Marine Advanced Retrofit System

Deliverable 1 - Baseline Emission Measurements on the Vessel

for:

New Technology Research and Development Program

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Abstract/Executive Summary

This report describes the first deliverable of the Marine Advanced Retrofit project funded by TCEQ. Baseline emission measurement on a marine vessel diesel engine was conducted. We calibrated advanced portable emission measurement devices in an engine dynamometer and installed the equipment on the vessel's engine. Engine-out emission concentration data on key, regulated criteria pollutants (species) was collected, including diesel nitrogen oxides (NO_x), particulate matter (PM), unburned hydrocarbons (HC) and carbon monoxide (CO), as well as other relevant species (e.g. sulfur dioxide and oxygen). The data from this measurement will be the basis for proper design of the proposed marine aftertreatment system

Introduction / Background

The goal of this project is to develop a diesel emission reduction aftertreatment retrofit system which includes both a selective catalytic reduction (SCR) and a diesel particulate filter (DPF) for diesel-powered harbor craft. This SCR-DPF aftertreatment retrofit system is especially important for vessels operating within the United States Environmental Protection Agency (US-EPA) National Ambient Air Quality Standards non-attainment areas, such as those within the state of Texas including the Port of Houston. The proposed retrofit system has the potential to reduce NO_x and PM by 75% and 90%, respectively; i.e. it would reduce the emissions on US-EPA Tier 0 and 2 (current regulation) engines down to Tier 2 and Tier 4 engine levels, respectively.

This stand-alone retrofit system will be applicable to not only newer, electronically controlled engines, but also to older, mechanically governed ones (i.e. Tier 1 and earlier). This is significant since these older and higher emitting engines may still have considerable remaining useful life, hence their replacement is neither desirable nor cost-effective. This retrofit system would provide a cost-effective solution, typically about $25,000 installed cost for engines up to 500 kilowatts (kw) or 680 hp which is significantly lower than current retrofit and repower options. It is planned to verify this aftertreatment technology before the start of their production and distributions, anticipated to take place in 2012.

Project Objectives / Technical Approach

Phase 1 is to include identifying a harbor vessel for which the SCR-DPF system is to be designed, followed by measuring its engine baseline emissions. These measurements are needed for proper design of the aftertreatment system, such as selection of the catalysts, computational fluid dynamics (CFD) analysis, or for selecting an engine for dynamometer testing in later phases. Also in Phase 1, advanced engineering models and simulation tools such as CFD, 1-D and 2-D catalyst kinetics models are to be used to achieve appropriate system design.

Developmental testing and analysis will be performed in Phase 2 in an engine dynamometer lab. The following regulated emissions will be measured: NO_x, PM, HC, non-methane hydrocarbon (NMHC), CO, and carbon dioxide (CO_2). Exhaust gas temperature before the particulate filter will be measured to ensure a proper passive regeneration temperature profile can be maintained for proper operation of the diesel soot filter.

In Phase 3, a prototype SCR-DPF aftertreatment system will be installed in the vessel and in-sito measurement of the conversion efficiency of emission species (both upstream and downstream of the aftertreatment system) will be made. Testing will be completed according to the US-EPA and Society of Automotive Engineers (SAE) testing protocols.

Tasks

Task 1 - Baseline engine emission measurement on the vessel

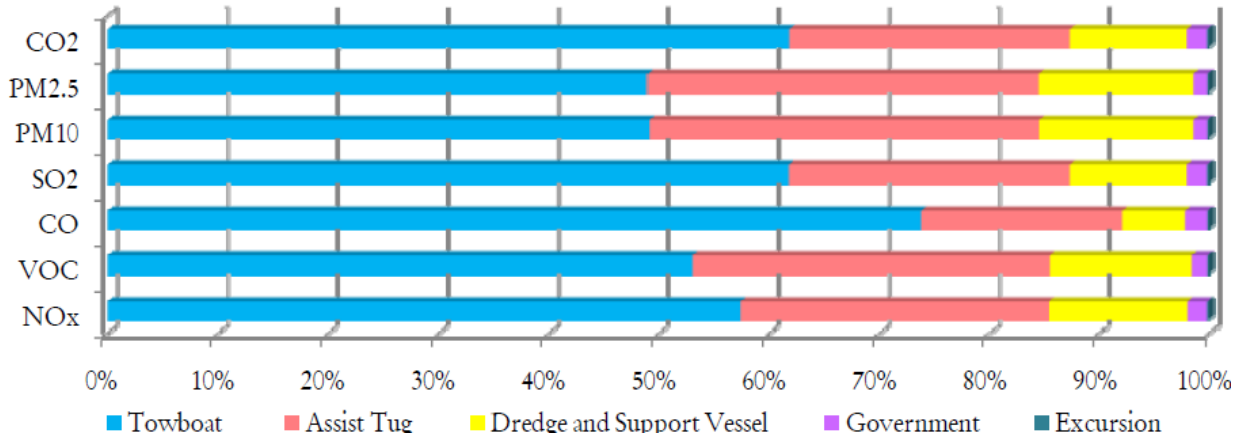
From the Grant Activities (Scope of Work):

