Queensland University of Technology

Comparative Investigations of Combustion Emissions from Eromanga Underground Mining Fuel

Final Report to IOR Energy Pty Ltd Presented by

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Abbreviations

ACARP	Australian Coal Association Research Program
CMD	Count Median Diameter
CO	Carbon Monoxide
CPC	Condensation Particle Counter
DustTrak	DustTrak Aerosol Monitor
EC	Electrostatic Classifier
EPA	Environmental Protection Agency
EUMF	Eromanga UMF
HEPA	High Efficiency Particulate Air Filter
ILAQH	International Laboratory for Air Quality and Health
M7_Idle	Engine mode 7 specified in R49 testing protocols (i.e. Idle)
M9_25%	Engine mode 9 specified in R49 (i.e. Rated Speed and 25% Power)
M10_50%	Engine mode 10 specified in R49 (i.e. Rated Speed and 50% Power)
M11_75%	Engine mode 11 specified in R49 (i.e. Rated Speed and 75% Power)
M12_100%	Engine mode 12 specified in R49 (i.e. Rated Speed and 100% Power)
NO	Nitric Oxide
NO_2	Nitrogen Dioxide
NO_x	Total Oxides of Nitrogen
$PM_{2.5}$	Mass concentration of particles with an aerodynamic diameter smaller than 2.5 µm
PNC	Total Particle Number Concentration
PSD	Particle Number Size Distribution
QUT	Queensland University of Technology
REF	Reference diesel fuel
SMPS	Scanning Mobility Particle Sizer
SE	Standard Error of the Mean
UMF	Underground Mining Fuel

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1. Introduction

Diesel-powered vehicles and equipment account for nearly half of all nitrogen oxides (NO_x) and more than two-thirds of all particulate matter (PM) emissions from US transportation sources. PM is created during the incomplete combustion of diesel fuel, and it varies in size from coarse particulates (less than 10 microns in diameter, PM_{10}) to fine particulates (less than 2.5 microns, $PM_{2.5}$) to ultrafine particulates (less than 0.1 microns). Ultrafine particulates, which are small enough to penetrate the cells of the lungs, make up 80-95% of diesel soot pollution. Also, PM irritates the eyes, nose, throat, and lungs, contributing to respiratory and cardiovascular illnesses and even premature death. In addition, diesel engines contribute to the problem by releasing particulates directly into the air and by emitting nitrogen oxides and sulphur oxides, which transform into "secondary" particulates in the atmosphere. Diesel emissions of nitrogen oxides contribute to the formation of ground level ozone, which irritates the respiratory system, causing coughing, choking, and reduced lung capacity. Diesel exhaust has been classified a potential human carcinogen by the U.S. Environmental Protection Agency (EPA) and the International Agency for Research on Cancer. Exposure to high levels of diesel exhaust has been shown to cause lung tumours in rats, and studies of humans routinely exposed to diesel fumes indicate a greater risk of lung cancer.

There are increasing evidences demonstrating that fuel composition and properties have impacts on engine emissions. For example, a recent ACARP project (C18014) showed that some alternative diesel fuels offered a substantial reduction (up to 92%) in the mass of PM emitted, with a significant increase in the number of ultrafine particles [1]. The researchers postulated that some alternative fuels might not reduce occupational health risk, and might even increase it, despite the large reduction in the emitted mass of PM.

Therefore, it is very important to fully understand its real engine emission characteristics, particular the particle size distributions, before the introduction of an alternative diesel fuels to the market, particularly for underground mining industry where the ventilation conditions are usually much worse than ground. Unfortunately, no testing standards are available for comparison of engine emissions from different fuels. Furthermore, the existing standard testing protocols for diesel vehicles and spark-ignition vehicles, such as ECE-R49 and its newer version the ESC, have not yet included particle number and particle size distributions.

The Eromanga Refinery is located in the small town of Eromanga 1000 kms west of Brisbane Australia. The refinery has been processing 1250 barrels per day of locally produced crude oil continuously since it was commissioned in 1986. The refinery produces high quality diesel fuels, heating oils and kerosenes as well as variety of speciality petroleum products for industrial uses. Eromanga Underground Mining Fuel® (Eromanga UMF) is a premium low emission diesel fuel produced at the Eromanga Refinery. Emission testing by industry and regulators over the years has consistently demonstrated the very low emission characteristics compared to other commercial diesel fuels. However, there is lack of evidences supporting the deduction by the fuel in particle number emissions, as well as the change in particle size distribution compared to other commercial diesel.

The aim of the project was to determine the difference in concentration and characteristics of emission products (i.e. CO_2, CO, NOx, $PM_{2.5}$, particle number concentration and particle size distributions) from a diesel engine operating on commercially available diesel fuels and on a diesel fuel supplied from the Eromanga Refinery. It is known that the tested Eromanga UMF has relative higher sulphur content with concentration up to 125 ppm. The small amount of sulphur has a negligible contribution to the formation of diesel particulate matters according to the literature, thus SO2 concentration was not monitored in this project, which is also consistent with the requirement in the testing standards in R-49.

2. Materials and Methods

2.1 Engine

The engine, a Perkins 1104C-44, is part of a family of 3-, 4- and 6-cylinder inline engines with outputs ranging from 28 kW to 193 kW. The 1104C-44 has been used recently in PJB man carriers, as the modern replacement for the old Kia 6/247. The abridged specifications are summarised in Table 1. More detailed about the engine is provided in Appendix 1.

Table 1: Specifics of Perkins 1104C-44

Model	Perkins 1104C-44
Cylinders	4 in-line
Capacity (L)	4.4
Bore × Stroke (mm)	105 × 127
Maximum power (kW/rpm)	64/2400
Maximum torque (Nm/rpm)	302/1400
Compression ratio	19.25:1
Aspiration	Naturally aspirated
Fuel Injection	Direct injection with mechanical rotary distributor pump
Emissions certification	EU Stage II non-road and EPA Tier2

2.2 Dynamometer test bed

To provide repeatable standard conditions, engine testing was conducted on a dynamometer. The test bed uses a well maintained Heenan & Froude water brake dynamometer, type D.P.X. 3. The dynamometer test room has a powerful air extraction system which is able to cope with the heat load of the Perkins engine, and this also ensures that the engine is always ingesting fresh, cool air. However, this air is drawn from the vicinity immediately outside the building, and is not climate controlled. The engine's intake air therefore matches the prevailing ambient outdoor conditions.

2.3 Fuels for testing

Results are presented for four different fuels in total tested in the project. IOR supplied Eromanga UMF and two commercial diesel fuels. QUT provided a third commercial diesel as a reference fuel which was tested in detail in a recent ACARP project [2]. The name and amount of tested fuels are listed below:

- 200L Eromanga UMF (for first & final test)
- 100L Reference Diesel (Fuel A)
- 100L Commercial Diesel (Fuel B)
- 100L Commercial Diesel (Fuel C)

Please note that, even for the same brand of fuel, the fuel composition may also slightly vary in different batches, leading to changing in engine emissions.

2.4 Fuel temperature control

As the change in fuel temperature while the engine is running can affect the engine emissions, efforts have been done by QUT to minimise this impact. A fuel tank was installed adjacent to the engine, with a heat exchanger in the supply pipe between the tank and the engine. The medium used for controlling the fuel temperature was the same recirculating water which is used to supply the dynamometer brake. As noted previously, this is maintained at a temperature close to ambient. The fuel temperature delivered to the engine was monitored with a temperature probe in the supply pipe, and found to be within circa 5 ˚C of ambient at all times during the test programme.

2.5 Measurement system

Engine exhaust from the manifold was diluted in a primary dilution tunnel with high efficiency particulate air (HEPA) filtered ambient air by an adjustable factor of about 10-35. One ejector diluter then diluted the sample by a further factor of about 10, using HEPA filtered compressed air. The purpose of the dilution was to bring down the temperature as well as the concentration of gases and particles within the measuring range of the instruments. Diluted exhaust was then sent to different gaseous and particle measuring instruments.

A CAI 600 series CLD NO_x analyzer and a CAI 600 series CO_2 analyzer were used to measure the NO_x and CO_2 concentration, respectively, in the raw exhaust. A second CO_2 meter (SABLE, CA-10) was used to record the CO_2 concentration from the diluted exhaust. Background corrected CO_2 was used as tracer gas to calculate the overall dilution ratio.

At the end of the two-stage dilution system, $PM_{2.5}$ emissions were measured by a TSI DustTrak (Model 8530). DustTrak readings were converted into a gravimetric measurement by using the tapered element oscillating microbalance to DustTrak correlation for diesel particles published by Jamriska et al. [3].

The particle number size distributions were measured by a scanning mobility particle sizer (SMPS) at a time resolution of two minutes. This SMPS consisted of a TSI 3080 electrostatic classifier (EC) and a TSI 3025 butanol based condensation particle counter (CPC). In addition, a Combustion DMS500 system (i.e. Fast Particle Sizer) was employed to measure particle size distribution at a high time resolution (up to 1 scan per second). Note that different measurement theories are utilised for the SMPS and DMS500 systems, thus differences between the two sets of data are expected.

