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# Comparison of real-time NOx emission measurements from two heavy-duty diesel engines

G M Hasan Shahariar[1,2], Thuy Chu-Van[1,2], Timothy A. Bodisco[3], Mojibul Sajjad[1,2], Kabir Adewale Suara[1,2], Zoran Ristovski[1,2] and Richard J. Brown [1,2*]
[1] Biofuel Engine Research Facility, QUT, Brisbane, QLD 4000, Australia
[2] International Laboratory for Air Quality and Health, QUT, Brisbane, QLD 4000, Australia
[3] School of Engineering, Deakin University, 75 Pigdons Rd, Geelong, Victoria 3216, Australia

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**Abstract**

This study investigated the real-time NOx emissions from a heavy-duty diesel truck and a bulk carrier ship. The test road vehicle was driven on a combination of a flat and hilly route from Brisbane to Toowoomba that covered urban, rural and motorway driving. On-board ship emissions were measured on the sea from the port of Gladstone to Newcastle. NOx emissions from both engines were compared and analysed to understand the influence of engine parameters as well as route variables and power transmission on NOx emissions. Results from these measurements show that truck NOx emissions increased with the engine power and speed however a significant NOx emission can be seen during the idling condition while producing low power. On the other hand, ship NOx emissions followed an approximate cubic relationship as a function of engine RPM that is completely different from that of the truck.

*Keywords: On-road emissions, On-board ship emissions, NOx emissions, Air pollution.*

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## 1. Introduction

Diesel engines are widely used in on-road and marine transportation for their outstanding power generation, fuel economy, durability and high thermal efficiency [1]. Combustion of fossil fuels causes a significant amount of gaseous and particle emissions that contribute to global greenhouse emissions, air pollution, and human health risks [2], [3]. NOx emissions contribute to smog formation, can causes various respiratory problems, heart disease, and exacerbation of asthma. Road vehicle and marine transport are historically major sources of air pollution in urban and coastal areas. Improving air quality is a primary concern for most of the countries.

The International Maritime Organization (IMO) has implemented regulations to control the shipping emissions and US Environmental Protection Agency (EPA) and the European Union are implementing regulations to control the pollutants from diesel engine emissions. In European emission standards, the emission characteristics of vehicles are performed through laboratory tests. The test is performed using a chassis-dynamometer and the vehicle is driven through a predefined test-cycle (New European Driving Cycle, NEDC). During the test cycle, the vehicle is run at different operating conditions and the exhaust emissions are sampled using different gas analysers to measure the pollutants in the exhaust stream [4], [5]. On-road vehicle driving is categorised as steady-state and transient cycles. The steady-state cycle can evaluate the vehicle engine performance and emission behavior at a specific range of operating conditions with a minimum engine speed time profile variation. Laboratory tests allow a wide range of operating conditions and repeatability. On the other hand, the transient cycle with varying speed is often carried out to obtain emission data from on-road driving [5], [6]. Some transient cycles like the worldwide harmonised light vehicles test cycle (WLTC) may be the representations of on-road measurements, however, vehicles vary depend on types, uses, and so many other factors, also one single cycle may not represent the real road driving emissions [7]. Vehicle driving parameters such as speed, acceleration, deceleration, stopping and gear shifting are important factors for emission measurements [8]. In this case, real driving emission testing can provide more realistic data than engine test bench or chassis-dynamometer [9], [10]. Moreover, in some cases, real driving emission testing found much higher values than that of the test bench. Based on the real driving measurements on 541 diesel cars, Euro 6 vehicles emissions were on average 4.5 times higher than Euro 6 limit and Euro 5 vehicles were 4.1 times higher than the limit [11], [12]. The engine emissions are influenced by both engine internal factors such as engine operating conditions, driving parameters, exhaust after-treatment systems and external factors including ambient air and temperature. These factors cannot be completely achieved in a test bench setup. In the case of ship emissions, three major measurements methods are available, known as onboard measurements, test-bed measurements and ship plume-based measurements [13]. Testbed measurements investigate the exhaust emissions at a wide range of engine load conditions and a variety of fuel types can be used [14]. This allows a detailed understanding of emission characteristics at a wide operating range. On the other hand, ship plume-based measurements may provide insights about the emission characteristics from ship plume [15], it is not convenient due to the uncertainties and high cost. Therefore, onboard ship emission measurements are necessary for the complete investigation of realistic emission factor [13], [16]. There are very few on-board measurements which have been performed and more investigations are necessary to improve the data quality and emission factors. The major emission source for the ship is the main engines (MEs) which are used for the ship propulsion. Most of the main engines are slow speed, two-stroke marine diesel engines, using heavy fuel oil (HFO) and having a maximum

