Air Quality
CONSULTANTS

Emissions of Nitrogen Oxides from Modern Diesel Vehicles

January 2016

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management & assessment

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1 Introduction

1.1 Defra provides road traffic emission factors that predict how fleet-averaged vehicle emissions will change year-on-year as newer, cleaner vehicles populate the national vehicle fleet (Defra, 2015). These emission factors are routinely used in air quality modelling. Historically, modelling carried out using these emission factors has predicted large reductions in nitrogen oxides (NOx) emissions and concentrations, but in recent years it has been found that these reductions have not been reflected in ambient measurements (Carslaw et al., 2011).

1.2 The reason for the disparity relates to the on-road performance of modern diesel vehicles. New vehicles registered in the UK have had to meet progressively tighter European type approval emissions categories, referred to as "Euro" standards. While the NOx emissions from newer vehicles should be lower than those from equivalent older vehicles, the on-road performance of some modern diesel vehicles has often been no better than that of earlier models (Carslaw and Rhys-Tyler, 2013).

1.3 Defra has attempted to account for the historical discrepancies using a new set of emission factors, published in 2014. There remains, however, some uncertainty regarding whether these emissions reflect the on-road performance of modern vehicles. This report considers recent evidence of on-road emissions performance and analyses it in the context of Defra’s vehicle emission factors.

1.4 The report only considers emissions of NOx from diesel vehicles. There is no evidence that emissions of other pollutants are affected by the issues discussed. Furthermore, there is good evidence that the on-road performance of petrol vehicles reflect the reductions imposed by the emission standards (TfL, 2015). Finally, this document only considers emissions of total NOx. No consideration is given to the function of NOx emitted as NO_2 (fNO_2) or how this may change over time.

2 Vehicle Emissions Standards

2.1 As explained in Section 1, new vehicles registered in the UK have to meet European type-approval emissions categories, referred to as "Euro" standards[1]. Compliance with these standards is demonstrated for new models/engines at the European level. The standards currently extend from ‘Euro 1’ to ‘Euro 6’ for cars and vans and Euro I to Euro VI for Heavy Duty Vehicles (HDVs)[2]. The Euro 1 and Euro I standards came into force in 1992. Euro VI has been mandatory for all new HDVs since January 2014. Euro 6 was intended to become a legal requirement for new vehicles in September 2015 but a derogation was agreed by the Department for Transport and Vehicle Certification Agency to allow the continued registration of Euro 5 vehicles until September 2016.

2.2 The emission standards for NOx are summarised in Table 1. It is important to recognise that the type-approval process does not dictate that vehicles should never emit more than the emission standards. Instead, the standards relate to the average emission over a very specific ‘test cycle’. At points on the test cycle, emissions will be much higher than this average. Similarly, a different test cycle will, almost by definition, give a different average emission. The emission standards thus only have direct meaning in the context of the test cycle over which they are tested.

2.3 Despite it not being possible to directly compare emissions across different test cycles, or indeed to compare the type-approval emission standards with real-world emissions, it is reasonable to expect that successive reductions in the type-approval emissions standards should have resulted in similar reductions in emissions over different test cycles and in the real world. As is noted in Section 1, for some diesel-engined vehicles, these reductions have not happened.

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[1] These standards were originally set in directive 70/220/EEC. They were subsequently replaced by directive 717/2007 for cars and vans and 88/77/EEC, later replaced by 05/55/EC for HDVs.

[2] Convention is to use Arabic numbers (i.e. 1,2,3 etc.) to denote the standards for cars and vans and roman numerals to denote the standards for HDVs.

Table 1: European Emissions Standards for NOx

Euro Standard		1/I	2/II	3/III	4/IV	5/V	6/VI
Passenger Cars (g/km)	**Petrol**	0.97[a]	0.5[a]	0.15	0.08	0.06	0.06
	Diesel		0.7[a]	0.5	0.25	0.18	0.08
Commercial Vehicles 1305–1760 kg (g/km)	**Petrol**	1.4a	0.6[a]	0.18	0.1	0.075	0.075
	Diesel		1.0[a]	0.65	0.33	0.235	0.105
Commercial Vehicles 1760-3500 kg (g/km)	**Petrol**	1.7a	0.7[a]	0.21	0.11	0.082	0.082
	Diesel		1.2[a]	0.78	0.39	0.28	0.125
HDVs (g/kwh)	**-**	8.0	7.0	2.0[b]-5.0	3.5	2.0	0.4[c] 0.46[d]

[a] NOx + Hydrocarbons.

[b] Enhanced Environmentally Friendly Vehicles only.

[c] Steady-state testing at the World Harmonised Stationary Cycle.

[d] Transient testing on the World Harmonised Transient Cycle.

Type-approval Test Cycles for Cars and Vans

2.4 Cars and vans are currently tested on a chassis dynamometer over the New European Drive Cycle (NEDC). This cycle, which is summarised in Figure 1, is fairly simple and does not ideally reflect the complexity of modern driving. A set of new, more complex, test cycles (the World Light-duty Test Cycles, or ‘WLTC’) are expected to be introduced in the next few years. One of the WLTC cycles is shown in Figure 2. There will also be a requirement to verify on-road emissions performance, known as Real Driving Emissions (RDE). Details of how the WLTC and RDE will be implemented are yet to be finalised.

2.5 Because the Euro 6 standard has been introduced using the NEDC cycle, but will eventually be updated to use the WLTC cycles and RDE, it is appropriate to consider two different sets of Euro 6 vehicles (commonly referred to as Euro 6a/b and Euro 6c). Phases A and B both use the NEDC cycle, while Phase C will use the WLTC cycles and RDE. While the value of the emission standard does not change between these phases, the on-road emissions between Euro 6a/b and Euro 6c are expected to be different; depending on how the European Commission implements WLTC and RDE and how the vehicle manufacturers respond to it.

Type-approval for HDVs

2.6 For HDVs, the engine is tested in isolation, in what is known as a ‘bench’ test. The same type of engine may then be used in multiple different types of HDVs, resulting in differing emissions. The current (Euro VI) regulatory test cycles for diesel engines are the World Harmonised Stationary Cycle (WHSC) and the World Harmonised Transient Cycle (WHTC). These tests were brought in with the introduction of the Euro VI standard to overcome some of the problems with earlier tests which did not reflect on-road performance. One of the key changes introduced by Euro VI regulations is the introduction of off-cycle testing. This follows a 'not-to-exceed' approach and ensures that emissions are controlled over the full range of speed and load combinations commonly in use.

2.7 Euro VI regulations also introduced in-use testing requirements that involve field measurements using Portable Emissions Measurement Systems (PEMS) (see Section 4). The testing is conducted over a mix of urban (0-50 km/h), rural (50-75 km/h) and motorway (> 75 km/h) conditions, with exact percentages of these conditions dependent on the vehicle category. The first of these in-use tests is conducted at the time of type approval emissions testing. Further tests are conducted as part of in-service conformity testing over the useful life of the vehicle. A minimum of three engines need to be tested and have a conformity factor ('CF')[3] under 1.5.

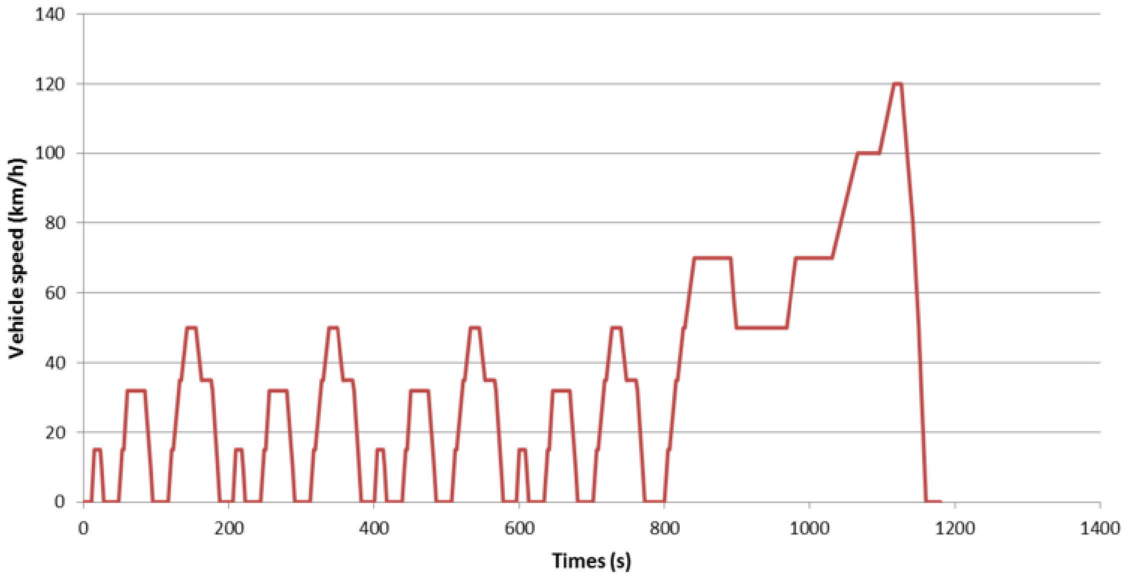

Figure 1: NEDC Test Cycle

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[3] The term 'conformity factor' or 'CF' is used throughout this document to denote emissions as a multiple of the respective standard. For example, if the emission standard is 0.08 g/km and a vehicle emits 0.16 g/km, it has a CF of 2.

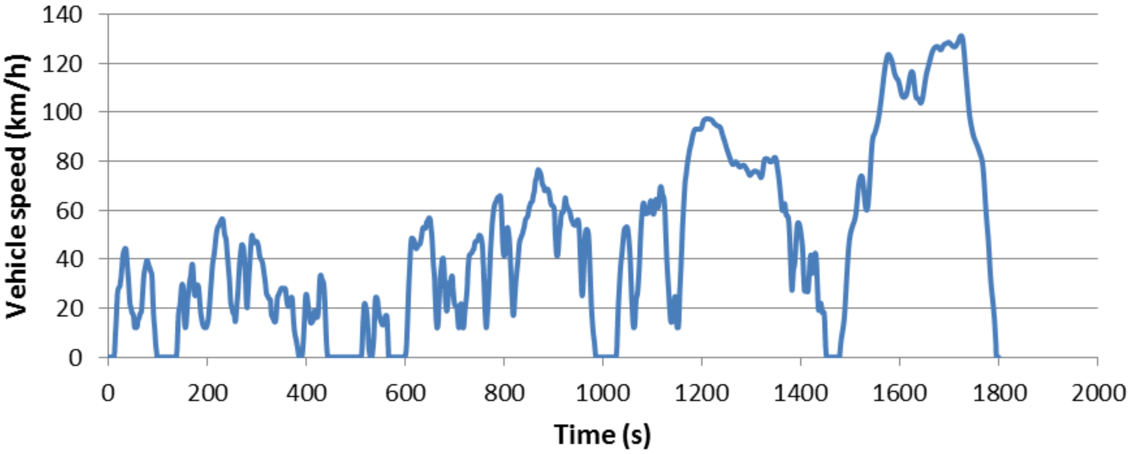

Figure 2: WLTC Class 3 Cycle

3 Emissions Control Technology

3.1 In order to understand why different vehicles might perform differently under different driving conditions, it is useful to have some understanding of how emissions are controlled. A number of different technological options are available to reduce tailpipe NOx emissions from diesel vehicles. These are summarised below. Different vehicles use different technologies, with factors such as cost, weight, size, and additional running costs determining the mix of technology used. As outlined below, different technologies perform well in different situations, which adds significantly to the complexity of determining how well 'typical' vehicles are performing.

3.2 Generally speaking, vehicles which command a higher sale price, and those which are larger, might be expected to carry more effective pollution control technology. It has been suggested that the additional cost of exhaust after-treatment might add as much as £10,000 to the cost of a HGV. On the same vehicle, the pollution control technology for Euro VI might weigh 80 kg more than that for a Euro V vehicle (TfL, 2015). For the same reasons, many of the earlier Euro 6 passenger cars, which tended to be large, premium models, were equipped with technology that is not being used for smaller cars.

3.3 The technological options outlined below are not mutually exclusive and are often employed in combination.

In-cylinder Control (ICC)

3.4 It is possible to achieve the Euro 6 standard for NOx with in-cylinder control strategies, i.e., adjusting the combustion process to keep engine-out emissions at a sufficiently low level. Low NOx emissions can be accomplished through a combination of Exhaust Gas Recirculation (EGR) (see below), compression ratio reduction, use of two-stage turbocharging, variable valve lift, combustion chamber reshaping, and a reduction of fuel injection pressure.

3.5 A shortcoming of relying solely on in-cylinder control strategies to control NOx relates to high-load operation. Engine-out NOx emissions are known to rise sharply with increased engine loads. Since the NEDC cycle does not include high-load events, a vehicle without specific NOx after-treatment could, in theory, be type-approved to a very stringent NOx emission standard and yet have very high emissions during acceleration or at higher speeds (ICCT, 2014).

Exhaust Gas Recirculation (EGR)

3.6 EGR systems work by routing a portion of engine-out exhaust gas back to the intake manifold. Since exhaust gas has a lower oxygen content than intake air, the effect of EGR is to lower the oxygen content in the cylinder, which leads to a cooler combustion process and a lower level of NO_X formation. Some EGR systems incorporate a heat exchanger to further cool the exhaust gas before recirculation.

3.7 A disadvantage of EGR is that the maximum exhaust recirculation rate that can be applied while maintaining stable combustion decreases with engine load. Therefore, EGR primarily reduces NOx formation during low load operation, and not during high-load events (such as during rapid acceleration) (ICCT, 2014).

Selective Catalytic Reduction (SCR)

3.8 SCR is an exhaust after-treatment technology that uses a catalyst to chemically break down NOx. This requires the injection of a reducing agent, which is stored in a separate tank that needs to be periodically refilled. Most SCR systems use an aqueous urea solution. Urea vaporizes in the exhaust to yield carbon dioxide and ammonia (NH_3). NOx emissions in the exhaust gas react with the NH_3 in the catalyst to yield gaseous nitrogen (N_2) and water.

3.9 The effectiveness of an SCR system is dependent on a range of design parameters, including catalyst material, catalyst volume, urea dosing/control strategy, and physical system layout. SCR efficiency typically falls dramatically at low exhaust temperatures, which tends to occur when demand on the engine is low. This is a particular concern since urban driving is often characterized by low-speed, stop-and-go conditions, which put a relatively low average load on a vehicle’s engine, resulting in a low temperature and thus low SCR efficiency. The performance of SCR systems can be improved with thermal management to increase exhaust temperatures.

3.10 Various aspects of system design affect the operating temperature thresholds of SCR, but the primary factor is the catalyst material. The (vanadium) catalysts used in virtually all European SCR systems have relatively poor low-temperature performance. This can be improved by optimizing the ratio of NO to NO_2 in the exhaust using an oxidation catalyst ahead of the SCR. Alternatively, it can be improved by increasing catalyst volume, or by using different NH_3 dosing strategies[4]. The latter strategy, however, may increase tailpipe NH_3 emissions in the absence of an effective ammonia slip catalyst downstream of the SCR catalyst (ICCT, 2014).

Lean NOx Traps (LNTs)

3.11 Lean NOx traps tend to be favoured for light duty applications. They combine oxidation and reduction catalysts with a NO_x adsorber that chemically binds and stores NOx under ‘lean-burn’ conditions (i.e., when engines operate with an excess of air as under normal conditions). When the NOx trap is saturated, it needs to be regenerated by switching engine operation to fuel-rich operation for a few seconds. This causes the stored NOx to be desorbed and subsequently reduced to N_2 and O_2 using a conventional three-way catalyst.

3.12 Unlike SCR systems, LNTs do not require an external reducing agent, and they are also generally lighter and more compact than SCRs. However, the periodic regeneration of the trap imposes a small fuel penalty.

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[4] This may, in turn, increase tailpipe NH_3 emissions in the absence of an effective ammonia slip catalyst downstream of the SCR catalyst.

3.13 Two of the most challenging aspects of LNT integration in a vehicle are establishing engine operating conditions for adequate NOx reduction while minimizing fuel consumption, and dealing with cold start conditions. Typical fuel penalties are in the order of 2–4%. Reducing light-off temperatures during cold starts can be accomplished through thermal management, or with delayed injection during start-up periods. Another problem with LNTs is that the NOx storage capacity of the catalyst is fixed. This means that, as engine load increases, the frequency of trap regeneration events also needs to increase, and this carries additional fuel penalties (ICCT, 2014).

4 Test Methods

4.1 This section briefly outlines the methods which are typically used to measure vehicle emissions.

Dynamometer Tests

4.2 As mentioned in Section 2, cars and vans are tested on a chassis dynamometer for type-approval testing. HGV engines are 'bench tested', again using a dynamometer. Dynamometer tests can be carried out over any conceivable drive cycle, and not just the test cycles discussed in Section 2. Drive cycles are often generated by a laboratory or as part of a specific campaign. TfL has developed its own, London-specific, drive cycles which it recreates on a chassis dynamometer. It developed some of these cycles by driving, at different times of day, a route which takes in Marylebone Road, Finchley Road, the North Circular, and Uxbridge Road.

PEMS

4.3 Portable Emissions Measurement Systems (PEMS) are carried in and on the vehicle being tested. Vehicles are then driven on open roads. Routes are typically planned in advance to represent the type of conditions desired for the test, but driving conditions nevertheless remain real and unpredictable.

4.4 As noted in Section 2, PEMS tests for HDV engine type approval are carried out on a single type of vehicle. This vehicle is selected based on the most representative vehicle type in which the engine is used. This means that the engine used in an inner-city bus may be tested in a long-haulage HGV on a long-haulage test route. The HDV type-approval PEMS test results are analysed over 'averaging windows', which have a comparable duration to the original test cycle. In order to make the tests comparable with the laboratory test, exclusion criteria were introduced for certain windows. Windows are excluded where the average engine power is less than 15% of the maximum power. This means that when a vehicle drives at lower speeds (e.g. in heavy urban traffic) data are not taken for evaluation for in-service conformity. Furthermore, 10% of the windows with the highest NOx emissions are also excluded. Thus, while PEMS tests for HDV type approval are unarguably invaluable for checking in-service conformity, they should not be taken as representing real-world emissions. The details of the PEMS requirement for car and van type approval have not yet been specified.

