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Real-driving emissions from diesel passenger cars measured by remote sensing and as compared with PEMS and chassis dynamometer measurements - CONOX Task 2 report

Commissioned by the Federal Office for the Environment (FOEN), Switzerland

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Preface

Understanding real driving (or on-road or real-world) emissions is crucial for taking cost-effective actions to reduce air pollution and improve air quality in urbanized areas all over the world. Remote sensing represents one means to monitor real driving emissions from large on-road fleets, and has been used in Europe in various applications already since the early 1990's to reach a better understanding of the European situation regarding real driving emissions. However, until present remote sensing has never been used in Europe for e.g. legislative or enforcement purposes, which instead have relied on other emission measurement approaches, providing results that are more or less representative for real driving emissions (e.g. chassis dynamometer or PEMS testing, idle tests). In light of "dieselgate", approaches capable of measuring the "real" real driving emissions, such as remote sensing, have gained an increasing interest, also for emission control purposes.

This report presents the outcome of a common European and US collaborative effort to analyse how large datasets from remote sensing measurements carried out in various locations and countries across Europe could be used as a complement to existing approaches to measure road vehicle emissions, in order to achieve a better understanding of the European issue of air pollution from road transport. The work presented in this report focuses on NO_x emissions from light-duty diesel vehicles, preferably passenger cars, corresponding to the Euro 4, 5 and 6 standards, since recent research has shown that these are key sources for NO_x emissions in Europe.

This work was part of the CONOX project[1], which was carried out during 2017 under a contract from the Federal Office for the Environment in Switzerland, BAFU (www.bafu.admin.ch).

[1] Study on comparing NO_x real driving emissions from Euro 5 and Euro 6 light-duty diesel vehicles as measured by remote sensing, PEMS and on chassis dynamometers

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Summary

In the present study more than 700,000 emission data records (exhaust components measured were NO, NO_2, CO, HC and PM), representing real driving conditions and retrieved from remote sensing measurements carried out in Spain, Sweden, Switzerland and United Kingdom between 2011 and 2017, were pooled and analysed, with a particular focus on analysing the real-world NO_x emission performance of Euro 5 and Euro 6 diesel passenger cars.

The results of the analysis, based on more than 200,000 emission measurements on diesel passenger cars, are:

- Average NO_x emissions from diesel passenger cars (by Euro standard, make, brand, model, engine family, etc.) as measured by remote sensing agree well with corresponding emissions measured on-board vehicles, e.g. by means of PEMS, thus remote sensing has been proven as a powerful tool for market surveillance and for complementing conventional test methods aiming at capturing real driving emissions.

- With help of remote sensing all top selling models can be measured. Despite large efforts and resources spent on PEMS tests in the past, these did not cover the market sufficiently, and high NO_x emitters were effectively escaping the tests.

- The real-world NO_x emissions from diesel passenger cars remain virtually unchanged by the EU emission legislation from Euro 1 through Euro 5, meaning that in real-world driving the average European diesel Euro 5 car emits 5-6 times more NO_x in excess of the Euro 5 standard.

- Euro 6 diesel passenger cars emit on average about half as much NOx as Euro 5 diesel cars, still the Euro 6 diesel cars emit on average about 5 times more NOx in excess of the Euro 6 standard.

- The introduction of effective DPFs (diesel particulate filters) along with the Euro 5 emission standard has effectively reduced the real-world emissions of particulate matter from Euro 5 and 6 diesel passenger cars down to very low levels.

- The remote sensing data analysis has yielded new knowledge and insights as regards the phenomena of emissions deterioration for diesel and petrol passenger cars, and further work on this topic is recommended.

- Real-world NO_x emissions from Euro 5 diesel passenger cars operating with hot engines show a clear dependence of ambient temperature, with emissions increasing strongly with decreasing ambient temperature below 20 degrees, and increasing again with increasing ambient temperature above 25 degrees.

Introduction

On-road emission measurements are crucial for a comprehensive understanding of road traffic related air pollution and for evaluating the effectiveness of various road vehicle emission control policies. Despite this, after 25 years of increasingly tightened road vehicle emission standards for both light- and heavy-duty vehicles, the emphasis in the EU legislation is still not on such control mechanisms. This situation has paved the way for steadily increasing discrepancies between the levels of vehicle emissions stated by the law or in emission inventories and the real-world emissions, especially for diesel vehicles (Carslaw et al., 2011; Chen and Borken-Kleefeld, 2014; Pujadas, 2017; Rushton et al., 2016; Sjödin et al., 2017 and 2008), with the worst example of legal delinquency being the "dieselgate" scandal, disclosed in 2015 (Thompson et al., 2014). The latter is also the main reason why the EU road vehicle emission legislation is now changing in a direction towards capturing conditions more representative of real driving.

The new EU RDE (Real Drive Emission) regulation demands in type approval tests also on-board emission tests on HDV from EURO VI on and for cars from EURO 6-d-temp (09/2017) on. Also, in-service conformity tests can be made based on on-board emission tests during on-road driving along a typical route, i.e. with emissions for a given vehicle being representative for real driving conditions. However, these tests are expensive, and a pre-selection of makes and models may be supported by less expensive methods.

On-road emission measurements by means of remote sensing, originally developed in the US in the late 1980's at the University of Denver (Bishop et al., 1989), have been carried out in Europe since the early 1990's (Sjödin, 1994), mostly for research purposes and mainly in four countries: Spain, Sweden, Switzerland and the UK.

The present report presents the first attempt to pool remote sensing data collected at various locations and countries across Europe, and to carry out a pan-European analysis of the pooled data. A single remote sensing campaign in any European country has typically contained in the order of ten thousands of vehicles (approximate range 20,000-70,000 records). By pooling several campaigns within and across countries this number can easily be increased tenfold.

Another important part of the work was to compile the results from official enquiry testing carried out by a number of European countries following dieselgate, as well as 3rd party testing of Euro 5 and Euro 6 light-duty diesel vehicles, and to compare these results, largely from PEMS measurements, with the results from the pan-European analysis of remote sensing data.

This report presents the results of the work within Task 2 of the CONOX[2] project, carried out on behalf of the Swiss Federal Office for the Environment (BAFU) in 2017 by a consortium of European and US researchers/experts in the field of real driving emissions, with a long experience of both remote sensing measurements and PEMS and chassis dynamometer measurements.

[2] Study on comparing NO_x real driving emissions from Euro 5 and Euro 6 light-duty diesel vehicles as measured by remote sensing, PEMS and on chassis dynamometers

Methods

Measurements and data overview

The data considered for the pan-European analysis carried out within this study were from remote sensing measurements carried out on various urban or near-urban locations in Spain, Sweden, Switzerland and United Kingdom between 2011 and 2017, see Table 1. In all, more than 700,000 vehicle passages were registered in these measurements, of which nearly 200,000 were diesel passenger cars with valid remote sensor readings for which the Euro standard could be identified. The diesel passenger car dataset was dominated by Euro 5 cars (39 %), followed by Euro 4 (33 %), Euro 3 (16 %) and Euro 6 cars (9 %). Almost 18,000 cars were Euro 6.

Table 1: Overview of the remote sensing measurements behind the analysis in this study.