> *"Task 1: Baseline Emissions Measurements on Vessel*
>
> *2.1. Task Statement: The PERFORMING PARTY will identify an appropriate marine vessel for in use testing, negotiate access to the vessel, and collect baseline emission data from the vessel.*
>
> *2.1.1. The PERFORMING PARTY will identify a suitable marine vessel for in-use emissions testing and negotiate an agreement with the vessel owner regarding timing of testing and lease terms.*
>
> *2.1.2. The PERFORMING PARTY will measure baseline raw emissions and exhaust temperatures on the selected vessel using Portable Emissions Measurement (PEMS) equipment and collect measurement of space limitations on the vessel in preparation for retrofit installation.*
>
> *2.1.3. Schedule: The PERFORMING PARTY shall complete this task within 2 months of the signed Notice to Proceed Date as issued by TCEQ.*
>
> *2.1.4. Deliverables: The PERFORMING PARTY shall submit a report to the TCEQ upon completion of this task. This report will include but is not limited to baseline emissions and exhaust temperature measurement data."*

Task 1.1: Identify marine vessel and engine selection

This project targets the reduction of criteria pollutants, particularly NO_x, from the marine emission sources in the EPA non-attainment areas of Texas. To develop the proposed aftertreatment system, it is necessary to gather emissions from a representative vessel engine. Together tow and tug boats produce almost 90% of the marine NO_x emissions in the Houston-Galveston area (Figure 1). For the purpose of this project, we chose a towboat as the test vessel. Tow and tug boats have fairly similar engines in terms of their power ratings; hence an aftertreatment system designed for one could be applicable to another with modest modifications.

Figure 1. Percentage of 2007 harbor vessel emissions by vessel type [1]



In collaboration with the Port of Houston Authority and other organizations in Texas, Bosch was able to identify an appropriate vessel for testing during this project. A diesel engine with a power rating of 600 hp was selected for emissions measurement. From the variety of vessel engines available to Bosch for emissions measurement, the one in the selected boat (Figure 2) appeared to meet the initially-targeted specifications for the engine power rating of a 600 hp, Tier 2 compliant engine.

Figure 2. The tow boat used for baseline emissions measurement of a marine diesel engine

Task 1.2: On site measurement

Consistent with the earlier project targets the emissions measurement on the vessel focused on engine NO_x and PM, with the vessel cruising in its typical, daily load-and-speed combinations (duty cycles). Other, relevant emission species were also collected and described in Task 1.3.

Description of measurement equipment

The portable system used in this on-site measurement included: various thermocouples to measure engine exhaust temperature along the exhaust pipe; a heated and a non-heated sampling tube for measuring exhaust unburned fuel (hydrocarbons or HC), NO_x species (NO and NO_2), CO, and diesel engine PM; and a magnetic reader to detect the engine speed, boost pressure, and temperature for calculating the engine exhaust mass flow rate and the exhaust flow static pressure. All the measurement signals (temperatures, species, pressure, speed) were then properly connected to and recorded on a data logger particularly prepared and tuned for the purpose of recording engine emission data (Figure 3).