4.5 PEMS tests carried out for other purposes (i.e. not as part of type approval) use various route types, averaging windows, and validation requirements and thus results from different organisations are unlikely to be directly comparable.

SEMS

4.6 Smart Emission Measurement Systems (SEMS) use smaller, lower-cost and lower-accuracy measurement equipment than those used by PEMS. While the method is less accurate than PEMS, it is practical to carry out more SEMS tests than PEMS tests. As with PEMS, vehicles are driven on open roads and thus tests have the potential to represent real driving conditions.

Remote Sensing

4.7 In remote sensing tests, equipment is set up at a fixed point at the side of the road (typically on a slight incline to ensure that vehicles are under load). As a vehicle passes, its speed and acceleration are recorded, as well as the vehicle license plate (which can be used to identify the age and Euro class of the vehicle, as well as other attributes such as engine technology). The gas plume left behind the vehicle is then tested through optical analysis for the presence of a range of pollutants, often including NO_2, NO, and CO_2.

4.8 If successive emission standards had driven a reduction in on-road vehicle emissions, it would be reasonable to expect that the exhaust plume of newer vehicles would have a lower NOx/CO_2 ratio than that of older vehicles (CO_2 emissions per vehicle have not fallen appreciably). The absence of such a pattern has been used to argue that there have been no reductions in on-road NOx emissions for certain vehicle categories. By estimating CO_2 emissions in g/km (based on standard models), it is also possible to calculate NOx emissions in g/km; however because of uncertainties in the CO_2 emissions models, these results remain uncertain.

4.9 A clear advantage of remote sensing is that a very large number of vehicles can be recorded in a relatively short period of time. However, remote sensing data only identifies a snapshot of each vehicle tested. Monitoring locations are specifically chosen to represent specific driving patterns and thus do not represent conditions over a full drive cycle. Furthermore, since the tests require quite a lot of highly visible instrumentation, the test itself may alter driving behaviour.

4.10 Given that Euro VI and Euro 6 vehicles are heavily reliant on pollution control technology which might behave very differently in different settings (see Section 3), the fact that remote sensing is spatially-limited may be a bigger issue for these vehicles than for earlier models.

5 Evidence of Real-world Performance

5.1 There is a growing body of evidence collected by various organisations which indicates how vehicles which conform to recent type-approval standards have performed under more representative driving conditions. The studies of principal relevance are summarised briefly below. Key statistics from the various studies are also set out in Table 2 and Table 3.

Emissions Analytics (2015)

5.2 Emissions Analytics has run PEMS tests on a large number of vehicles (c.a. 200-250 passenger cars per year in the EU with similar numbers in the US). EU testing is predominantly carried out in London on a proprietary route intended to reflect typical driving conditions. Each test takes between 2.5 and 3 hours. Vehicles tested typically have at least 2,000 km on the odometer. In its November 2015 bulletin (Emissions Analytics, 2015), Emissions Analytics issued Figure 3, which shows a clear improvement in emissions from Euro 6 diesel cars when compared with Euro 5 vehicles.

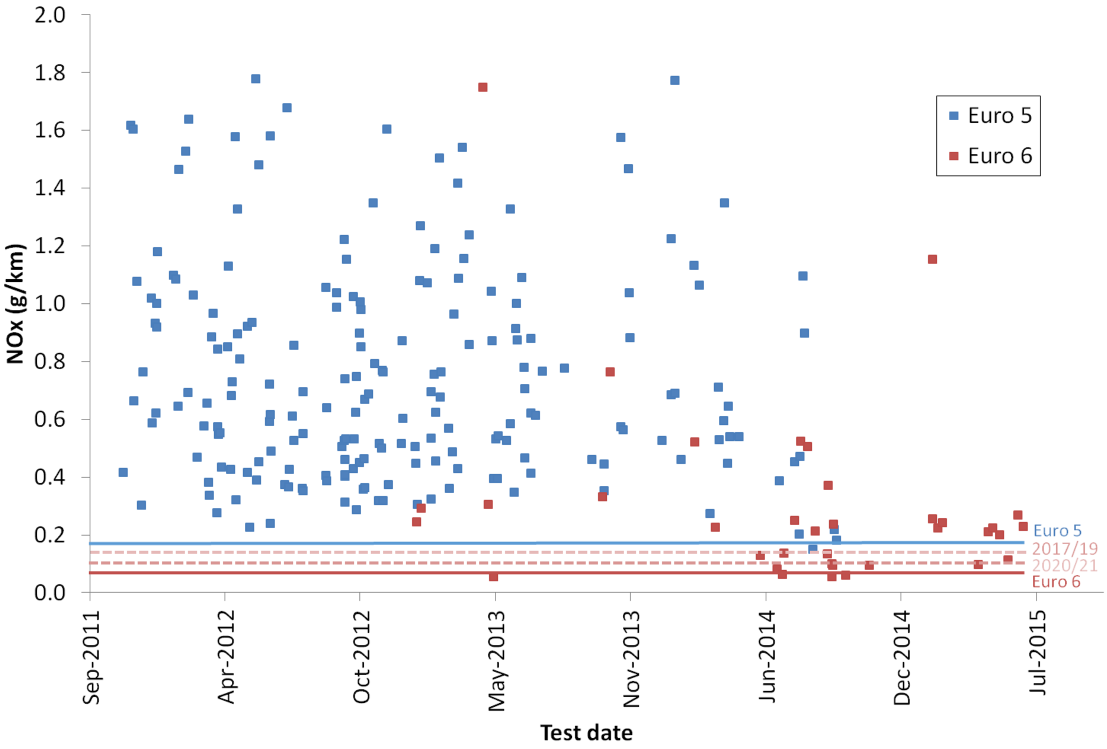

Figure 3: Emissions Analytics PEMS Results for Euro 5 and Euro 6 Diesel Cars issued in November 2015 (Taken from Emissions Analytics, 2015)

Supplied by www.emissionsanalytics.com

TfL (2015)

5.3 Transport for London has measured NOx emissions from 9 Euro 6 diesel cars, using a chassis dynamometer and its London-specific drive cycles (see Paragraph 4.2). The results have been presented both for the test average, and also (for three of the Euro 6 vehicles and three Euro 4 cars for comparison) by averaging the emissions across specific speeds. The results have been compared with the emissions from the European Environment Agency's COPERT 4[5] model. The results are reproduced in Figure 4. They show a large reduction in real-world emissions between Euro 4 and Euro 6, but that the on-road performance of Euro 6 vehicles is similar to the predicted performance of Euro 4 vehicles.

5.4 Strictly speaking, the COPERT 4 speed-emission functions relate to drive-cycle average speeds and not instantaneous averages and so (Figure 4) is not a like-for-like comparison. This point is, however, largely academic since the COPERT 4 functions are usually treated as relating to a specific section of road rather than a drive-cycle average in any event.

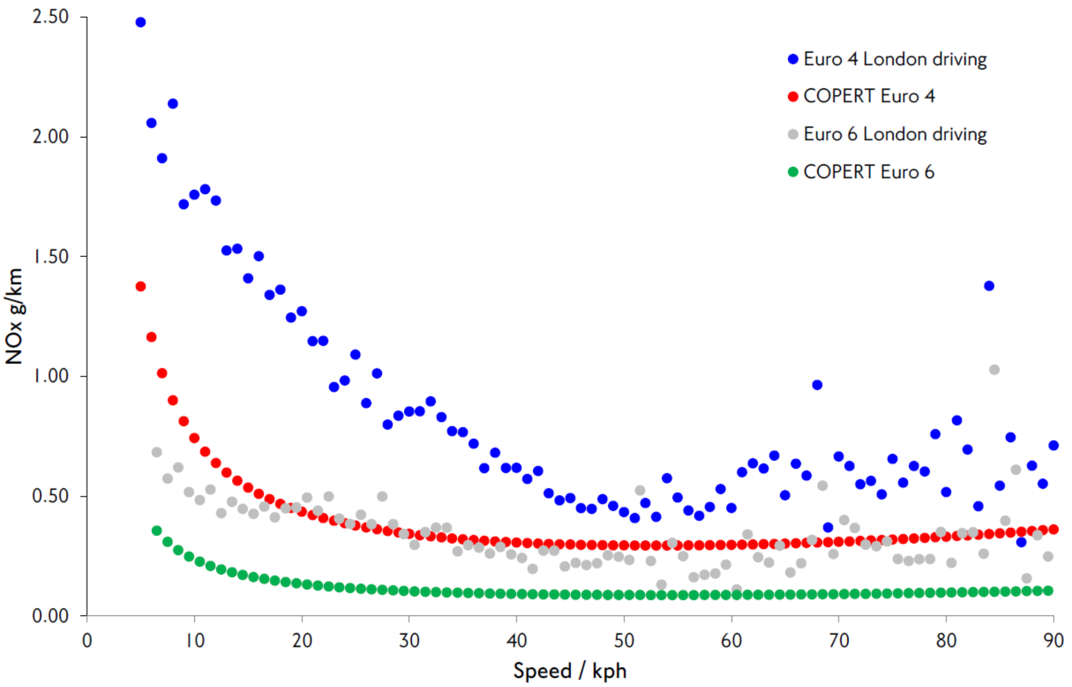

Figure 4: Comparison of London Emissions Functions with COPERT 4 Functions (diesel cars) (taken from TfL, 2015)

5.5 TfL also presented results for HDVs. Drive-cycle average data were presented for four Euro VI vehicles. These showed that, under 100% payload, emissions NOx ranged from 0.4 to 1.2 g/km. Unladen emissions were higher, ranging from 0.7 g/km to 2.7 g/km. The increase in unladen emissions probably reflects poorer SCR performance at lower temperatures (see Paragraph 3.8). TfL also presented speed-specific emissions for two Euro V and two Euro VI

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[5] The authors did not specify which version of COPERT 4 was used (v10 or v11), which will have some impact on the findings.

vehicles (Figure 5). In each case, Euro VI emissions were lower than the equivalent Euro V emissions.

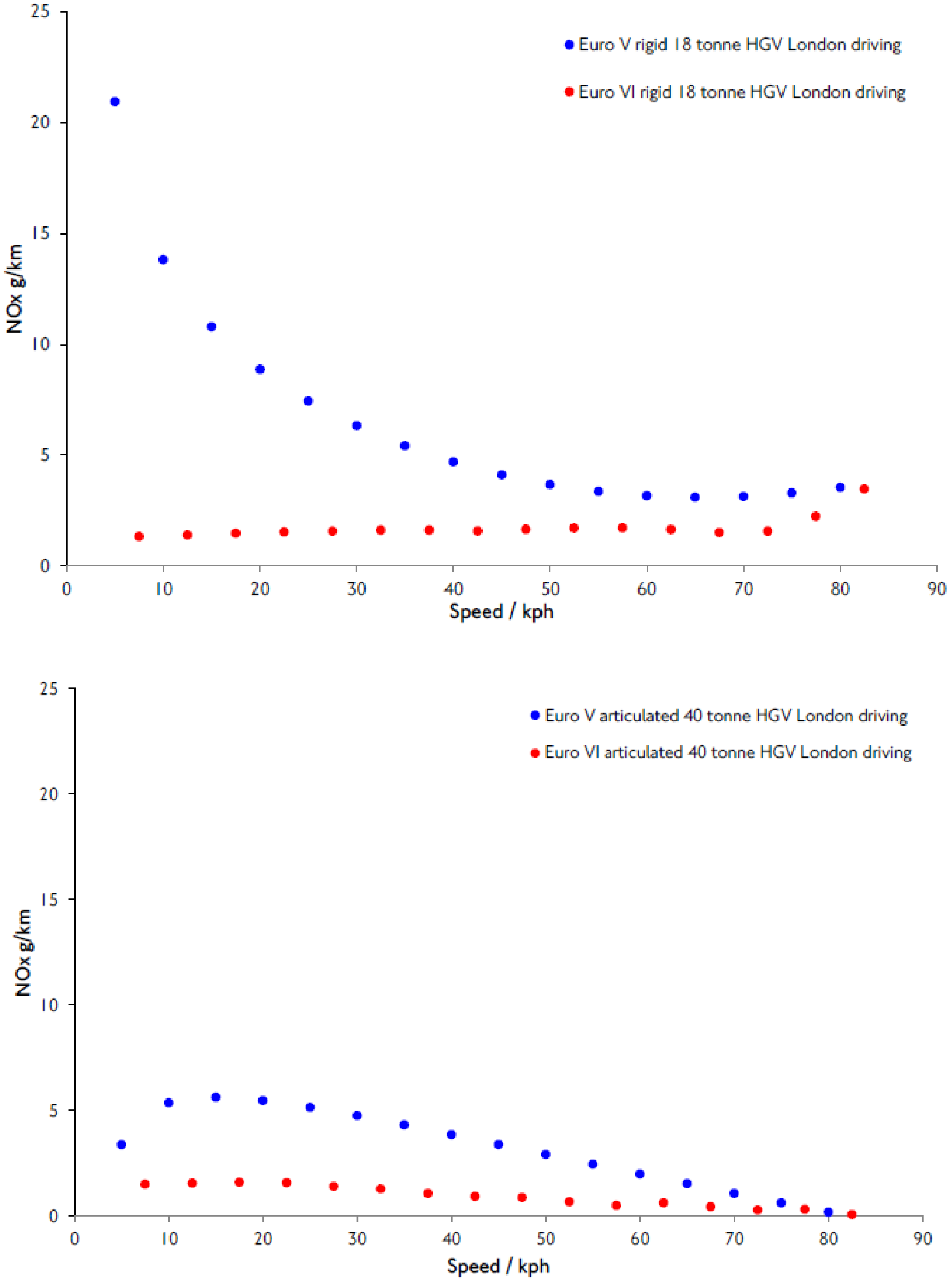

Figure 5: Comparison of Euro V and Euro VI Emissions Over a Range of Load Speeds (each row of dots refers to one vehicle) (TfL, 2015)

Tu GRAZ (2013)

5.6 The Swiss-German Handbook of Emissions Factors for Road Transport, developed in part by Tu Graz, is based on measurements from more than a thousand cars spanning Euro 0 to

Euro 6. Three phases of the Common Artemis Driving Cycles (CADC) were simulated using the Passenger Car and Heavy Duty Emission Model (PHEM); based on engine maps collected from 50 Euro 5 diesel cars and 19 Euro 6 diesel cars. Only hot-start factors were reported. Emissions were found to increase slightly from Euro 4 to Euro 5, with this worsening at higher speeds and engine loads; in fact no significant improvement was observed between Euro 1 and Euro 5 diesel cars. A reduction of more than 50% was, however, observed between Euro 5 and Euro 6 diesel cars (Figure 6)[6].

5.7 Four Euro VI HDVs were tested on a chassis dynamometer and one Euro VI engine was bench-tested. All tested vehicles and engines were found to have very low NOx levels in all operating conditions. At medium and high engine loads, emissions met the WHTC emissions limit. On cycles with low average engine loads (normalised engine power around 10%[7]) the results were variable; with only some models meeting the WHTC limit. Testing was also carried out at 5% engine load and below, and this showed very high emissions but the authors note that these conditions are of minor importance. Overall, it was felt by the authors that the reduction in fleet-average Euro VI emissions when compared with Euro V emissions was at least commensurate with the reduction in type approval limits (i.e. a 77% reduction based on the WHTC limits).

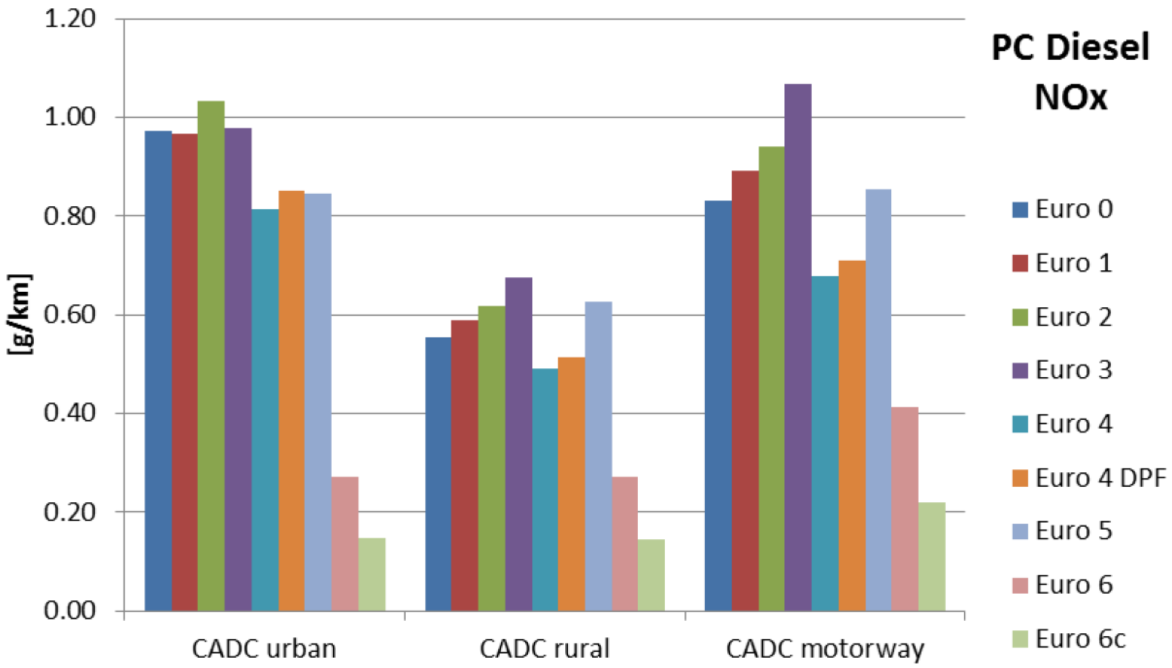

Figure 6: **NOx Emission Factors for Cars Derived by Tu Graz (taken from Tu Graz, 2013)**

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[6] Using these results to comment on the COPERT 4 functions introduces a circularity, since recent updates to COPERT 4 make use of these same data.

