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Toward reconciling instantaneous roadside measurements of light duty vehicle exhaust emissions with type approval driving cycles.

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ABSTRACT A method is proposed to relate essentially instantaneous roadside measurements of vehicle exhaust emissions, with emission results generated over a type approval driving cycle. An urban remote sensing dataset collected in 2008 is used to define the dynamic relationship between vehicle specific power and exhaust emissions, across a range of vehicle ages, engine capacities, and fuel types. The New European Driving Cycle is synthesized from the remote sensing data using vehicle specific power to characterize engine load, and the results compared with official published emissions data from vehicle type approval tests over the same driving cycle. Mean carbon monoxide emissions from petrol cars ≤3 years old measured using remote sensing are found to be 1.3 times higher than published original type approval test values; this factor increases to 2.2 for cars 4 – 8 years old, and 6.4 for cars 9 – 12 years old. The corresponding factors for diesel cars are 1.1, 1.4, and 1.2 respectively. Results for nitric oxide, hydrocarbons and particulate matter are also reported. The findings have potential implications for the design of traffic management interventions aimed at reducing emissions, fleet inspection and maintenance programs, and the specification of vehicle emission models.

INTRODUCTION

Exhaust emissions from road vehicles continue to be a significant source of atmospheric pollution. In European cities, emissions of particulate matter (PM) and oxides of nitrogen (NO_x) from road traffic are of particular concern in the context of their impact on public health.[1] The European Parliament has introduced legislation relating both to the emissions characteristics of new vehicles for type approval (also known as vehicle certification), and for ambient air quality.[2,3] This legislation has been implemented in the domestic laws of member states of the European Community such as the United Kingdom.[4,5] The introduction of limit values (g/km) for polluting emissions (CO, HC, NO_x, and particulate matter) in exhaust gases (commonly referred to as 'Euro' standards) for new vehicle type approval in Europe has reduced emissions of some pollutants progressively since the adoption of the Euro 1 standard which implemented closed loop three-way catalytic converters for light vehicles in the early 1990's.[6] The Euro 5 standard came into force in January 2011, applicable to the registration and sale of new light vehicles, and Euro 6 is due to be implemented in January 2015.[2]

Whilst the progressive tightening of exhaust emission standards for vehicle type approval over time has been successful in reducing the emissions of some pollutants, the reliance on legislated driving cycles (such as the New European Driving Cycle, or NEDC) to assess vehicle emissions has been criticized because of the differences between the specification of the laboratory based driving cycle, and the 'real-world' operation of vehicles which encompasses a range of confounding factors such as variability in highway design and operation, variation in ambient conditions, influence of other road users, and variability in driver behavior.[7,8,9] A better understanding of the 'in-use' exhaust emissions characteristics of the vehicle fleet has been achieved in recent years using remote sensing techniques.[6,10] However, an analytical challenge has been to relate essentially instantaneous (typically circa 500 millisecond) roadside measurements of exhaust gases from remote sensing in terms of concentrations (ppm) or grams per kilogram (kg) of fuel burnt, to those observed over a type approval driving cycle in laboratory conditions quantified (for the purposes of the European statutory limit values) in units of grams per kilometer (g/km).[2]

This paper utilizes an urban remote sensing dataset collected in London, United Kingdom in 2008, to determine the relationship between vehicle dynamics and exhaust emissions. The paper uses the concept of vehicle specific power (VSP), characterizing vehicle engine load, to facilitate this linkage.[11] The NEDC is synthesized from the remote sensing data using VSP (by Euro standard, engine capacity, and fuel type), and the emission results compared with data from vehicle type approval tests over the same driving cycle, with a view to moving towards a reconciliation of these measurement techniques. The development of such a reconciliation will help policy makers to arrive at a more coherent and holistic interpretation of the available data relating to road vehicle exhaust emissions, thereby helping to inform future policy interventions relating to both vehicle type approval and local air quality management. It will also assist in determining the rate and extent of changes in vehicle exhaust emissions with respect to vehicle age and fuel type, relative to original type approval performance, informing fleet inspection and maintenance programs, and the development of vehicle emissions models.

EXPERIMENTAL

This section describes (1) the remote sensing surveys; (2) vehicle specific power; (3) the European type approval driving cycle; (4) derivation of emission values over a synthesized driving cycle; and (5) reconciliation of remote sensing emissions data with published vehicle type approval (certification) data.

