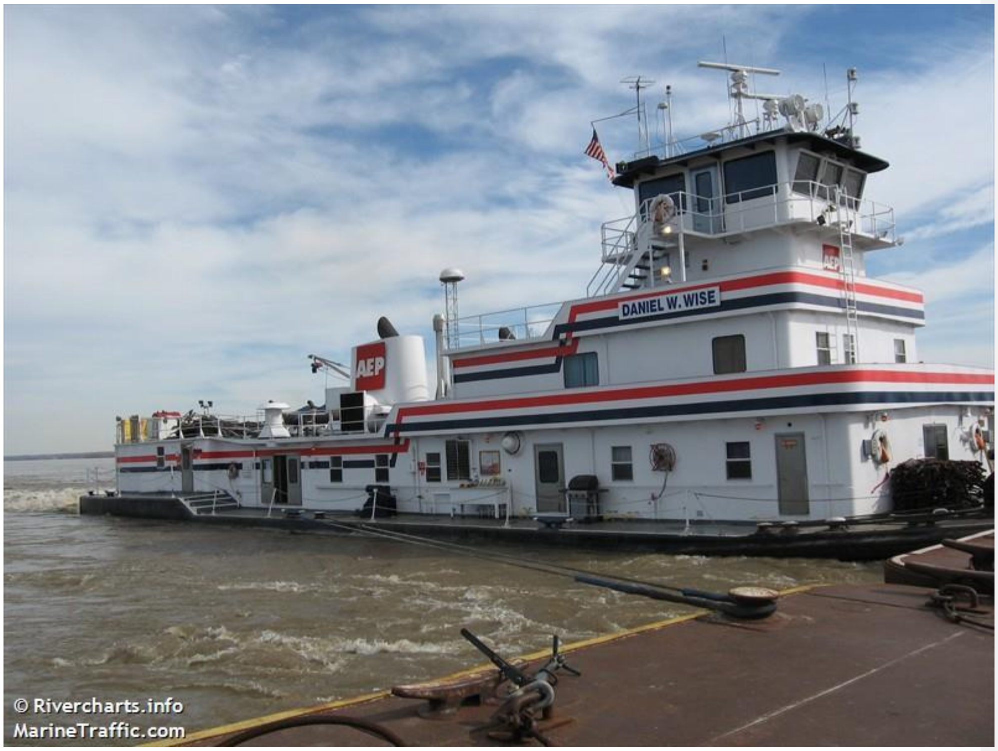
Emission Benefits from Repowering the MV Daniel W. Wise



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Executive Summary

Background: Emissions from tow/push boats are a significant fraction of the criteria pollutants and greenhouse gases from inland river activities. These towboats are typically powered by large engine EMD Series 645 engines dating to the 1970s and meeting Tier 0 standards. One of the most economically feasible methods for significantly reducing emissions from these towboats is to remove and replace the old marine engine with a new engine meeting EPA Tier 3 standards, also known as repowering. This project replaced the EMD Series 645 engines from 1978 in the MV Daniel W Wise with EMD Series 710 Tier 3 engines.

Methods: This research project was conducted to measure the emissions benefits achieved by repowering the MV Daniel Wise. In situ emission testing was conducted for three phases following accepted federal and ISO protocols. The first phase measured the baseline emission rates and factors of the existing EMD 645 main propulsion engine before the repowering took place. The second testing phase involved measuring emissions after the removal and replacement of the EMD 645 engines with the EMD 710 engines. The final phase of the research involved the re-measurement of emissions when engine completed 17,000 hours of operation and was slightly past mid-life.

Results: The replacement/repower EMD 710 engine had significantly lower NOx and PM emissions than the EMD 645 engine that was replaced. Thus repowering the MV Daniel Wise towboat was significantly beneficial to the air basin that it operates. Using the mid-life emissions factors, calculations in Table 0-1 show NOx emissions were reduced 236 tons per year and PM mass emissions were reduced 12 tons per year for each of the years that the vessel operates. This result is significant to the people living in communities where the MV Wise operates. Results did not show a statically significant saving for fuel or green house gases.

Comment [DY1]: define at onset (nitrogen oxides)

Comment [DY2]: define at onset (particulate matter)

Table 0-1 Benefits of Replacing the EMD 645 with an EMD 710 Engine

	NOx	**PM**	**CO**	**CO_2**
645 engine (g/kWhr)	13.5	0.38	0.44	640
710 eng @17,000	7.4	0.06	0.4	
Benefits, %	45	84	0	
Benefits, tons/yr	236	12	0	0

1 Background

1.1 Marine emissions and standards

The Environmental Protection Agency (EPA) has noted that locomotive and marine diesel engines are significant contributors to air pollution in many cities and ports and need to be reduced. For example, with the earlier emission standards, EPA estimated that by 2030, locomotives and marine diesel engines are estimated to contribute 65 percent of national mobile source diesel $PM_{2.5}$ emissions and 35 percent of national mobile source NOx emissions, a key precursor to ozone and secondary PM formation. Accordingly, the EPA set new emission standards for marine engines.

US EPA regulations [1] divided marine engines into three categories based on displacement (swept volume) per cylinder, as shown in Table 1-1. Categories 1 and 2 are further divided into subcategories, depending on displacement and net power output. Category 1 and Category 2 marine diesel engines typically range in size from about 500 to 8,000 kW (700 to 11,000 hp). These engines are used to provide propulsion power on many types of vessels including tugboats, pushboats, supply vessels, fishing vessels, and other commercial vessels in and around ports. They are also used as stand-alone generators for auxiliary electrical power on many types of vessels.

Table 1-1 Marine Engine Categories

Category	Displacement per Cylinder (D)		Basic Engine Technology
	Tier 1-2	Tier 3-4	
1	$D < 5\ dm^3$†	$D < 7\ dm^3$	Land-based non-road diesel
2	$5\ dm^3 \le D < 30\ dm^3$	$7\ dm^3 \le D < 30\ dm^3$	Locomotive engine
3	$D \ge 30\ dm^3$		Unique marine engine design
† And power ≥ 37 kW A cubic decimeter is one-thousandth cubic meter and one liter.			

The EPA issued a series of emission standards, going stepwise from Tier 1 to Tier 2 to Tier 3 and finally to Tier 4. For each step the standards for exhaust emissions of new engines became tougher and required more advanced technology than the previous generation. For example, emission standards for Category 1 and 2 engines included NOx+THC, PM, and CO. There were no smoke requirements for marine diesel engines as the regulators believed the new PM standards would have a sufficient effect on limiting

[1] US Environmental Protection Agency (EPA), *40 Code of Federal Regulations*, *Part 1042 Control of Emissions from New and In-use Marine Compression Ignition Engines and Vessels*

smoke emissions. Relative to this project are the specific values for Category 2 engines meeting Tier 3 marine emission standards. These are shown in Table 1-2.

Table 1-2 Tier 3 Standards for Marine Diesel Category 2 Engines‡

Power (P)	Displacement (D)	NOx+HC†	PM	Date
kW	dm^3 per cylinder	g/kWh	g/kWh	
P < 3700	7 ≤ D < 15	6.2	0.14	2013
	15 ≤ D < 20	7.0	0.27[a]	2014
	20 ≤ D < 25	9.8	0.27	2014
	25 ≤ D < 30	11.0	0.27	2014
‡ Option: Tier 3 PM/NOx+HC at 0.14/7.8 g/kWh in 2012, and Tier 4 in 2015. † Tier 3 NOx+HC standards do not apply to 2000-3700 kW engines. a - 0.34 g/kWh for engines below 3300 kW.				

Values for NOx for Tier 3 can be compared with values from earlier Tiers that were contained in the "International Convention on the Prevention of Pollution from Ships", known as MARPOL 73/78[2], which set limits on NOx and SOx emissions from ship exhausts, and prohibited deliberate emissions of ozone depleting substances. NOx limits depended on the engine maximum operating RPM speed. For 130<RPM<2,000, the equation for Tier 1 is 45/RPM^0.2 and for Tier 2 the equation is 44/RPM^.023. For an engine operating at 900RPM, the Tier 1 value is 11.5 g/kWh and for Tier 2, the value is 9.20 g/kWh. The corresponding EPA Tier 2 standard for NOx +THC depended on the displacement per cylinder rather than an equation as shown in Table 1-3. A Tier 2 engine with a displacement of 710cc or 11.6 dm^3 had a standard of 7.8g/kWh.

Table 1-3 Tier 2 Marine Emission Standards

Category	Displacement (D)	CO	NOx+THC	PM	Date
	dm^3 per cylinder	g/kWh	g/kWh	g/kWh	
2	5.0 ≤ D < 15	5.0	7.8	0.27	2007[a]
	15 ≤ D < 20 Power < 3300 kW	5.0	8.7	0.50	2007[a]
	15 ≤ D < 20 Power ≥ 3300 kW	5.0	9.8	0.50	2007[a]
	20 ≤ D < 25	5.0	9.8	0.50	2007[a]
	25 ≤ D < 30	5.0	11.0	0.50	2007[a]
a - Tier 1 certification requirement started in 2004					

[2] International Maritime Organization, *Annex VI of MARPOL 73/78 "Regulations for the Prevention of Air Pollution from Ships and NOx Technical Code*".

Thus NOx emission values declined from T1 of 11.5 to T2 of 7.8 to T3 of 6.2 g/kWh, a reduction of 46% from Tier 1 and 20% from Tier 2.

1.2 MARAD Request for Proposals (RFP)

Over the past few years, the Maritime Administration (MARAD) has partnered with other government agencies, industry, and academia on efforts to reduce vessel and port air emissions and greenhouse gases as well as support the use of alternative fuels and energy sources. In 2012, the Maritime Administration Office of Environment solicited proposals via a RFP for projects that demonstrate either criteria pollutant emissions or carbon emissions reductions from marine vessels through repowering, re-engineering or installation of other pollution reduction technologies, or the use of alternative fuel/energy for US-flagged vessels that operate on inland or coastal waterways. Eligible applicants included vessel owners, operators, or sponsors. Awardees were required to demonstrate a reduction of emissions of nitrogen oxides (NOx), sulfur oxides (SOx), particulate matter (PM), or carbon through an approved emission testing scheme. Data collected under funded projects, including that related to costs, emissions, and fuel consumption must be made available to MARAD and will be made publically available. MARAD's goal was to use the results and data to support further air emissions reduction research and demonstration projects and to demonstrate the public benefit of future incentives to improve vessel-related environmental stewardship.

1.3 Southeast Missouri Regional Planning Commission proposal

The SEMO RPC submitted a proposal under the MARAD announcement. The proposal involved partnering with AEP River Operations, LLC to replace/repower the propulsion engines on the Mississippi River towboat Daniel W. Wise. The Daniel Wise is typical of this class of vessels that are often powered by EMD Series 645 engines dating to the 1970s and 1980s. The engines on the Daniel Wise were built in 1978 and are Tier 0 engines, which typically have few modern emissions controls and may be referred to as unregulated. In addition, these engines are likely to be rebuilt after 30,000 hours with an EPA approved 1042 kit and placed back into service. Then the opportunity is lost to reduce emissions by repowering the vessel.

The proposal involved repowering the vessel and measuring emissions at three distinct time intervals: 1) baseline with the EMD 645 engines installed, 2) following repowering and installation of the EMD 710 engines and 3) after the EMD 710 engines had been in service for several years. This rather than rely on manufacturer data, this approach collects real-world data and enables the calculation of actual real-world benefits. Furthermore other private and public sector entities could perform necessary benefit and cost calculations of repowering.

1.4 UCR partnership

The SEMO RPC selected the University of California Riverside (UCR) to complete vessel emissions testing. UCR is well known for emissions testing having participated in over 30 marine measurement campaigns since 2003 and their data was used in establishing regulation in California and providing guidance numbers for the US EPA. UCR uses state-of-art equipment and follows protocols meeting the specifications outlined in the ISO 8178 series of testing standards.

Under the proposed project, three separate objectives were met:

1. Real-world, base line emission data were obtained for engines that were thorough several rebuilds and received normal maintenance.
2. Real-world emission data from a new, more modern, less polluting engines were obtained both: 1) immediately upon installation, and then, 2) prior to the first full rebuild, typically scheduled for 30,000 hours of operations. For this project, the engines were re-measured after 17,000 hours.
3. Real-world fuel economy data were obtained to determine the fuel efficiency impact of these new, more efficient engines. This project provided an opportunity to make real-world evaluations of the fuel economy and air pollutant emissions impact that these fuels have on new engines under normal operating conditions.

2 Project approach

This section outlines the approach to determining the emission benefits when two ~3,000 HP Tier 0 propulsion engines on the *Daniel W Wise* towboat were re-powered with 'state of the art' Tier 3 engines. Emissions were measured at each certification mode and overall emissions figured from applying the fraction of time that the engine spends at each load.

Test plan included three phases of emissions testing. Phase I was the baseline measurement of emissions from the Tier 0 main propulsion engine of the vessel. Phase II was after the towboat underwent replacement of the main and auxiliary engines. Emissions were measured at Phase II and later in Phase III after the main engines accrued about 17,000 of operation. Testing was conducted underway while the vessel operated near Paducah, KY operating on the Mississippi or Ohio Rivers.

