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Portable Emissions Measurement System (PEMS) data for Euro 6 diesel cars and comparison with emissions modelling

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Abstract

This paper reviews the emissions performance of 39 Euro 6 diesel passenger cars using a Portable Emissions Measurement System (PEMS). Comparisons are made with current emissions regulations (in particular the Euro 6 standard for nitrogen oxides (NO_x = NO+ NO_2) of 0.80 g km^{-1}) and predictions by the speed dependent emission factors of COPERT. The mean NO_x emission was 0.36 ± 0.36 g km^{-1}, the mean nitrogen dioxide (NO_2) emission was 0.17 ± 0.19 g km^{-1}. The average fraction NO_x emitted as NO_2 (known as primary NO_2 or fNO_2) was 44%. Each vehicle was analysed over a test route composed of urban and motorway driving. On average NO_x emissions were 5.3 times the Euro 6 limit for urban driving and 3.8 times the limit for motorway. A wide range of deviation ratios (ratio between real world measurements and type approval limit) were found, the highest being 27.3 for an urban section. The average PEMS measured NO_x emission was 1.6 times COPERT's average estimate. Similarly with primary NO_2 (44% compared to 30% assumed by COPERT). Scenario analysis was then performed to assess the sensitivity of the mean annual roadside concentrations of NO_2 to the discrepancies between type approval limits, COPERT estimates and on road emissions measured by PEMS.

Key-words: Euro Standards, Primary NO_2, Nitrogen oxides (NO_x), COPERT, On-road emissions, Diesel passenger cars, Portable Emissions Measurement System (PEMS), Euro 6

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1 Introduction

Successive Euro Standards have failed to effectively reduce urban concentrations of nitrogen dioxide (NO_2) (Beevers et al. 2012; Carslaw et al. 2011; Franco et al. 2013). In this paper we will investigate the real world nitrogen oxides ($NO_x = NO+ NO_2$) emissions of the latest Euro 6 standard diesel vehicles, compare these to estimates from emissions modelling and evaluate what this could mean for future urban air quality.

A key focus of this paper is primary NO_2 (fNO_2, the amount of NO_x emitted directly as NO_2). When NO_x is released into the atmosphere as a mixture of NO and NO_2 chemical reactions take place with ozone (O_3), which reacts with the NO component to produce nitrogen dioxide. This is balanced by the photo-dissociation of NO_2 to NO. Given well mixed air and sufficient time this results in an equilibrium ratio of NO_2 to NO_x (depending on the total oxidant as the sum of ozone and NO_2 (Clapp & Jenkin 2001)). However at road-side locations there is insufficient time for such reactions during dispersion and mixing of fresh emissions, and often ozone is already depleted in busy streets limiting reaction with NO. In these circumstances the proportion of NO_x emitted directly as primary NO_2 becomes very important. Hence primary NO_2 is particularly important for road-side concentrations of NO_2 near busy roads. Introduction of successive Euro standards has marked an increase in the percentage fNO_2, mainly attributed to the addition of oxidative after-treatment systems known as diesel oxidation catalysts (DOCs) (Grice et al. 2009; Alvarez et al. 2008; Carslaw et al. 2011).

To evaluate the real world performance of Euro 6 diesel vehicles a Portable Emissions Measurement System (PEMS) has been used. PEMS devices can be fitted to the tailpipe of nearly all vehicles without any modification, they then record real time emissions as the vehicles drive on open roads. PEMS were approved for EU engine certification of heavy duty engines in 2009, becoming mandatory for heavy duty type approval in 2011 (EC, 2011, 2009). Their introduction into test procedure is expected to reduce the problem of NO_2 exceedances in urban areas (Degraeuwe et al., 2015; Weiss et al., 2012). As of September 2017 new models being registered for sale in the EU will be subject to a real driving emissions (RDE) test procedure using PEMS (EC, 2015a). The on road NO_x emission limit will be higher than the Euro 6 standard of 0.08 g km^{-1}. The RDE emission limit will take the form of a not-to-exceed (NTE) value dependant on a conformity factor, the agreed conformity factor for NO_x of 2.1 (NTE limit of 0.168 g km^{-1}) will be legally binding from September 2017 (Europarl, 2016).