Remote Sensing Surveys. The remote sensing survey campaign in London in 2008 has been described elsewhere in the literature[6], so the description here will be limited to a brief overview. The surveys were carried out at 13 urban sites (speed limit 30mph) in the period from March to August 2008 using a commercial AccuScan™ 4600 remote sensing device (RSD). The instrument measured three exhaust gas ratios; CO/CO_2, HC/CO_2, and NO/CO_2. These measured ratios are utilized to produce estimates of grams of pollutant per kg of fuel burnt, following the form used by Pokharel et al (2002) and Burgard et al (2006).[12,13]

$$\frac{gCO}{kgFuel} = \frac{28 \times Q \times 860}{(1 + Q + (2 \times 3Q')) \times 12} \qquad (1)$$

$$\frac{gHC}{kgFuel} = \frac{2 \times 44 \times Q' \times 860}{(1 + Q + (2 \times 3Q')) \times 12} \qquad (2)$$

$$\frac{gNO}{kgFuel} = \frac{30 \times Q'' \times 860}{(1 + Q + (2 \times 3Q')) \times 12} \qquad (3)$$

where $Q = \frac{CO\%}{CO2\%}$, $Q' = \frac{HC\%}{CO2\%}$, and $Q'' = \frac{NO\%}{CO2\%}$

This assumes a fuel carbon fraction of 86%, 12g/mole for carbon, 28g/mole for carbon monoxide, 44g/mole for HC, 30g/mole for nitric oxide, and 3 carbon atoms per molecule of fuel (propane). A factor of 2 is applied to Q' because the non-dispersive infrared HC measurement calibrated with propane determines only around 50% of the HC mass compared to the flame ionization detector (FID) techniques used in the NEDC type approval test.[14] The RSD instrumentation also reports a 'smoke number', recorded in units of grams of diesel particulate matter per 100 grams of fuel, based on opacity measurements made at ultraviolet wavelengths in the 230 nm UV spectral range.[15,16]

In addition to exhaust emission data, the survey instrumentation measured vehicle speed and acceleration, and photographed each vehicle so that the license plate could be recorded. The vehicle license plates were cross referenced against the UK Driver and Vehicle Licencing Agency vehicle registration database in order to determine relevant technical information for each observed vehicle, including classification, age, and fuel technology. The date of manufacture of the vehicle was used to estimate the European emission standard for passenger cars as follows: 'Pre-Euro', pre 1993; 'Euro 1', 1993-1996; 'Euro 2', 1997-2000; 'Euro 3', 2001-2005; and 'Euro 4', 2006-2008.[6]

Vehicle Specific Power. VSP is a commonly used metric of engine load, being a function of vehicle speed, acceleration, drag coefficient, tire rolling resistance, and highway gradient. The United States Environmental Protection Agency defines VSP in units of kilowatts (kW) per ton as:

$$VSP = 4.39 \sin(slope)\, v + 0.22va + 0.0954v + 0.0000272v^3 \qquad (4)$$

where slope is the road grade in degrees, “v” is vehicle speed in mph, and “a” is vehicle acceleration in mph/s.[11] VSP was calculated using Equation (4) for each remote sensing observation where data permitted.

European Type Approval Driving Cycle. The current European type approval driving cycle (NEDC), comprises (from a cold start) four repeated identical urban cycles of 195 seconds duration each, followed immediately by an extra-urban cycle of 400 seconds duration, resulting in a total cycle time of 1180 seconds. Each urban cycle has a theoretical distance of 1.013 km, and the extra-urban cycle has a theoretical distance of 6.955 km, resulting in a total test distance of 11.007 km. The average speeds of the urban and extra-urban cycles are 19 kilometers per hour (kph), and 62.6 kph respectively. Gear selection and change points are specified for manual transmissions. During application, a tolerance of ±2 kph is permitted between the indicated speed and the theoretical speed during acceleration, during steady speed, and during deceleration when the vehicle's brakes are used. The time tolerance is ±1.0 seconds, applicable equally at the beginning and at the end of each required gear change.[2] The NEDC speed and acceleration profiles are illustrated in Figures 1(a) and 1(b), and the calculated resultant VSP for the driving cycle from Equation (4) is presented in Figure 1(c). During the urban cycle, the mean VSP is 1.39 (maximum 11.73, minimum -5.73); during the extra-urban cycle, the mean VSP is 6.54 (maximum 28.66, minimum -16.83); the mean VSP for the total NEDC is 3.14.