Temperature of engine raw exhaust was monitored by thermocouple sensors to evaluate the engine stability at each mode. To calculate the engine power, the torque and engine speed applied to the engine during the period of testing were manually recorded about every two minutes.

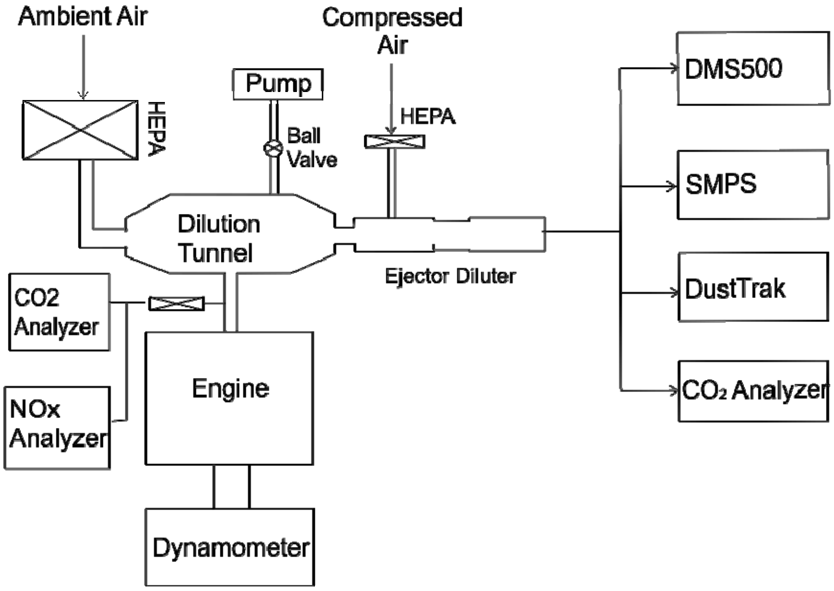

Figure 1: Schematic diagram of used engine exhaust measurement system

A schematic of the experimental setup is provided in Figure 1. The technical details of all the measurement systems are given in Appendix 3.

2.6 Testing regime

R49 standard testing protocol is a 13-mode steady-state diesel engine test cycle introduced by ECE Regulation No.49 and then adopted by the EEC (EEC Directive 88/77, EEC Journal Official L36, 8 Feb. 1988). It had been used for certification of heavy-duty highway engines through the Euro II emission standard. The power settings for the R49 test are listed in Table 2. In this project, samples were only collected at idle (0% load), mode 9 (25% load), mode 10 (50% load), mode 11 (75% load) and mode 12 (100% load).

Table 2: Speed and power setting for the R49 steady state test cycle. The modes tested in this project are highlighted.

Mode	Speed Setting	Power setting [%]
1	Idle	0
2	Intermediate	10
3	**Intermediate**	**25**
4	Intermediate	50
5	Intermediate	75
6	Intermediate	100

7	**Idle**	**0**
8	Rated	10
9	**Rated**	**25**
10	**Rated**	**50**
11	**Rated**	**75**
12	**Rated**	**100**
13	Idle	Idle

To prevent from contamination by the fuel used in previous tests, a proper fuel changing procedure was adopted in this project to empty the remained fuel in the fuel tanks, as well as the residue fuel within the engine and the spill back line. The fuel filter was also changed for each different fuel.

Each fuel was tested in two separate identical cycles in a day, with the exception of Eromanga UMF which was tested twice (i.e. four cycles in total).
The one-day testing procedures for each diesel fuel are presented as follows:

1. Change fuel and filters;
2. Initial warm up of the engine to operating temperatures by running it at the maximum torque with a speed of 1400 rpm for 15 minutes, and then change to mode 3 for 5 minutes;
3. Start measurements from mode 7, then mode 9, 10, 11 and mode 12, for 20 minutes at each mode;
4. Stop the engine and take a one-hour break;
5. Repeat item 2 & 3.

2.7 Data analysis

A quality check was first conducted for all collected data to ensure the data valid for further analysis. It includes that, to minimise the possible interference during changing the engine mode, data in the first 5 minutes for each mode were removed. In addition, the raw emission data were corrected with the calculated dilution rate which was in the range of 100 - 300.

All valid data then were imported into ACCESS database and averaged in one-minute base to reduce the size of the database. The Microsoft EXCEL 2007 pivot table and IBM SPSS Statistics 21 were utilised to further analyse the data and present the results. Univariate ANOVA was conducted to compare the engine emissions from different fuels. A 5% significance level was used for all statistical tests.

3 Results and Discussion

In this section, the engine's stability and the results' reproducibility are discussed first, followed by comparisons of individual measurement parameters ($PM_{2.5}$, particle number, particle size distribution, CO_2, CO, NO, NO_2 and NO_x). The histogram graphs provide a good way for quick understanding the whole picture of the differences of the fuel's emissions among different fuel type and tested engine mode. As the statistical analysis produced a huge amount of results, to avoid increasing the size of the report by irrelevant information, only major findings on comparisons to the Eromanga UMF are summarised in the text. The statistical results are used to confirm if a visible difference is really statistically significant. Note that in 'Statistics' a "*significant*" result means the result is probably true (i.e. not due to chance), but does not necessarily mean it is highly important. In this report, all results are statistically significant, unless special statement is given. A summary table including all statistically significant results is attached in Appendix 4. Also, the whole SPSS statistical results are provided as a separate web version file.

To make the graphs clear, consistent abbreviations (i.e. M7_Idle, M9_25%, M10_50%, M11_75% and M12_100%) are used to refer to each tested engine mode (see Table 2 for details). Engine is unstable at Mode 3, so the data in this mode are not discussed below. The error bar in all histograms refers to the standard error calculated based on all valid data for each fuel at specific engine mode.

3.1 Stability of the engine

The engine-generated power and the raw exhaust temperature are used to evaluate the stability of the engine performance throughout the project.

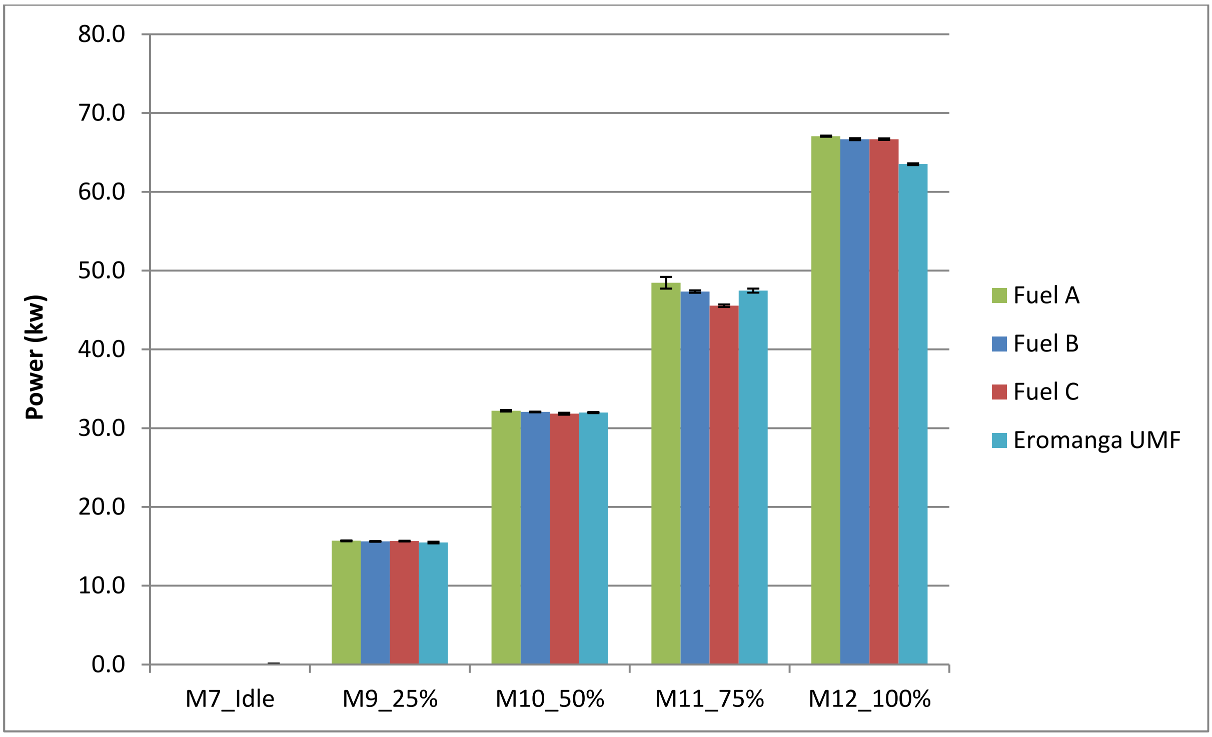

Figure 2. Power generated by the engine using different fuels at five different engine modes

As shown in Figure 2, no statistically significant difference in generated power was seen between the tested fuels for engine mode 7, 9 and 10. At engine mode 11, the generated power by Fuel A was statistically significant lower than the other fuels, while at engine mode 12 the generated power of Eromanga UMF was statistically significantly lower (about 5%) than the other fuels.

