Field Characterisation of Diesel Particulate Emissions From a Euro 0 Engine

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Introduction

The Australian Defence Force (ADF) operates a large fleet of vehicles fitted with diesel engines of various types and age. As part of OH&S requirements, exposures to personnel in transport modules of two trucks fitted with Euro 0 engines, (an older vehicle and one with newly refurbished engine) were determined to ensure compliance with occupational exposure guidelines. A field study was undertaken to determine diesel particulate (DPM) concentrations and carbon characteristics[1] in real time under various driving conditions. As exposure limits generally required knowledge of inorganic and metal content in DPM with particle size, size fractionated chemical speciation was also determined.

Methods

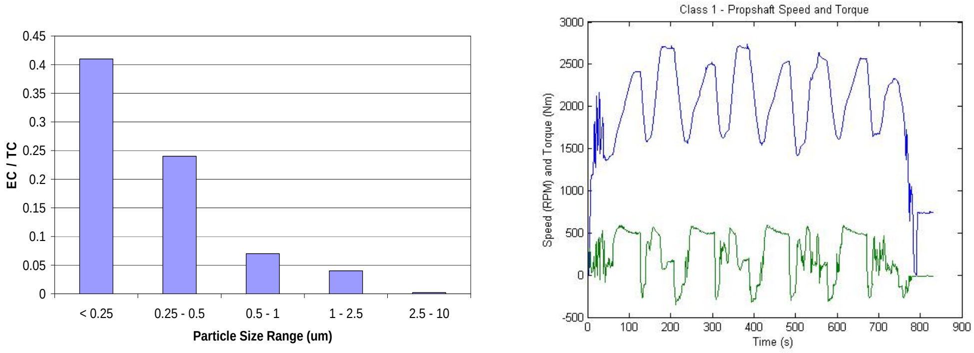
The vehicle was powered by a Mercedes Benz OM 353.959 six-cylinder direct injected engine with exhaust gas driven turbocharger (Euro 0). Displacement was 5.675 L with 124 kW maximum power at 2800 rpm and 520 Nm torque at 1800 rpm. Engine emissions were determined from chassis dynamometer measurements (Vipac Engineers, Melbourne).

Vehicle trials were conducted on test circuits in a rural area with moist track surface, free from vehicular and dust pollution. Trials were conducted on sealed road, dirt track and gradient circuits. Black carbon (BC) was continuously measured using a calibrated aethalometer (Magee Scientific) while DPM was measured using a calibrated photometer (TSI Dustrak 8520) for particles of 0.1 µm to >10 µm in size, in addition to particle size distribution in the range 0.3 µm to 20 µm (Grimm 1108, 16 channels). Concentrations of total polycyclic aromatic hydrocarbons (PAH) were determined using the PAS 2000 (EcoChem Analytics) with ultrafine and nanoparticles (UFNP) measured by the TSI P-Trak. The gaseous and vapour concentrations of NO_2, CO and VOCs were measured using electrochemical sensors (Odalog, Apptek Int.) and a photoionisation detector (ppb RAE 3000) respectively. Filter samples of elemental, organic and total carbon (EC, OC and TC), were analysed by NIOSH Method 5040 with soluble inorganic ions by selective ion electrode and metals by ICP-MS. The engine operating point (engine speed and output torque) and the wind speed and direction, relative to the direction of vehicle travel were also measured. Tailpipe UFNP size from 0.010 – 1.0 µm (Grimm SMPS) and mass distributions (Sioutas impactor) for particles containing EC, OC, inorganic ions and metals were determined for idling conditions only, using a ventilation duct diluter fitted with a fan.

Results

The only pollutant with concentrations close to exposure limits of US and Federal German regulatory authorities was DPM, with an averaged exposure of ~ 0.01 mg m^{-3} EC. Exposures were dependent on wind speed and direction, relative to vehicle direction of travel, and was influenced by emission levels and load on the steepest gradient. DPM mass distribution (< 0.25 µm, 0.25 - 0.5 µm, 0.5 – 1 µm, 1 – 2.5 µm, 2.5 – 10 µm) under idling conditions was consistent with the UFNP size distribution which showed a peak at 0.05 µm (50 nm) and a shoulder at 0.015 µm (15 nm), indicating nanoparticle formation.

Under idling conditions, the EC/TC distribution (Figure 1a) followed the same trend as the UFNP size distribution, with a weighted average EC content of 28%. This was in agreement with 23% EC/TC found for an open face filter measurement and BC/DPM correlation slopes of 21-26%, based on TC as 80% DPM in this study.



(a) **(b)**

Figure 1a. EC / TC size distribution of diesel exhaust particulates under idling conditions, b. Vehicle speed and engine torque for travel at high engine load on sealed road circuit.