Country	Measurement year(s)	No of passages, all vehicles	Number of valid remote sensor readings (NO) for diesel passenger cars by Euro standard (E)						
			E0	E1	E2	E3	E4	E5	E6
Spain	2015, 2017	294,861	191	343	4,038	18,741	29,246	27,144	11,007
Sweden	2016	34,944	1	3	10	55	431	3,416	2,218
Switzerland	2011-2016	212,981	92	115	680	5,148	17,311	27,858	4,139
United Kingdom	2012, 2013, 2015	173,550	111	125	894	7,381	17,979	18,718	430
Total		**716,336**	**395**	**586**	**5,622**	**31,325**	**64,967**	**77,136**	**17,794**

Figure 1 displays the most abundant vehicle makes among Euro 5 diesel passenger cars in the pan-European remote sensing dataset. Volkswagen, particularly when including also family members such as Audi and Skoda, was by far the most common make.

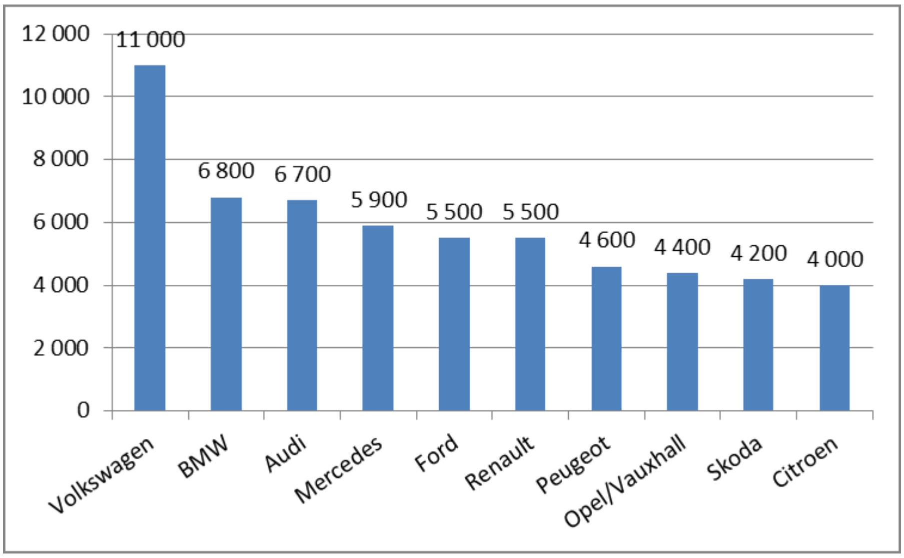

Figure 1. The ten most abundant vehicle makes among Euro 5 diesel passenger cars in the pan-European remote sensing dataset.

Remote sensing instruments

The remote sensing instruments used in the campaigns listed in Table 1 were:

- the Denver University FEAT instrument with NO_2 capability in the 2012 measurements and parts of the 2013 measurements in the UK,
- the Opus AccuScan RSD 4600 instrument in the 2015 measurements in Spain, in the measurements in Switzerland from 2011 through 2015, and in the 2015 measurements and parts of the 2013 measurements in the UK, and
- the new Opus AccuScan RSD 5000 instrument with NO_2 capability in the 2017 measurements in Spain, and in the 2016 measurements in Sweden and Switzerland.

For the remote sensing data that did not include NO_2, NO_2 emissions were estimated in order to derive NO_X emissions by applying NO_2/NO_X–fractions by Euro standard for diesel and gasoline cars derived from the remote sensing measurements including NO_2. This approach was only applied to emission data on an aggregated level, such as average emissions by Euro standard.

Database

An SQL Server database, accessible over the internet, was developed to host raw and refined remote sensing data along with vehicle information from national vehicle registers. A web interface provides export and import functions as well as search queries to retrieve optional selections of subsets of data. The database contains about 100 parameters, of which about two thirds are remote sensing parameters and one third are related to vehicle information. The database parameters including explanations are listed in Appendix 1.

Emissions derived from remote sensing data

Remote sensing provides directly – from the pollutant to CO_2 ratios measured in the raw vehicle exhaust and the fuel combustion equation – emission factors expressed in g per kg (or litre) fuel burned. This unit has been used throughout the analysis presented in this study. A method to convert g/kg fuel remote sensing emission factors into g/km was developed within Task 1 of the CONOX project, based on the same remote sensing dataset as in the present study (Borken-Kleefeld, 2017). Converting all g/kg fuel emission data in the remote sensing database into g/km was outside the scope of the present study. Using emission factors converted to g/km instead of in g/kg fuel for this analysis might in some cases had yielded slightly different results than those presented, but would not have altered the overall conclusions and messages.

Results

Average emissions by Euro standard

NOx emissions in gram per kg fuel by Euro standard and country for diesel and petrol passenger cars according to the remote sensing measurements are presented in Figure 2 and 3. The pattern of virtually no or only minor reductions in diesel passenger cars' on-road NOx emissions between Euro 1 and Euro 5 – as recognized in earlier remote sensing studies (see e.g. Chen and Borken-Kleefeld, 2014) – is consistent for all the four involved countries. Also consistent for all the involved countries is the 50% drop in NOx emissions from Euro 5 to Euro 6. Still, Euro 6 diesel passenger cars' on-road NOx emissions are on average 5-6 times higher than the Euro 6 limit.

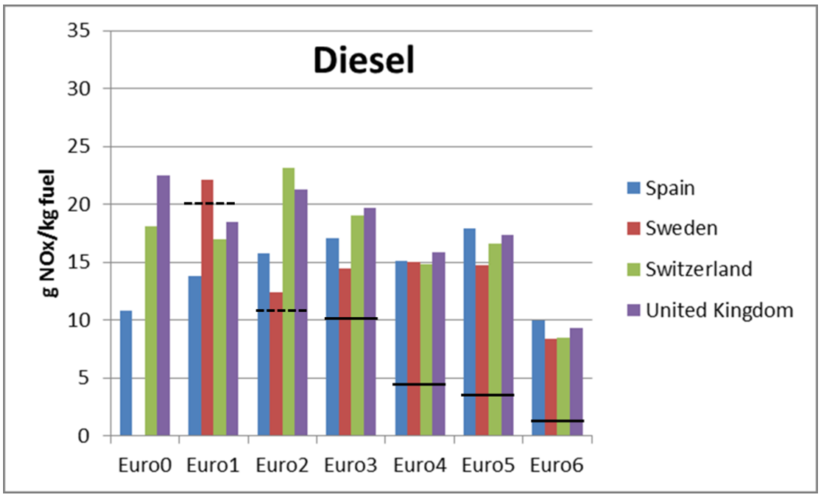

Figure 2. Average NOx emissions (in g/kg fuel burned) by Euro standard and country for diesel passenger cars as measured by remote sensing. Black lines indicate the emission standard.[3]