Figure 3. Schematic view of emission measurement instruments and communication used on the marine vessel

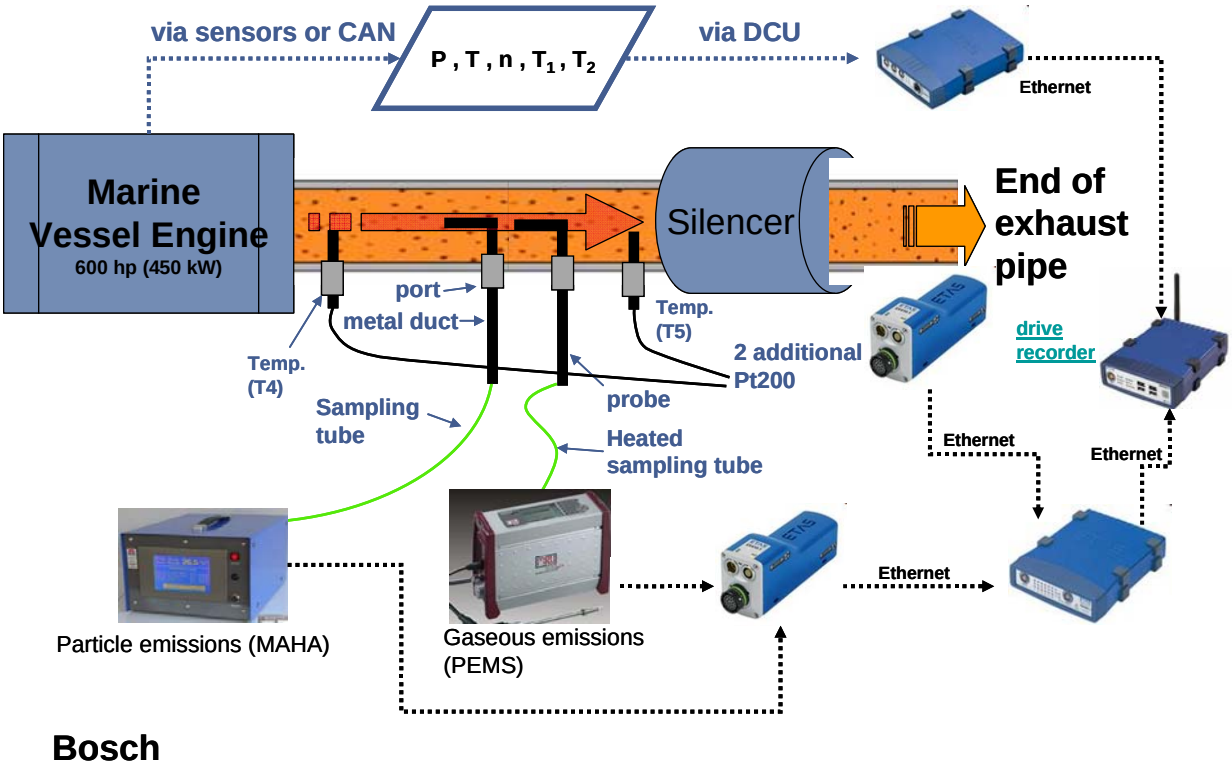


Figure 3 displays installation of the emissions measurement instruments. Particulate and gaseous emission ports were installed between the vessel engine and the silencer. Temperature measurement equipment was installed before and after these ports (between the vessel engine and the silencer). A drive recorder collects the data (including engine data) via an ethernet connection.

Preparation of measurement equipment

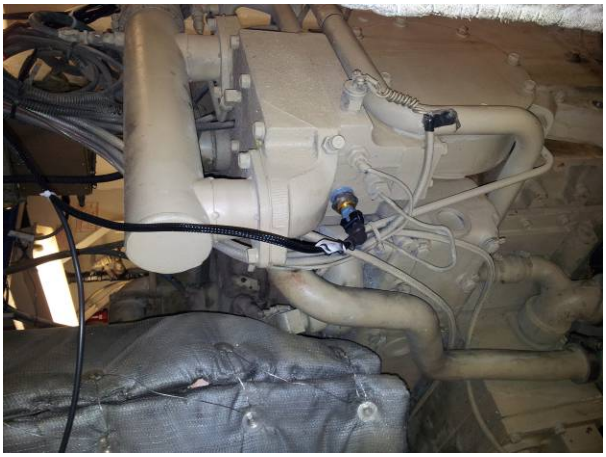
Prior to the installation of the devices on the engine, these instruments were installed in an engine dynamometer at Bosch and all instruments were tested and properly calibrated. Measurement procedure was rehearsed a few times to assure a trouble-free measurement when installed on the boat.