2.1 Vessel details

The vessel for this project was built in 1978 by the St Louis Ship in St Louis MO and was named the *Hugh B Steger* by the owner, M/G Transport Services Inc. In 1994 the vessel was sold to the Memco Barge Line Inc. of Chesterfield MO. Later in 1998 the firm became the AEP River Operations and the vessel was renamed the *Daniel W. Wise* #0589325*, see* Figure 2-1. The vessel is 138 feet long, 44 feet wide and operates as a twin screw towboat. It is typical of those that operate on the Ohio, Mississippi, Illinois, and Tennessee Rivers.

Figure 2-1 Photo of the Daniel W Wise

2.2 Main and auxiliary engines

The *Daniel W. Wise is* powered by two main propulsion engines (ME) and two auxiliary engines/generators (AE). Before the repower project, the main engines (ME) were 645 Electro Motor Division (EMD) Tier 0 diesel engines. The MEs are used for propulsion and the AEs are used for hoteling while at berth to include air conditioning, lighting and other critical electrical systems. Selected properties of the main engines prior to repower are shown in Table 2-1.

Table 2-1 Selected Properties of the Main Engines

	Main Engine (ME)
Manufacturer/Model	Electro-Motive Division of GM/ EMD 645
Manufacturer Year	1978
Technology	2-Stroke 45-degree V engines
Certification Standard	Tier 0
Max. Power Rating	2875 hp
Rated Speed	900 rpm
# of Cylinders	16

2.3 Test fuels

Commercial diesel fuels representative of those normally used by the vessel were used as the test fuels rather than the purchase of specially designed certification fuels. The vessel normally burns either #2 diesel fuel or a mixture of 5 volume percent into #2 diesel fuel.

2.4 Test matrix

As the propulsion of the vessel was a direct drive of the propeller by the diesel engine, the correct engine mapping and test conditions followed the ISO 8178 E3 test modes as specified in 40CFR Parts 94 and 1042. Prior to emission testing, UCR worked with the crew to generate data points for the maximum measured brake power versus engine speed on the open water using the methods as specified in 40 CFR Parts 1065.510 and §94.107. These data points shape the lug curve for that engine as installed on a river towboat. Of particular interest are the points at 100%, 75%, 50% and 25% power since these are associated with the ISO 878 E-3 duty cycle seen in Table 2-2.

Table 2-2 Planned Test Points Based on ISO 8178-4, E3 Cycle

Mode No.	Engine speed(percent of maximum test speed)	Percent of maximum test power	Minimum time in mode (minutes)	Weighting factors
1	100	100	5.0	0.20
2	91	75	5.0	0.50
3	80	50	5.0	0.15
4	63	25	5.0	0.15

During emissions measurement, the engines would operate at the final duty cycle consisting of the E-3 load points. Practically speaking, the achievable load points were determined at the time of testing and depended on several factors; including time constraints due to the boat revenue service, the river current, wave pattern, wind speed/direction and cargo load. Efforts were made to conduct the emissions measurements at loads and RPM as close as practical to those specified in ISO 8178 E-3. While not specified in the ISO protocol, UCR's experience with other sources indicates that the engine should be run near full power for at least 30 minutes before measuring emissions in order to stabilize the PM emissions.

2.5 Emission measurements

Below is a brief description of the sampling system utilized for the testing. For a full description refer to Appendix A.

2.5.1 Sample location

Two ports were drilled into the exhaust pipe of the main engine. These two ports were drilled 6" apart from each other and as far as possible from the engine to have properly mixed exhaust. The sampling probes used for emissions testing were $3/8^{th}$ inch stainless steel tubing. These probes were inserted into the stack, a distance equal to $1/3^{rd}$ of the total diameter of the stack. These distances were sufficiently away from any effects found near the stack walls. Figure 1-3 shows pictures of installed setup for sampling gaseous and particulate emissions from the engine. On one port, a dilution tunnel was installed to measure particulate matter and record diluted gaseous concentrations. Another port was used to record raw concentrations of gaseous pollutants.

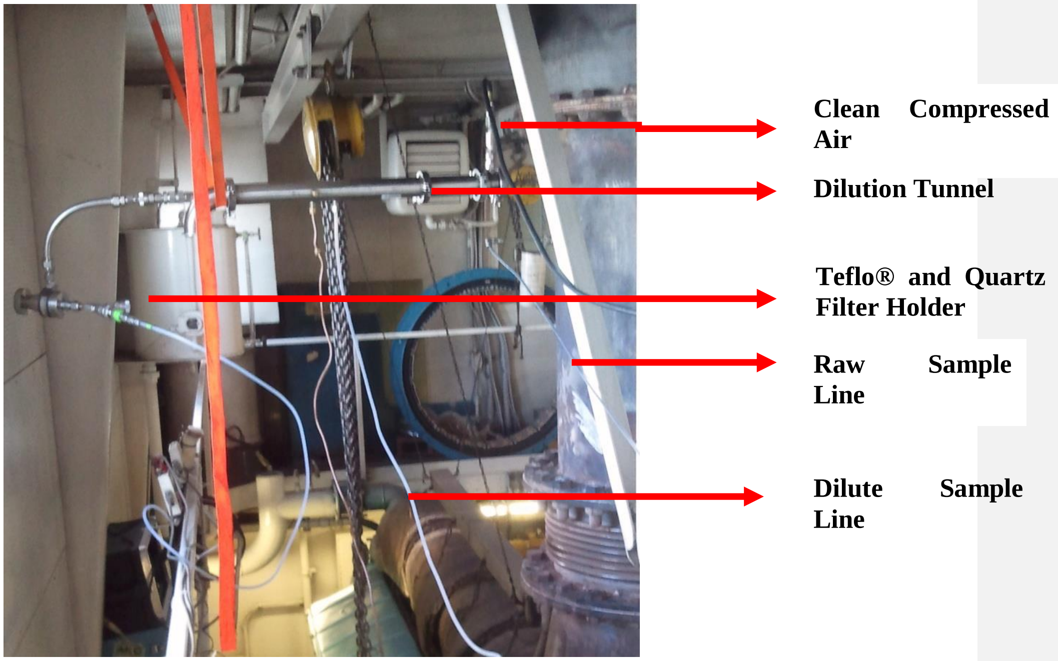

Figure 2- 1 Sampling Ports on the Main Engine Exhaust for the EMD 645

2.5.2 Gaseous emissions

A Horiba Portable gas analyzer (PG250) was used to measure the concentrations of carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2) and nitric oxides (NO_x) gasses from the raw exhaust and in the dilution tunnel to get the dilution ratio. The PG-250 instrument was calibrated with EPA protocol gases as per the ISO protocols and has proved to be easily transportable, highly reliable and versatile gas analyzer. Unlike other portable gas analyzers that rely upon electro-chemical sensors, the Horiba PG-250 utilizes the same measurement principles as a permanently installed in CEMS and is in compliance with MARPOL *ANNEX VI*. During testing, concentration data were stored on a data logger every second for later analysis. There was a start and end time for each test with the difference in times being the sample time, which was greater than the five minutes required in the ISO regulations. The concentration data between the start time and end time were used in the data analysis.

2.5.3 PM emissions

In addition to gaseous emissions, the project measured $PM_{2.5}$ mass emissions and the speciated $PM_{2.5}$emissions as elemental carbon (EC) and organic carbon (OC). As described earlier, the PM mass in the raw exhaust was sampled using a partial dilution method and collected on filter media. Specifically the samples for total $PM_{2.5}$ mass was collected on a Teflo® filter and samples for determining the elemental and organic carbon fractions of the $PM_{2.5}$ mass were collected on Tissuquartz filter. Elemental and organic carbon was determined off-line using the NIOSH method. Diesel $PM_{2.5}$ primary consists of elemental carbon, organic carbon, sulfate and ash. The diesel fuels in this project have extremely low sulfur and no metals so the total carbon should be reflected by the elemental and organic carbon.

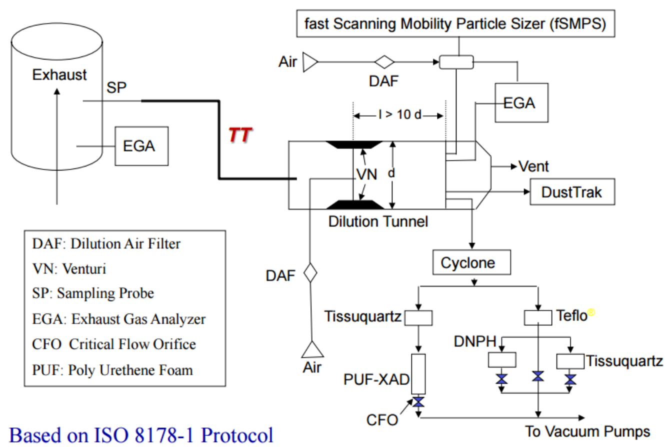

Figure 2-2 Schematic of the Dilution Sampling System

As part of the quality check UCR planned to compare the measured elemental and organic mass fractions with total PM mass since the mass was determined by two independent methods.

2.5.4 Exhaust flow measurements

The calculated emission factor requires the measurement of the engines exhaust flow rate. The exhaust gas flow can be determined by the following methods:

1. Direct Measurement Method
2. Carbon Balance Method
3. Air and Fuel Measurement Method
4. Air Pump method

For main engine on the Daniel W Wise exhaust flow we calculated with available fuel flow rate and air pump method. The fuel consumption rate was recorded using a fuel flow meter installed by the vessel operator. The fuel flow measurement is a direct measure of the inlet and return fuel rate.

The air pump method utilized the intake manifold temperature and boost pressure to calculate a secondary approach for exhaust flow. Both methods were in agreement where the fuel flow method is the basis of this report.

2.6 Measuring activity

Measuring the actual in-use loads and time spent at each load is key to measuring the true emission benefits. The standard EPA protocols assume certain loads and fractions of time at each load but as an earlier UCR study of the benefits of a hybrid tug[3] showed, there were significant differences between the EPA values and the actual measured values. For example, times spent idling and during transient at low power within the harbor were significant; yet not included in the EPA protocol. To get the actual in-use activity, UCR reviewed the operating data as expressed in histograms on the Electronic Control Module (ECM) of the Tier3 engine. Based on past experience, UCR will assume that the activity for the Tier 0 vessel is similar to the Tier 3 engine. When those data are combined with output from the log on the vessel, then there will be enough data to report on the typical loads and times that a river towboat spends on each type of activity.

2.7 Calculations

Emissions data collected from the Tier 0 and the Tier 3 engines were analyzed for both the modal and the overall emission factors for criteria pollutants. For the Tier 3 engine, values at the ISO 8178 E-3 load points will be compared with the EPA certification and in-use standards and values provided by the engine manufacturer to ensure the UCR measured values are representative of that engine. In addition, the greenhouse gas saving was determined from the change in CO_2 levels and confirmed with the crew records for fuel savings.

2.7.1 Emission rates in g/hr

Mass emissions of CO_2, NO_x and CO in g/hr were calculated using the measured concentrations in the exhaust and the calculated exhaust mass flow. For $PM_{2.5}$ mass

[3] Jayaram, V. et al., *Evaluating Emission Benefits of a Hybrid Tug Boat*, UC, Riverside's Final Report to the California Air Resources Board, October 2010

emissions the concentration in the dilute exhaust is calculated as a ratio of the measured filter weight to the total sample flow through the filter. This value is converted to a concentration in the raw exhaust by multiplying with the dilution ratio. The raw $PM_{2.5}$ concentration is used with the exhaust flow to determine the mass emissions in g/hr.

2.7.2 Emission factors in g/kW-hr

The emission factor at each mode is calculated as the ratio of the calculated mass emissions (g/hr) in the exhaust to the reported engine load (kW).

An overall single emission factor representing the engine is determined by weighting the modal data according to the ISO 8178 E3 cycle requirements and summing them. The equation used for the overall emission factor is as follows:

$$\boldsymbol{EF_{WM} = \frac{\sum_{i=1}^{n}(g_i \times WF_i)}{\sum_{i=1}^{n}(P_i \times WF_i)}}$$

where:

- EF_{WM} Overall weighted average emission factor in g/kW-hr
- n Total number of modes in the ISO duty cycle
- g_i Calculated mass flow in g/hr for the i^{th} operating mode
- WF_i weighing factor for the i^{th} operating mode
- P_i Engine load in kW for the i^{th} operating mode

2.7.3 Benefits of repower

The emission benefits of re-powering a river towboat are calculated from the measured in-use emissions and activity of the Tier 0 and Tier 3 engines. First the total emissions for the criteria pollutants (CO, NOx, and PM) and a greenhouse gas (CO_2) are calculated by summing emissions across all operating modes and applying the activity or fraction of time spent at that load as determined in the project. Two approaches can be used for figuring the fraction of time at each load. In one approach, the standard loads and time spent at each load, as specified in the EPA protocols, are used to calculate the benefits. In the second approach, the actual loads and time spent at each load are measured for an in-use towboat operating on the river and those values are used to determine the true benefits.