The emissions model used for comparison in this study is COPERT (Computer Program to Calculate Emissions from Road Transport). COPERT is developed by the European Environment Agency and is the tool recommended by the European Monitoring and Evaluation Program (EMEP). It is currently used in 22 out of the 28 EU member states for road transport emissions and projections (Kioutsioukis et al. 2010). To evaluate the possible implications of discrepancies between PEMS measurements and COPERT 4v11 estimates modelling was performed for different road flows and backgrounds for the year 2030.

2 Method

39 Euro 6 diesel passenger cars were monitored by Emissions Analytics over a set route in the Greater London area. All vehicles were tested on the same route (with minor variation due to unavoidable circumstances such as road works). The route chosen was composed of motorway and urban driving (here urban is taken to mean a road in an urban/ residential area with a speed limit of 30mph). To analyse the difference in emissions between urban and motorway driving each trip was also broken down (by purpose built software which identified locations by GPS) into its composite urban and motorway parts. These shall be referred to as urban/ motorway sections whereas the whole journey shall be referred to as the trip.

As driving style (i.e. aggressive acceleration) can have large effect on the emissions of a vehicle the tests were evaluated to ensure the driving style was representative of normal driving and uniform throughout the study. The driving style for each trip was evaluated using the Relative Positive Acceleration (RPA) (Weiss et al. 2011; Thompson et al. 2014) metric and found to be within the World Harmonised Light- Duty Test bounds for normal European driving (average 0.1 m s^{-2} and 0.2 m s^{-2} for motorway and urban respectively (Tutuianu et al. 2013)).

3 Test Vehicles

The vehicles ranged in engine size from 1.4ℓ- 3ℓ and deployed the three main NO_x after treatment technologies Lean NO_x Traps (LNT), Selective Catalytic Reduction (SCR) and Exhaust Gas Recirculation (EGR) (vehicles in the study fitted with LNT and SCR were also fitted EGR in combination, vehicles referred to as EGR are fitted with EGR alone). Vehicles were tested from 13 different manufactures. The distribution of engine sizes (average 2 ℓ), abatement technologies (7 EGR, 19 LNT and 13 SCR) and manufactures are comparable to the EU average to ensure the study is representative; the 13 manufactures sampled provided 70% of the new car fleet in 2016 (Eurostat 2013; ICCT 2015; SMMT 2016). Table 1 lists the vehicles in the study and their characteristics.

4 Data Analysis

Cold starts (classified as the first 300 seconds of the journey (Weiss et al. 2011)) have been removed, this was to ensure continuity as all vehicles were not able to soak overnight.

Emissions are reported as the trip or section average in grams per kilometre (g km^{-1}) which is calculated by summing the total emissions in a section/ trip and diving by total distance travelled. The Deviation Ratio (DR, sometimes called conformity factor) is also used to evaluate results. The DR is a measure of by how many times a vehicles emissions exceed the relevant Euro Standard. In this study-

$$Deviation\ Ratio = \frac{average\ section\ emission\ in\ g\ km^{-1}}{Euro\ 6\ standard\ (0.08\ g\ km^{-1})}$$

Results are presented as the mean and standard deviation.

Table 1. Specification of test vehicles

Vehicle ID	Year of manufacture	Engine displacement [ℓ]	Mileage at start [km]	NO_x after treatment
E1.5	2015	1.5	1675	EGR
E1.6	2014	1.6	2363	EGR
E2.2a	2012	2.2	6013	EGR
E2.2b	2012	2.2	225	EGR
E2.2c	2013	2.2	1164	EGR
E2.2d	2015	2.2	590	EGR
E2.2e	2015	2.2	531	EGR
L1.4a	2014	1.4	2245	LNT
L1.4b	2014	1.4	1463	LNT
L1.5	2015	1.5	1263	LNT
L2.0a	2015	2.0	1059	LNT
L2.0b	2014	2.0	2568	LNT
L2.0c	2014	2.0	745	LNT
L2.0d	2015	2.0	451	LNT
L2.0e	2015	2.0	1312	LNT

