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Buses retrofitting with diesel particle filters: Real-world fuel economy and roadworthiness test considerations

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ABSTRACT

Retrofitting older vehicles with diesel particulate filter (DPF) is a cost-effective measure to quickly and efficiently reduce particulate matter emissions. This study experimentally analyzes real-world performance of buses retrofitted with CRT DPFs. 18 in-use Euro III technology urban and intercity buses were investigated for a period of 12 months. The influence of the DPF and of the vehicle natural aging on buses fuel economy are analyzed and discussed. While the effect of natural deterioration is about 1.2%–1.3%, DPF contribution to fuel economy penalty is found to be 0.6% to 1.8%, depending on the bus type. DPF filtration efficiency is analyzed throughout the study and found to be in average 96% in the size range of 23–560 nm. Four different load and non-load engine operating modes are investigated on their appropriateness for roadworthiness tests. High idle is found to be the most suitable regime for PN diagnostics considering particle number filtration efficiency.

Introduction

Millions of premature deaths occur annually worldwide due to poor air quality. Several studies have established a relation between inhalation of particulate matter (PM) and adverse health effects (Dellinger et al., 2008; Dockery et al., 1993; Lelieveld et al., 2015; Pope and Dockery, 2006; Ware et al., 1981; B. Wang et al., 2016). (Kumar et al., 2010) summarizing the recent advances concerning the impact of atmospheric nanoparticles on human health. Pagotto et al. (2001) have found metals and other elements responsible for toxicological effects in PM sample associated with vehicle activities. Morawska et al. (2008) reviewed the existing knowledge on ultrafine particles and the consequences of human exposure.

In the effort to mitigate PM emission from the transportation sector, several aftertreatment technologies have been proposed and developed, while the most efficient of them has been shown to be the diesel particle filter (DPF) (Mayer et al., 1998). Due to the relative installation simplicity of this device on in-use vehicles, a massive DPF retrofitting is being performed worldwide, especially in heavy-duty trucks and buses, which can be kept in service for more than 15 years (Boudart and Figliozzi, 2012). DPF retrofit has reportedly led to great particle emissions reduction, usually above 99% (Mayer, 2008; Tartakovsky et al., 2015).

Despite the cleaner exhaust gases, worsening in the fuel economy have been reported when a DPF is used (Alleman et al., 2004; Lapuerta et al., 2012; Lin, 2002; Liu et al., 2011), due

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to the increased backpressure caused by the filter. Climate change and fossil oil availability challenges call for continuous efforts to improve vehicle efficiency (Tartakovsky et al., 2012). Hence, increase in fuel consumption due to DPF could be a serious obstacle. Mikulic et al. (2010)) used a MY2003 Volvo D12 turbocharged diesel engine and an empty DPF can (to overcome increasing backpressure due to PM accumulation in the DPF) operating in the ESC test cycle to investigate the influence of DPF generated backpressure on the engine fuel consumption. A linear correlation between backpressure increase and fuel consumption was observed. For the B50 mode it was found that an increase of one mbar in the backpressure corresponds to 5.61 g/hr increase in the fuel consumption, and for the C75 mode, this value is 7.64 g/hr. In mid-1990s, Stamatelos (1997)) has performed a review of the effect of DPF on the efficiency of vehicle diesel engines. He has focused on investigating the combined influence of backpressure imposed by DPF on the engine and additional energy required for filter regeneration on the overall efficiency of the diesel power plant. Quite a number of studies reported on change in a vehicle fuel economy after DPF retrofitting in real-world usage conditions (LeTavec et al., 2002; Richards et al., 2003). However, a reliable assessment of fuel economy penalty in real-world usage conditions caused by DPF adding into the engine exhaust system remains to be a challenging task due to a need to separate the effects of vehicle aging, changes in driving and ambient conditions, driving style, single vehicle peculiarities, *etc.* This information is very important in light of the massive usage of PDFs in Euro VI vehicles, as well as in DPF-retrofitted older generation heavy-duty diesel vehicles.

