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Real-world operation conditions and on-road emissions of Beijing diesel buses measured by using portable emission measurement system and electric low-pressure impactor

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ABSTRACT

On-road measurement is an effective method to investigate real-world emissions generated from vehicles and estimate the difference between engine certification cycles and real-world operating conditions. This study presents the results of on-road measurements collected from urban buses which propelled by diesel engine in Beijing city. Two widely used Euro III emission level buses and two Euro IV emission level buses were chosen to perform on-road emission measurements using portable emission measurement system (PEMS) for gaseous pollutant and Electric Low Pressure Impactor (ELPI) for particulate matter (PM) number emissions. The results indicate that considerable discrepancies of engine operating conditions between real-world driving cycles and engine certification cycles have been observed. Under real-world operating conditions, carbon monoxide (CO) and hydrocarbon (HC) emissions can easily meet their respective regulations limits, while brake specification nitrogen oxide ($bsNO_x$) emissions present a significant deviation from its corresponding limit. Compared with standard limits, the real-world $bsNO_x$ emission of the two Euro III emission level buses approximately increased by 60% and 120% respectively, and $bsNO_x$ of two Euro IV buses nearly twice standard limits because Selective Catalytic Reduction (SCR) system not active under low exhaust temperature. Particle mass were estimated via particle size distribution with the assumption that particle density and diameter is liner. The results demonstrate that nanometer size particulate matter make significant contribution to total particle number but play a minor role to total particle mass. It is suggested that specific certified cycle should be developed to regulate bus engines emissions on the test bench or use PEMS to control the bus emissions under real-world operating conditions.

1. Introduction

Due to their adverse health effects and their abundance in the vicinity of roads, particularly in urban areas, diesel emissions have become of great concern in the past decade. The measuring of emissions from vehicles, and hence their control are major issues, since vehicle emissions typically account for about 50% of particulate matter (PM) and NO_x emission inventories (Wichmann and Peters, 2000). This study focuses on the real-world operating condition and emission characteristics of diesel buses. This research was motivated by the recognition that in Beijing, indeed in the major cities of many developing countries, buses are the most widely used passenger transportation. Many of the buses are propelled by a heavy duty diesel engine, and are the major contributors to the urban environmental pollution because they are the only diesel vehicles which move frequently in the day-time (Van Poppel and Lenaers, 2005). Many Chinese metropolises do not allow heavy-duty diesel vehicles day time access to some urban areas.

Emission certification tests are a means of comparing the emissions of vehicles and checking whether they stay within certain limits; however, for heavy-duty vehicles, in most case decisions have been made without data from on-road operation or even chassis dynamometer studies and consider standalone engine test bench measurements (Pelkmans and Debal, 2006). The difficulty of test bench measurements to evaluate emission rate is increased by the addition of the electronic control module (ECM) to modern heavy-duty vehicles due to potential for multiple operating modes (Cocker et al., 2004). For instance, in fuel saving mode, refers to such mode as "off-cycle" mode, the ECM allows emission in excess of certification standard to obtain better fuel economy, but does not turn on during engine certification standard test. In this case, emission inventory estimation that based on engine certification measurement loses the original significance.

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Under this directive, increased concerns about the emissions produced from heavy-duty vehicles have placed an emphasis on the in-use monitoring of on-road vehicles (U.S.EPA, 2005). In recent years, the US Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) have implemented regulations to further control diesel emissions by measuring on-road emissions for in-use diesel engines in a defined portion of the engine operation known as the Not-To-Exceed (NTE) zone (Johnson et al., 2009). The new in-use regulation was the outcome of 1998 Consent Decrees (Federal Register, 2003) where “off-cycle” NO_x emissions exceeded certification levels during some in-use driving. However, at present time, this legislation is focused only on the measuring of gaseous pollutants. The measurements and the equipments required for PM regulation are in the debating process, and maybe enforce in the year 2011.

Currently there are many methods for particle number and size determination. The methods most commonly used are ELPI, scanning mobility particle sizer (SMPS) and condensation particle counter (CPC) (Keskinen et al., 1992). Many researchers presented the particle distribution of diesel and gasoline vehicles operating in steady states measured by SMPS in good agreement with ELPI (Maricq et al., 2006; Zervas and Dorlhene, 2006; Zervas et al., 2006). Unfortunately, SMPS has an insufficient resolution power for real time size distribution monitoring and CPC only used to counter total particle number instead of size distribution. ELPI has been used for the measurement of exhaust gas particle number and distribution, and also to estimate particle mass. Generally, the estimated mass is 1.5-2 times higher than the mass collected on filters, but if the effective particle density is estimated as a function of size, this value will possibly meet quiet well with the mass collected on filters (Marjamaki et al., 2000; Van Gulijk et al., 2004; Zervas et al., 2005; Maricq et al., 2006).