L2.0f	2013	2.0	2019	LNT
L2.0g	2014	2.0	640	LNT
L2.0h	2014	2.0	2563	LNT
L2.0i	2015	2.0	2910	LNT
L2.0j	2014	2.0	1000	LNT
L2.0k	2014	2.0	1492	LNT
L2.0l	-	2.0	742	LNT
L2.0m	2014	2.0	4356	LNT
L2.0n	2015	2.0	4276	LNT
L2.0o	2014	2.0	1696	LNT
L2.0p	2014	2.0	4192	LNT
S1.6a	2014	1.6	2406	SCR
S1.6b	2014	1.6	544	SCR
S1.6c	2013	1.6	2178	SCR
S1.6d	2014	1.6	2028	SCR
S2.0a	2015	2.0	2502	SCR
S2.0b	2015	2.0	2093	SCR
S2.0c	2014	2.0	2567	SCR
S2.0d	2014	2.0	5270	SCR
S2.0e	2013	2.0	4061	SCR
S2.0f	2014	2.0	3842	SCR
S2.0g	2015	2.0	1184	SCR
S3.0h	-	3.0	1861	SCR
S3.0i	-	3.0	1393	SCR

- data not available

PEMS testing

The on- road tail pipe emissions were measured by Emissions Analytics using a SEMTECH-DS, developed by Sensors Inc (Sensors Inc 2010). SEMTECH-DS PEMS measurements fulfil official emissions testing requirements of the EU and

US and have been found to be accurate within the range of lab based testing methods (EPA 2008b; EPA 2008a; EC 2011; Weiss et al. 2012).

The SEMTECH unit includes multiple gas analysers, a GPS receiver (recording vehicle speed, latitude, longitude and altitude), exhaust flow meter and an interface for connection to the vehicles on- board engine diagnostics (OBD) port. Non-Dispersive Ultraviolet (NDUV) is used to measure nitric oxide (NO, reported as NO_2) and NO_2 simultaneously and separately with NO_x calculated as the sum of both (Sensors Inc 2014). For further detail on PEMS installation and SEMTECH-DS see (Hu et al. 2012; Weiss et al. 2012; Kousoulidou et al. 2013). Leak tests along with zero and span calibration tests were performed before and after each trip in line with recommendation.

PEMS are powered by external batteries meaning engine operation is not effected apart from by additional weight. The PEMS weigh 95kg (equivalent to an additional passenger) the drivers then bring the additional weight to 220kg. This weight is uniform for each test. Additional weight may bias results by affecting the power to mass vehicle ratio (Weiss et al. 2012) and potentially increasing CO_2 emission by up to 3%; it is reasonable to assume a similar margin for NO_x (Fontaras & Samaras 2010; Weiss et al. 2012).

COPERT
The latest COPERT (4v11) speed dependant emission factors were used to generate an average COPERT emission estimate for each trip. This is done using the road links method previously used by the INCERT model (Kousoulidou et al. 2013) whereby the PEMS speed profile is split into equal one km lengths, the average speed of each link calculated and the relevant speed dependent emission factor applied to each length. In turn this generated a COPERT emissions profile from which an average can be taken. This process was performed by specialised software created by the authors and the iMove model (Valiantis et al. 2007).

5 Results and Discussion of PEMS data

Figure 1 shows the trip average NO and NO_2 emissions of each vehicle, there was huge variability within the results. 2 vehicles (S2.0e, L2.0b) met the Euro 6 limit of 0.08 g km^{-1}, a further 2 vehicles (L2.0a, S2.0b) were within 10% of the Euro 6 limit. This shows that with current technology both LNT and SCR (when used in conjunction with EGR) are capable of meeting the Euro 6 emission limit during real world driving. The mean trip average emissions (0.36 ± 0.36 g NO_x km^{-1}) correspond to a DR of 4.5, the highest deviation ratio was 22 by vehicle S3.0h. 11 vehicles met the not-to-exceed limit (DR < 2.1).

