad (13)$$

The stoichiometric air-to-fuel ratio is based on the hydrogen-to-carbon ratio and is given as

$$\left(\frac{A}{F}\right)_{stoich} = \frac{MW_{Carbon} + \alpha * MW_{Hydrogen}}{138.18 * (1 + .25 * \alpha)} \quad (14)$$

The equivalence ratio can be determined from a wet or dry exhaust gas. A dry basis is used in this analysis and is given as

$$\phi = \frac{2 * (1 + .25 * \alpha) * (2 * C_{CO_2,d} + 2 * C_{CO,d} + C_{THC,d})}{2 * C_{CO_2,d} + C_{H_2O,d} + 2 * C_{O_2,d} + C_{CO,d}} \dot{M}_{fuel} \quad (15)$$

The concentration of “dry water” is somewhat of a misnomer, but is given as

$$C_{H_2O,d} = \frac{.5 * \alpha * (C_{CO_2,d} + C_{CO,d})}{1 + \frac{C_{CO,d}}{3.5 * C_{CO_2,d}}} \dot{M}_{fuel} \cdot \quad (16)$$

The concentration of oxygen in the exhaust was not measured but is approximated by experimental data for lean-burn engines given in Heywood [8].

The brake specific mass emission for each exhaust constituent is determined by

$$bs_i = \frac{\dot{M}_i}{P}, \quad (17)$$

where the power is determined from the measured prop shaft speed and torque and is given as

$$P = \frac{T * N}{5252}. \quad (18)$$

Transient Test Reduction Method

A similar methodology as given above was used for the transient runs brake-specific mass emissions. However, it must be noted that the uncertainty associated with the determination of the mass of each constituent emission may be higher for transients tests using raw exhaust gas measurement techniques. The problem stems from the inherent time delays, diffusion, and dispersion of the measured constituent at each analyzer. Therefore, the value of the instantaneous (5 Hz) mass, or mass rate, is affected by these delays. It is possible to reconstruct the actual value of the constituent level in the exhaust stack through various techniques. The approach taken in this analysis was the shifting of the measured exhaust constituent so that the rise (or fall) of the signal corresponds to the rise (or fall) of shaft power and fuel flow rate. Fuel flow was used as a parameter in this analysis since the shaft could be disengaged from the engine, thus nullifying the inferred engine power signal. Each constituent was shifted individually based on this criterion.

Results

For the steady state runs, the engine speed, prop shaft power, vehicle speed, and exhaust temperature are shown in Figure 1 to Figure 4, respectively. It is noted that the reported power in Figure 2 is that of the prop shaft and not that of the engine. Therefore, the reported brake-specific mass emissions are influenced by the transmission efficiency and will thus be lower than those reported. The emission results for the steady state runs are presented in mass rate units (g/hr) and in brake-specific mass units (g/bhp-hr) in bar charts for the gaseous constituents, PM, and fuel consumption in Figure 5 to Figure 16. The magnitude of each of the bars in Figure 5 to Figure 16 represent the average of the two runs performed at each point; the “error” bars represent the spread of the data. The average of the data is shown in the table below each chart. The results for the transient runs are presented in brake-specific mass units for the exhaust constituents as illustrated in Table 4.

Fuel and oil samples were collected and analyzed. The results from these analyses are given in the Appendix. The fuel sample analyses were typical for in-use natural gas and diesel fuels used. It is noted that the ethane content for the natural gas was relatively high at 7.5%. The oil analysis shows that the James C. Echols' starboard engine has a high tin content and the port engine has high copper content, an indication of engine wear. The Elizabeth River Ferry IIs' starboard engine has high tin, implying wear and the port engine oil has high water content, indicating a coolant leak.

The data for the steady runs and the transient tests are included on a disk in an Excel spreadsheet. The steady state sheet contains the average of the last 60 seconds of data collection for the measured parameters along with the calculated parameters. The Excel file also contains the graphs shown in Figure 1 to Figure 16. Table 4 is also contained in one of the sheets.

Figure 1 shows the steady-state test engine speeds for the 40, 60, 80, and 100% points along with the idle speed. The differences in engines are shown in the idle speed and the associated steady-state set points. The differences in prop shaft power and ground speed shown in Figure 2 and Figure 3, respectively, may be attributed to differences in vessel design and vessel loading. The vessel loading is dependant upon, among other conditions, river current direction and magnitude and tidal conditions. While there were no attempts made to replicate test conditions in this study, a comparison of Figure 1 and Figure 2 shows that the two natural gas engines were operated in a repeatable manner and the two diesel engines were operated in a repeatable manner for the steady-state tests.

The data for the prop shaft torque (hence power) were filtered to account for instances where the torque value would "instantaneously" change (impulse) to a very high (or low) value. The speed signal did not show this impulse. Generally, only one or two data points (0.2 to 0.4 seconds) would show this impulse and were replaced with a linearly interpolated value between adjacent data points.

A comparison of the exhaust temperature of the four engines is shown in Figure 4. This is the temperature used in the WVU Annubar flow calculation. The natural gas exhaust gas temperature measurement location was located within 15 feet of each engine's exhaust manifold and located under the first deck. The diesel exhaust temperature measurement probe was further away from the engine than the natural gas measurement and located at the upper deck access panel location. As shown in this figure, the natural gas-powered exhaust temperature is greater than the diesel ferry, as expected. The exhaust temperatures also indicate that the two natural gas engines were operated in a repeatable manner and the two diesel engines were operated in a repeatable manner for the steady-state tests. The only discrepancy in the exhaust temperature is the 40% speed point between the starboard and port side engines for the James C. Echols ferry. It is noted that the prop shaft power for these two engines at the 40% speed are within 7% of each other.

In general, the emission results from this study showed that the THC emissions from the natural gas-powered ferry are ~2.5 times higher than the diesel-powered ferry. The CO emissions are generally lower for the diesel-powered ferry, except for the 100% speed point. NOx is generally lower for the diesel-powered ferry, except at the 40% speed point. The natural gas ferry has significantly lower PM emissions, as expected. It is noted that a modern electronically controlled diesel engine operating on low sulfur diesel fuel and fitted with an exhaust PM after treatment system will have PM emission levels equivalent to that of a natural gas fueled engine. Both ferries have equivalent fuel consumption.

The idle point data for the Elizabeth River Ferry II port engine showed significantly higher mass emissions rates for THC, CO, CO₂, NO_x, and fuel consumption rates than the starboard side engine. This may be attributed to over fueling at the idle point as alluded to in the oil analysis for this engine as shown in Figure 25. However, the concentration levels of THC, CO, CO₂, and NO_x were equivalent for both engines, but the measured fuel rate was approximately four times higher for the port engine than the starboard engine, leading to a higher (or lower) calculated mass rate for the port (or starboard) engine. This is borne out in Equation (1) or (2) where the emission mass rate was linearly proportional to the fuel mass rate. Thus, if the idle data was incorrect for one of these engines, then the resulting mass emission rate (or brake-specific) was incorrect. No other data points appeared to have a discrepancy in the fuel measurement; care must be exercised in interpreting the idle data for the diesel engines.

The over fueling reference in the port-side oil analysis, Figure 25, of the Elizabeth River Ferry II's port engine was supported by higher mass rate and brake-specific mass emissions for this engine compared to the starboard engine. Generally, the emissions measured during the steady state and transient tests from the port engine were higher than those measured for the starboard engine.

The CO emission levels for the James C. Echols' port engine were significantly higher than that of the starboard engine as shown in Figure 6 and Figure 12 for the 40% point. This may be attributed to incomplete combustion condition, as supported by the lower exhaust temperature in Figure 4 at this steady-state point. However, the THC emissions in Figure 5 and Figure 11 were not significantly different between the two engines.

The transient test results between the two ferries are presented in Table 4. It is cautioned that the techniques used to derive this data may have an error on the order of 10% and that care must be exercised in interpreting this data. The data showed that the James C. Echols ferry required ~30% more work to perform the test than the Elizabeth River Ferry II ferry. Both ferries covered the same distance of ~1.37 miles. The brake specific THC mass emissions from the natural gas-powered ferry (1.51 g/bhp-hr) were 2.5 times that of the diesel ferry (0.6 g/bhp-hr). The brake specific CO mass emissions for the natural gas-powered ferry (13.7 g/bhp-hr) were 2.6 times that of the diesel ferry (5.2 g/bhp-hr). The brake specific NO_x mass emissions from the natural gas-powered ferry (25.5 g/bhp-hr) were 10 percent higher than that of the diesel ferry (23.0 g/bhp-hr). The brake specific PM results show that the diesel-powered ferry (0.50 g/bhp-hr) was emitting 50 times greater than the natural gas-powered ferry (0.01 g/bhp-hr). The brake specific fuel consumption (bsFC) results show that the natural gas-powered ferry (274 g/bhp-hr) and diesel ferry (270 g/bhp-hr) were equivalent in fuel consumption.

The results from an additional set of tests for the James C. Echols' port engine are shown in Table 5. This test was performed in an ad hoc manner to examine the effects on emissions from adjusting the natural gas carburetor to a leaner setting. The test consisted of operating the engine at the three points as shown in the figure. The engine was operated at each point for approximately five minutes; the data from the last 60 seconds of each set point were averaged for the results shown in the table. The NO_x data for Point 1 was negative, no errors in the NO_x data collection could be found for this point. This observation merits further investigation following a well laid out test plan.

