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Performance of optimised SCR retrofit buses under urban driving and controlled conditions

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HIGHLIGHTS

- Use of remote sensing technique to measure in-service NO_2 and NOx emissions.
- Focus on urban-optimised selective catalytic reduction (SCRT) system.
- On-road and controlled vehicle test track emissions.
- 45% reduction in NOx and 61% reduction in NO_2 cf. non-SCRT buses.
- Important implications at a European level for meeting NO_2 limits.

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ABSTRACT

This work presents the first comprehensive real-world emissions results from urban buses retrofitted with an optimised low-NO_2 selective catalytic reduction (SCR) system. The SCRT system combines a CRT (Continuously Regenerating Trap) to reduce particle emissions and SCR to reduce NO_x emissions. The optimised low-NO_2 SCRT was designed to work under urban conditions where the vehicle exhaust gas temperature is often too low for many SCR systems to work efficiently. The system was extensively tested through on-road and test track measurements using a vehicle emission remote sensing instrument capable of measuring both nitric oxide (NO) and nitrogen dioxide (NO_2). Over 700 on-road measurements of the SCRT system were made in London. Compared with identical buses operating under the same conditions fitted with a CRT, NO_2 emissions were reduced by 61% and total NO_x by 45%. Under test track conditions reductions in NO_x of 77% were observed. The test track results do reveal however that compared with an original Euro III bus without a CRT, the SCRT retrofit bus emissions of NO_2 are 50% higher. Engine-out and tailpipe measurements of several important engine parameters under test track conditions showed the important effect of SCR inlet temperature on NO_x conversion efficiency. Overall, we conclude that retrofitting urban buses to use low-NO_2 SCRT systems is an effective method for delivering NO_x and NO_2 emissions reduction.

1. Introduction

1.1. Background

The main issues of wider air quality interest in the context of the current paper are NO_2 concentrations and NO_x emissions. The former are regulated by the Ambient Air Quality Directive (Directive 2008/50/EC), which sets an annual average Limit Value of 40 $\mu g\ m^{-3}$ and an hourly Limit Value of 200 $\mu g\ m^{-3}$ not to be exceeded more than 18 times a year, both to be attained by 2010 with the possibility of a time extension to 2015 in certain circumstances. The annual average Limit Value is the more stringent and a large fraction of EU Member States, including the UK, are not achieving it at the time of writing, largely in locations where transport emissions are significant. NO_x emissions from traffic make a large contribution to total NO_x emissions in most member States of the EU, where a country's total NO_x emission is regulated by the National Emissions Ceilings Directive (Directive 2001/81/EC) and here there are also many Member States who are failing to comply with their emission ceiling targets.

As well as legal compliance, the impacts of air pollutants on health and the wider environment are also important and until

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recently there was uncertainty over the health effects of NO_2. While it is well accepted that NO_2 can cause adverse effects in exposure studies in chambers, the associations reported for NO_2 in epidemiological studies were difficult to distinguish from those of particulate matter. However, a recent comprehensive review by the World Health Organisation (WHO, 2013) concluded that there was now increasing evidence of independent associations with NO_2.

In urban areas buses can make an important contribution to emissions of NO_x and primary NO_2. In the London Atmospheric Emissions Inventory (LAEI) for 2010 for instance (GLA, 2013), buses on average contribute 33% of the total road transport NO_2 emissions in central London and 16% across London as a whole. This proportion increases to 85% at locations such as Oxford Street in central London that restrict other vehicle types except taxis. Locations of this type are also associated with high ambient concentrations of NO_2—well above EU annual and hourly Limit Values. For example, the roadside ambient measurement site on Oxford Street recorded an annual mean NO_2 concentration of 135 $\mu g\ m^{-3}$ in 2013 (the annual mean Limit Value is 40 $\mu g\ m^{-3}$) and had 1506 h (the Limit Value allows 18 h > 200 $\mu g\ m^{-3}$) where the concentration was greater than 200 $\mu g\ m^{-3}$. Approximately 60% of the annual mean NO_2 concentration at Oxford Street in 2013 can be attributed to primary NO_2 emissions from the road itself (Carslaw and Beevers, 2005). Reducing emissions of primary NO_2 from the bus fleet could therefore be an effective way in which to reduce ambient NO_2 concentrations at many locations.

Retrofitting heavy duty vehicles such as urban buses offers the possibility of reducing emissions of key pollutants such as NO_x and particulate matter relatively quickly and cheaply compared for example to the purchase of new vehicles. The long service life and slow fleet turnover of heavy duty vehicles encourages authorities to consider options such as retrofitting older vehicles to bring about rapid reductions in emissions. In the State of California for example, an overall goal to reduce diesel emissions by 85% by 2020 includes the adoption of various regulations targeting diesel vehicles such as accelerated fleet turnover, retrofit requirements, and fuel regulations (Kozawa et al., 2014).