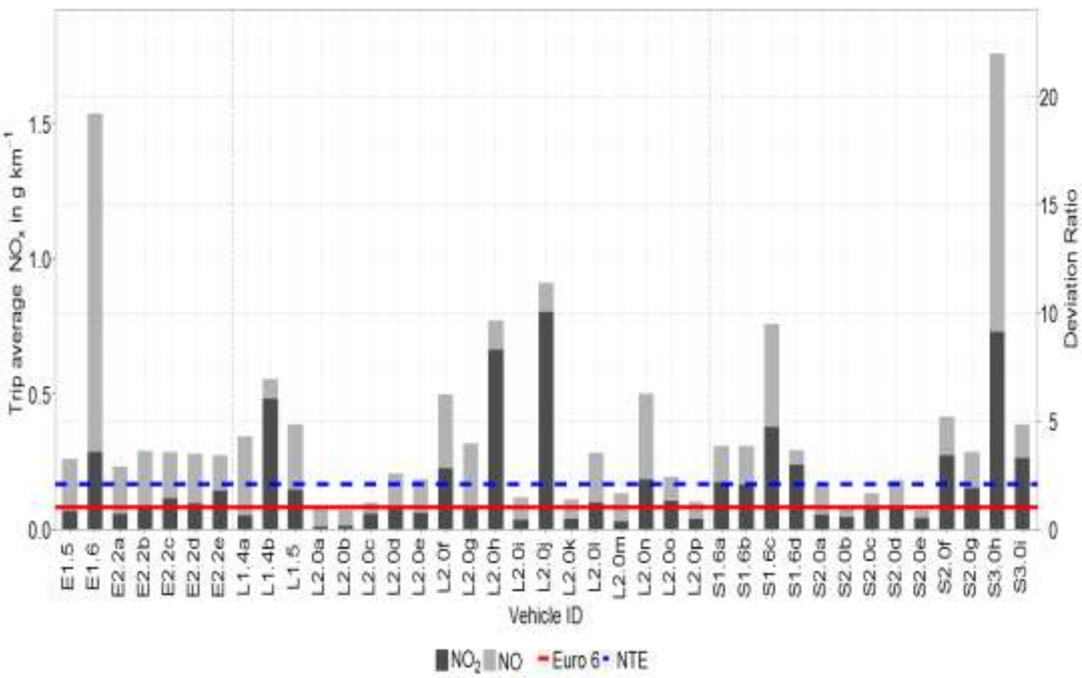

Figure 1. PEMS measurements showing trip average NO_x and NO_2 for 39 Euro 6 diesel vehicles

Of the 39 vehicles, 22 exceeded the Euro 6 NO_x standard with NO_2 (dark grey) emissions alone (i.e. trip average over 0.08 g NO_2 km^{-1}). The PEMS average NO_2 emission was 0.17 ± 0.19 g NO_2 km^{-1}, over double the Euro 6 limit for total NO_x. Our results show high values of absolute NO_2 emissions with the highest being 0.801 g km^{-1}, ten times the Euro 6 limit for total NO_x. The average fNO_2 of the trip was 44 ± 20%. Of the 11 vehicles that met the NTE limit one (S2.0c) exceeded the Euro 6 limit with NO_2 alone, this highlights the problem with regulating NO_x levels whilst having no legal limit for NO_2.

Comparison with COPERT

In Figure 2 we compare the PEMS measurements (red) for NO_x and NO_2 to the COPERT estimates (green). As expected (due to all trips having very similar speed and distance characteristics) COPERT's estimates display very little variation, this is because COPERT aims to provide an average for the fleet. The PEMS averages were higher in some instances and lower in others but overall were higher. The PEMS average NO_x was 1.6 times the COPERT average of 0.23 ± 0.01 g NO_x km^{-1} (DR=2.9), the average NO_2 estimate, 0.07 ± 0.003 g NO_2 km^{-1}, was 2.5 times lower that the PEMS measured average. The PEMS average fNO_2 (44 ± 20%) was higher than the 30% assumed by COPERT.

