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In Service CO2 and NOX Emissions of Euro 6/VI Cars, Light- and Heavy- dutygoods Vehicles in Real London driving: Taking the Road into the Laboratory.

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Abstract

Driving on-the-road has more frequent and prompt acceleration/decelerations than in the type-approval light-duty test conditions (NEDC), with Real Driving Emissions (RDE) of CO_2 and NO_X known to be considerably higher. Despite permissible limits of NO_X emissions at type approval reducing significantly, in-service emissions from diesel vehicles have, in reality, not reduced at all through the Euro 1–5 / I–V emission standards. TfL commissioned a programme of laboratory testing to better understand the in- service emission performance of Euro 6/VI vehicles over the TfL London Drive Cycle (LDC). This cycle was constructed from instrumented car data making repeated circuits of a set route at different times of day. Twelve Euro 6 passenger cars were tested over the entire 140 kms of the LDC from a warm-start. Three HGVs were tested over the suburban sub-cycle (40kms) in laden and un-laden condition.

NO_X emissions from the petrol cars were at a low level and below, or at, their type approval limit of 0.06 $g.km^{-1}$. Only one SCR equipped diesel car achieved NO_X emissions close to their 0.08 $g.km^{-1}$ type approval limit. NO_X emissions from diesel cars with only LNT NO_X controls were between 3 and 13 times higher than their type approval limit (conformity factors). A diesel supermini was emitting NO_X at the same level as the fully laden 40T artic HGV tested.

Keywords: real driving emissions (RDE), CO_2, NO_X, Euro 6/VI, laboratory testing.

1 Introduction

In Europe, all new vehicles must go through a process of type-approval to ensure that they conform to common standards. Part of this process includes standards for the control of emissions from the vehicle. The latest Euro 6 standards for diesel and petrol passenger cars

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came into force in September 2014, with NOX not to exceed 0.08 and 0.06 $g.km^{-1}$ respectively over the NEDC test.

The Euro 6 standard for emissions from light duty cars and vans was defined in UN ECE Regulation 715/2007. The main change is a reduction in the limit for NOX from diesel engines of 55 percent, whilst the other legislated emissions remain unchanged from Euro 5b. Euro 5b has been mandatory for new cars since January 2013 and introduced a particle number limit for diesel engines, the first time that a count of particles, rather than a total mass, has been regulated. Euro 6 petrol engine emissions limits are unchanged from Euro 5, except for the introduction of a particle number limit, in line with that of diesel engines.

European Regulation UN ECE 595/2009 introduces the Euro VI standard for heavy duty diesel engines. It reduces the limit for NOx emissions by 77 percent, whilst continuing to set demanding limits for control of particulates and other gases. In addition, the test protocol has been changed to broaden the range of speed/load conditions over which the engine must meet the emissions limits. This is followed up by a requirement to verify the emissions performance over a period of on-highway driving with portable emissions equipment (PEMS). Additionally, for Heavy Duty diesel engines, an ammonia (NH3) concentration limit of 10 ppm applies to diesel (WHSC + WHTC) and gas (WHTC) engines. This has been introduced to control ammonia slip from Selective Catalytic Reduction (SCR) systems used to control NOX emissions. A further proposed measure to limit the NO2 component of NOx emissions (known as primary NO2) may be defined at a later stage. Some Euro VI provisions, including an extended on-board diagnosis (OBD) and certain testing requirements are to be phased-in by 2016 for new types and 2017 for all new vehicles.

It is crucial that Euro 6/VI vehicles emit less NOX and other pollutants than their predecessors if London and Europe's air quality is to improve. It is especially important for central London that Euro 6/VI diesel vehicles are cleaner as it plans to operate the 'world's first' Ultra-Low Emission Zone (ULEZ), which will come into force on 7th September 2020. The plans follow a consultation on the proposed scheme in 2015 and 2016. The emission standard that diesel vehicles (cars, LGVs, HGVs and Bus/ Coach) must attain to drive without a charge in the zone is Euro 6/VI. Euro 4 (and newer) petrol cars and vans may drive without a charge in the zone as their NOX emission standard is at the same level or less than comparable Euro 6 diesel limits. The charge if a vehicle is not compliant with the ULEZ standard is expected to be £12.50 for light-duty and £100 for heavy-duty vehicles.