[7] For a typical 40 ton truck operated on a flat motorway an average engine power of about 25% to 35% of rated power can be assumed. In urban driving these values are in the range of 10% to 20%.

TNO (2015)

5.8 Tests carried out on passenger cars by TNO included dynamometer tests, PEMS and SEMS. The study was carried out over three phases. Phase 1 used four, pre-production Euro 6 diesel cars on a dynamometer. In the CADC cycle, average emissions ranged from 0.08 g/km to 0.27 g/km. In Phase 2, six production diesel cars using various emissions control technologies were tested on a dynamometer as well as on the road. NOx emissions varied from 0.01 g/km to 0.8 g/km, with the majority of vehicles emitting more than 0.4 g/km. Phase 3 focused on six production vehicles equipped with both EGR and SCR. The real-world emissions were measured at between 0.15 g/km and 0.85 g/km.

5.9 Phase 3 of the TNO study went on to conclude that the settings of the engines and the EGR systems have more influence on NOx emissions than the settings of the SCR, and that low real-world NOx emissions are possible with effective settings of the engine and the EGR system in combination with an effective SCR system. It also noted that the urea tanks in nearly all the vehicles tested were too small for the SCR to reduce emissions below 0.08 g/km in real-world conditions.

TNO (2104)

5.10 TNO also looked at HGV emissions using both PEMS and SEMS. The analysis was separated into ‘long-haulage’ vehicles, and those that operate typically in an urban environment. Results were analysed in two ways: first according to the formal in-service conformity checking procedure, and second using an approach developed by TNO to be more representative of real-world emissions.

5.11 In terms of the in-service conformity tests, all Euro VI engines were found to have CFs below 1.5, with some CFs as low as 0.1-0.2 (Figure 7). This contrasts with measured CFs up to 5 for the Euro V engines tested (i.e. 5 times the Euro V standard) (Figure 8).

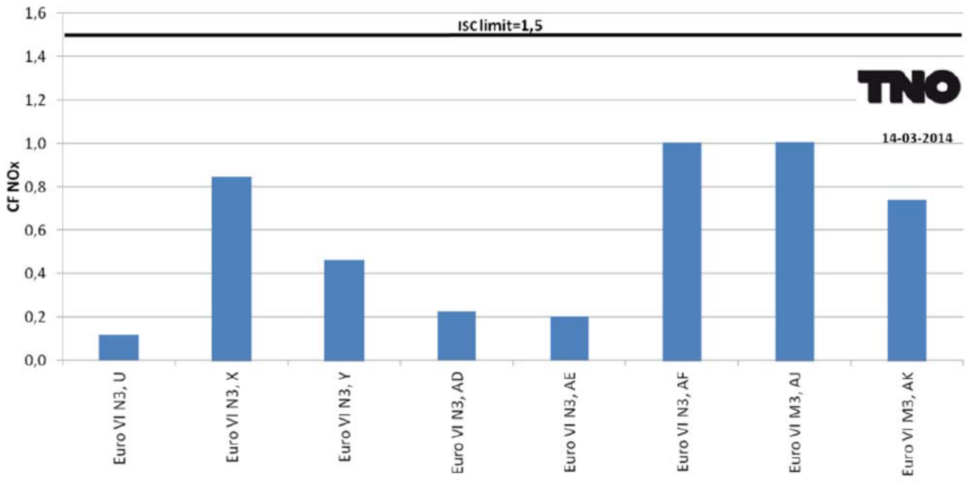

Figure 7: Conformity Factors (90th Percentile) for Euro VI NOx Emissions (taken from TNO, 2014)

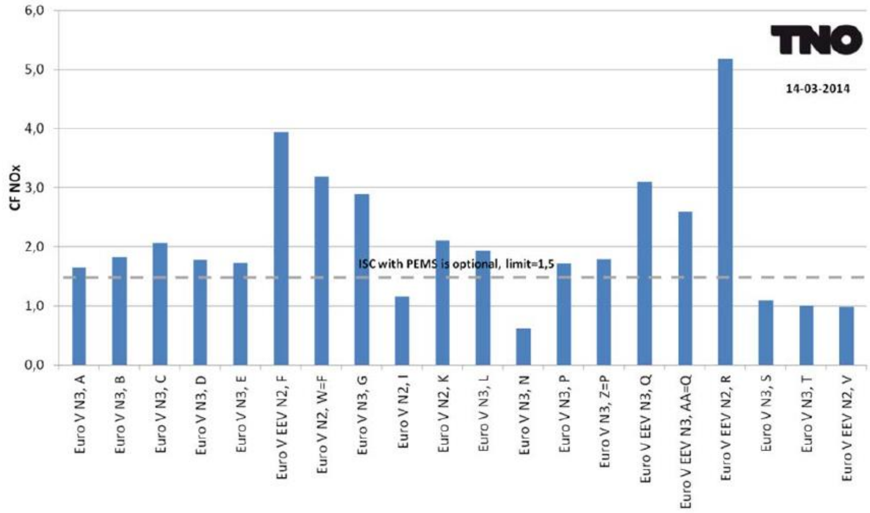

Figure 8: Conformity Factors (90th Percentile) for Euro V NOx Emissions (taken from TNO, 2014)

5.12 The picture for real-world emissions was less clear-cut. The six Euro VI long-haulage (extra-urban) vehicles showed very low NOx emissions compared with Euro V vehicles at both high and low driving speeds (Figure 9). The two urban vehicles also showed an improvement compared with Euro V, but did not perform as well as the long-haulage vehicles (Figure 10). Emissions were shown to decrease with higher speeds and higher payloads.

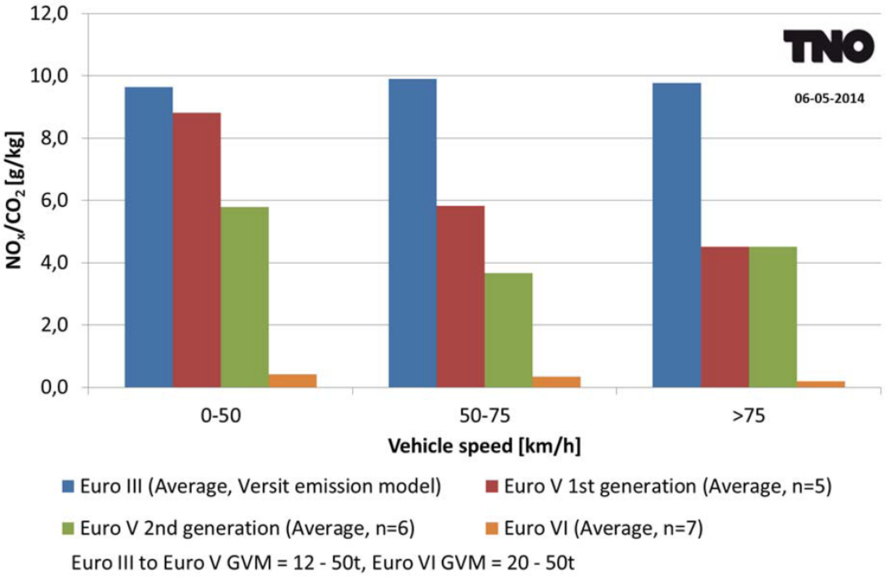

Figure 9: Real-world NOx from Extra-urban HDVs Over Different Speed Ranges (taken from TNO, 2014)

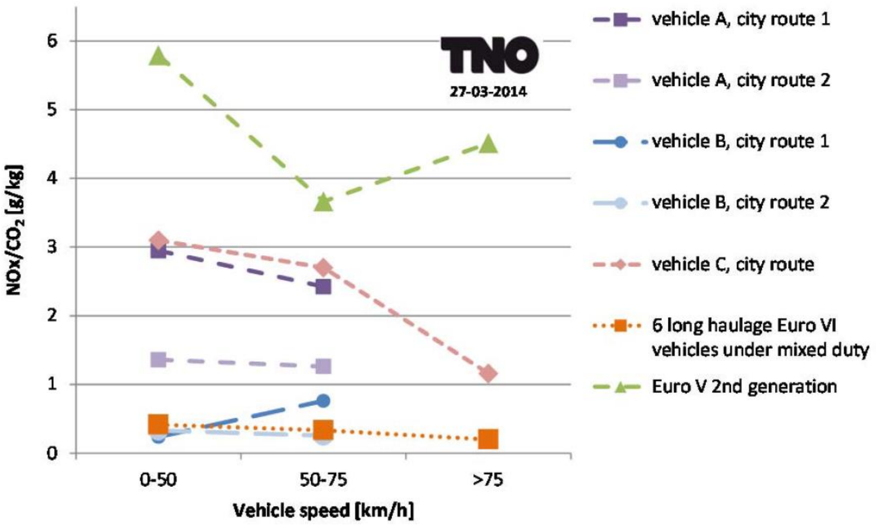

Figure 10: **Real-world NOx from Euro VI Urban HDVs (also showing average Euro V and average long-haul Euro VI emissions) (taken from TNO, 2014)**

ADAC (2015)

5.13 German motoring organisation ADAC has tested 36 Euro 6 diesel cars on a dynamometer, using both the WLTP cycle and its own proprietary test cycle. Its results are summarised in Figure 11. The worst performing vehicle emitted 20 times the Euro 6 standard over the ADAC proprietary test cycle. Only one of the vehicles tested met the standard under both WLTP and the ADAC cycle. A clear differentiation was observed with vehicles incorporating SCR performing best on average.

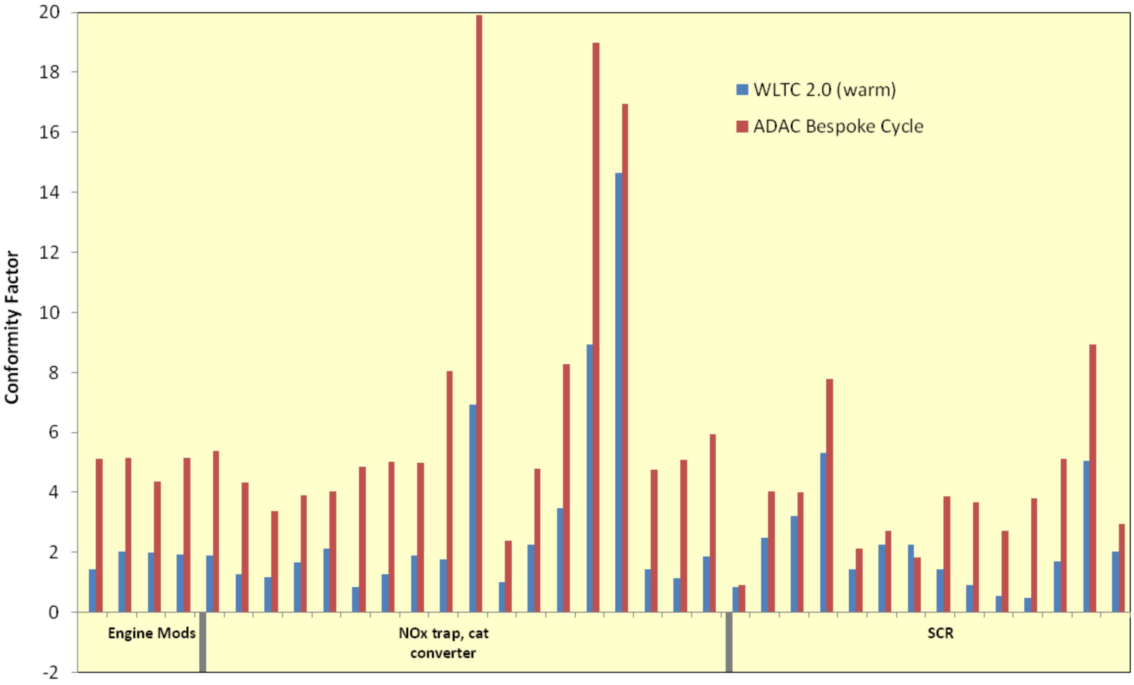

Figure 11: **CFs for 36 Diesel Cars Tested by ADAC (derived from ADAC (2015))**

ICCT White Paper (2014)

5.14 The International Council on Clean Transportation compiled data from several PEMS studies carried out in various locations. A total of 12 Euro 6 diesel passenger cars were tested; the majority of which were equipped with SCR.

5.15 The ICCT study combined tests using different routes and different driving styles. In some cases the vehicles were driven repeatedly over the same route, but for others, only a single PEMS trip was available. Data were analysed in various different ways, with the characteristics of each drive cycle examined. One way in which the data were analysed is by defining emissions windows based on CO_2 emissions (i.e. not based on duration or distance). Figure 12 summarises some of the results. It shows that, for the most part, the tested vehicles were performing at relatively low CFs, but that some very large exceedences occurred over a few of the windows considered.

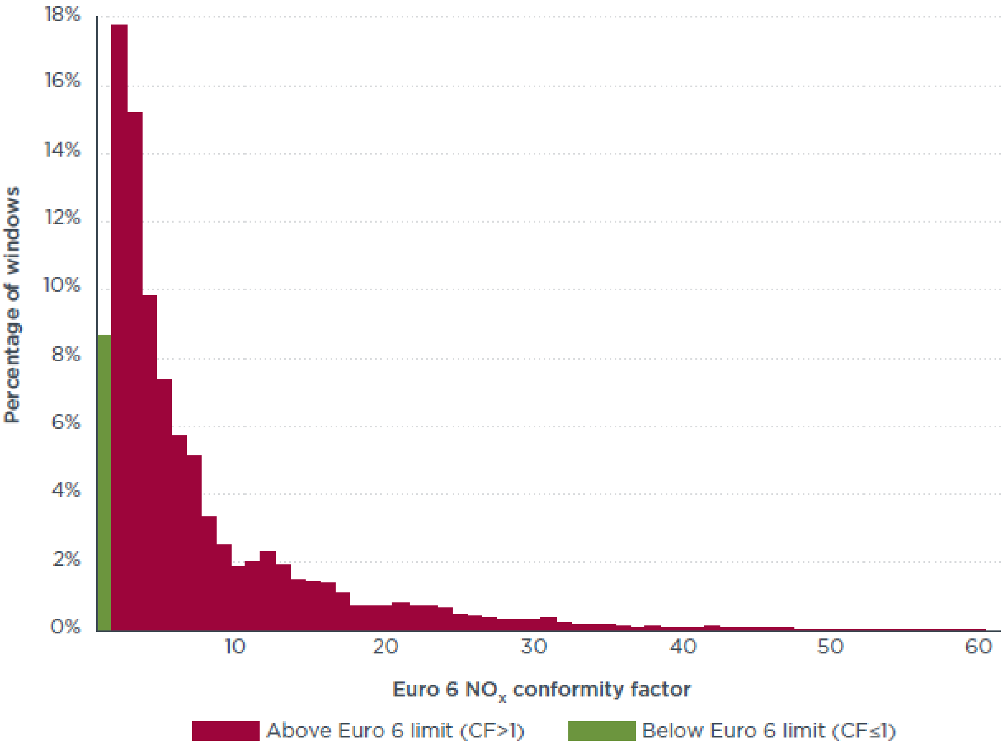

Figure 12: Driving Windows vs CF (ICCT, 2014) [8]

Weiss *et al*., (2012)

5.16 Weiss *et al.* analysed the emissions from one Euro 6 (SCR) and six Euro 4 to Euro 5 diesel cars using PEMS. Emissions from the Euro 6 car were considerably lower than those from the Euro 4 to Euro 5 cars, but all cars exceeded their standards by between 164% (Euro 6) to 294% (Euro 5).

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[8] This figure includes three US (Tier 2 Bin 5/ULEV II) vehicles as well as 12 Euro 6 vehicles. Windows are based on the amount of CO_2 emitted over a given time period.

Carslaw and Rhys-Tyler (2013)

5.17 Carslaw and Rhys-Tyler (2013) carried out remote sensing in central and suburban locations around London in 2012. A total of 93,000 observations were made, resulting in 68,000 usable records. No Euro 6 or Euro VI vehicles were tested. Some of their results are shown in Figure 13.

5.18 Clear reductions in NOx emissions from petrol vehicles were observed with each new Euro class introduction. There were no significant reductions in NOx emissions from diesel vehicles with each Euro class. The highest emissions were recorded for Euro 2 to Euro 3 diesel cars. Euro 5 diesel cars emitted around 25% less than Euro 2 to Euro 3 cars, and a similar level to pre-euro diesel cars.

5.19 Diesel LGVs were observed to emit between 4% and 9% more NOx than equivalent passenger cars. The results for HGVs showed that NOx emissions decreased by 20% since Euro II, but then remained stable from Euro III to Euro V.