- Total emissions (g/hr), TE = summation across all operating modes of (weighing factor for a mode * emission factor for that mode g/hr).
- The next equation calculates the benefits for the criteria pollutants and the fuel economy based on CO_2:
- % Emissions benefit = 1-(TE Tier 3 condition/TE Tier 0 condition) * 100

3 Results: Baseline Engine

The EMD 645 family of diesel engines was designed and manufactured by the Electro-Motive Division of General Motors for locomotive, marine and stationary engine use. The 645 series was an evolution of the earlier 567 series and a precursor to the later 710 series. First introduced in 1965, the EMD 645 series remained in production on a by-request basis long after it was replaced by the 710, and was later supported by Electro-Motive Diesel, Inc., which purchased the assets of the Electro-Motive Division from General Motors in 2005.

3.1 Test protocol and fuels

The primary goal of this phase of the testing program was to establish baseline emissions from the main engine of the Daniel W Wise tow-boat following the methods outlined in Chapter 2. Basically, at each steady state test mode the protocol requires the following:

- Allowing the gaseous emissions to stabilize before measurement at each test mode.
- Measuring gaseous and $PM_{2.5}$ concentrations for > 5 minutes and a time period long enough to get measurable filter mass
- Recording engine speed (rpm) and fuel flow rate in order to calculate engine load and the mass flow rate of the exhaust, respectively.

Fuels samples were taken during the testing and selected properties are shown in Table 3-1.

Table 3-1 Selected Fuel Properties

Properties	Units	Fuel 1	Fuel 2
Centane Number		47	46.5
Viscosity @ 40 °C	cSt	2.4	2.333
Density	kg/m3	–	842.3
API Gravity @ 60°F		36	36.4
Sulfur Content	ppm	9	7.9
FAME	% v/v	–	4.8

3.2 Engine operating loads

The steady state load points on the main engine of the tow boat were achieved while the boat towed/pushed barges full of coal from one location to another in the rivers near Paducah. The Captain of the boat was provided with the targeted RPM points which corresponded to load points defined in the ISO 8178 E3 test cycle for emission measurements. Table 3-2 shows that engine RPM (revolutions per minute) achieved during the testing was very close to the targeted load points. The RPM was recorded from engine computer and engine load was computed using the specified engine speed assuming the power followed the propeller law as indicated in Figure 3-1. Note the overall excellent agreement between the targeted and actual RPM and loads.

Table 3-2 Test Matrix for EMD 645 Engine Operation

	Targeted E-3 Values		Actual Values	
Mode No.	**% engine/ RPM**	**% max/power kW**	**RPM/% engine**	**power kW %/max**
1	100/900	100/2144	100/900	2144/100
2	91/819	75	816/91	1595/75
3	80/720	50	719/80	1076/50
4	63/567	25	565/63	535/25

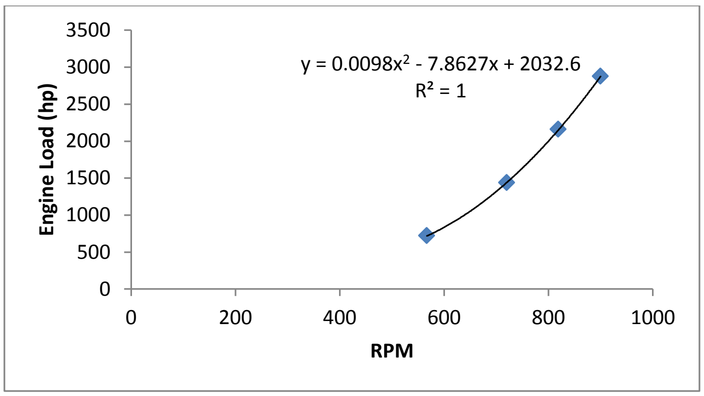

Figure 3-1 Correlation between RPM and Engine Load

3.3 Gaseous and PM modal emission rates

Values in this section are corrected from earlier reports as it was discovered later that the fuel flow was biased 15.4% higher than the true value.

Gaseous and $PM_{2.5}$ emission measurements on ME engine were made based on the ISO 8178-1 protocol. Briefly, a partial dilution system with a venturi was used for $PM_{2.5}$ sampling. Carbon dioxide, nitrogen oxides and carbon monoxide were measured in both the raw and the dilute exhaust. The ratio of the concentration of carbon dioxide and nitrogen oxides in the raw to the in the dilute was used to determine the dilution ratio for $PM_{2.5}$ sampling.

The primary gaseous emissions measured during this test program include a greenhouse gas carbon dioxide (CO_2), and the criteria pollutants: nitrogen oxides (NO_x), carbon monoxide (CO). Each of these gaseous species was measured using the ISO standard instrumentation. In addition to gaseous emissions, the $PM_{2.5}$ mass emissions and the speciated $PM_{2.5}$ emissions as elemental carbon (EC) and organic carbon (OC) were measured. As described earlier, the PM mass in the raw exhaust was sampled using a partial dilution method and collected on filter media. In-use emission measurements were collected from the diesel engine during boat operation in the Ohio River. Emission measurements were performed in the descending order of the modes stated in the ISO 8178-4 E3 test cycle. Best efforts were made to operate the engine at load points specified in the E3 test cycle. A detailed list of the gaseous and $PM_{2.5}$ modal emission rates in g/hr for the EMD 645 marine diesel engine is provided in Table 3-3.

Values are based on duplicate measurements made at each steady state test mode. Each gaseous measurement was a five to ten minute average of one hertz data obtained from the instrument. The standard deviation of five to ten minute averages was <2% for CO_2. This indicates that the load on the engine while testing that mode was steady, thereby validating the measurement at each of those test modes. In the case of $PM_{2.5}$, each measurement refers to a filter sample. The surprising low emissions of PM required that filter collection was for nearly 20 minutes instead of the usual five minutes.

Table 3-3 Emissions Rates for EMD -645 Engine in g/hr

Electro-motive EMD 645 baseline 2875 BHP @ 900 RPM						
load	NOx	CO	CO2	PM2.5	EC	OC
			g/hr			
100	30127	1089	1359874	943	10	576
75	21774	595	1042534	584	15	402
50	15120	505	735811	465	11	244
25	7495	468	391547	159	10	94

Modal emissions data in Table 3-3 are helpful in developing the emission contribution to local inventories of the Daniel W Wise before repowering the towboat.

3.4 Calculated modal and overall emission factors for gases and PM

Modal emission rates in Table 3-3 were divided by the load at each operating mode to develop the emission factor of each pollutant. Values for the modal emission factors are shown in Table 3-4.

Table 3-4 Emission Factors for EMD -645 Engine in g/kW-hr

Electro-motive EMD 645 baseline 2875 BHP @ 900 RPM						
load	NOx	CO	CO2	PM2.5	EC	OC
			g/kW-hr			
100	14.0	0.51	634	0.44	0.01	0.32
75	13.7	0.37	653	0.36	0.01	0.30
50	13.9	0.31	669	0.40	0.01	0.29
25	14.0	0.88	732	0.29	0.02	0.21
Weighted Avg.	13.9	0.45	656	0.39	0.01	0.25

An overall emission factor was developed from the modal emission factors using the ISO 8178 E-3 emission weighting factors shown in Table 2-2. Note the NOx emission factor of 13.9 g/kW-hr exceeds the Tier 1 value of 11.5 g/kW-hr by 13.9/11.5 = ~120% .

Diesel particulate matter can be fractionated into elemental and organic carbon EC and OC). Data in Table 3-4 shows PM, and EC/OC in g/kW-hr obtained from two separate methods: gravimetric measurements of $PM_{2.5}$ collected on Teflo® filters and total carbon analysis of $PM_{2.5}$ collected on parallel Tissuquartz filters by a thermal/optical carbon analyzer (±20% measurement uncertainty). Note the engine has < 5% elemental carbon, a value rarely seen for a diesel engine, even when operating with a #2 diesel fuel.

A graphical representation of the modal and weighted emission factors for each of the pollutants is presented in Figure 3-2.

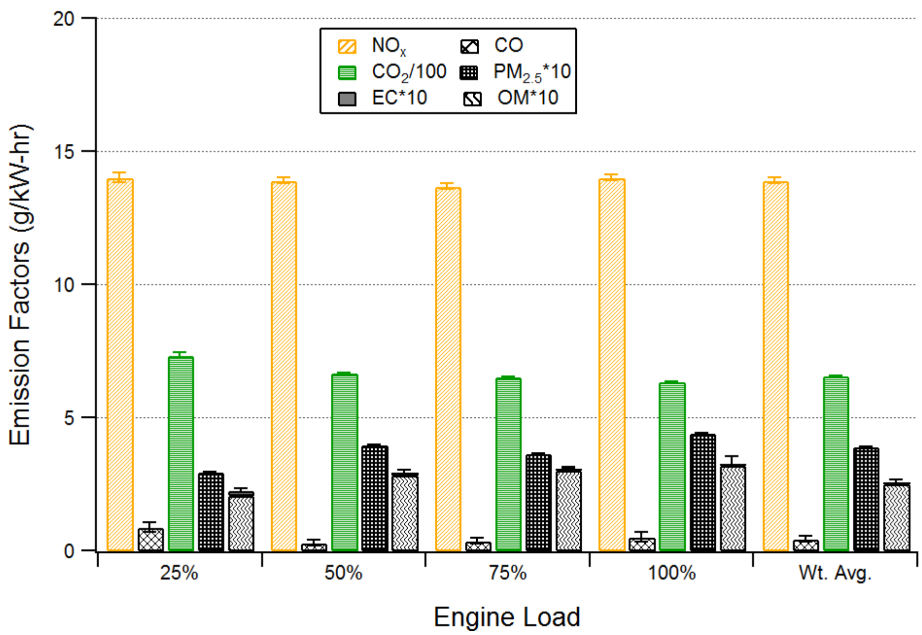

Figure 3-2 Modal & Weighted Emission Factors for Main Engine EMD 645

4 Results: Repowered Engine after Installation

This section reports the testing results after the MV Daniel W Wise was repowered with the new EMD engines and had several hundred hours.

4.1 Test engine

The EMD 710 is a line of diesel engines built by General Motors' Electro-Motive Division, now owned by Electro-Motive Diesel. The 710 series replaced the earlier EMD 645 series in the early 1980s when the 645 series proved to be less competitive. The EMD 710 is a relatively large, medium speed, two-stroke diesel engine with 710 cubic inches (11.6 liters) displacement per cylinder. Selected properties are in Table 4-1 and more information is listed in https://en.wikipedia.org/wiki/EMD_710 - cite_note-2

Figure 4-1 EPA Engine Identification

Table 4-1 Test Engine Details

Manufacturer	EMD
Engine Model	12-710G7C
Serial number	13-B1-1023
Rated power	3,000HP (2,237kW)
Rated engine speed	904 RPM
Operating cycle	2-stroke, uniflow scavenged
Cylinder arrangement	V-12
Bore	230mm
Stroke	279mm
Displacement per cylinder	11.6L
Fuel injection	Direct mechanical unit injection

4.2 Emission testing

Testing methods and equipment for testing the EMD 710 added during the repower were similar to those used in the baseline testing of the EMD 645 marine diesel engine.

Emissions testing followed the ISO-8178-4 E3 test cycle for main propulsion engines. Triplicate measurements were made at each load point. In-use emission measurements were collected from the diesel engine during boat operation in the Ohio River. Emission measurements were performed in the descending order of the modes stated in the ISO 8178-4 E3 test cycle. Best efforts were made to operate the engine at load points specified in the E3 test cycle. Results showed the targeted load points and actual measured RPM points were very close as indicated in Table 4-2. Load is calculated from RPM using the propeller law curve so the actual columns are reverse of the targeted values.

Table 4-2 Test Matrix for the EMD 710 Engine Operation

	Targeted E-3 Values		Actual Values	
Mode No.	**% engine/ RPM**	**% max/power kW**	**RPM/% engine**	**power kW %/max**
1	100/886	100/2237	886/100	2237/100
2	91/806	75/1678	808/91	1678/75
3	80/709	50/1118	719/81	1132/51
4	63/558	25/559	575/65	576/26

4.3 Calculated modal emission rates

***Values in this section are corrected from earlier reports as it was discovered after the initial calculations that the fuel flow was biased 15.4% higher than the true value*.**

Gaseous and $PM_{2.5}$ emission measurements on the main propulsion engine were made based on the ISO 8178-1 protocol. Briefly, a partial dilution system with a venturi was used for $PM_{2.5}$ sampling. Carbon dioxide, nitrogen oxides and carbon monoxide were measured in both the raw and the dilute exhaust. The ratio of the concentration of carbon dioxide and nitrogen oxides in the raw to the in the dilute was used to determine the dilution ratio for $PM_{2.5}$ sampling.

The primary gaseous emissions measured during this test program include a greenhouse gas carbon dioxide (CO_2), and the criteria pollutants: nitrogen oxides (NO_x), carbon monoxide (CO). Each of these gaseous species was measured using the standard ISO instrumentation. In addition to gaseous emissions, the project measured the $PM_{2.5}$ mass emissions and the speciated $PM_{2.5}$ emissions as elemental carbon (EC) and organic carbon (OC). As described earlier, the PM mass in the raw exhaust was sampled using a partial dilution method and collected on filter media. A detailed list of the gaseous and $PM_{2.5}$ modal emission rates in g/hr for the EMD 710 diesel engine is provided in Table 4-3.