At 1750 rpm, 175 Nm and higher engine loads, the average EC/TC was 45%. This finding was in agreement with the BC/DPM correlation slopes of 31% - 37% for the dirt track and ~60% for the gradient circuits. Thus the carbon and chemical speciation characteristics conformed to those of US and Federal German regulatory authorities for exposure and risk assessment.

The vehicle speed and torque at the higher engine load on sealed road is shown in Figure 2b. The results suggest the EC/TC distribution was dependent on combustion conditions which varied widely over the engine operating range.[2] Lower EC content during idling is also consistent with incomplete oxidation of volatile OC at lower exhaust temperature.[1]

ICP-MS analyses showed high Fe (4%) and Al (1%) with lower Cu (0.2%) content, indicating engine wear.[3,4] Zn (0.1%), Mg (1.2%), Ca (3%), K(4%), Na (2.3%) with phosphate (9.5%) rich particles suggest corrosion inhibitors, detergents and stabilizers in lubricant oil.[4,5] Whereas engine wear metals were uniformly distributed across the particle size range, the lubricant minerals were predominantly concentrated in the < 0.25 µm size fraction, consistent with combustion conditions.

Conclusions

Consistency of BC/DPM correlations with EC/DPM provides support for real time measurements of BC-derived EC exposures[6]. Averaged real time EC exposures were below the occupational limits of US and Federal German regulatory authorities (0.1 mg m^{-3}). Size fractionated EC, metal and ion characteristics were consistent with UFNP particle size distribution under idling conditions. Higher EC/TC at higher engine loads was in agreement with more oxidation of volatile OC at higher exhaust temperatures[1] and combustion conditions.[2] Future work will focus on higher resolved size fractionated chemical speciation.

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Introduction

The Australian Defence Force (ADF) operates a large fleet of vehicles fitted with diesel engines of various types and age. As part of OH&S requirements, exposures to personnel in transport modules of two trucks fitted with Euro 0 engines, (an older vehicle and one with newly refurbished engine) were determined to ensure compliance with occupational exposure guidelines. A field study was undertaken to determine diesel particulate (DPM) concentrations and carbon characteristics[1] in real time under various driving conditions. As exposure limits generally required knowledge of inorganic and metal content in DPM with particle size, size fractionated chemical speciation was also determined.

Figure 1. Unimog vehicle with cargo and personnel modules showing the sampling location at the dummy on the passenger side.

Figure 2. Smoke candle coloured exhaust plume. of Unimog truck showing turbulence at rear of vehicle travelling at 20 km/h and plume entry at opening.

Figure 3. Sampling locations in personnel module of Unimog truck on exhaust side

Instrumentation and Methods

- Mercedes Benz OM 353.959, 6 cyl, direct injection, turbocharger (Euro 0)
- Circuits – Sealed road (Class 1), dirt track (Class 3), gradients
- TSI DustTrak 8520 (0.1 µm - 10µm) – PM10 (truck exhaust calibration)
- Magee Scientific Aethalometer – Black carbon (BC)
- Sioutas Impactor (< 0.25 µm – 10 µm) - Mass size distribution (5 stages)
- Grimm SMPS (0.011 µm – 1 µm) – Ultrafine and nanoparticle size distribution
- Grimm 1108 (0.3 µm - 20µm) – 16 channel particle size distribution (PSD)
- TSI P –Track – Concentrations of ultrafine and nanoparticles
- EcoChem Analytics PAS 2000 – Total PAHs.
- OdaLog electrochemical sensors and ppb Rae 3000 – NO_2, CO and VOC vapours
- Elemental, Organic and Total carbon (EC, OC, TC) – NIOSH Method 5040
- Soluble inorganic ions – Ion selective electrode
- Engine metals – Inductive Coupled Plasma – Mass spectrometry (ICP-MS)
- Diluter – Ventilation duct fitted with fan (dilution factor of 4)

Results and Discussion

- ♦ Diesel particulate exposures in module – average ~ 0.01 mg m^{-3} EC.
- ♦ PM_{10} - Dependent on wind direction and speed, travel direction (Fig 4a, b)
- ♦ Exposure – Influenced by cargo load on steep gradient
- ♦ Particle Size Distribution (PSD) - Unimodal, peak at 50 nm, shoulder 15 nm
- ♦ Mass Size Distribution - Follows PSD during idling (Figure 5)
- ♦ Euro 0 engine PSD similar to modern design engine PSD

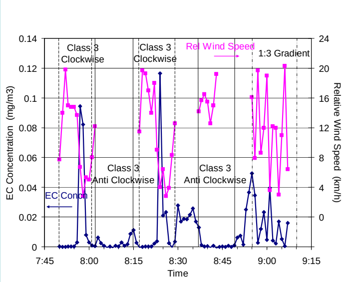

Figure 4a. PM_{10} levels in module on test circuits showing dependence on wind speed and load.