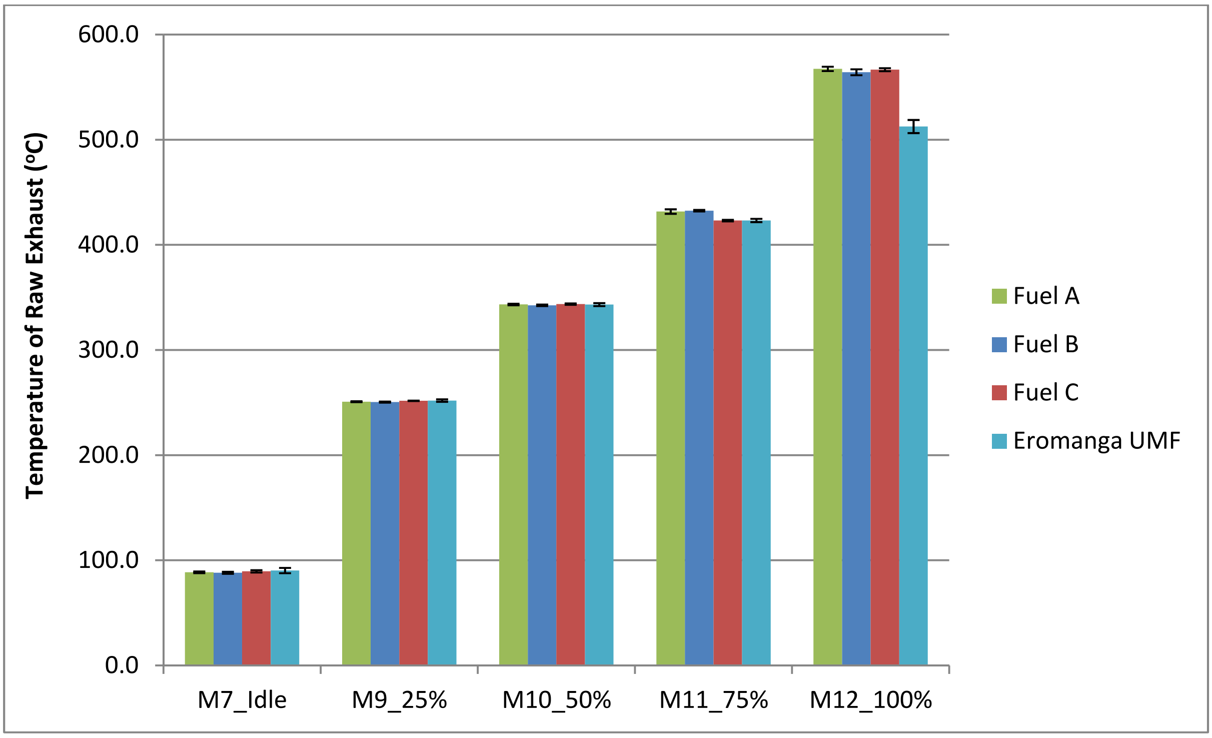

Figure 3. Raw exhaust temperature while the engine was running with different fuels at five different engine modes

Figure 3 shows that no statistically significant difference in the raw exhaust temperature was seen between the tested fuels for engine mode 7, 9 and 10. At engine mode 11, the raw exhaust temperature with Fuel A and Fuel B were statistically significant higher than the other fuels, while at engine mode 12 the temperature with Eromanga UMF was statistically significantly lower (about 50^{o}C) than other fuels. In summary, the fuel types did change the engine performance when the engine was running at relative lower loadings (i.e. M7, M9 and M10). The Eromanga UMF generated less power at higher loadings compared to other fuels.

3.2 Reproducibility of the results

To evaluate the reproducibility of the results, selected data measured in 4 rounds (i.e. 4 full cycles) for the Eromanga UMF are discussed below. The generated power and raw exhaust temperature, as well as CO_2 and $PM_{2.5}$ concentrations, are presented in Figures 4-7. As seen in these figures, the generated power and raw exhaust temperature had a very high reproducibility, further suggesting that the engine was running under a quite stable condition. Slight but acceptable variations (2-5%) were observed in CO_2 and $PM_{2.5}$ concentration at all engine modes, with the exception of idle mode where no visible variation can be identified.

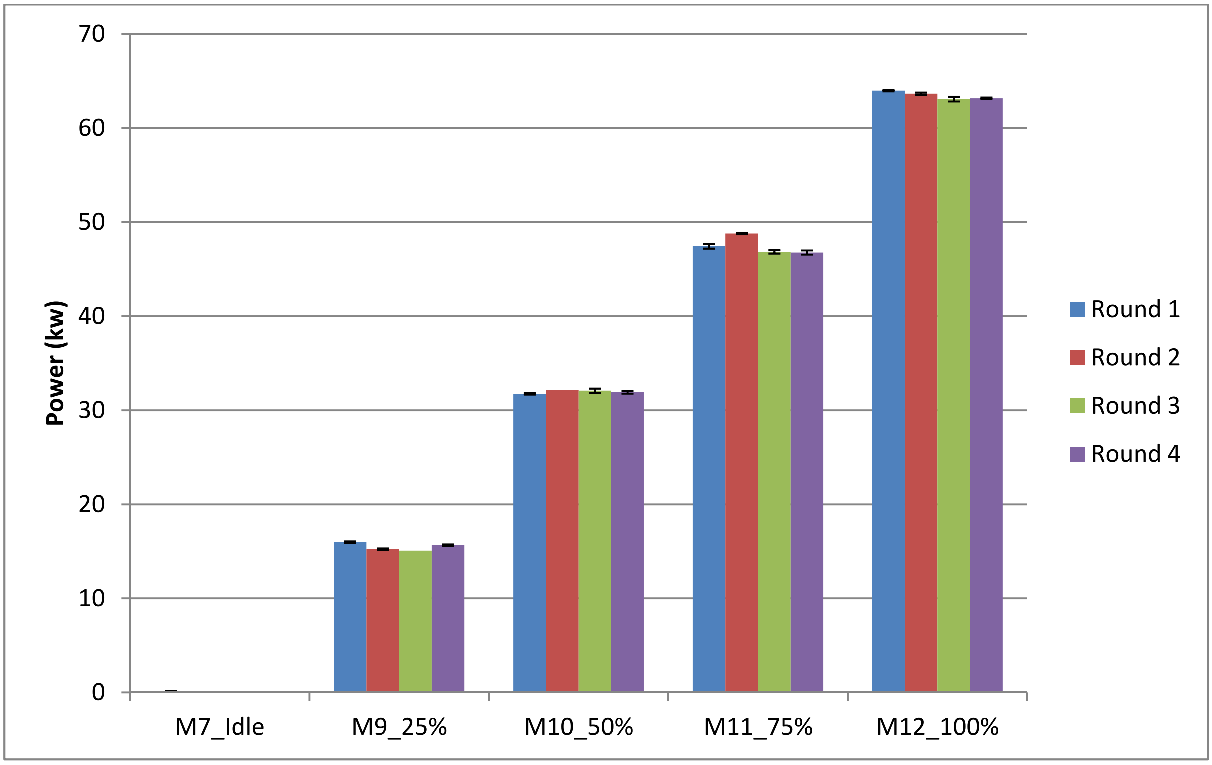

Figure 4. Power generated by the engine using Eromanga UMF at five different engine modes in four identical rounds.