2 Objective

TfL commissioned a Programme of laboratory testing, carried out at Millbrook Proving Ground Ltd, to better understand the in-service emission performance of Euro 6/VI vehicles. A key objective for this work was to strengthen the evidence on the effectiveness of Euro 6/VI regulations in lowering vehicles NOX emissions in real London driving conditions.

3 Method

A laboratory testing approach was adopted so direct comparisons between vehicles could be carried out, and the results benchmarked against earlier testing of Euro 4/IV and 5/V (TfL, 2016). The test-cycle speed profile was created from real (observed) driving in London.

THE TfL LONDON DRIVE CYCLE

A 'London Drive Cycle' for light-duty vehicles has been developed by TfL as part of an on-going Vehicle Emission Study (TfL, 2016). The drive cycle was developed in association with www.millbrook.co.uk, who tracked a car (VBox GPS and CAN Bus link) being driven by an experienced driver, driving normally, making repeated circuits of a set route in the North-East of London (see Figure 1) at different times of day (AM peak, Inter-peak and in Free-flow conditions). The route contained sections of (urban) motorway, suburban and urban (central London) roads. The speed profiles for the (urban) motorway, suburban and urban sub-cycles are presented in Figure 2. The LDC doesn't consider fluctuations in road gradient i.e. it assumes that London is flat.

Figure 1. The TfL London Drive Cycle route
{Background © Copyright GoogleTM 2015}

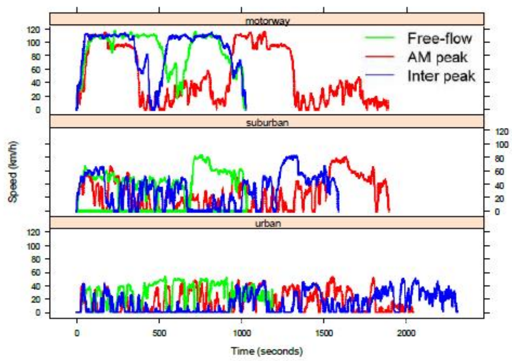

Figure 2. The London Drive Cycle Speed Profile
(a) motorway; (b) suburban; (c) urban.

The distribution of the LDC's speed, acceleration and VSP (Vehicle Specific Power - Jimenez- Palacios, 1999) are compared against the NEDC and WLTP cycles in Figures 3 and 4 respectively. In Figure 5 the VSP distribution for the AM peak, Inter-peak and Free-flow LDC sub-cycles are dis- aggregated. VSP sums the loads on an engine resulting from acceleration, aerodynamic drag, rolling resistance and hill climbing, which is divided by the mass of the vehicle. VSP therefore expresses in a single term an estimate of the work an engine is doing, per vehicle tonne mass, at any instance in a journey. Positive VSP have been found (Wyatt et al, 2014) to correlate well with fuel consumption and is now commonly applied in vehicle emission studies, particularly in the US (Liu et al, 2015). For clarity, idling periods (defined as vehicle speed < 0.5 ms^{-2} and acceleration in the range ± 0.1 ms^{-2}) are removed from the distributions. The proportion of time spent idling during the LDC, NEDC and WLTP cycles is 16.4, 13.1 and 27.2 % respectively. Summary statistics for the drive cycles are documented in Table 1.

Table 1. Drive-cycle summary.

