LIFE11 /ENV/ES/584

AIRUSE

Testing and development of air quality mitigation measures in Southern Europe

ABATEMENT OF NOX EMISSIONS FROM VEHICLES

REPORT 22

12/2016

Authors:

Xavier Querol (Project coordinator)

A. Karanasiou
F. Amato
C. Vasconcelos

A. Alastuey
M. Viana
T. Moreno
F. Plana
N. Perez

M. Cabañas
R. Bartoli
S. Martinez
M. Sosa

E. Montfort

I.Celades
A. Escrig
V. Sanfelix
S. Gomar

R. Harrison

C. Holman
D. Beddows
M. Harding

K. Eleftheriadis

L. Diapouli
S. Vratolis
M. Gini
E. Bairaktari
S. Dalaina
V. Galifianakis

F. Lucarelli

S. Nava
G. Calzolai
R. Udisti
S. Becagli
R. Traversi
M. Severi
S. Borselli
M. Giannoni

C. Alves

C. Pio
T. Nunes
L. Tarelho
M. Duarte
M. Cerqueira
E. Vicente
D. Custódio
H. Pinto

V.L. Gianelle
C. Colombi

INDEX

1. INTRODUCTION

Most EU Member States (MSs) have locations which exceed the annual mean limit value for nitrogen dioxide (NO_2), with the highest concentrations occurring close to busy roads. MSs were obliged to meet this Limit Value by 2010, but according to the European Environment Agency (EEA, 2014) 20 MSs recorded exceedances at one or more monitoring stations in 2012. While the Limit Value was exceeded at only one rural background station and 2 % of all urban background stations, it was exceeded at 37 % of traffic stations, with a maximum annual mean concentration of 94 µg m^{-3}, nearly two and a half times the limit value. The EEA concluded that NO_2 concentrations need to be substantially reduced for the annual Limit Value to be met.

Progress towards meeting this limit value has been more challenging than originally envisaged and a time extension for compliance up to 2015 has been requested by most MSs. Some cities, however, are unlikely to achieve the limit value until a decade or more after this date. In the United Kingdom (UK), for example, official estimates suggest that compliance in London, West Yorkshire and the West Midlands will not occur until after 2030 (Defra, 2014).

The principal reason for the lack of compliance is that road transport nitrogen oxides (NOx) emissions have not declined as anticipated by the progressively more stringent vehicle emission limits introduced in Europe over the last two decades. Velders et al. (2011) for example, have estimated that in the Netherlands the higher than expected emissions from heavy duty vehicles have more than doubled the total road length with possible exceedance of the ambient NO_2 limit value; from approximately 100 km to 250 km along cities streets and motorways, by 2015.

Another contributory factor is the increase in the proportion of the vehicle NOx emissions in the form of NO_2. This is thought to be due to a combination of increased diesel cars in the vehicle fleet and the use of certain exhaust after-treatment devices that increase NO_2 in the exhaust. The average proportion of new diesel cars sold in the European Union (EU) has increased from approximately 20% two decades ago to 50% in 2013 (ACEA, 2014), while the increasing use of diesel oxidation catalysts and particle filters on diesel vehicles has increased the proportion of the NO_2 (f-NO_2).

An increasing f-NO_2 in vehicle exhaust is an important factor influencing ambient NO_2 concentrations close to roads and can have a large effect on the exceedence of the NO_2 limit values in these locations (Carslaw & Rhys-Tyler, 2013).

Figure 1 shows the NOx emissions from Euro 2[1] to Euro 6 gasoline and diesel passenger cars obtained using remote sensing data from Leeds in north east England (Tate, 2014). It clearly shows that NOx emissions from gasoline cars have declined and that for the more recent cars the variation between cars built to the same EU emissions standard is small. This confirms earlier data from London (Carslaw & Rhys-Tyler, 2013) that showed that emissions from Euro 5 gasoline cars are approximately a factor of 20 lower than pre Euro 1 gasoline cars. It can be concluded that the emissions from modern gasoline cars are well controlled.

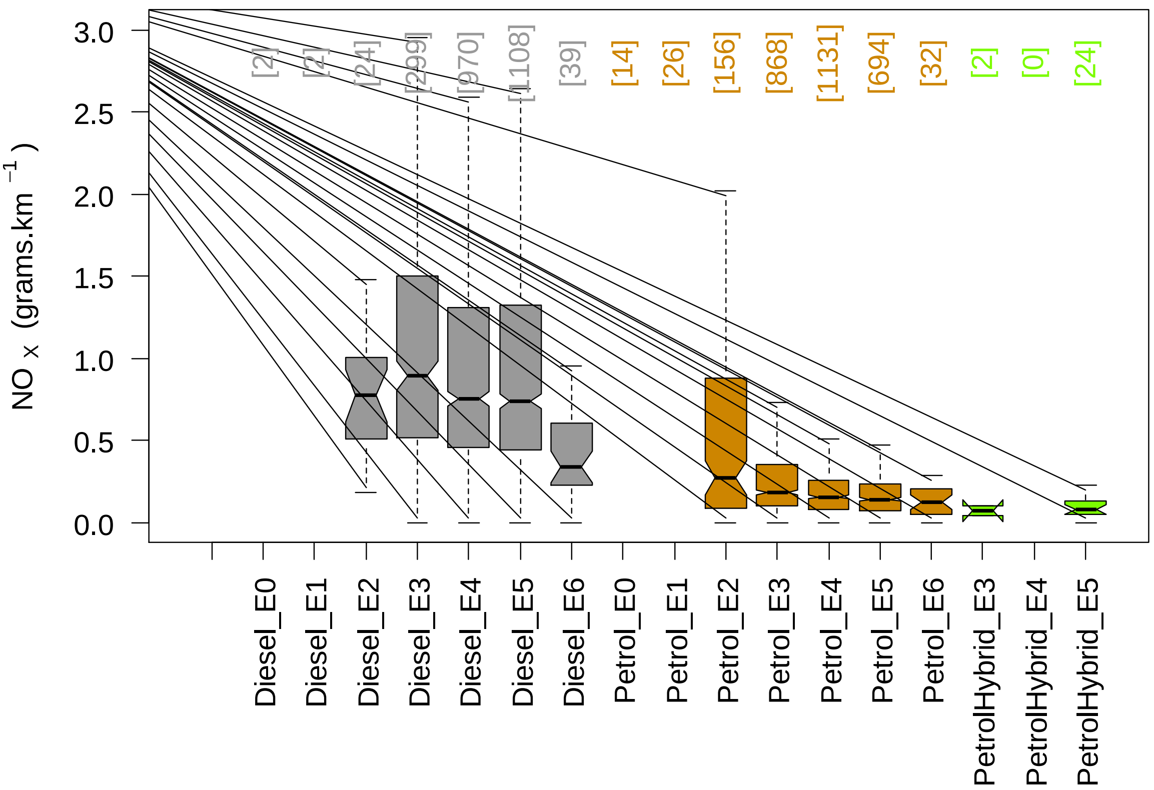

Figure 1-1 Box and whisker plot of diesel and gasoline passenger car NOx emissions according to EU emission standard measured using remote sensing in Leeds, UK. In the shaded areas the horizontal line shows the median; the top and bottom of the shaded area show the 75th and 25th percentile respectively; the horizontal lines at the end of the dotted lines (whiskers) show the approximate 95th confidence limits (Tate, 2014)

Conversely Figure 1 shows that diesel car emissions have been poorly controlled with large variations between cars built to the same standard and between Euro 2 and Euro 5 there is little evidence of an improvement. Carslaw & Rhys-Tyler (2013) have shown that Euro 4 and 5 diesel cars have higher NOx emissions than pre Euro 1 and Euro 1 diesel cars. There is

[1] Light duty vehicle emissions standards are denoted with Arabic numerals (1, 2, 3 etc.) and heavy duty engine emissions standards by Roman numerals (I, II, III etc.). Euro 1/I standards were first implemented in 1992, with the most recent Euro 6 and VI implemented from 2014 and 2013 respectively.

limited data that Euro 6 diesel cars have lower emissions, possibly 40% lower (Carslaw, 2014), but still well in excess of the type approval emission limit. Emissions of NOx from Euro 5 gasoline cars are on average a factor of 10 less than the equivalent diesel cars (Carslaw & Rhys-Taylor, 2013).