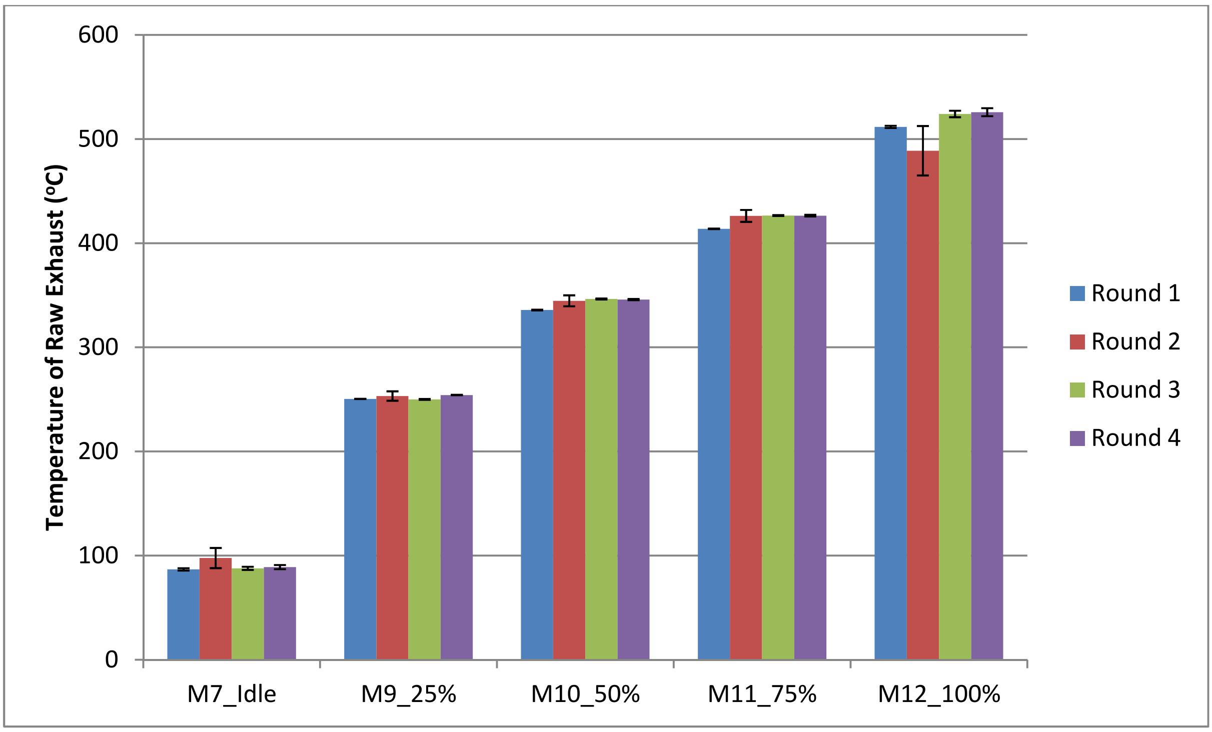

Figure 5. Raw exhaust temperature while the engine was running with Eromanga UMF at five different engine modes in four identical rounds.

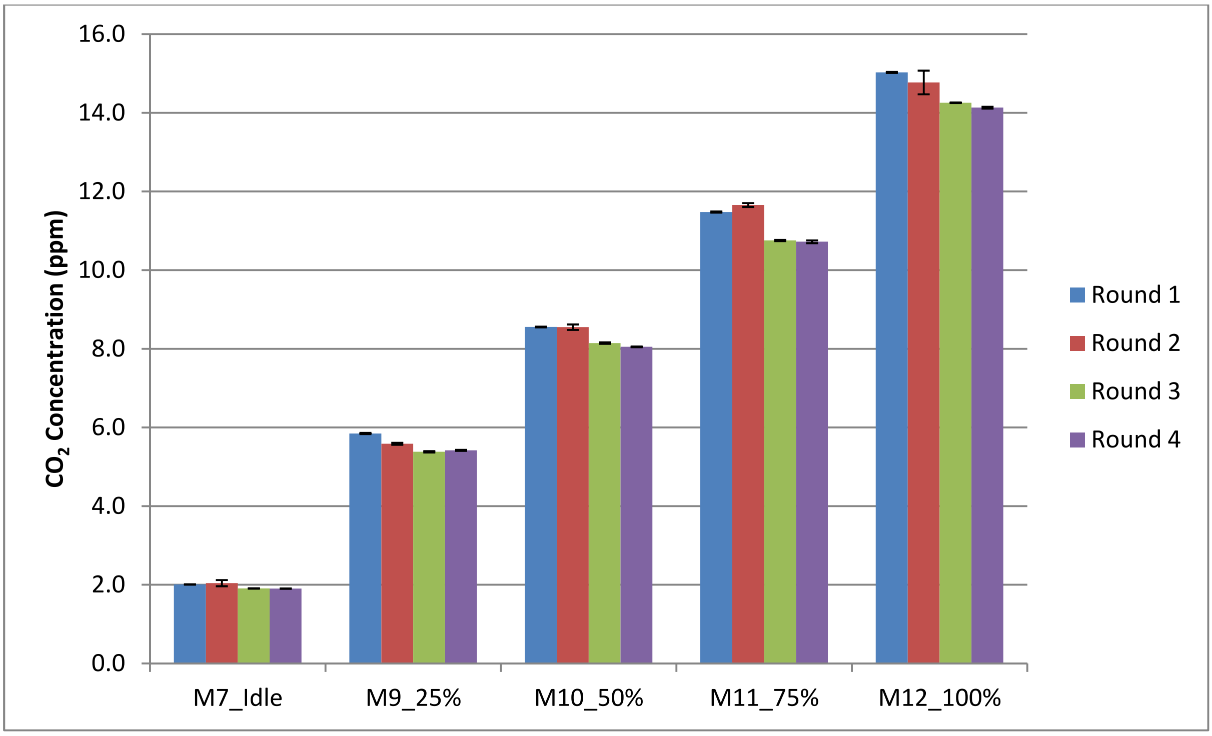

Figure 6. Concentrations of carbon dioxide emitted by the engine using Eromanga UMF at five different engine modes in four identical rounds.

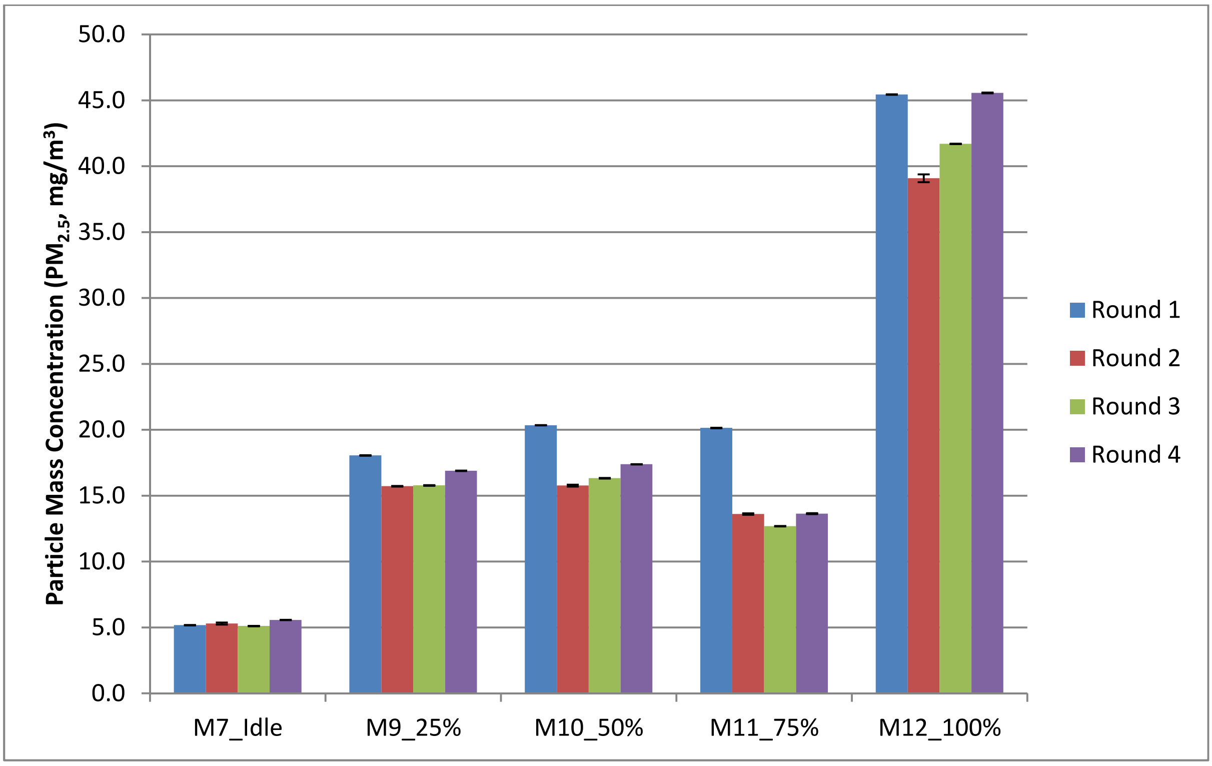

Figure 7. Concentrations of $PM_{2.5}$ emitted by the engine using Eromanga UMF at five different engine modes in four identical rounds

3.3 Particle Mass Concentration

Figure 8 shows concentrations of particle mass (i.e. $PM_{2.5}$) emitted by the engine with different fuels for each engine mode. It demonstrates that there were statistically significant variations in particle emission between the tested fuels. Eromanga UMF produced overall a lower particle mass in all engine modes than other fuels, particularly a 65% reduction observed at engine mode 12.