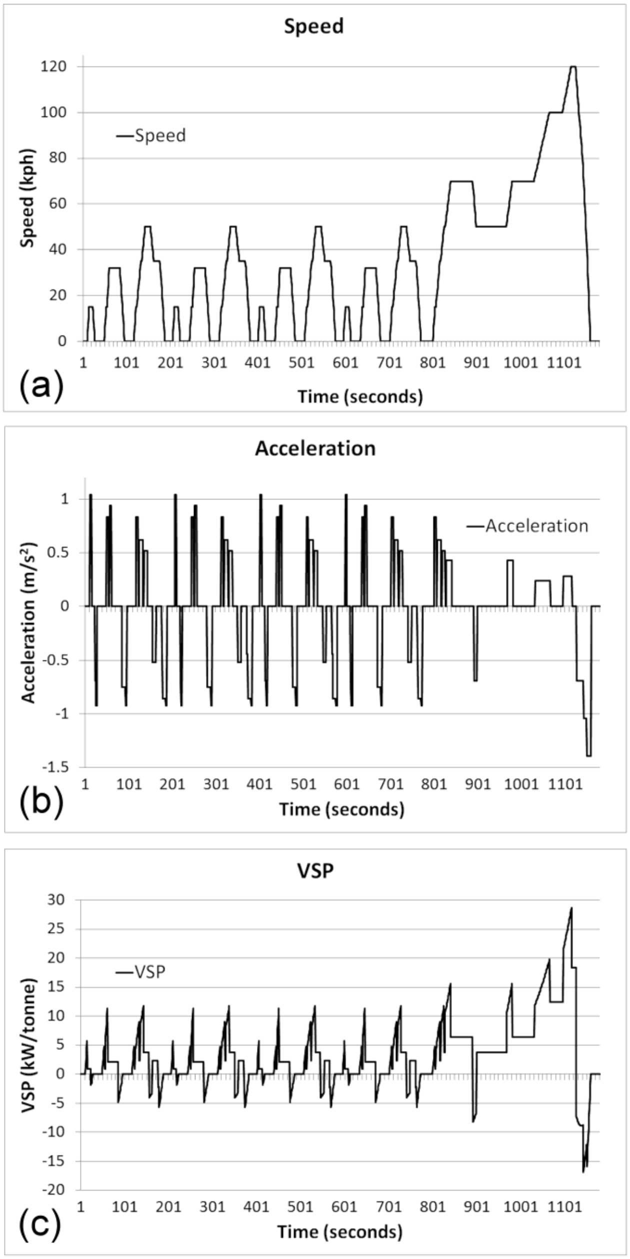

Figure 1. New European Driving Cycle: Profiles with respect to time for (a) speed, (b) acceleration, and (c) Vehicle Specific Power.

Derivation of Emission Values over a Synthesized Driving Cycle. The frequency distribution of VSP over the NEDC is derived at a resolution of 2 (i.e. in VSP bins of 0<VSP≤2, 2<VSP≤4….18<VSP≤20, VSP>20). This could in principle be carried out at a higher or lower level of resolution depending on data availability. The mean emission rates derived from the remote sensing surveys for the respective VSP bins are then applied to the NEDC frequency distribution, and these are then summed (in this case at a frequency of 1Hz) to provide an estimate of the emission rate over the total driving cycle (Equation 5). In practice, the remote sensing data were classified not only by fuel type (petrol, diesel), and Euro standard (Euro 2, Euro 3, and Euro 4), but also by engine capacity.

$$Emis_{DC} = (F_{B1}.E_{B1} + F_{B2}.E_{B2} + ...F_{Bn}.E_{Bn}) / \sum_{B1}^{Bn} F \qquad (5)$$

where $Emis_{DC}$ = mean emissions rate over the synthesized driving cycle (grams/kg of fuel); F = frequency of occurrence of the VSP value in bins $_{B1..Bn}$ over the driving cycle; and E = mean emissions rate (grams/kg of fuel) associated with the VSP value in bins $_{B1..Bn}$ derived from the remote sensing data.

Reconciliation of remote sensing emissions data with published vehicle type approval (certification) data. The UK Vehicle Certification Agency (VCA) publish exhaust emission and fuel consumption test results for vehicles which have undergone the type approval test over the NEDC.[17] Data are available for tests from year 2000 onwards. The VCA data include the following variables: manufacturer; model and description; transmission; engine capacity; fuel type; Euro standard (Euro 2 onwards); fuel consumption over the test cycle (urban, extra-urban, and combined in liters/100km); and exhaust emissions (g/km) over the combined test cycle (CO, HC, HC+NO_x, NO_x, and PM, depending on the prevailing Euro standard). The VCA data were cleaned to remove any exact duplicate records in the data set, and were categorized according to fuel type, Euro standard, and engine capacity (using the commonly used European Environment Agency engine capacity classifications; petrol engines <1.4 liters, 1.4-2.0 liters, and >2.0 liters; diesel engines <2.0 liters, and > 2.0 liters).[18] Since both fuel consumption (liters/100km) and emissions (g/km) are available over a known driving cycle distance (11.007 km) for each vehicle tested, it is possible to calculate exhaust pollutant emissions in units of grams / liter of fuel consumed over the combined cycle. The European type approval process specifies fuel density (diesel 833 – 837 kg/m^3 at 15°C; petrol 740 – 754 kg/m^3 at 15°C), and also stipulates that test vehicles must undergo preconditioning at between 20-30 degrees C prior to testing.[2] Therefore, assuming fuel density at 15°C of 747 kg/m^3 (petrol) and 835 kg/m^3 (diesel), a mean test temperature of 25°C, and estimates of coefficients of thermal expansion of fuel (petrol 0.00095 per degree C; diesel

0.00083 per degree C), it is possible to convert grams of pollutant per liter of fuel into units of grams of pollutant per kilogram of fuel for the VCA test results.[19] This permits direct comparison with the exhaust pollutant emission rates calculated over the synthesized NEDC using the remote sensing data (based on emissions rate per VSP bin).