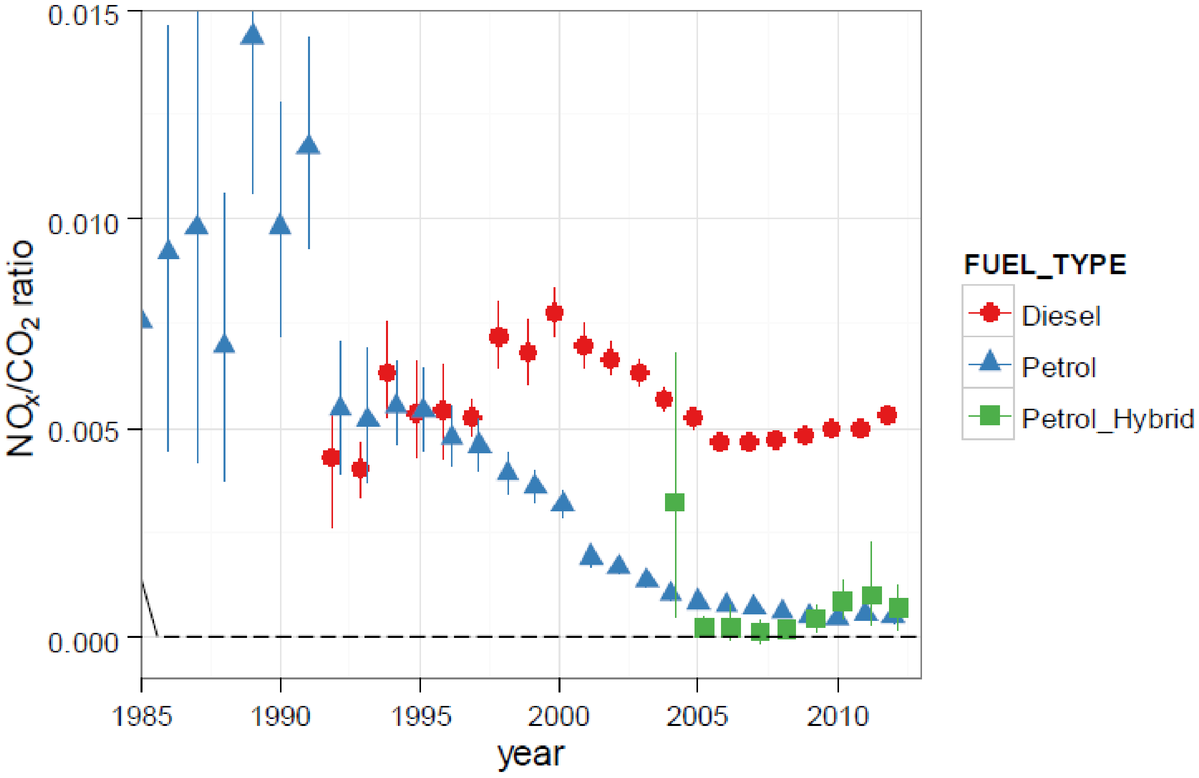

Figure 13: NOx/CO_2 Ratios for Passenger Cars by Year of Manufacture (taken from Carslaw and Rhys-Tyler, 2013)

Tate (2013)

5.20 Remote sensing was carried out at five locations in Cambridge for 10 days in summer 2013. A total of 15,391 valid records were collected. The results for diesels cars showed little improvement between Euro 0 and Euro 5. The results for Euro 6 showed a substantial reduction on earlier standards, albeit that this was based on only four vehicles (Figure 14).

The author used his data to estimate emissions in g/km. While emitting much less than the Euro 5 cars, the average Euro 6 cars were estimated to emit, on average, 3.3 times the emission standard.

5.21 In terms of HGVs, the results suggested no real reduction from Euro III to Euro V. Only one Euro VI vehicle was tested and this emitted about 40% less NOx than the average Euro III and Euro IV vehicles tested.

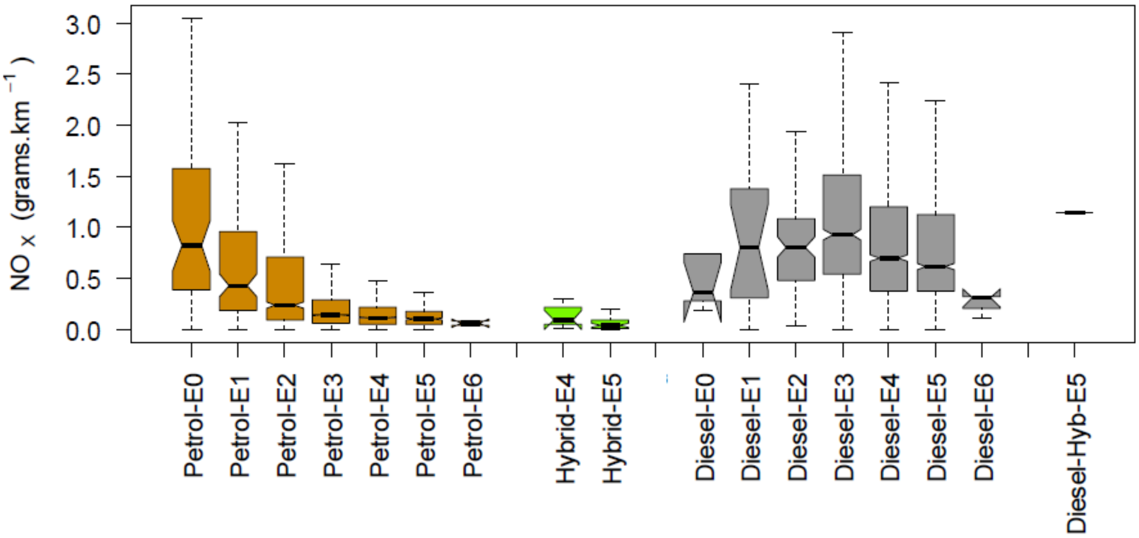

Figure 14: **Predicted NOx from Passenger Cars at Five Locations in Cambridge (taken from Tate, 2013)**

Tate (2015)

5.22 Remote sensing data from spring/summer 2015 were presented by Tate (2015). Excerpts are given in Figure 15 and Figure 16. These show no real change in NOx emissions from diesel cars between Euro 3 and Euro 5, followed by an appreciable reduction to Euro 6; albeit that Euro 6 vehicles continued to emit nearly 4 times the emission standard in the conditions tested. In terms of HGVs, the results show a similar picture, with no real reduction between Euro III and Euro V, but a large (ca. 55 %) reduction between Euro V and Euro VI.

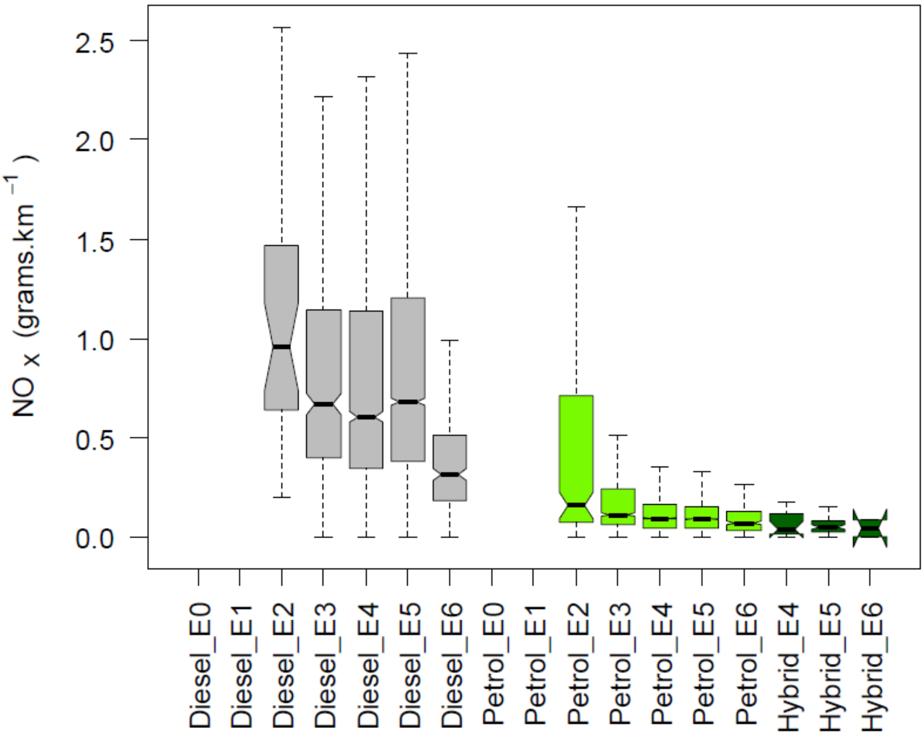

Figure 15: Summary of Results by Tate (2015) from Remote Sensing Collected in Spring/Summer 2015 (Passenger Cars) (taken from Tate, 2015)

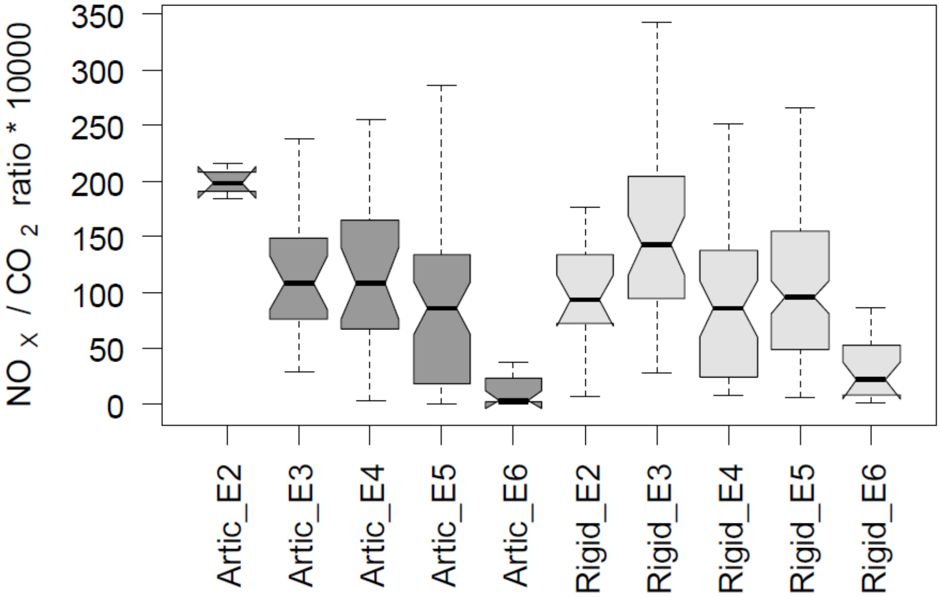

Figure 16: Summary of Results by Tate (2015) from Remote Sensing Collected in Spring/Summer 2015 (Heavy Commercial Vehicles) (taken from Tate, 2015)

Summary for Diesel Passenger Cars

5.23 Key statistics relating to passenger cars from the studies cited above are set out in Table 2. In reviewing this table it must be recognised that each individual study contains its own range and this is not shown. Furthermore, the results are specific to the vehicles and driving conditions of each individual test. Finally, as explained in Paragraph 2.2, it is important to recognise that the type approval limit is specific to the test cycle to which it relates and it would be unreasonable to expect it not to be exceeded in any conditions.

Euro 5 Vehicles

5.24 Table 2 suggests that Euro 5 emissions are between 40% and 150% those of Euro 4. In practice, there does not appear to be any basis for assuming any appreciable change between Euro 4 and Euro 5.

Euro 6 Vehicles

5.25 There appear to be clear and large differences in the on-road performance of different vehicles. Some Euro 6 vehicles emit very low levels of NOx while others do not appear to perform well at all. The technology used may be a significant contributor to this variability but other factors also appear to be relevant. The key messages from the studies cited above appear to be:

- Euro 6 vehicles are, on average, performing significantly better than earlier vehicles. For example, Euro 6 vehicles appear to be achieving reductions of between 50% and 70% when compared with Euro 5 vehicles;
- over all drive cycles considered (apart from NEDC), Euro 6 vehicles tend to emit significantly more than the Euro 6 standard of 0.08 g/km; and
- while it is reasonable to expect the introduction of Euro 6c will improve this picture, until the details are specified there is no real basis for predicting the effect of the standard.

5.26 Taking a weighted average[9] of the dynamometer, PEMS and SEMS results summarised in Table 2, suggests that NOx emissions from Euro 6 diesel cars, averaged over the various drive cycles shown, have been 3.9 times the emission standard (i.e. 0.31 g/km)[10]. This average is also within the range of the results from remote sensing data.

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[9] i.e. taking account of the number of vehicles in each test (the CF for each test was multiplied by the number of vehicles in the test and the result was divided by the total number of vehicles in all tests).

[10] All results have been treated equally and no account has been taken of the fact that the same vehicles appear in more than one reported test. Remote sensing data have not been included in these averages since they do not represent drive-cycle averages and are subject to greater uncertainty.

Table 2: Summary of Real-world Emissions Tests for Diesel Cars [a,b]

Source	No. Veh. Tested			E6 Tech.	Driving Conditions /Test Cycle	Cycle Ave. Speed (kph)	Ave E6 CF	Normalised to E4		E6/ E5
	E4	E5	E6					E5	E6	
Dynamometer Tests										
TU Graz, 2014 [c]	-	50	19	na	CADC (urban)	18	2.9	1	0.3	0.3
					CADC (rural)	58	2.9	1.2	0.5	0.4
					CADC (m/way)	97	5.0	1.2	0.6	0.5
TNO, 2015 Phase 1	-	-	4[d]	LNT, SCR	CADC (complete)	58	1.8	-	-	-
TNO, 2015 Phase 2	-	-	5	LNT, SCR, EGR	CADC (complete)	58	4.3	-	-	-
					WLTC (cold)	19-92	1.7	-	-	-
			1		WLTC (hot)		1.5	-	-	-
TNO, 2015 Phase 3	-	-	6	SCR	CADC (complete)	58	2.6	-	-	-
					WLTC (cold)	19-92	2.1	-	-	-
					WLTC (hot)		1.6	-	-	-
ADAC, 2015	-	-	4	ICC	WLTC (hot)	19-92	1.8	-	-	-
	-	-	18	LNT			3.1	-	-	-
	-	-	14	SCR			2.1	-	-	-
	-	-	4	ICC	ADAC Bespoke	na	4.9	-	-	-
	-	-	18	LNT			7.3	-	-	-
	-	-	14	SCR			3.9	-	-	-
TfL, 2015	3	-	9	na	Bespoke London-specific	16-87	5.3	-	na	-
PEMS Tests (and SEMS tests where indicated)										
Weiss et al 2012	2	4	1	EGR, ICC, DPF, SCR	Rural-motorway, rural-urban, rural-up/downhill	range	1.6	0.4	0.3	-
ICCT, 2014	0	0	12			range	6.5	-	-	-

Source	**No. Veh. Tested**			**E6 Tech.**	**Driving Conditions /Test Cycle**	**Cycle Ave. Speed (kph)**	**Ave E6 CF**	**Normalised to E4**		**E6/ E5**
	E4	**E5**	**E6**					**E5**	**E6**	
Emissions Analytics, 2015	-	200	36	na		na	3.8	-	-	0.4
TNO, 2015 Phase 2	0	0	2	LNT, SCR	Bespoke	32[e] – 93	5.4	-	-	-
TNO, 2015 Phase 3	0	0	7[f]	SCR		32[e] - 93	4.1	-	-	-
Remote Sensing										
Carslaw and Ryhs-Tyler, 2013	>1,000		0	-	Central and urban London	-	-	1.0	-	-
Tate, 2013	>1,000		4	-	Cambridge	-	3.3	0.9	0.3	0.3
Tate, 2015	na	na	na	na	na	-	3.8	1.1	0.5	0.4

[a] Most values have been interpreted from published graphs and are thus approximate.

[b] E4, E5, and E6 refer to Euro 4, Euro 5 and Euro 6 respectively.

[c] Includes data from ADAC and TNO.

[d] US vehicles, not yet given Euro 6 type approval.

[e] excludes idling.

[f] includes 5 PEMS and 2 SEMS tests.

Summary for Heavy Duty Vehicles

5.27 Key statistics relating to HDVs from the studies cited above are set out in Table 3. While some of the remote sensing studies have looked at buses separately, this is not attempted here. The number of tested vehicles is much lower for HDVs than for passenger cars; for example the TfL data represent just three vehicles. Caution must thus be applied in drawing too much from the data. It must also be recognised that each individual study contains its own range and this is not shown. Furthermore, the results are specific to the vehicles and driving conditions of each individual test.

5.28 The overall picture for HDVs is less clear than that for cars. Drive-cycle average emissions appear to be very variable between vehicles and between tests. This may relate, as suggested by TNO, to the fact that conformity testing only includes some vehicle-engine combinations and not others. Despite this variability, there is good evidence that Euro VI emissions are consistently better than those for Euro V and earlier vehicles.

Table 3: Summary of Real-world Emissions Tests for HDVs

Reference	Number of Vehicles Tested		Description	Special Conditions	Units and Vehicle Types	
	Euro V	Euro VI				
Absolute Emissions					**g/km**	
					Euro V	**Euro VI**
TfL, 2015	-	1	Bespoke London-specific Dynamometer Tests	N2[a] Rigid	-	0.7
		1		N3[a] Rigid	-	2.7
		1		N3[a] Artic	-	1.4
Relative Changes					**Normalised to Euro III**	
					Euro V	**Euro VI**
TNO, 2014	11	7	PEMS and SEMS using real-world testing procedure	Extra-urban vehicles[b]	0.6	0.03
Carslaw and Ryhs-Tyler, 2013	1,000s	0	Remote sensing	-	1.0	-
Tate, 2013	287	1	Remote sensing	-	1.5	0.6[c]
Tate, 2015	na		Remote sensing	Artic	0.8	0.04
				Rigid	0.7	0.2

Reference	Number of Vehicles Tested		Description	Special Conditions	Units and Vehicle Types	
	Euro V	Euro VI				
Relative Changes					Normalised to Euro V	
					Urban Euro VI	Extra-urban Euro VI
TNO, 2014	11	6	PEMS and SEMS using real-world testing procedure	0.50 kph	0.3	0.07
				50-75 kph	0.4	0.09
				>75kph	0.3	0.04
TFL, 2015	1	1	Bespoke London-specific chassis-dynamometer tests	Rigid	0.4 (0.06-1)[d]	
	1	1		Artic	0.3 (0.1 – 0.4)[d]	
Tu Graz, 2013	11[e]	5	Chassis-dynamometer and bench	-	<0.23[f]	
Tate, 2013	287	1	Remote sensing	-	0.4	
Tate, 2015	na		Remote sensing	Artic	0.05	
				Rigid	0.23	

Note: Most values have been interpreted from published graphs and are thus approximate.

[a] N2 = 3.5 to 12 tonnes; N3 < 12 tonnes.

[b] average of the three speed ranges given in Figure 9.

[c] If this single articulated vehicle were compared only against other articulated vehicles then the Euro VI to Euro III and Euro V values would be similar.