Conclusions

This effort evaluated the in-field mass rate and brake-specific mass emissions of THC, CO, CO₂, NO_x and PM for two ferries operating on the Elizabeth River in Norfolk, VA. In general, the results from this study show that the THC emissions from the natural gas-powered ferry were ~2.5 times higher than the diesel-powered ferry. The CO emissions were generally lower for the diesel-powered ferry, except for the 100% speed point. NO_x was generally lower for the diesel-powered ferry, except at the 40% speed point. The natural gas ferry had significantly lower PM emissions, as expected. It is noted that a modern electrically controlled diesel engine with low sulfur diesel fuel and a PM after treatment device will have equivalent PM emission levels as that of natural gas. Both ferries have equivalent fuel consumption.

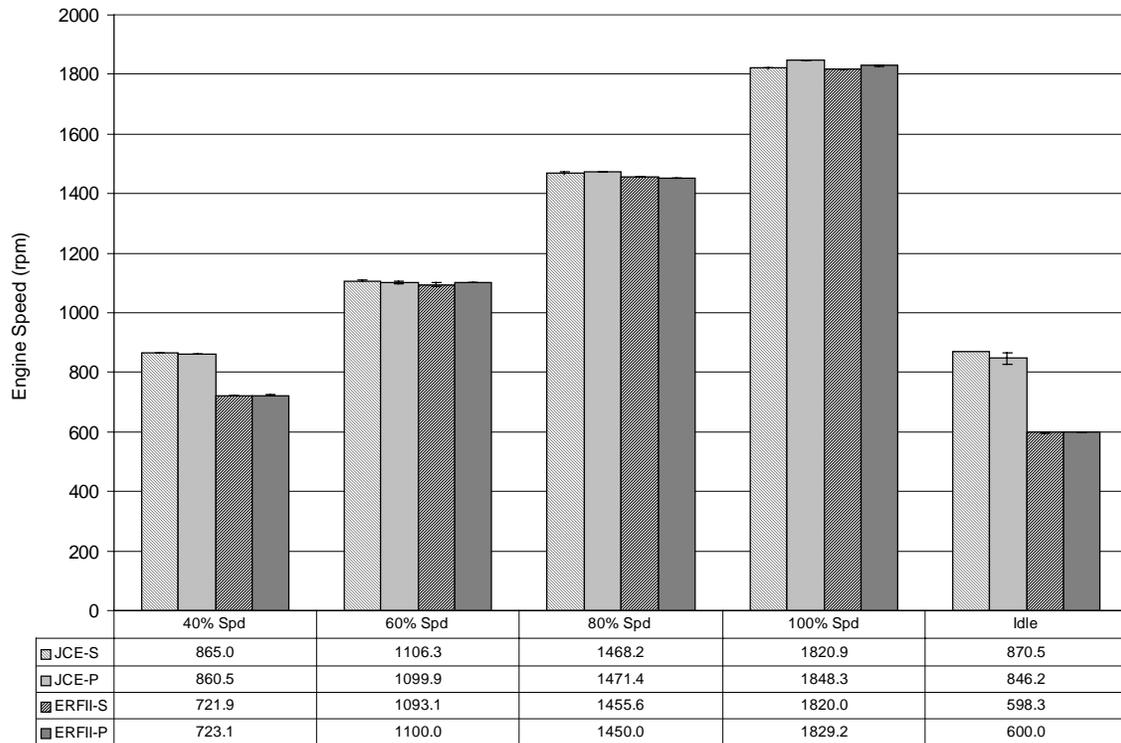


Figure 1 Comparison of the Wheel House engine speed for the four engines.

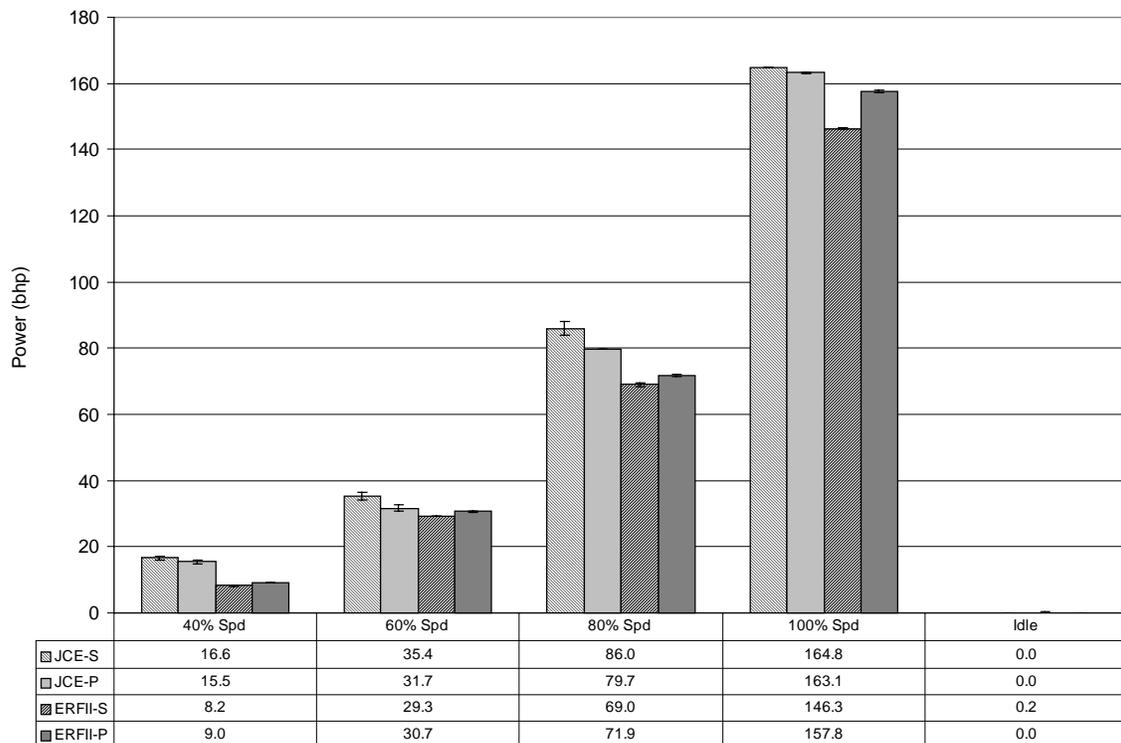


Figure 2 Comparison of the prop shaft power for the four engines.

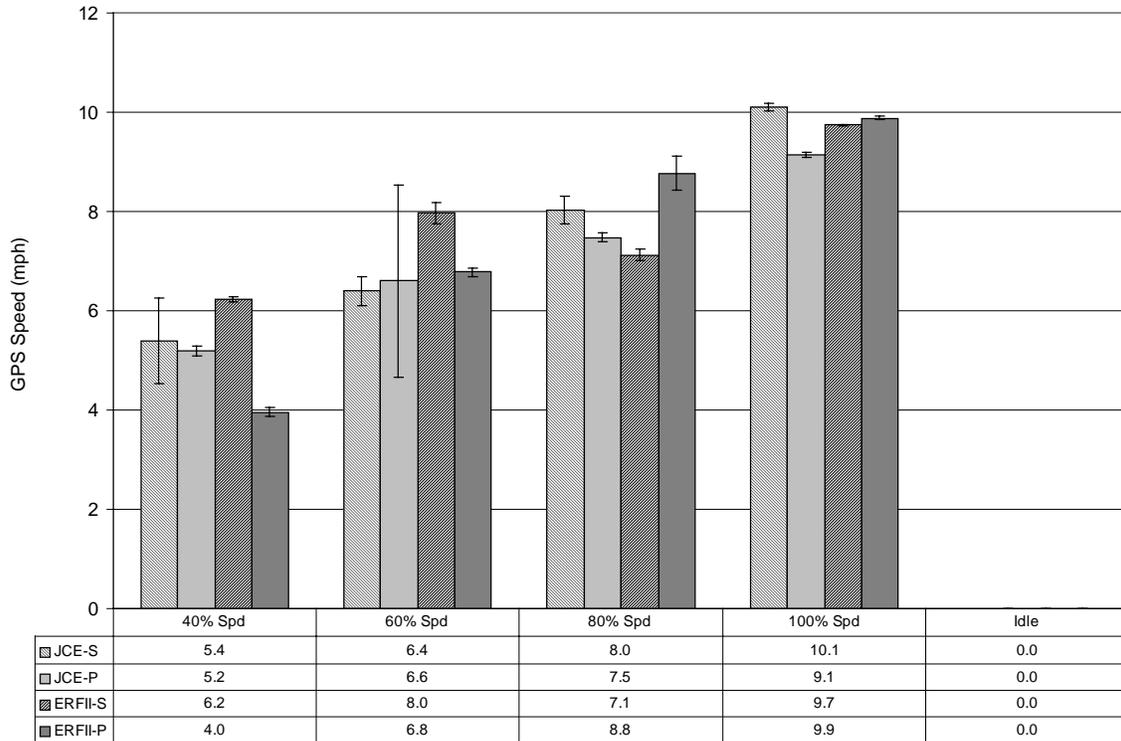


Figure 3 Comparison of the ground speed for the four ferries.