RESULTS AND DISCUSSION

Overall, 119,319 vehicles were observed passing through the remote sensing survey sites, of which 54,599 had valid emissions measurements and vehicle identification, across all vehicle types. The mean vehicle speed through the survey sites was 32.4 kilometers per hour (kph) (std. deviation 9.1kph), and the mean vehicle acceleration was +0.2 m/s^2 (std. deviation 0.6m/s^2).

Figure 2 provides an illustrative example of the relationship between VSP and emissions of nitric oxide from diesel powered passenger cars observed in the remote sensing surveys. Figure 2(a) presents data for Euro 3 diesel passenger cars, and Figure 2(b) presents data for Euro 4 diesel passenger cars, in units of grams of nitric oxide per kg of fuel. VSP has been aggregated into bins at intervals of two from -10 to +20. Most observations lie in the VSP range -4 to +14, as indicated by the increasing height of the confidence intervals at each tail (high and low) of the distribution. Whilst both groups of vehicles present a similar positive relationship between VSP and emissions when VSP is greater than 2, the absolute level of nitric oxide emissions from the Euro 4 vehicles is significantly lower according to a pair wise Mann Whitney test (Euro 4 un-weighted mean 4.2g/kg; Euro 3 un-weighted mean 6.9g/kg).[6]

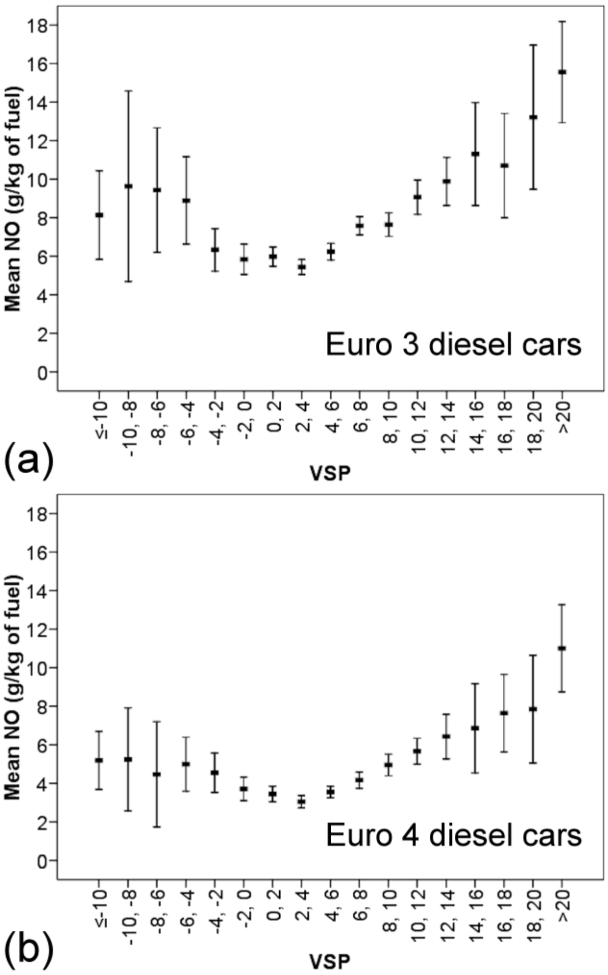

Figure 2. Mean nitric oxide emissions (grams per kg of fuel) by VSP bin for observed diesel passenger cars; (a) Euro 3 emissions standard, and (b) Euro 4 emissions standard. Error bars indicate 95% confidence level about the mean.

Figures 3a and 3b present the frequency distribution of VSP observed from the light vehicles in the remote sensing surveys (mean VSP 4.28), and the frequency distribution of VSP in the total NEDC (mean VSP 3.14) respectively. The range of VSP values observed in the remote sensing surveys encompasses the range of VSP values generated by the driving cycle, although the different operating phases in the NEDC result in a distribution with more than one mode, whereas the VSP distribution from the remote sensing surveys has only one mode. If one considers only the urban cycles within the NEDC (780 seconds), the resultant mean VSP is 1.39 (standard deviation 3.31, n=780) as noted previously. Therefore, notwithstanding the fact that the total NEDC includes an extra-urban element (with speeds up to 120 km/h), the frequency distribution of VSP over the total NEDC (1180 seconds), and in particular the mean, resembles more closely the observed urban RSD data than the urban element of the NEDC alone. This is not surprising given that the survey sites were located to observe moving traffic (ideally under load), whereas the urban element of the NEDC contains stops when the engine is idling.