A study from Zurich, in which annual remote sensing measurements were made at the same site between 2000 and 2012, concluded that NOx emissions from diesel cars have increased over this period, despite the tightening of emissions standards. The NOx emissions from pre-Euro 1 diesel cars were slightly lower than those from Euro 5 cars, with the highest real-world NOx emissions from Euro 2 and 3 cars (Chen & Borken-Kleefeld, 2014).

Carslaw & Rhys-Tyler (2013) measured the emissions from over 10,000 diesel passenger cars using remote vehicle emissions sensing and concluded that both engine size and manufacturer are important determinants of NOx emissions. Carslaw et al. (2013) showed that NOx emissions are also dependent on vehicle specific power. Diesel vehicles have become more powerful over recent years, increasing on average in the EU from approximately 77 kW to 97 kW between 2001 and 2013. Over the same period gasoline cars increased from 73 kW to 80 kW (International Council on Clean Transportation, 2014a).

Carslaw & Rhys-Tyler (2013) also showed that the trend in NOx emissions from light duty commercial vehicles, which are predominantly diesel fuelled, and heavy duty vehicles (HDVs) have also shown little improvement from pre Euro 1/I to Euro 5/V.

1.1. Scope of Report

This report focuses on NOx emission abatement technologies used on light and heavy duty diesel vehicles as it is clear from the above that gasoline cars have well controlled NOx emissions. Commercial vehicles and buses are predominantly diesel fuelled.

2. NO_X EMISSION CONTROL

2.1. Introduction

If complete combustion of the fuel in an engine were possible vehicle exhaust would contain only carbon dioxide (CO_2) and water vapour. However, in reality vehicle exhaust also contains particulate matter (PM) and a range of other compounds depending on the fuel. Additionally NO_x is formed by oxidation of atmospheric nitrogen (N_2) at the high temperatures in an engine.

Controlling vehicle emissions has been an evolutionary process of gradual improvement to the combustion process, engine management system and, for gasoline cars catalytic after-treatment, over many decades. Emissions were initially reduced by controlling the formation of pollutants in the engine, but as emission limits became more stringent the manufacturers have increasingly had to also remove pollutants in the engine exhaust using after-treatment devices.

There is a compromise during engine design between optimising for fuel consumption, emissions and performance. For diesel engines the emissions trade-off is between PM, NOx and CO_2 emissions. Engine conditions with low PM and CO_2 emissions tend to be when high NOx emissions occur, and vice versa.

For gasoline vehicles the use of three way catalysts (TWC) has been standard since the Euro I emission standard was introduced in 1992. These devices effectively control the NOx, carbon monoxide and hydrocarbon emissions in the exhaust, but only within a very narrow ratio of air to fuel in the engine. This means that it is more difficult to reduce CO_2 emissions from a conventional gasoline vehicle.

Diesel engines are more fuel efficient because they use a higher air to fuel ratio (i.e. a leaner mixture). There is too much oxygen (O_2) in the exhaust for a TWC to control the NOx emissions, and therefore different technologies have had to be developed. Reducing PM and NOx emissions from diesel vehicles, while also reducing CO_2 emissions, has been one of the greatest challenges for the modern motor industry.

To reduce CO_2 emissions from gasoline vehicles direct injection (GDI) engines have been developed which also run on leaner air to fuel ratios than conventional gasoline engines, and have emission more similar to diesel engines. TWC also cannot be used with these engines.

The use of sophisticated electronically controlled fuel injection systems has allowed much more precise timing of when the fuel enters the combustion chamber and has resulted in the manufacture of engines with increased power, lower fuel consumption and lower emissions. They have also facilitated the use of GDI engines which require very complex engine management systems to manage the fuel injection under all operating modes.

Exhaust gas recirculation (EGR) has been used for several decades in diesel engines, but has become increasingly sophisticated as NOx emissions limits have reduced. EGR combined with engine improvements is considered capable of meeting the Euro 6 NOx emission limits for passenger cars (International Council for Clean Transportation, 2014b), but not the recent HDV emission standards.

There are two after-treatment systems to control NOx emissions in commercial use; selective catalytic reduction (SCR) and lean NOx traps (LNT)[2]. Each has advantages but also disadvantages. In general, from Euro IV SCR has been used on HDVs. For passenger cars

[2] Also known as NOx Adsorbers Catalysts (NACs)

EGR and/or SCR or LNT are used to meet the Euro 6 standards. These abatement techniques are described in the following sections.

To reduce PM emissions diesel vehicles have been fitted with oxidation catalysts for many years. These devices remove the soluble organic fraction of the particles, but to reduce PM emissions further diesel particle filters (DPFs) are required. DPFs are standard equipment for new diesel cars in the EU but have not been required to meet the HDV emission standards until Euro VI. However, a large number of HDVs have been retrofitted with DPFs, particularly those that operate in urban areas.

The most common type of DPF fitted to HDVs is the continuously regenerating trap (CRT®). It was first used commercially in 1995 and retrofitted to buses in Sweden, and then in London and Germany. The filter needs to be regenerated periodically to avoid the buildup of back pressure in the engine. In the presence of O_2 regeneration occurs when the temperature exceeds approximately 550°C. However, diesel exhaust temperatures are generally considerably lower. To reduce the regeneration temperature to within the normal exhaust temperature range NO_2 is used. This, however, increases the f-NO_2 in the exhaust.

For this reason a number of cities have retrofitted buses with both CRT and SCR (known as SCRT) that allows filter regeneration without increasing NO_2 emissions. For example, the Transport Authority of Barcelona (TMB) retrofitted 411 Euro II and III diesel buses with ‘low NO_2 SCRT’. These systems have also been used in the UK, Belgium, and Scandinavia.

For cars and vans passive regeneration of the DPF takes place automatically when the vehicle is driven on motorways or other fast roads when the exhaust temperature is high. Under other driving conditions, when the PM loading on the DPF is approximately 45%, the vehicle’s engine management system will inject fuel into the engine after combustion to increase the exhaust temperature. If the journey is too short to complete regeneration a warning light will come on to show that the DPF is partially blocked. Typically driving for 10 minutes above approximately 65 km h^{-1} regenerates the DPF.

2.2. Exhaust gas recirculation (EGR)

For many years the main method for reducing NOx emissions from both heavy and light duty diesel engines was EGR. NOx emissions are mainly produced at the high engine temperatures generated when the vehicle is operating under load. EGR returns a proportion of the exhaust gas to the combustion chamber, reducing the amount of O_2, which reduces the combustion temperature and hence NOx emissions. This, however, increases the fuel consumption. In some EGR systems the exhaust gas is cooled to further reduce NOx emissions.

The efficiency of the EGR depends on the amount of recirculated exhaust gas and its temperature. Disadvantages of EGR include the increase in engine-out PM emissions (if a DPF is installed it needs to be regenerated more frequently) and higher CO_2 emissions. Possibly of greater significance is that it principally reduces NOx formation during low load operation and not during real-world high-load events (Zheng et al., 2004). Therefore there is concern that Euro 6 diesel cars that rely solely on EGR to control NOx will have high emissions under motorway driving conditions.