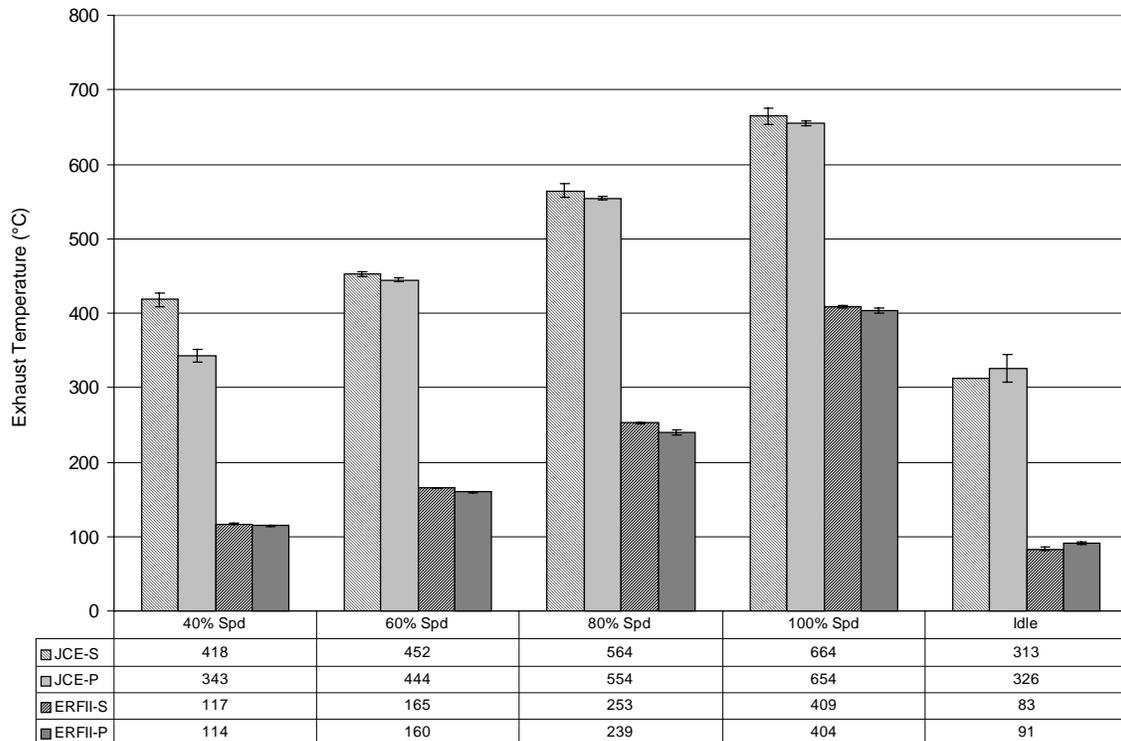


Figure 4 Comparison of the exhaust temperature for the four engines.

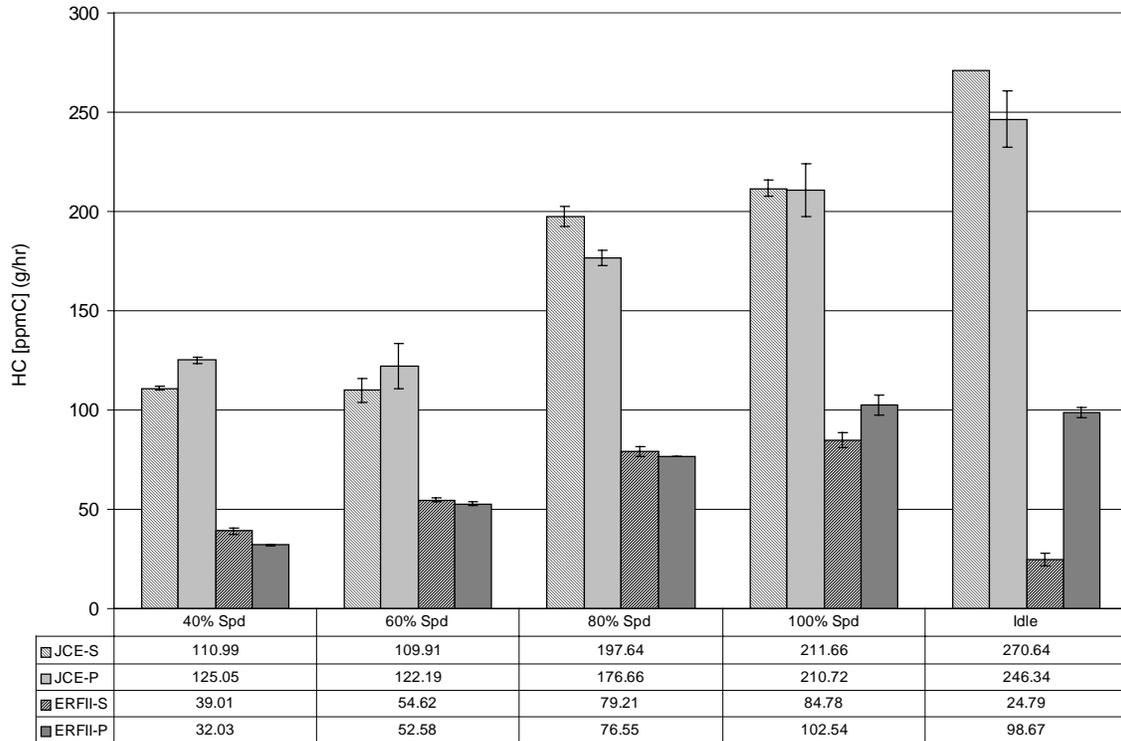


Figure 5 Comparison of the THC emission mass rate for the four engines.

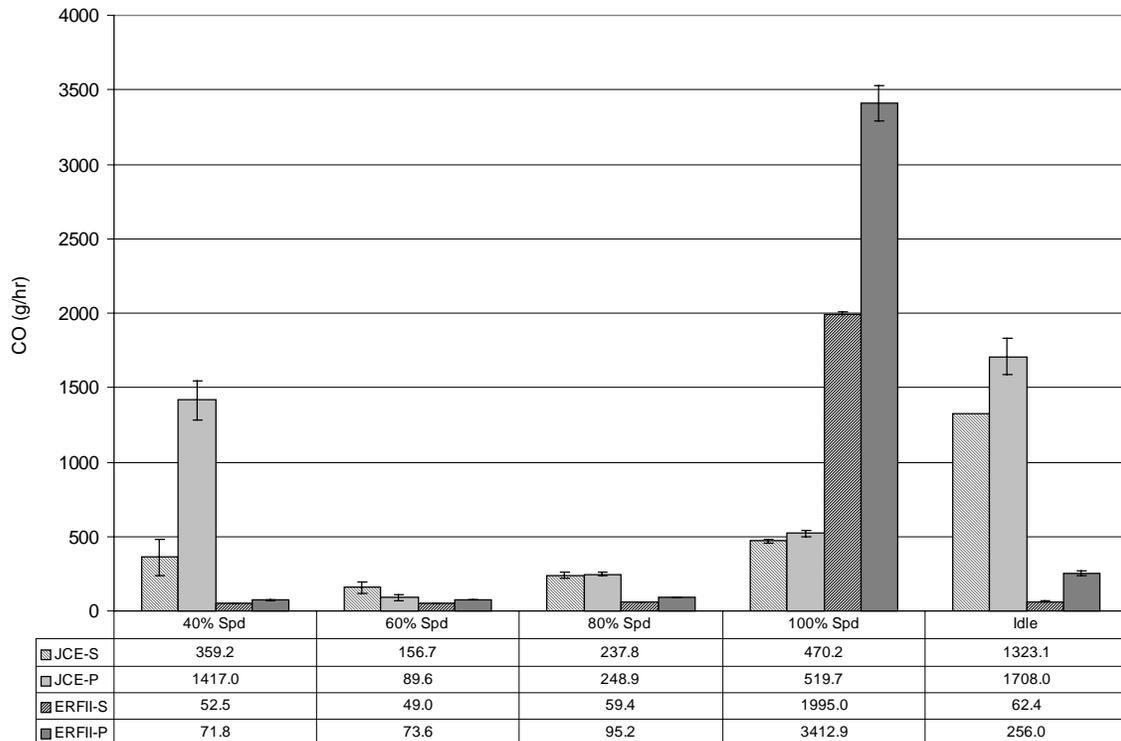


Figure 6 Comparison of the CO emission mass rate for the four engines.

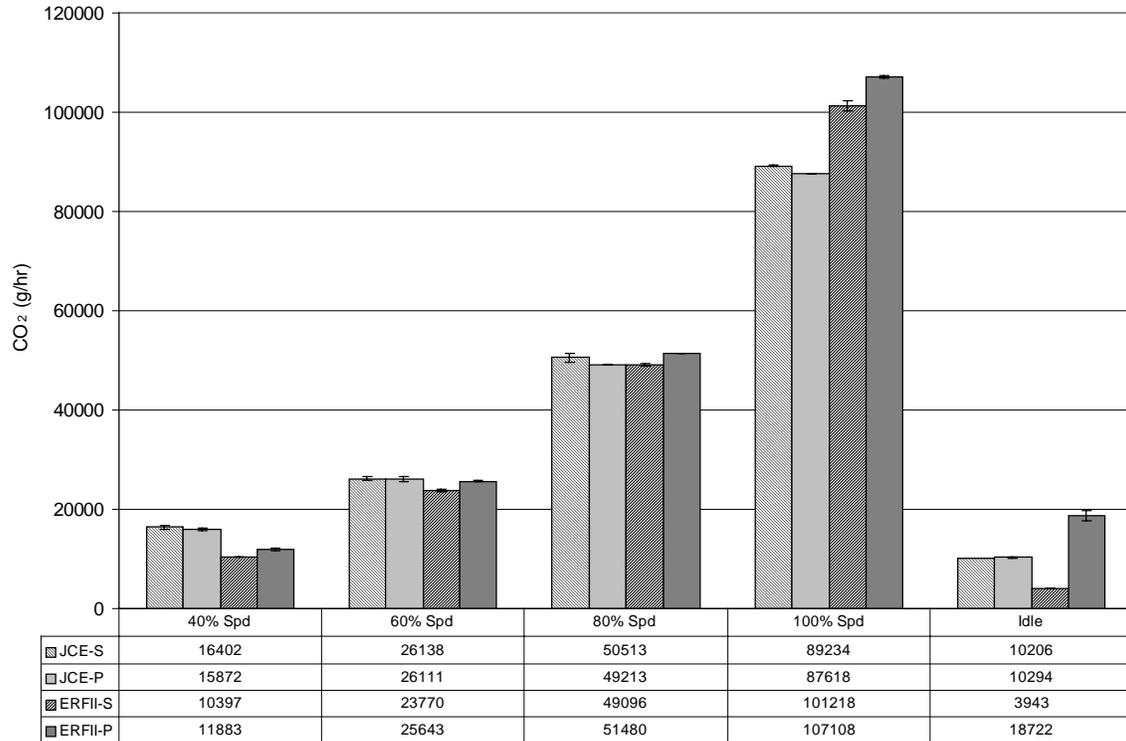


Figure 7 Comparison of the CO₂ emission mass rate for the four engines.

