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Remote measurement of diesel locomotive emission factors and particle size distributions

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HIGHLIGHTS

- We demonstrate a system for measuring emissions factors for passing trains using slow instruments.
- We measure emission factors for 56 passing trains using readily available monitoring equipment.
- Method is effective for $PM_{2.5}$, SO_2, NO_x, and size distribution during clean background conditions.
- The results are consistent with comparable published results.
- Significant correlation between particle number and both SO_2 and NO_x were identified.

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ABSTRACT

A technique for analysing exhaust emission plumes from unmodified locomotives under real world conditions is described and applied to the task of characterizing plumes from railway trains servicing an Australian shipping port. The method utilizes the simultaneous measurement, downwind of the railway line, of the following pollutants; particle number, $PM_{2.5}$ mass fraction, SO_2, NO_x and CO_2, with the last of these being used as an indicator of fuel combustion. Emission factors are then derived, in terms of number of particles and mass of pollutant emitted per unit mass of fuel consumed. Particle number size distributions are also presented.

The practical advantages of the method are discussed including the capacity to routinely collect emission factor data for passing trains and to thereby build up a comprehensive real world database for a wide range of pollutants.

Samples from 56 train movements were collected, analyzed and presented. The quantitative results for emission factors are: $EF(N) = (1.7 \pm 1) \times 10^{16}$ kg^{-1}, $EF(PM_{2.5}) = (1.1 \pm 0.5)$ g kg^{-1}, $EF(NO_x) = (28 \pm 14)$ g kg^{-1}, and $EF(SO_2) = (1.4 \pm 0.4)$ g kg^{-1}. The findings are compared with comparable previously published work. Statistically significant ($p < \alpha$, $\alpha = 0.05$) correlations within the group of locomotives sampled were found between the emission factors for particle number and both SO_2 and NO_x.

1. Introduction

Airborne emissions by diesel fuelled engines operating on land are categorised as either on-road or off-road. Emissions from railway locomotives fall into the second category. Being supposedly a relatively clean transport mode, rail transports were not subject to emission control in the US prior to 1990 (Popp et al., 1999). Due to the rapid growth of the train use for goods and passenger transport however, airborne pollution from trains has begun to draw increasing attention. Furthermore it is expected that rail will undergo significant expansion in the future and will therefore draw increasing attention from a regulated emission and health effects standpoint (Sawant et al., 2007).

As with all diesel engine airborne emissions, the emissions from railway locomotives affect both human health and the environment. The effects are most apparent in areas adjacent to and

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downwind of railway tracks and stations. Because diesel exhaust plumes contain some of the most notorious pollutants and greenhouse gases, including NO_x, CO_2, SO_x, volatile organic compounds (VOCs), methane and particulate matter (PM) the effects of diesel exhaust on the human body and the environment have been repeatedly targeted in wide range of investigations (Knibbs et al., 2011; Martuzevicius et al., 2008; Riedl and Diaz-Sanchez, 2005; Swanson et al., 2007; Tsukue et al., 2010).

Traditionally, diesel airborne emission studies have focused on the above species. However, more recently, the target of measurement has included measurement of the particle number (PN) concentration (Ban-Weiss et al., 2009, 2010; Huang et al., 2012; Liu et al., 2011; May et al., 2007; Nickel et al., 2013; Thompson et al., 2004; Zhu et al., 2011). Studies in this field also focus on the factors influencing the characteristics of the emission, through parameters, such as emission factor and size distribution, and relate them to the operational modes, or duty cycles of the engines. Emission of SO_2, for instance, is known to be dependent on the sulphur content of the fuel, while emission of other compounds, like the NO_x, is known to be dependent on the engine conditions and engine load. In the locomotive fields, operating load is specified in terms of throttle notch setting (Transport_Canada, 2007). The notch system in the context of locomotives, is a transmission system which grades the use of train engine power according to the required speed of the train. This system is comparable to the gearbox system used in a car. Normally a train engine uses nine throttle positions, the first of which is the idle position. The remaining eight are referred to as power positions and these constitute eight notch positions. The first notch is typically used to initiate movement. The larger the notch number, the greater the power used by the train, and the faster the train moves.

Globally rail transport currently comprises about 40% of non-maritime freight transport (European-Commission, 2009). Being the most efficient intra-continental transport modality in terms of fuel (Davis et al., 2009), and hence CO_2 emission, rail transport is likely to undergo significant expansion in the future. Emissions from the diesel fuelled locomotives widely used by the rail transport industry, are however gaining increasing attention from a regulated emissions and health effects standpoint (Sawant et al., 2007), and given the above scenario this growth in concern is likely to accelerate.

