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Compositional characterization of $PM_{2.5}$ emitted from in-use diesel vehicles

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ABSTRACT

In Asian developing countries diesel vehicles contribute significantly to urban air pollution. The emission factors (EF) and exhaust gas composition of these vehicles may be different from those in the US and Europe, where most emission measurements are taken. This study focuses on the fine particulate matter ($PM_{2.5}$) emission from in-use diesel vehicles in Bangkok, with the goal of providing EF and source profiles that are more appropriate for developing countries. The chassis dynamometer test results for 93 vehicles, including 39 light duty (LD) and 54 heavy duty (HD) of the age models between 1972 and 2005, are presented. PM EF are lower for vehicles of newer year models, consistent with the implementation of engine standards. The average $PM_{2.5}$ EF of 0.23 g km^{-1} for LD, and 1.76 g km^{-1} for HD trucks and buses are generally higher than the literature reported values. Old HD trucks produce the highest PM EF of above 3 g km^{-1}. Black carbon (BC), measured by an optical method, is well correlated with elemental carbon (EC) by TOT, but is consistently about 1.7 times higher. Between the LD and HD fleets, there is no significant difference in the fractional composition (BC, EC, OC, water soluble ions and elements) of emitted $PM_{2.5}$. The composite source profile, weighted against the fleet composition and the vehicle km travelled (VKT) for the city has an average OC of 19%, EC of 47%, and sulfate of 2%, which are close to those reported for 1980s US diesel vehicles.

1. Introduction

Traffic is a major source of air pollution in urban areas worldwide (Colvile et al., 2001). In Asian developing countries, a fast increase in vehicle population in conjunction with a slow increase in road surface areas and improper traffic management often lead to traffic congestion, which can further seriously deteriorate urban air quality. Of special concern are diesel powered vehicles that emit a complex mixture of toxic gaseous pollutants and fine particles (Kagawa, 2002; Kerminen et al., 1997). Diesel vehicles contribute significantly to the fine particulate air pollution burden which is one of the most significant problems in large urban areas of Asian developing countries (Kim Oanh et al., 2006; Gupta and Kumar, 2006).

Diesel particulate matter and its chemical composition have important health, atmospheric and climate implications (Maricq, 2007). The emission depends on a number of factors such as vehicle age, engine design and operating conditions, lubricant oil and fuel quality, as well as environmental conditions (Maricq, 2007; Yanowitz et al., 2000; Docekal et al., 1992). Diesel emissions in developing countries, where old and poorly maintained fleets are common and exhaust emission control devices are rare, could differ greatly from those in developed countries for which majority of studies have been conducted (Maricq, 2007; Gillies and Gertler, 2000), yet is inadequately documented in the literature.

Urban areas in developing countries experienced a rapid growth of vehicle fleets in recent years. In Bangkok, the capital city of Thailand, over the period from 1994 to 2006, the vehicle fleet grew at a rate of 5% per annum (DIESEL, 2008). In 2007 alone, more than 680,000 new vehicles (92,500 light duty diesel; above 11,600 heavy duty diesel; 366,000 motorcycles; and others), were registered in the city (DLT, 2008), i.e. a growth of 62% in the last five years. Traffic contributes the majority (50–90%) of the NO_x, CO, PM, and non-methane hydrocarbon (HC) emissions (BMA and UNEP, 2001). Ambient PM_{10} levels often exceed the Thailand 24-h standard of 120 $\mu g\ m^{-3}$, e.g. 15% of measurements at roadside stations made by the Pollution Control Department during 2006–2007 (PCD, 2007). During the dry and more polluted season, $PM_{2.5}$ seasonal average is about 50 $\mu g\ m^{-3}$, well above the US EPA 24-h standard of 35 $\mu g\ m^{-3}$. $PM_{2.5}$ constitutes most of PM_{10}, i.e. 58–66% (Kim Oanh et al., 2006).

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In order to manage the PM air quality the information on quantitative source contributions is required. A detailed emission inventory can provide such information, however, being resource intensive it is rarely available for urban areas of developing countries. Consequently, there is a growing effort to estimate source contributions using receptor modeling approaches (Kim Oanh et al., 2009). A multi-year source apportionment study for $PM_{2.5}$ in six Asian cities including the Bangkok Metropolitan Region (BMR) identified diesel vehicles as one of the major contributing sources (Kim Oanh et al., 2006). However, lack of local PM source profiles has hindered attempts to make accurate quantitative source apportionments for the cities.

In fact, there is no published compilation of PM profiles of major emission sources in Asia or the developing world. Data for a few sources have been reported, i.e. biomass burning in Bangladesh (Sheesley et al., 2003) or estimated composition of secondary aerosol (Chen et al., 2001). However, no comprehensive source profiles for in-use diesel vehicles in Asia have been recorded, although an initial effort was presented which characterized the exhaust emission of one engine in India for concentrations of some metals and EC/OC (Sharma et al., 2005). Commonly, whenever the Chemical Mass Balance (CMB) model (Watson et al., 1997) is used for PM source apportionment in the developing world, the required source profiles are drawn from those developed in North America (Chen et al., 2001; Chowdhury et al., 2007; Lee et al., 2008; Park et al., 2001). The lack of region specific source profiles may be circumvented through the use of statistical multivariate models such as Positive Matrix Factorization (Chueinta et al., 2000; Hien et al., 2004), Factor Analysis-Multiple Regression (Okamoto et al., 1990) or Simple Factor Analysis (Kavouras et al., 2001; Chimidza and Moloi, 2000). However, these multivariate models require a large number of ambient samples (Henry et al., 1984) that may not readily be available in most developing countries. In addition, the interpretation of the resulting source profiles produced by the statistical models is still made based on comparison with North American source profiles, and often with subjectivity and ambiguity which result in much uncertainty of the source contribution estimates. Regardless of the type of receptor models used, source profiles for major PM emission sources in developing countries would surely increase the confidence in receptor modeling results for these locations.