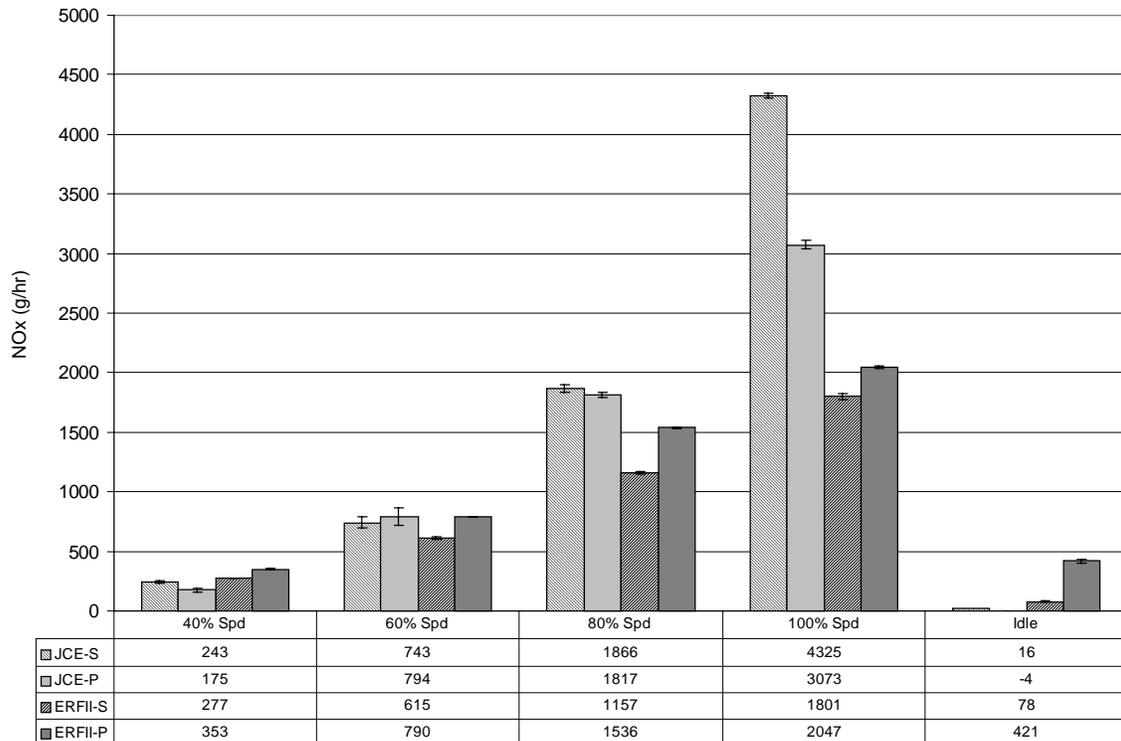


Figure 8 Comparison of the NO_x emission mass rate for the four engines.

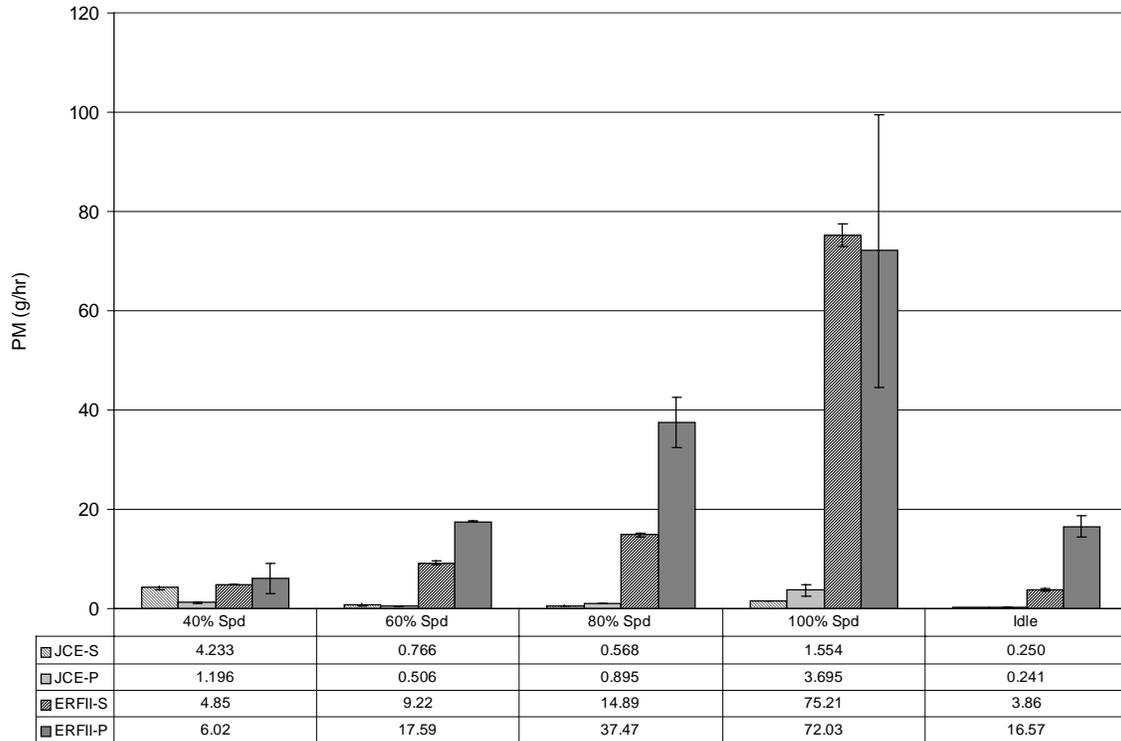


Figure 9 Comparison of the PM emission mass rate for the four engines.

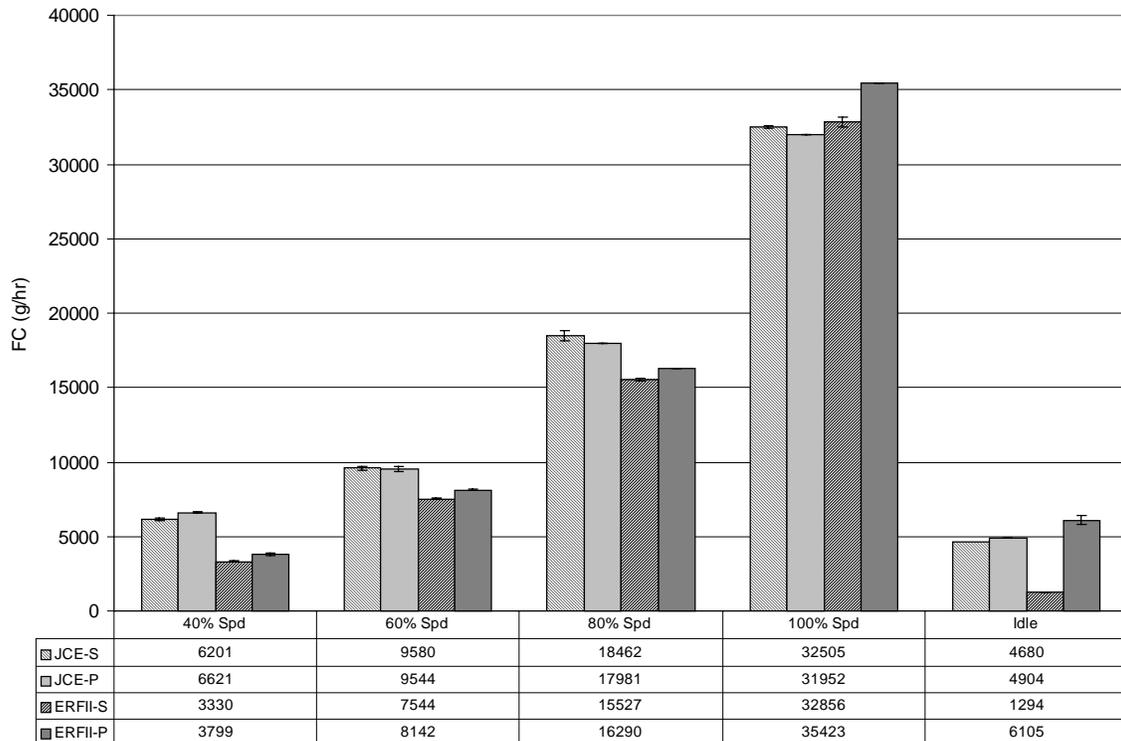


Figure 10 Comparison of the fuel consumption mass rate for the four engines.