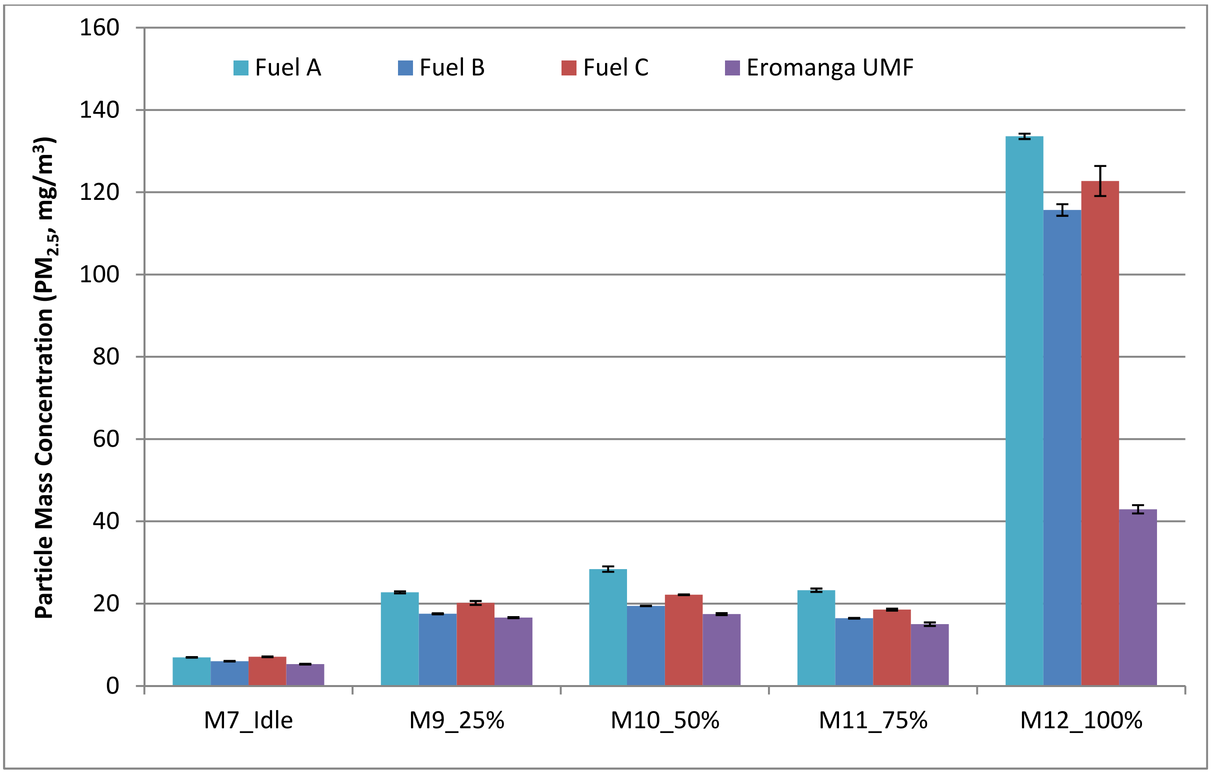

Figure 8. Concentrations of $PM_{2.5}$ emitted by the engine using different fuels at five different engine modes

3.4 Particle Number Concentration

Concentrations of total particle number, TPN1 and TPN2, were measured by SMPS and DMS500, respectively. Figures 9 and 10 present TPN1 and TPN2, respectively, for each tested fuels. In general, TPN2 was slightly higher than TPN1 for all tested engine modes, which is likely due to the difference in the measured range of the two types of instrumentation. DMS500 measured particles with a wider diameter range (5-1000 nm) than SMPS (12-500 nm).

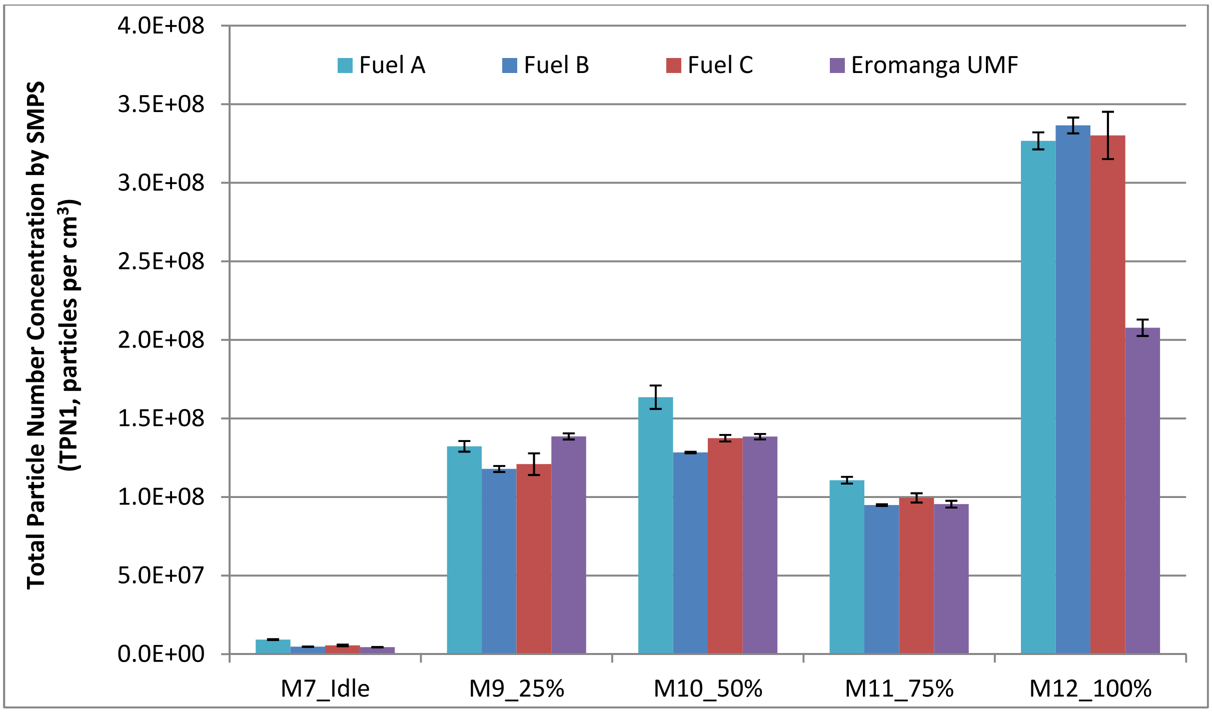

Figure 9. Total number concentrations of particles (TPN1) emitted by the engine using different fuels at five different engine modes, which were measured by the SMPS

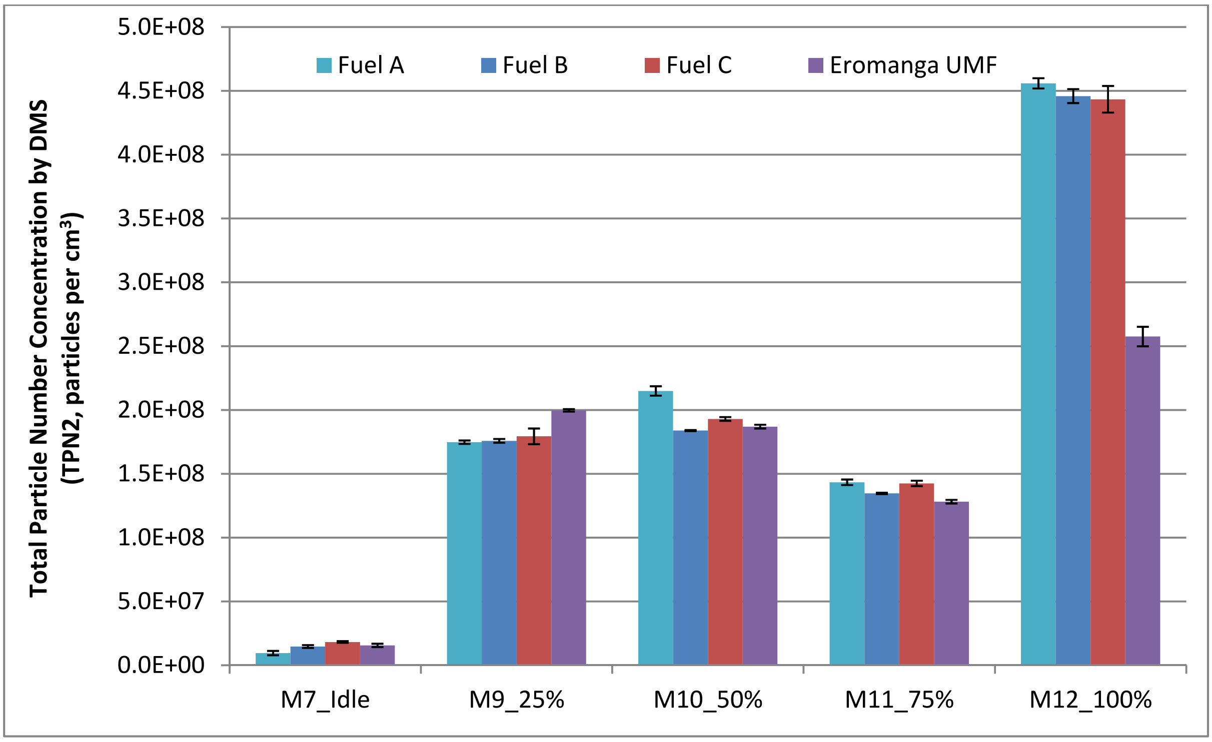

Figure 10. Total number concentrations of particles (TPN2) emitted by the engine using different fuels at five different engine modes, which were measured by the DMS500

Although different measurement theories are applied for SMPS and DMS500, the results showed a very similar trend for the two sets of data. As seen from the figures, Eromanga

UMF produced a comparable magnitude of total particle number to other fuels at all engine modes, with the exception of engine mode 12 where Eromanga UMF showed about a 40% reduction in the total particle number.