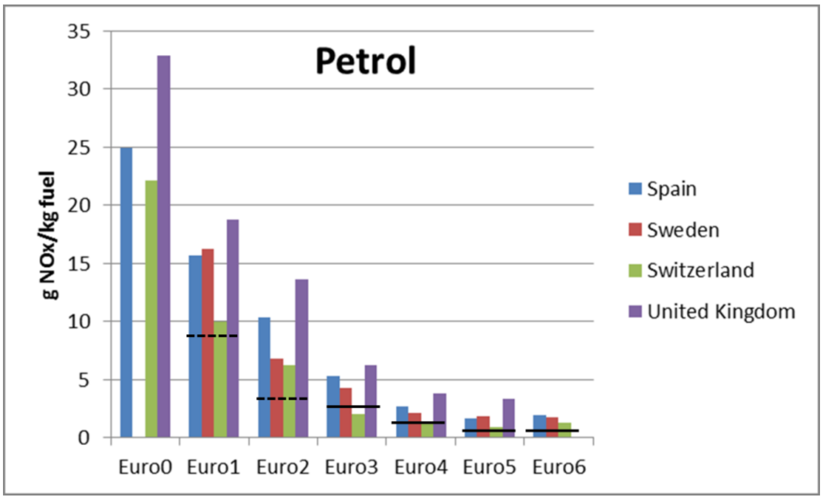

Figure 3. Average NOx emissions (in g/kg fuel burned) by Euro standard and country for petrol passenger cars as measured by remote sensing. Black lines indicate the emission standard.[2]

[3] For Euro 1 and 2 the standard is expressed as the sum of NOx and HC, therefore the line is dotted for these two standards.

As apparent from Figure 3, contrary to diesel passenger cars, on-road NO_X emissions from petrol cars have been reduced drastically since the first EU regulation entered into force in the early 1990's, with Euro 5 and 6 levels exhibiting a reduction of well above 90% compared to the pre-Euro level. Still, according to Figure 3, real-world emissions of Euro 5 and 6 on average are about 50% higher than as indicated by the corresponding emission standards. This is quite understandable considering the presence of the more dynamic driving, ambient conditions, road grades, etc., in the remote sensing measurements compared to the conditions in the legislative emission testing.

According to the remote sensing measurements, as for petrol cars' NO_X emissions also the reduction of diesel passenger cars' on-road PM emissions in Europe appears to be a success story, with Euro 5 and Euro 6 showing very low levels, see Figure 4. The remote sensing instruments measure PM emissions as opacity (i.e. smoke density) which is equivalent to smoke particles in the exhaust, mostly smaller than 0.1 µm (aerodynamic diameter) or equivalent to $PM_{2.5}$.

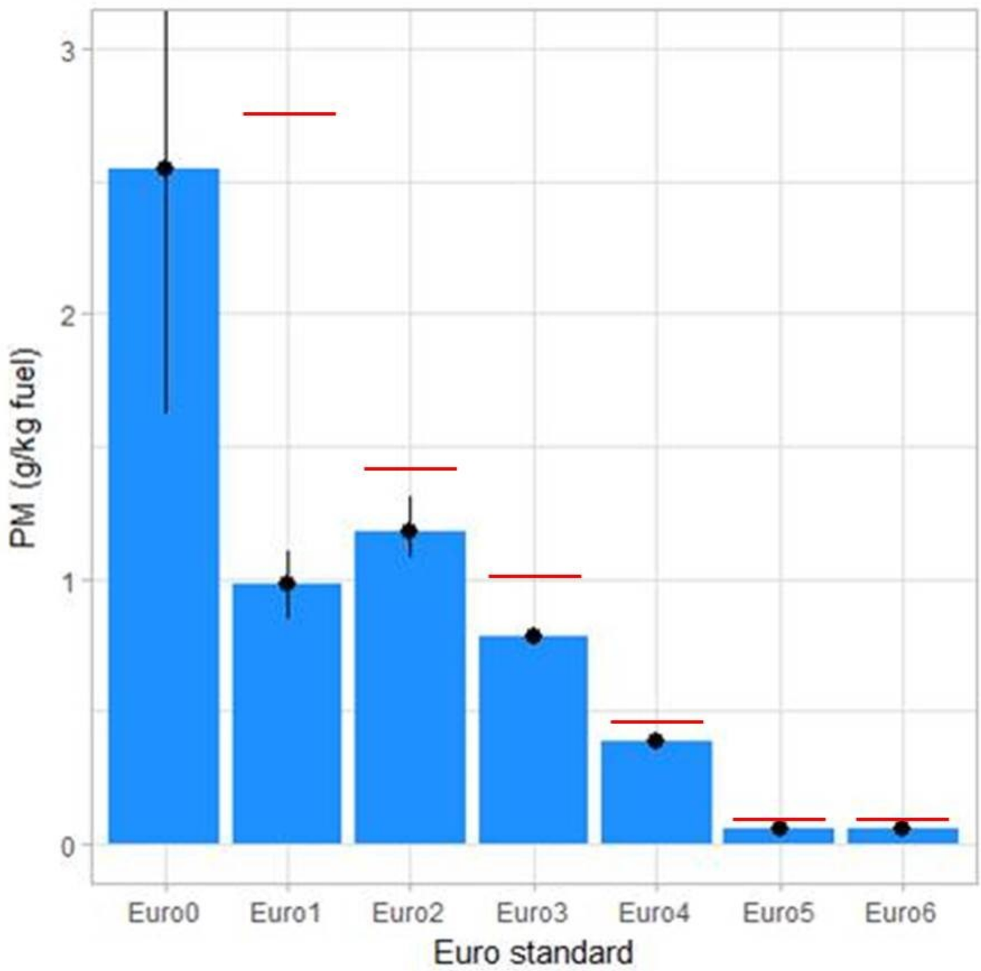

Figure 4. Average PM emissions (in g/kg fuel burned) by Euro standard for diesel passenger cars as measured by remote sensing – all involved countries. Red lines indicate the emission standard.

Comparison of remote sensing with on-board testing results

Remote sensing and portable emissions measurement system (PEMS) share the common objective of measuring on-road emissions of vehicles. The two techniques differ mainly on which/how many vehicles are being selected, and how their emissions are measured.

Remote sensing is able to measure emissions from thousands of vehicles per day as they pass by. A snapshot of the exhaust plume content is collected from each passing vehicle, equivalent to about one second's worth of emissions data for a single operating condition. The vehicle's speed and acceleration are also measured, so the operating condition is determined, at least to some extent.

Portable emissions measurement system testing (i.e. PEMS) uses sensors and analytical equipment mounted on a selected vehicle to directly measure the second-by-second emission rate of a vehicle as it is being driven on the road during a given trip, driving style and weather conditions.

In this study NO_X emission factors relative to fuel consumption (g NO/kg fuel burned) derived from remote sensing measurements and on-board measurements were compared for Euro 5 and 6 diesel passenger cars, both on an aggregated and on a more detailed level.

Sources of on-board test data for the comparison

In the aftermath of dieselgate, several EU member states conducted real driving emission testing on selected samples of Euro 5 and Euro 6 diesel passenger cars. For the present study, on-road NO_X and CO_2 emission data including reports were collected from the national enquiry testing conducted in the UK, the Netherlands, France and Germany.

In all real driving emission tests conducted, various kinds of PEMS equipment were used. In most cases the regulatory-compliant equipment that measures exhaust gas concentration with analysers coupled with a direct measurement of the exhaust mass flow (EFM) was used. In the Netherlands instead the smart emissions measurement system (SEMS) equipment was used, measuring exhaust gas NO_X concentration by means of NO_X sensors, and with an indirect calculation of the exhaust mass flow. The latter technique was considered to be accurate enough for the purpose of the high-emitter screening tests (within 10% of the emission values collected from cars tested in the laboratory). For simplicity reasons, any portable equipment used will here be entitled PEMS.