Installation of measurement equipment on the marine vessel

Once internally tested and calibrated in an engine dynamometer lab at Bosch, the measurement devices were next shipped to the marine vessel site. A local marine engine mechanic was commissioned to install various weld-on sockets on the engine for our temperature sensors, probes, exhaust emissions sampling lines (Figure 6) and also to install the magnetic reader on the engine flywheel (Figure 4). The gaseous measurement device (MRU) and particulate measurement (MAHA) device were located close to the exhaust pipe, as shown in Figure 6.

Figure 4. Vessel engine with aftertreatment wiring harness (left) and mounted speed sensor (right)

Figure 5. Engine coolant temperature (left) and communication devices (right)



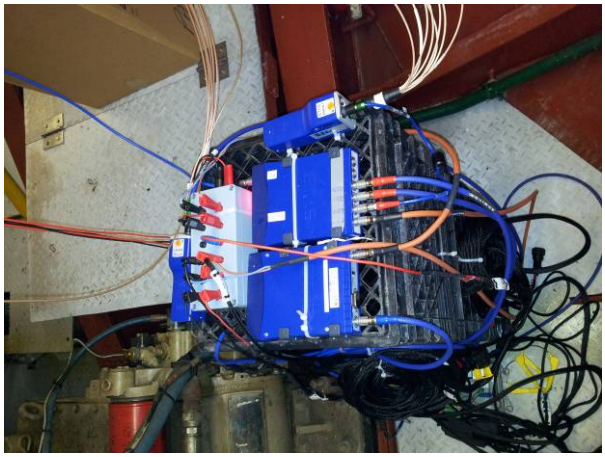


Figure 6. Gaseous and particulate emission probes (left) and the measurement devices (right)

Data collection

Test runs

Upon completing the installation of all the measurement components, first various pilot runs were conducted to assure proper data collection would indeed take place by the instruments. To do so, the vessel was navigated by the boat captain through its various engine modes (low speed-low load, low speed-high load, etc.) and the collected data was next inspected. Amongst various inspections, this initial data was also benchmarked against the engine data previously attained from the engine manufacturer, assuring overall proper system operations.

Collecting the main, definitive engine emissions data

Once the 'quality control' phase was completed, the vessel was next sent into its routine navigation drive cycles and the main phase of the measurement commenced while data was being collected. The device installation and measurement started on Nov. 21, 2011, and were terminated on December 1, 2011.

Task 1.3: Data analysis

The results of the data collection were consistent with our initial expectation, particularly with data received from the engine manufacturer.

Figure 7 shows a typical load profile/driving cycle of the vessel. The vessel duty cycle appears to be a combination of low idle (approximately700 revolutions per minutes (rpm)) and full load at (approximately 2050 rpm) operations. The transient operation before and after full load is known as parking and manoeuvring, especially when the loaded barge tried to dock at the harbor.