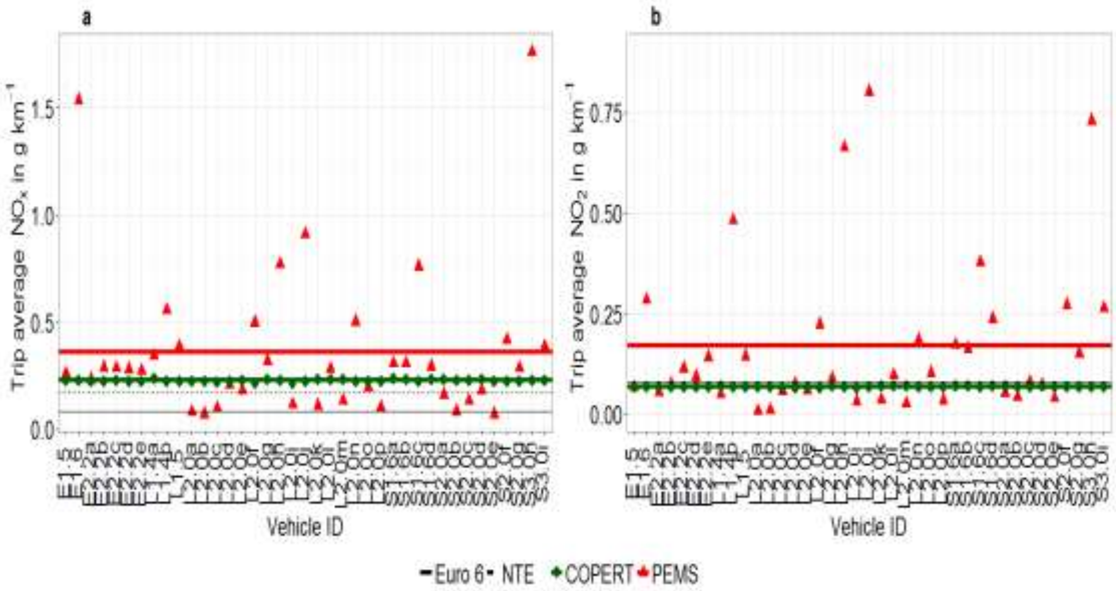

Figure 2. Comparison of COPERT 4v11 projections to PEMS measurements for NO_x (a) and NO_2 (b). Green line is COPERT average, red line is PEMS average

Within the results 5 vehicles particularity stand out as the worst; L2.0h, S3.0h, E1.6, S1.6c and L2.0j. These vehicles all have on road emissions higher than 0.63 g NO_x km^{-1} (the average COPERT 4v11 emission factor for Euro 5). We find that when these 5 are removed the PEMS average becomes much more aligned to the COPERT average estimate and the standard deviation is greatly reduced. This indicates that to effectively reduce NO_2 concentrations in hotspot urban areas policy makers should consider discriminating on the basis of actual on road emissions as opposed to Euro class.

Table 2. Effect of removing 5 worst vehicles

	PEMS average before	PEMS average worst 5 removed	COPERT average
NO_x	0.36 ± 0.36 g NO_x km^{-1} DR=4.5	0.25 ± 0.13 g NO_x km^{-1} DR=3.1	0.23 ± 0.01 g NO_x km^{-1} DR=2.9
NO_2	0.17 ± 0.19 g NO_2 km^{-1}	0.11 ± 0.10 g NO_2 km^{-1}	0.07 ± 0.003 g NO_2 km^{-1}

Urban and Motorway sections

The sections of the trip identified by GPS as urban and motorway driving are now analysed. When compared to their motorway counterparts urban NO_x emissions were 1.7 ± 1.0 times higher, though there was large variability and in some cases urban emissions were lower. Urban sections average NO_x emissions were 0.43 ± 0.42 g km^{-1}, DR = 5.4, motorway section emissions were 0.31 ± 0.37 g NO_x km^{-1}, DR = 3.9. The highest urban deviation ratio was 27.3 for vehicle S3.0h. fNO_2 was not significantly different (45 ± 21%) to the trip average.

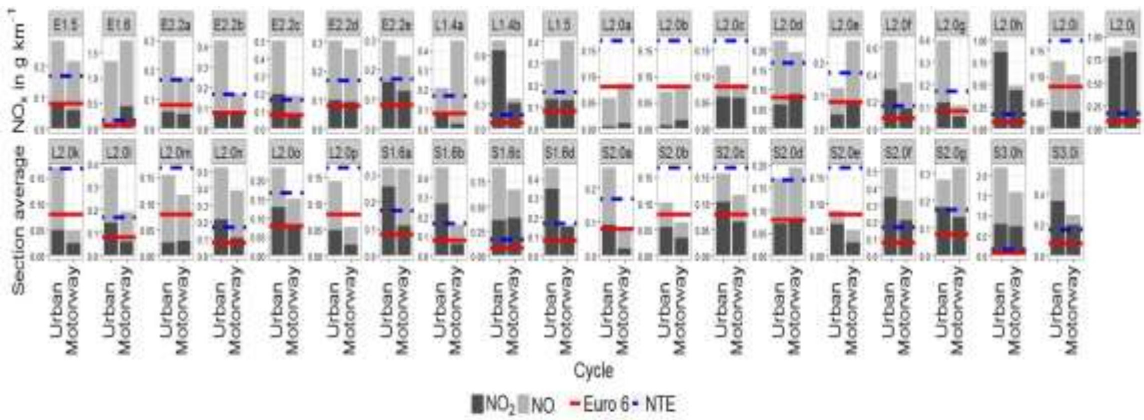

Figure 3. Comparison of urban and motorway trip average NO_x emissions (caution y-axis scale varies)