The national NO_X emission screening approaches consisted of various on-road or on-track testing. In some cases vehicles were driven on a track following the NEDC speed profile - usually performed on a chassis dynamometer for type approval testing - whereas in other cases the NEDC speed profile was slightly altered to defeat a potential car manufacturer strategy aiming at detecting the regulatory cycle. Such tests were performed on either a cold or a hot engine, each with 20 minutes duration. Finally, testing according to the real driving emission (RDE) test procedure, typically lasting between 1.5 and 2 hours, was also conducted in some cases.

All PEMS tests that reported both NO_X and CO_2 measurements were used for the comparison with remote sensing data. As for the remote sensing data used for the comparison, the validity of the data was carefully reviewed, including the exclusion of data sampled during zero power events, i.e. decelerations.

Average emissions by Euro standard

In Figure 5 the average NOx emission factors, expressed in grams per kg fuel burned, derived from the national PEMS testing (red bars) and from the CONOX remote sensing data (blue bars) are compared for Euro 5 and Euro 6 diesel passenger cars, respectively. For the Euro 5 comparison there were 128 PEMS tests and about 58,000 remote sensing measurements, whereas for the Euro 6 comparison there were 173 PEMS tests and about 16,000 remote sensing measurements. Since NOx emissions were found to be highly dependent on parameters such as vehicle make and model (Baldino *et al.*, 2017), calculated standard errors for both dataset are indicated, as are the type approval limits as measured by PEMS.

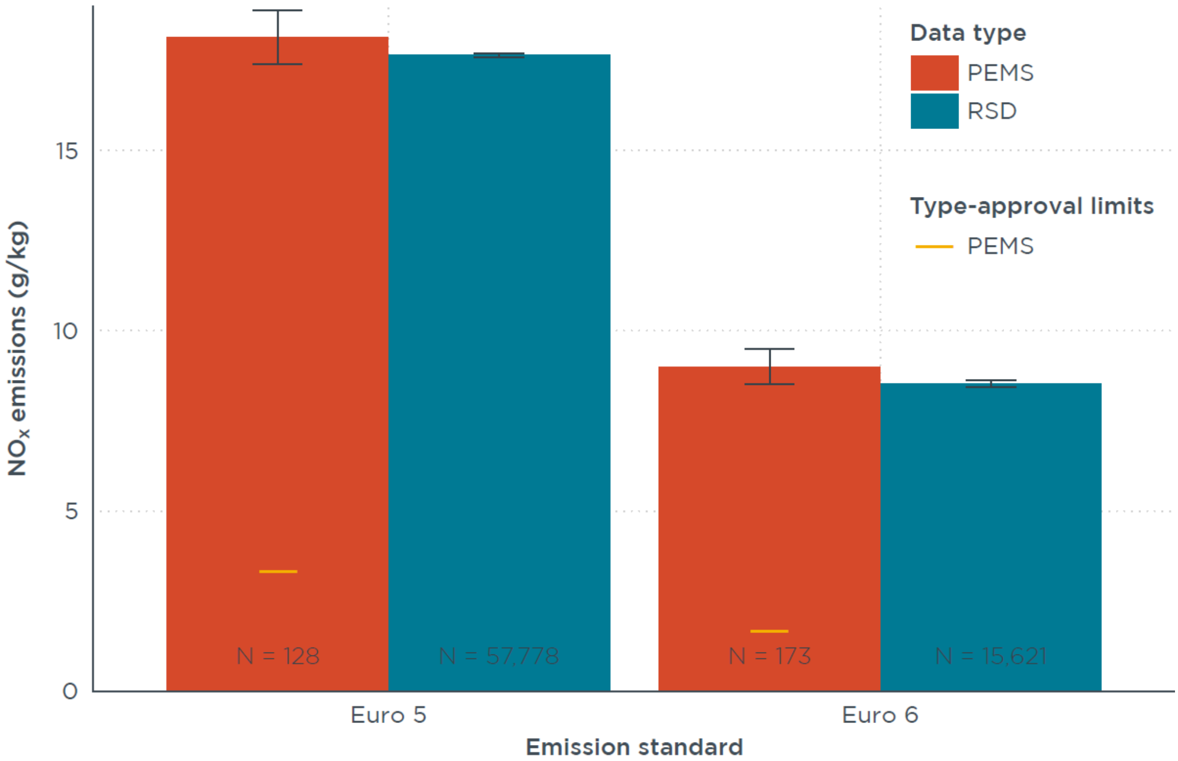

Figure 5. **Average real driving NOx emission factors (in g/kg fuel burned) for Euro 5 and Euro 6 diesel passenger cars according to PEMS (red bars) and remote sensing measurements (blue bars), respectively.**

Figure 5 reveals a striking agreement between the PEMS and remote sensing datasets with regard to average NOx emissions on a fuel consumption basis for both Euro 5 and Euro 6 diesel passenger cars. Moreover, the two measurement approaches show more or less an identical improvement in real-world NOx emission performance from Euro 5 to Euro 6, with remote sensing indicating a 53% improvement, and PEMS indicating a 50% improvement.

Even though the real-world NOx emission performance of Euro 6 diesel passenger cars has improved relative to Euro 5, the results of the PEMS vs remote sensing comparison also confirm that the Euro 5 and Euro 6 real-world emissions levels remain on levels more than five times higher than their respective type-approval limits.

Comparison between remote sensing and PEMS by make and model of Euro 5 and 6 diesel cars

Results from a large number of both governmental and 3rd party PEMS testing on Euro 5 and 6 diesel passenger cars were used to make comparisons with emission data derived from the CONOX remote sensing database of NO_x emissions on a make, brand and vehicle model basis.

Governmental PEMS testing data (on 105 Euro 5 models and 93 Euro 6 models) were retrieved from Belgium, Germany, France, UK and the Netherlands. 3rd party PEMS testing data (on 124 Euro 5 models and 220 Euro 6 models) were from organisations such as TNO, Emissions Analytics, Allgemeiner Deutscher Automobil-Club (ADAC), Deutsche Umwelthilfe (DUH) and the Auto motor und sport magazine.

2-3 PEMS tests were carried out on each model, thus yielding a seemingly large PEMS dataset for Euro 5 and 6 diesel passenger cars. The questions that were addressed in the present analysis were:

- Were all models with (excessively) high NOx emissions found in the PEMS testing?
- Were at least all the top ten selling models included in the PEMS testing?
- How does the picture look in the remote sensing data, and how does remote sensing compare with the PEMS data, on a make, brand and model basis?

The top selling vehicle models in Spain, Sweden, Switzerland and United Kingdom in Europe in 2016 are listed in Table 2.

Table 2. The top selling vehicle models in Spain, Sweden, Switzerland and UK in 2016, by alphabetical order.