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* Corresponding author. Email: richard.brown@qut.edu.au

operating speed up to 300 rpm. On the other hand, the smaller auxiliary engines (AEs) are used to generate electricity especially when the ships are stationary and at berth in ports near to the locality. Therefore, emissions from auxiliary engines significantly contribute to residential areas of air pollution. Auxiliary engines are generally medium or high-speed marine diesel engines (engine speeds 500-2500 rpm) with an estimated power output 30-3000 kW [17]. In road-transport application, diesel engines are classified as light duty (power range 52.2 to 126.8 kW), medium duty (power range 126.8 to 186.4 kW) and heavy-duty (power range greater than 186.4 kw). The gross vehicle weight rating (GVWR) is, for light duty (less than 14541 kg), medium duty (14541 kg to 24608 kg) and heavy-duty (more than 24608 kg). Heavy-duty diesel vehicles tend to operate in both urban and localized areas are responsible for ambient air pollution. Moreover, shipping-related emissions are contributing to air pollution especially in coastal areas and cities. According to the study of Eyring et al., more than 70% of ship emissions have been found up to 400 km inland [18]. Therefore, a combined study is required for both types of engines to understand the emission behavior and influencing factors. The findings will contribute to updating the existing policy by considering both emission sources to maintain air quality.

The aim of the current study is to investigate the engine performance and NOx emissions from a large bulk career ship through on-board measurement and a heavy-duty truck equipped with NOx after-treatment system through real driving emission measurements to get insights on emission behaviour relying on engine types and applications.

## 2. Experimental method and setup

### 2.1 On-board ship emission measurements

The measurements were conducted on October and November 2015 in a bulk carrier ship on the voyage from port Gladstone to Newcastle. HFO was used as the fuel and the fuel properties were obtained from the bunker delivery receipt and laboratory analysis [13]. The specifications of the ship and engine are given in table 1. Two sampling points were created in the exhaust line after the turbocharger of the main engine. The position of the sampling points was approximately 0.2 m downstream from the turbocharger. The measuring instruments were installed on a deck in the machinery room. The first sampling point was for particle measurements, where raw hot exhaust flow was directed through a dilution system. The second sampling port was used for the gaseous exhaust measurement. The concentration of the gases including nitrogen oxides (NOx) in the raw exhaust gas was measured using a Testo 350 XL portable emission analyser through a dilution system. The length of the exhaust sampling line was around 1.2 m and the exhaust flow rate was around 0.98-1.2 standard liter per minute (SLPM). Engine performance data such as engine power, fuel consumption, engine revolution, and exhaust gas temperature were measured by ship instrumentation. The schematic of exhaust sampling line is given in figure 1.

***Table 1:*** *The specifications of the ship and the engine.*

| | |
|---|---|
| Owner of the ship | CSL Australia |
| Build year | 2002 |
| Engine type | 2-stroke, single acting, cross head, marine diesel engine |
| Output and revolution | 6880 kw and 102 rpm |
| Number of cylinders and bore x stroke | 6 and 500 x 1910 mm |

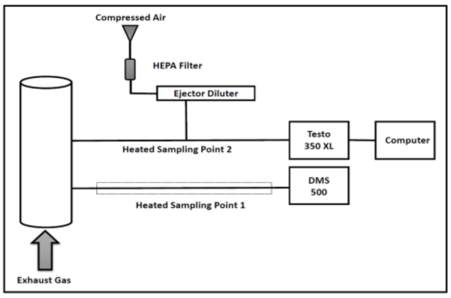


***Figure 1:*** *The schematic of  the ship exhaust sampling line.*

### 2.2 Real-time truck emission measurements

The experimental investigation was conducted on a K200 Kenworth Truck equipped with an SCR NOx after-treatment system. The truck was driven from Brisbane to Toowoomba both in the flat and hilly route that covered city, motorway and rural route to perform the measurements. The specifications of the test vehicle and engine are given in table 2. The gaseous emissions were measured using an ECM miniPEMS system that contains NOx, $O_2$, exhaust temperature, exhaust pressure sensors, OBDII and GPS. The measured data was stored to an SD card. The sensor used for the NOx measurement was a ceramic exhaust sensor manufactured by ECM (Engine Control and Monitoring). The precision of the sensor from the manufacturer specification id ± 5 ppm (0-200 ppm), ± 20 ppm (200-1000 ppm) and ± 2.0 % (>1000 ppm). Two NOx sensors were connected to the exhaust pipe before and after the SCR catalyst to measure the NOX concentration in both conditions. A pressure sensor and a temperature were also connected to the exhaust pipe to obtain the exhaust pressure and temperature data. The PEMS also connected with the truck's ECU to record the engine performance data and vehicle parameters. The schematic of the exhaust line is given in figure 2.