Millstein and Harley (2010) assessed the impact of a heavy duty vehicle retrofit scheme in California using an Eulerian air quality model where older vehicles were fitted with diesel particulate filters (DPF) to reduce particle emissions and SCR to reduce emissions of NO_x. The Millstein and Harley (2010) analysis found that it would be expected that black carbon concentrations would reduce by about 12%, O_3would increase by 3–7% and NO_2 would reduce by 2–4% at background locations. At the regional scale, the reduction in NO_x emissions leads to lower secondary NO_2 formation and hence decreases in concentrations of NO_2, which more than offsets increased primary NO_2 emissions from the retrofit of older trucks with DPF. While there was an overall reduction in predicted in NO_2 concentrations, it was also found that NO_2 concentrations would increase in locations of high numbers of heavy diesel vehicles due to the increase in primary NO_2 emissions. The latter issue is arguably more important in Europe owing to stricter limits on NO_2 concentrations.

The on-highway measurements by Kozawa et al. (2014) in California on I-710 showed evidence of an increase by 30% in the NO_2/NO_x ratio from 2009 to 2010 due to the increased used of catalysed DPFs. However, the ratio plateaued and began to drop in late 2011. A similar trend was reported by Bishop et al. (2012) for trucks servicing the Port of Los Angeles, and was explained by DPF age due to a reduction of oxidative potential in the DPF as it ages.

One of the now well-established disbenefits of catalytic DPF technology is the strong oxidising conditions that results increased oxidation of NO to NO_2. In Europe the increased emission of NO_2 is of concern due to the effect on atmospheric concentrations of NO_2 and the increased difficulty in meeting ambient NO_2 EU Limit Values. Neither heavy duty nor light duty vehicle emissions legislation specifically considers the NO_2 component of NO_x (EC, 2009, 2007; Carslaw and Beevers, 2004). However, in California limits have been set for the verification of vehicle retrofit emissions technologies as part of the Diesel Risk Reduction Program (CARB, 2000). The first version of the protocol included a post-control NO_2 emission limit defined as 20% (by mass) of the total baseline NO_x emission, which was later suspended. A modified NO_2 limit of 30% was introduced that was effective 2007, and of 20% effective from 2009. The modified limit is defined as the maximum absolute percentage increase over the baseline NO_2 emission level. For example, for an engine with a baseline NO_2 fraction of 12%, it corresponds to total NO_2 emissions of 42% or 32% of the NO_x, effective 2007/2009, respectively.

One of the key vehicle emission technologies used to reduce emissions of NO_x from heavy duty vehicles such as urban buses is Selective Catalytic Reduction (SCR). In vehicular SCR systems NO_x reacts with ammonia (NH_3) over a catalyst that reduces it to N_2 and water. In principle these systems offer an effective way in which to reduce emissions of NO_x from heavy duty vehicles. In practice however, the performance of SCR systems under urban-type driving conditions has been shown to be less effective (Hallquist et al., 2013; Velders et al., 2011; Fu et al., 2013; Carslaw and Rhys-Tyler, 2013). In the analysis of London bus emissions by Carslaw and Rhys-Tyler (2013) it was shown that those using Original Equipment Manufacturer (OEM) SCR did not reduce total emissions of NO_x appreciably compared with non-SCR buses.

A key issue regarding SCR technology is the exhaust temperature, which must be sufficiently high for the chemical reactions to proceed efficiently. This issue is particularly important in urban areas and for vehicles such as buses that often have undemanding duty cycles that result in lower exhaust gas temperatures. For these reasons there is interest in the development of SCR technology that works more effectively under urban driving conditions. In this paper we consider a low-NO_2 SCRT system that combines a CRT (Continuously Regenerating Trap) to reduce particle emissions and SCR to reduce NO_x developed by Johnson Matthey and Eminox. In London, Transport for London (TfL) and the Department for Transport recently invested £10 M in retrofitting 900 Euro III buses with SCRT technology. The programme was completed in March 2014 with the aim of reducing emissions of NO_x from the London bus fleet.

In this paper we consider the effectiveness of a low-NO_2 SCRT system as retrofitted to TfL buses. The emissions of NO and NO_2 were measured in two settings: on-road measurements in London and controlled testing of one bus at a test track location. Measurements were made using a vehicle emission remote sensing technique. The study had the following principal aims. First, to establish the real-world emissions performance of buses retrofitted with the low-NO_2 SCRT system compared with nominally identical vehicles without the system. Second, to better understand the emissions performance of the technology through controlled emissions tests that included the continuous measurement of important engine and exhaust parameters. Finally, to improve current understanding regarding the effectiveness of such systems for reducing urban NO_2 and NO_x concentrations.

2. Experimental

2.1. Instrument details

The University of Denver FEAT (Fuel Efficiency Automobile Test) system was hired for a duration of 6 weeks during the summer of 2013. This instrument is described at length in other studies e.g.