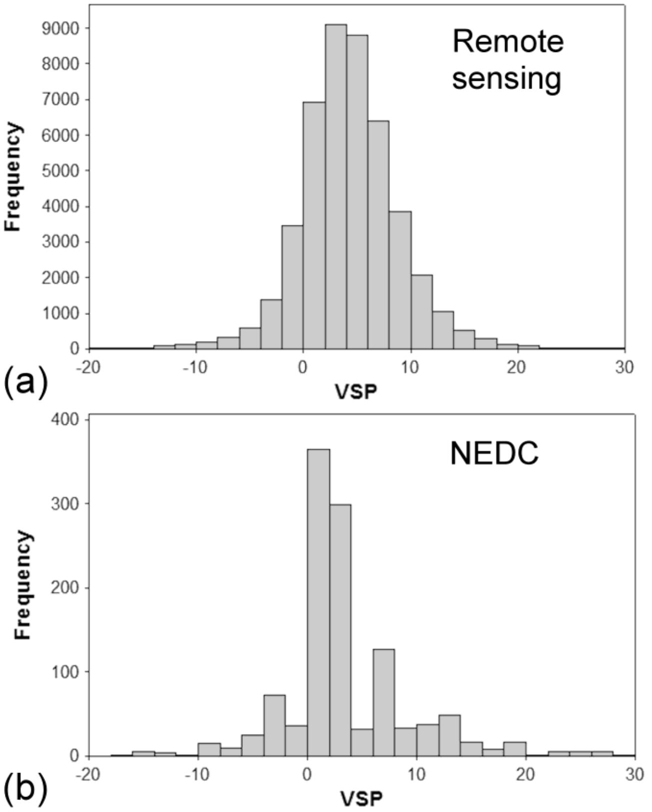

Figure 3. Comparison between (a) the frequency distribution of VSP observed from the light vehicles in the remote sensing surveys (mean VSP 4.28, standard deviation 5.04, n=45,855), and (b) the frequency distribution of VSP in the total NEDC (mean VSP 3.14, standard deviation 6.02, n=1,180).

Table 1 presents an illustrative example of the application of Equation (5), calculating the mean emissions rate over the synthesized driving cycle (Emis_{DC}) in units of grams of pollutant per kg of fuel, again using data for Euro 3 and Euro 4 diesel passenger cars. Where appropriate, VSP bins have been subdivided by acceleration state (negative, zero, positive), and the subdivisions populated with emission rates where the data permits, to reflect the potential differences in mean emissions rates which occur with differing acceleration rates within the same VSP bin.

Table 1. Example derivation of mean emission rates of nitric oxide for a synthesized NEDC from the observed remote sensing observations.

VSP Bin	**Acceleration**	***F***	***E* (Nitric oxide g/kg, Euro 3 diesel car)**	***E* (Nitric oxide g/kg, Euro 4 diesel car)**
<-10	Negative	12	8.14	5.19
-10 to -8	Negative	16	9.64	5.24
-8 to -6	Negative	10	9.44	4.46
-6 to -4	Negative	25	8.89	5.00
-4 to -2	Negative	73	6.34	4.55
-2 to 0	Negative	50	5.84	3.71
	Zero	280		
0 to 2	Zero	50	5.72	3.42
	Positive	22	6.80	3.50
2 to 4	Zero	277	4.27	2.89
	Positive	22	5.61	3.06
4 to 6	Positive	32	6.24	3.55
6 to 8	Zero	100	7.58	4.17
	Positive	28		
8 to 10	Positive	34	7.64	4.95
10 to 12	Positive	38	9.07	5.67
12 to 14	Zero	30	9.89	6.43
	Positive	19		
14 to 16	Positive	17	11.31	6.86
16 to 18	Positive	8	10.70	7.64
18 to 20	Zero	10	13.22	7.85
	Positive	7		
>20	Positive	20	15.56	11.01
		$\Sigma F_{B1..Bn}$ =1180	**$Emis_{DC}$ = 6.59g/kg**	**$Emis_{DC}$ = 4.12g/kg**