Audi A3	Renault Clio
Audi A4	Renault Megane
BMW 3-series	Seat Ibiza
Fiat 500	Seat Leon
Ford Fiesta	Skoda Octavia
Ford Focus	Volvo V40
Kia Ceed	Volvo V60
Mini New Mini	Volvo V70
Nissan Qashqai	Volvo XC60
Opel/Vauxhall Astra	Volvo XC70
Opel/Vauxhall Corsa	VW Golf
Peugeot 208	VW Passat
Peugeot 308	

The results of the comparison between NO_x emissions derived from remote sensing measurements and from PEMS testing on a vehicle model basis (of Euro 5) are presented in Figures 6 to 8. The following observations can be made from these figures:

- There is a good agreement between the remote sensing results and the PEMS results.
- The governmental PEMS tests data tend to show higher emissions, whereas the 3rd party testing tend to show lower emissions than the remote sensing data.
- Despite large efforts and resources spent on PEMS tests, these do not cover the market sufficiently, and high NO_x emitters are effectively escaping the tests.

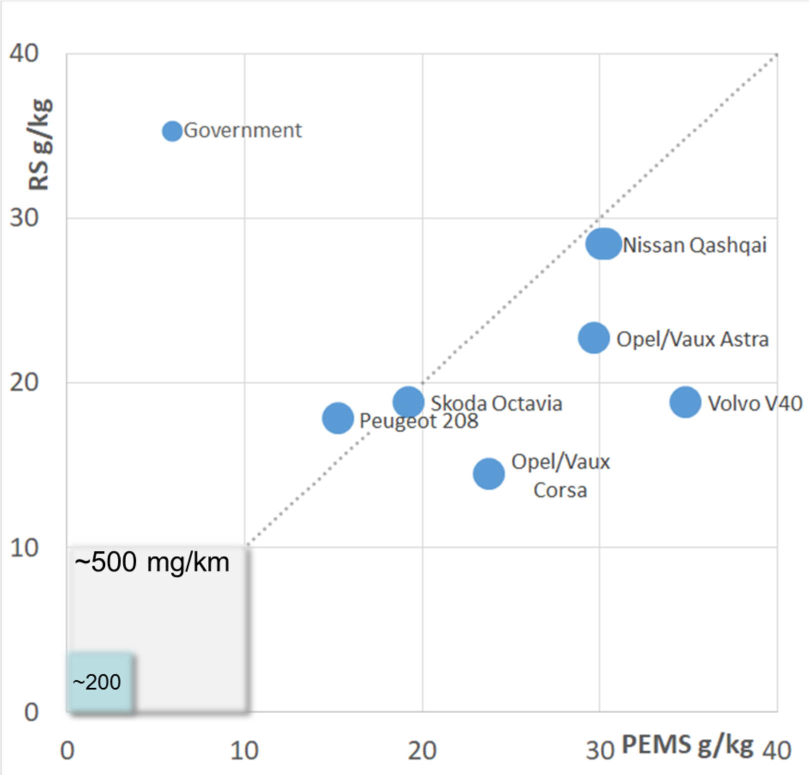

Figure 6. Comparison of average NOx emission factors (in g/kg fuel) derived from remote sensing measurements and governmental PEMS testing, respectively, by vehicle model (Euro 5).

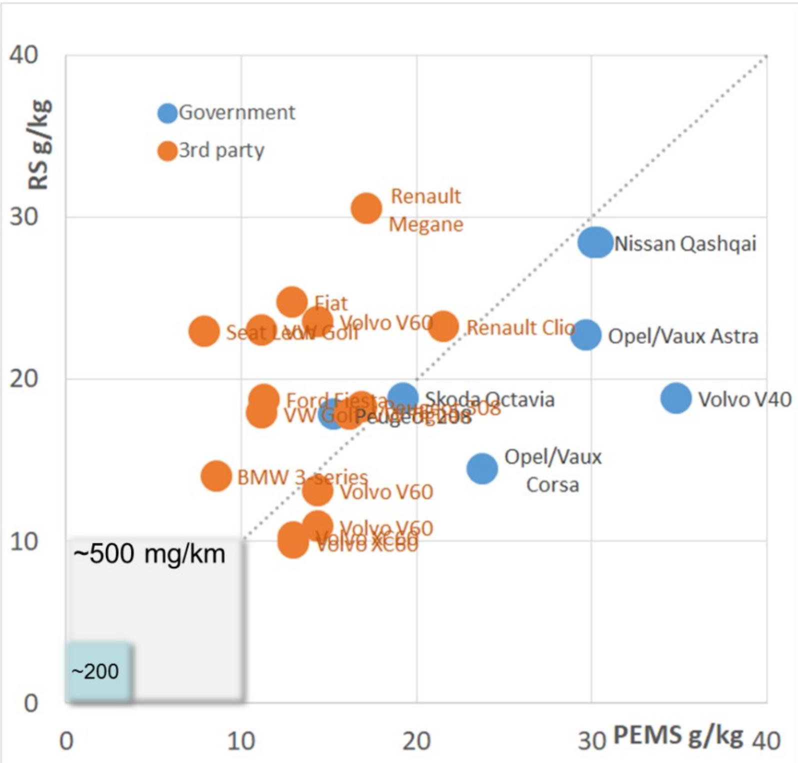

Figure 7. Comparison of average NOx emission factors (in g/kg fuel) derived from remote sensing measurements and governmental (blue circles) and 3rd party PEMS testing (orange circles), respectively, by vehicle model (Euro 5).

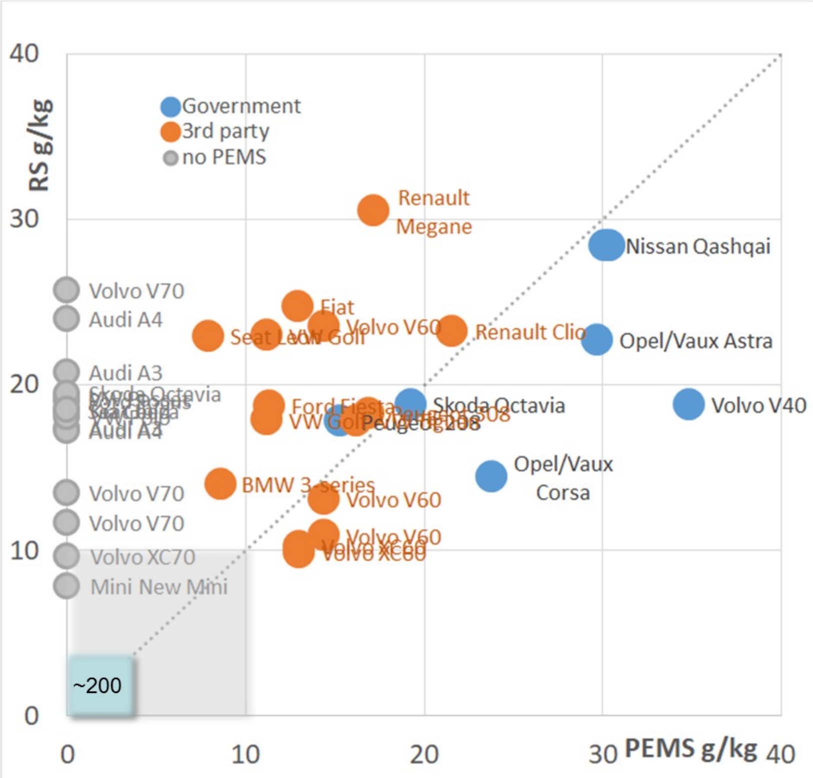

Figure 8. **Comparison of average NOx emission factors (in g/kg fuel) derived from remote sensing measurements and governmental PEMS (blue circles) and 3rd party testing (orange circles), respectively, by vehicle model (Euro 5). Grey circles represent models captured in the remote sensing measurements but not in the PEMS tests.**

In Figures 9 and 10 NOx emissions derived from remote sensing measurements and from PEMS testing are compared for various models and engine families of Volvo and VW Group Euro 5 diesel cars, respectively.