Table 4-3 Emissions Rates for EMD-710 Engine in g/hr

Electro-motive GM 3000 BHP @ 900 RPM						
load	NOx	CO	CO2	PM2.5	EC	OC
			g/hr			
100	25559	2316	2036135	473	38	328
75	20707	697	1475644	110	18	127
50	13791	327	673161	31	6	34
25	6238	298	297435	13	5	15

4.4 Calculated modal and overall emission factors for gases and PM

Modal emission rates in Table 4-3 were divided by the load at each operating mode to develop the emission factor of each pollutant. Values for the modal emission factors are shown in Table 4-4 and graphically in Figure 4-2.

Table 4-4 Emissions Factors for EMD-710 Engine in g/kWhr

Electro-motive EMD 710 0hr 3000 BHP @ 900 RPM						
load	NOx	CO	CO2	PM2.5	EC	OC
			g/kW-hr			
100	8.4	0.74	636	0.08	0.01	0.07
75	9.3	0.31	635	0.05	0.01	0.06
50	14.2	0.38	648	0.03	0.01	0.03
25	15.2	0.72	696	0.03	0.01	0.04
Weighted Avg.	9.9	0.47	640	0.05	0.01	0.07

Diesel particulate matter can be fractionated into elemental and organic carbon. Note from the values in Table 4-4 that on average the EC is about 12% of the total carbon.

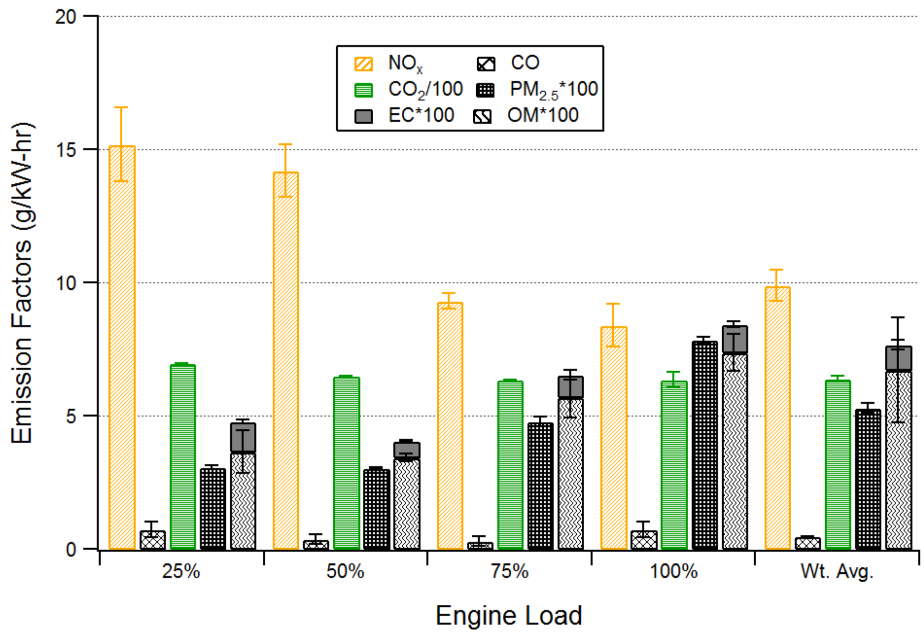

Figure 4-2 Modal Emission Factors for Main Engine EMD 710

As a quality check, the $PM_{2.5}$ emissions were obtained with two separate methods. One was a gravimetric measurement of $PM_{2.5}$ collected on Teflo® filters, and the second was the total carbon analysis of $PM_{2.5}$ collected on parallel Tissuquartz filters and subsequently analyzed by the NIOSH thermal/optical carbon method. The results of the NIOSH method are elemental carbon and organic mass. Total mass is counted by adding the elemental carbon with the organic carbon multiplied by a factor of 1.2 to account for hydrogen and oxygen attached to the carbon in the organic fraction. Overall, good agreement is observed between two different PM measurement methods as shown in Figure 4-3

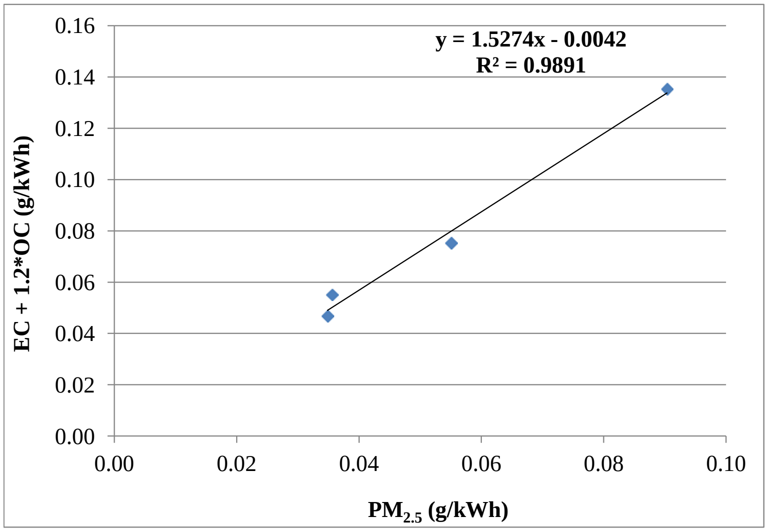

Figure 4-3 Parity Plot of PM Mass vs. Total Carbon

4.5 Analysis showing flow rate was biased high

Independent confirmation of data always adds to the credibility and confidence in measured values. As no data were available for the EMD 645 engine, we waited until the analysis of the EMD 710 engine. Those comparisons are shown in the following sections.

4.5.1 Comparison with EPA Tier 3 emissions

Since the purchased engine was reported to meet EPA Tier 3 standards, it was appropriate to compare the UCR measured values with the EPA Tier 3 standard. That comparison is shown in Table 4-5. As is evident the NOx emission factor is almost double the standard and the PM is about 50% of the standard. UCR had requested the manufacturer data for the delivered engine but did not receive the data so we undertook a deeper examination of the data to provide an explanation of the significant differences. Note the EPA allows a measurement allowance of ~20% for in-use measurements. In this case, the measured value with the measurement allowance still exceeds the standard.

Table 4-5 Comparison of UCR Measurements with EPA Standards in g/kW-hr

	NOx	PM	CO
EPA Tier 3 Standard	6.2	0.14	5.0
UCR measured	11.6	0.06	0.5

4.5.2 Mass and energy balances

Another deeper analysis would checks of the mass and energy balances. The UCR measurement of CO_2 emissions as 738 g/kW-hr seemed high. Further calculating the fuel efficiency with the UCR data showed the fuel efficiency was about 36/37%; a value well short of the expected 41/42%.

As UCR did not have access to manufacturer data, we looked for published data on the EMD 12 710G7C engine. One report[4] from Southwest Research Institute was on the development of the 12-710 marine engine on a test stand. In that report two fuels were used for the five tests. Fuel #1 was EPA locomotive certification fuel with a density of 7.08 lb/gal and a net heat of combustion of 18,262 BTU/lb. Fuel #2 was TxLED with properties of 6.93 lb/gal and 18,396 BTU/lb. Shown in Table 4-6 are the fuel efficiency percentage for the SwRI data on a test stand and the UCR captured on water. The column labeled lb/hr is the measured fuel flow from an installed flow monitor. The next column labeled HP is the calculated power if 100% of the delivered fuel is converted into useful energy. Finally, the ratio of engine brake horsepower (BHP) to HP is the fuel efficiency.

Table 4-6 Fuel Efficiency Data

	SwRI Test #1					**SwRI Test #2**					**UCR data**				UC/Sw
Mode	lb/hr	HP	BHP	%Eff		lb/hr	HP	BHP	%Eff		lb/hr	HP	BHP	%Eff	Ratio
1	1005	7210	3085	42.8%		995	7191	3046	42.4%		1139	8171	3000	36.7%	1.154
2	750	5381	2288	42.5%		745	5384	2270	42.2%		852	6110	2249	36.8%	1.146
3	507	3637	1530	42.1%		502	3628	1518	41.8%		588	4221	1526	36.2%	1.157
4	270	1937	763	39.4%		268	1937	759	39.2%		311	2234	755	33.8%	1.159

The last column in Table 4-6 is the ratio of engine efficiency measured by SwRI and UCR. Note the UCR numbers are on average 15.4% lower fuel efficiency based on the installed flow monitor. Note the ratio was the same for each mode thus eliminating the question of whether measurements on water were different from measurements on a test stand. From this analysis UCR concluded that the reported fuel flow was biased 15.4% higher and looked to correct the measured data.

4.5.3 Adjusting UCR data for fuel flow bias

In the UCR analysis, the exhaust flow was calculated from a carbon mass balance; namely, the carbon entering as fuel is the same as the total carbon exiting in the

[4] Osborne, D. T.; Fritz, S. G.; *EMD 12-710G7A Marine Engine Development*; SwRI Report 03.11561; December 2007

exhaust. Calculating total carbon in the exhaust theoretically requires adding the carbon from: 1) carbon dioxide; 2) carbon monoxide 3) total hydrocarbons and 4) particulate matter (PM). Since 99+% of the carbon in the exhaust is carbon dioxide; for practical purposes, the balance is based on the measured concentration of carbon dioxide in the exhaust. Clearly if the mass of carbon entering the engine is based on a feed fuel flow meter that is biased high, then the mass exhaust flow will be biased the same percentage high for all pollutants, assuming that the measured concentration of carbon dioxide and other gases is accurate. Thus earlier measured values for emission factors were reduced by the bias in fuel flow rate and corrected values are shown in Table 4-7. While still higher than Tier 3, the values are similar to those seen for some Tier2 engines.

Table 4-7 Comparison of UCR Measurements with EPA Standards in g/kW-hr

	NOx	PM	CO
EPA Tier 3 Standard	6.2	0.14	5.0
UCR measured	11.6	0.06	0.5
UCR adjusted for flow	9.81	0.05	0.4

Looking at the corrected values, the ratio of measured NOx emission factor to Tier 3 is 1.58 and for PM, the ratio is i0.36. Another perspective, the NOx exceeds standard by 58% and the PM is 64% below standard. With such significant changes, one might question whether there is a NOx-PM tradeoff, meaning that the engine is operating in a regime where the PM is lower and the NOx is higher. From past experience the data suggest a trade-off is occurring.

Note the values for the EMD 645 measured with the same fuel flow meter should also be adjusted for fuel flow and this is shown in Table 4-8. A similar flow correction for the CO_2 value brings the emission factor to 640 gCO_2/kW-hr and more in line with the expected value.

Table 4-8 Adjusted Emission Factors for the EMD 645 Engine

	NOx	PM	CO
UCR measured	16.0	0.45	0.52
UCR adjusted for flow	13.5	0.38	0.44

4.5.4 Accuracy of CO_2 and NOx measurements

UCR calibrated the instruments in the field with EPA protocol gases and the instruments functioned normally. Gaseous data from UCR can be compared with the SwRI data for CO_2 by looking at the overall break specific fuel consumption, which SwRI reports as 0.329 lb/hp-hr. Applying the measured content of the fuel as 86wt% carbon, the SwRI BSFC converts to 627 gr CO_2/kW-hr. The UCR measured value of 738 g CO_2/kW-hr is corrected to 624 g CO_2/ kW-hr when adjusted for the bias in fuel flow and is now statistically the same as the SwRI value.

Direct comparisons with NOx from SwRI and UCR are difficult; however, UCR calculates the dilution ratio between the raw exhaust and the dilution tunnel with both CO_2 and NOx. Results from this study showed the dilution ratio measured with either CO_2 or NOx was the same. Given that the CO_2 values are accurate and the analysis instrument was working normally, UCR opines the NOx values are accurate as well.

5 Results: Repowered Engine after 17,000 hr

This section reports the results after the MV Daniel W Wise was repowered with the new EMD engines and had run for about 17,000 hours.

5.1 Test engine

The EMD 710 engine replaced the earlier EMD 645 series and was unchanged since the installation/repowering project except for regularly scheduled maintenance. The engine operated reliably without major problems.