[d] Very approximate figures derived from Figure 5, noting that the speed ranges for the different vehicles do not align and so taking the nearest recorded speeds to be equivalent.

[e] Vehicles with EGR+SCR were considered separately from those with SCR only and there was some overlap between these vehicles. Thus, the actual number of vehicles tested was slightly lower than this.

[f] This is the WHTC Euro VI standard / the Euro V standard, which the authors determined was reflected in their data.

6 COPERT Emission Functions

6.1 Defra has produced an ‘Emissions Factor Toolkit’ (EFT) which combines assumptions regarding the make-up of the vehicle fleet in any given year (Appendix 0), with estimates of emissions per vehicle at different average speeds. The EFT is recommended by Defra for use by local authorities when they report air quality to it. The current version of the EFT (V6.02) uses values of NOx taken from the European Environment Agency’s COPERT 4 V10 model.

6.2 For Defra’s own modelling, which it uses for reporting to the European Commission, Defra has used a more recent version of the COPERT 4 model (COPERT 4 V11). Defra has not provided details on its exact approach, but the basic source information is in the public domain and has been made available for this current report by Ricardo Energy & Environment.

6.3 The emissions predicted by COPERT 4 are speed-specific. As noted in Paragraph 5.4, strictly speaking, these speeds relate to drive-cycle averages (i.e. the average speed of a single vehicle over the length of its route) but are frequently taken to represent points on the network (i.e. the average speed of multiple vehicles on a given section of road over the course of an hour or a day).

Passenger Cars

6.4 In order to summarise COPERT’s[11] assumptions for diesel cars across all Euro standards, emissions have been generated for the full range of possible speeds at 5 kph increments. The results have then been averaged across all speed increments. The results are shown in Figure 17. When presented in this way, COPERT’s functions predict small increases from Euro 1 to Euro 3, a reduction from Euro 3 to Euro 4, an increase from Euro 4 to Euro 5, and a substantial reduction from Euro 5 to Euro 6.

6.5 One difference between the COPERT V10 and COPERT V11 data relates to the relative increase in emissions from Euro 4 to Euro 5. The data in Table 2 did not provide any real basis for assuming any change between Euro 4 and Euro 5. Appendix 0 shows that vehicles prior to Euro 5 are of diminishing importance in any event and so the following discussion focuses on Euro 6 vehicles.

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[11] All references to COPERT in this report are to COPERT 4.

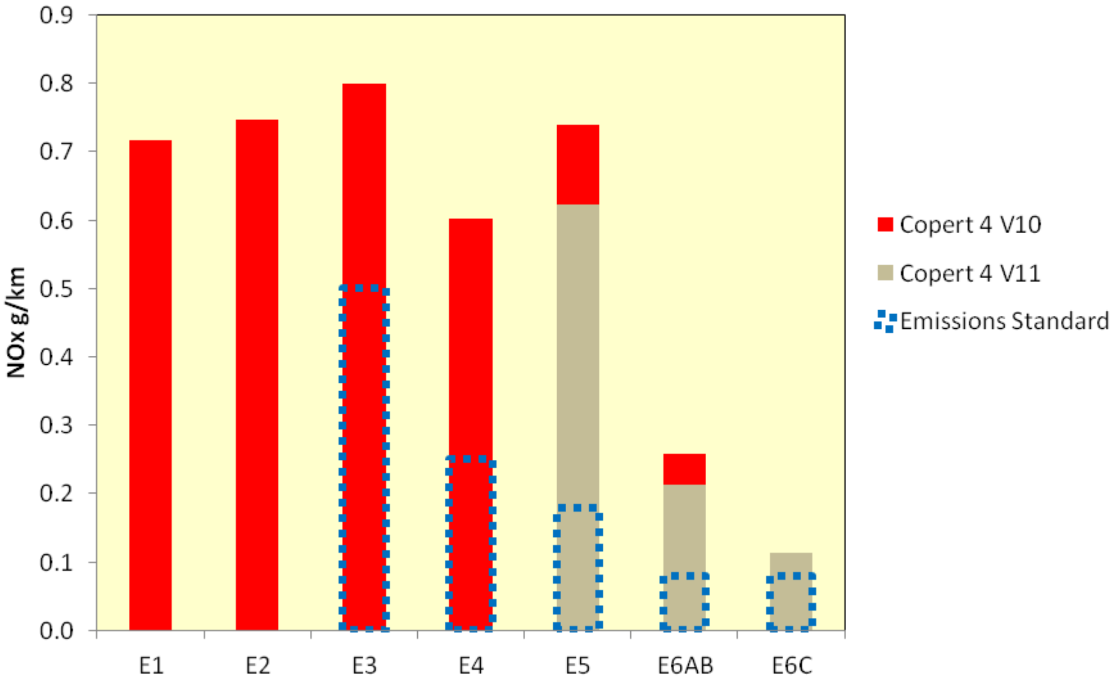

Figure 17: Average NOx from Diesel Cars across Different Euro Standards

6.6 Figure 18 summarises the COPERT emission factors for Euro 6 diesel cars by speed. It also shows the emission standard. Figure 19 shows the same information, in terms of CFs. It also shows the range of CFs that were summarised in Table 2. While each of the studies in Table 2 has its own specific speed range, the data are not sufficiently precise to warrant applying the measurements to specific speeds. From these data it can be seen that:

- COPERT V10 assumes that Euro 6ab cars emit, on average, between 2.3 and 5.0 times the standard;
- COPERT V11 assumes that Euro 6ab cars emit, on average, between 2.0 and 3.9 times the standard; and
- COPERT V11 assumes that Euro 6c cars will emit, on average, between 1.1 and 2.1 times the standard.

6.7 With the exception of Euro 6c (for which no real-world test data are available), the COPERT functions are within the range of the values from Table 2. The COPERT data are, however, predominantly below the average value from Table 2, suggesting that there is probably a small underestimate of Euro 6ab emissions on balance.

6.8 Defra, in its own modelling, defines the CF of the COPERT functions by comparing the predicted NOx emission at 33.6 kph against the emissions standard. 33.6 kph is used because this is the average speed of the NEDC test cycle. Following this approach, the CF for Euro 6 vehicles in COPERT V10 is 3.2, while in COPERT V11 it is 2.8. The approximate average CF in Table 2 is 3.9; again suggesting a slight under-prediction in COPERT.

6.9 In formulating its national air quality action plan, Defra carried out a sensitivity test whereby the CF for Euro 6 cars was increased to 5[12]. Figure 20 shows the effect of this adjustment. It clearly results in an over-estimate on average when compared with the real-world emission tests.

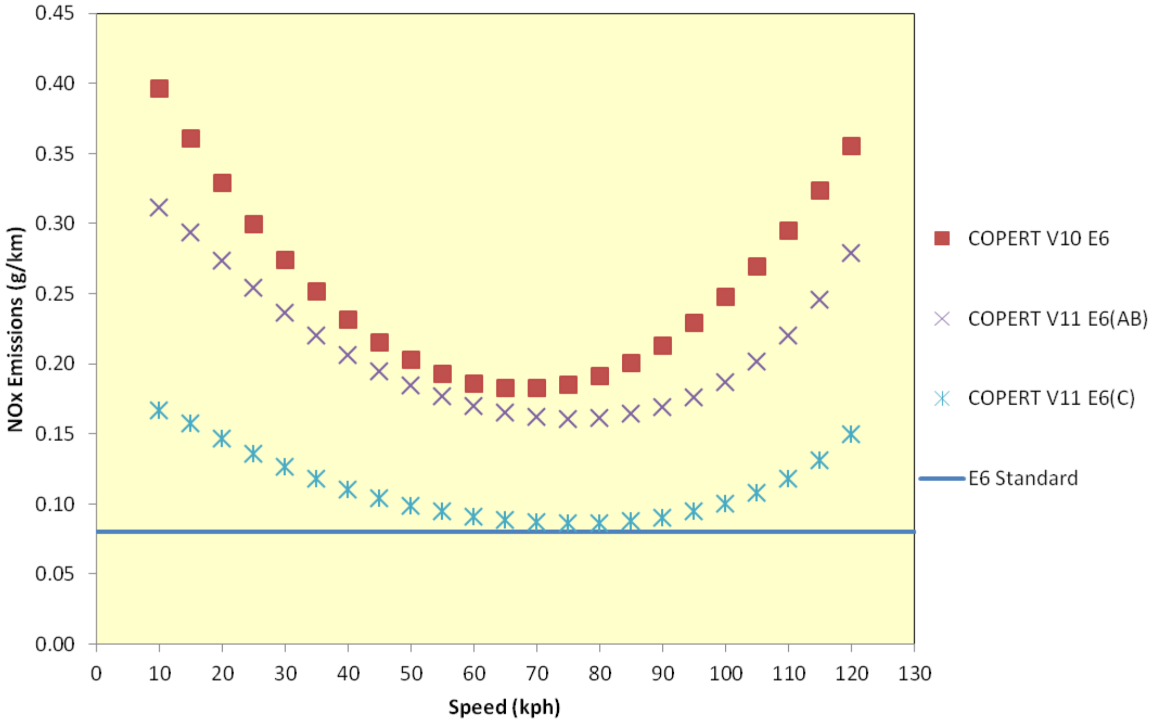

Figure 18: COPERT Speed-emissions Curves for Euro 6 Vehicles

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[12] i.e. all emissions were multiplied by 1.8 which is the required increase to move from a CF of 2.8 to 5 at 33.6 kph

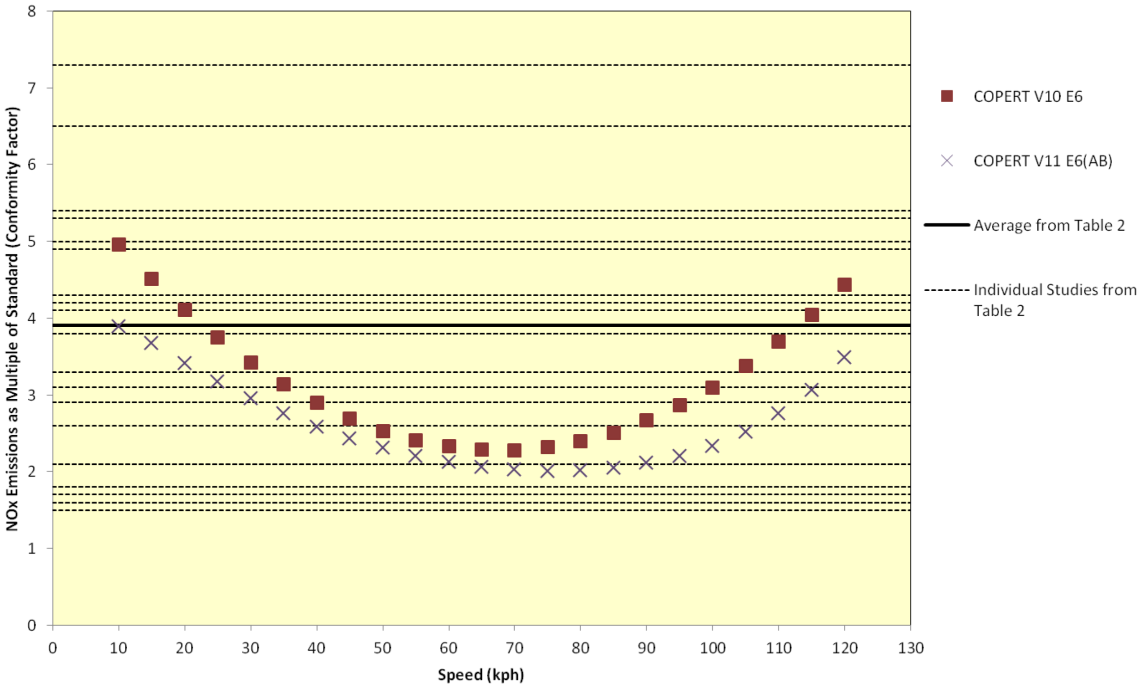

Figure 19: COPERT Speed-emissions Curves for Euro 6 Vehicles Expressed as Multiples of Emission Standard – Also Summarising Data from Table 2

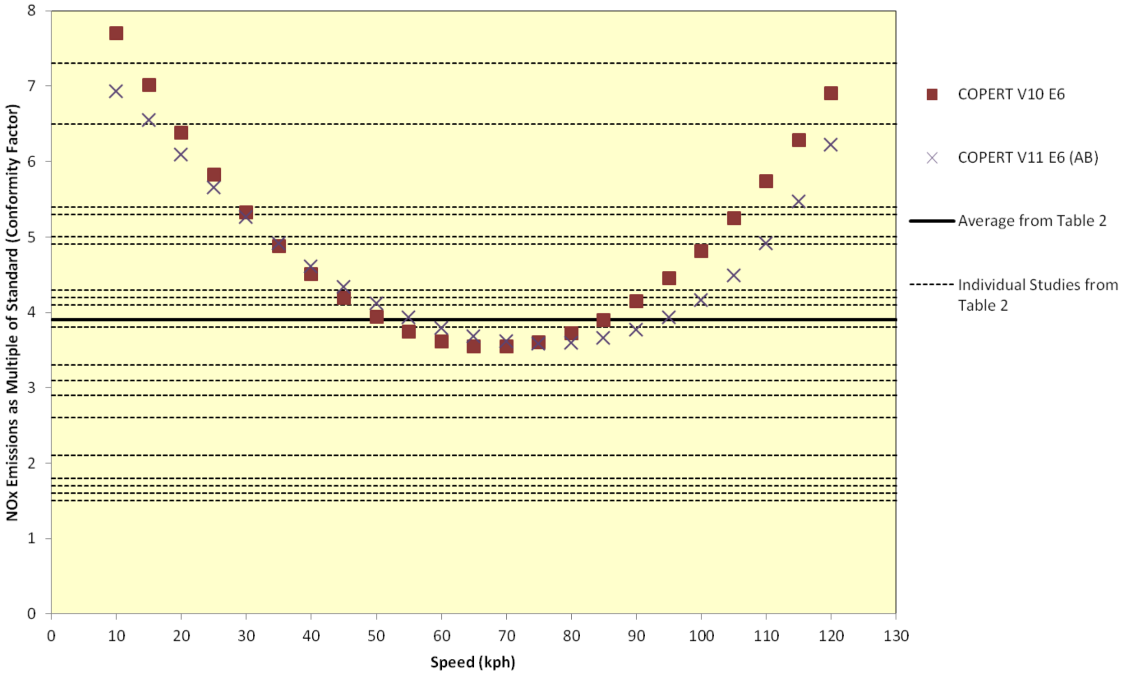

Figure 20: COPERT Speed-emissions Curves for Euro 6 Vehicles After Applying a CF of 5, Expressed as Multiples of Emission Standard– Also Summarising Data from Table 2

HDVs

6.10 As explained in Paragraph 5.28, there is clear evidence that Euro VI vehicles emit less than earlier vehicle types, but the key question for modelling is whether COPERT 4 is able to predict these emissions accurately. Also, while Euro VI is increasingly dominating vehicle fleets, Euro V vehicles remain important (Appendix A1).

6.11 COPERT provides HDV emissions for a large number of different vehicle types. For Euro V, emissions are further differentiated between EGR and SCR technology. Unlike for LDVs, it is difficult to compare COPERT emissions directly with the emission standard. This is because the former is expressed in g/km while the latter is expressed in g/kwh. One way of comparing the data is looking at relative trends across the Euro standards. This is shown in Figure 21. The proportionate reduction from Euro III to Euro VI assumed in COPERT V10 is largely in line with the reduction in the emission standard, but for specific Euro classes between Euro III and Euro VI, there are deviations between COPERTs assumptions and those suggested by the emission standards.

6.12 In formulating EFT V6.02, Defra has assumed that 75% of HGVs (and buses outside London) use SCR and 25% use EGR. For London buses, the proportion using SCR is assumed to be 90%. These proportions have been used to simplify the following analysis. Figure 22 shows how speed-specific emissions from Euro V vehicles (under COPERT V10 and V11) relate to those from Euro III vehicles (under COPERT V10). The COPERT predictions range from 0.9 (a 10% reduction from Euro III) to 0.2 (an 80% reduction).

6.13 To place these predictions in context, the averages from Table 3 are shown as horizontal lines[13]. It has not been possible to directly compare equivalent size/load vehicles in Figure 22. Furthermore the sample sizes represented by the horizontal lines are all relatively small. Figure 22 should therefore be treated as indicative, however, it does suggest that emissions from Euro V vehicles may have been underestimated in both COPERT V10 and V11.

6.14 Figure 23 shows the same comparison for Euro VI vehicles; again with values from Table 3 indicated as horizontal lines to provide context[14]. Values range from 0.2 (an 80% reduction from Euro III) to 0.03 (a 97% reduction) and are largely within the range of the measurements.

6.15 Figure 24 summarises the COPERT Euro VI emissions in g/km. The available emissions test results that were presented in g/km are also shown to provide context. At lower speeds, the COPERT emissions are higher than most of the measurements, but at higher speeds they are lower than the measurements. It should be noted that each line in Figure 24 represents a single vehicle. Furthermore, the lines which vary by speed were derived by reading coarse-scale graphs and should thus be taken as indicative only.