It can be seen that in the case of Volvo there is an apparent difference in NOx emission performance between the engine families 1.6 litres on the one hand and the engine families 2.0 and 2.4 litres on the other hand, whereas in the case of the VW Group there are no significant differences between the four engine families represented in the measurements. It's worth pointing out that the Volkswagen Group 1.2, 1.6 and 2.0 litres engines are those recognised in "dieselgate" to be fitted with defeat devices.

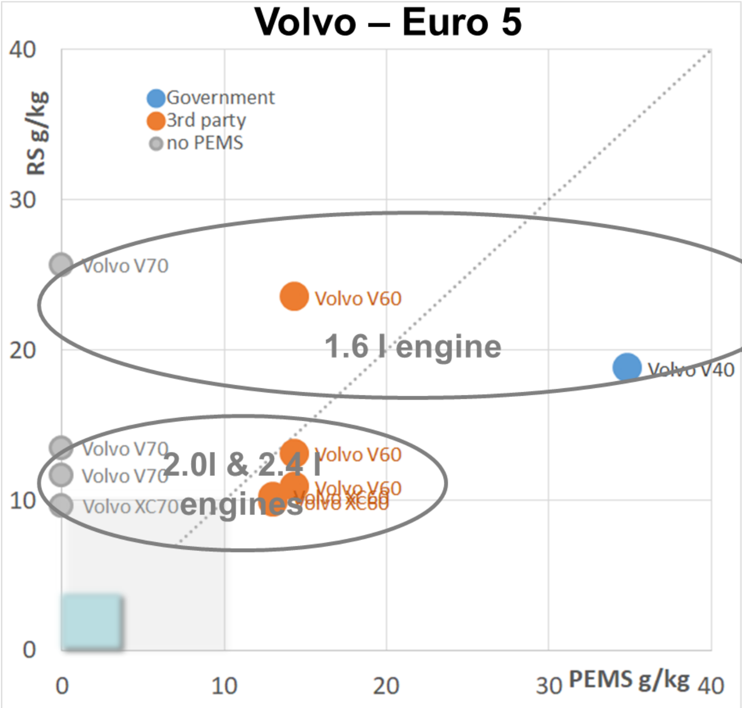

Figure 9. Comparison of average NOx emission factors (in g/kg fuel) derived from remote sensing measurements and governmental PEMS (blue circles) and 3rd party testing (orange circles), respectively, for different models and engine families of Volvo Euro 5 diesel cars. Grey circles are models captured in the remote sensing measurements but not in the PEMS tests.

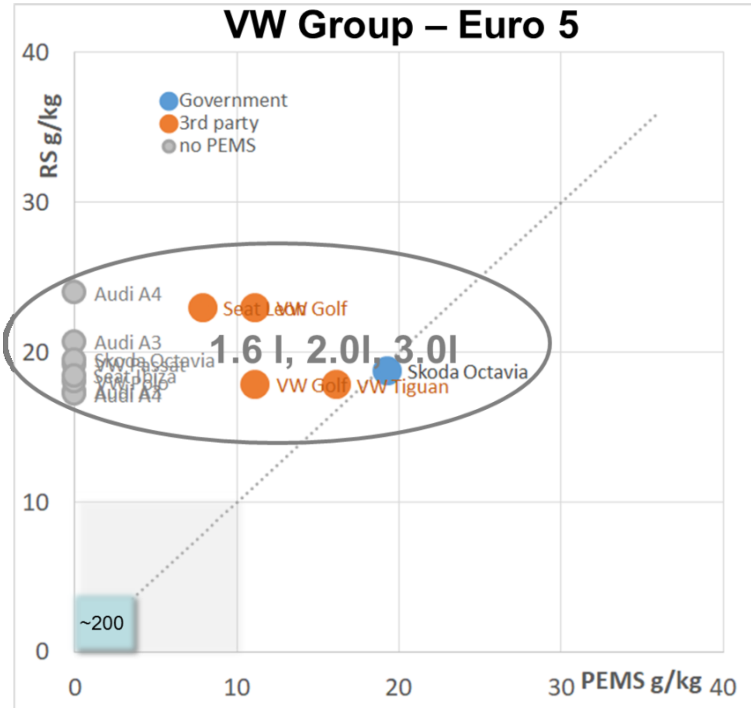

Figure 10. Comparison of average NOx emission factors (in g/kg fuel) derived from remote sensing measurements and from the national PEMS and 3rd party testing, respectively, for different brands, models and engine families of VW Group Euro 5 diesel cars. Grey circles are models captured in the remote sensing measurements but not in the PEMS tests.

In Figure 11 the average NOx emissions by brand of Euro 5 diesel passenger cars according to the remote sensing measurements are presented, rank ordered from the lowest to the highest average NOx emissions. The ranking in Figure 11 is based on a total of ≈64,000 remote sensing records from four countries.

The ranking shows a distinct pattern by manufacturer/make (not by brand), though it is relatively uniform. There is a factor of almost three of difference in average NOx emissions between the best and the poorest performing makes.