2.3. Selective catalytic reduction (SCR)

The main after-treatment used to reduce NOx emission from diesel engines is selective catalytic reduction (SCR). It continuously removes NOx by creating a rich microclimate where NOx is converted to N_2 using ammonia (NH_3), while the overall exhaust remains lean. NH_3 is produced from an aqueous solution of urea stored in a tank on-board the vehicle. The urea solution is injected into the exhaust stream upstream of the SCR where it forms gaseous NH_3 which is stored on the catalyst. The NOx from the engine reacts with the stored NH_3 to produce N_2 and water.

Since 2008, when the first generation of vehicles fitted with SCR were introduced, a distribution network for urea solution, known as diesel emission fluid (DEF) or AdBlue® has developed. On-board systems alert HDV drivers when to re-fill the DEF tank. For light duty vehicles the tank is refilled during the annual service. The SCR system needs to be tuned to ensure that little NH_3 passes through the catalyst and is emitted from the vehicle. This is known as NH_3 slip.

There have been substantial advances in SCR technology over recent years but there remain a number of challenges particularly related to its performance under low-temperature conditions and the need to precisely match urea injection with NOx emissions (Johnson, 2014).

The temperature of diesel exhaust gas is relatively low. To convert urea to NH_3 requires the exhaust gases to be above approximately 190 ^{o}C and the SCR at a slightly higher temperature to begin to control NOx, but the system is more efficient at higher temperatures. The engine needs to be warm before the SCR starts to control the NOx emissions, which at low vehicle speeds may take many minutes. In addition, when a vehicle is idling the exhaust temperature may be as low as 100 ^{o}C. SCR systems do not work well during short urban trips with low engine loads. As EGR does work well under these conditions, a SCR combined with EGR may be necessary for Euro 6 cars to have low in-service emissions under all driving conditions.

SCR catalysts were typically based on vanadium pentoxide (V_2O_5). These catalysts were relatively low cost but originally had poor low temperature performance. This has been improved by optimising the proportion of NO_2 in the exhaust to approximately 50% of the NOx using an oxidation catalyst ahead of the SCR catalyst (Johnson, 2008).

According to Görsmann (2015) copper-zeolites and iron-zeolites[3] are beginning to be used to produce better NOx reduction, particularly when used with a DPF, as they are more stable at the high temperatures produced during DPF regeneration. Cu-zeolites show little sensitivity to the NO_2/NOx ratio, tolerate high NH_3/NOx ratios, have low NH_3 emissions, good low temperature activity and thermal stability, but there are concerns that Cu-zeolites may increase the emissions of nitrous oxide (N_2O), a potent greenhouse gas. Fe-zeolites have poorer low temperature performance and also require the f-NO_2 in the exhaust to be increased using an oxidation catalyst. Conversely, they have better high temperature performance and are more resistant to sulphur (S) in the fuel or lubricants than Cu-zeolites. There is no ideal catalyst. Daimler, for example has chosen to use Fe-zeolites to meet the Euro VI emission limits for their engines, whilst other engine manufacturers have chosen Cu-zeolites. In the future, however, manufacturers may choose to use both types of zeolites together to take advantage of their different characteristics.

Good NOx reduction rates can be achieved under steady-state engine conditions, and initially SCR systems used a fixed ratio of DEF to NOx. It is much more difficult to control NOx emissions under the transient conditions typical of urban driving. This requires good control of the amount of DEF injected to provide a high NOx reduction rate while keeping emissions of NH_3 to a minimum. The first generation DEF control systems used a NOx sensor downstream of the SCR to control the rate of injection. However, during transient operation there was too much time delay in the response of the system to effectively control the emissions. Second generation controls have been developed to reduce this response time. For example, a NH_3 sensor may be placed in the middle of the SCR to allow a rapid increase in DEF dosing until NH_3 is detected by the sensor. This results in faster SCR control and higher NOx conversion efficiency, while minimising the risk of NH_3 emissions. However the time lag remains of the order of a minute. It should be noted that it is not currently possible to detect the amount of NH_3 stored on the catalyst using on-board sensors. In addition, according to Skaf et al. (2014) NH_3 interferes with NOx sensors. Therefore on-board measurements of NOx in the exhaust may reflect high NH_3 emissions as well as NOx.

In the future is it likely that there will be increasing integration of engine and after-treatment control systems to optimise the performance of the SCR system and enable fuel economy benefits through increased engine-out emissions but low post SCR NOx (Stanton et al., 2013). Thermal management of after-treatment devices through engine management will become an essential element of NOx control to enable SCR to operate at peak efficiency over a wide range of driving conditions.

[3] Zeolites are micro-porous aluminium silicate minerals

A typical Euro VI HDV after-treatment system consists of a diesel oxidation catalyst (DOC), a DPF, a SCR and, possibly an NH_3 oxidation catalyst (AOC)[4]. The order in which these components are placed varies. An advantage of placing the DOC and DPF upstream of the SCR is that the DOC oxidises some of the NO to NO_2 which can make the SCR more effective (although this does depend on the catalyst). An AOC can be used after the SCR to reduce the NH_3 emissions, and allow a high dosage of DEF to be used without increasing NH_3 emissions. The advantage of placing the SCR upstream of the DPF is that it will be closer to the engine where the exhaust temperature will be higher, with increased NOx conversion efficiency, but poorer DPF regeneration. As both the DPF and the SCR require NO_2 there can be competition between these two requirements.

These problems can be potentially overcome by integrating the SCR catalyst into the DPF as one multifunctioning unit. In some after-treatment systems, such as Johnson Matthey's SCRT® system the SCR coating is applied directly to the DPF, which enables the SCR to get hotter quicker and increases the SCR volume, both of which result in more efficient NOx conversion (Görsmann, 2015). There are other advantages including allowing earlier urea injection with improved cold start NOx reduction, less space needed for after-treatment and less weight. However the substrate must be sufficiently porous to keep the engine backpressure at acceptable levels without incurring an additional fuel penalty and the SCR catalyst loading must be higher than on a separate SCR system. As both components use NO_2 the f-NO_2 needs to be higher than for a separate SCR system, up to approximately 75%. In addition, to achieve high NOx conversion a second SCR may be required depending on the catalyst formulation in HDV applications (Johansen et al., 2014).

SCR was first introduced to meet the Euro IV HDV emission standards. Engine manufacturers took advantage of the trade-off between NOx, PM and fuel consumption, to calibrate the engine to have higher engine-out NOx but lower PM emissions and improved fuel consumption. The SCR was used to control the NOx emissions, giving overall lower exhaust emissions than Euro III engines, at least under the controlled conditions of the European type approval test.

Engines fitted with SCR systems and tested in the laboratory, using standard EU type approval test procedures, show good NOx reduction efficiencies. However, this has not been reflected in real driving conditions, especially in urban areas. This is thought to be due to the low exhaust temperature under many urban driving conditions.

The catalyst formulation and its loading as well as the design of the catalyst substrate can all affect SCR performance. For example, the use of high porosity substrates with increased cell density can improve SCR conversion efficiency and potentially allow up to 50% reduction in volume (Görsmann, 2015). Other developments include the use of solid urea or magnesium

[4] Also known as an ammonia slip catalyst (ASC)

chloride ($MgCl_2$) as the storage medium. Solid urea needs to be heated in the presence of water vapour to decompose to NH_3. $MgCl_2$ stores NH_3 and cartridges can be readily handled, and recharged. The advantage is that both of these storage devices occupy less space and are lighter that a urea tank (Johnson, 2008).

Hydrocarbons can also be used as the reductant in SCR (HC-SRC[5]). Passive systems use hydrocarbons present in the exhaust as the reducing agent whilst active systems use additional fuel added upstream of the catalyst. However, HC-SCR is less efficient at removing NOx than NH_3-SCR and the active system can give rise to undesirable increases in emissions of carbon monoxide, hydrocarbons, PM and CO_2. There may also be an increase in the emissions of N_2O.