Since state-of-the-art engine and exhaust gas after treatment technologies have allowed a drastic decrease in PM emissions, conventional particle mass measurement methods have reached their limits and can't ensure accurate measurement of today's low PM emission levels (Burtscher et al., 2016). Particle number (PN) measuring is found to be a solution, since it is superior to particle mass assessment in terms of resolution, speed and precision, especially for the ultrafine particle fraction, the range where most of the PN concentration (PNC) lies (Kittelson, 1998).

PN as an additional PM measurement parameter is being introduced in vehicles emission legislation. In 1998 the VERT Association has published a list of DPFs that reached 95% PN filtration efficiency in the range from 20 to 500 nm (Mayer et al., 1998). In 2001 the Particulate Measurement Program (PMP) was formed and resulted in development of the UNECE regulation No. 83 revision 4, which led to the implementation of the first PN legislation by the European Union, the Euro 5B standard, with a limit of particles/km for light-duty diesel vehicles, based on standard cycles (Bischof, 2015). A program for heavy-duty diesel vehicles was developed later on. It followed the PMP procedures, and was published in the UNECE Regulation No. 49, introduced in 2011. It stablished Euro-VI emission standards of particles/kWh for the World Harmonized Stationary Cycle (WHSC) and of particles/kWh for the World Harmonized Transient Cycle (WHTC).

Despite the great advance that has been made in regulating vehicle PN emissions, the existing legislation is limited to the type approval of new engines. There is no international legislation that controls PN emission levels of in-use vehicles. The only national legislation prescribing PN measurement for periodic inspection of DPF-equipped engines is applied in Switzerland for off-road and construction machinery (Stäubli and Kropf, 2016). Bischof (2015) reports that transmission smoke meters and opacimeters also reach their limits and are not suitable for tests of diesel engines meeting Euro V or Euro VI standards. Giechaskiel et al. (2014) further confirmed in their comprehensive review that measurement of exhaust gas opacity is not suitable for modern diesel engines because PM emissions are far below the detection limit of conventional smoke meters. They overviewed recent programs dealing with a search for measurement principles that can be suitable for the roadworthiness tests. There was no discussion on suitable engine operating mode/s for particle diagnostics. In a more recent study of Kadijk et al. (2016), total 213 in-use diesel light-duty vehicles with DPF were investigated. The study confirmed the inappropriateness of the smoke measurement for roadworthiness tests of vehicles with DPF. PN measurements at low idle regime were performed and found to be beneficial compared to the smoke measurement. In their latest study Kadijk et al. (2017) tested 14 light-duty vehicles of Euro 3, 4, 5 and 6 generations with a purpose to propose a new roadworthiness emission test procedure aimed at identifying vehicles with a malfunctioning or removed DPF. The vehicles were tested at low and high idle, as well as at free acceleration regimes. Opacity measurements were performed at the free acceleration and high idle modes. PN measurements were carried out at low idle and chassis dyno (NEDC) tests. No attempt was made to separate the influence of engine and DPF. No assessment of particle number filtration efficiency (PNFE) was performed. While most of authors agree on a need to apply PN measurements in the roadworthiness tests, various attempts are still made to develop the improved methods of opacimetry (Kadijk et al., 2016; Axmann et al., 2017). For example, Axmann et al. (2017) suggested a novel multi-wavelength opacimeter for measurement of both NO_x and soot concentrations in the exhaust gas of diesel engines during the periodical inspection tests.

A number of wide-scale bus retrofit projects were performed worldwide. Between others the projects in Berlin, Switzerland, Santiago de Chile, Bogota, Teheran can be mentioned (Lutz, 2013; Mayer et al., 2004; Reinoso, 2011; Cortes et al., 2016). PN measurements were carried out in these projects at different engine operating modes (various loads, low idle, high idle, *etc.*), but information on PN measurement procedure most suitable for roadworthiness tests is still lacking.

The main goals of the present study were to evaluate the impact of DPF-retrofitting on fuel economy of in-use diesel buses during real-world usage conditions and to propose a measurement procedure suitable for PN diagnostics in roadworthiness tests. DPF filtration efficiency in real-world usage, as well as the influence of different parameters on fuel economy are also addressed.

1. Methodology

1.1. *Vehicles studied*

A pilot group composed of 18 in-use buses of popular models from leading European bus manufacturers were selected for