Solving air quality problems in cities by retrofitting - Case studies showing real-world driving performances

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Abstract.

Urban air quality has been widely discussed and debated over the last decades. It started mainly with the focus on fine particles and concern was in major cities in certain developing countries. Lately, more and more weight has been put on nitrogen oxides (NOx), also in European cities. Public and political pressure has been increasing over the last years, while additional studies on the current situation of air quality together with health risks have been published. There are multiple sources of nitrogen oxides (NOx) and the whole picture is complex in nature. However, traffic has been shown to be one of the main reasons. As it is known today, older generation diesel vehicles emit a great deal of NOx. It is believed that the situation would improve while a newer fleet is taking place. But, unfortunately the progress has not been as expected there. The current knowledge on the difference between heavy-duty engines laboratory condition homologations, application specific chassis dynamometer tests and lastly real world driving conditions is underlining the importance of improvements in exhaust emission reduction technologies.

This study shows the differences between chassis dynamometer and real-world emissions on city busses. Online monitoring and portable measurement technologies together with retrofitting and upgrading the vehicles using state of the art emission reduction technology has been studied for measuring and reducing the harmful exhaust gas compounds, especially NOx in real-drive conditions in city driving. The retrofitting of buses with an improved emission after treatment systems has proven to be a feasible and quick solution for reducing local NOx emissions significantly. The comparison of new buses and the retrofitted ones clarifies the potential of the retrofit approach. Several case studies are presented, and some European city retrofit programs are referred to in this study.

1. Introduction

Many cities around the world are suffering from pollution. During the last decades, the major concern has been fine particles, but lately the focus has been shifting towards nitrogen oxides which have negative effects on humans and the environment in many ways [1]. In Europe (EU-28), the transport sector contributed to 13 % and 15 % of total PM10 and PM2.5 primary emissions. Respectively, the transport sector is accounting for a 46 % share of total nitrogen oxides emissions, thus making the
transport sector the largest contributor of NO\textsubscript{x} emissions [2]. A major part of the transport sector’s nitrogen oxides emissions originates from diesel vehicles.

It is well known that the previous heavy-duty engine certification test cycles used for Euro I-V type approval were weighing high engine loading areas and did not correspond to actual applications that the engines were used for. While new emission legislation phases decreased regulated emissions, the gap between emissions of the engine certification test cycles and real-world driving grew. The first indications from this development were identified from the application specific chassis dynamometer test cycles, such as Braunschweig for city buses. Later on real-driving emission measurements revealed that the problem was real [3] [4]. This development continued until the Euro VI legislation in which new test cycles i.e., the World Harmonized Steady Cycle (WHSC) and the World Harmonized Transient Cycle (WHTC), as well as requirements for in-use testing were implemented.

Introduction of Euro VI and US2010 heavy-duty engine emission legislations brought in-use testing requirements, in addition to the engine dynamometer certification testing, to the certification procedure. Engine manufacturers are obligated to prove emission compliance during the in-service period, using in-service conformity test procedures. Earlier heavy-duty emission legislations (Euro I-V) missed these kind of in-service testing requirements, which now drives OEM’s to also pay attention to real-world emissions.

In the case of city buses, the deviation in emissions between the heavy-duty engine certification test cycle and real-world emissions is at its highest with Euro IV-V, including EEV vehicles a result of the combination of relatively low emissions limit values and the lack of real driving emissions requirements. In Europe, the major share (over 50 %) of city bus fleets are older than Euro VI. Currently, the average bus fleet renewal percentage rate is around 8 % [5]. Taking this into account, it is clear that in the case of a normal renewal pace of city buses, it will take many years to achieve a bus fleet with a majority of low emission buses like Euro VI vehicles.

To decrease nitrogen oxide emissions in cities, the retrofitting of older buses offers a fast and cost-efficient solution complementing the natural renewal pace to Euro VI. This paper shows that state of the art retrofit emission reduction technologies can decrease the PM and NO\textsubscript{x} emissions into a comparable level with Euro VI vehicles.