***Table 2:*** *The specifications of the test vehicle and engine.*

| | |
|---|---|
| Test vehicle model | K200 Kenworth |
| Engine | Cummins ISXe5 |
| Engine type | 4-cycle, in-line, 6 cylinder, Turbocharged/charge air cooled |
| Compression Ratio | 17.2:1 |
| Cylinder bore and stroke | 137 x 169 mm |

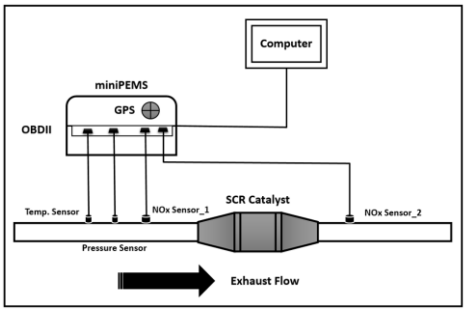


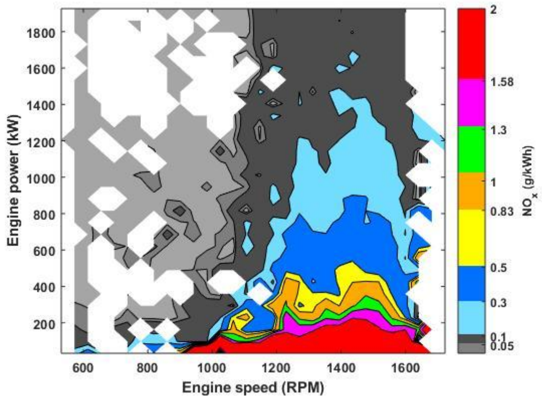
***Figure 2:*** *The schematic of the truck exhaust line.*

## 3. Results and discussion

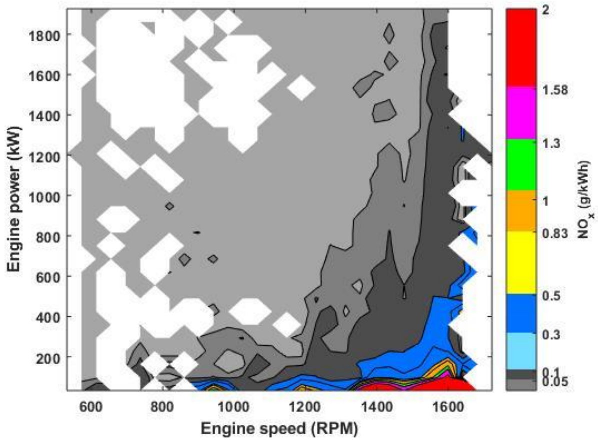
The NOx emissions obtained from the real-time measurement from two different types of the heavy-duty diesel engine are presented below. The truck trip covered city road, motorway, rural road; also, there was a variation in altitude (maximum height 700 m and minimum height 56 m). There was a frequent shifting of the driving parameters such as gear engagement, acceleration, deceleration, hard acceleration, cruising due to traffic condition. All these parameters have meaningful influences on vehicle performance and emissions. On the other hand, marine engine operation is comparatively stable compared to road vehicle engine.

Figure 3(a) and (b) show the NOx emissions before and after the SCR catalyst. Variation in color represents the change in NOx quantites and white region indicates no data points. NOx emission is high at relatively higher engine speed and low power. However, at idling condition while the engine is producing less power NOx emission is highest. The catalyst NOx conversion is better at all conditions excepts the idling condition. There is still high NOx there that can be seen in figure 3(b). NOx emission after the SCR at idling condition are limited due to low exhaust temperature. NOx emission strongly influenced by combustion temperature, which in the case of ship the engine power correlates strongly with exhaust temperature and hence NOx emissions(figure 3(c)). Ship NOx data follows an approximate cubic curve related to the specialized ship application where the engine is directly mechanically coupled to the propeller with no gear box. This result is speed power relationship of form Power ∞ RPM$^3$ due to the thrust co-effficent characteristics of a propeller. This is significantly in contrast to NOx characteristics in the pre-catalyst measurements from the truck which has a gear box ((figure 3(a)).