Drive Cycle	Road Type	Time Period	Duration (seconds)	Distance (km)	Average Speed (km.h^{-1})	Maximum Acceleration (m.s^{-2})
TfL London Drive Cycle (LDC)	Urban	Free-flow	1202	8.92	26.73	2.67
		AM peak	2048	8.93	15.69	1.97
		Inter-Peak	2311	8.93	13.91	2.48
	Suburban	Free-flow	1036	13.33	46.31	2.4
		AM peak	1894	13.33	25.33	2.67
		Inter-Peak	1591	13.33	30.16	2.31
	Motorway	Free-flow	1023	24.61	86.60	1.62
		AM peak	1884	24.61	47.03	1.69
		Inter-Peak	1030	24.61	86.02	2.46
NEDC	-	-	1220	11.01	32.47	1.06
WLTP	-	-	1800	23.14	46.26	1.80

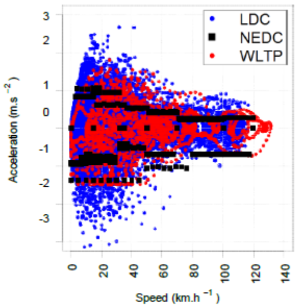

Figure 3. Distribution of Speed and Accelerations over the LDC, NEDC and WLTP cycles

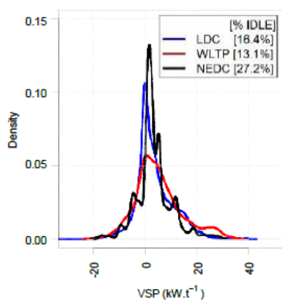

Figure 4. VSP density distributions for the LDC, NEDC and WLTP cycles (idling periods excluded)

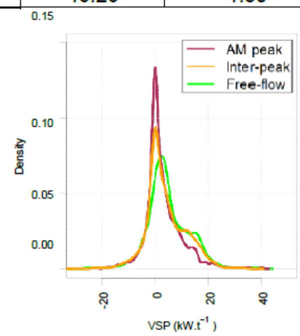

Figure 5. VSP density distributions for the LDC in Free-flow, AM- and Inter-peak periods (idling periods excluded)

The LDC covers a broad range of low and high speed driving conditions, with maximum accelerations in all but the motorway sub-cycles greater than those in the WLTP (and therefore NEDC). The LDC VSP range (positive and negative) is also greater than the WLTP. This indicates the London test driver is driving slightly more aggressively than driving represented in the WLTP when road space is available to do so. However in London AM peak and even Inter-peak periods there is little opportunity to drive freely, instead being limited to the behavior of the processions of vehicles circulating the UK's capital City. This explains why the proportion of time spent with the engine under moderately high power demands (VSP in the range 20 – 30 kW.t^{-1}) in the LDC is lower than on the WLTP. Pellecuer et al's (2016) analysis of high resolution vehicle telematics data also found that in high demand, slow moving traffic conditions drivers' behaviour was constrained, with lower VSP than the norm. The LDC is considered to be a long (140kms) real-driving cycle, representative of vehicle speed profiles on heavily trafficked UK and perhaps European city streets.

LABORATORY TESTING

The Euro 6 passenger cars were tested over the entire 140 kms of the LDC from a warm-start in the Millbrook Vehicle Emission testing laboratories that meet the requirements of Directive 2007/46 EC Article 41, Section 3 and have been designated as a Category A Technical Service for Individual Vehicle Approvals (IVA). The sample of 12 passenger cars included a range of:

- Powertrains | petrol (2), diesel (9) and petrol-HEV (1);

- Exhaust after-treatments | 3 way Cat, LNT and SCR;
- Market segments | Compact, Supermini, Small family, Family/MPV, SUV/4x4, Prestige/sports and Hybrid; and
- Marques | BMW, Fiat, Lexus, Mercedes, Peugeot, Volvo and Volkswagen.

Three Heavy-Goods Vehicles (HGVs) were tested over the suburban sub-cycle (only) in both laden and un-laden conditions. The vehicles included: Rigid HGV N2 7500kg, Rigid HGV N3 18000kg and Artic HGV N3 40000kg.

4 Results

PASSENGER CARS

The passenger car average NOX and CO2 emission performance in relation to their type-approval figure are illustrated in Figure 6. The data is also documented in Table 2. NOX emissions from the petrol cars were at a low level and below or at their type approval limit of 0.06 g.km^{-1}. The petrol-HEV was an order of magnitude cleaner than the petrol-ICE's. Only one SCR (selective catalytic reduction) equipped diesel car achieved NOX emissions close to their 0.08 g.km^{-1} type approval limit. There was significant variation in the NOX performance of the diesel cars equipped with only LNT (Lean NOX Trap) NOX controls (conformity factors 2.9 - 13.2). The average Euro 6 diesel car NOX emission factor over the 'real' LDC speed profiles was 0.36 g.km^{-1}. This is less than its predecessors but 4.5 times greater than their type approval limit (Laboratory, NEDC).