2. General Outlook on City Buses Emissions

Since 2002, VTT has conducted on a regular basis chassis dynamometer tests for city buses emissions performance evaluations. The measurement procedure is thoroughly documented, and accredited by the Finnish Accreditation Service FINAS (FINAS T259). The test methodology is described in detail in an article by Nylund et al. [6]. Based on the measurements, VTT has created a publicly available database of city bus emissions performance [7]. This unique database combines measurement results of diesel and CNG (Compressed Natural Gas) city buses from Euro I to Euro VI. Originally the data was used for refining the Helsinki Region Transport services (HSL) procurement process yearly with the newest emissions and fuel consumption data.

A major part of the VTT’s database constitutes performance data of two- and three-axle diesel and CNG city buses tested on a chassis dynamometer and running the German Braunschweig test cycle with a hot start procedure.

To gain better comparability with the current Euro VI heavy-duty engines certification test cycle WHTC, it was decided in 2017 that the corresponding World Harmonized Vehicle Cycle (WHVC) will be included in the test procedure. Currently VTT’s city bus test procedure includes the Braunschweig test cycle tested with a hot start and the WHVC test cycle tested as a combined cold (14 %) and hot (86 %) start test cycle.

Figure 1 shows the development of NO\textsubscript{x} emissions for two- and three-axle diesel and CNG buses in the Braunschweig hot start cycle. In case of two-axle diesel buses, NO\textsubscript{x} emissions decreased while legislation evolved from Euro I to Euro III, but after that no clear reductions was seen until Euro VI legislation. For two-axle CNG buses, the decreases in NO\textsubscript{x} emissions have been a bit faster.
Nevertheless, from Euro I to Euro V/EEV legislation phases, the deviation in NO\textsubscript{x} emissions has been high for CNG vehicles due to the two different combustion technologies used. A spark-ignited stoichiometric combustion with a three-way catalyst (TWC) offered low NO\textsubscript{x} emissions, whereas a spark-ignited lean combustion did not. In current Euro VI compliant CNG buses, only a stoichiometric combustion with a three-way catalyst is used. Overall, NO\textsubscript{x} emissions are at a really low level for both diesel and CNG two-axle Euro VI certified vehicles.

In the case of three-axle buses, VTT’s database covers vehicles from Euro V to Euro VI. Euro VI legislation has decreased three-axle buses NO\textsubscript{x} emissions, but the decrease has not been as great as with two-axle buses. In addition, it seems that the variation in NO\textsubscript{x} emissions is higher with three-axle buses.

Figure 1. 2- and 3-axle city buses average NO\textsubscript{x} emissions for individual emissions classes on Braunschweig hot start cycle [7].

**Błąd! Nie można odnaleźć źródła odwołania.** shows PM emissions for two- and three-axle diesel and CNG buses. For diesel buses, three main reduction steps can be identified. First reduction step is from Euro I to Euro II/III level. Second is from Euro II/III to Euro IV/V/EEV level and third from Euro IV/V/EEV to Euro VI level. All heavy-duty diesel engines certified for Euro VI or US2010 legislation are equipped with a Diesel Particulate Filters (DPF), which ensures really low PM levels. In the case of CNG fuelled vehicles, PM emissions have not been a problem. Both spark-ignited combustion technologies (stoichiometric and lean) ensure low PM emissions without additional exhaust after treatment devices.
Figure 2. 2- and 3-axle city buses average PM emissions for individual emissions classes on Braunschweig hot start cycle [7].

Bląd! Nie można odnaleźć źródła odwołania. shows CO\textsubscript{2} equivalent emissions for a hot start Braunschweig cycle for two- and three-axle diesel and CNG vehicles. In the case of two-axle diesel vehicles, there was not significant progress until EEV vehicles, which show improved fuel efficiency, compared to Euro I - V vehicles. Euro VI certified vehicles show greatly reduced NO\textsubscript{x} emissions and simultaneously 5...10 % lower CO\textsubscript{2} emissions compared to EEV vehicles. This is partly explained by a full exploitation of the SCR system in Euro VI diesel vehicles, but also improvements in transmissions. In the Euro V/EEV phase, some OEM’s did not use SCR, instead they used EGR (Exhaust gas recirculation) only technology, which did not offer as low fuel consumption as that which could be achieved with SCR.