Figure 7. Diagram of vessel driving cycle

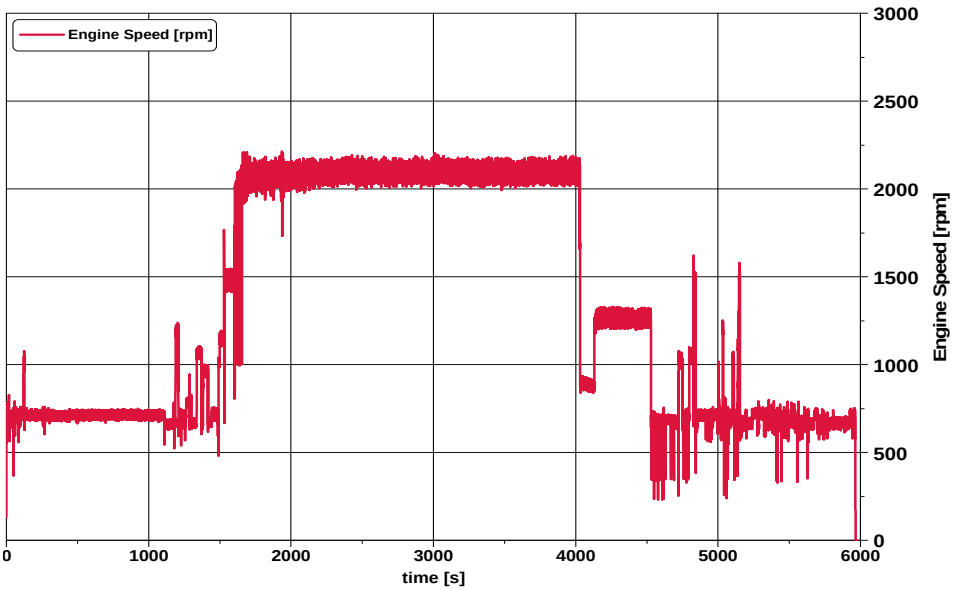


Figure 8 displays the engine speed (red) along with the emission of criteria pollutants: NO (blue), NO_2 (pink) and CO (green). During full load operation (1600 to 4000 seconds) the NO_x value is approximately 880 parts per million (ppm) and CO concentration about 300 ppm. Observed peak emissions are consistent with the expected transient operation.

Figure 8. Diagram of CO, NO, and NO_2 emissions

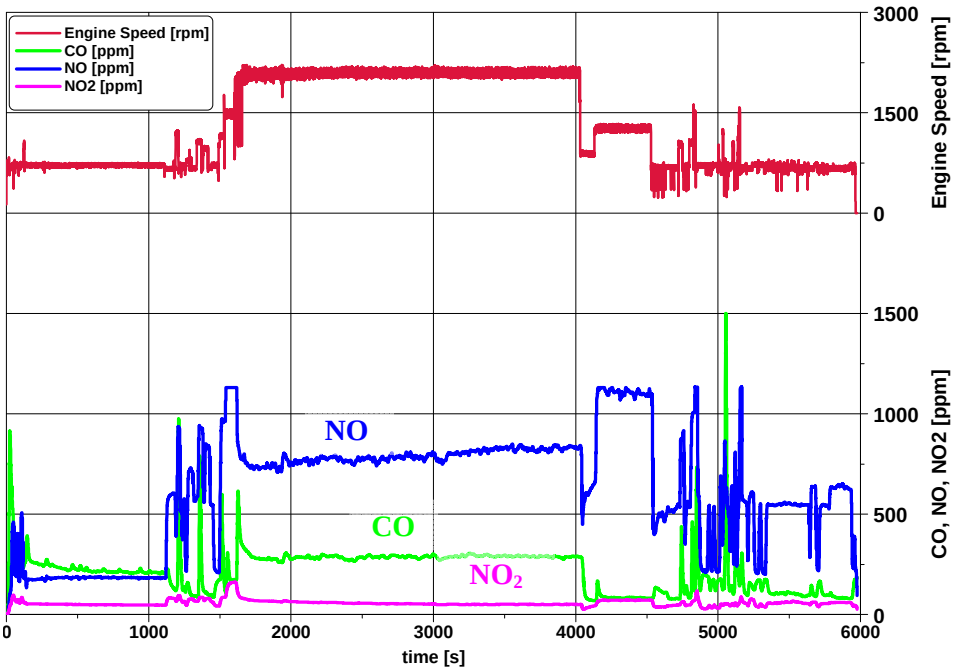


Figure 9 demonstrates the engine speed (red) and the measured concentration of oxygen (cyan) and CO_2 (gray) in the marine engine exhaust gas.