The average NOX and CO2 results are presented for each road type (motorway, suburban, urban) and time period (AM peak, Inter-peak and Free-flow) in Figure 7. The impact of driving conditions (time of day) on the discrepancy between the measured and type-approval CO2 figures is greatest in the urban setting. In the AM and Inter-peak periods speeds fall from the Free-Flow average of 26.8 km.h^{-1} to 15.7 and 13.9 km.h^{-1} respectively. The increased frequency of stop-start motions (see Figure 2) in the AM and Inter-peak periods come with a fuel and therefore CO2 penalty. The petrol-HEV has the lowest discrepancy between the type-approval CO2 figure and measured values for the slower LDC urban AM and Inter-peak sub-cycles. This is expected as the hybrid powertrain captures and re-uses energy that would have otherwise been lost under braking. The benefit of the HEV powertrain is greatest in more intensive stop-start driving conditions.

The single high NOX emitting Euro 6 diesel super-mini performs worst in the urban (central London) driving conditions tested. It is concerning that the diesel super-mini with poor NOX exhaust controls emitted so much of a critical air pollutant in normal urban driving conditions. In urban areas population density and therefore exposure to associated air pollution is considerably higher, such as in central London. This is exacerbated by high buildings restricting the dispersion of vehicle emissions from streets.

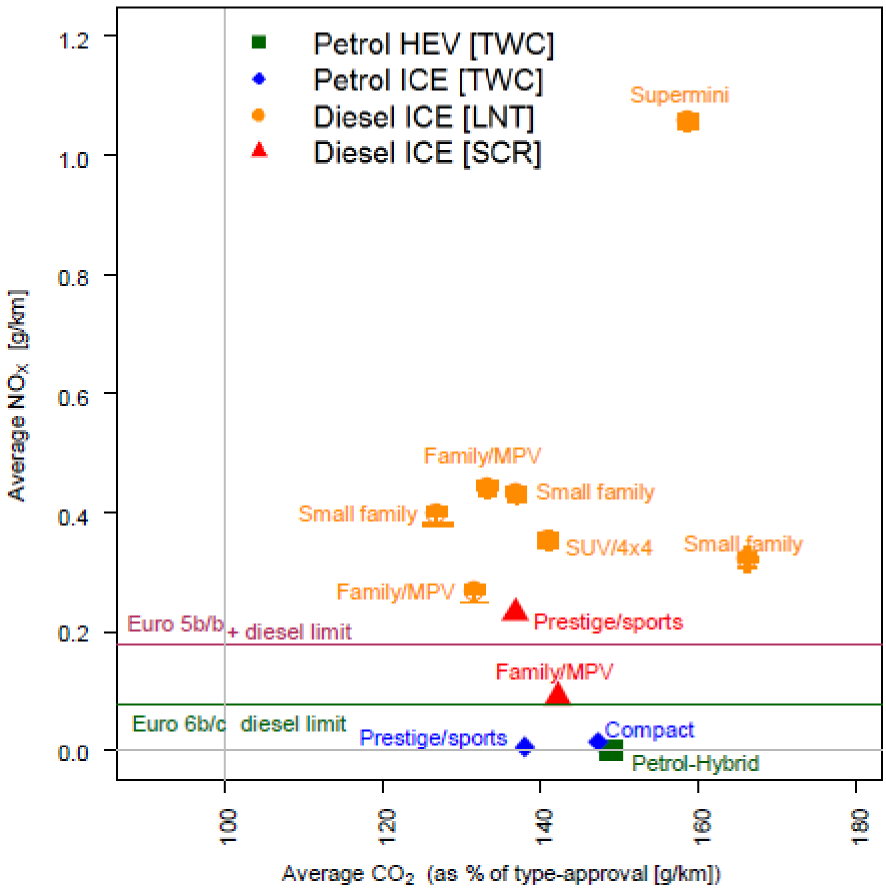

Figure 6: The Euro 6 passenger car average NOX and CO2 emissions in relation to their type-approval over the TfL London Drive Cycle