Overall it can be said that Euro VI and US2010 certified vehicles equipped with DPF and SCR technology offer great emissions performance in a chassis dynamometer environment.

Figure 3. Average CO\textsubscript{2} emissions of Euro I - Euro VI 2- and 3-axle city buses on the Braunschweig hot start cycle [7].

3. Experimental Setup

3.1. VTT’s Heavy Duty Chassis Dynamometer
VTT’s heavy-duty chassis dynamometer test facility was set up in 2002 for the performance evaluation of heavy-duty on-road vehicles. Since then, the measurements are carried out on regular basis. Vehicles from Euro I to Euro VI in multiple vehicle categories i.e. city buses, long-haul trucks, delivery trucks etc. have been measured. Information of the VTT’s chassis dynamometer and emissions measurement equipment is listed below in Table 1.

Table 1. VTT’s heavy-duty chassis dynamometer and emission measurement devices used for the tests

| Device Information                                                                 | Information                                                                 |
|-----------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| HD Chassis Dynamometer                                                            | Froude Consine Ltd, maximum power ± 300 kW (54–110 km/h)                     |
| Emission sampling and dilution system                                             | Pierburg AG, CVS-12-WT, Maximum flow: 120 m3/min                             |
| Emission analyzer system                                                           | AMA i60 (THC, CH4, NO2, NO, CO2, CO)                                        |
| FTIR                                                                              | Rowaco and Gasmet Cr-2000 (N2O, NH3, NO, NO2)                                 |
| Fuel balance                                                                       | Sartorius Combics 1                                                          |
| Test fuel                                                                          | EN 590 standard diesel fuel                                                   |

Two test cycles were used for retrofit exhaust after treatment devices performance measurements, hot start Braunschweig and combined cold (14 %) and hot (84 %) start WHVC cycle. For both test cycles, the test inertia corresponding to a half load was simulated.

Table 2 shows chassis dynamometer test vehicles base information. The retrofit exhaust after treatment (EAT) device used was Proventia NOxBUSTER® City. The system includes DPF and SCR.

Table 2. Information of test vehicles

| Certification emission legislation | Emissions base technology for Euro VI retrofitting | Number of vehicles | Chassis type | Mileage before retrofitting | Mileage after retrofitting |
|------------------------------------|----------------------------------------------------|--------------------|--------------|-----------------------------|----------------------------|
| Euro V/EEV EGR-only                |                                                    | 3                  | 3-axle       | 200,000…300,000 km         | app. 100,000 km            |
| Euro V/EEV SCR-only                |                                                    | 1                  | 3-axle       | 830,000 km                 | 5,000 km                  |

3.2. Proventia NOxBuster and Procare Drive System

NOxBUSTER® City DPF+SCR is a tailored after treatment retrofit solution to upgrade vehicles up to Euro VI emission standard in a cost-efficient way, as well as minimized modifications for the vehicle itself. An optimized urea mixing and dosing strategy, combined with advanced catalyst technology and proper thermal management provides high NOx and NO2 reduction rates also at low exhaust gas temperatures (<200 °C) in real city traffic. Due to the technical advantages and good references, NOxBUSTER® City has been widely used on the city bus retrofit market. Typically, the original muffler with catalysts is replaced by a new system in its original place. AdBlue tank and lines can often be maintained, but the pump and dosing control must be upgraded.

PROCARE™ Drive is a web-based NOx monitoring system that monitors the performance of the vehicle’s exhaust after treatment device (NOx, backpressure, exhaust temperatures, location, speed) online 24/7, using GPS and 3G wireless technology. The Proventia PROCARE™ Drive provides a reliable method for fleet operators or authorities to monitor the amount of NOx emitted and the functionality of the EAT system in real time.
4. Results and Discussion on Retrofitting

Case studies covered in this paper are based on EEV vehicles which have been retrofitted with the state of the art exhaust aftertreatment technology to correspond OEM (Original Equipment Manufacturer) Euro VI vehicles emissions. Two main emissions reduction paths were used in EEV vehicles as discussed earlier, EGR-only and SCR-only. The case studies presented in this paper cover both base technologies as shown in Table 2. EEV retrofit Euro VI results are based on three EGR-only and one SCR-only retrofit Euro VI vehicles chassis dynamometer measurement results.