5.2 Emission testing

Testing methods and equipment for testing the EMD 710 added during the repower were similar to those used in the baseline testing of the EMD 645 marine diesel engine. Example field setups for August 2015 are shown in Figure 5-1

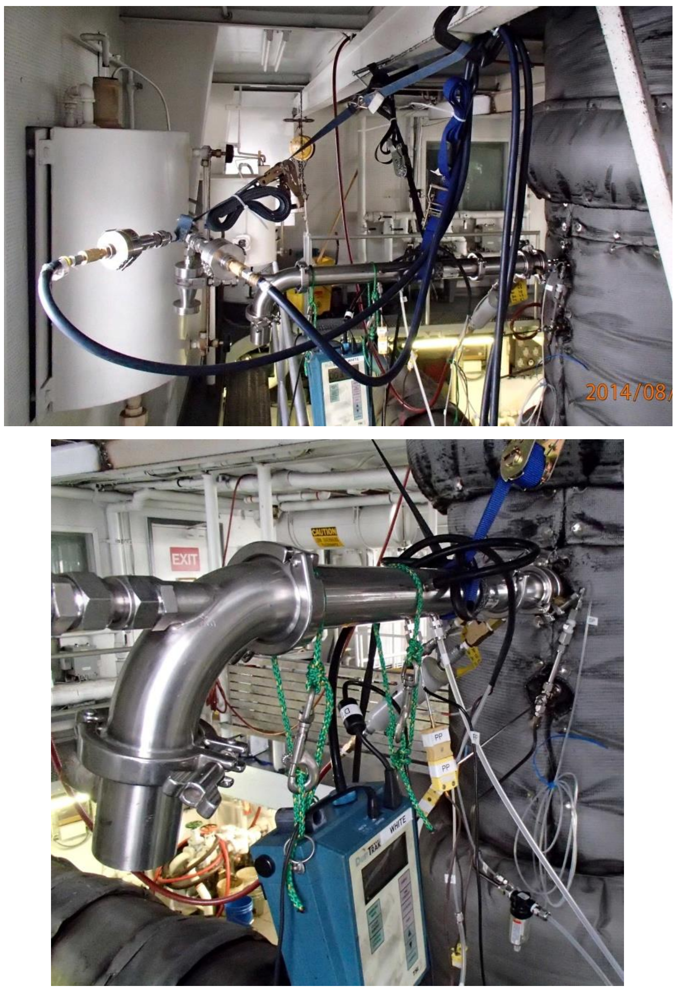

Figure 5-1 Field Setup for August 2015 Testing

Emissions testing followed the ISO-8178-4 E3 test cycle for main propulsion engines. Triplicate measurements were made at each load point. In-use emission measurements were collected from the diesel engine during boat operation in the Ohio River. Emission measurements were performed in the descending order of the modes stated in the ISO 8178-4 E3 test cycle. Best efforts were made to operate the engine at load points specified in the E3 test cycle. Results showed the targeted load points and actual points were very close as indicated in Table 4-2. As in the earlier test the columns for the actual values are reversed from the Targeted Values as RPM is the measured parameter and all other values are calculated from RPM. For the August 2015 test, some test measurements were made at 6% power, where the engine is near idle and emission on near the slow speed operation.

Table 5-1 Test Matrix for the EMD 710 Engine Operation

	Targeted E-3 Values		Actual Values	
Mode No.	**% engine/ RPM**	**% max/power kW**	**RPM/% engine**	**power kW/%max**
1	100/886	100/2237	900/100	2237/100
2	91/806	75/1678	818/91	1746/78
3	80/709	50/1118	720/81	1144/51
4	63/558	25/559	567/65	542/24
5	VSR		350/39	140/6

5.3 Measured modal emission rates

Values in this section are corrected for the fuel flow high bias of 15.4%.

Gaseous and $PM_{2.5}$ emission measurements on the main propulsion engine were made based on the ISO 8178-1 protocol as described in Section 4. The primary gaseous emissions measured during this test program include a greenhouse gas carbon dioxide (CO_2), and the criteria pollutants: nitrogen oxides (NO_x), carbon monoxide (CO). Each of these gaseous species was measured using the standard ISO instrumentation. In addition to gaseous emissions, the project measured the $PM_{2.5}$ mass emissions. As described earlier, the PM mass in the raw exhaust was sampled using a partial dilution method and collected on filter media. A list of the gaseous and $PM_{2.5}$ modal emission rates in g/hr for the EMD 710 diesel engine is provided in Table 5-2. Calculated exhaust flow rates were adjusted for the fuel flow bias of 15.4 % found in the earlier work.

Table 5-2 Emissions Rates for EMD-710 Engine in g/hr

Electro-motive EMD 710 17,000hr 3000 BHP @ 900 RPM						
load	NOx	CO	CO2	PM2.5	EC	OC
			g/hr			
100	13,154	861	1,420,143	144	65.1	150.6
75	12,405	438	1,107,837	131	39.5	115.3
50	8,507	256	740,787	68	14.2	64.3
25	5,551	277	383,895	30	5.5	31.7
10	1,548	150	114,947	9	3.1	9.7

5.4 Calculated modal and overall emission factors for gases and PM

Modal emission rates in Table 4-3 were divided by the load at each operating mode to develop the emission factor of each pollutant at each mode. Values for the modal emission factors are shown in Table 5-3and graphically in Figure 5-2.

Table 5-3 Emissions Factors for EMD-710 Engine in g/kWhr

Electro-motive EMD 710 17,000hr 3000 BHP @ 900 RPM						
load	NOx	CO	CO2	PM2.5	EC	OC
			g/kW-hr			
100	5.9	0.38	634.8	0.064	0.029	0.067
75	7.1	0.25	634.2	0.075	0.023	0.066
50	7.4	0.22	645.6	0.060	0.012	0.056
25	10.2	0.51	708.8	0.056	0.010	0.059
10	12.1	1.17	896.2	0.074	0.025	0.076
Weighted Avg.	7.4	0.3	647.2	0.063	0.014	0.042

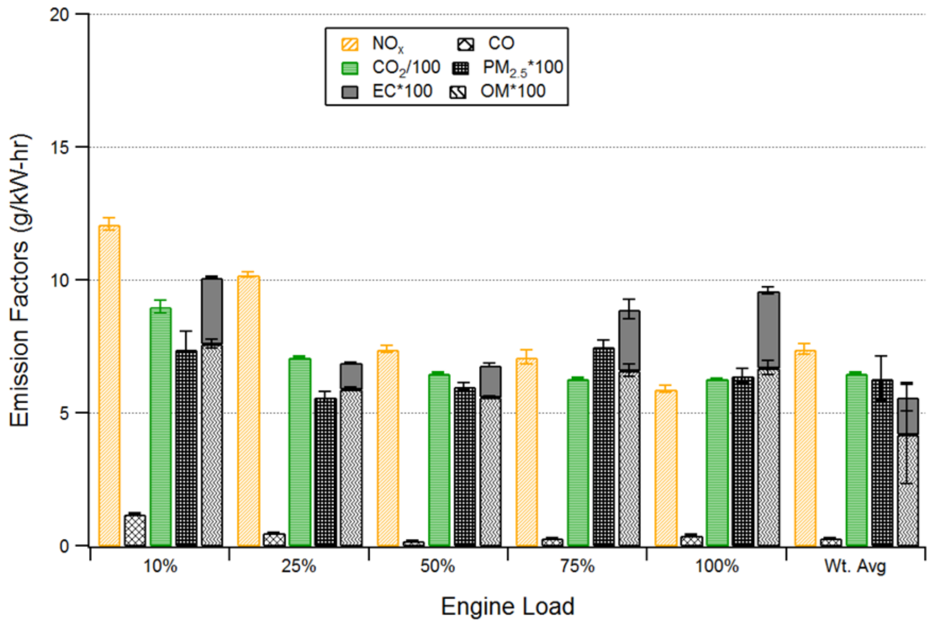

Figure 5-2 Modal Emission Factors for Main Engine EMD 710

5.5 Comparison of data across three test campaigns

A comparative perspective of emissions results for the engine after being newly installed and after running for about 17,000 hours is of value. Reportedly the useful life of these engines is about 30,000 hours so 17,000 hours in just past 50% of the useful life.

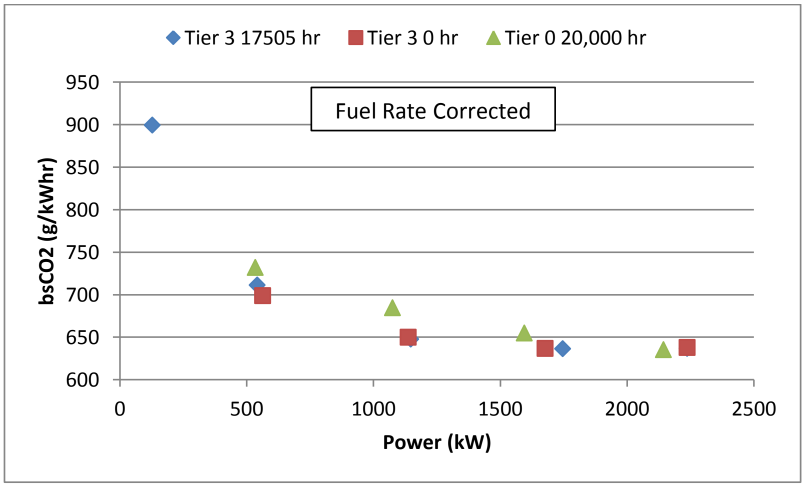

Figure 5-3 Comparative Break-specific Fuel Consumption (g/kW-hr)

Note the close agreement with the specific fuel consumption for the EMD engines which is an expected characteristic of the engineering.

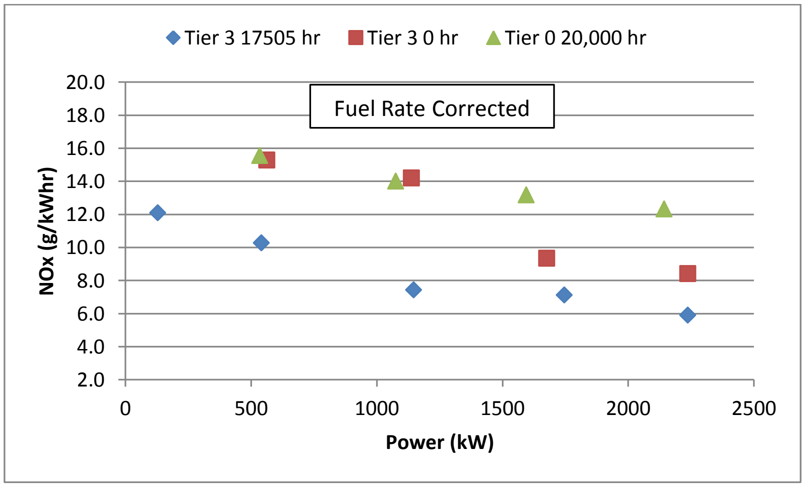

Figure 5-4 Comparative Break-specific NOx Emissions (g/kW-hr)

This plot shows the decline in the NOx values over all the modes where emissions were measured at 17,000 hours.

5.6 A focus on the key parameters

Given that the vessel fights the current of the Mississippi and Ohio Rivers as heavy loads are moved up river, the engines often run near full load. Unfortunately the purchased engines did not have an installed data logger so we are not able to quantify the activity from the recorded histograms of RPM vs. load. Comparative values for the two measurements of NOX and PM are shown in Table 5-4 along with the Tier 3 standard.

Table 5-4 Comparative Values for EMD 710 Engine (g/kW-hr)

	NOx	PM	CO
EPA Tier 3 Standard	6.2	0.14	5
UCR engine new	9.8	0.05	0.4
UCR engine @ 17,000	7.4	0.06	0.3

A couple of key observations:

1. The measurements for the third campaign at 17,000 followed ISO 8178-1, 2, 4 protocols and standards and the team members making the measurements for the 17,000 campaign were all different from those who measured the engine after just being installed. Note results are close indicating a close conformity with testing methods.

Comment [DY3]: thanks for pointing this out.

2. Even with the heavy work load and activity typical of these engines, the measured NOx emission factor had been reduced from 9.8 to 7.4 g/kW hr over the 17,000 hours. This value is within 20% of the Tier 3 value so is considered the same as the Tier 3 standard since the EPA measurement allowance is 20% for in-use measurements. We are not certain why the NOx emissions factor decreased between the initial test and the test at 17,000 hours but looking at Figure 5-4 it is clear the emission factor right after repowering was due to the modal emissions measured at the 25% and 50% loads. Other loads were closer to the modal NOx emission factor measured at 17,000 hours. While both emission factor values are accurate, we believe the number at mid-life and 17,000 hours better represents the emissions over the length of the engine so use that value to figure the emission benefits.
3. The PM mass emissions is basically within the statistical error so there was no significant deterioration in PM mass emissions up to the mid-point of the useful lifetime. Of note is the PM mass emissions are still 43% of the emission standard.

6 Discussion: Benefits of Repower

6.1 Strategy Overview

Emissions from marine vessels can be reduced through: 1) switch to alternative or cleaner burning fuels; 2) installation of a low-emission rebuild kit, if available; 3) accelerated retirement/replacement of existing vessels; and 4) repowering, which involves replacing an older often mechanical engine with a newer, electronic one. The newer engine would meet one of the EPA's new emission standards for Category 1, 2, and 3 commercial marine engines. Use of newer engines to replace older marine engines will reduce emissions of most pollutants as manufacturers of marine engines to incorporate many of the controls adopted for on-road use, including basic redesign of the combustion chambers, retarding the timing, improving high-pressure fuel injection systems, upgrading or adding after cooling and turbo charging, injecting water into the air intake using humid air motors (HAM), and exhaust gas recirculation (EGR).