2.4. Lean NOx trap (LNT)

Lean NOx traps (LNTs) store NOx under lean engine operations and release it under richer conditions. The lean phase may last 30-90 seconds and then there is a brief return to stoichiometric or rich operation, for perhaps 3-5 seconds to remove the stored NOx for reduction to N_2 using a conventional three-way catalyst (TWC) mounted downstream. Storage times are increasing with improved catalyst formulations. This approach is also suitable for use with gasoline direct injection engines which operate under both rich and lean conditions.

According to Johnson (2015) this is the preferred technology for small diesel vehicles meeting Euro 6 emissions. It is less efficient at reducing NOx than SCR, and has a nominal removal efficiency of 70-80% removal. The main advantage of LNT for light duty vehicles is that a DEF storage tank, which takes up significant space on a small vehicle, is not required (Johnson, 2008).

A typical system comprises a noble metal catalyst, for example platinum, to oxidise NOx and an alkaline and/or alkaline earth component such as barium and/or potassium to trap the NOx as nitrites/nitrates. In simple terms the NOx is oxidised and stored as a nitrite or nitrate on the trap. The engine is switched to rich conditions; the NOx is released and then reduced to form N_2 and O_2 by the TWC. However NH_3 and other reduced compounds are also produced during the process and, if uncontrolled, emitted from the vehicle exhaust.

Over 90% NOx removal has been demonstrated with new LNTs. The main problem has been their sensitivity to fuel and lubricant S which rapidly reduces the NOx conversion efficiency as the LNTs need to be regenerated periodically at high temperatures. The introduction of zero S (<10 ppm) diesel in Europe, improved catalyst formulations which are less S sensitive, and new control strategies that have reduced the desulphurisation temperature are making LNT more effective.

[5] Also known as lean NOx absorbers or lean De-NOx catalysts

For GDI engines it has been suggested that as NOx emissions are generally considered to be low at low loads, control strategies could concentrate on reducing emissions when both emissions and exhaust temperature are higher. This could reduce the amount of expensive platinum group metals required for the catalyst making LNTs more economical for use on large GDI engines (Johnson, 2008).

Combined SCR and LNT systems are being developed which combine the advantages of both technologies. In this case a SCR catalyst stores the NH_3 generated during the LNT rich operation, this NH_3 then reacts with the NOx. This approach increases system efficiency enabling a decrease in the catalyst loading, and hence cost, for the same conversion efficiency (Johnson, 2008).

There have also been improvements in the LNT materials used. Second generation LNTs are able to hold more than twice the NOx at 130 ^{o}C compared to the first generation, and release it at higher temperatures when the downstream SCR is operational (Johnson, 2015).

An example of the combined use of LNT and SCR is the diesel Cold Start Concept (dCSC^{TM}) developed by Johnson Matthey. This component traps NOx from cold start and releases it when the downstream SCR is sufficiently hot to convert the NOx (Görsmann, 2015).

3. REAL WORLD EMISSIONS

3.1. Introduction

This section assesses the performance of NOx abatement technologies used on light and heavy duty diesel vehicles under real world driving conditions. It draws largely on work undertaken in London (Carslaw & Rhys-Tyler, 2013) and Leeds (Tate, 2014) using vehicle emissions remote sensing and data from portable emission measurement systems (PEMS). PEMS measure instantaneous emissions as a vehicle is driven and cannot be directly compared to the emissions measured under laboratory conditions.

Data from the most recent Euro standards, nominally Euro 4 and IV (from 2005) to Euro 6 and VI (from 2014 and 2013 respectively) has been used to understand the in-service performance of NOx abatement devices. These vehicles represent the majority of vehicles on the road today. NOx, NO_2 and NH_3 emissions are discussed separately.

3.2. Nitrogen oxides (NO_x)

3.2.1. Cars

The remote sensing data in Figure 1 (Tate, 2014) and from Carslaw & Rhys-Tyler (2013) both show that there has been no real reduction in NOx emissions from diesel cars up to Euro 5. Euro 4 and 5 NOx emissions were slightly lower than Euro 3, but similar to pre Euro 1. These vehicles use relatively unsophisticated EGR to control NOx emissions.

The Leeds remote sensing data provides some evidence that NOx emissions from Euro 6 diesel cars are lower than from Euro 4 and 5 diesel cars (see Figure 1) [6].

According to Ligterink et al. (2013) NOx emissions from Euro 6 diesel cars have a very large variation in NOx emissions. Depending on the test conditions and vehicle technology the spread is 10% to 1000% of the limit value, when measured under laboratory conditions that simulate real world driving. This wide variation is mainly due to the type, functionality and control strategy of the after-treatment device. The authors concluded that during type approval the control strategies are active and effective, but during real world operation they are not operational all the time.

A meta-analysis of PEMS emissions data of Euro 6 diesel cars (and some equivalent US certified cars) undertaken by the International Council on Clean Transportation (2014b) found that the average on-road emission of NOx were seven times the emission limit. A sizable share of the emissions occurred during discrete events lasting a few seconds. These were not, in general, due to "untypical" driving but were due to normal transient increases in engine load or during regeneration of the DPF. This suggests that while the Euro 6 emissions may be lower than Euro 5, they are still far in excess of the type approval limit. These high emissions occurred for cars using all three abatement technologies (i.e. EGR, SCR and LNT).

The International Council on Clean Transportation (2014b) suggests that it is difficult to inject the optimum amount of urea in a SCR system, particularly during rapid changes in engine load. For LNT systems there is a fixed NOx capacity and under high-load situations NOx can break through. Another possible explanation for the high NOx emissions for Euro 6 cars is the pressure on manufacturers to reduce CO_2 emissions. Robust control of NOx emissions is likely to result in a fuel penalty that would affect compliance with the CO_2 standards, thereby creating an incentive for manufacturers to optimize fuel consumption to the detriment of real world NOx performance. The authors concluded that the vehicle NOx control strategies are optimised for the current type-approval test procedures, but are not sufficiently robust to give acceptable on-road performance. This approach is currently legal but is unlikely to be when PEMS testing is introduced for EU type-approval of light duty vehicles in the future.

[6] The remote sensing data cannot be compared to the limit value.

The principle of introducing a 'real driving emissions' (RDE) test using PEMS has been agreed for passenger cars; although the details are yet to be finalised. PEMS tests are required from 2015 for reporting and monitoring purposes, with RDE testing scheduled to become an integral part of the type approval process when the Euro 6c standard comes into effect in 2017 for new types and 2018 for all new cars. Negotiations have taken longer than anticipated and there is concern that there could be a delay in implementation.

Of particular importance is the conformity factor. This is the ratio of in-service emissions measured using PEMS to the test cycle emissions limits. This will be determined on the basis of the initial monitoring data. The European Commission has estimated that a conformity factor of 1 would result in compliance with the ambient NO_2 limit value virtually everywhere by 2020, but with a conformity factor of 4 non-compliance in 2020 would be 3 times higher (European Commission, 2013).

PEMS data is not directly comparable with laboratory emissions data as measured on a chassis dynamometer. The Type 1 test in the EU type approval procedure is designed to be as reproducible as possible, and standardises a range of factors that influence emissions under real world driving conditions. These include road gradient, traffic conditions, ambient temperature and driver behaviour. One to one comparison of the laboratory and RDE test results is not possible. The PEMS data will be analysed statistically over periods of similar duration as the Type 1 test.

The proposed RDE procedures include PEMS testing over a 90 to 120 minute long trip, which would include urban, rural and motorway driving on working days. The test would include cold start but data would be excluded from the evaluation until the engine coolant temperature reaches 70 ^{o}C or for a maximum of five minutes. However, these details remain subject to final agreement (May, 2015).