The average results for EEV vehicles are presented as a baseline for retrofitting. Emissions of OEM Euro VI vehicles are presented in two categories: 1. Average results for vehicles driven less than 150,000 km and 2. Average results of all Euro VI vehicles tested. These two categories are presented to highlight the effects of mileage on NOx emissions, between the low mileage and high mileage vehicles. In the case of EEV retrofit Euro VI vehicles, the retrofitted vehicles had been driven between app. 200,000 km…830,000 km before retrofitting, whereas the mileage after retrofitting varies between 5,000 km…100,000 km.

4.1. Chassis dynamometer results

Figure 4 shows a comparison of diesel EEV Retrofit Euro VI emissions performance compared to OEM EEV and Euro VI vehicles. On average, the reduction of NOx and PM emissions in EEV retrofit Euro VI vehicles are in the range of 87.5 % for NOx and 80 % for PM emissions, compared to average EEV vehicles emissions. Based on the chassis dynamometer testing, the NOx emissions performance of the retrofitted Euro VI vehicles is on average at the same level with the average (including high mileage Euro VI vehicles) OEM Euro VI performance. Nevertheless, results from the database also highlight that the OEM Euro VI vehicles have in the best case extremely low NOx emissions (see a deviation in results in the Figure 4). Regarding PM emissions, EEV retrofit Euro VI vehicles perform well. In the case of OEM Euro VI vehicles, which normally have extremely low PM emissions, there are some first hints suggesting NH3 slip which results in abnormally high PM levels.

![Figure 4. Comparison of Retrofit Euro VI emissions performance on EEV and OEM Euro VI vehicles on the Braunschweig and WHVC cycles](image)

4.1.1. EGR-only as a base emission reduction technology for Euro VI retrofitting

Figure 5 shows the emissions performance with EGR-only vehicles as a base for retrofit Euro VI. VTT’s database shows that OEM EGR-only EEV vehicles have high NOx emissions and, thus, average NOx emissions reduction gained with the retrofit EAT system is high, app. 90%. The average NOx emissions performance in the Braunschweig and WHVC cycles are criss-crossed with the OEM Euro VI vehicles...
average results, but are of the same magnitude. The reduction in PM emissions is app. 80 % and in average PM emissions, the performance is also comparable with OEM Euro VI vehicles.

4.1.2. SCR-only as a base emission reduction technology for Euro VI retrofitting. Figure 6 presents the results of SCR-only as a base technology for retrofit Euro VI. The variation in NO\textsubscript{x} emissions of OEM SCR-only EEV vehicles is high. This is mainly due to the less sophisticated SCR control systems and SCR catalyst materials used in EEV engines, causing a high variation in emission reduction performance. Nevertheless, on average, the reduction in NO\textsubscript{x} emissions gained with retrofitting is app. 90 %. In comparison to the average NO\textsubscript{x} results of OEM Euro VI vehicles the tested SCR-only based retrofit Euro VI vehicle performs rather well, giving NO\textsubscript{x} emissions in between the results of low mileage and average OEM Euro VI vehicles. In the case of PM emissions, the SCR-only based retrofit Euro VI vehicle reduces PM emission app. 92 %, compared to OEM EEV SCR-only vehicles and also performs extremely well, compared to OEM Euro VI vehicles.

**Figure 5.** EGR-only as a base Retrofit Euro VI emissions performance compared on EEV and OEM Euro VI vehicles on Braunschweig and WHVC cycles
Figure 6. SCR-only as a base Retrofit Euro VI emissions performance, compared on EEV and OEM Euro VI vehicles on Braunschweig and WHVC cycles

4.1.3. Comparison against NO\textsubscript{x} monitoring system. PROCARE™ Drive monitoring systems were installed to retrofitted vehicles described in chapters 4.1.1 and 4.1.2. Data from the chassis dynamometer measurements was compared to sensor based monitoring system emissions. It was seen that the monitoring system showed 24 to 300% more emissions than actually measured, and the trend was that inaccuracy was greater with lower emissions. Possible reasons for this include sensor characteristics, such as oversensitivity to NO\textsubscript{2} or other nitrogen species after a sensor light-off [8][9]. Even though the absolute NO\textsubscript{x} values are in some cases over estimated, the NO\textsubscript{x} monitoring system provides valuable information about the average NO\textsubscript{x} reduction efficiencies during the vehicle operation in different driving and ambient conditions.