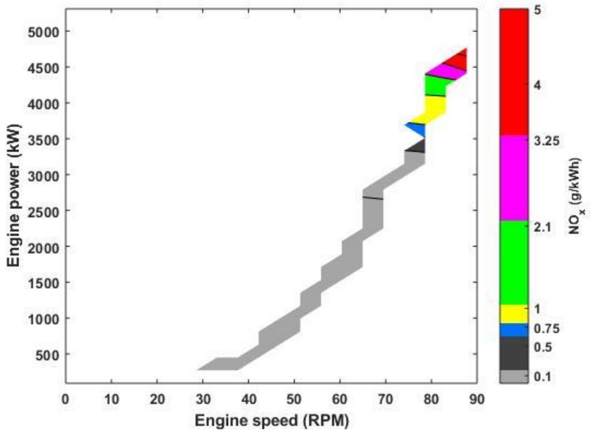
NOx emission with respect to engine speed rate (RPM/s) that is calculated by the equation (ΔRPM/Δt) is shown in figure 4 (a),(b),(c). The variation of engine speed is much higher in the truck engine than marine engine due to the wide range of driving dynamics and route variables. One thing is common in both engines that high NOx emission can be seen at stable conditions. Truck engine repeatedly switches gears for the acceleration, deceleration, stopping due to the traffic conditions and route variables. Ship engine speed is almost stable during the whole course and NOx emissions increases with the engine power.



(a)

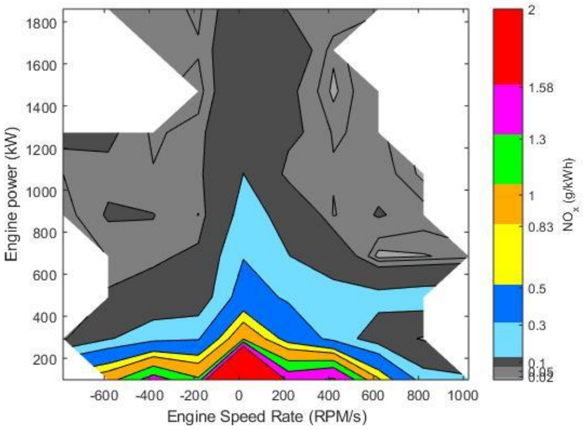


(b)

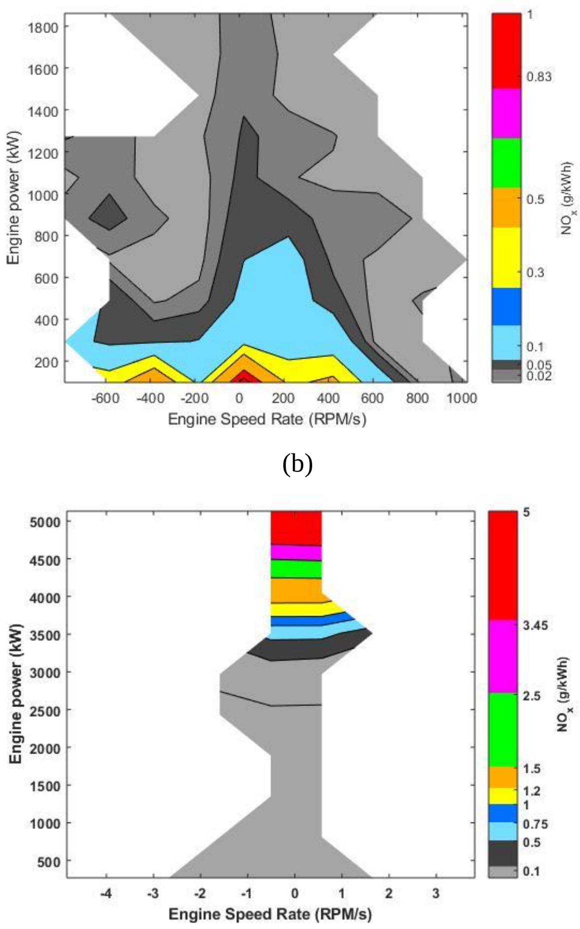


(c)

***Figure 3:*** *NOx emission with engine speed and power (a) truck engine before SCR catalyst, (b) truck engine after SCR catalyst, (c) ship engine.*



(a)



(b)

(c)

***Figure 4:*** *NOx emission with engine speed rate (rpm/s) and power (a) truck engine before SCR catalyst, (b) truck engine after SCR catalyst, (c) ship engine.*

## 4. Conclusion

The current study presents the real-time NOx emission measurements of a modern heavy-duty truck and a bulk carrier ship. The truck covered urban, rural and motorway driving on both flat and hilly route and ship emission measured during the voyage on the sea. The study has shown that there is a significant difference between the NOx emission behavior of the on-road and seagoing vehicle. The measurements also showed that on-road NOx emissions is significantly high at idling condition. However, ship NOx follows an approximate cubic relationship.

## 5. Acknowledgments

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