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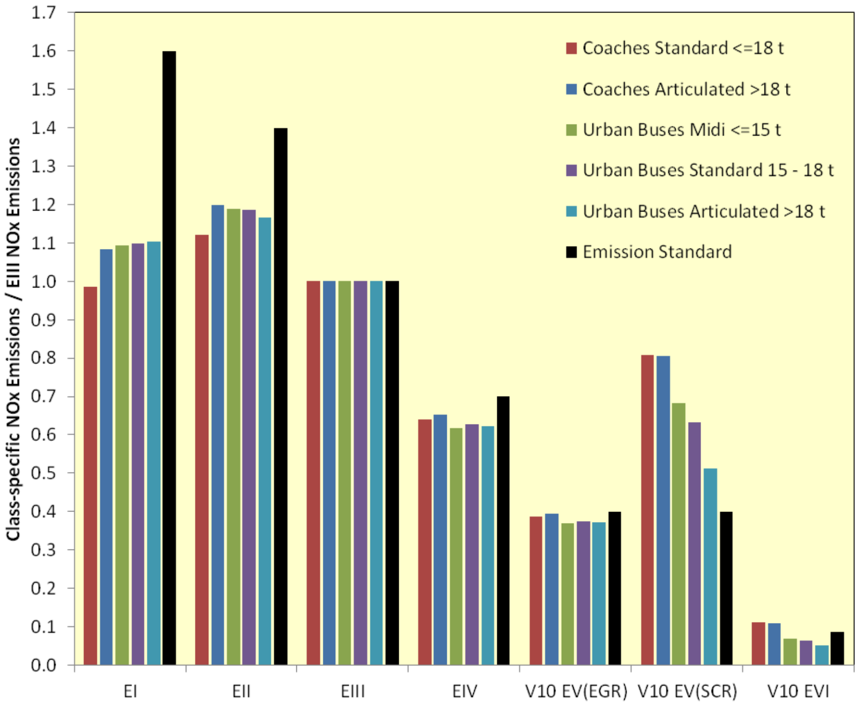
[13] No attempt has been made to represent the emissions test results for specific speeds as it is considered that this would represent a spurious level of precision to this high-level analysis.

[14] The value from Table 3 which was based on a single remote sensing measurement is not shown.



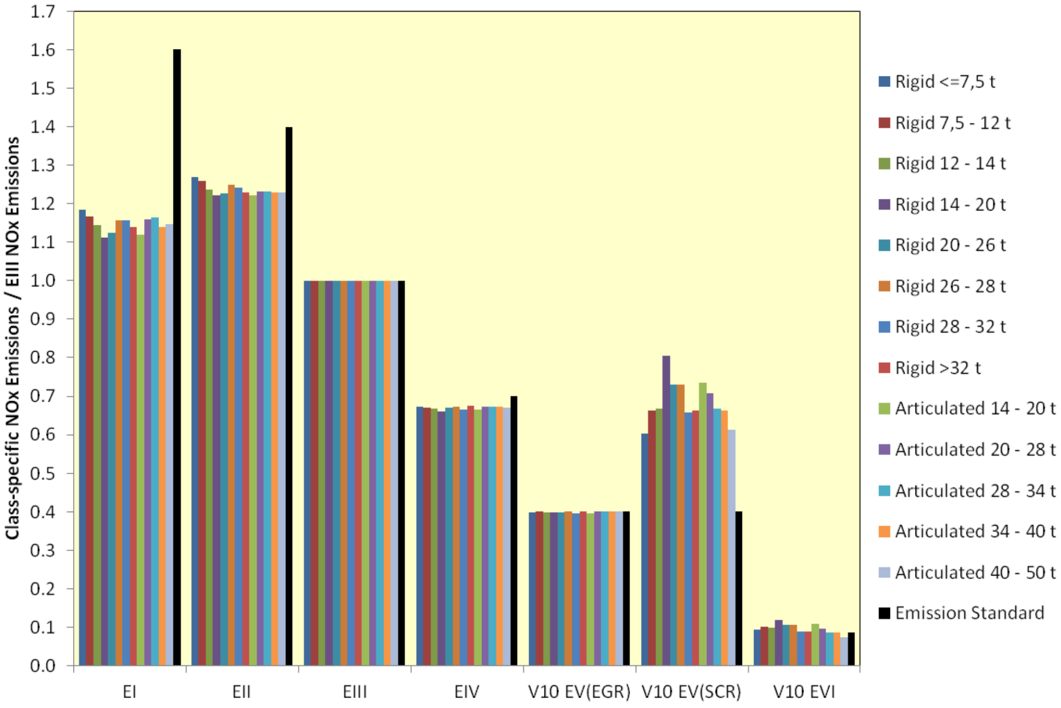


Figure 21: Predicted Average[15] NOx Emissions from Different HDVs taken from COPERT 4 V10 (Also showing the Emission Standard)

6.16 The final way in which Table 3 presents results for Euro VI vehicles is normalised to those of Euro V. Figure 25 shows the COPERT data in this way, again with the measurement results

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[15] A simple arithmetic average of all applicable vehicle speeds in 5kph increments.

summarised for context. As explained in Paragraph 6.13, the comparisons of COPERT predictions against real-world test results should be understood in the context of the relatively small test sample sizes (which all relate to specific vehicles with specific loads). Nevertheless, based on the data available, the reduction from Euro V to Euro VI does appear to be over-predicted in COPERT with respect to most of the measurements; the exceptions being the TNO records for extra-urban vehicles and the Tate, 2015 remote sensing data for articulated vehicles.

6.17 The conclusions drawn from Figure 22 to Figure 25 can be summarised as follows:

- absolute Euro VI emissions, based on minimal vehicle tests, are possibly slightly under-predicted;
- the reductions from Euro III to Euro V may have been over-predicted;
- the reductions from Euro III to Euro VI are not obviously incorrect; and
- the reductions from Euro V to Euro VI may have been over-predicted.

6.18 These conclusions are contradictory, but the number of tested vehicles, the testing conditions, and the tentative way in which the emissions tests have been compared with the COPERT emissions functions should all be taken into account. The Euro III to Euro VI analysis is based on quite a small set of measurements, while the Euro V to Euro VI analysis uses a larger dataset (Table 3). Overall, there appears to be a clear possibility that emissions from both Euro V and Euro VI vehicles are under-predicted by COPERT.

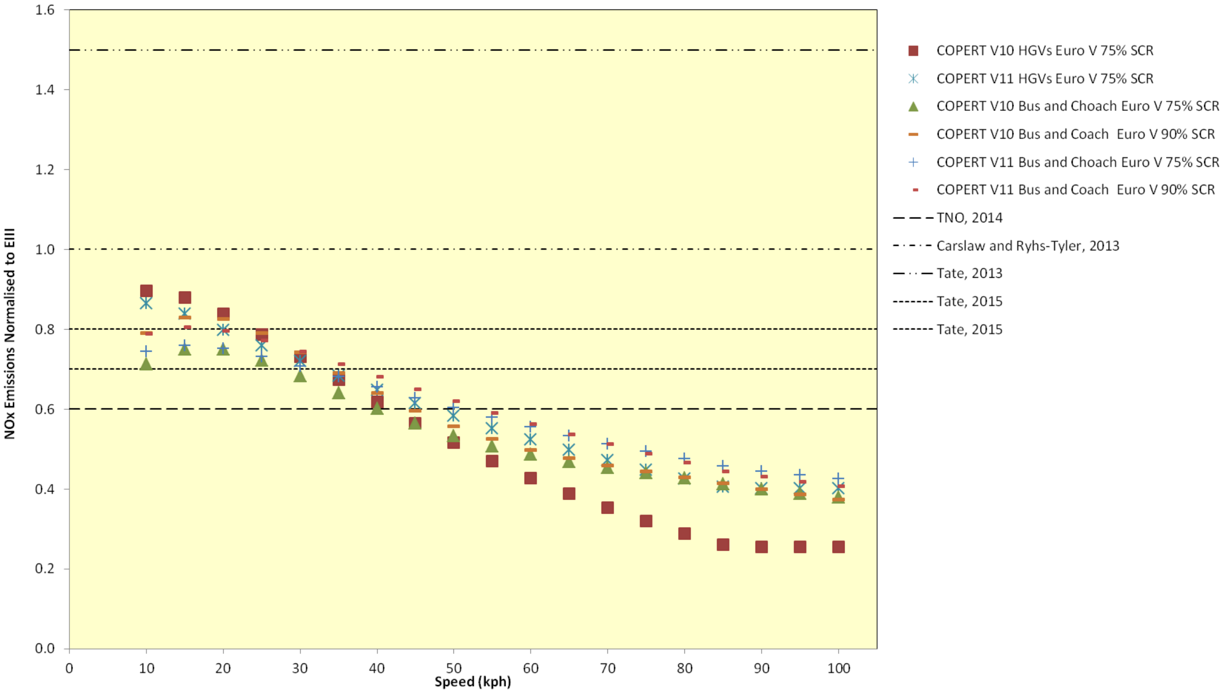

Figure 22: Average[16] Predicted NOx Emissions by Speed from Euro V Vehicles, Expressed as a Fraction of Euro III Emissions – Also Summarising Measurements

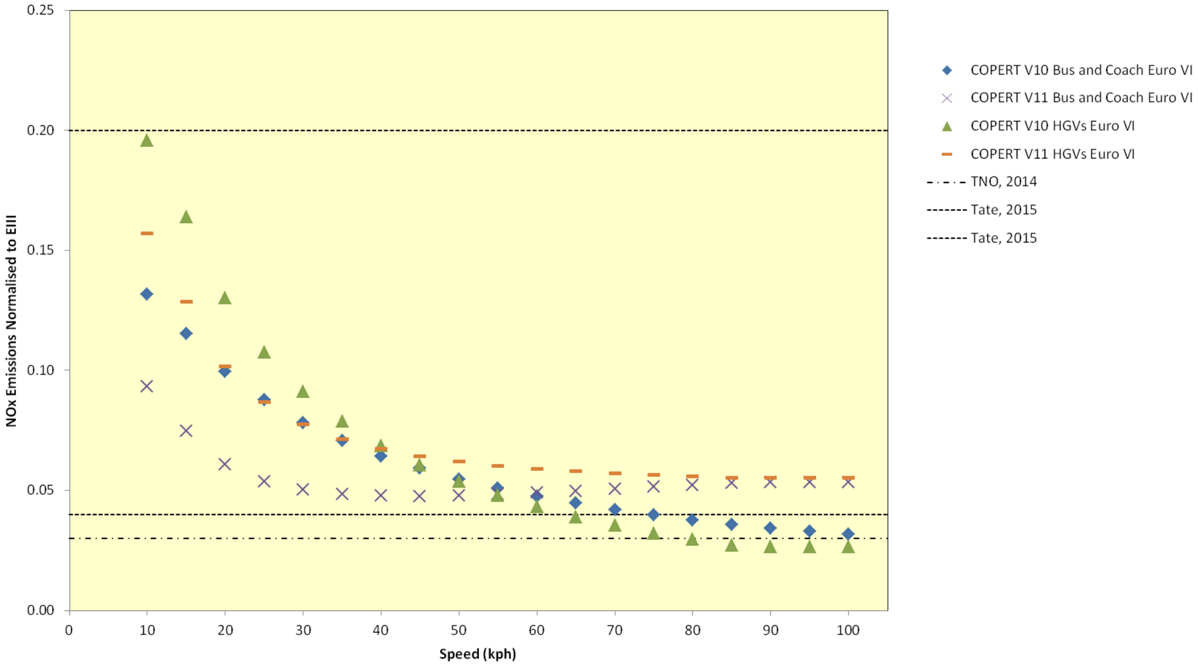

Figure 23: Average[16] Predicted NOx Emissions by Speed from Euro VI Vehicles, Expressed as a Fraction of Euro III Emissions – Also Summarising Measurements

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[16] An arithmetic average from all relevant vehicle types, not accounting for fleet proportions except where indicated.

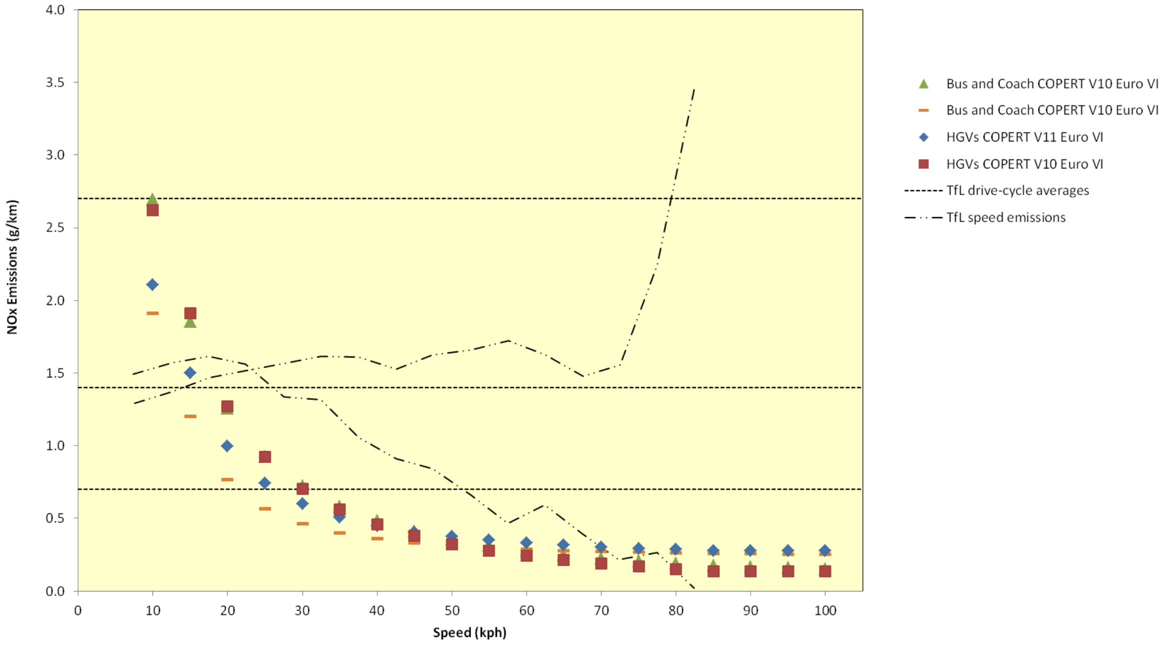

Figure 24: Average[16] Predicted NOx Emissions by Speed from Euro VI Vehicles – Also Summarising Measurements [17]

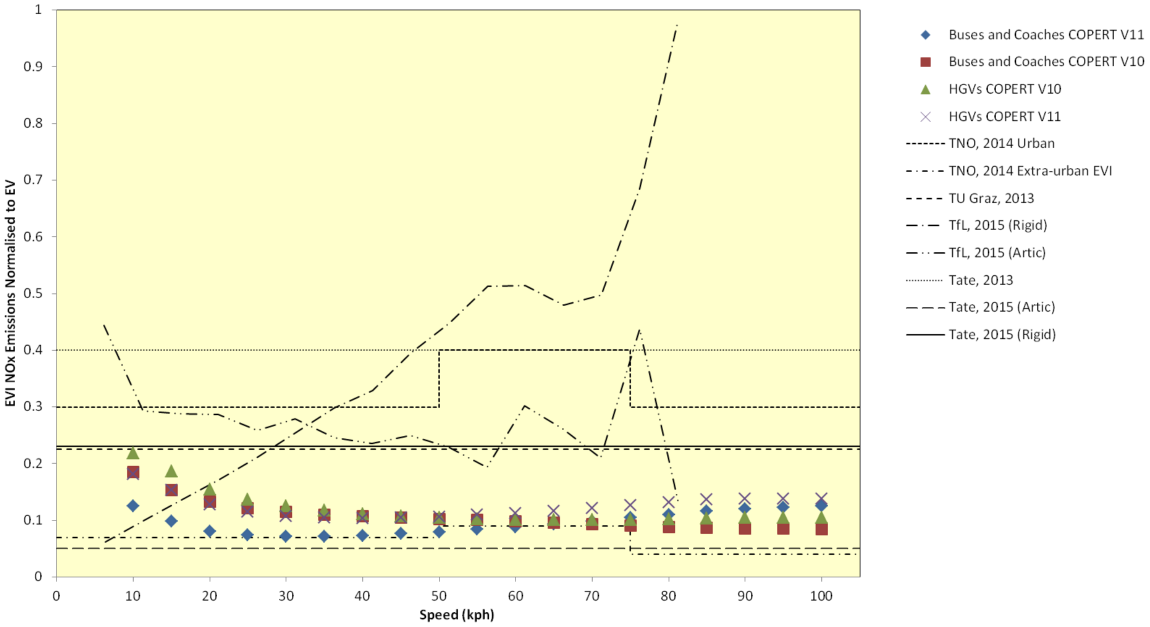

Figure 25: Average[16] Predicted NOx Emissions by Speed from Euro VI Vehicles Normalised to Euro V[18] Emissions – Also Summarising Measurements [17]

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[17] Lines which vary by speed were derived by reading coarse-scale graphs and should thus be taken as indicative only.

[18] Assuming the Euro V fleet is made up of 75% SCR and 25% EGR following the approach in the EFT for HGVs and buses outside London.

7 Changes in Emission Performance over Time

7.1 COPERT contains some assumptions regarding engine durability and the EFT adds assumptions regarding the failure of pollution control equipment. There is, however, little basis upon which to test these assumptions; particularly in terms of Euro 6 and Euro VI vehicles. As explained in Section 3, the Euro 6 and Euro VI standards require quite a large technological investment and there is a possibility that equipment may fail over time. There is also the possibility that urea tanks may not be optimally refilled. There are, however, requirements in the Euro VI standard for in-service testing, and Euro 6c may contain similar requirements. No evidence is presented here of whether emissions will increase as vehicles become older but the possibility has been taken into account in the modelling recommendations set out below.

8 Future Emissions Test Regimes

8.1 Recent attention in the media has been given to the use, by certain vehicle manufacturers, of technology to ‘cheat’ the emissions tests. The precise nature of this so-called ‘defeat software’ is not known, nor are the precise implications of it within the current European emission test procedures. It is, however, known that all manufacturers exploit the flexibilities in the test procedures, such that real-world emissions are very different from those under test conditions. With the introduction of PEMS, real-world emissions will be measured during the test procedures. There is no reason to expect emissions performance in the future to be any worse than that indicated by the ‘real world’ emissions tests presented in Section 5.

9 Conclusions

9.1 The current version of the EFT uses COPERT 4 V10 functions for NOx and these can be retained until the EFT is formally updated.

Cars

Euro 5 and earlier

9.2 There is no strong evidence that the COPERT functions predict incorrect emissions from Euro 5 or earlier diesel cars. No adjustment is considered necessary.