Modelling of implications for roadside concentrations

COPERT speed dependant emission factors, emissions regulation and the findings from the PEMS measurements have been used to inform six Euro 6 diesel NO_x emission factors and fraction primary NO_2 scenarios. These six scenarios have been modelled for the year 2030 by the UK Integrated Assessment model UKIAM (Oxley et al. 2013; Oxley. More specifically the Background, Road and Urban Transport modelling of Air quality (BRUTAL (Oxley et al. 2009)), which is the road transport high resolution (1km) module of the UKIAM designed to model roadside concentrations of air quality pollutants in urban environments. BRUTAL takes aggregated vehicle and technology dependant emissions factors for PM_{10} and NO_x from iMove and applies them spatially (using a bottom up approach).The scenarios have been chosen to represent the different deviation ratios of the Euro 6 diesel cars and also variation in the percentage primary NO_2.

Table 3. Description, average NO_x emissions factors and NO_2 fraction of scenarios

Average Euro 6 emissions…	**Scenario name**	**NO_x [g/km]**	**Average DR**	**f-NO_2**	
S1… meet the Euro 6 standard	**S1**	0.08	1.0	a – 0.3	b – 0.44
S2… meet the Euro 6c standard (as modelled by COPERT 4v11)	**S2**	0.10	1.3	a – 0.3	b – 0.44
S3… meet the 2017 not-to-exceed real world limit	**S3**	0.17	2.1	a – 0.3	b – 0.44
S4… as modelled by COPERT 4v11 speed dependant emission factors	**S4**	0.19	2.4	a – 0.3	b – 0.44
S5… are those found by the O'Driscoll et al. PEMS study	**S5**	0.34	4.5	a – 0.3	b – 0.44
S6… are those found by the O'Driscoll et al. PEMS study differentiating between motorway and urban driving	**S6** Motorway A, B,C	0.31 0.43	3.9 5.4	a – 0.3	b – 0.44

Results of modelling (2030)

Figure 4 shows the results of the scenario analysis; a, b, and c represent different background levels of NO_2 categorised as low (8-11μg m^{-3}), medium (13-16 μg m^{-3}) and high (18-22 μg m^{-3}). At each background level 5 different roads with different flows (in vehicles per day) were modelled, these are labelled with the corresponding flow in the legend (e.g F = 25000). All locations represent urban driving (i.e. A, B or C roads in built up urban or residential areas) and have the same traffic mix of diesel cars (44% diesel with 91% Euro 6). Each scenario has its own tile for each background level and the line joins Sa (fNO_2 = 0.3) to Sb (fNO_2 = 0.44). The steeper the positive gradient the greater the increase in annual mean roadside concentration between Sa and Sb.