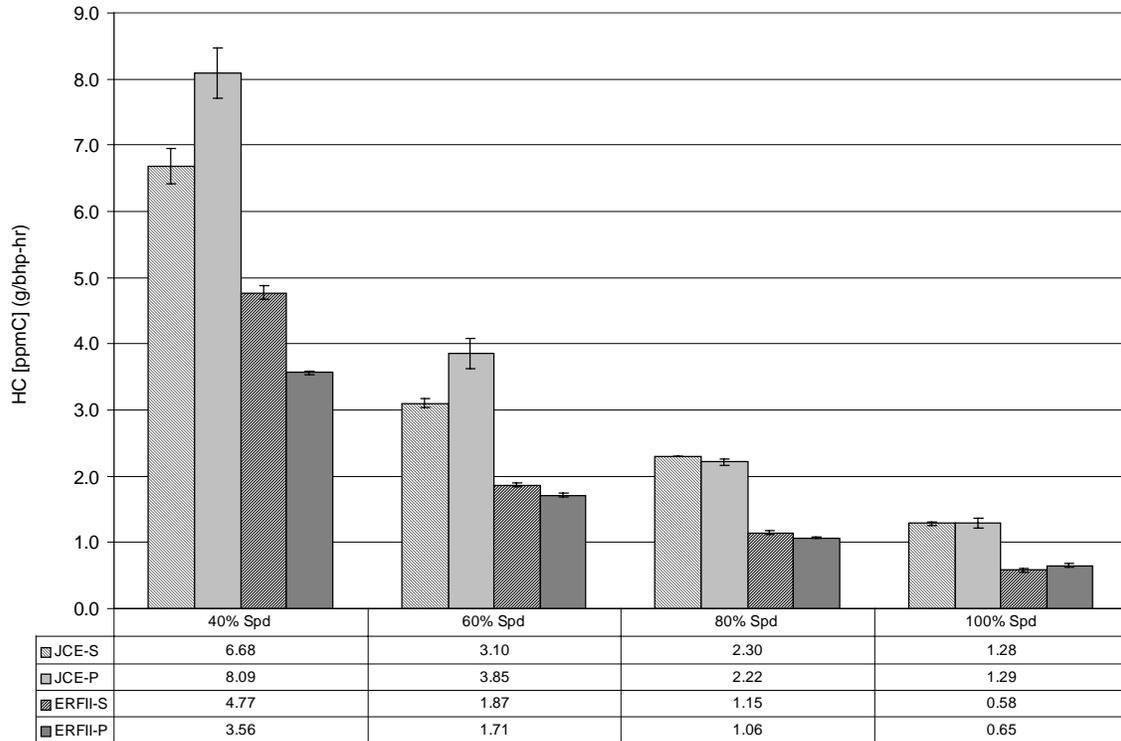


Figure 11 Comparison of the THC brake-specific mass emission for the four engines.

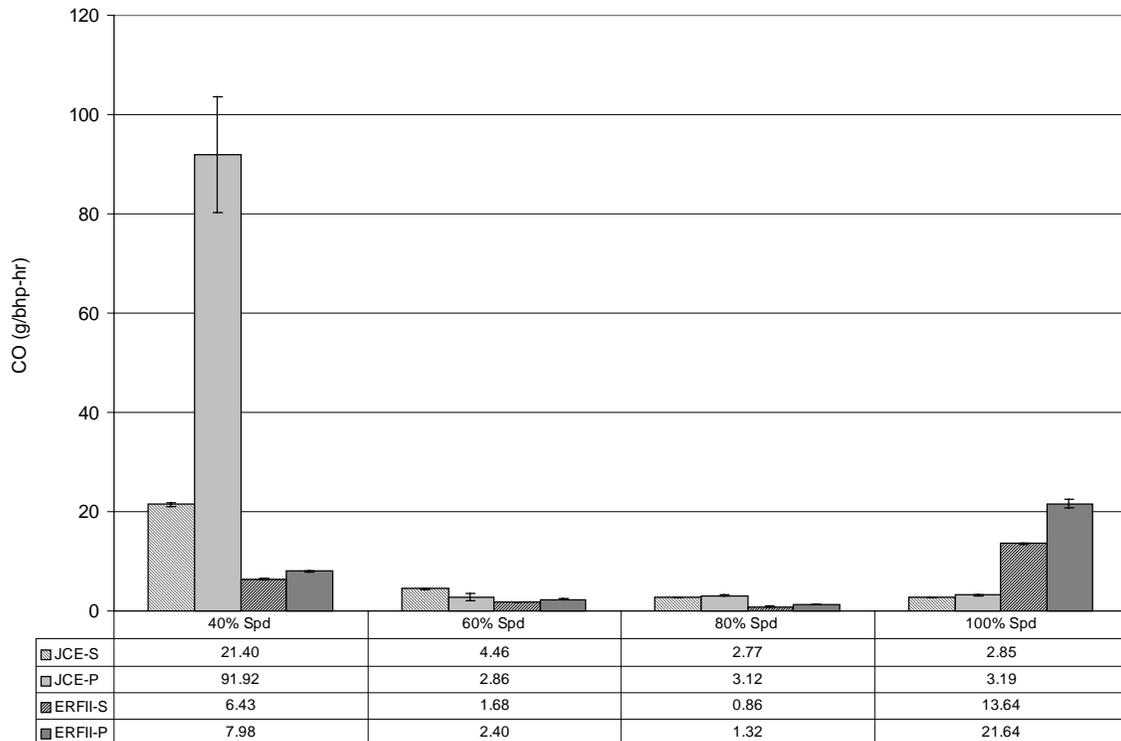


Figure 12 Comparison of the CO brake-specific mass emission for the four engines.

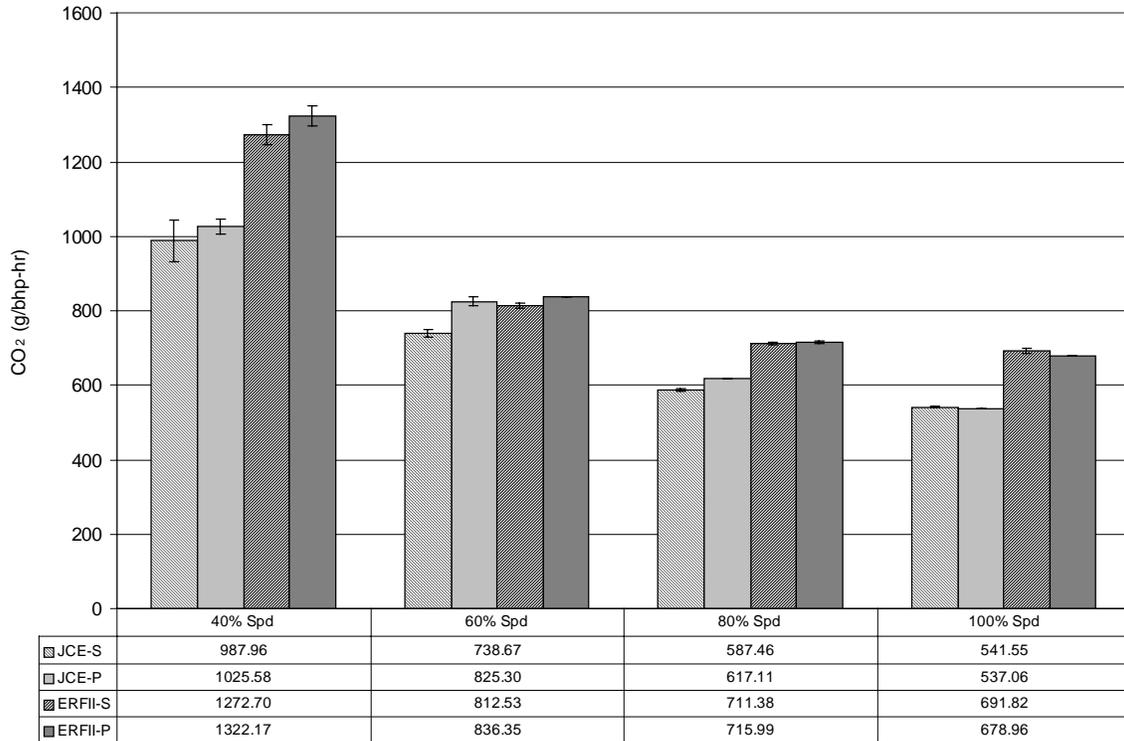


Figure 13 Comparison of the CO₂ brake-specific mass emission for the four engines.