3.5 Particle Size Distribution

Count median diameter of engine-emitted particles, CMD1 and CMD2, were measured by SMPS and DMS500, respectively. Figures 11-12 shows the comparisons of CMD in different engine modes for all tested fuels. It is noticed that CMD1 and CMD2 were very close across all tested engine modes, with an exception of the idle mode where CMD2 had overall higher values and also a larger variation. The reason is still unknown, but it might be related to the distinctive physical properties of particles from different engine modes and the applied measurement theories.

In addition, compared to other tested fuels, particles from the Eromanga UMF had a consistent smaller particle size at engine modes 9-12, with about 25% size reduction at the full load mode (i.e. engine mode 12). Further investigation on the full size distribution, see Figure 13, confirmed that the CMD reduction by Eromanga UMFs was not due to the formation of new particles.

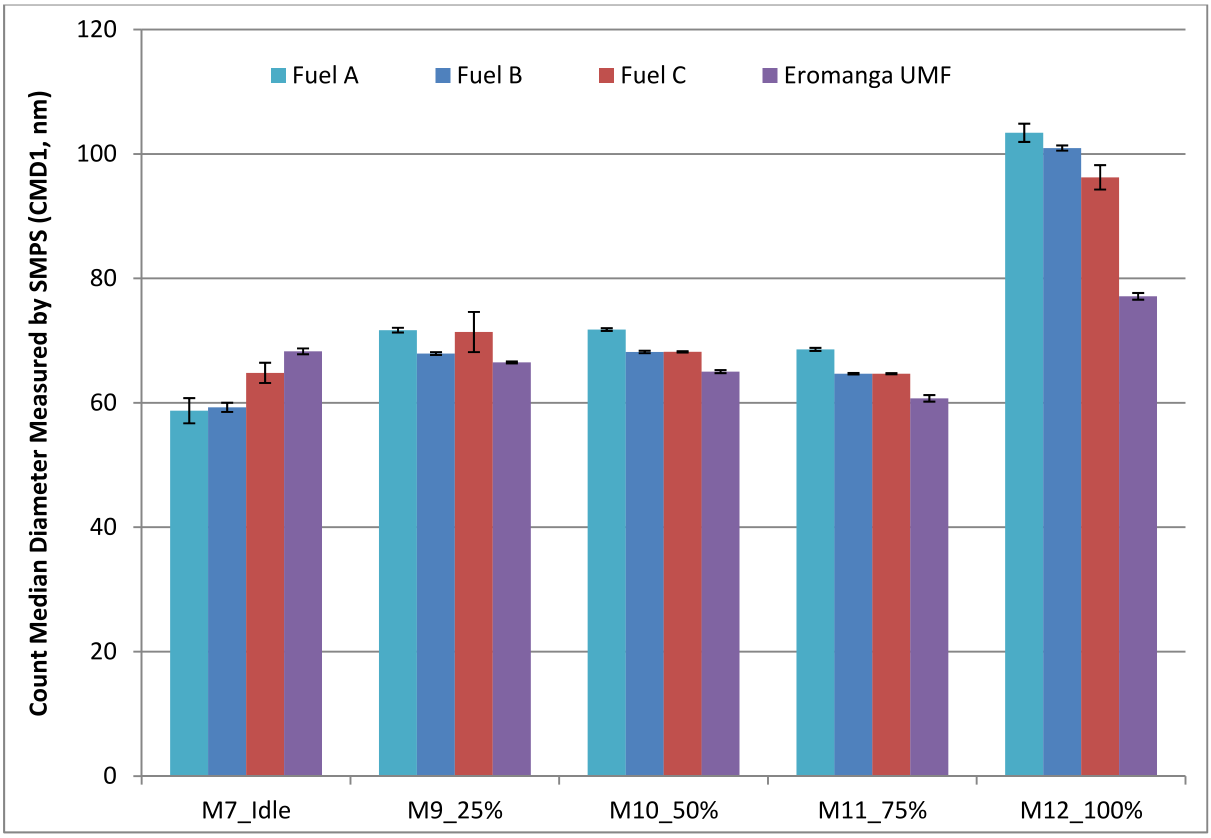

Figure 11. Count median diameter of particles (CMD1) emitted by the engine using different fuels at five different engine modes, which were measured by the SMPS

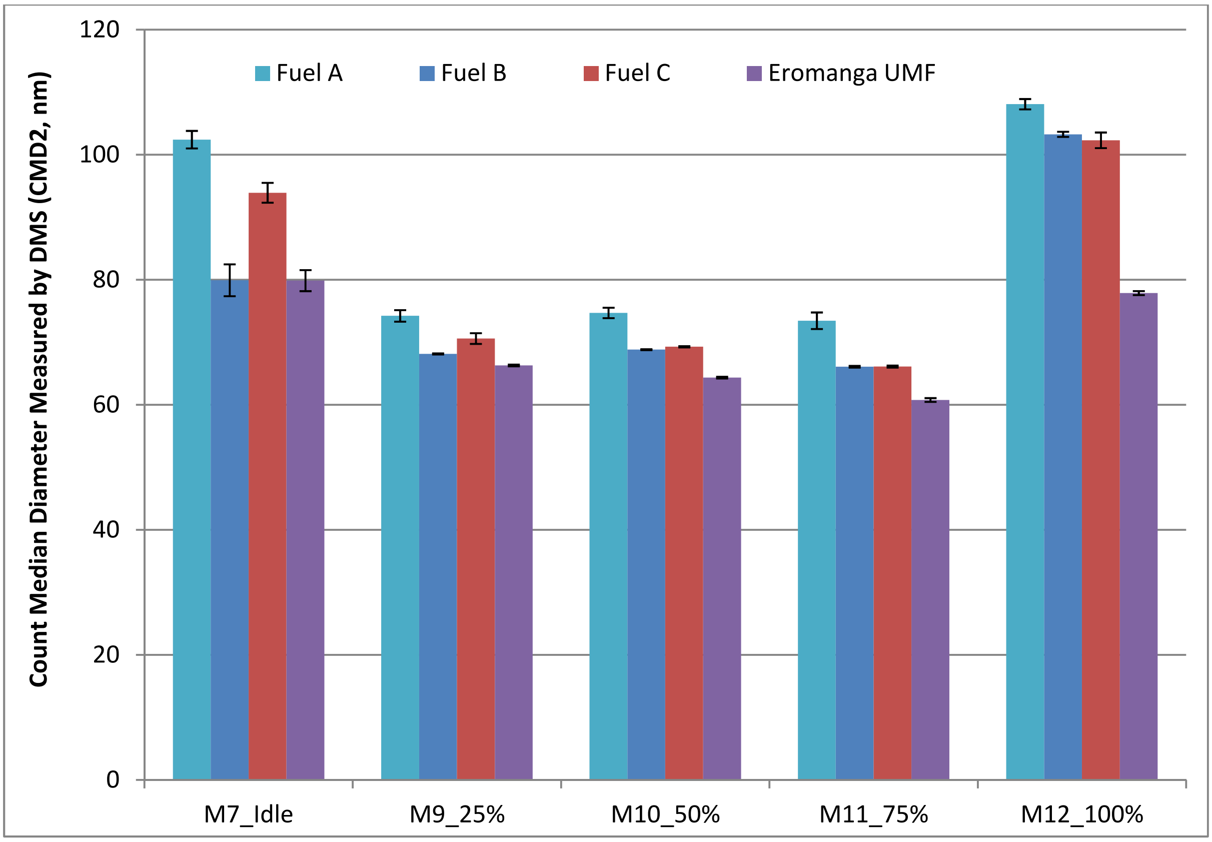

Figure 12. Count median diameter of particles (CMD2) emitted by the engine using different fuels at five different engine modes, which were measured by the DMS500