Table 2: Euro 6 passenger cars tested and summary results recorded over the urban and suburban sections of the LDC

Market		**Trans-**	**Emission**	**type- approval**	**verage CO2**	**CO2 as % type-**	**Average NOX**	**f-NO2**
Compact	Petrol-	CVT	3 way	82	122	149	0.0004	N/a
Compact	Petrol	Manual	3 way	99	146	147	0.0151	N/a
Prestige/sport	Petrol	Auto	3 way	195	269	138	0.0066	N/a
Small family	Diesel	Auto	LNT	111	141	127	0.399	0.347
Small family	Diesel	Manual	LNT	98	134	137	0.433	0.336
Family/MPV	Diesel	Manual	LNT	107	141	132	0.268	0.218
Family/MPV	Diesel	Manual	LNT	109	145	133	0.443	N/a
Small family	Diesel	Manual	LNT	97	161	166	0.321	N/a
SUV/4x4	Diesel	Auto	LNT	124	175	141	0.353	N/a
Supermini	Diesel	Manual	LNT	88	140	159	1.059	N/a
Prestige/sport	Diesel	Auto	SCR	110	151	137	0.232	0.609
Family/MPV	Diesel	Auto	SCR	103	147	142	0.090	0.308

There was a high variability in the primary NO2 emissions from diesel cars and between driving conditions as illustrated in Figure 8, with averages documented in Table 2. Primary NO2 emissions from petrol cars were at a low-level, around the lower-detectable limit of the test bench so are not reported. The NO2 fraction of total NOX was only speciated for 5 of the 9 diesel passenger cars tested. The fraction of NOX emissions emitted as NO2 (termed f-NO2) from one SCR equipped diesel car exceeded 0.8 in free-flow motorway driving, falling to 0.4 in congested urban conditions. The average diesel car f-NO2 was 0.363. There was no discernable relationship between f-NO2 and speed/ acceleration or VSP.