Euro 6

9.3 The EFT does not currently include Euro 6c. Thus all Euro 6 vehicles are assumed to be Euro 6ab vehicles. The evidence compiled within this report suggests a small under-prediction in the COPERT functions when compared with the Euro 6ab cars that have been tested. While it would be convenient to apply an adjustment to the COPERT emissions based on the data summarised in Table 2, it is not considered that this would be appropriate. This is because all of the studies collated here have their own specific features and so the comparison in Table 2 is only indicative[19]. It is appropriate that future-year modelling should be based on the EFT (unadjusted), but that a sensitivity test be carried out which uses a multiplier of 1.6 which brings about a CF of 5, following the approach recently taken by Defra. The predictions would be those in Figure 19 and Figure 20.

9.4 Figure 26 shows how emissions from an average passenger car[20] (in inner London and at 30 kph) are predicted to change over time under both the base (EFT) and adjusted (uplifted emissions with CF of 5) scenarios. This takes account of the speed with which Euro 6 vehicles are predicted to enter the vehicle fleet, but does not take specific account of the delay in mandatory introduction of Euro 6 vehicles (see Paragraph 2.1). The lines are specific to the location and speed chosen but the general patterns will be the same for other locations and speeds.

9.5 In the absence of any significant reduction in efficacy of Euro 6 over time, and in the absence of any Euro 6c vehicles, it is reasonable to expect emissions to fall somewhere between these two scenarios. In practice, it is likely that the introduction of Euro 6c will reduce emissions when compared with Euro 6ab and thus both tests may over-predict future vehicle emissions.

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[19] And the same data could be interpreted in different ways to give slightly different averages.

[20] Taking account of other factors contained in the EFT regarding fleet compositions, degradation etc.

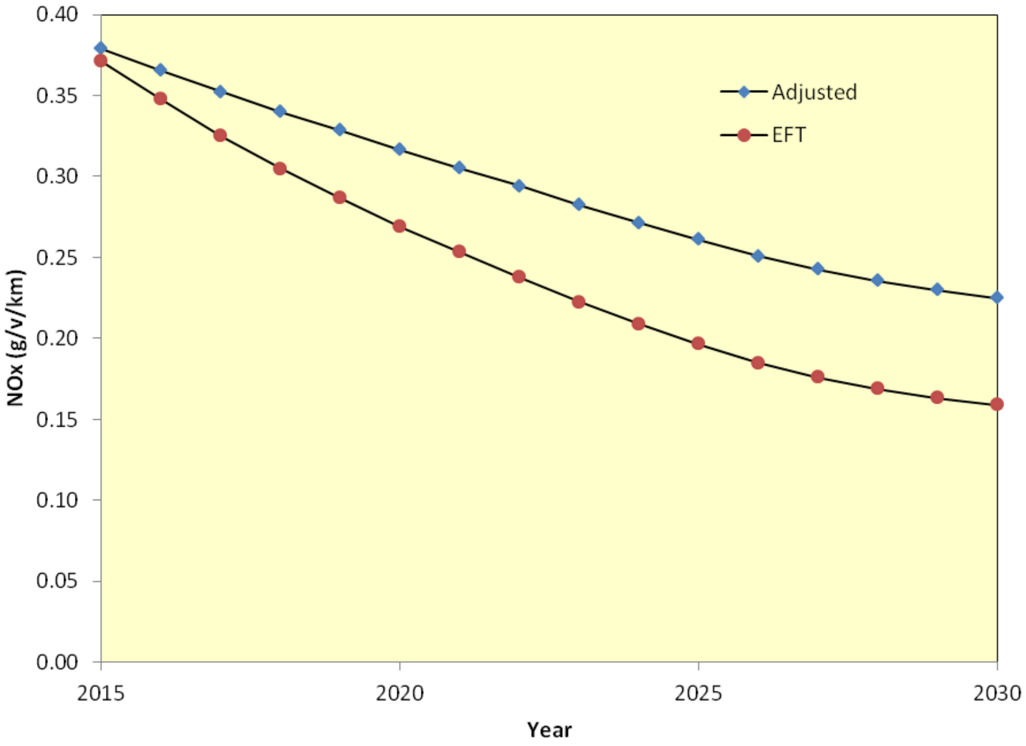

Figure 26: **Emissions from an Average Passenger Car over Time Using Two Emissions Calculations (Fleet set to Inner London, Speed set to 30 kph)**

Taxis and LGVs

9.6 The number of Euro 6 Taxis and LGVs for which real-world emissions data have been reported is much smaller than the number of cars and to avoid additional complexity they have not been collated in this report. It is considered reasonable to treat Taxis and LGVs in the same way as passenger cars; i.e.:

- Euro 5 and earlier vehicles are unadjusted from the EFT; and
- a sensitivity test should be carried out whereby Euro 6 vehicles are adjusted to achieve a CF of 5 at 33.6 kph.

9.7 In practice, the COPERT vehicle splits that are incorporated into the EFT do not align precisely with the categories to which the emissions standards apply (i.e. those in Table 1). Those LGVs which are treated in the EFT using the COPERT functions for passenger cars should be adjusted as described above for passenger cars. Those LGVs and taxis which are treated using the COPERT functions for LGVs, could be adjusted so that emissions at 33.6 kph are 0.625 g/km (i.e. 5 times the emission standard for commercial vehicles in the 1,760-3,500 kg size range). This requires multiplying all Euro 6 diesel LGV emission by 1.74. Figure 27 shows how emissions from an average LGV are predicted to change over time under both the base (EFT) and adjusted (uplifted emissions) scenarios.

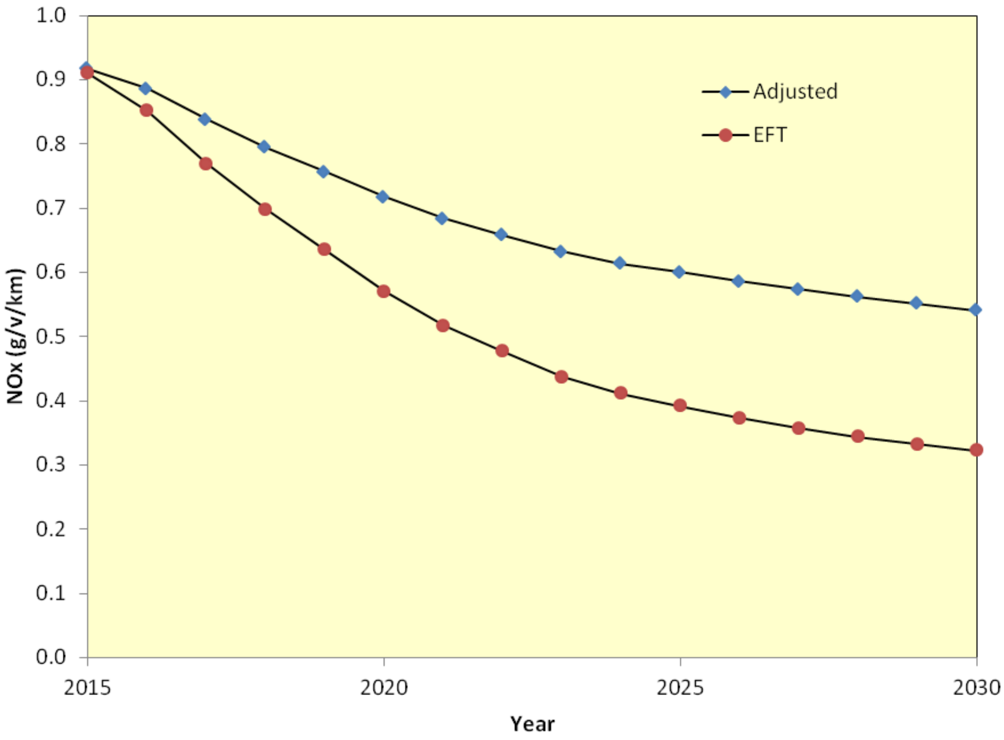

Figure 27: Emissions from an Average LGV over Time Using Two Emissions Calculations (Fleet set to Inner London, Speed set to 30 kph)

HDVs

Euro IV and Euro V

9.8 Based on the available evidence compiled for this report, Euro V emissions from HDVs are possibly under-predicted in COPERT. On average, there does not appear to be any significant evidence of an appreciable reduction in emissions per vehicle between Euro III, Euro IV and Euro V standards. It is thus considered reasonable to carry out a sensitivity test in which the COPERT Euro III functions are used to represent all Euro IV and Euro V vehicles regardless of the technology employed (i.e. EGR or SCR).

Euro VI

9.9 There also appears to be some evidence that Euro VI emissions may be under-predicted. There is, however, no definitive basis upon which to adjust the emissions. A pragmatic approach to adjustment could be used as a sensitivity test to account for this potential under-prediction.

9.10 For each type of HDV included in COPERT, emissions have been calculated at 5 kph increments. The average of these speed-specific emissions has then been calculated. The ratio of Euro VI to Euro V (which has already been uplifted to match Euro III) has then been set at 0.2. 0.2 is slightly lower than the relative change in the emission standards and is within the range of values set out in Table 3. Figure 28 and Figure 29 show how this adjustment affects the average Euro VI predictions (in g/km and normalised to Euro III emissions). Taking account of the caveats regarding comparisons with real-world tests for HDVs in Section 6, when compared with the real-world data, the adjusted data appear to be slightly high, but not nonsensical. They thus provide a reasonable basis for an upper-bound sensitivity test.

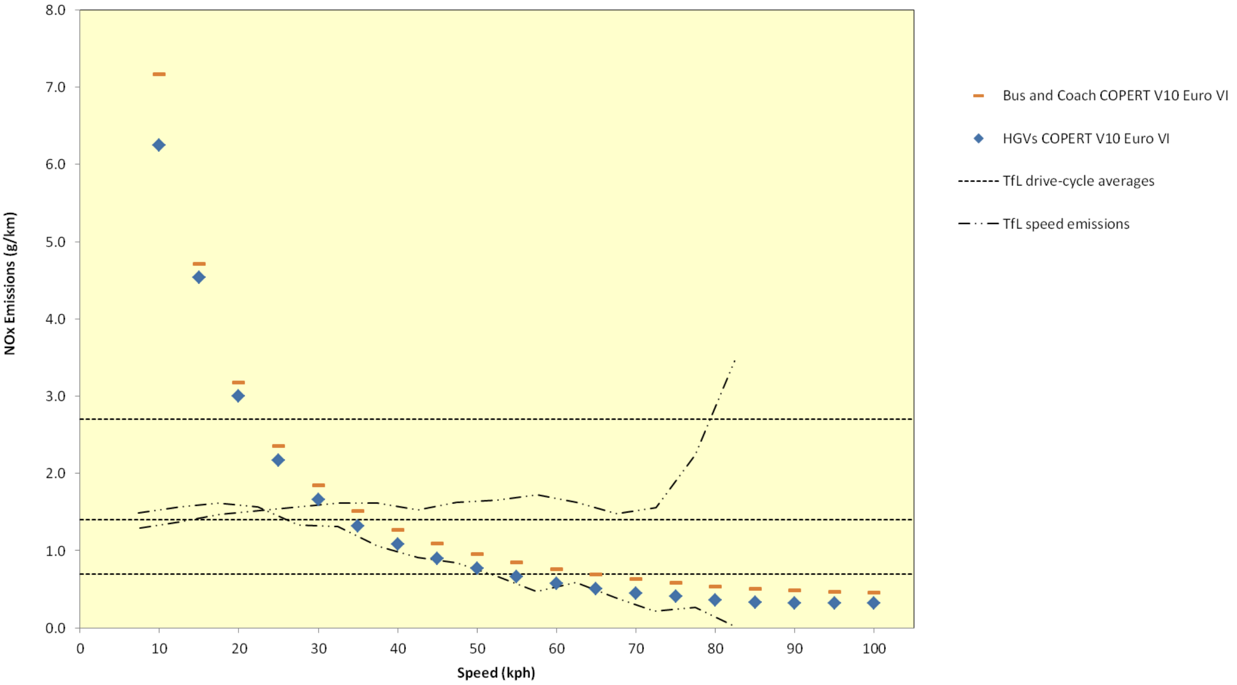

Figure 28: Average[16] Predicted NOx Emissions by Speed from Euro VI Vehicles – Following Uplift – Also Summarising Measurements [17]

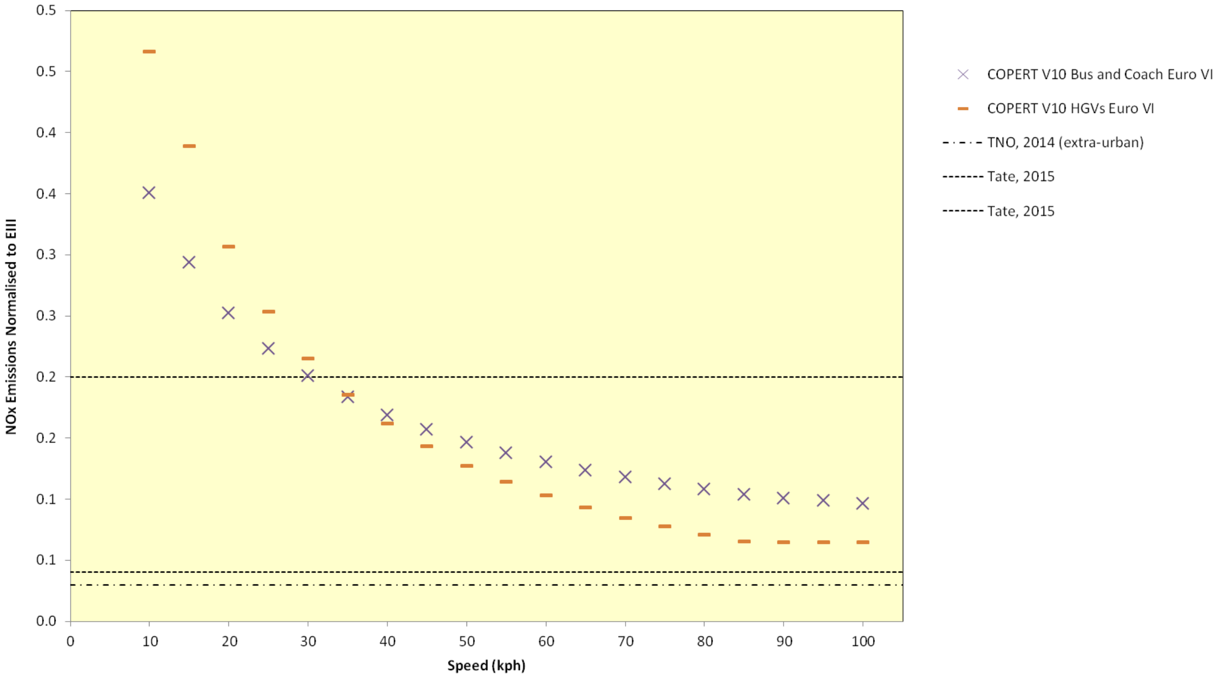

Figure 29: Average[16] Predicted NOx Emissions by Speed from Euro VI Vehicles, Expressed as Fraction of Euro III Emissions – Following Uplift – Also Summarising Measurements

9.11 Figure 30 shows how emissions from an average HDV are predicted to change over time under both the base (EFT) and adjusted (uplifted emissions) scenario.

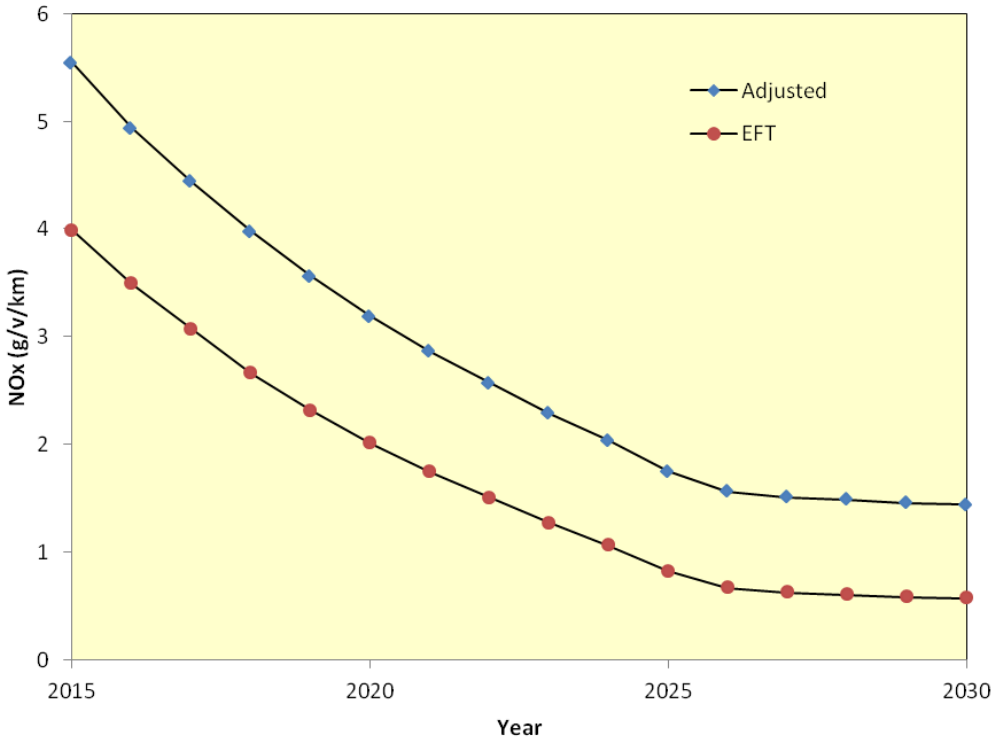

Figure 30: Emissions from an Average HDV over Time Using Two Emissions Calculations (Fleet set to Inner London, Speed set to 30 kph)

Delay to Mandatory Introduction of Euro 6 Standard

9.12 As explained in Paragraph 2.1, the Euro 6 standard was intended to become a legal requirement for new vehicles in September 2015 but a derogation has been agreed to allow the continued registration of Euro 5 vehicles until September 2016. The fleet projections used in the EFT were developed before this derogation was agreed. Any effect of this delay is likely to be small in the context of other factors discussed in this report[21].