3.2.2. Light duty commercial vehicles (vans)

There is less information available on the real world emissions of vans. The remote sensing data from London (Carslaw & Rhys-Tyler, 2013), however, suggests that these vehicles behave in a similar way as diesel cars.

3.2.3. Heavy good vehicles (HGVs)

Remote sensing data from London (Carslaw & Rhys-Tyler, 2013) shows that there has been little change in real world NOx emissions of heavy goods vehicles (HGVs) from Euro III to Euro V, although PEMS data from the Netherlands (Vermeulen et al., 2012; 2014) suggests that some Euro IV and V trucks have lower emissions than earlier models, although there is large variability between individual vehicles.

According to Vermeulen et al. (2014) early Euro IV trucks, introduced before the standard was mandated from 2005, did not, on average, result in a reduction in real-world NOx emissions compared to vehicles built to previous standards under low speed urban driving conditions. However, the second generation of Euro IV HDVs had, on average, lower emissions at low and intermediate vehicle speeds than the earlier models, but some individual vehicles still performed badly. Early Euro V HDVs had lower average emissions at all vehicle speeds than Euro IV, but again some vehicles performed badly, and not only at low vehicle speeds. The authors concluded that meeting Euro V emissions type approval does not guarantee low emissions. However, the second generation of Euro V vehicles showed significantly lower average NOx emissions at low speed.

Euro VI HDVs are required to comply with a mandatory RDE test conformity factor of 1.5. Testing of a number of Euro V and VI HDVs (Vermeulen et al., 2014) showed that the in-service NOx emissions of Euro V HDVs varies significantly, but that 75% achieved a non-mandatory conformity factor of 1.5. On the other hand all the Euro VI vehicles met the mandatory NOx conformity factor of 1.5, with some vehicles having a factor of well below 1.

The first long distance Euro VI trucks had very low NOx emissions compared to Euro V vehicles, including at low speeds. The authors conclude that the Euro VI legislation has led to significantly lower real-world NOx emissions, although not all Euro VI vehicles have low emissions under all driving conditions.

Chassis dynamometer data from the VTT (the Technical Research Centre of Finland) (International Council on Clean Transportation, 2015) of 38 Euro IV to VI HDVs also show that the new Euro VI certification protocols are, in general, effective at reducing NOx emissions under a wide range of test cycles, including one that simulates urban driving. The changes to the type approval engine tests include cold start and reductions in the average engine load and power during the test cycles. The authors concluded that the good Euro VI NOx abatement is a result of more efficient catalyst formulations, better thermal management of the catalyst, improved urea dosing strategies and other after-treatment optimisations. The average urea consumption for vehicles tested increased approximately 25% from Euro V to VI, showing that the SCR systems were more often operational. In addition, the Euro VI HDVs showed a much smaller range in NOx emissions.

Vermeulen et al. (2014), however, have shown using PEMS that there remain issues with some Euro VI distribution trucks and buses. These vehicles have lower emissions than previous generations, but in busy urban driving conditions, with low driving speeds, some vehicles continue to have high NOx emissions. Under cold start urban driving conditions emissions can be an order of magnitude higher than when the engine is warm. The vehicles tested were all new and little is known of the deterioration in the NOx abatement over time under real driving conditions.

International Council on Clean Transportation (2015) recommended that other jurisdictions considering adopting EU emission standards should not adopt the Euro V standard, but instead go directly from Euro IV to Euro VI standards to achieve a significant NOx reduction and implement strong in-use compliance and enforcement programmes to ensure low in-service emissions.

3.2.4. Buses

The remote sensing data from London (Carslaw & Rhys-Tyler, 2013) shows little reduction in NOx emissions from Euro III to Euro V buses. Euro III buses show significant differences in emissions by manufacturer, reflecting their different NOx control strategies. Euro V buses with SCR fitted by the original engine manufacturer (OEM) have no lower emissions than buses using EGR. The lack of improvement in SCR equipped buses is consistence with the PEMS data for urban driving conditions described below.

The Dutch in-service PEMS testing programme included two Euro VI city buses and a 12 t urban distribution truck (Vermeulen et al., 2014). The NOx emissions of these vehicles were lower than from second generation Euro V HDVs. Two of the three vehicles, however, had significantly higher emissions that the Euro VI long distance trucks. This is thought to be due to the low exhaust temperature rendering the after-treatment less effective under certain operating conditions. The NOx emissions decreased at higher vehicle speeds and higher payloads when engine temperatures increase. The third vehicle performed well, showing that it is possible to maintain low emissions in urban areas. One of the vehicles that performed poorly under congested traffic conditions had an engine conformity factor of less than 1.5 suggesting that the RDE test requirements do not always identify vehicles with high NOx emissions in-service.

It is not realistic to expect a vehicle certified to a certain emissions standard to stay below the limits under all driving conditions. Even during the type approval tests emissions will go above the limit as it is an average over the whole test cycle against which it is assessed. To assess the conformity factor the PEMS data is averaged over a period of similar duration as the laboratory engine test, but certain data is excluded, for example when the average engine power is less than 15% of maximum. This means that when a vehicle drives at low speeds, for example, in heavy traffic, data is excluded in the evaluation of RDE conformity. This is a real shortcoming of the RDE procedures for urban buses, and probably also for urban goods distribution vehicles.

Another shortcoming is that the engine manufacturer only has to test three engines from each ‘family’ of engines, and to test these in the type of vehicle in which the engine is most commonly used. As long distance trucks sell more than urban buses manufacturers will tend to test their engines in trucks rather than buses, which have different in-service operating patterns. NOx emissions from a truck may be low under the RDE tests, while the emissions from the same type of engine in an urban bus could be higher due to the different driving conditions it encounters during its working life.

3.3. Nitrogen dioxide (NO_2) emissions

3.3.1. Introduction

Nitrogen oxides are emitted from combustion sources, such as road vehicles, mainly as nitric oxide (NO), which reacts with ozone (O_3) in the atmosphere to form NO_2. Some NO_2 is directly emitted, but for many years it was generally accepted that this fraction was small, possibly around 5% (Air Quality Expert Group, 2007). There is evidence from both analyses of ambient monitoring data and vehicle measurements that show that this proportion has increased in recent years.

Grice et al. (2009) reviewed the literature of vehicle f-NO_2 and made a series of recommendations of typical emissions as shown in Table 1.

Table 1: Recommended Primary NO_2 emission percentages for different vehicle types (f-NO_2) (Grice et al., 2009)

Vehicle type		**f-NO_2 (%)**
Gasoline cars	Euro 2 and earlier	4
	Euro 3-6	3
Diesel cars/vans	Euro 2 and earlier	11
	Euro 3	30
	Euro 4-6	55
HGVs	Euro II and earlier	11
	Euro III	14
	Euro IV-VI	10
Buses	Euro II and earlier	11
	Euro III no DPF	14
	Euro III with DPF	35
	Euro IV-VI	10

These f-NO_2 values are similar to those of Kousoulidou et al. (2008) with the exception of HDVs where the f-NO_2 for Euro IV was assumed to be 14%; Euro V 18% and Euro VI 35%.

The f-NO_2 for diesel cars, not fitted with exhaust treatment technology, is more than twice that from gasoline cars. There has been a significant increase from Euro III onward when diesel oxidation catalysts and then DPFs, were fitted. Similar increases occurred for Euro III HDVs fitted with DPFs, although this has reduced with the use of SCR from Euro IV.