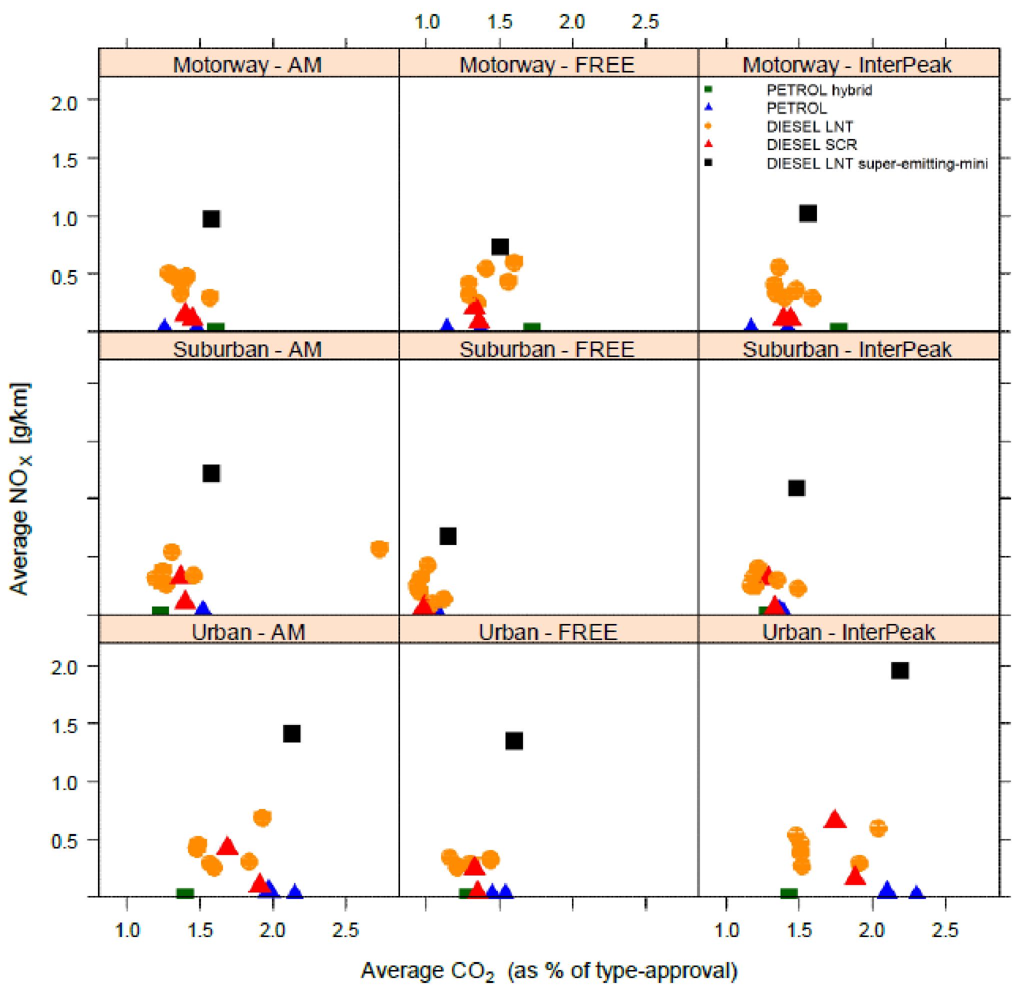

Figure 7: The Euro 6 passenger car average NOX and CO2 emissions in relation to their type-approval over the TfL London Drive sub-Cycles (top-row) motorway; (middle-row) suburban; (bottom-row) urban, (left-column) AM peak; (middle-column) Free-Flow; (right-column) Inter-a peak

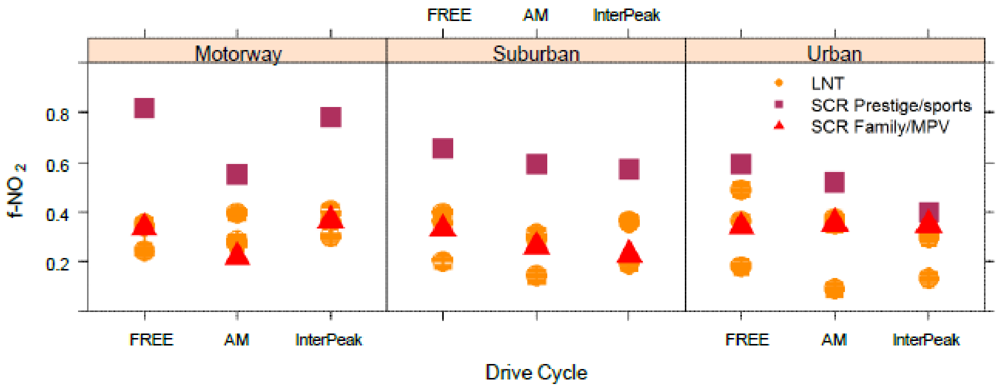

Figure 8: The fraction of NOX emissions emitted as NO2 (f-NO2) for Euro 6 diesel passenger cars
(a) motorway; (b) suburban; (c) urban

The sensitivity of CO2 and NOX emission rates (grams.sec^{-1}) relative to the load on the engine for one illustrative diesel passenger car (annotated * in Table 2) are explored in Figures 9 and 10 respectively. This analysis is conducted to illustrate the influence a more aggressive driving style (drive cycle) would have on emissions. In Figure 9 the second-by-second emission rates are plotted against the calculated VSP for that instant (second). The measurements are also grouped by driving mode (idle, acceleration, cruise and deceleration). The driving mode definitions proposed by Frey et al (2003) are used:

- Idle | Vehicle speed < 0.5 ms^{-2} and Acceleration in the range ± 0.1 ms^{-2};
- Cruise | Vehicle speed > 0.5 ms^{-2} and Acceleration in the range ± 0.1 ms^{-2};
- Acceleration | > 0.1 ms^{-2}; and
- Deceleration | < - 0.1 ms^{-2}.