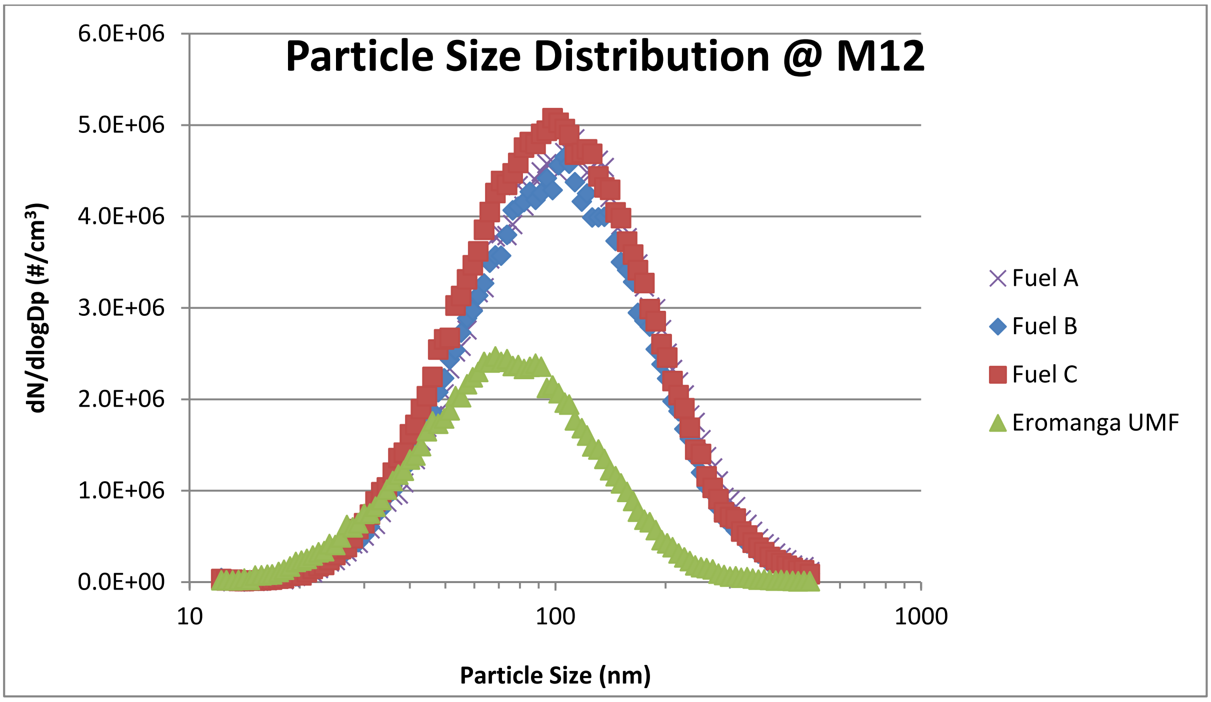

Figure 13. Particle Size Distribution at M12 (100% load)

The full particle size distributions for all tested fuels and engine modes are provided in the Appendix 4.

3.6 Carbon Oxides

CO_2 and CO emitted by the engine are demonstrated in Figure 14 and Figure 15. Please note that their units are different. Compared to CO, CO_2 concentrations had a smaller variation among different fuels. Compared to other commercial diesel fuels, Eromanga UMF had a slightly lower CO_2 and CO emission, particularly at engine mode 12.

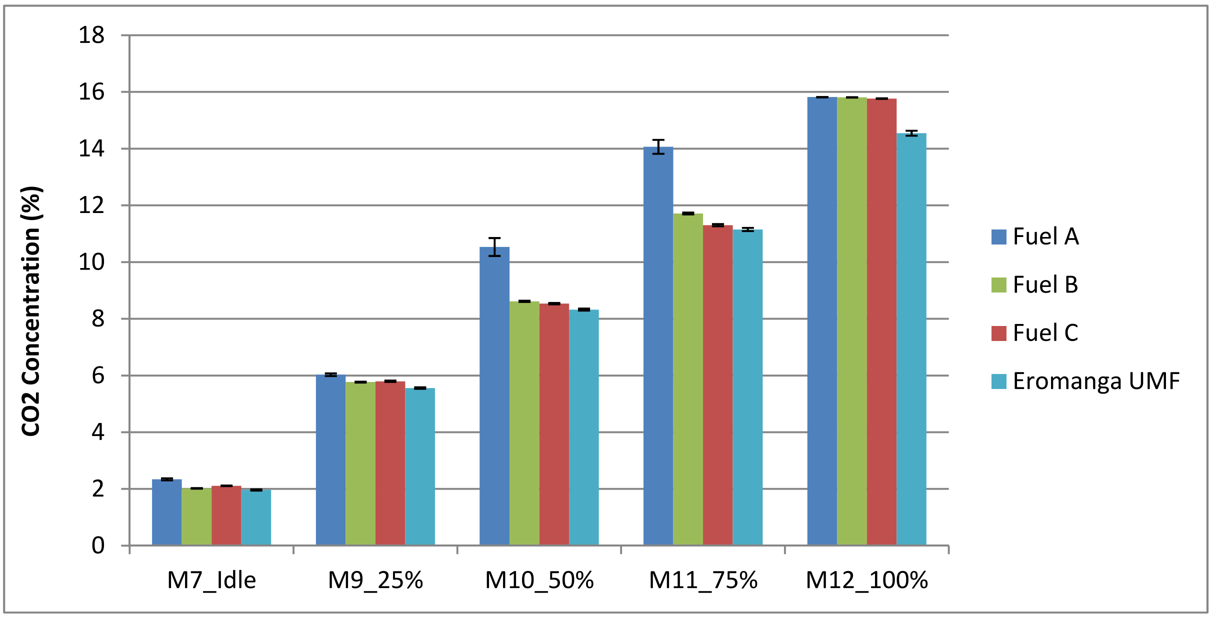

Figure 14. Concentrations of carbon dioxide emitted by the engine using different fuels at five different engine modes

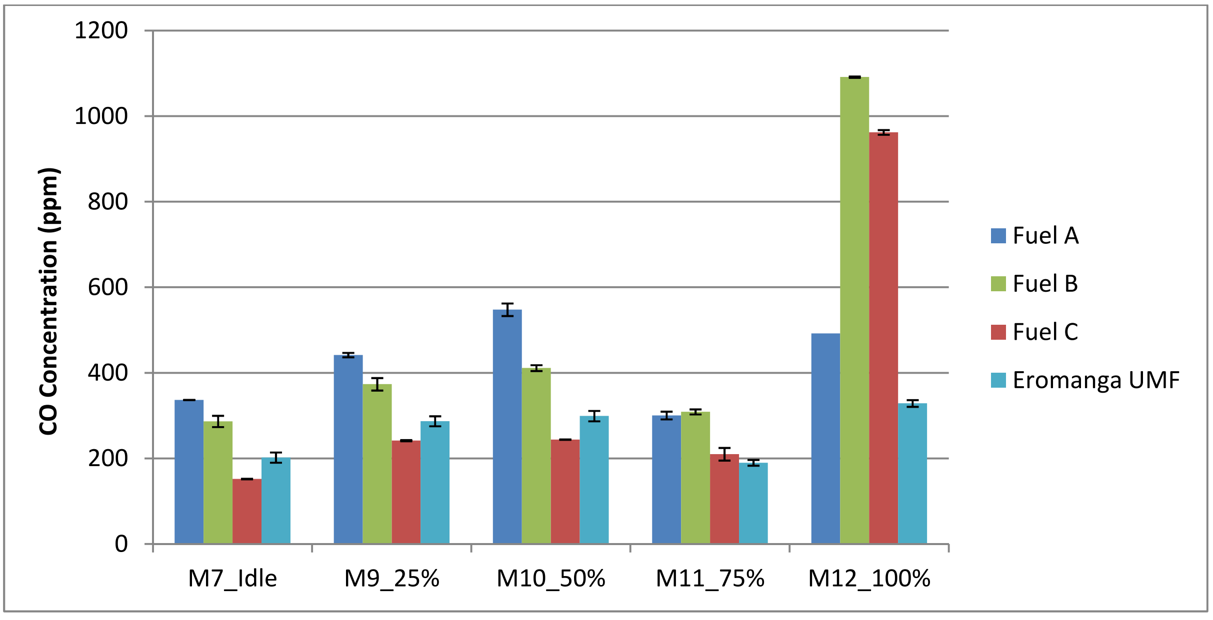

Figure 15. Concentrations of carbon monoxide emitted by the engine using different fuels at five different engine modes

3.7 Nitrogen Oxides

NO, NO_2 and NO_x emitted from the engine are presented in Figures 16-18.