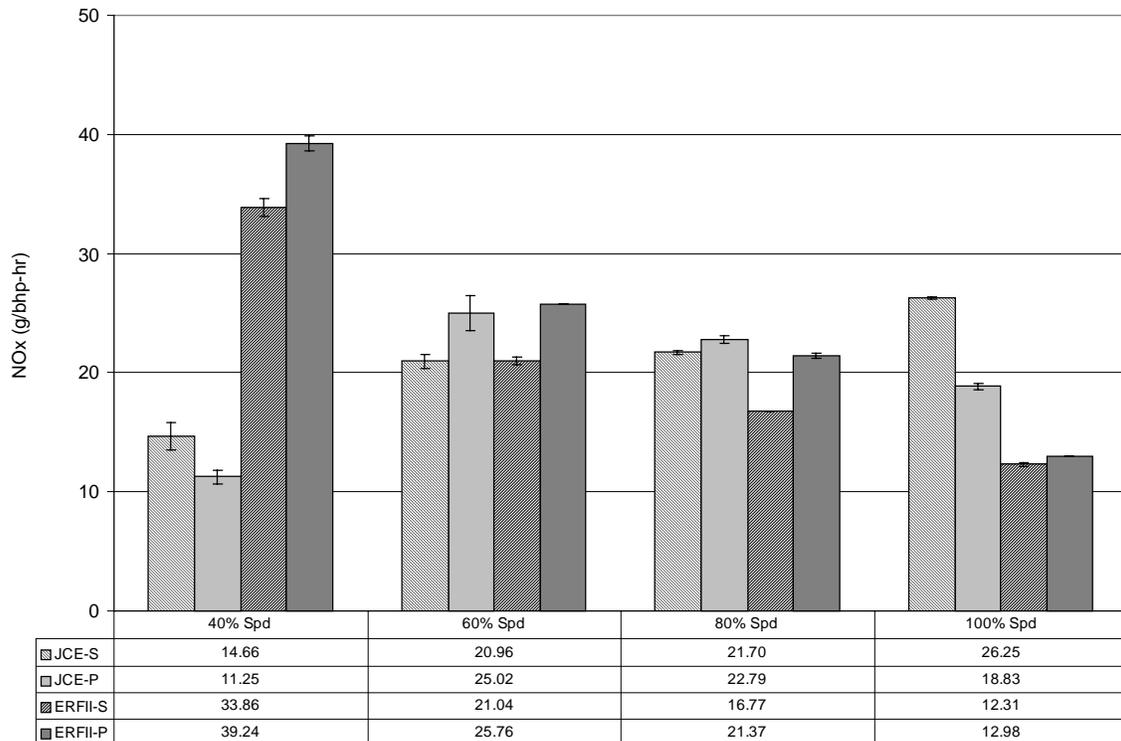


Figure 14 Comparison of the NO_x brake-specific mass emission for the four engines.

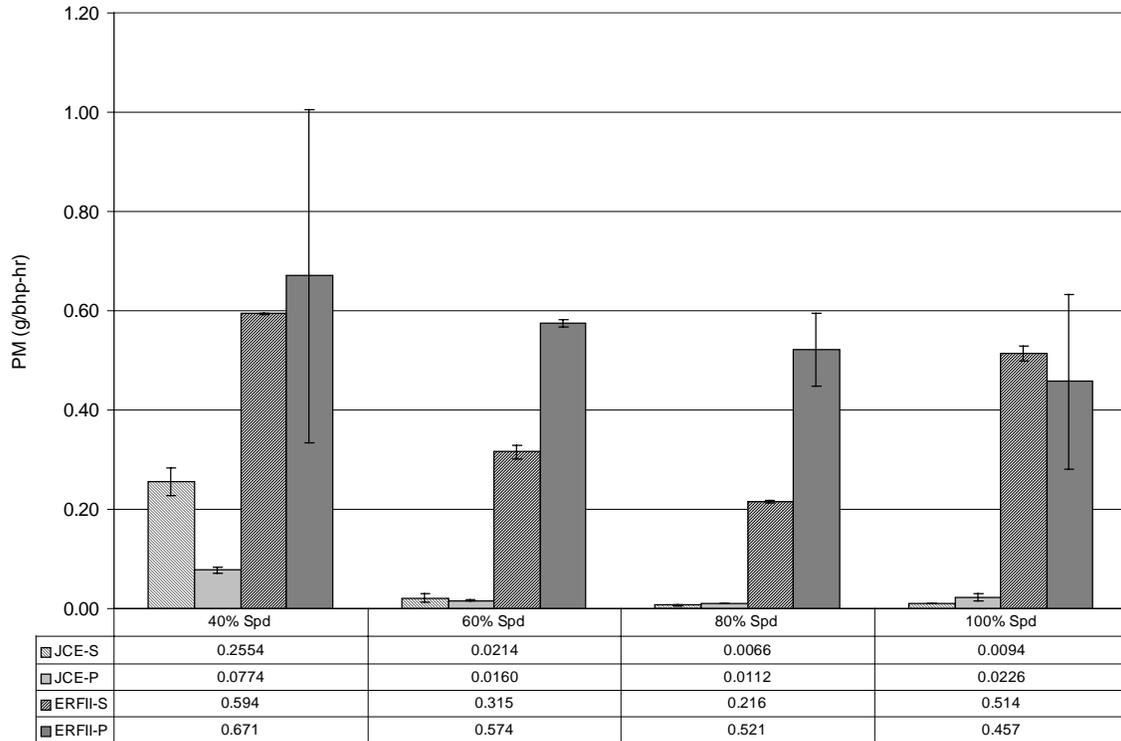


Figure 15 Comparison of the PM brake-specific mass emission for the four engines.

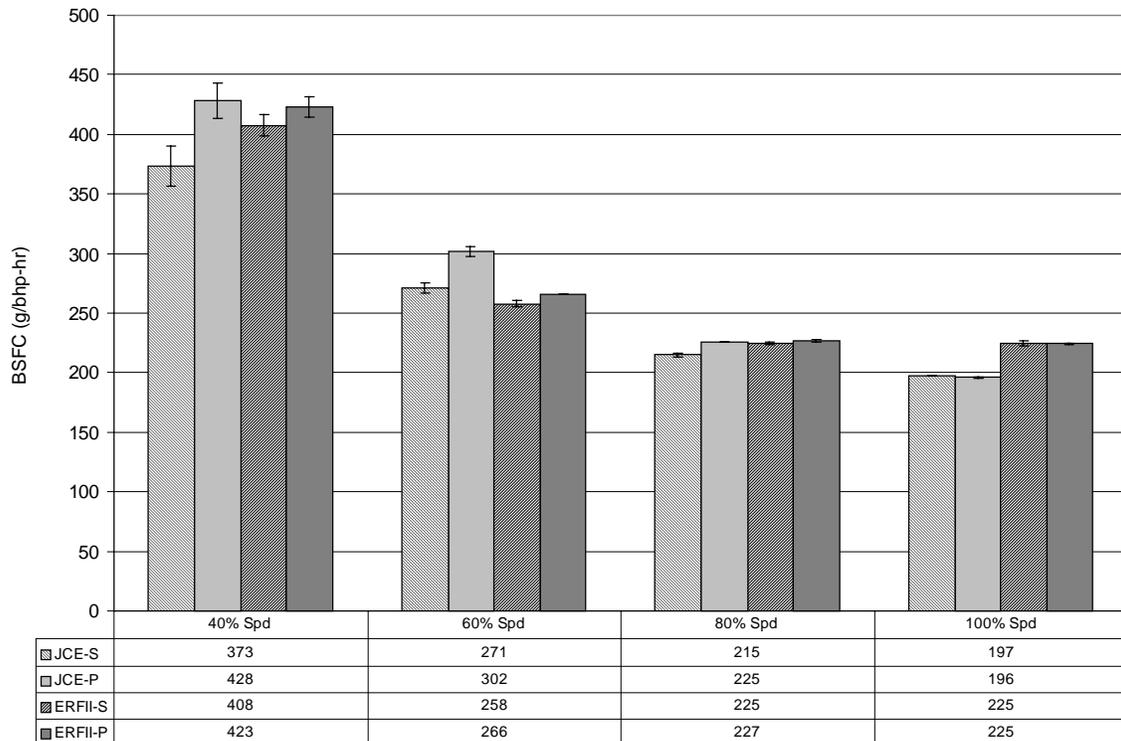


Figure 16 Comparison of the brake-specific fuel consumption for the four engines.

Table 4 Transient runs brake-specific mass emission results.

Seq.	Run	Desc.	Work bhp-hr	Distance miles	THC g/bhp-hr	CO g/bhp-hr	CO ₂ g/bhp-hr	NOx1 g/bhp-hr	NOx2 g/bhp-hr	PM g/bhp-hr	FC g/bhp-hr
Natural Gas											
18	14	JCE-P	20.62	1.352	1.5104	12.507	746.2	26.24	24.25	0.01184	276.4
18	16	JCE-P	22.64	1.366	1.5090	14.829	727.1	24.68	23.04	0.00807	270.8
Diesel											
20	12	ERFII-P	15.53	1.378	0.5074	4.283	809.0	21.82	20.61	0.4334	256.7
20	13	ERFII-P	15.82	1.380	0.6944	6.181	888.9	24.10	22.40	0.5647	282.9

Table 5 Emissions data from the James C. Echols ferry port engine with adjusted carburetor.