Table 2 presents the comparison between petrol car mean emission rates obtained from VCA NEDC type approval tests, and emission rates derived from remote sensing data over a synthesized NEDC ($Emis_{DC}$). Table 3 presents a similar comparison for diesel cars. When interpreting these results, a number of important caveats should be noted. Firstly, the remote sensing device used in the surveys in London in 2008 measured nitric oxide (NO), whereas the type approval test measures total oxides of nitrogen (NO_x). Differences in NO and NO_x emissions may be expected, particularly in newer diesel cars as the proportion of primary NO_2 in total NO_x increases. Recent studies suggest that the proportion of primary NO_2 in total NO_x in diesel car exhaust is in the range 11-14% at Euro 2, increasing to approximately 55% at Euro 4. In contrast, the proportion of primary NO_2 in total NO_x in petrol car exhaust is estimated to be in the range 1-4%, with higher values for petrol cars with direct injection fuel systems.[20,21,22] Secondly, European legislation stipulates that emissions of oxides of nitrogen (NO_x) are expressed in nitrogen dioxide (NO_2) equivalent values.[23] A conversion from NO to NO_2 equivalent values (assuming a factor of 46/30) for the remote sensing data is included in Tables 2 and 3. Thirdly, the estimation of particulate matter based on opacity measurements in the remote sensing surveys differs fundamentally from the gravimetric approach used in the NEDC tests, so comparisons of trends within the two data sources may be more appropriate than direct comparisons between the two data sets. Fourthly, the calculated mean emission values in the VCA data set are measures of central tendency across the vehicles tested by VCA in the laboratory, whereas the mean calculated from the RSD measurements are based on the methodology described in Equation (5) and Table 1. Whilst aspects of driver behavior such as gear changing and gear selection are controlled within known tolerances in the NEDC type approval test, there is no such control in the data obtained from remote sensing. Higher and more variable emission rates may be expected in the data obtained from remote sensing than from the VCA data, due to uncontrolled variability in driver behavior. Finally, the VCA test results were obtained from the vehicles when they were new. In the RSD data collected in 2008, the observed Euro 4 vehicles were between 0 and 3 years old; the Euro 3 vehicles were between 4 and 8 years old; and the Euro 2 vehicles were between 9 and 12 years old. Mechanical deterioration of engines, failures in emission control systems, and variation in levels of maintenance over time may also be sources of variability in the emissions data obtained using remote sensing.

Table 2. Comparison between petrol car emission rates derived from VCA NEDC type approval tests, and emission rates derived from remote sensing data over a synthesized NEDC.

Euro emission standard	Engine capacity (liters)	Mean emission rates (grams per kg of fuel burnt)[a]							
		VCA				Remote sensing ($Emis_{DC}$)			
		NO_x[b]	CO	HC	HC+NO_x	NO	NO (as NO_2 equivalent)[C]	CO	HC[d]
Euro 4	<1.4	0.69 ± 0.02	8.51 ± 0.28	1.22 ± 0.02	-	0.73 ± 0.18	1.12 ± 0.28	11.15 ± 2.39	0.98 ± 0.60
	1.4-2.0	0.46 ± 0.01	7.45 ± 0.11	0.90 ± 0.01	-	0.60 ± 0.13	0.92 ± 0.20	8.42 ± 1.36	0.30 ± 0.17
	>2.0	0.35 ± 0.01	4.93 ± 0.10	0.66 ± 0.01	-	0.31 ± 0.34	0.48 ± 0.52	4.40 ± 1.55	0.38 ± 0.32
	Total	0.45 ± 0.01	6.62 ± 0.08	0.85 ± 0.01	-	0.62 ± 0.10	0.95 ± 0.15	8.88 ± 1.12	0.52 ± 0.20
Euro 3	<1.4	0.76 ± 0.07	11.69 ± 0.50	1.75 ± 0.07	-	1.41 ± 0.19	2.16 ± 0.29	21.25 ± 2.17	2.44 ± 0.60
	1.4-2.0	0.79 ± 0.03	10.56 ± 0.24	1.44 ± 0.03	-	1.52 ± 0.15	2.33 ± 0.23	21.63 ± 2.03	1.86 ± 0.26
	>2.0	0.54 ± 0.02	7.20 ± 0.24	0.98 ± 0.03	-	0.83 ± 0.19	1.27 ± 0.29	16.02 ± 2.98	1.62 ± 0.60
	Total	0.69 ± 0.02	9.45 ± 0.17	1.31 ± 0.02	-	1.37 ± 0.10	2.10 ± 0.15	20.70 ± 1.37	2.00 ± 0.24
Euro 2	<1.4	-	12.42 ± 0.82	-	3.82 ± 0.22	3.33 ± 0.32	5.11 ± 0.49	64.78 ± 7.29	8.04 ± 1.11
	1.4-2.0	-	10.00 ± 0.41	-	3.30 ± 0.11	4.67 ± 0.31	7.16 ± 0.48	61.75 ± 5.02	8.53 ± 0.90
	>2.0	-	6.03 ± 0.50	-	2.14 ± 0.18	3.61 ± 0.56	5.54 ± 0.86	47.94 ± 8.98	5.55 ± 1.00
	Total	-	9.36 ± 0.32	-	3.08 ± 0.09	4.19 ± 0.22	6.42 ± 0.34	60.21 ± 3.77	7.93 ± 0.63

[a] Range (±) indicates bounds of 95% confidence interval for the mean. [b] VCA NO_x assumed as NO_2 equivalent values.[23]
[c] Conversion assumes (46/30)NO. [d] A factor of 2 is applied to HC values derived from remote sensing because the non-dispersive infrared HC measurement determines only around 50% of the HC mass compared to the FID techniques used in the NEDC type approval test.[14]

Table 3. Comparison between diesel car emission rates derived from VCA NEDC type approval tests, and emission rates derived from remote sensing data over a synthesized NEDC.