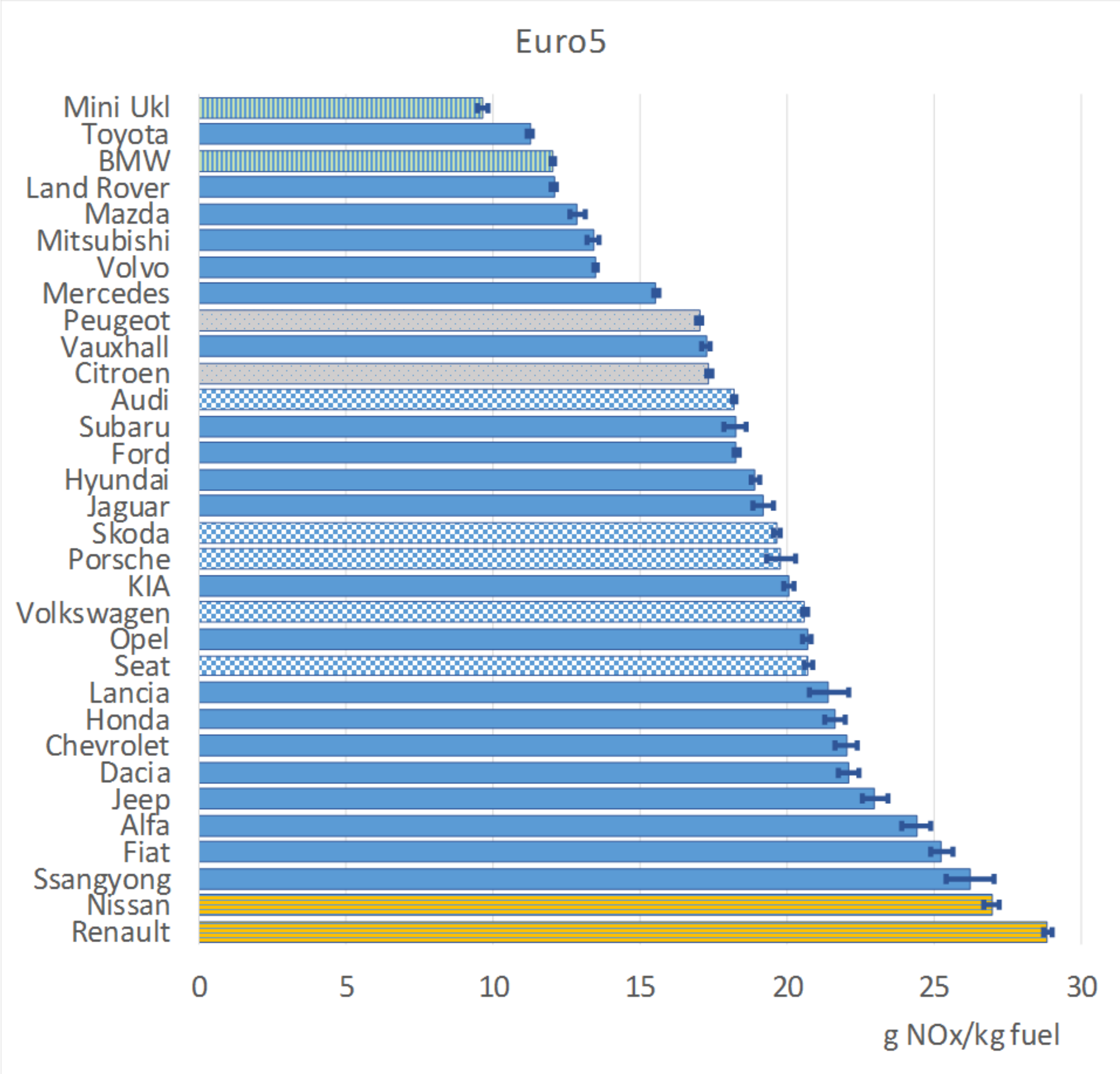

Figure 11. **Average NOx emissions (in g/kg fuel) derived from remote sensing measurements (≈64,000 records) in Spain, Sweden, Switzerland and United Kingdom by brand (Euro 5), rank ordered from the lowest to the highest average NOx emissions. Brands with bars marked with the same green, grey, checkered blue and yellow colours belong to the same manufacturer (e.g. Mini/BMW and Nissan/Renault).**

In Figure 12 the average NOx emissions by brand of Euro 6 diesel passenger cars based on a total of ≈10,000 remote sensing records are presented. The brands are listed in the same order as for Euro 5 cars in Figure 11. Apparently there is a much larger difference in NOx real-world emission performance within the Euro 6 than in the Euro 5 category, with about one order of magnitude difference between the best and the poorest performing makes. It is interesting to note that some of the makes/brands that are among the poorest performing within the Euro 5 category are also among the poorest performing within the Euro 6 category. A likely explanation is that since the introduction of the Euro 6 standard NOx from diesel vehicles are not anymore controlled by combustion only but also tail-pipe through a combination of in-cylinder (e.g. EGR) and after-treatment control systems (e.g. SCR). Therefore, most Euro 6 diesel vehicles have one more leverage (the NOx after-treatment) to correctly reduce NOx emissions tail-pipe, or not. That could explain why the discrepancy between the best and poorest emitters gets even larger. The poorest have not improved from Euro 5 to Euro 6 (e.g Renault-Nissan), or seem to get even worse (Fiat).

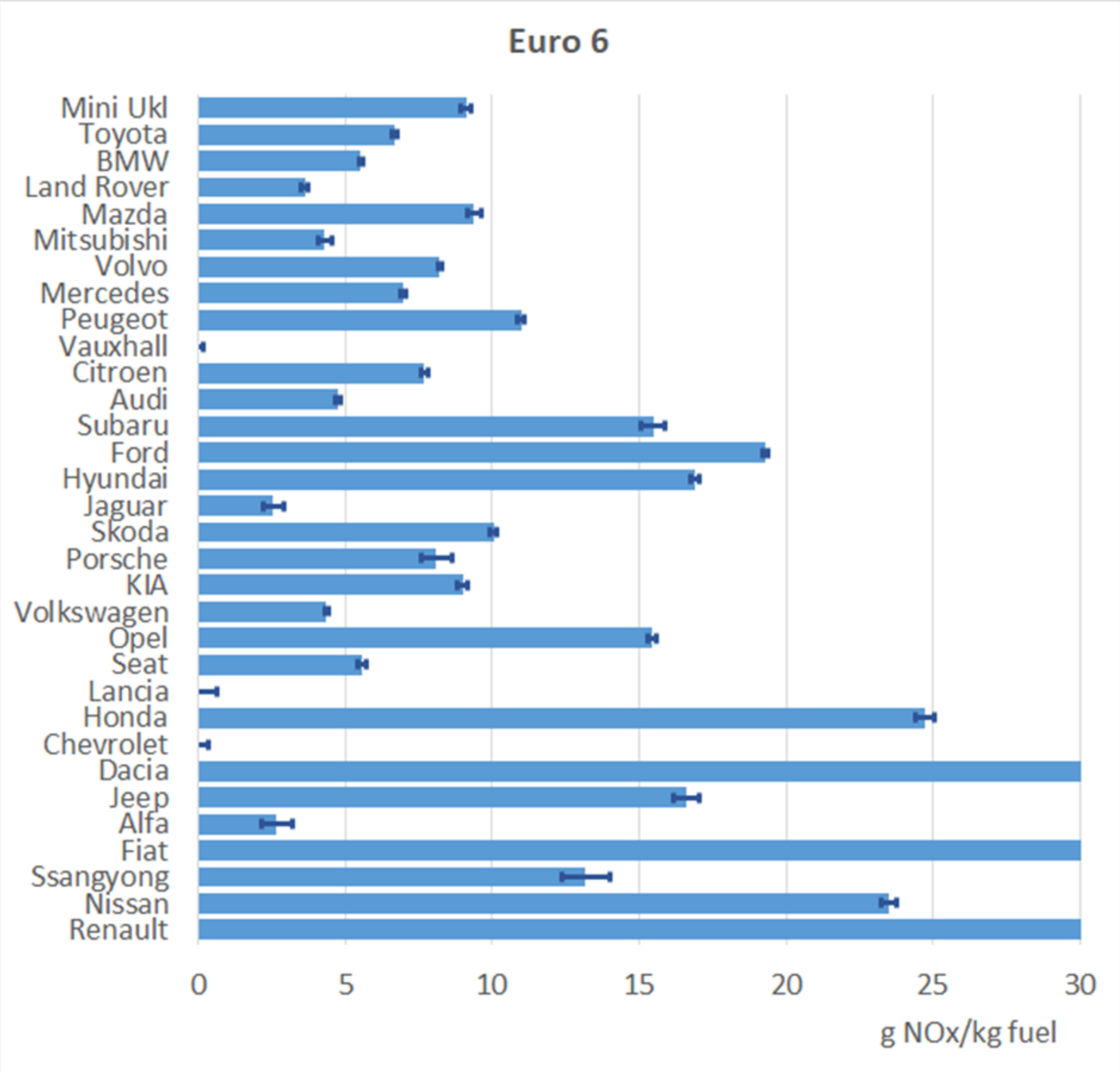

Figure 12. **Average NOx emissions (in g/kg fuel) derived from remote sensing measurements (≈10,000 records) in Spain, Sweden, Switzerland and United Kingdom by brand (Euro 6). Brands are listed (from top to bottom) in the same order as in Figure 11.**

Passenger car emissions deterioration

This section considers the effect of deterioration on the emissions performance of petrol and diesel passenger cars based on the full CONOX database. While the focus of the project is on the emissions of NO_X from diesel passenger cars, the database itself provides detailed information on other vehicle types and pollutants. For a consideration of the effect of vehicle deterioration on emissions from vehicles it is useful to consider pollutants other than NO_X. This is because the deterioration of vehicles and in particular their exhaust after-treatment systems are unlikely to affect one pollutant without affecting others. By considering the behaviours of several pollutants, more insight can be gained into the types of changes that have occurred. In addition, as the method presented is giving credible results for some pollutant, it can be considered reliable also for other pollutants.