In considering repower; the following factors may affect emissions benefits:

- Age and emissions characteristics of engine
- Annual hours of usage
- Any change in usage (type or hours) after the project
- Any change in engine horsepower
- Disposition of replaced vessel/engine (must be scrapped for full benefits)

6.2 Calculation of benefits from repower

From the corrected emission factors listed in Table 4-7 and Table 4-8, the below Table 6-1 was created. Percent benefits are calculated using the formular: Benefits = 1-V_{710}/V_{645}. The initial benefits calculation suggested a 2% fuels benefit based on weight of fuel (volumetric efficiency will depend on the density) but that advantage is lost when the engine was tested at 17,000 hours. The reality of the measurement for fuel saving is that 2% is within the statistical error and not likely to be significant.

Table 6-1 Benefits of Replacing the EMD 645 with an EMD 710 Engine

	NOx	PM	CO	CO_2
645 engine (g/kWhr)	13.5	0.38	0.44	640
710 engine (g/kWhr)	9.81	0.05	0.4	624
Benefits, %	27	87	0	2
Benefits, tons/yr	143	13	0	284
710 eng @17,000	7.4	0.06	0.4	647
Benefits, %	45	84	0	
Benefits, tons/yr	236	12	0	0

Given that the engine operates at 69% power from the weightening factors, then the average power is 2,063kW. Iin 2014, the operating hours of the MV Daniel W Wise were 8,567 hrs on the port engine and 8,560 on the starboard engine. Using 8,500 hours as the annual operating hours, the calculated benefits for the for both engines operating the same are shown in Table 6-1.

7 Summary

Emissions measurements were made from the main engine of the *MV Daniel W. Wise* both before and after repowering the main propulsion engines and after the main engines reached about 50% of their useful life. Testing followed the protocol according of ISO 8178 E3 test cycle to determine the emissions rate of gaseous and particulate pollutants. From these measurements, the calculations indicate significant benefits in emissions for the inventories of the air districts where the MV Daniel W Wise operates both right after the engines were replaced and even when the engines reached about 50% of their useful life.

Based on the mid-life emission factors, the project pointed to a path to remove 236 tons per year of NOx and 12 tons per year of PM mass by just repowering one vessel. There were no measureable fuel and greenhouse gas saving in this study. Clearly these values would be multiplied many fold if a number of vessels were repowered so this is an opportunity for the river communities.

Appendix A – Sample Collection Methods

ISO 8178-1[5] and ISO 8178-2[6] specify the measurement and evaluation methods for gaseous and particulate exhaust emissions when combined with combinations of engine load and speed provided in IS0 8178- *Part 4: Test cycles for different engine applications*. The emission results represent the mass rate of emissions per unit of work accomplished. Specific emission factors are based on brake power measured at the crankshaft, the engine being equipped only with the standard auxiliaries necessary for its operation. Per ISO, auxiliary losses are <5 % of the maximum observed power. IMO ship pollution rules and measurement methods are contained in the "International Convention on the Prevention of Pollution from Ships", known as MARPOL 73/78[7], and sets limits on NO_x and SO_x emissions from ship exhausts. The intent of this protocol was to conform as closely as practical to both the ISO and IMO standards.

Gaseous and Particulate Emissions

A properly designed sampling system is essential to accurate collection of a representative sample from the exhaust and subsequent analysis. ISO points out that particulate must be collected in either a full flow or partial flow dilution system and UCR chose the partial flow dilution system with single venturi as shown in Figure A-1.

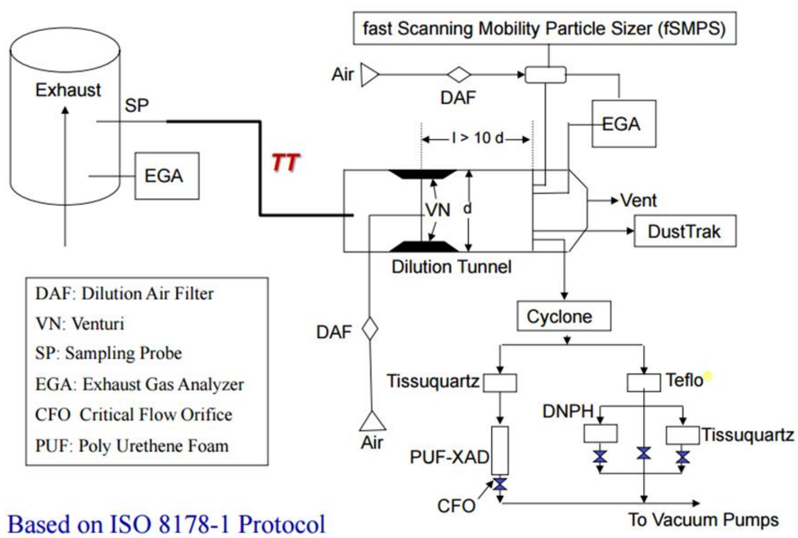

Figure A-1 Partial Flow Dilution System with Single Venturi

[5] International Standards Organization, IS0 8178-1, *Reciprocating internal combustion engines - Exhaust emission measurement -Part 1: Test-bed measurement of gaseous particulate exhaust emissions*, First edition 1996-08-l5

[6] International Standards Organization, IS0 8178-2, *Reciprocating internal combustion engines - Exhaust emission measurement -Part 2: Measurement of gaseous and particulate exhaust emissions at site,* First edition 1996-08-l5

[7] International Maritime Organization, *Annex VI of MARPOL 73/78 "Regulations for the Prevention of Air Pollution from Ships and NOx Technical Code*".

The flow in the dilution system eliminates water condensation in the dilution and sampling systems and maintains the temperature of the diluted exhaust gas at <52°C before the filters. ISO cautions the advantages of partial flow dilution systems can be lost to potential problems such as: losing particulates in the transfer tube, failing to take a representative sample from the engine exhaust and inaccurately determining the dilution ratio.

An overview of UCR's partial dilution system is shown in Figure A-1. Raw exhaust gas is transferred from the exhaust pipe (EP) through a sampling probe (SP) and the transfer tube (TT) to a dilution tunnel (DT) due to the negative pressure created by the venturi (VN) in DT. The gas flow rate through TT depends on the momentum exchange at the venturi zone and is therefore affected by the absolute temperature of the gas at the exit of TT. Consequently, the exhaust split for a given tunnel flow rate is not constant, and the dilution ratio at low load is slightly lower than at high load. More detail on the key components is provided in Table A-1.

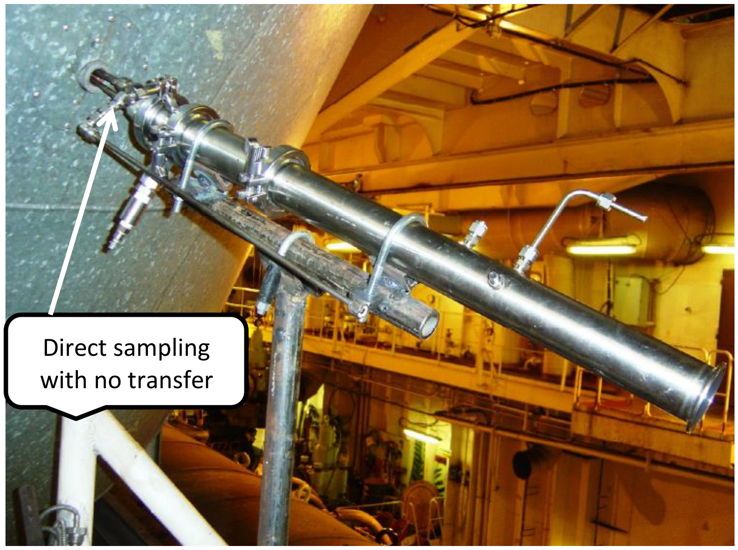

Figure A-2 measurement layout on an engine exhaust stack

Dilution Air System

ISO recommends the dilution air be at 25 ±5°C, filtered and charcoal scrubbed to eliminate background hydrocarbons. The dilution air may be dehumidified. To ensure the compressed air is of a high quality UCR processes any supplied air through a field processing unit that reduces the pressure to about 30psig as that level allows a dilution ratio of about 5/1 in the geometry of our system. The next stages, in sequence, include: a liquid knock-out vessel, desiccant to remove moisture with silica gel containing an indicator, hydrocarbon removal with activated charcoal and a HEPA filter for the fine aerosols that might be present in the supply air. The silica gel and activated carbon are changed for each field campaign. Figure A-3 shows the field processing unit in its transport case. In the field the case is used as a framework for supporting the unit

Table A-1 Components of a Sampling System: ISO/IMO Criteria & UCR Design

Section	Selected ISO and IMO Criteria	UCR Design
Exhaust Pipe (EP)	In the sampling section, the gas velocity is > 10 m/s, except at idle, and bends are minimized to reduce inertial deposition of PM. Sample position is 6 pipe diameters of straight pipe upstream and 3 pipe diameters downstream of the probe.	UCR follows the ISO recommendation, as closely as practical.
Sampling Probe (SP) -	The minimum inside diameter is 4 mm and the probe is an open tube facing upstream on the exhaust pipe centerline. No IMO code.	UCR uses a stainless steel tube with diameter of 8mm placed near the center line.
Transfer Tube (TT)	• As short as possible and < 5 m in length; • Equal to/greater than probe diameter & < 25 mm diameter; • TTs insulated. For TTs > 1m, heat wall temperature to a minimum of 250°C or set for < 5% thermophoretic losses of PM.	UCR no longer uses a transfer tube.
Dilution Tunnel (DT)	• shall be of a sufficient length to cause complete mixing of the exhaust and dilution air under turbulent flow conditions; • shall be at least 75 mm inside diameter (ID) for the fractional sampling type, constructed of stainless steel with a thickness of > 1.5 mm.	UCR uses fractional sampling; stainless steel tunnel has an ID of 50mm and thickness of 1.5mm.
Venturi (VN) --	The pressure drop across the venturi in the DT creates suction at the exit of the transfer tube TT and gas flow rate through TT is basically proportional to the flow rate of the dilution air and pressure drop.	Venturi proprietary design provided by MAN B&W; provides turbulent mixing.
Exhaust Gas Analyzers (EGA)	One or several analyzers may be used to determine the concentrations. Calibration and accuracy for the analyzers are like those for measuring the gaseous emissions.	UCR uses a 5-gas analyzer meeting IMO/ISO specs

Figure A-3 Field Processing Unit for Purifying Dilution Air in Carrying Case

Calculating the Dilution Ratio

According to ISO 8178, "it is essential that the dilution ratio be determined very accurately" for a partial flow dilution system such as what UCR uses. The dilution ratio is simply calculated from measured gas concentrations of CO_2 and/or NO_x in the raw exhaust gas, the diluted exhaust gas and the dilution air. UCR has found it useful to independently determine the dilution ration from both CO_2 and NO_x and compare the values to ensure that they are within ±10%. UCR's experience indicates the independently determined dilution ratios are usually within 5%. At systematic deviations within this range, the measured dilution ratio can be corrected, using the calculated dilution ratio. According to ISO, dilution air is set to obtain a maximum filter face temperature of <52°C and the dilution ratio shall be > 4.

Dilution System Integrity Check

ISO describes the necessity of measuring all flows accurately with traceable methods and provides a path and metric to quantifying the leakage in the analyzer circuits. UCR has adopted the leakage test and its metrics as a check for the dilution system. According to ISO the maximum allowable leakage rate on the vacuum side shall be 0.5 % of the in-use flow rate for the portion of the system being checked. Such a low leakage rate allows confidence in the integrity of the partial flow system and its dilution tunnel. Experience has taught UCR that the flow rate selected should be the lowest rate in the system under test.

Measuring the Gaseous Emissions: CO, CO_2, HC, NO_x, O_2, SO_2

Measurement of the concentration of the main gaseous constituents is one of the key activities in measuring emission factors. This section covers the ISO/IMO protocols and that used by UCR. For SO_2, ISO recommends and UCR concurs that the concentration of SO_2 is calculated based on the fact that 95+% of the fuel sulfur is converted to SO_2.

Measuring Gaseous Emissions: ISO & IMO Criteria

ISO specifies that either one or two sampling probes located in close proximity in the raw gas can be used and the sample split for different analyzers. However, in no case can condensation of exhaust components, including water and sulfuric acid, occur at any point of the analytical system. ISO specifies the analytical instruments for determining the gaseous concentration in either raw or diluted exhaust gases.

- Heated flame ionization detector (HFID) for the measurement of hydrocarbons;
- Non-dispersive infrared analyzer (NDIR) for the measurement of carbon monoxide and carbon dioxide;
- Heated chemiluminescent detector (HCLD) or equivalent for measurement of nitrogen oxides;
- Paramagnetic detector (PMD) or equivalent for measurement of oxygen.

ISO states the range of the analyzers shall accurately cover the anticipated concentration of the gases and recorded values between 15% and 100% of full scale. A calibration curve with five points is specified. However, with modern electronic recording devices, like a computer, ISO allows the range to be expanded with additional calibrations. ISO details instructions for establishing a calibration curve below 15%. In general, calibration curves must be < ±2 % of each calibration point and by < ±1 % of full scale zero.

ISO outlines their verification method. Each operating range is checked prior to analysis by using a zero gas and a span gas whose nominal value is more than 80 % of full scale of the measuring range. If, for the two points considered, the value found does not differ by more than ±4 % of full scale from the declared reference value, the adjustment parameters may be modified. If >4%, a new calibration curve is needed.