Euro emission standard	Engine capacity (liters)	Mean emissions (grams per kg of fuel burnt)[a]							
		VCA				Remote sensing ($Emis_{DC}$)			
		NO_x[b]	CO	PM	HC+NO_x	NO	NO (as NO_2 equivalent)[c]	CO	PM[d]
Euro 4	<2.0	4.43 ± 0.03	3.33 ± 0.10	0.28 ± 0.01	-	4.44 ± 0.37	6.81 ± 0.57	3.64 ± 1.66	0.96 ± 0.10
	>2.0	3.59 ± 0.03	2.31 ± 0.10	0.19 ± 0.01	-	3.54 ± 0.46	5.43 ± 0.71	2.90 ± 1.71	0.83 ± 0.12
	Total	4.15 ± 0.03	3.00 ± 0.08	0.25 ± 0.01	-	4.12 ± 0.29	6.32 ± 0.44	3.38 ± 1.23	0.94 ± 0.08
Euro 3	<2.0	8.44 ± 0.10	4.35 ± 0.16	0.72 ± 0.01	-	6.77 ± 0.45	10.38 ± 0.69	6.32 ± 1.61	1.75 ± 0.16
	>2.0	6.93 ± 0.13	3.46 ± 0.19	0.69 ± 0.02	-	6.33 ± 0.60	9.71 ± 0.92	4.29 ± 1.57	1.63 ± 0.18
	Total	7.83 ± 0.09	3.99 ± 0.12	0.71 ± 0.01	-	6.59 ± 0.36	10.10 ± 0.55	5.63 ± 1.19	1.72 ± 0.12
Euro 2	<2.0	-	9.04 ± 0.69	1.30 ± 0.21	12.16 ± 0.29	9.47 ± 1.09	14.52 ± 1.67	11.20 ± 1.91	2.88 ± 0.34
	>2.0	-	6.60 ± 0.69	1.73 ± 0.52	11.22 ± 0.52	7.05 ± 1.19	10.81 ± 1.82	6.02 ± 2.11	2.11 ± 0.43
	Total	-	8.01 ± 0.51	1.48 ± 0.25	11.76 ± 0.28	8.76 ± 0.85	13.43 ± 1.30	9.24 ± 1.42	2.60 ± 0.27

[a] Range (±) indicates bounds of 95% confidence interval for the mean. [b] VCA NO_x assumed as NO_2 equivalent values.[23]
[c] Conversion assumes (46/30)NO. [d] Remote sensing estimate of PM based on opacity measurements; VCA PM values based on gravimetric measurement.

The mean emission rates of NO (NO_2 equivalent) derived from remote sensing for Euro 4 petrol cars are around double the NO_x values reported by VCA. At Euro 3, the values derived from remote sensing are approximately three times the VCA values. Assuming a proportion of NO_2 in total NO_x of 1 – 4%, there is clearly a large difference in the results for the two methods. A degree of consistency in the results for the Euro 4 petrol cars category might have been expected since the observed vehicles in the RSD surveys were relatively new (≤3 years old), and therefore any age / maintenance related deterioration would be expected to be low. However, 'real-world' NO emissions are seen to be higher than the values observed in the type approval tests. The larger difference observed at Euro 3 may reflect in part the fact that the observed Euro 3 vehicles in the RSD surveys were between 4 and 8 years old, with associated age / mileage related degradation. Guidance published by the European Environment Agency (EEA) suggests a linear mileage correction factor for urban NO_x emissions up to a maximum of 2.2 for Euro 1 and Euro 2 petrol cars (from 45,000km up to 120,000km). At Euro 3 and Euro 4, the EEA suggest no urban NO_x degradation for petrol cars with engine capacities ≤1.4 liters, but a linear mileage correction factor up to a maximum of 1.57 (assumed average mileage of 17,000km up to a maximum of 160,000km) for engine capacities greater than 1.4 liters.[18] However, research in the United States, based on time series analysis of repeat annual observations, has indicated that fleet averaged emission deterioration is near zero for model years newer than 2001.[10] Given that the remote sensing data set utilized in this study represents a single point in time, it is not possible to state definitively whether (a) the relatively larger differences in emission rates between RSD and VCA data for earlier Euro standards are due to age related deterioration, or (b) that the difference is due to a larger discrepancy between VCA and 'on-road' emission rates for earlier Euro standards independent of age effects.