As reported by Frey et al (2003) and Wyatt et al (2014), positive VSP correlates well with instantaneous fuel consumption and CO2 emissions. As expected, higher power demands and therefore emission rates of CO2 are seen when the vehicle is accelerating. For the vehicle speeds, rates of acceleration and VSP range of the LDC, the correlation of positive VSP with CO2 is linear. The NOX emission rate increases exponentially with positive VSP. This analysis and data illustrates that NOX emissions are much more sensitive to driving style than fuel consumption / CO2 emissions.

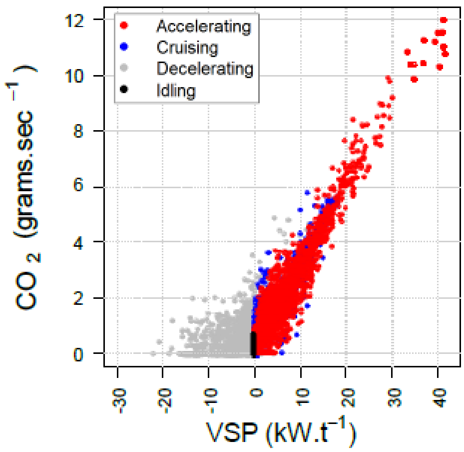

Figure 9. The influence of VSP on CO_2 emission rates for an illustrative (*) Euro 6 diesel small family car (by driving mode)

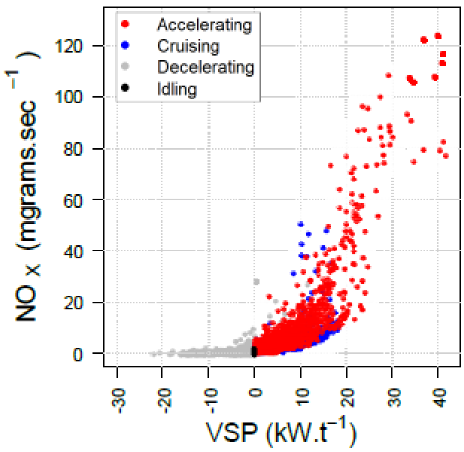

Figure 10. The influence of VSP on NO_X emission rates for an illustrative (*) Euro 6 diesel small family car (by driving mode)

HEAVY GOODS VEHICLE

Three HGVs were tested over the suburban cycle (only) in both laden (fully) and un-laden condition. As the Millbrook VTEC laboratory is only capable of 20,000kgs inertia simulation the larger 40T class N3 HGV was tested using a PEMS (Portable Emission Measurement System) with the vehicle following the drive cycle whilst driving on the large, flat circular track at the Millbrook testing ground. The summary results are presented in Table 3. A total PM measure was only available for the combined AM peak and Free-flow suburban sub-cycles. No NOX recording was available for the for the N3 rigid 18000kg un-laden Free-flow suburban sub-cycle.

The levels of PM emissions remained consistent regardless of payload, controlled by the diesel particulate filter (DPF). It is interesting to note that the NOX emissions are considerably lower in the fully loaded condition for each vehicle type. This may be attributed to the increased engine exhaust temperatures on the laden vehicle allowing for more effective dosing of the SCR catalyst. In a number of cases, these cycle average emission levels are almost as low as those of diesel passenger cars, indicating the effectiveness of Euro VI (heavy-duty) at controlling NOx from heavy-duty engines, under the right conditions.

NOX emissions from the three HGVs tested were highest when un-laden vehicles were driven in AM peak driving conditions with frequent stops-and-starts and extended idling periods. The change in NOX emissions from laden to un-laden, and between AM peak and Free-flow conditions, was greatest for the 40T N3 artic. In fully laden (GVW 40 tonnes) NOX emissions were at a moderate level of moderate level in the AM peak, roughly halving when completing the same route in Free-flow traffic conditions as less fuel intensive stops-and-starts are undertaken. When running empty (un-laden) NOX emissions are at a low-level, around the Euro 6 emission standard for a category N1-III Light- Commercial Vehicle (1750 – 3500kg GVW). When the same vehicle follows the same route in congested AM peak driving conditions, NOX emissions increase 18 times. This analysis indicates Euro VI emission controls are now able to control NOX emissions in all but extreme low average engine load situations, when the

SCR is not able to maintain an operational/ effective temperature.