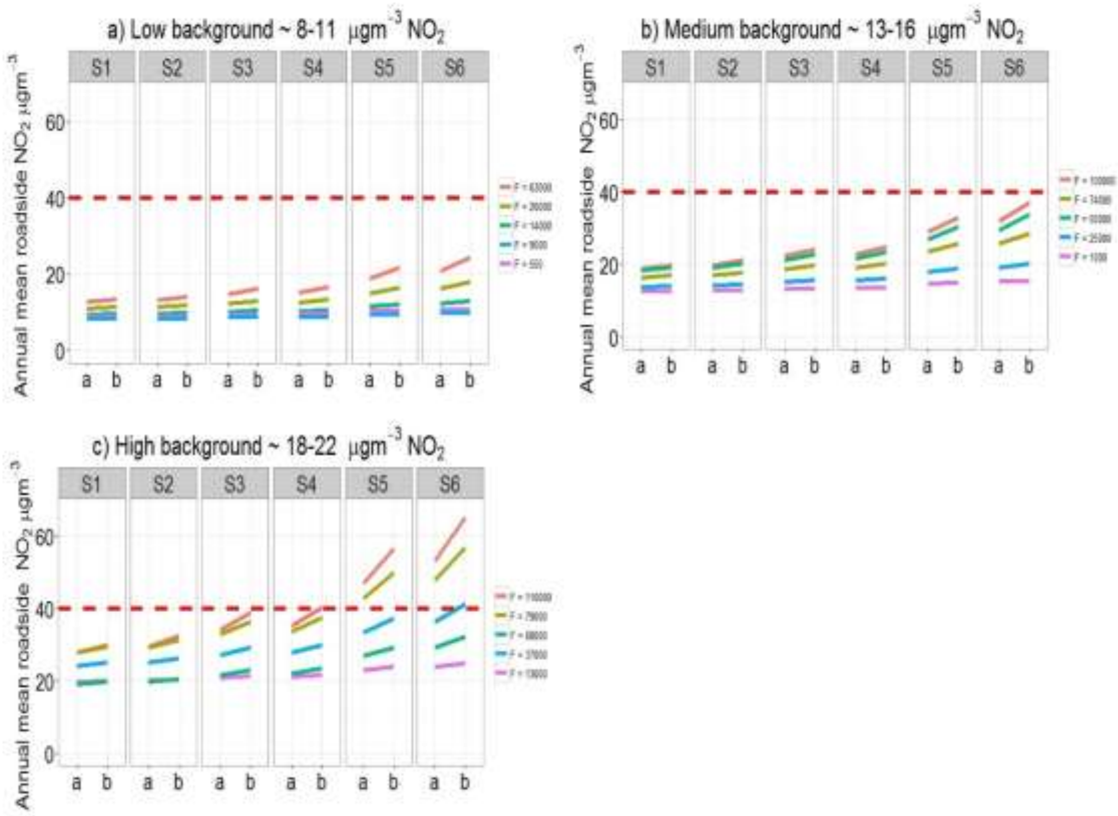

Figure 4. Roadside concentrations for roads with varying flows and a) low, b) medium and c) high backgrounds

Figure 4 shows an increase in roadside concentrations as the deviation ratio of the scenarios increases (from S1 – S6). As expected increase is most prevalent in locations with highest vehicles flows at higher background concentrations. This indicates the importance of lowering on road emissions of Euro 6 diesel cars by 2030.

At locations with low background and low flows there was little difference in roadside concentrations between the a) $fNO_2 = 0.3$ and b) $fNO_2 = 0.44$ scenarios. However in areas with higher background (Figure 4c) roadside concentrations significantly increased. The biggest increase was for the high background road with an 110,000 vehicle flow, annual mean roadside concentration between S6a and S6b increased by 8.4 µg m^{-3}.

6 Conclusion

Our study found that NO_x and primary NO_2 emissions from Euro 6 diesel passenger cars varied widely, the average NO_2 emission (0.17 ± 0.19 g km^{-1}) was over double the Euro 6 limit for total NO_x. The average fNO_2 was 44 ± 20%. Two vehicles (one deploying Lean NO_x Traps the other Selective Catalytic Reduction) were able to meet the Euro 6 emissions standard for NO_x (0.08 g km^{-1}) during real world driving.

The average NO_x emission of 0.36 ± 0.36 g km^{-1} equates to a deviation ratio of 4.5 which rose to 5.4 for urban driving. Urban section NO_x emissions were 1.7 ± 1.0 times those of motorway sections and had an average deviation ratio of 5.4. To effectively reduce NO_2 concentrations in areas with danger of limit value exceedance policy makers should consider discriminating on the basis of actual on road emissions as opposed to Euro standards of vehicles, as removal of the five worst polluting vehicles was required to reduce the average emissions to a level comparable with COPERT.

Trip average measured emissions were higher than COPERT estimates in the majority of cases. Real world emissions NO_2 emissions were on average 2.5 times COPERT estimates. The study average fNO_2 of 44% was higher than the COPERT assumption of 30%. Scenario analysis showed that this 14% variation in fNO_2 or Euro 6 diesels could lead to a 8.4 μg m^{-3} increase in annual mean roadside concentrations in 2030 for busy urban roads.

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