4.2. Real world NO\textsubscript{x} emissions monitoring results
PEMS (Portable emissions measurement system) tests have been performed for various buses during the last years. The target has been to evaluate the real-drive emissions of the typical city buses when they have been retrofitted with the Proventia NOxBUSTER® City DPF+SCR after treatment system. As an example, Figure 7 below shows that the PEMS measurement results (Conformity Factor 0.34) for a retrofitted Euro IV bus are well below Euro VI emission standards and clearly lower than allowed PEMS results. Test evaluation was performed in accordance with In-Service Conformity testing as described in UNECE Regulation 49, revision 6. The test vehicle was a city bus of category M3 (class I or II), year model 2007 (9 dm\textsuperscript{3} engine, automatic) and the PEMS route in Stockholm was suitable for this vehicle category (70% urban, 30% rural).
As explained earlier in this paper, there is also a need and opportunity to reduce emissions further for more modern buses in real driving conditions. Figure 8 shows the reality with a typical EEV bus in German city driving. The test vehicle was an articulated city bus, year model 2009 (10.5 dm$^3$ engine, automatic) and the PEMS route in Paderborn was the route that the bus drives in normal duty. As can be seen, the original EAT system yields emissions significantly higher than obtained after retrofitting. The repeatability of the measurement and NOxBUSTER performance is also shown.

When real drive emissions are in focus, the sensitivity for varying ambient conditions and on-road durability need to be studied, too. Figure 9 illustrates the monthly average NO$_x$ conversion rate over a tracking period of more than one-year (16 months).
Figure 9. The average NOx conversions over the 16 months tracking period for typical London city bus.

As seen above, the winter period affects the exhaust temperature, despite insulation of the exhaust line and EAT. However, the NOx emissions do not react equally significantly and the performance of the NOxBUSTER® City DPF+SCR after treatment system is kept almost constant.

5. Conclusions
Public transportation is a major contributor of nitrogen oxides emissions in cities. To solve the current nitrogen oxides emissions problem caused by the public transportation, in addition to fleet renewal and adding e.g., electric buses over time, additional measures targeting the existing fleet are needed. The current situation can be improved quickly by retrofitting older city buses to correspond to Euro VI emissions legislation. The research results presented in this paper showed that by retrofitting older vehicles (Euro IV-EEV), the NOx and PM emissions can be reduced to correspond to emissions of Euro VI vehicles in a chassis dynamometer environment. Results from real-world operation also confirmed NOx emissions performance that is well within the Euro VI legislation.

Euro III-EEV vehicles still form the majority of the bus fleet of European cities. Retrofitting older vehicles that are still in operation for several years to come can rapidly and cost-efficiently reduce nitrogen oxide emissions caused by the city buses. The cost of a retrofit system is less than 1/10 of a price of a new bus, making retrofitting a feasible solution in many cases.

The behaviour of NOx emissions real-time measurement sensors in vehicle real world operation conditions is not yet completely understood. Especially in extremely low NOx concentrations the first indications suggest that NOx sensors tend to overestimate NOx emissions. More detailed research is needed to be able to fully understand the phenomenon behind this behaviour.

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Abbreviations

CNG  Compressed natural gas
DOC  Diesel oxidation Catalyst
DPF  Diesel particulate filter
EAT  Exhaust after treatment
EGR  Exhaust gas recirculation
HSL  Helsinki region transport services
NOₓ  Nitrogen oxides
OEM  Original equipment manufacturer
PEMS  Portable emissions measurement system
PM  Particulate matter
SCR  Selective catalytic reduction
TWC  Three-way catalyst
WHSC  World Harmonized Steady Cycle
WHTC  World Harmonized Transient Cycle
WHVC  World Harmonized Vehicle Cycle