Keuken et al. (2011) showed that the use of oxidation catalysts to reduce PM emissions from diesel cars increased from 5% in 2000 to between 55% and 70% in 2010 in the Netherlands, but suggested that overall, despite the increase in NO_2 emissions, there was a health benefit of their introduction due to lower PM emissions. Primary NO_2 emissions from road traffic in the

Netherlands is expected to increase from 8 kt in 2000 to 15 kt by 2015 and subsequently to decrease to 9 kt by 2020.

The retrofitting of many buses in London with catalytically-regenerative DPFs is thought to explain some of the changes in primary NO_2 emissions. The timing of the retrofit scheme fits in with the observations at roadside and kerbside monitoring sites. By 2005 over 90% of Transport for London (TfL) buses were operating with DPFs (Air Quality Expert Group, 2007).

The amount of primary NO_2 has important implications for meeting the EU ambient NO_2 limit values. An assessment of the formation of NO_2 concentrations in areas of Helsinki with heavy traffic (Anttila et al, 2011) found that the proportion of f-NO_2 in the road transport emissions increased from below 10% in the 1990s to approximately 20% in 2009 due to the increase in diesel cars. To achieve the EU ambient NO_2 limit values, the authors concluded that the f-NO2 emissions need to be reduced alongside the total NOx emissions.

Grice et al. (2009) also found that in locations where high f-NO_2 from traffic is a key factor contributing to exceedances of the ambient limit values, both NOx and NO_2 emissions need to be reduced, but elsewhere total NOx emissions should be reduced. At sites exceeding the ambient NO_2 limit in Greece, for example, their analysis suggests that f-NO_2 is not important and the focus should be on reducing total NOx emissions from traffic. However, at the time of the study there was an extremely low number of diesel cars in Greece which meant that a large proportion of NOx emissions were from gasoline vehicles, which have lower f-NO_2.

The diesel proportion of new cars sold in different EU countries varies from over 70% (Luxembourg, Ireland and Portugal) to under 40% (Denmark and Netherlands) (ACEA, 2014). The issue of f-NO_2 will become increasingly important in those countries with very high diesel car populations.

3.3.2. Light duty vehicles

The remote sensing data from London (Carslaw and Rhys-Tyler, 2013) shows that the f-NO_2 from diesel cars has increased from typically 10-15% for pre Euro 3 cars to 25-30% for Euro 4 and 5. For Euro 3 these levels are lower than the estimates of Grice et al. (2009). For Euro 4 and 5 there is a wide range of f-NO_2 from approximately 12% to 55%. The authors found similar f-NO_2 for light goods vehicles.

For Euro 4 and 5 diesel cars with engine capacities less than 2 L the mean f-NO_2 was 27%; but for larger vehicles it was 43%. For Euro 5 cars the average f-NO_2 for one manufacturer was 12%; while for another it was 38%. The authors consider that this wide range is most likely to be due to the engine control strategy utilised which varies with manufacturer and vehicle model, and noted that if all manufacturers followed the control strategies of the one with the lowest f-NO_2 emissions there could be a significant reduction in NO_2 emissions.

3.3.3. Heavy duty vehicles

The remote sensing data from London (Carslaw & Rhys-Tyler, 2013) for HGVs show that for HDVs there has been a clear reduction in f-NO_2 from approximately 20% for Euro II and III to 5-10% for Euro IV and V. There is also evidence to suggest the smaller HGVs (3.5-12 t) tend to emit higher f-NO_2 ratio than larger HGVs (>12t). These values are also somewhat different to those of Grice et al. (2009).

The f-NO_2 emissions from buses are far more variable than from trucks, ranging from near zero to over 40%. The highest f-NO_2 emissions were observed from vehicles fitted with DPFs, and there was a large variation by manufacturer, with an average f-NO_2 emission of 15-20%, which is lower than in Grice et al. (2009).

Euro IV and V buses with SCR have a f-NO_2 range from close to zero to approximately 30%. For two bus manufacturers almost all the NOx measured was in the form of NO, suggesting the SRC did not complete the conversion of NO_2 to N_2. Low f-NO_2 for Euro IV SCR buses has also been observed in a PEMS study by Fu et al. (2013). These buses were not fitted with a DPF. As the injection of urea under low temperature (urban) driving conditions is low, the SCR is unlikely to have been operating efficiently, and therefore the low f-NO_2 is likely to be related to the optimisation of the combustion conditions in the engine rather than being related to the SCR system.

Buses that meet the voluntary environmental enhanced vehicle (EEV) emission standards have higher f-NO_2 ratios due to the increased oxidation of the engine gases upstream of the SCR due to the use of a DPF, although the SCR does not appreciably reduce total NOx. The EEV emission standards are between Euro III and VI depending on the pollutant and test cycle. For NOx emissions EEVs are required to meet the Euro V steady state and transient limit values. For PM mass emissions these vehicles meet the Euro IV steady state limit, but for the transient test the requirement lies between the Euro V and VI limit values.

Vermeulen et al. (2014) used PEMS to measure f-NO_2 from Euro VI vehicles. They found that the proportion of NO_2 increases from 20% under cold start conditions to 40-80% for trips with warm engines. The range of f-NO_2 emissions is large especially for warm operating conditions, due to the different NOx control strategies used. The authors noted that under these conditions the NOx emissions are very low, and therefore imply low accuracy of the measured f-NO_2.

There is some evidence that the f-NO_2 decreases as the DPF ages and there is a reduction in the oxidative potential of the DPF (Carslaw et al., 2015).

3.4. Ammonia (NH_3) emissions

There has been concern that the use of urea in SCR will increase exhaust emissions of NH_3, an important precursor to secondary PM. However the remote sensing data from London

(Crawshaw and Rhys-Tyler, 2013) shows that emissions are low from Euro IV and V HDV. When expressed as a ratio to CO_2 emissions Euro IV SCR buses emit considerably less NH_3 than older catalyst-equipped gasoline cars.

4. RETROFITTING BUSES

Transport for London (TfL) has undertaken the largest bus retrofit programme in the world, starting with DPFs and more recently fitting SCR to its Euro III buses. By the end of 2015 nearly 2,000 buses will have been retrofitted with SCR. The remaining Euro III buses in TfL's fleet will be retired and replaced with Euro VI buses (Mayor of London and Transport for London, 2015). The Transport Authority of Barcelona (TMB) has also embarked on a ‘low NO_2 SCR’ retrofitting programme, with over 400 Euro II and III diesel buses retrofitted.

The results of a TfL commissioned study on the in-service efficacy of retrofitted ‘low NO_2 SCR’ is described in this section.

The Euro III buses have been fitted with a specially designed ‘low-NO_2 SCRT’. The optimised system is designed to work more efficiently under urban driving conditions than the OEM fitted SCR (Carslaw & Rhys-Tyler, 2013) to minimise the emissions of both NOx (see section 3.2.4) and NO_2. It combines a DPF to reduce PM and a SCR to reduce NOx emissions. The SCR is close coupled and thermally managed so the catalyst activity is maximised. The calibration increases the urea injection when operating conditions allow. The SCR catalyst is three times the volume of those used in a standard SCR.

Carslaw et al. (2015) tested emissions from London buses retrofitted with this device using remote sensing under normal driving conditions and on a test track. The on-road tests show that the ‘low-NO_2 SCRT’ on average reduces NOx by 45% and NO_2 by 61% compared with similar buses fitted only with a DPF. There are times, however, when even the ‘low NOx SCRT’ system fails to reduce NOx, at other times the NOx reduction is greater than 90%. It seems that the system cannot reduce NOx when the engine is cold or following a period of driving through congested traffic, when the exhaust temperature is low.

Under test track conditions NOx reductions of 77% were observed with the ‘low NO_2 SCRT’ system compared to the ‘base’ bus fitted only with a DPF. However, the bus fitted with a SCR but no DPF reduced NOx emissions by 90% compared to the ‘base bus’. The higher efficiency of the SCR compared to the ‘low NO_2 SCRT’ was related to the higher inlet temperature resulting from the engine exhaust not having to pass through a DPF first. When inlet temperatures were greater than 200 ^oC the NOx removal from the ‘low NO_2 SCRT’ was approximately 90%.