Description	Prop Shaft Torque	Prop Shaft Speed	Exhaust Temp.	Ground Speed	Engine Speed	THC	CO	CO ₂	NOx1	NOx2	FC	Power	bsTHC	bsCO	bsCO ₂	bsNOx1	bsNOx2	bsFC
	ft-lb	rpm	C	mph	rpm	g/h	g/h	g/h	g/h	g/h	g/h	hp	g/bhp-h	g/bhp-h	g/bhp-h	g/bhp-h	g/bhp-h	g/bhp-h
Point 1	555	724	541	9.12	1463	858	406	53720	-	-	20368	76.5	11.2	5.31	702	-	-	266
Point 2	309	559	499	7.65	1133	116	157	26626	614	551	9761	32.9	3.52	4.77	809	18.6	16.7	297
Point 3	192	446	477	5.99	898	105	106	18006	386	311	6627	16.3	6.39	6.47	1102	23.6	19.0	406

References

- 1 *Title 40 Code of Federal Regulations, Part 86*, U.S. Government Printing Office, Washington, DC, 2000.
- 2 *Title 40 Code of Federal Regulations, Part 89*, U.S. Government Printing Office, Washington, DC, 2000.
- 3 *Title 40 Code of Federal Regulations, Part 92*, U.S. Government Printing Office, Washington, DC, 2000.
- 4 *Title 40 Code of Federal Regulations, Part 94*, U.S. Government Printing Office, Washington, DC, 2000.
- 5 "Reciprocating Internal Combustion Engines – Exhaust Emissions Measurement", International Organization for Standardization, ISO/DIS 8178, Geneva, Switzerland, 1993.
- 6 "Measurement of Carbon Dioxide, Carbon Monoxide, and Oxides of Nitrogen in Diesel Exhaust," 6SAE Standard, SAE J177, Warrendale, PA 1995.
- 7 *Internal Combustion Engines Applied Thermosciences*, 2nd Ed., C. R. Ferguson and A. T. Kirkpatrick, John Wiley and Sons, Inc., New York, NY, 2001.
- 8 *Internal Combustion Engine Fundamentals*, J. B. Heywood, McGraw-Hill, Inc., New York, NY, 1988.

Appendix - Fuel and Oil Sample Data Sheets

James C. Echols Natural Gas and Oil Samples Analyses



Gas Analytical Services, Inc.

221 Industrial Dr.; Stonewood, WV 26301
P.O. Box 1028; Bridgeport, WV 26330
304-623-0020
(fax) 304-624-8065

Client: West Virginia University - Mechanical/Aerospace Engineering

Date: 7 November 2001

The attached analyses have been calculated utilizing a high precision analytical method of chromatography on a SRI gas chromatograph. All results reflect intercomparison with NIST traceable standards (16-A-12-94/16-A-11-96) and have been quantified utilizing multi-level calibrations to provide linear detector response for high/low level compound concentrations. Supercompressibility of the sample is calculated using AGA 8 extended routines. ASTM standards D-1945/1947 (analytical methods of compressed natural gas) have been applied. GPA Standard 2261 [Analysis for Natural Gas by Gas Chromatography] has been satisfied

All gas samples were conditioned to exceed hydrocarbon dewpoint prior to analysis. Water vapor and/or sulfur declarations (if present) have been determined at location during the sampling, and reflect system operating conditions (pressure, turbulence and temperature) as per ASTM/AGA requirements. Repeatability and precision of the instrument and its associated equipment, as well as minimum detection limits and sampling rates, meet or exceed AGA precision requirements for the individual compound concentrations.

C.E. Honaker

C. E. Honaker, Metrologist
Gas Analytical Services, Inc.

Figure 17 Cover letter for the James C. Echols natural gas analysis.



Gas Analytical Services, Inc.

P.O. Box 1028
 Bridgeport, WV 26330-0461
 Phone: (304) 623-0020
 FAX: (304) 624-8065

Analysis #:	17475
Run Date:	11/07/2001
Run Time:	09:05
Cylinder #:	

**FRACTIONAL
ANALYSIS**

Customer: WV University -MAE Department	Sample Date: 11/07/2001
Field: Morgantown, WV	Sample Time: 00:00
Station: Echols Ferry	Cust. Cylinder:
Meter: WVU P.O.# 2V066R-04	Effective Date: 11/07/2001
	Sample Pressure: 0.00 PSIG

Component	MOL%	GPM
Methane	90.542	
Ethane	7.509	2.00
Propane	1.466	0.40
I-Butane	0.173	0.06
N-Butane	0.123	0.04
I-Pentane	0.077	0.03
N-Pentane	0.029	0.01
Nitrogen	0.026	
CO2	0.000	
Oxygen	0.004	
Hexanes+	0.052	0.02
Total:	100.000	2.56

Analytical Results at Base Conditions	
BTU/SCF (Dry):	1106.071
BTU/SCF (Saturated):	1087.746
PSIA:	14.730
Temperature (°F):	60.000
Z Factor (Dry):	0.99750
Z Factor (Saturated):	0.99746

Analytical Results at Contract Conditions	
BTU/SCF (Dry):	1106.071
BTU/SCF (Saturated):	1087.746
PSIA:	14.730
Temperature (°F):	60.000
Z Factor (Dry):	0.99750
Z Factor (Saturated):	0.99746

Calculated Specific Gravities	
Ideal Gravity:	0.6124
Real Gravity:	0.6137

Gross Heating Values are Based
 on GPA 2145-91.
 Compressibility is Calculated using AGA-8.

Notes and Comments

Figure 18 James C. Echols natural gas analysis report.

O I L S C I E N C E R E P O R T

CUSTOMER ACCOUNT NO: 526
 West Virginia University
 M and A Engineering
 PO Box 6101
 Morgantown, WV 26506

LUBE BRAND:
 LUBE TYPE: motor
 TOTAL MILES/HOURS: 0

UNIT ID: #002 DATE: 11/16/01
 SYSTEM: Engine, CNG
 COMP/HPGR: Engine 2, CNG, Ferry
 PO: CR card FUEL: Ind gas
 WARRANTY:

ATTN: Byron L Rapp, ext 2384 [NOTE: * = OILSCIENCE PROPRIETARY VALUES: (NORMAL: 1 OR 2. ABNORMAL: 3. SEVERE: 4.)]
 PHONE: 304-2933111

Test No: 000526-00001
 Date Sampled: 11/01/01
 Date Received: 11/08/01

Iron	ppm	21
Chromium	ppm	1
Zinc	ppm	915
Aluminum	ppm	1
Manganese	ppm	1
Tin	ppm	30
Phosphorus	ppm	738
Calcium	ppm	880
Nickel	ppm	<1
Copper	ppm	106
Lead	ppm	4
Boron	ppm	295
Silicon	ppm	8
Sodium	ppm	31
Barium	ppm	1
Magnesium	ppm	381
Titanium	ppm	<1
Viscosity (SAE)		40
Viscosity (SUS)		719
Viscosity	*	2
Fuel Dilution	*	2
Coolant Leak	*	2
Sludge K		0.90
Soot	*	2
Particulates	*	2
Migration	*	2
Oxidation	*	2
New Oil	*	2
Lube Drain		
Total Mi/Hrs		
Sample Mi/Hrs		

TEST NUMBER: 000526-00001

- EVALUATIONS: (baseline test results, first sample). Tin and copper levels are above normal. Other wear metal levels are all in normal ranges, no other undue potential wear conditions evident. (note: zinc, phosphorus, calcium, boron, magnesium and some sodium are additives. Copper could be an additive to the oil but not frequently used). Tin signifies wear of bearing overlay, may have other source also. Viscosity, and other physical conditions of oil normal, good. Water absent. Sulfur result is attached.
- ACTION: Abnormal tin could signify wear of bearing overlay. Some of the copper may be related to bearing wear trend /or other source. Oil condition satisfactory. It can continue in use. Resample after 200 hrs and monitor tin.

OILSCIENCE (310) 676-5951. 3940 Marine Ave, Suite L, El Camino Village, Lawndale, CA 90260

Figure 19 James C. Echols starboard engine oil analysis result.

O I L S C I E N C E R E P O R T

CUSTOMER ACCOUNT NO: 526
 West Virginia University
 M and A Engineering
 PO Box 6101
 Morgantown, WV 26506

LUBE BRAND:
 LUBE TYPE: motor
 TOTAL MILES/HOURS: 0

UNIT ID: 4003 DATE: 11/16/0
 SYSTEM: Engine, CNG
 COMP/MFGOR: Engine 3, CNG, Ferry
 PO: or card FUEL/NAT Gas
 WARRANTY:

ATTN: Byron L Rapp. ext 2384 [NOTE: * = OILSCIENCE PROPRIETARY VALUES: (NORMAL: 1 OR 2. ABNORMAL: 3. SEVERE: 4.)]
 PHONE: 304-2933111

Test No: 000526-00002
 Date Sampled: 11/01/01
 Date Received: 11/08/01

Iron	ppm	17
Chromium	ppm	<1
Zinc	ppm	890
Aluminum	ppm	1
Manganese	ppm	1
Tin	ppm	4
Phosphorus	ppm	715
Calcium	ppm	937
Nickel	ppm	<1
Copper	ppm	110
Lead	ppm	5
Boron	ppm	280
Silicon	ppm	4
Sodium	ppm	19
Barium	ppm	1
Magnesium	ppm	250
Titanium	ppm	<1
Viscosity (SAE)		40
Viscosity (SUS)		710
Viscosity *		2
Fuel Dilution *		2
Coolant Leak *		2
Sludge K		0.59
Soot *		2
Particulates *		2
Migration *		2
Oxidation *		2
New Oil *		2
Lube Drain		
Total Mi/Hrs		
Sample ML/Hrs		

TEST NUMBER: 000526-00002

- EVALUATIONS: (baseline test results, first sample). Copper level is above normal. Other wear metal levels are all in normal ranges, no other preliminary wear conditions evident. (note: zinc, phosphorus, calcium, boron, magnesium and some sodium are normal additives. Copper could be an additive in the oil but not often used). Viscosity, and all other physical conditions of oil are good. Water absent. Sulfur result is attached.
- ACTION: No immediate maintenance indicated. Resample after 500 hrs and monitor.

OILSCIENCE (310) 676-5951. 3940 Marine Ave, Suite L, El Camino Village, Lawndale, CA 90260

Figure 20 James C. Echols port engine oil analysis result.