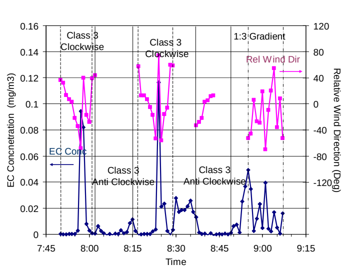

Figure 4b. PM_{10} levels in module on test circuits showing dependence on wind direction and load

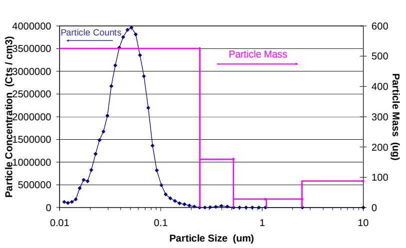

Figure 5. Mass and particle size distribution of the Unimog exhaust during idling.

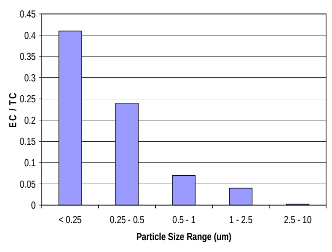

Figure 6. EC/TC size distribution of diesel particulates under idling conditions.

- ✱ EC/TC - Trends with PSD and weighted average content of 28% (Figure 6) Agreement with open face filter measurement (23%).
- ✱ TC – 75% - 90% DPM (Assume 80%)
- ✱ BC/DPM - Correlation slope of 21% - 26%, good agreement with EC/TC
- ✱ Carbon and chemical speciation conform with characteristics defined by US and Federal German regulatory authorities for exposure and risk assessment.

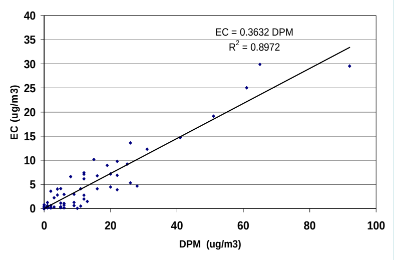

Figure 7. BC/DPM for travel on dirt track at 1750 rpm and 175 Nm showing a correlation slope of 0.36 and correlation coefficient of 0.89.

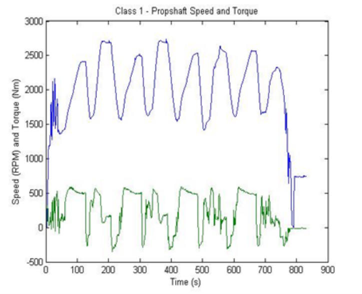

Figure 8. Engine speed and output torque for travel on sealed road at 2400 rpm and 500 Nm.

- ✱ 1750 rpm, 175 Nm – Dirt track engine operating point, EC/TC of 45%
- ✱ BC/DPM – Correlation slope of 36% (Figure 7), good agreement with EC/TC
- ✱ 2400 rpm, 500 Nm – Sealed road engine operating point (Figure 8)
- ✱ Lower idling EC/TC - Incomplete oxidation of OC at lower exhaust temperature[1]. EC/TC changes - combustion conditions vary widely over operating range[2].

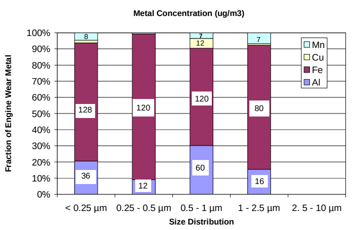

Figure 9. Particle size distribution of engine wear metals showing relatively uniform distribution over the size range.

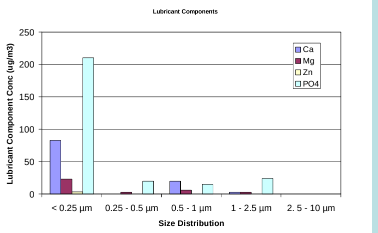

Figure 10. Particle size distribution of lubricant minerals showing localisation in < 0.25 µm size fraction.

- ✱ Engine wear metals[3,4] uniformly distributed over particle size spectrum (Fig. 9)
- ✱ Lubricant minerals[4,5] concentrated in the < 0.25 µm size fraction (Fig. 10).

Conclusions

- ➢ BC/DPM correlations consistent with EC/TC – supports BC equivalence with EC for real time measurements of diesel engine particulates.[6]
- ➢ Averaged real time EC exposures were below the occupational limits of US and Federal German regulatory authorities (0.1 mg m^{-3} EC).
- ➢ EC/TC distribution dependent on engine operating point[1]
- ➢ Engine wear metal PSD uniformly distributed, but lubricant components localised in < 0.25 µm size fraction, consistent with combustion.

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