The test track results show that it took approximately 20 minutes for the ‘low NO_2 SCRT’ to warm up at a mean speed of approximately 30 km h^{-1}.

Although the tests showed that the absolute emissions of NOx were lower with the ‘low NO_2 SCRT’, the absolute emissions of NO_2 were higher compared to the ‘base bus’. The original Euro III engine would have had no after-treatment such as a DPF and therefore would have had lower absolute emissions of NO_2 compared with the retrofitted bus.

The reduction in primary NO_2 emissions compared to buses fitted with DPFs are important as buses can make a significant contribution to roadside NO_2 concentrations. According to Carslaw et al., (2015) urban buses account for one third of the road transport primary NO_2 emissions in central London, and on individual road links this can be even higher. These road links are where there are exceedances of the EU ambient NO_2 limit values. Retrofitting urban buses with a ‘low-NO_2 SCRT’ system could therefore make an important contribution to the reduction in ambient NO_2 concentrations and achievement of the EU limit value. Buses tend to have a long service life and therefore a slow fleet turnover, making them particularly suitable for a retrofit programme.

5. RECOMMENDATIONS

5.1. Light duty vehicles

A new type approval test cycle for light duty vehicles is to be introduced for Euro 6c from 2017 for new types and 2018 for all new cars. This test cycle, the World Harmonized Light duty test Procedure (WHLP), has been developed from measurements of real world driving conditions, and is considered to be more representative of European driving conditions than the existing test cycle. It will include steeper transient accelerations as well as higher speeds and loads. Other changes to the test procedure include tightening the specifications for warming the engine prior to testing and lowering the test temperature. It is anticipated that adoption of the WHLP will require advanced control for cold start and will make NOx abatement more challenging (Forzatti et al., 2015).

Real driving emissions (RDE) tests are also to be introduced for passenger cars with the introduction of the Euro 6c standards. This measure is expected to ensure that real world emissions of NOx from diesel cars and vans are low.

Progress has been made with the development of the RDE requirements, but agreement between the motor manufacturers and the legislators on the compliance factor (the ratio of the in-service emissions to the laboratory Type 1 test emissions) is urgently needed and at the lowest reasonable level.

The RDE data should be made publically available to inform consumer choice.

5.2. Heavy duty vehicles

For HDVs the Euro VI emission standard introduced ‘not to exceed’ limits to control off-cycle emissions; that is emissions that occur under driving conditions not included in the test cycles, and RDE tests. Other changes include an emission limit for NH_3. An emission limit for NO_2 may be defined in implementing regulations. There is evidence that these measures together have resulted in Euro VI long distance trucks having low NOx emissions.

To control in-service emissions from all HDVs the legislation needs to ensure that the RDE tests include urban buses and distribution trucks. The different operating cycles of these vehicles need to be explicitly recognised, so that the issue of poor NOx control during and following periods of idling in congested traffic is addressed.

More information is needed on urban bus and distribution vehicle emissions during operation. For example understanding how quickly NOx emissions increase under idling conditions. This is important because these vehicles operate where public exposure to NO_2 is the greatest.

5.3. NO_2 emissions

There is evidence that SCR can reduce NO_2 as well as NOx emissions significantly, but this needs to be kept under review as the technology develops, and appropriate emission limits legislated if necessary.

5.4. Emission factors

New emission factors need to be developed for use in inventories that explicitly consider the in-service performance of abatement technology used in Euro 6 and VI vehicles, and its effectiveness under different during conditions.

The introduction of NOx after-treatment is relatively recent and there is insufficient knowledge of in-service deterioration in the efficiency of these devices. Measurements need to be undertaken on older vehicles to ensure that robust emission data is available for use in inventories.

5.5. Retrofitting

Retrofitting pre Euro VI urban buses and distribution trucks with ‘low NO_2 SCRT’ devices may offer a relatively cost-effective way of achieving the ambient NO_2 limit value, whilst also reducing PM emissions, where exceedences are close to busy roads with a high percentage of these vehicles.

6. SUMMARY AND CONCLUSIONS

There is little robust evidence that real world NOx emissions from diesel vehicles declined from when the Euro emission standards were first introduced in the early 1990s until the Euro 6 (light duty) and VI (heavy duty) standards were introduced. In addition, PM abatement has increased the proportion of NO_2 in the NOx emitted from vehicles. Both these factors, together with the increasing proportion of diesel cars in the vehicle fleet, have contributed to the difficulty in achieving the EU ambient NO_2 limit values in many cities across Europe.

There is some in-service evidence that NOx emissions for Euro 6 cars are typically lower than from earlier generations, but they remain on average many times the type approval emission limit. Portable emissions measurement system (PEMS) testing shows that there is a very large variation in emissions depending on the test conditions and vehicle. There is concern that Euro 6 cars using exhaust gas recirculation (EGR) on its own will have high NOx emissions during motorway driving. The introduction of a new test cycle and real driving emissions (RDE) tests with the Euro 6c legislation are likely to address this issue.

The same picture can be seen with NOx emissions from early generations of HDVs fitted with selective catalytic reduction (SCR). These devices were not very successful at reducing real world NOx emissions especially, but not exclusively, at low speeds. Although some Euro IV and V HDVs have been shown to have low real world NOx emissions under all driving conditions, good abatement of the emissions from these vehicles is not universal.

Controlling real world emissions of NOx from diesel vehicles is not easy. Huge progress has been made with the efficiency of NOx abatement using SCR and LNT over the last decade or so, but further development is needed to reduce emissions when the exhaust temperature is low during cold start and in congested driving conditions.

Future developments in vehicle emission legislation are likely to focus on closing the gap between the NOx emissions measured during the laboratory type approval tests and real driving conditions for both heavy and light duty vehicles.

The introduction of the ‘not to exceed’ emission standards, designed to capture emissions under conditions excluded from the test cycles, and RDE tests has resulted in Euro VI NOx emissions being low, at least for long distance trucks. There remain problems, however, with emission from urban buses and distribution vehicles. The SCR does not operate when the engine is cold, and it can take many minutes to warm up, and following periods in congestion the engine-out temperature can also fall to below the SCR operating temperature.

Combined NOx abatement systems that exploit the advantages of different abatement systems are likely to be used increasingly in the future. Sophisticated EGR combined with SCR enables lower emissions under low loads. Alternatively, low NOx traps (LNTs) combined with SCR allow the NOx to be trapped under cold conditions and released when the SCR is warm. Systems that combine SCR with diesel particle filters (DPFs) are also commercially available.

For light duty vehicles the new more stringent driving cycle and test procedures and RDE tests to be introduced with the Euro 6C standard from 2017/2018 are likely to reduce in-service NOx emissions. It is important that the introduction of these measures is not delayed, and that the agreed conformity factor is as low as reasonable. As these standards will only apply to new vehicles it will be a number of years before the benefits are observed at ambient monitoring stations.

There have been important changes to the heavy duty engine emissions legislation over recent years, with the introduction on 'not to exceed' emission limits and RDE tests. These seem to be effective at reducing NOx emissions from long distance trucks. The RDE requirements, however, need to be modified to ensure that NOx emissions from urban buses and distribution vehicles are low under all driving conditions.

Retrofitting urban buses and distribution vehicles offers a cost effective method to significantly reduce NOx and NO_2 emissions and could have an important role to play in achieving the ambient EU limit values in locations where these vehicles are an important source.

New emission factors for use in inventories are needed. These need to take account of the impact of different technologies under different driving conditions, and it may no longer be sufficient to have emission factors based solely on the Euro standard the vehicle or engine was built to meet.