Figure 9. Diagram of O_2 and CO_2 during operation

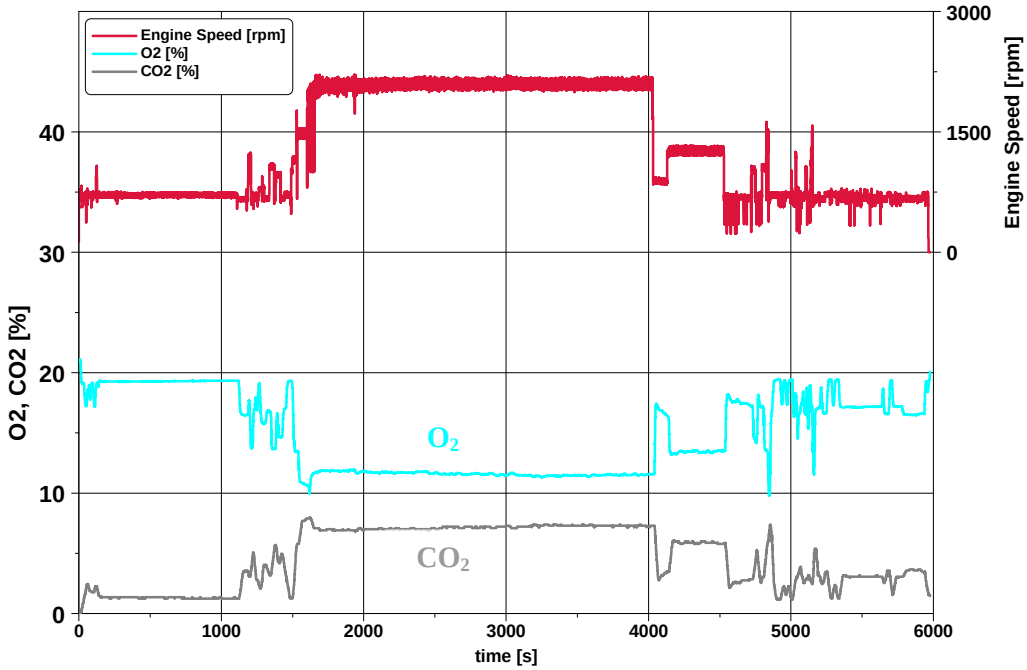


Figure 10 reveals the engine speed (red) along with the measured concentrations of diesel PM (black), unburned HC (gray), and SO_2 (green). Due to the transient engine operation and partly 'cold' engine temperature conditions, PM at times peaks to 330 micrograms per cubic meter (mg/m³) (between 1050 and 1600 seconds) During normal operation the PM emissions are in the range of 1-3 mg/m³.

Figure 10. Diagram of PM, HC, and SO_2 emissions

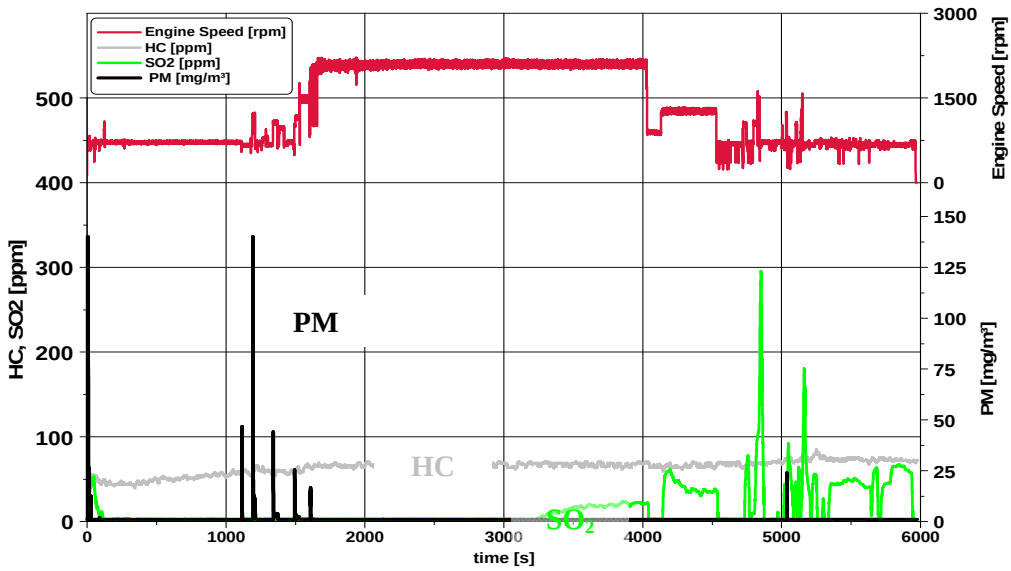


Figure 11 displays the engine speed (red), the exhaust temperature at the point of sampling measured both using a thermocouple (blue) and a PT-200 temperature sensor (magenta). The temperature was measured

here using both probes for synchronizing their values against each other and assuring measurement accuracy. Temperatures larger than 250°C are needed for achieving proper conversion rates in aftertreatment system catalysts. The minimum idle engine temperature is seen to be around 120°C and at full load around 390°C.