Table 3. Euro VI HGV tests and summary results over the suburban AM peak and Free-flow sub-cycles of the LDC

HGV class	**GVW (kg)**	**Fuel**	**Loading**	**LDC suburban phase**	**Average Speed ($km.h^{-1}$)**	**NOX ($grams.km^{-1}$)**	**CO2 ($grams.km^{-1}$)**	**PM ($grams.km^{-1}$)**
N2 rigid	7500	Diesel	0 %	AM	25.3	1.082	356.5	
				FreeFlow	46.2	0.271	289.6	
			TOTAL		32.7	0.676	323.1	0.003
			100 %	AM	24.6	0.472	546.7	
				FreeFlow	45.3	0.177	419.7	
			TOTAL		31.9	0.325	483.2	0.003
N3 rigid	18000	Diesel	0 %	AM	25.0	0.776	774.1	
				FreeFlow	46.0	N/a	569.7	
			TOTAL		32.4	N/a	671.9	0.006
			100 %	AM	24.6	0.798	1024.5	
				FreeFlow	45.2	0.128	758.7	
			TOTAL		31.9	0.463	891.6	0.007
N3 artic	40000	Diesel	0 %	AM	25.1	2.473	995.8	
				FreeFlow	45.8	0.137	731.5	
			TOTAL		32.4	1.305	863.7	0.007
			100 %	AM	24.4	1.559	2075.0	
				FreeFlow	45.2	0.818	1519.9	
			TOTAL		31.8	1.188	1797.4	0.007

5 Summary and Conclusions

It can be seen from this analysis of test results that, in urban driving, Euro 6 petrol cars emit very low levels of NOX. Diesel cars at Euro 6 show a significant improvement over those at Euro 5. Some models of light-duty diesel vehicles may require re-calibration to satisfy the RDE protocol for emission verification, which is expected to be introduced from 2017 onwards, and for all new cars from 2019 following the introduction of a new World Light Duty Test Protocol (WLTP) in 2017. It is understood that conformity factors for the RDE testing have been agreed with the European Commission, to be phased in in two stages (initially 2.1 moving to 1.5 later), but that some important details such as 'dynamic boundary conditions' for the testing are still to be finalized This process will be similar to that already in place for heavy duty engines where substantial reductions in real-world NOX emissions have been observed.

TfL has also tested examples of heavy-duty buses (MLTB cycle) and heavy-duty goods vehicles (TfL Suburban Cycle) at Euro VI. In each case, the results have been impressive, with emissions of NOX significantly reduced from vehicles at Euro V. This is especially true at lower road speeds, which is clearly advantageous for urban and suburban areas. Heavy-duty Euro VI emission controls on the sample of tested vehicles were found to be able to control NOX emissions in all but the most extreme low average engine load situations i.e. empty running (un-laden) in congested driving conditions. As the SCR is not able to maintain an operational/ effective temperature NOX emissions were found to increase by an order of magnitude. Sustainable road freight management and logistics should therefore avoid running HGVs empty in peak periods, preventing unnecessarily high emissions of NOX.

One area of concern, and for possible further research, is that of primary NO2 emissions. This is the fraction of total NOX which is constituted of NO2 at the point that it leaves the vehicle tailpipe. There are suggestions that this may be more important when considering human exposure in urban streets than the emissions of NO (which later oxidise in the atmosphere to form secondary NO2). Some diesel exhaust after-treatment systems increase the fraction of total NOX which is NO2, despite reducing the total mass emission of NOX. There are discussions at the European Commission about a potential primary NO2 limit, which may even constitute a future Euro standard (Euro VII ?).

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