Well controlled NOx and NO_2 emissions from all diesel vehicles are essential to enable the ambient NO_2 limit values to be achieved as soon as possible.

7. REFERENCES

ACEA, 2014. Pocket Guide 2014-15, Brussels.

Air Quality Expert Group, 2007. Trends in Primary Nitrogen Dioxide in the UK. Defra, London.

Anttila P., J-P Tuovinen, J. Niemi, 2011. Primary NO_2 emissions and their role in the development of NO_2 concentrations in a traffic environment. Atmospheric Environment 45(4), 986-992.

AVL, 2015. Real Driving Emissions (RDE). https://www.avl.com/real-driving-emissions-rde-/-/asset_publisher/gYjUpY19vEA8/content/real-driving-emissions-rde-?redirect=https%3A%2F%2Fwww.avl.com%2Freal-driving-emissions-rde-%3Fp_p_id%3D101_INSTANCE_gYjUpY19vEA8%26p_p_lifecycle%3D0%26p_p_state%3Dnormal%26p_p_mode%3Dview%26p_p_col_id%3Dcolumn-2%26p_p_col_count%3D1, accessed 15th May 2015.

Carslaw D., 2014, Recent findings from comprehensive vehicle emission remote sensing measurements. Frontiers in Air Quality Science, 23rd-24th June 2014, MRC-PHE Centre for Environment & Health, London.

Carslaw D., S. Beevers. J. Tate., E. Westmoreland, M. Williams, 2011. Recent evidence concerning higher NOx emissions from passenger cars and light duty vehicles. Atmospheric Environment, 45, 7053-7063.

Carslaw D., M. Priestman, M. Williams, G. Stewart, S. Beevers, 2015. Performance of optimised SCR retrofit buses under urban driving and controlled conditions. Atmospheric Environment, 105, pp 70 -77.

Carslaw D. & G. Rhys-Tyler, 2013. New insights from comprehensive on-road measurements of NOx, NO_2 and NH_3 from vehicle emission remote sensing in London, UK. Atmospheric Environment, 81, 339-347.

Carslaw D., M. Williams, J. Tate, S. Beevers, 2013. The importance of high vehicle power for passenger car emissions. Atmospheric Environment 68, 8-16.

Chen Y. & J. Borken-Kleefeld, 2014. Real-driving emissions from cars and light commercial vehicles – results from13 years remote sensing at Zurich/CH. Atmospheric Environment, 88, 157-161.

Defra, 2014. Updated projections for nitrogen dioxide (NO_2) compliance. London.

European Commission, 2013. European Commission Staff Working Document – Impact Assessment accompanying the Clean Air Package. SWD(2013) 531, 18 December 2013.

European Environment Agency, 2014. Air quality in Europe - 2014 report, Publications Office of the European Union, Luxembourg.

Forzatti P., L. Lietti and L. Castoldi, 2015. Storage and Reduction of NOx over LNT Catalysts. Catalysts Letters. 124, 483-504.

Fu M., Y. Ge , X. Wang, J. Tan, L. Yu, B. Liang, 2013. NOx Emissions from Euro IV busses with SCR systems associated with urban, suburban and freeway driving patterns. Science of the Total Environment. 452-453, 222-226.

Görsmann C., 2005. Catalytic Coatings for Active and Passive Diesel Particulate Filter Regeneration. Monatshefte fur Chemie. 136, 91–105.

Görsmann C., 2015. SAE 214 Heavy-duty emission control symposium: improving air quality while reducing the emission of greenhouse gases. Johnson Matthey Technological Review. 59 (2) 139-151.

Grice S., J. Stedman, A. Kent, M. Hobson, J. Norris, J. Abbott, S. Cooke, 2009. Recent trends and projections of primary NO_2 emissions in Europe. Atmospheric Environment 43, 2154–2167.

Johansen K., H. Bentzer, A. Kustov, K. Larsen, T. Janssens and R. Barfod, 2014. Integration of vanadium and zeolite type SCR functionality into DPF in exhaust aftertreatment systems –advantages and challenges, SAE Technical Paper. 2014-01-1523, doi:10.4271/2014-01-1523.

Johnson T., 2015. Review of vehicular emissions trends. SAE International Journal of Engines. 8 (3), doi: 10.4271/2015-1-0993.

Johnson T., 2014. Vehicle emissions in review, SAE International Journal of Engines. 7(3), 1207-1227.

Johnson T., 2008. Diesel engine emissions and their control: an overview, Platinum Metals Review. 52 (1), 23-37.

International Council on Clean Transportation, 2014a. European vehicle market statistics: Pocketbook 2014, Berlin.

International Council on Clean Transportation, 2014b. Real-world exhaust emissions from modern diesel cars: a meta-analysis of PEMS emissions data from EU (Euro 6) and US (Tier 2 Bin 5/ULEV ii) diesel passenger cars. Part 1: aggregated results. Berlin.

International Council on Clean Transportation, 2015. Comparison of real-world off-cycle NOx emissions control in Euro IV, V and VI, ICCT Briefing. Berlin.

Keuken M., M. Roemer, P. Zandveld, R. Verbeek, G. Velders, 2012. Trends in primary NO_2 and exhaust PM emissions from road traffic for the period 2000-2020 and implications for air quality and health in the Netherlands. Atmospheric Environment. 54, 313-319.

Kousoulidou M., L. Ntziachristos, G. Mellios, Z. Samaras, 2008. Road-transport emission projections to 2020 in European urban environments. Atmospheric Environment. 42, 7465–7475.

Ligterink N., G. Kadijk, P. van Mensch, S. Hausberger, M. Rexeis, 2013. Investigations and real world emission performance of Euro 6 light-duty vehicles. Report TNO 2013 R11891. TNO, Delft.

May J., Real driving emissions, Universities Internal Combustion Engine Group Meeting, 8th April 2015. http://www.aecc.eu/content/pdf/150408_UnICEG_RDE_AECC.pdf, accessed 29th April 2015.

Mayor of London and TfL, 2015. Mayor & TfL expand Europe's greenest bus fleet. https://www.tfl.gov.uk/infofor/media/pressreleases/2014/september/mayorandtfl-expandeuropesgreenestbusfleet, accessed 30th April 2015.

Skaf Z., T. Aliyev, L. Shead and T. Steffen, 2014. The state of the art in selective Catalytic reduction control, SAE Technical Paper. 2014-01-1533. doi:10.4271/2014-01-1533.

Stanton D., S. Charlton, and P. Vajapeyazula, 2013. Diesel engine technologies enabling powertrain optimization to meet U.S. greenhouse gas emissions, SAE International Journal of Engines. 6(3):2013, 1757-1770. doi:10.4271/2013-24-0094.

Tate J., 2014. Euro VI light-duty emission performance: recent remote sensing measurements and emission model (PHEM) results. APRIL meeting 24th February 2015. London.

Velders G., G. Geilenkirchen, R. de Lange, 2011. Higher than expected NOx emission from trucks may affect attainability of NO_2 limit values in the Netherlands, Atmospheric Environment. 45, 3025-3033.

Vermeulen R., H. Dekker. W. Yonk, 2012. Real-world NOx emissions of Euro V and Euro VI heavy-duty vehicles. Report TNO-060-DTM-2012-01193, TNO, Delft.

Vermeulen R., J. Spreen, N. Ligterink, W. Yonk, 2014, The Netherlands in-service testing programme for heavy-duty 2011-2013. TNO Report 2014 R10641, TNO, Delft.

Zheng M., G. Reader & J. Hawley, 2004. Diesel engine exhaust gas recirculation - a review of advanced and novel concepts, Energy Conversion and Management. 45, 883–900.