The mean emission rates of NO (NO_2 equivalent) derived from remote sensing for Euro 4 diesel cars are around 50% higher than the NO_x values reported by VCA. At Euro 3, the values derived from remote sensing are on average 30% higher than the VCA values. Assuming a proportion of NO_2 in total NO_x of perhaps 30% at Euro 3, increasing to 55% at Euro 4, average NO emissions from remote sensing at Euro 3 are nearly twice the VCA values, and over three times higher at Euro 4. Of course, the actual NO_2/NO ratios in the fleet observed during remote sensing are not known. The EEA assume no additional mileage related emissions degradation for diesel cars beyond that assumed in baseline emission factors corresponding to fleet average mileage (30,000 – 60,000km).[18] It should be noted in passing that the absolute levels of NO emitted from Euro 3 and Euro 4 diesel cars, observed in the remote sensing surveys, are statistically significantly higher than from comparable petrol cars.[6]

Mean CO emission rates for Euro 4 petrol cars with engine capacity equal to or greater than 1.4 liters are broadly comparable for the two data sources, within 15% depending on engine capacity category. Mean CO emissions from Euro 4 petrol cars with engine capacities less than 1.4 liters derived from remote sensing measurements are estimated to be 34% higher than the mean VCA value. Again, higher emission rates are observed in the remote sensing data for earlier (Euro 3 and Euro 2) vehicle categories, relative to the VCA data. This is particularly acute at Euro 2 (observed vehicles between 9 and 12 years old), where the mean CO emission rate derived from the RSD data is between 5 and 8 times the original Euro 2 type approval value. This result is despite the fact that CO is one of the exhaust gases measured in the UK Department for Transport compulsory annual exhaust emissions test, although such tests are carried out at engine idle, and not under load.[24] The EEA suggest maximum mileage correction factors for CO emissions from Euro 1 and Euro 2 cars of between 1.67 and 2.39 in an urban context, depending on engine capacity.[18] In contrast, mean CO emission rates for diesel cars from remote sensing data remain within 9% to 45% of the VCA values across all Euro categories and engine capacities.

Mean hydrocarbon (HC) emission rates for Euro 4 petrol cars derived from the RSD data are generally lower than the comparable VCA type approval values. This situation is reversed at Euro 3. Mean HC at Euro 3 in the VCA data is 1.5 times the equivalent Euro 4 value; mean HC at Euro 3 in the remote sensing data is 3.8 times the equivalent Euro 4 value. The EEA suggest maximum mileage correction factors for HC emissions from Euro 3 and Euro 4 petrol cars of between 1.00 and 1.44 in an urban context (mileage ≥160,000km), relative to emission rates at average mileage values (range 18,000 to 32,000km).[18]

In the VCA data, mean PM emissions for diesel cars at Euro 4 are 17% of Euro 2 values and 35% of Euro 3 values. In the remote sensing data, the equivalent trend values are 36% and 55%. The PM emission rates reported from remote sensing (based on opacity measurements) are generally 1.8 to 3.7

times higher than the reported VCA (gravimetric) values, the wider divergence occurring with newer (Euro 4) vehicles.

When interpreting these comparisons, due cognizance should be paid to the differences in instrumentation and measurement techniques utilized. The form of remote sensing used in this study does not permit the accurate representation of the significant proportions of idling time in the (NEDC) type approval laboratory test, because idling whilst stationary is not included in the RSD measurements (emissions measurements from the RSD instrumentation are obtained when the vehicles are in motion). It is likely that the urban remote sensing data included an unknown proportion of cold start observations; future work could control this issue by careful site selection, and possibly thermal imaging.[25] Other factors which are difficult to control, and which could make reconciliation more challenging, include the use of ancillary equipment such as air conditioning, vehicle loading, and other aspects of variability in driver behavior such as gear changing. However, the significance of some of these issues will depend on the nature of the driving cycle under investigation. The future collection of time series data will permit the assessment of the significance of the relationships between emissions and vehicle age / mileage, which will be influenced by prevailing local inspection / maintenance regimes. Further data collection is required to refine the technique to explicitly account for the fraction of NO_2 in total NO_x. Future research will also benefit from the inclusion of RSD data from higher speed (extra-urban) survey sites, to explicitly capture high VSP values generated by consistent higher speed cruising, rather than from lower speed acceleration events. It is considered likely that this will have a bearing on emissions rates of some pollutants.

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SUPPORTING INFORMATION

Summary of the 2008 remote sensing surveys and results; graphical presentations of VSP / emissions relationships by pollutant and fuel type; summary of VCA type approval data, six figures and five tables. This material is available free of charge via the Internet at http://pubs.acs.org.

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