For the time being, most published works on real-world vehicle emissions focuses on automobiles and (Kittelson et al., 2006; Chen et al., 2007; Sawant et al., 2007; Durbin et al., 2008), however very little work have been published on urban buses. The objectives of the current research were to survey bus real-world operating condition and compare with European steady cycle (ESC) and European transient cycle (ETC). Meanwhile, on-road emissions have been investigated to estimate the discrepancy between engine certification legislation limits and real-world emissions. Two Euro III and two Euro IV emission level buses were choose for this survey, because most of Beijing buses are using this two types of engines after renewed in the year 2008.

2. Experimental methods

2.1. Tested vehicles and protocol

Four testing vehicles were provided by the commercial fleet of the Beijing Public Transportation Group (BPTG). Table 1 shows the technical specifications of the engines corresponding to each of testing buses. The driving cycle used within this study was designed by BPTG for bus testing, which is made up of slow speed sections because of the presence of traffic-lights, roundabouts, pedestrian crossings, etc, and of high speed sections (López et al., 2009). The characteristics of the road relating to gradients and surface conditions would affect the repeatability, however, geographically the land surface of Beijing is very flat and the entire roads are well built and paved.

The selected buses were equipped with portable emission measuring devices before starting their routine service during their normal environmental conditions. The total weight of balancing weight, instruments and experimenters matched with BPTG's yearly average passenger carrying capacity.

Table 1
Technical specifications of the test vehicles.

	EURO III urban buses		EURO IV urban buses	
	Vehicle I	Vehicle II	Vehicle III	Vehicle IV
Engine type	Diesel engine turbocharged with intercooler		Diesel engine turbocharged with intercooler	
Displacement (L)	6.6		6.8	
Cylinders	In-line 6 cylinders		In-line 6 cylinders	
Maximum Power at rpm	162 kW at 2500 rpm		165 kW at 2500 rpm	
Maximum torque at rpm	850 N·m at 1400 rpm		850 N·m at 1400 rpm	
Mileages (km)	10530	11081	59220	42897
GVWR (kg)	18000	18000	17800	17800
Overall length (m)	12	12	12	12
Emission Level	EURO III	EURO III	EURO IV	EURO IV
After treatments	None	None	SCR	SCR

2.2. Gaseous Pollutants measuring Equipments

The PEMS was a SEMTECH-DS analyzer that collects instantaneous and accumulated data under real-driving conditions. This equipment is meant for on-road emissions monitoring of diesel vehicles, and uses heated flame ionization detector (HFID) for total hydrocarbon (THC), non-dispersive ultraviolet (NDUV) analyzer for nitric oxide (NO) and nitrogen dioxide (NO_2), non-dispersive infrared (NDIR) for CO and carbon dioxide (CO_2) measurements (Chen et al., 2007). The carbon balance method was used to determine fuel consumption. The equipment also includes a barometer for measuring humidity and ambient temperature.

A four inch outside diameter (OD) stainless steel SEMTECH emission flow meter (EFM) was used in conjunction with SEMTECH-DS analyzer for continuous and direct measurement of vehicle exhaust. The condensation of water and high molecular weight hydrocarbon was prevented by heating transfer tubing and filter up to 190 °C. Instantaneous and total mass emissions were calculated conventionally using raw exhaust flow and the exhaust components concentrations.

Real-time engine performances were recorded by the vehicle interface system. This data set was used to recalculate emissions in brake-specific mass units (g/kWh^{-1}) for comparison with engine dynamometer certification testing results (Thompson et al., 2002).

2.3. PM Measuring Equipment

ELPI is a real-time particle size spectrometer designed for real-time monitoring of aerosol particle size distribution, and measures airborne particle size distribution in the size range of 0.03 − 10 μm using 12 channels. The operating principle of an ELPI is based on particle charging, inertial classification in a cascade impactor, and electrical detection of the aerosol particles (Marjamaki et al., 2000). The stages of the impactor are insulated electrically and each stage is connected individually to an electrometer current amplifier. The current value of each channel is proportional to the number of particles collected, and thus to the particle concentration in the particular size range (Keskinen et al., 1992). The current values are converted to an aerodynamic size distribution using particle size dependent relations describing the properties of the charger and the impactor stages.

To avoid the condensation of high concentrated and temperature exhaust during the process of sampling, two ejector dilutors were used in series with dried and High Effective Particle Air (HEPA) filtered high pressure air which provided by oil-less air compressor. In the first dilutor, the dilution air was preheated to 195 °C, mixed with the sample air in the ejector cavity. The mixed sampling flow was also heated to 195 °C in the diffusion cavity, resulting in a homogeneous dilution of gases and particles. An AVL4000 five gases analyzer use to determine dilution rate by measuring diluted carbon dioxides.