Summary

9.13 Figure 31 shows how emissions from a nominal road (in Inner London with 5% HDVs) are predicted to change over time under both the base (EFT) and adjusted scenarios. This combines all of the vehicle-specific uplifts. Emissions are clearly higher using the adjusted scenario, and show a flatter profile from 2010 to 2014. There are, however, still appreciable year-on-year reductions in future years. Given that both emissions tests would need to be verified and adjusted to match the same base-year measurements, it is the trend over time

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[21] By way of reference, Figure A1.1 shows that the EFT assumes Euro 6 vehicles made up 11% of the (distance-weighted) fleet in 2015 and 0% of the fleet in 2014. Some Euro 6 vehicles are known to have been on the road in 2013 (e.g. Tate, 2013).

going forward that is of principal interest. This is shown in Figure 32. The combined effect of all of the adjustments suggested above is a slightly shallower rate at which fleet-average emissions are predicted to reduce into the future.

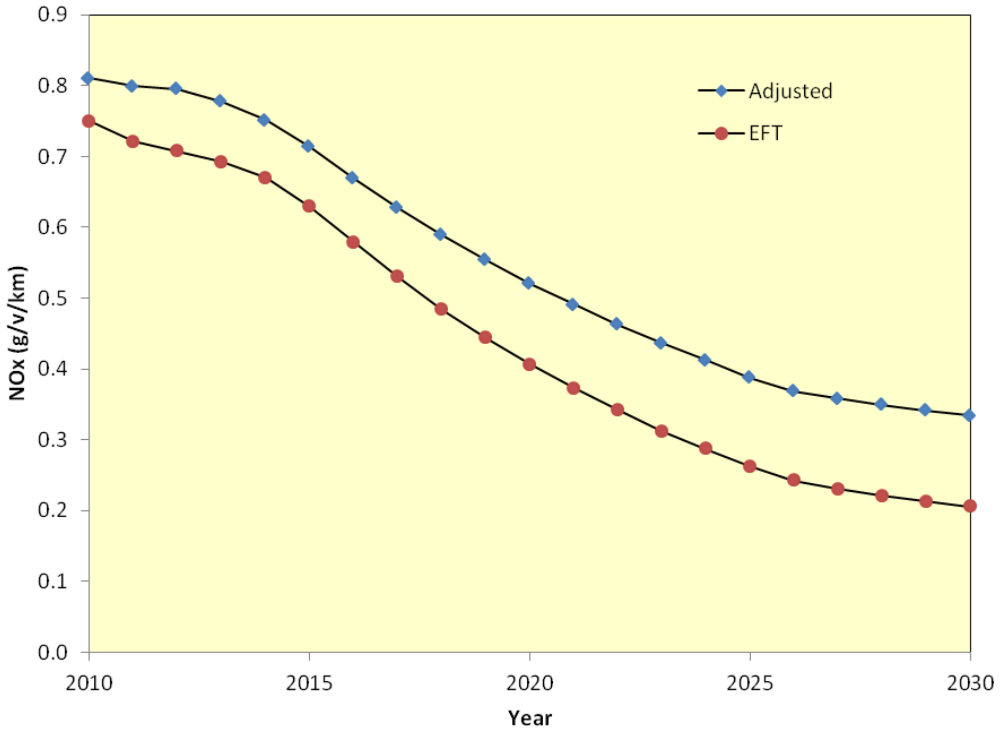

Figure 31: **Emissions from an Average Vehicle from 2010 to 2030 Using Two Emissions Calculations (Fleet set to 5% HDV in Inner London, Speed set to 30 kph)**

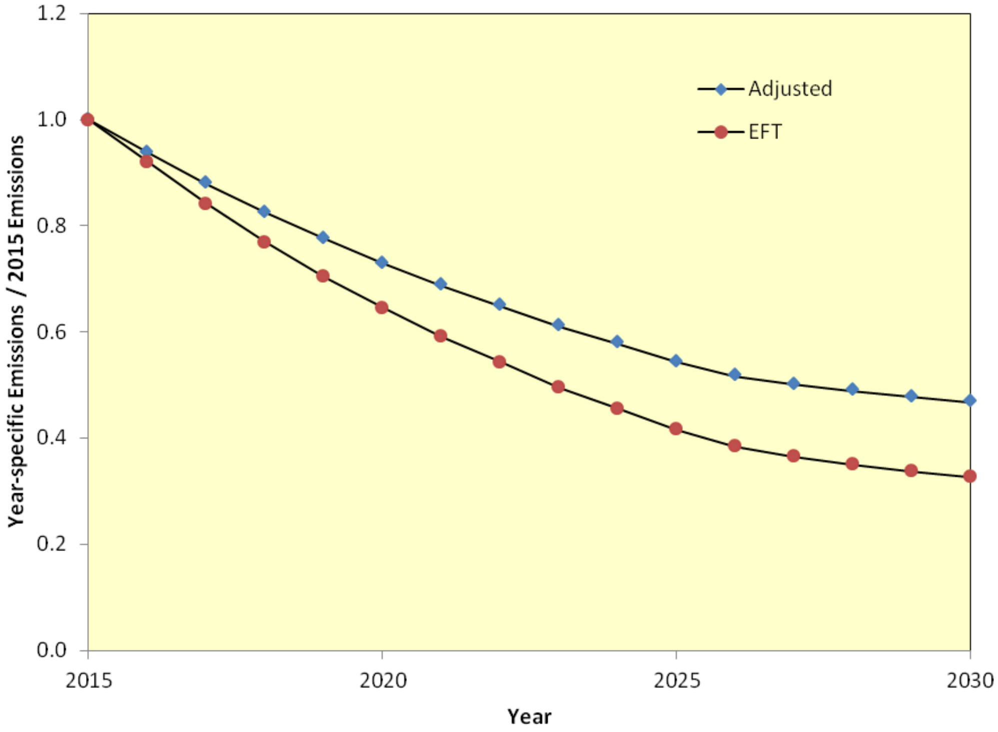

Figure 32: **Emissions from an Average Vehicle from 2015 to 2030 Using Two Emissions Calculations (Fleet set to 5% HDV in Inner London, Speed set to 30 kph) Normalised to Emissions in 2015**

9.14 Figure 33 shows a worked example of how total predicted annual mean nitrogen dioxide concentrations might change year-on-year using different modelling approaches for a roadside location. The sensitivity test shows higher predicted concentrations in the future than the EFT-based modelling, but much lower concentrations than would be the case if traffic emissions were held constant at the base year.

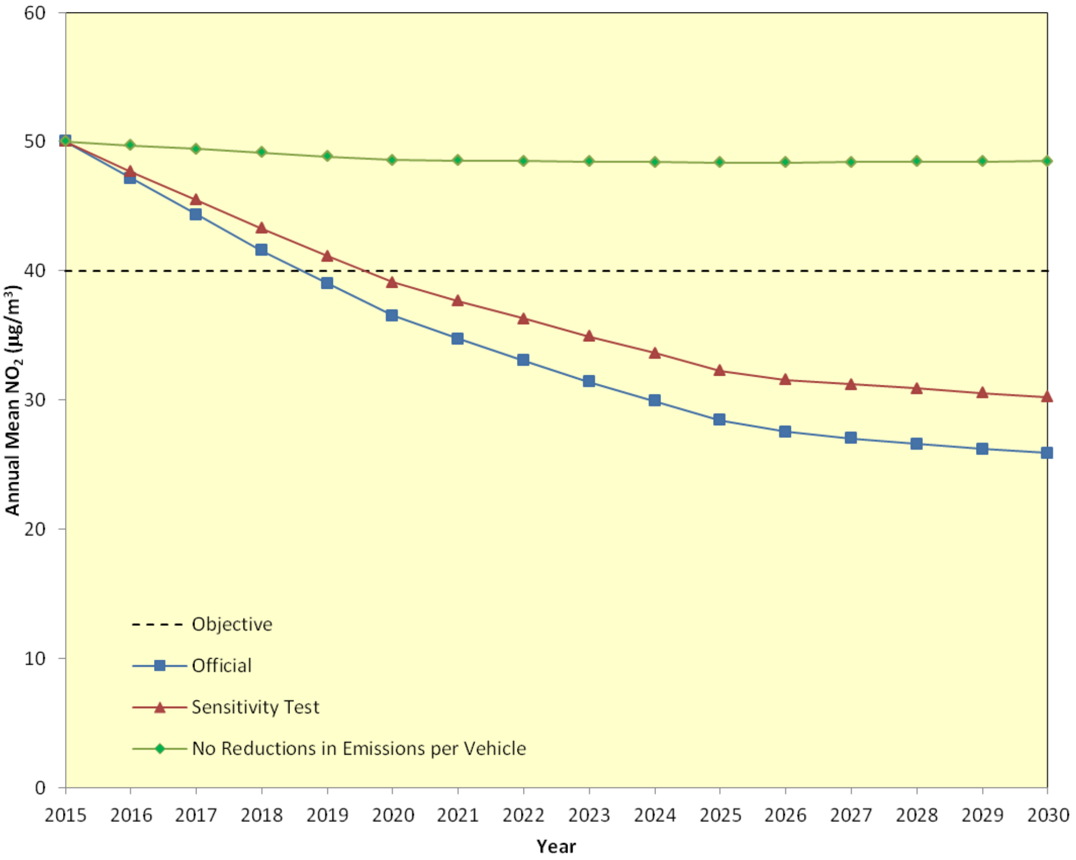

Figure 33: Example Predictions of Annual Mean Nitrogen Dioxide through Time using Different Methods[22]

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[22] Results are for a roadside receptor in outer London. The adjacent road has an assumed average speed of 40 kph, with 10% HDVs. Traffic flows have been assumed not to change year on-year. Background NO_2 was derived from Defra's maps (http://uk-air.defra.gov.uk/data/laqm-background-maps?year=2011) and adjusted as set out in (AQC, 2016). Mapped background NO_2 in 2015 was 28.5 µg/m^3. Measured total NO_2 in 2015 was 50 µg/m^3 and each approach was verified and adjusted against this measurement following standard methods. Defra's NOx to NO_2 calculator (http://laqm.defra.gov.uk/review-and-assessment/tools/background-maps.html#NOxNO2calc) has been used to convert NOx from NO_2 and vice-versa. "*No reduction in Vehicle Emissions*" describes a scenario in which the fleet for 2015 is assumed to represent every year in the EFT, the traffic component of the background maps has been held constant at 2011 levels, and 2015 has been used to represent every year in the NOx from NO_2 calculator.

10 References

ADAC (2015) *ADAC Position zur Festschreibung des maximal erlaubten Übereinstimmungsfaktors für die Prüfung der Übereinstimmung*, [Online], Available: https://presse.adac.de/meldungen/technik/files/adacpositionrdecf.pdf.

Carslaw, D., Beevers, S., Westmoreland, E. and Williams, M. (2011) *Trends in NOx and NO2 emissions and ambient measurements in the UK*, [Online], Available: uk-air.defra.gov.uk/reports/cat05/1108251149_110718_AQ0724_Final_report.pdf.

Carslaw, D. and Rhys-Tyler, G. (2013) *Remote sensing of NO2 exhaust emissions from road vehicles*, July, [Online], Available: http://uk-air.defra.gov.uk/assets/documents/reports/cat05/1307161149_130715_DefraRemoteSensingReport_Final.pdf.

Emissions Analytics (2015) *November 2015 Bulletin - Issued by email*.

ICCT (2014) *Real-world Exhaust Emissions from Modern Diesel Cars*, [Online], Available: http://www.theicct.org/sites/default/files/publications/ICCT_PEMS-study_diesel-cars_20141010.pdf.

Tate (2013) *Vehicle Emission Measurements and Analysis - Cambridge City Council*, [Online], Available: https://www.cambridge.gov.uk/sites/default/files/documents/Cam_VEMS_ProjectReport_v1.0.pdf.

Tate (2015) *Real Driving Emissions: Results from teh 2015 remote sensing campaigns (UK) - Presentation to Routes to Clean Air - Air Quality Conference - IAQM - 23rd October 2015*.

TfL (2015) *In-service Emissions Performance of Euro 6/VI Vehicles*, [Online], Available: https://www.london.gov.uk/sites/default/files/In-service%20emissions%20performance%20of%20Euro%206VI%20vehicles%20WEBSITE%20COPY.pdf.

TNO (2015) *Detailed investigations and real-world emission performance of Euro 6 diesel passenger cars*.

TNO (2104) *The Netherlands In-Service Emissions Testing Programme for Heavy-Duty 2011-2013*.

TU Graz (2013) *Update of Emission Factors for Euro 5 and Euro 6 vehicles for the HBEFA Version 3.2*.

Weiss, M., Bonnela, P., Kühlweina, J., Provenza, A., Lambrecht, U., Alessandrinia, S., Carrieroa, M., Colomboa, R., Fornia, F., Lanappea, G., Lijoura, P.L., Manfredia, U., Montignya, F. and Sculatia, M. (2012) *Will Euro 6 reduce the NOx emissions of new diesel cars? – Insights from on-road tests with Portable Emissions Measurement Systems (PEMS)*, Atmospheric Environment, V62, p 657-665.

Acknowledgements

The authors are grateful to Dr Tim Murrells at Ricardo Energy & Environment for his review of and advice on a draft of this report.

Appendix A1: Examples of Predicted Fleet Mixes

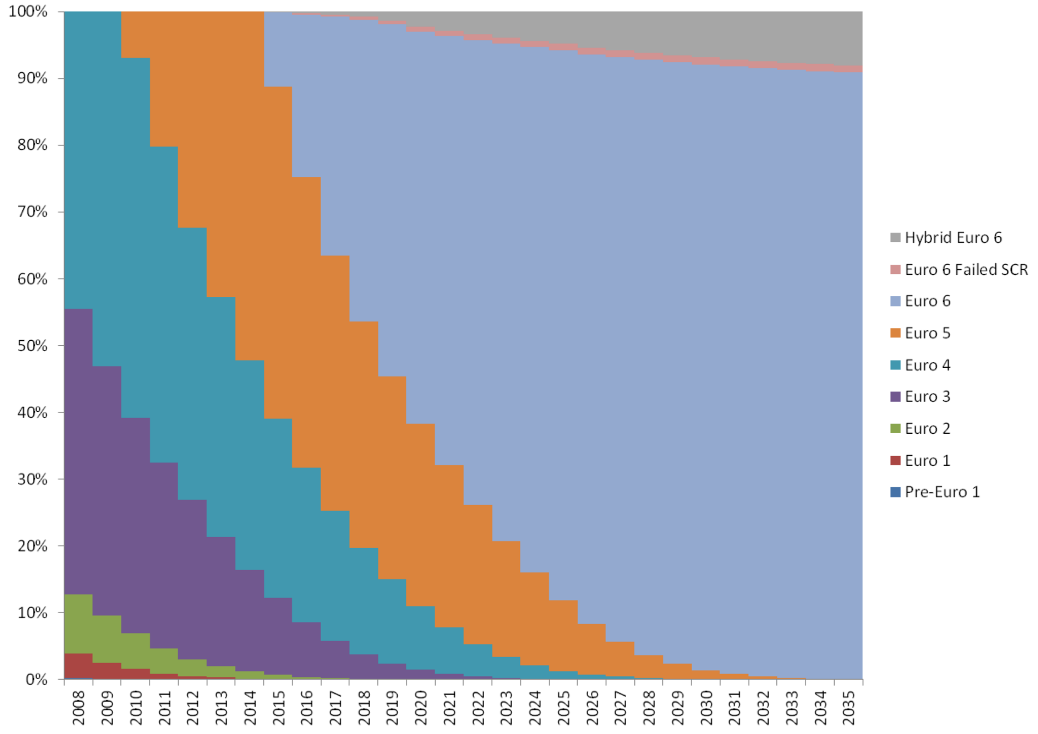

Figure A1.1: **Diesel Car Fleet Projections used in EFT**

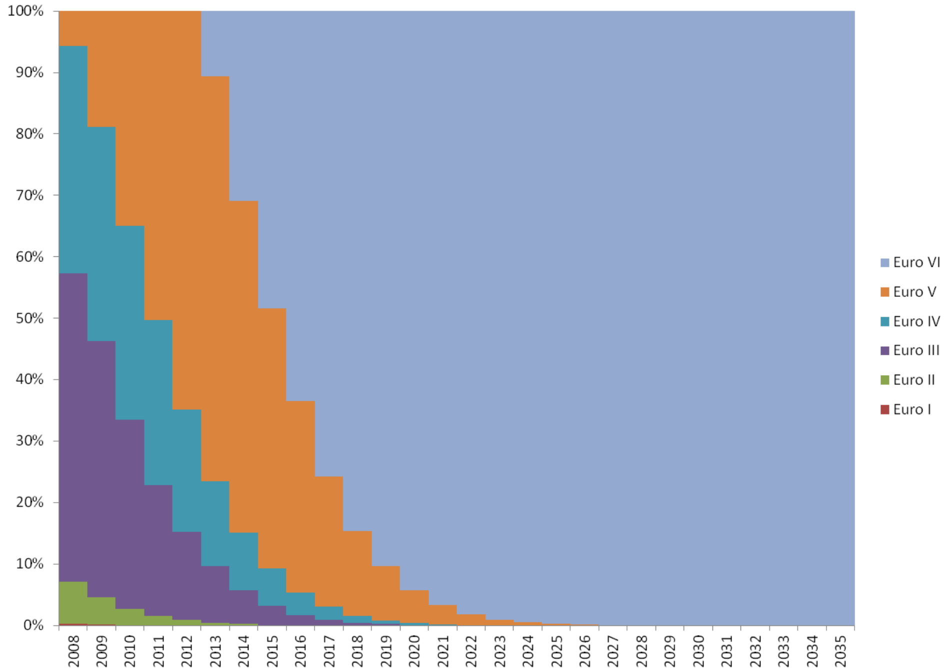

Figure A1.2: **Fleet Projections for Articulated HGVs outside London used in EFT**