ISO & IMO specify the operation of the HCLD. The efficiency of the converter used for the conversion of NO_2 into NO is tested prior to each calibration of the NO_x analyzer. The efficiency of the converter shall be > 90 %, and >95 % is strongly recommended.

ISO requires measurement of the effects from exhaust gases on the measured values of CO, CO_2, NO_x, and 0_2. Interference can either be positive or negative. Positive interference occurs in NDIR and PMD instruments where the interfering gas gives rise to the same effect as the gas being measured, but to a lesser degree. Negative interference occurs in NDIR instruments due to the interfering gas broadening the absorption band of the measured gas, and in HCLD instruments due to the interfering gas quenching the radiation. Interference checks are recommended prior to an analyzer's initial use and after major service intervals.

Measuring Gaseous Emissions: UCR Design

The concentrations of CO, CO_2, NO_x and O_2 in the raw exhaust and in the dilution tunnel are measured with a Horiba PG-250 portable multi-gas analyzer. The PG-250 simultaneously measures five separate gas components with methods recommended by the ISO/IMO and USEPA. The signal output of the instrument is connected to a laptop computer through an RS-232C interface to continuously record measured values. Major features include a built-in sample conditioning system with sample pump, filters, and a thermoelectric cooler. The performance of the PG-250 was tested and verified under the U.S. EPA ETV program.

Figure A-4 Setup Showing Gas Analyzer with Computer for Continuous Data Logging

Details of the gases and the ranges for the Horiba instrument are shown in Table A-2. Note that the Horiba instrument measured sulfur oxides (SO_2); however, the UCR follows the protocol in ISO and calculates the SO_2 level from the sulfur content of the fuel as the direct measurement for SO_2 is less precise than calculation.

Table A-2 Detector Method and Concentration Ranges for Monitor

Component	Detector	Ranges
Nitrogen Oxides (NOx)	Heated Chemiluminescence Detector (HCLD)	0-25, 50, 100, 250, 500, 1000, & 2500 ppmv
Carbon Monoxide (CO)	Non dispersive Infrared Absorption (NDIR)	0-200, 500, 1000, 2000, & 5000 ppmv
Carbon Dioxide (CO_2)	Non dispersive Infrared Absorption (NDIR)	0-5, 10, & 20 vol%
Sulfur Dioxide (SO_2)	Non dispersive Infrared Absorption (NDIR)	0-200, 500, 1000, & 3000 ppmv
Oxygen	Zirconium oxide sensor	0-5, 10, & 25 vol%

For quality control, UCR carries out analyzer checks with calibration gases both before and after each test to check for drift. Because the instrument measures the concentration of five gases, the calibration gases are a blend of several gases (super-blend) made to within 1% specifications. Experience has shown that the drift is within manufacturer specifications of ±1% full scale per day shown in Table A-3. The PG-250 meets the analyzer specifications in ISO 8178-1 Section 7.4 for repeatability, accuracy, noise, span drift, zero drift and gas drying.

Table A-3 Quality Specifications for the Horiba PG-250

Repeatability	±0.5% F.S. (NO_x: </= 100ppm range CO: </= 1,000ppm range) ±1.0% F. S.
Linearity	±2.0% F.S.
Drift	±1.0% F. S./day (SO_2: ±2.0% F.S./day)

Measuring the Particulate Matter (PM) Emissions

ISO 8178-1 defines particulates as any material collected on a specified filter medium after diluting exhaust gases with clean, filtered air at a temperature of </= 52ºC, as measured at a point immediately upstream of the primary filter. The particulate consists of primarily carbon, condensed hydrocarbons and sulfates, and associated water. Measuring particulates requires a dilution system and UCR selected a partial flow dilution system. The dilution system design completely eliminates water condensation in the dilution/sampling systems and maintains the temperature of the diluted exhaust gas at < 52°C immediately upstream of the filter holders. IMO does not offer a protocol for measuring PM. A comparison of the ISO and UCR practices for sampling PM is shown in Table A-4.

Table A-4 Measuring Particulate by ISO and UCR Methods

	ISO	**UCR**
Dilution tunnel	Either full or partial flow	Partial flow
Tunnel & sampling system	Electrically conductive	Same
Pretreatment	None	Cyclone, removes >2.5µm
Filter material	Fluorocarbon based	Teflon (TFE)
Filter size, mm	47 (37mm stain diameter)	Same
Number of filters in series	Two	One
Number of filters in parallel	Only single filter	Two; 1 TFE & 1 Quartz
Number of filters per mode	Single or multiple	Multiple
Filter face temp. °C	< 52	Same
Filter face velocity, cm/sec	35 to 80.	~33
Pressure drop, kPa	For test <25	Same
Filter loading, µg	>500	500-1,000 + water w/sulfate
Weighing chamber	22±3°C & RH= 45%± 8	Same
Analytical balance, LDL µg	10	0.5
Flow measurement	Traceable method	Same
Flow calibration, months	< 3months	Every campaign

Sulfur content. According to ISO, particulates measured using IS0 8178 are “conclusively proven” to be effective for fuel sulfur levels up to 0.8%. UCR is often faced with measuring PM for fuels with sulfur content exceeding 0.8% and has extended this method to those fuels as no other method is prescribed for fuels with a higher sulfur content.

Calculating Exhaust Flow Rates

The calculated emission factor requires the measurement of the engines exhaust flow rate. The exhaust gas flow can be determined by the following methods:

1. Direct Measurement Method
2. Carbon Balance Method
3. Air and Fuel Measurement Method
4. Air Pump method

Method 1: Direct Measurement of exhaust

Actual exhaust mass flow rate can be determined from the exhaust velocity, cross sectional area of the stack, and moisture and pressure measurements. The direct measurement method is a difficult technique, and precautions must be taken to minimize measurement errors. Details of the direct measurement method are provided in ISO 5167-1.

Method 2(a)-Carbon Balance

Carbon Balance is used to calculate the exhaust mass flow based on the measurement of fuel consumption and the exhaust gas concentrations with regard to the fuel characteristics. The method given is only valid for fuels without oxygen and nitrogen content, based on procedures used for EPA and ECE calculations. Detailed calculation steps of the Carbon Balance method are provided in annex A of ISO 8178-1. Basically: In…lbs fuel/time * wt% carbon * 44/12 → input of grams CO2 per time Out… vol % CO2 * (grams exhaust/time * 1/density exhaust) → exhaust CO2 per time

Note that the density = (mole wt*P)/(R* Temp) where P, T are at the analyzer conditions. For highly diluted exhaust, M ~ of the atmosphere.

Method 2(b)-Universal Carbon/Oxygen balance

The Universal Carbon/Oxygen Balance is used for the calculation of the exhaust mass flow. This method can be used when the fuel consumption is measurable and the fuel composition and the concentration of the exhaust components are known. It is applicable for fuels containing H, C, S, 0, N in known proportions. Detailed calculation steps of Carbon/Oxygen Balance method is provided in annex A of ISO 8178-1.

Method 3-Air and Fuel Measurement Method

This involves measurement of the air flow and the fuel flow. The calculation of the exhaust gas flow is provided in Section 7.2 of ISO 8178-1.

Method 4-Air Pump Method

Exhaust flow rate is calculated by assuming engine is an air pump, meaning that the exhaust flow is equal to the intake air flow. The flow rate is determined from the overall engine displacement, and rpm; corrected for temperature and pressure of the inlet air and pumping efficiency. In the case of turbocharged engines, this is the boost pressure and intake manifold temperature. This method should not be used for diesel engines equipped with additional air input for cylinder exhaust discharge, called purge or scavenger air, unless the additional flow rate is known or can be determined.

Added Comments about UCR's Measurement of PM

In the field UCR uses a raw particulate sampling probe fitted close to and upstream of the raw gaseous sample probe and directs the PM sample to the dilution tunnel. There are two gas streams leaving the dilution tunnel; the major flow vented outside the tunnel and the minor flow directed to a cyclone separator, sized to remove particles >2.5um. The line leaving the cyclone separator is split into two lines; each line has a 47 Gelman filter holder. One holder collects PM on a Teflon filter and the other collects PM on a quartz filter. UCR simultaneously collects PM on Teflon and quartz filters at each operating mode and analyzes them according to standard procedures.

Briefly, total PM was collected on Pall Gelman (Ann Arbor, MI) 47 mm Teflo filters and weighed using a Metler Toledo UMX2 microbalance with a 0.1 ug resolution. Before and after collection, the filters were conditioned for 24 hours in an environmentally controlled room (RH = 40%, T= 25 $^{\circ}$ C) and weighed daily until two consecutive weight measurements were within 3 µg or 2%. It is important to note that the simultaneous collection of PM on quartz and Teflon filters provides a comparative check of PM mass measured by two independent methods and serves as an important Quality Check for measuring PM mass.

Measuring Real-Time Particulate Matter (PM) Emissions-DustTrak

In addition to the filter-based PM mass measurements, UCR uses a Nephelometer (TSI DustTrak 8520) for continuous measurements of steady-state and transient data. The DustTrak is a portable, battery-operated laser photometer that gives real-time digital readout and has a built-in data logger. It measures light scattered by aerosol introduced into a sample chamber and displays the measured mass density as units of mg/m^3. As scattering per unit mass is a strong function of particle size and refractive index of the particle size distributions and as refractive indices in diesel exhaust strongly depend on the particular engine and operating condition, some question the accuracy of PM mass measurements. However, UCR always references the DustTrak results to filter based measurements and this approach has shown that mass scattering efficiencies for both on-road diesel exhaust and ambient fine particles have values around 3m^2/g. For these projects, a TSI DustTrak 8520 nephelometer measuring 90 degree light scattering at 780nm (near-infrared) is used.

Figure 0-1 Picture of TSI DustTrak

Measuring Non-Regulated Gaseous Emissions

Neither ISO nor IMO provide a protocol for sampling and analyzing non-regulated emissions. UCR uses peer reviewed methods adapted to their PM dilution tunnel. The methods rely on added media to selectively collect hydrocarbons and PM fractions during the sampling process for subsequent off-line analysis. A secondary dilution is constructed to capture real time PM.

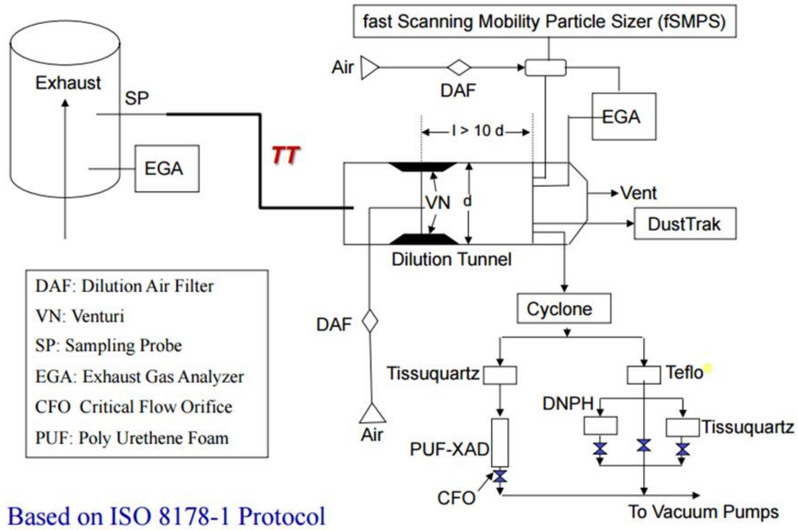

Figure A-5 Extended setup of the PFDS for non-regulated emissions

Appendix B – Quality Control

Pre-test calibrations

Prior to departing from UCR all systems were verified and cleaned for the testing campaign. This included all instruments used during this testing project. All systems were found to be within specifications and the systems were prepared for testing.

On-site calibrations

Pre- and post-test calibrations were performed on the gaseous analyzer using NIST traceable calibration bottles. Post-test dilution ratio was verified by removing the probe from the dilution tunnel and sampling from the raw exhaust. This method has been used in addition to operating two gas analyzers and has been shown to be reliable. Hourly zero checks were performed with each of the real time PM instruments. Leak checks were performed for the total $PM_{2.5}$ system prior to each sample point.

Post-test and data validation

Post-test evaluation includes verifying consistent dilution ratios between points, verifying brake specific fuel consumption with reported manufacturer numbers. Typically this involves corresponding with the engine manufacturer to discuss the results on an emissions basis of interest. The brake specific fuel consumption results were with-in reason and thus suggest the load and mass of emissions measured are reasonable and representative. Thus, this suggests the data collected for the test article are accurate and representative of a properly functioning system.