In this paper, we discuss emission factors (EF) and source profiles of PM emitted from in-use diesel vehicles in BMR, Bangkok and the surrounding provinces, of Thailand. The measurements presented here were taken as a supplement to the on-going project "Developing Integrated Emissions Strategies for Existing Land Transport (DIESEL)". The DIESEL project was implemented by the Thailand Pollution Control Department (PCD) with assistance from the World Bank, Clean Air Initiative for Asian Cities (CAI-Asia) and the US-Asia Environmental Partnership (DIESEL, 2008). However, the DIESEL plan was to measure only mass of PM and selected gaseous pollutants (THC, CO, NO_x, and CO_2). Our measurements were added to obtain information on chemical composition relevant to source apportionment study and radiative transfer modeling by the particles. This paper focuses on PM EF and source profiles; our other paper (Subramanian et al., 2009) presents climate-relevant measurements.

2. Experiment design

2.1. Driving cycle

The final version of driving cycles used in the tests (Fig. 1A, Supplementary) basically combined the "Point" and ETC/EUDC cycles to represent the frequent stop-and-go modes inside the Bangkok city and faster driving modes outside. The Point cycle was developed specifically for Bangkok (JICA, 2004). The ETC/EUDC cycle is used in Europe for emission certification of diesel vehicles (Dieselnet, 2007). The LD driving cycle included LD Point2 and EUDC (maximum speed of 50 km h^{-1}) and EUDC2 (maximum speed of 90 km h^{-1}). The bus driving cycle includes ETC1 (maximum speed of 50 km h^{-1}), Point2 Idle, and Point2 transient (maximum speed of 44 km h^{-1}). HD trucks are not allowed inside the city during the rush hours and, therefore, run at higher speed than the buses. The driving cycle for HD trucks combines HD Point2 transient and ETC1 for urban driving, and ETC2 of higher speed (average of 72 km h^{-1}, maximum of 87.5 km h^{-1}) for faster driving conditions in rural areas. Prior to each test, the vehicles were pre-conditioned by an AC2540 cycle (a warm-up cycle for 5 min).

Note that during the course of the DIESEL project the driving cycles for the LD and HD trucks remained almost the same while that for the HD buses had been revised. Accordingly, the previous version of the HD bus driving cycle had a faster acceleration and a higher maximum speed. Therefore, the early test results of HD buses with the previous driving cycle were not included in the data analysis for this paper with the aim to provide representative source profiles for the urban diesel fleet.

2.2. Selection of vehicles for chassis dynamo testing

Bangkok contains a large fleet of diesel vehicles with over 1 million light duty (LD) and over 100,000 heavy duty (HD) vehicles (Table 1A, Supplementary). To select representative test vehicles, a simple stratified sampling strategy was implemented by the DIESEL project which considered several factors including engine types, model year and vehicle types. Due to their high emission, relatively more HD (than LD) vehicles were tested. Within each category (LD, HD bus, HD truck) the number of tested vehicles of a particular group (model year) was taken proportionally to the actual number of registered in-use vehicles in Bangkok. Buses constitute a larger fraction of the heavy-duty fleet in Bangkok because of a limitation on the use of trucks inside the city. Further information on the recruitment is given in the DIESEL Project report (DIESEL, 2008). The tests were performed at the Automotive Emission Laboratory of PCD, Thailand using a chassis dynamometer system with Schenck/Pierburg test beds, a dilution system and a constant volume sampler following the European Union Directive 70/220/EEC test protocol (DIESEL, 2008).

This paper therefore reports the test results of 93 vehicles that run on the final version of the driving cycles implemented by the DIESEL project including 39 LD (van and pickup), 29 HD trucks and 25 HD buses. A summary of the vehicle characteristics (year model, weight, odometer, engine standard) and the grouping is given Table 1 along with the EF results. Most of the tested vehicles are of Japanese made with the model years ranged between 1972 and 2005. Vehicle age and engine technology are expected to be closely related as standards for new vehicles are progressively implemented (PCD, 2009). LD duty vehicles of the year models before 1995 have no engine standards while those between 1995 and 1996 generally follow the pre-Euro standard (ECE R 83-01, App C). From 1998 onward LD vehicles commonly follow EuroI or EuroII. Similarly, the HD vehicles of 1992 or before have no engine standard, those between 1993 and 1997 follow the pre-Euro standard (ECE R 49-1) and vehicles of year models 1998 or later would follow EuroI and EuroII standards. Therefore, the LD, HD trucks and HD buses are further classified according to the model years into 18 vehicles groups (Table 1) to represent the evolution of the engine standard enforcement in Thailand from no-standard to EuroII (PCD, 2009). There was only a short period between enforcements of EuroI and