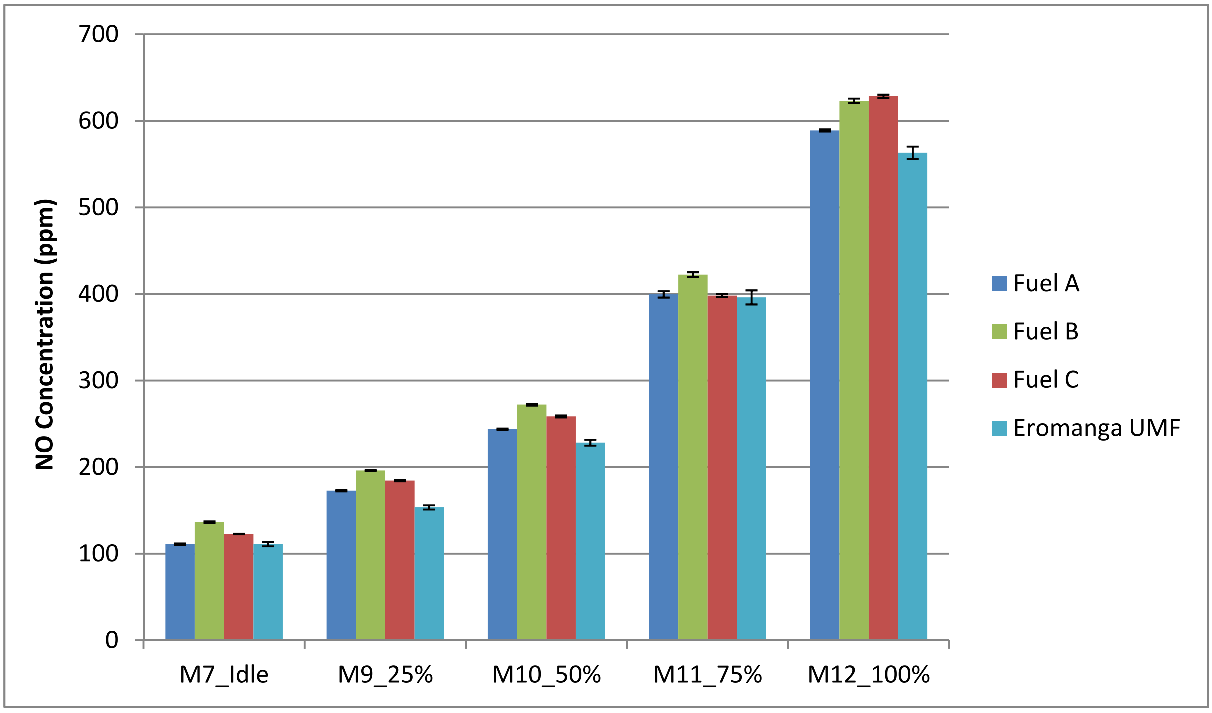

Figure 16. Concentrations of nitric oxide emitted by the engine using different fuels at five different engine modes

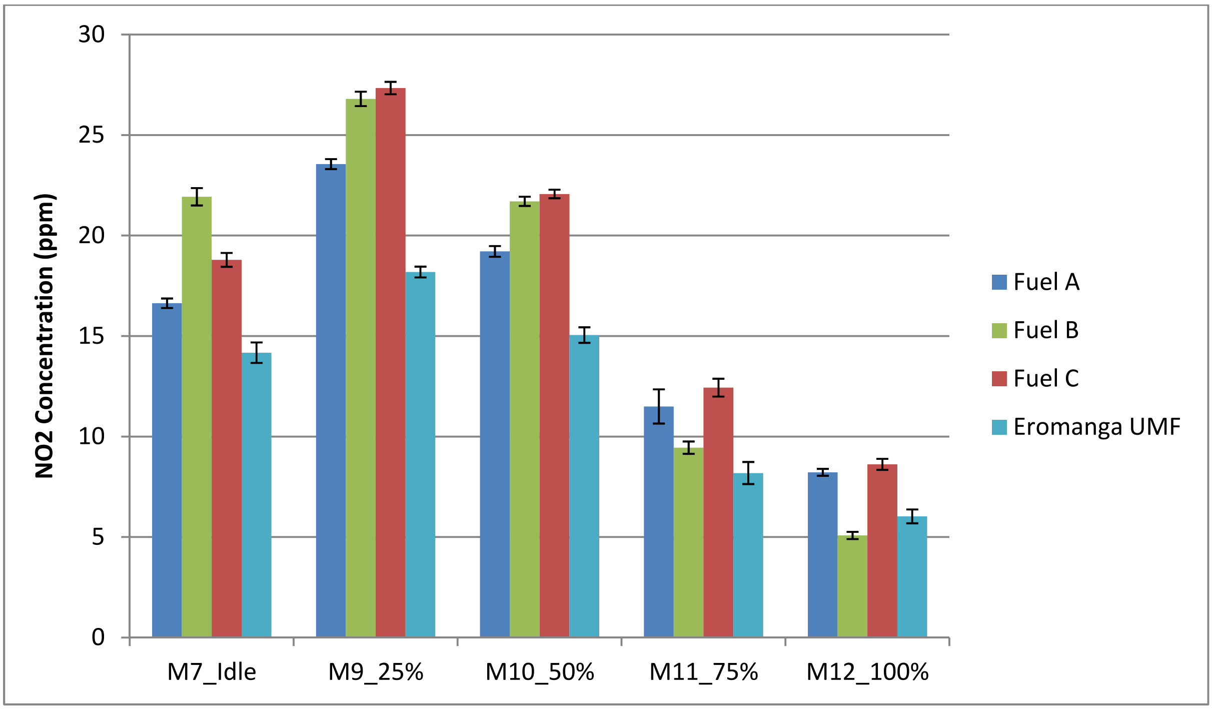

Figure 17. Concentrations of nitrogen dioxide emitted by the engine using different fuels at five different engine modes

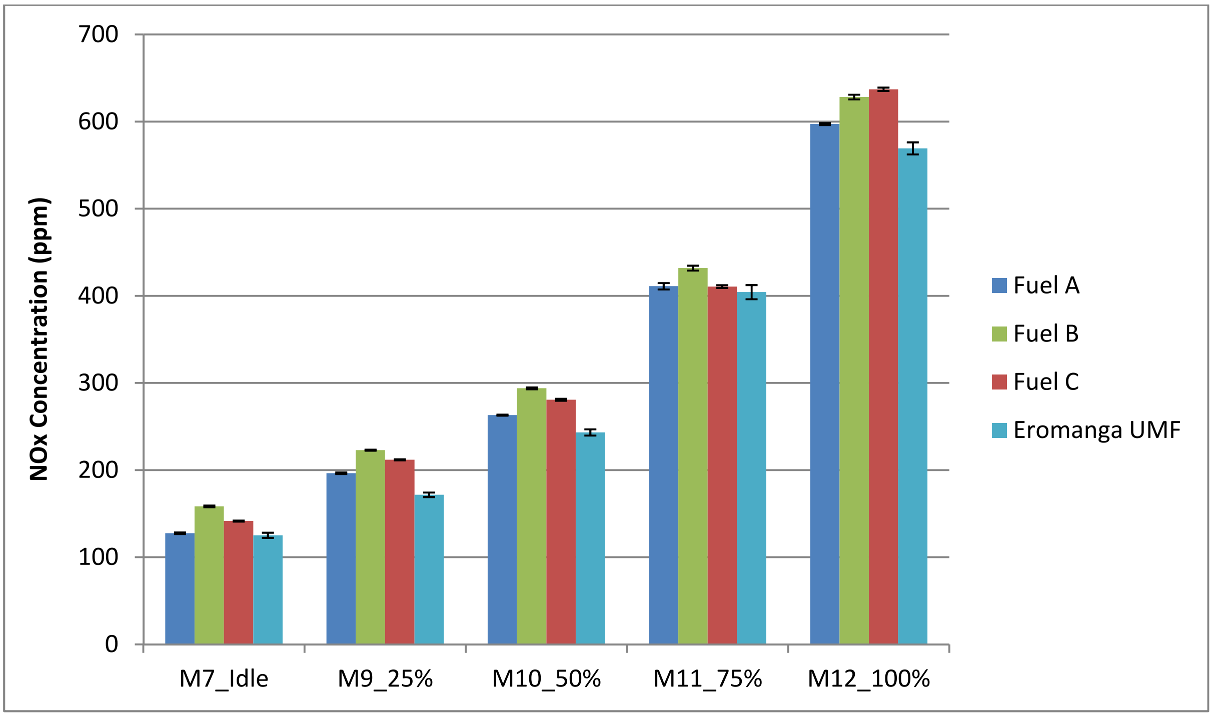

Figure 18. Concentrations of nitrogen oxides emitted by the engine using different fuels at five different engine modes

All nitrogen oxides (i.e. NO, NO_2 and NO_x) emissions from Eromanga UMF were comparable or lower than the emissions from other commercial diesel fuels.

4 Conclusions

In short, this project produced some major findings as follows:

1. The results have relatively good reproducibility considering the testing conditions (e.g. using a manual dynamometer);
2. In overall, carbon oxide, nitrogen oxide and particle emissions from Eromanga UMF were lower than emissions from other tested fuels, in particular for full engine load mode (i.e. engine mode 12);
3. No statistically significant difference in engine performance (e.g. power and exhaust temperature) was seen between all tested fuels in all engine modes, with exception of full mode where Eromanga UMF produced about 5% less power than others;
4. The Eromanga UMF had a slightly smaller particle count mean diameter (CMD) than the other fuels, however the reduction of particle numbers and size were found to not be due to new smaller particle formation, instead due to a reduction of larger particles.

Please note that, even for the same brand of fuel, the composition changes with different batch number, probably leading to significant changes in engine emissions. Also, the engine and instrumentation conditions may change from one lab to another one. Therefore, the results discussed above are only valid for the fuels provided and the engine conditions during the test periods.

5 References

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