OIL SCIENCE LABORATORY

3940 Marine Avenue, Suite L, El Camino Village • Lawndale, California 90260-2333
Phone: 1-800-313-5555 • (310) 676-5951 • Fax: (310) 676-5952

November 16, 2001

West Virginia University, MAE Dept.
Attn: Byron L Rapp
PO Box 6101
Morgantown, WV 26506

Samples: Nat gas engine oils, CNG, as indexed.

LABORATORY RESULTS

<u>Sample #</u>	<u>Sulfur, wt%</u>
#002	0.7654
#003	0.6338

Paul N Rollins

Quality assurance in inspection and test.

Figure 21 James C. Echols starboard and port engines sulfur content.

Elizabeth River Ferry II Diesel and Oil Samples Analyses



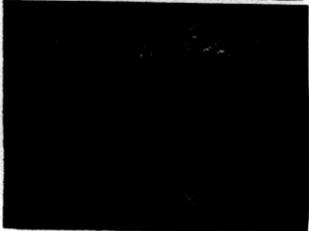
21730 S. Wilmington Ave., Suite 201
 Carson, CA 90810
 310-513-2031 Telephone
 310-513-2035 Facsimile

CORE LABORATORIES

BYRON L RAPP
 WEST VIRGINIA UNIVERSITY

 MAE DEPT \ PO BOX 6106
 MORGANTOWN, WV 26505

Date Reported:
 Date Received:



Analytical Report

Test	Result	Units	Method	Date	Analyst
Sample Number: 111359-001		Sample ID: Sample #0305			
Sample Date:		Description:			
API Gravity by Hydrometer	31.5	60/60 degF	ASTM D-1298	11/20/01	OE
Aromatics by Supercritical Fluid Chromatography					
Total Aromatics	37.8	wt%	ASTM D-5186	11/20/01	DD
Monoaromatics	22.6	wt%		11/20/01	DD
Polynuclear Aromatic Hydrocarbons	15.2	wt%		11/20/01	DD
Cetane Index, Calculated	43.2		ASTM D-976	12/4/01	GLC
Cetane Number	41.6		ASTM D-613	12/3/01	FB
Distillation					
IBP	368.2	deg.F	ASTM D-86	11/20/01	OE
5% Rec	418.2	deg.F			OE
10% Rec	440.3	deg.F			OE
20% Rec	465.8	deg.F			OE
30% Rec	487.8	deg.F			OE
40% Rec	506.9	deg.F			OE
50% Rec	525.7	deg.F			OE
60% Rec	544.8	deg.F			OE
70% Rec	565.3	deg.F			OE
80% Rec	588.5	deg.F			OE
90% Rec	622.9	deg.F			OE
95% Rec	655.5	deg.F			OE
FBP	674.7	deg.F			OE
Recovery	97.7	%			OE
Residue	1.5	%			OF
Loss	0.8	%			OE
Hydrocarbon Type - FIA					
Aromatics	35.9	lv%	ASTM D-1319	11/27/01	FB
Olefins	1.0	lv%			FB
Saturates	63.1	lv%			FB
Kinematic Viscosity @ 40 deg. C	2.797	cSt	ASTM D-445	11/20/01	OE

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Figure 22 Elizabeth River Ferry II diesel fuel analysis report.



21730 S. Wilmington Ave., Suite 201
 Carson, CA 90810
 310-513-2031 Telephone
 310-513-2035 Facsimile

CORE LABORATORIES

BYRON L RAPP
 WEST VIRGINIA UNIVERSITY

Date Reported: 12/4/01
 Date Received: 11/14/01

MAE DEPT \ PO BOX 6106
 MORGANTOWN, WV 26505

Analytical Report

Test	Result	Units	Method	Date	Analyst
Sample Number: 111359-001			Sample ID: Sample #0305		
Sample Date:			Description:		
Sulfur, Total by X-Ray Fluoresc.	0.191	wt%	ASTM D-4294	12/3/01	PW

Approved By:


 ERIC L. COOK
 ASSISTANT MANAGER

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Figure 23 Elizabeth River Ferry II diesel fuel sulfur content result.

O I L S C I E N C E R E P O R T

CUSTOMER ACCOUNT NO: 526
West Virginia University
M and A Engineering
PO Box 6101
Morgantown, WV 26506

LUBE BRAND:
LUBE TYPE: diesel motor
TOTAL MILES/HOURS: 0

UNIT ID: 0004 DATE: 11/16/0
SYSTEM: Engine, diesel
COMP/MFG: Engine 4, Diesel, Ferry
PO: cr card FUEL: diesel
WARRANTY:

ATTN: Byron L Rapp. ext 2384 [NOTE: * = OILSCIENCE PROPRIETARY VALUES: (NORMAL: 1 OR 2. ABNORMAL: 3. SEVERE: 4.)]
PHONE: 304-2933111

Test No:	000526-00003	
Date Sampled:	11/01/01	
Date Received:	11/08/01	
Iron ppm	24	
Chromium ppm	2	
Zinc ppm	1294	
Aluminum ppm	<1	
Manganese ppm	1	
Tin ppm	77	
Phosphorus ppm	1134	
Calcium ppm	563	
Nickel ppm	<1	
Copper ppm	16	
Lead ppm	5	
Boron ppm	660	
Silicon ppm	13	
Sodium ppm	35	
Barium ppm	1	
Magnesium ppm	810	
Titanium ppm	<1	
Viscosity (SAB)	40	
Viscosity (SUS)	724	
Viscosity *	2	
Fuel Dilution *	2	
Coolant Leak *	2	
Sludge K	0.07	
Soot *	1	
Particulates *	2	
Migration *	2	
Oxidation *	2	
New Oil *	1	
Lube Drain		
Total Mi/Hrs		
Sample Mi/Hrs		

TEST NUMBER: 000526-00003

EVALUATIONS: (baseline test results, first sample). High tin level. Marginal wear of other bearing alloy elements, copper and lead but those aren't excessive. Marginal ring, chromium wear. (normal additive group present, but calcium is low and magnesium relatively high, in diesel engine oil). Tin wear level especially looks problematic. Water absent. Sulfur result is attached. Viscosity normal, and system conditions otherwise are normal.

ACTION: Tin level is very high. If no recent repair (new bearing(s)) then the source of tin wear should be checked ASAP.

OILSCIENCE (310) 676-3951. 3940 Marine Ave, Suite L, El Camino Village, Lawndale, CA 90260

Figure 24 Elizabeth River Ferry II starboard engine oil analysis result.

O I L S C I E N C E R E P O R T

CUSTOMER ACCOUNT NO: 526
 West Virginia University
 M and A Engineering
 PO Box 6101
 Morgantown, WV 26506

LUBE BRAND:
 LUBE TYPE: diesel motor
 TOTAL MILES/HOURS: 0

UNIT ID: #005 DATE: 11/16/01
 SYSTEM: Engine, diesel
 COMP/MFG: Engine 5, Diesel, Ferry
 PO: or card FUEL: diesel
 WARRANTY:

ATTN: Byron L Rapp, ext 2384 [NOTE: * = OILSCIENCE PROPRIETARY VALUES: (NORMAL: 1 OR 2, ABNORMAL: 3, SEVERE: 4.)]
 PHONE: 304-2933111

Test No:	000526-00004
Date Sampled:	11/01/01
Date Received:	11/08/01
<hr/>	
Iron ppm	50
Chromium ppm	2
Zinc ppm	1291
Aluminum ppm	<1
Manganese ppm	<1
Tin ppm	5
Phosphorus ppm	1033
Calcium ppm	1042
Nickel ppm	<1
Copper ppm	14
Lead ppm	6
Boron ppm	192
Silicon ppm	30
Sodium ppm	30
Barium ppm	1
Magnesium ppm	564
Titanium ppm	<1
Viscosity (SAE)	30
Viscosity (SUS)	662
Viscosity *	2
Fuel Dilution *	2
Coolant Leak *	3
Sludge K	1.83
Soot *	2
Particulates *	2
Migration *	2
Oxidation *	2
New Oil *	2
Lube Drain	
Total Mi/Hrs	
Sample Mi/Hrs	

TEST NUMBER: 000526-00004

- EVALUATIONS: (baseline test results, first sample). Minor iron/steel wear; minor top and wear; marginal copper. Other wear metal levels are all at normal, acceptable levels. (normal additive group present, but calcium is low and magnesium relatively high, for diesel engine oil). Water present, 0.1%. Possible coolant leak /or condensation. Minor soot, overfueling, could be related to potential coolant leak. Sulfur result is attached.
- ACTION: A coolant leak, and/or related overfueling, condensation condition is evident. Running of service tests for coolant leak and a check of injectors is advised. Oil should be drained following servicing. Resample after 500 hrs and monitor.

OILSCIENCE (310) 676-5951, 3940 Marine Ave, Suite L, El Camino Village, Lawndale, CA 90260

Figure 25 Elizabeth River Ferry II port engine oil analysis result.



OIL SCIENCE LABORATORY

3940 Marine Avenue, Suite L, El Camino Village • Lawndale, California 90260-2333
Phone: 1-800-313-5555 • (310) 676-5951 • Fax: (310) 676-5952

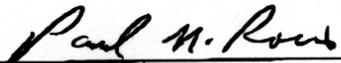
November 16, 2001

West Virginia University, MAE Dept.
Attn: Byron L Rapp
PO Box 6101
Morgantown, WV 26506

Samples: Diesel engine oils, as indexed.

LABORATORY RESULTS

<u>Sample #</u>	<u>Sulfur, wt%</u>
#004	0.5100
#005	0.5176


Paul N Rollins

Quality assurance in inspection and test.

Figure 26 Elizabeth River Ferry II starboard and port engines sulfur content.