CE-CERT

College of Engineering: Center for Environmental Research and Technology

Analytical Laboratory
University of California, Riverside
Data Results For TEFLON Filters

Project Name: Original AEP River Operations - Kentuck | **Project Fund #:**
PI/Contact: Wayne Miller | **Send Results: Nick Gysel**

Sample ID	Serial ID	Date Received	Initial Weight (mg/filter)	Final Weight (mg/filter)	NET Weight (mg/filter)	Initials	COMMENTS
AT120473	n/a	2/x/2013	191.2060	192.6972	1.4912	MV	
AT120474	n/a	2/x/2013	189.2139	191.2111	1.9972	MV	
AT120475	n/a	2/x/2013	194.4568	196.2289	1.7721	MV	
AT120476	n/a	2/x/2013	190.1723	191.7284	1.5561	MV	
AT120477	n/a	2/x/2013	153.2872	154.4464	1.1592	MV	
AT120478	n/a	2/x/2013	187.4435	188.9519	1.5084	MV	
AT120479	n/a	2/x/2013	182.9071	184.0064	1.0993	MV	
AT120481	n/a	2/x/2013	178.7453	179.3674	0.6221	MV	
AT120482	n/a	2/x/2013	165.5829	166.2499	0.6670	MV	

Figure B-0-1 Sample Chain of Custody Form

PRAXAIR.

Praxair Distribution, Inc.
5700 S. Alameda St.
Los Angeles, CA 90058
Tel: 323-585-2154
Fax: 714-542-6689

11/06/2012

UC RIVERSIDE
DIESEL LAB
1200 COLUMBIA AVE
RIVERSIDE, CA 925210000
Attention: LUCI PACOCHA 909-781-5791,

Work Order No. **21895565**
Customer Reference No.

Product Lot/Batch No. **109230503**
Product Part No. **NI CD12CNP18PAS**

CERTIFICATE OF ANALYSIS

Primary Standard

Component	Requested Concentration	Certified Concentration	Analytical Principle	Analytical Accuracy
Carbon dioxide	**12 %**	**11.76 %**	**L**	**± 1%**
Carbon monoxide	**500 ppm**	**501 ppm**	**L**	**± 1%**
Nitric oxide	**2000 ppm**	**1929 ppm**	**U**	**± 1%**
Propane	**500 ppm**	**515 ppm**	**Q**	**± 1%**
Nitrogen	**balance**	**balance**		

Analytical Instruments: **Horiba Instruments Inc.~VIA-510~NDIR~Non-dispersive Infrared**
Thermo Environmental~42i~Nitric Oxide Analyzer~Chemiluminescence
Horiba Instruments Inc.~FIA-510~THC- Total Hydrocarbon Analyzer~FID - Flame Ionization Detector

Cylinder Style: **AS**
Cylinder Pressure @70F: **2000 psig**
Cylinder Volume: **140 ft3**
Valve Outlet Connection: **CGA-660**
Cylinder No(s). **CC92665**
Comments: **[NOx] = 1947 ppm for reference only.**
All values not valid below 150 psig.

Filling Method: **Gravimetric**
Date of Fill: **10/31/2012**
Expiration Date: **11/06/2014**

Analyst: **Chas Manning**

Approved Signer: **Nelson Ma**

Figure B-2 Sample Protocol Gas Analysis

Appendix C –Test Modes and Load Estimates

Test Cycles and Fuels for Different Engine Applications

Engines for off-road use are made in a much wider range of power output and used in a more applications than engines for on-road use. The objective of IS0 8178-4[8] is provide the minimum number of test cycles by grouping applications with similar engine operating characteristics. ISO 8178-4 specifies the test cycles while measuring the gaseous and particulate exhaust emissions from reciprocating internal combustion engines coupled to a dynamometer or at the site. The tests are carried out under steady-state operation using test cycles which are representative of given applications.

Table C-1 Definitions Used Throughout ISO 8178-4

Test cycle	A sequence of engine test modes each with defined speed, torque and weighting factor, where the weighting factors only apply if the test results are expressed in g/kWh.
Preconditioning the engine	1) Warming the engine at the rated power to stabilize the engine parameters and protect the measurement against deposits in the exhaust system. 2) Period between test modes which has been included to minimize point-to-point influences.
Mode	An engine operating point characterized by a speed and a torque.
Mode length	The time between leaving the speed and/or torque of the previous mode or the preconditioning phase and the beginning of the following mode. It includes the time during which speed and/or torque are changed and the stabilization at the beginning of each mode.
Rated speed	Speed declared by engine manufacturer where the rated power is delivered.
Intermediate speed	Speed declared by the manufacturer, taking into account the requirements of ISO 8178-4 clause 6.

Intermediate speed

For engines designed to operate over a speed range on a full-load torque curve, the intermediate speed shall be the maximum torque speed if it occurs between 60% and 75% of rated speed. If the maximum torque speed is less than 60% of rated speed, then the intermediate speed shall be 60% of the rated speed. If the maximum torque speed is greater than 75% of the rated speed then the intermediate speed shall be 75% of rated speed.

[1]International Standards Organization, IS0 8178-4, *Reciprocating internal combustion engines - Exhaust emission measurement - Part 4: Test cycles for different engine applications,* First edition IS0 8178-4:1996(E)

The intermediate speed will typically be between 60% and 70% of the maximum rated speed for engines not designed to operate over a speed range on the full-load torque curve at steady state conditions. Intermediate speeds for engines used to propel vessels with a fixed propeller are defined based on that application.

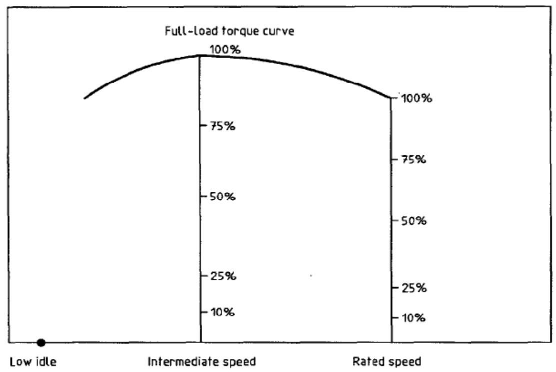

Figure C-1 Torque as a Function of Engine Speed

Engine Torque Curves and Test Cycles

The percentage of torque figures given in the test cycles and Figure C-1 represent the ratio of the required torque to the maximum possible torque at the test speed. For marine test cycle E3, the power figures are percentage values of the maximum rated power at the rated speed as this cycle is based on a theoretical propeller characteristic curve for vessels driven by heavy duty engines. For marine test cycle E4 the torque figures are percentage values of the torque at rated power based on the theoretical propeller characteristic curve representing typical pleasure craft spark ignited engine operation. For marine cycle E5 the power figures are percentage values of the maximum rated power at the rated speed based on a theoretical propeller curve for vessels of less than 24 m in length driven by diesel engines. Figure C-2 shows the two representative curves.

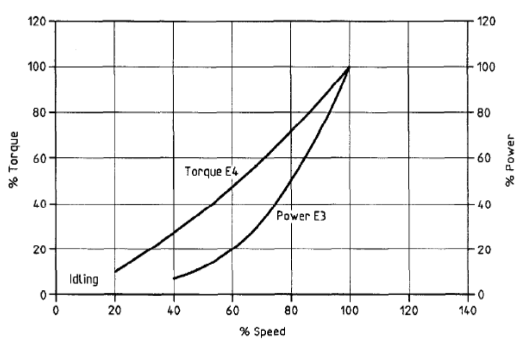

Figure C-2 Examples of Power Scales

Modes and Weighting Factors for Test Cycles

Most test cycles were derived from the 13-mode steady state test cycle (UN-ECE R49). Apart from the test modes of cycles E3, E4 and E5, which are calculated from propeller curves, the test modes of the other cycles can be combined into a universal cycle (B) with emissions values calculated using the appropriate weighting factors. Each test shall be performed in the given sequence with a minimum test mode length of 5 minutes or enough to collect sufficient particulate sample mass. The mode length shall be recorded and reported and the gaseous exhaust emission concentration values shall be measured and recorded for the last 3 min of the mode. The completion of particulate sampling ends with the completion of the gaseous emission measurement and shall not commence before engine stabilization, as defined by the manufacturer.

Table C-2 Combined Table of Modes and Weighting Factors

B-Type mode number	1	2	3	4	5	6	7	8	9	10	11
Torque	100	75	50	25	10	100	75	50	25	10	0
Speed	Rated speed					Intermediate speed					Low idle
Off-road vehicles											
Cycle C1	0,15	0,15	0,15		0,1	0,1	0,1	0,1			0,15
Cycle C2				0,06		0,02	0,05	0,32	0,3	0,1	0,15
Constant speed											
Cycle D1	0,3	0,5	0,2								
Cycle D2	0,05	0,25	0,3	0,3	0,1						
Locomotives											
Cycle F	0,25							0,15			0,6
Utility, lawn and garden											
Cycle G1						0,09	0,2	0,29	0,3	0,07	0,05
Cycle G2	0,09	0,2	0,29	0,3	0,07						0,05
Cycle G3	0,9										0,1
Marine application											
Cycle E1	0,08	0,11					0,19	0,32			0,3
Cycle E2	0,2	0,5	0,15	0,15							
Marine application propeller law											
Mode number E3	**1**					**2**		**3**	**4**		
Power (%)	100					75		50	25		
Speed (%)	100					91		80	63		
Weighting factor	0,2					0,5		0,15	0,15		
Mode number E4	**1**					**2**		**3**	**4**		**5**
Speed (%)	100					80		60	40		Idle
Torque (%)	100					71,6		46,5	25,3		0
Weighting factor	0,06					0,14		0,15	0,25		0,4
Mode number E5	**1**					**2**		**3**	**4**		**5**
Power (%)	100					75		50	25		0
Speed (%)	100					91		80	63		Idle
Weighting factor	0,08					0,13		0,17	0,32		0,3

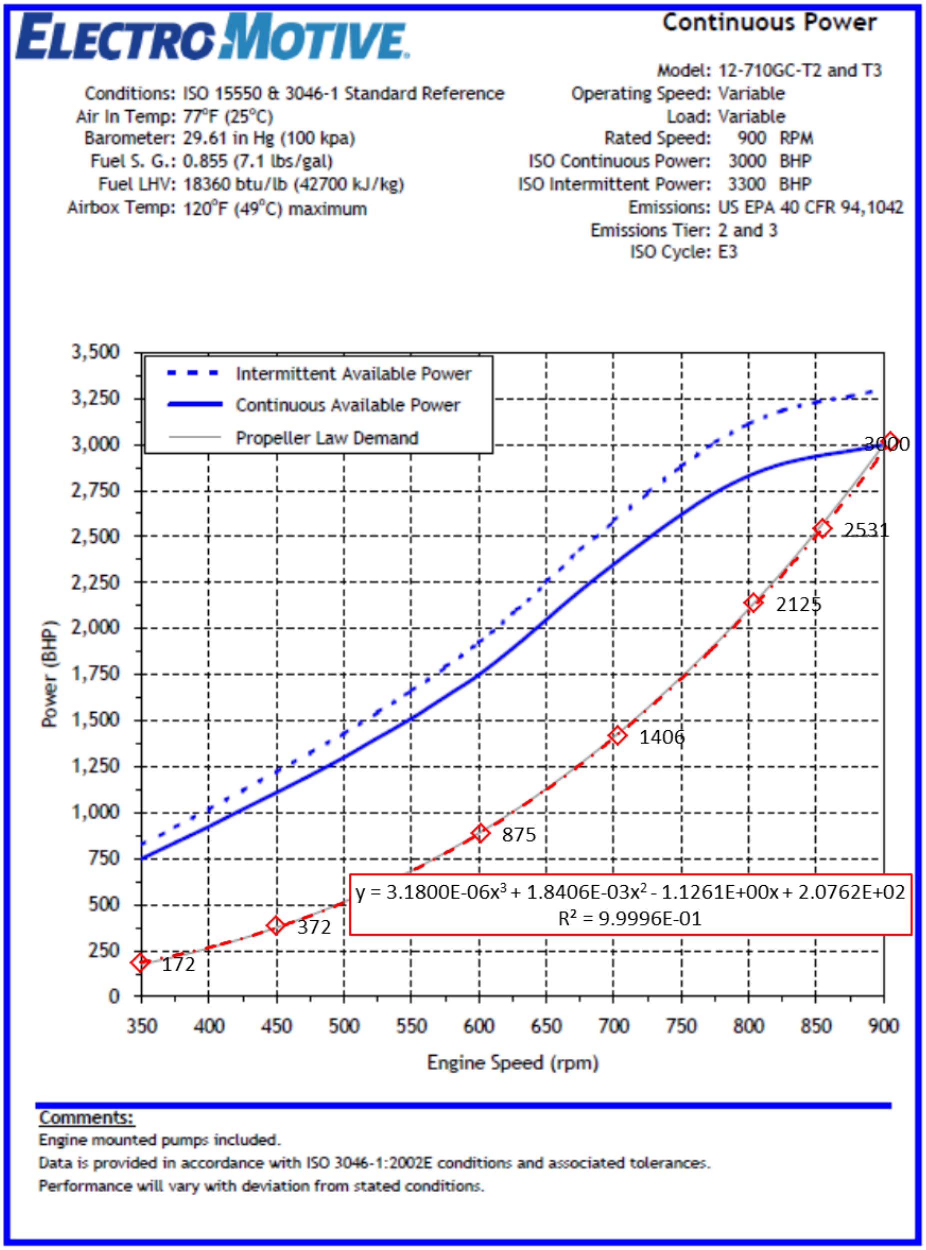

Figure C-3 Power Curve for EMF 12-710 GC