Figure 11. Diagram of exhaust temperatures during operation

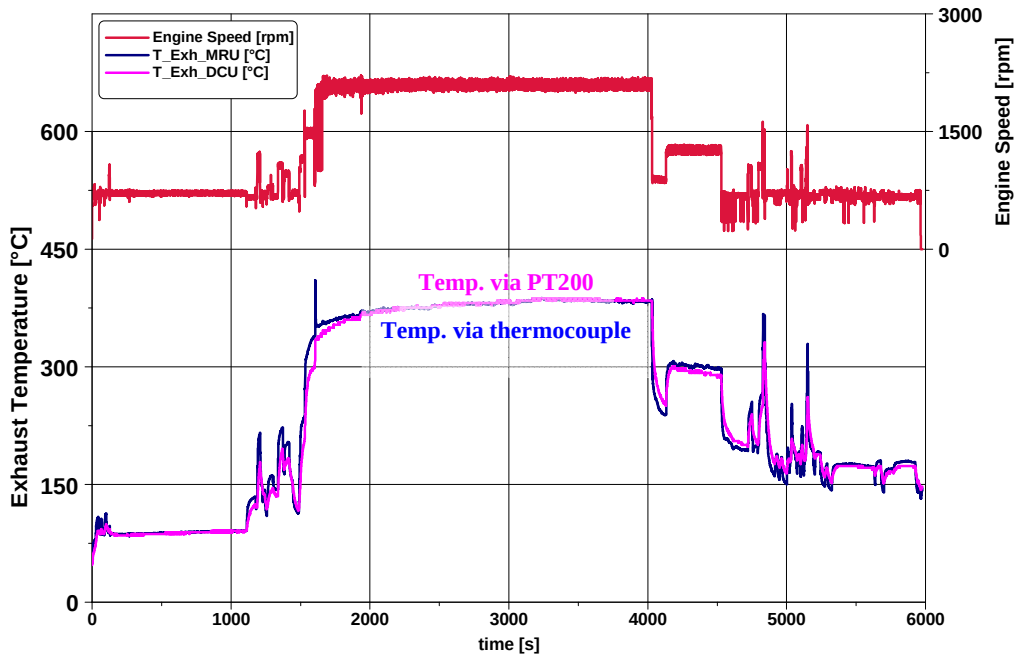


Figure 12 indicates the engine speed (red) along with the exhaust mass flow rate, itself calculated using boost pressure, boost temperature, and the engine speed. The exhaust gas mass flow rate is needed for proper design of the SCR urea dosing strategy, i.e. to calculate the amount of urea for various engine operation modes.

Figure 12. Diagram of exhaust gas mass flow

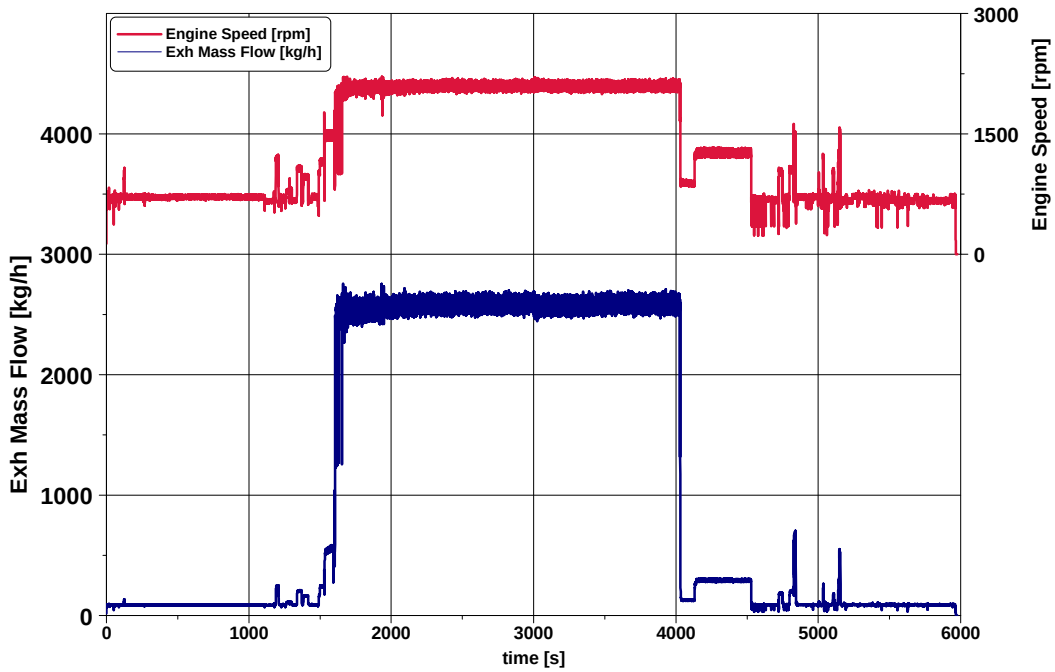


Table 1 reveals that the measured concentration of the engine species (including NO_x, HC, CO, and PM) fall well within the published engine performance data made available to Bosch by the engine manufacturer, Cummins. Emissions values from Figures 8 and 10 were used to calculate the specific emissions in gramps per kilowatt-hour (g/kWh) at rated speed for a 600 hp or 450 kw engine.