Diesel-electric locomotives have electrically driven traction wheels powered by an on board diesel fuelled generator (Fritz and Cataldi, 1991). These locomotives are the predominant means of propulsion for long haul freight trains. Although relatively efficient in terms of fuel consumption compared to direct drive diesel locomotives, they are a significant contributor to mobile source emissions; contributing 11% and 4% of the US mobile source emissions inventory for NO_x and PM_{10} respectively (Sawant et al., 2007). In the European Union (EU-27) diesel powered trains contribute 2.0% and 2.8% respectively of mobile source NO_x and $PM_{2.5}$ emissions (Borken-Kleefeld and Ntziachristos, 2012). In Australia, railways contribute 3.1%, 1.8% and 2.5% of mobile source NO_x, PM_{10} (excluding dust emissions from roads) and SO_2 emissions respectively (NPI, 2012).

Sawant et al. (2007) have provided a comprehensive review of the very limited body of work examining emissions from trains, noting the lack of data on speciated gas and particle phase emissions. The authors pointed out that the relatively poorly regulated non-road sources are now substantial contributors to the total emissions inventory, with diesel locomotives contributing a significant fraction of that inventory in terms of NO_x and PM emission.

A range of remote emission factor and size distribution measurement methods have been developed for assessing mobile sources under real world operating conditions. These include mobile labs and plume capturing techniques. Typically remote measurement methods employ very high temporal resolution instruments so that a full instrument response is achieved within the very brief intervals when the plume of a mobile source is accessible (Bishop and Stedman, 1996; Hak et al., 2009; Jonsson et al., 2011; Moosmüller et al., 2003; Zhu et al., 2011). Others have sought to circumvent the problem of transient plume concentrations by capturing and holding plume samples for long enough to perform the necessary analysis (Johnson et al., 2008; Kittelson et al., 2002; Morawska et al., 2007).

The current study employs a plume reservoir technique to reduce the rate of change in plume concentration, thereby allowing the use of a more readily available suite of instruments to be employed for size distribution and emission factor measurements. The approach is applicable to low frequency mobile sources such as trains provided that the interval of passage is no less than about 2 min.

This paper addresses an urgent need for rail side measurements of train engine emissions which are a serious issue globally. For example in Australia there is a burgeoning coal mining for export industry which ships large quantities via rail to ports in populated areas. The emissions from these trains are perceived as a threat to the health of residents and hence to coal industry viability.

The approach has been used here to measure the emitted particle size distributions and to assess the emission factors of passing diesel locomotives using remote measurements of a range of the mixing ratios of a range of gaseous and particulate pollutants with respect to CO_2. Correlations between the various emissions factors are also presented.

2. Experimental methods

The measurement campaign focused on the emissions of trains entering and leaving the Port of Brisbane. Approximately 73 trains per week access the port, the majority of which (approximately 60) are loaded with coal for export. The trains typically are driven by 2 Clyde/EMD 2300 class diesel-electric locomotives selected from a pool of 22 driving 41 of 73-tonne wagons with a typical payload of 1900 tonnes. The locomotives use standard locomotive diesel oil (ADO) with an energy density of 38.6 MJ L^{-1} and an end use (i.e. combustion only) CO_2 emission factor of 69.7 g MJ^{-1} or 2.690 kg L^{-1} and fuel consumption was in the range 0.003–0.005 L per gross tonne-km (GTK) (QR-Network-Access, 2002). The specific chemical composition of the diesel fuel used by the locomotives was not available in the current study, however by referring to the Australian National Standard for Diesel Fuel, it can be inferred that the sulphur and PAHs content of the fuel used by the locomotives should not have exceeded 50 ppm and 11% (on mass basis), respectively (Orbital-Australia, 2010). Data on the chemical and physical contents of diesel fuel compliant with the Australian National Standard are presented in Table S1 of the supplement.

The methodology employed, involved the operation of a mobile laboratory adjacent to the railway line. The mobile laboratory contained an array of instrumentation for the analysis of ambient particle and gas concentrations. CO_2 was included in the measurements as a measure of the fuel combustion gas content in the sample.

The measurements were conducted in two campaigns lasting for a total of 7 days, the first lasting 4 days was conducted between 30^{th} August and the 3rd September 2007 and the second lasting 3 days was conducted between 11th February and the 14th February 2008. The results for the two campaigns were treated as a single group of measurements for analysis purposes.

2.1. Instrumentation

The mobile monitoring station was equipped with an SMPS (TSI 3934) for particle size distribution measurements, a condensation