Table 1. Engine emissions in grams per kilowatt-hour at rated speed in accordance with ISO 8178 Cycle E3

Emissions (g/kWh)	**From Engine Manufacturer (Cummins)**	**Measured**
NO_x	9.08	8.0
HC	.74	.06
CO	2.74	1.5
PM	NA	.01

Discussion/Observations

Objectives vs. Results

Task 1 has been completed and the anticipated objectives have been achieved. Results of the baseline measurements have confirmed initial expectations as highlighted in earlier reports.

Critical issues

Fuel selection

To synchronize our aftertreatment technology development with the upcoming (June 2012) EPA regulations regarding marine and locomotive fuel requirements, all our tests on the marine engine were conducted exclusively using Ultra Low Sulfur Diesel (ULSD) fuel. We took great care to make sure the targeted marine engine on the vessel could use ULSD fuel without inducing any potential damage to the vessel engine [2]. Several discussions were pursued a priori including with Cummins, the US EPA, experienced marine engine experts and marine fuel suppliers focusing on the use of ULSD fuel and its potential short or long terms effect on an older engine.

Temperature of exhaust gas

Baseline measurements indicated that under some vessel operating conditions the engine exhaust temperature may be somewhat low for harnessing an optimal operation of the aftertreatment system. To ensure improved 'light-off' temperature of the catalysts the aftertreatment system will be installed as close to the engine as possible.

Speed sensor

During the baseline emissions measurements at times the engine speed sensor displayed erratic signals. This is under investigation. In later stages we will also study the engine speed probe mounting position, to assure no adverse effect on the SCR urea dosing strategy.

Technical and commercial viability of the proposed approach

To date, all steps have progresses as expected; we do not see any major risk in achieving the expected project goals. Technical barriers have not been identified to date.

Scope for future work

The following is a summary of the remaining tasks and phases to be pursued and reported in the coming work:

- Phase I
    - Task 1: Baseline engine emissions measurements on vessel
        - Complete
    - Task 2: System design and CFD analysis
        - 2.1- Initial CAD layout using measurements from vessel and estimated catalyst sized
        - 2.2- Tank layout incl. hoses, supply/return lines
        - 2.3- Layout of wiring harness
        - 2.4- CFD modeling and analysis
        - 2.5- Catalyst selection
        - 2.6- Final CAD layout using results from 2.2 and 2.3.
- Phase II
    - Task 1: System installation and baseline measurements
        - 1.1- Procure all components of aftertreatment system
        - 1.2- Engine selection and purchase
        - 1.3- Install engine (without aftertreatment) on engine test bed
        - 1.4- Baseline raw emissions measurement without aftertreatment
    - Task 2: Final design changes and measurement of emissions reduction
        - 2.1- Install aftertreatment system
        - 2.2- Final design changes to system and emissions measurement with aftertreatment.
- Phase III
    - Task 1: Measurement of actual emissions reduction on marine vessel
        - 1.1- Ship and install system on marine vessel
        - 1.2- Install PEMS equipment for emissions measurement
        - 1.3- Final analysis of data and report writing

Summary/Conclusions

Vessel was identified, agreement with vessel owner was reached, baseline measurements were conducted, and the analysis of the engine emissions data is underway. The baseline emissions measurement on the vessel engine was conducted using portable emission measurement equipment. The collected data appeared to fall within the expected emission values of the engine, such as those provided by the engine manufacturer. At this juncture, it is fair to conclude that our designed aftertreatment system should be able to provide emission reduction targets as proposed in the initial grant proposal made to NTRD, i.e. reduction of diesel NO_x and PM by 75% and 95%, respectively.

Acknowledgements

The Port of Houston Authority assisted in identifying an appropriate vessel company for this project. Buffalo Marine Service Inc. provided their vessel for on-site, baseline emission measurement. The cooperation and assistance from both organizations is highly appreciated.

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