Exhaust emissions deterioration of diesel and gasoline vehicles has been investigated before based on remote sensing data from Switzerland (Borken-Kleefeld and Chen, 2014; Chen and Borken-Kleefeld, 2016). These data are unique because of the long series of annual measurements at the same site since 2001 with (mostly) the same RSD instrument. The CONOX database provides more opportunities for analysing more recent vehicles (Euro 4 and Euro 5 cars), with a finer resolution in terms of manufacturers or possibly models, and in particular for cross-comparison between:

- fleets with their particular mix of manufacturers and models,
- locations with their particularities in terms of driving and ambient conditions,
- countries with different set-ups and cultures for inspection and maintenance, and
- instruments, notably the FEAT and RSD 5000 instruments providing direct NO_2 data.

CONOX brings together campaigns from the year 2011 onwards. Therefore, we can trace the temporal development of Euro 4 cars, mandatory from 2005, as well as of Euro 5 vehicles. There are fewer data for earlier Euro standards but these data will be considered in more detail later. The analyses shown in this section are illustrative of the types of analysis that can be undertaken using remote sensing data.

Ideally, to robustly quantify the effect of vehicle deterioration on emissions, a representative sample of vehicles would be tracked over time and mileage. However, such information is generally not available and other indicators of deterioration need to be considered. The CONOX database has the date when a vehicle was sampled – and through vehicle information databases, the date when the vehicle was manufactured or first registered. The CONOX database can therefore be used to provide a measure of the age of the vehicle, which is a useful indicator for considering deterioration effects. Ideally, the actual mileage of the vehicle would be known at or close to the time of sampling, but that has not been available up to now.[4]

The analysis in this report therefore focuses on vehicle age as being a proxy for vehicle deterioration. Several countries survey the average annual vehicle mileage as a function of vehicle age, though this information is not updated often. For larger samples this data can be used for a more comprehensive analysis. It is particularly needed as there are not-negligible differences between countries (Figure 13). Vehicles of the same age will have a different use and wear, likely to affect also the performance of the after-treatment systems, depending on country, possibly also by vehicle type and size.

[4] In some EU member states, such as United Kingdom and Sweden, it is now possible to also return the vehicle mileage at the last motor inspection (MOT), which should help future studies into vehicle deterioration.

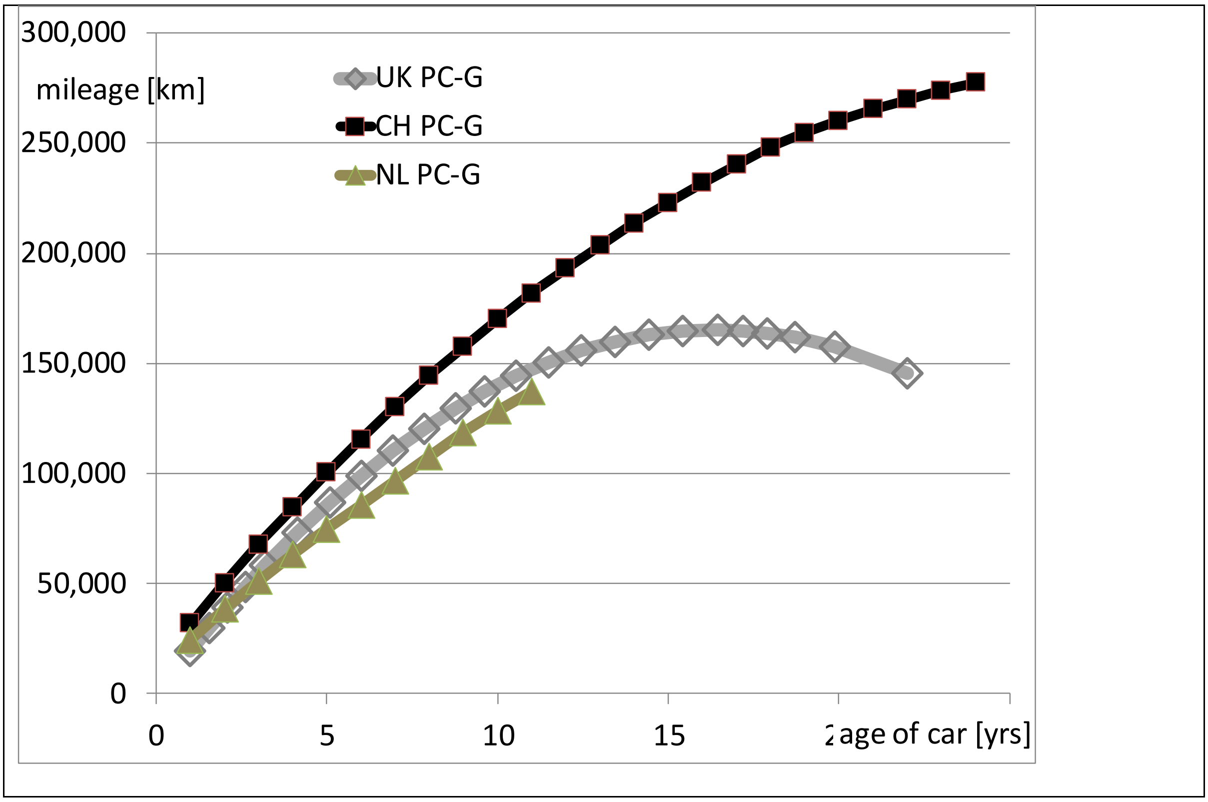

Figure 13: **Cumulative vehicle mileage as function of vehicle age for gasoline cars in Switzerland, the UK and the Netherlands according to official statistical data. The countries differ in absolute mileage and longer term mileage developments. Beyond a vehicle age of five years trend start to deviate more significantly (Bundesamt für Raumentwicklung 2002; Boulter 2009; CBS 2013)**

Numbers of vehicles

The numbers of vehicles analysed is shown in Figure 14, split by fuel type and Euro class for passenger cars. There are proportionately higher numbers of early Euro standard petrol vehicles compared with diesel vehicles, which is expected based on the more recent growth of diesel passenger cars.

Records on Euro 4 and 5 diesel cars originate essentially from campaigns in the UK and Switzerland, providing 90% of all records, with Swedish remote sensing records providing the rest (Figure 15).

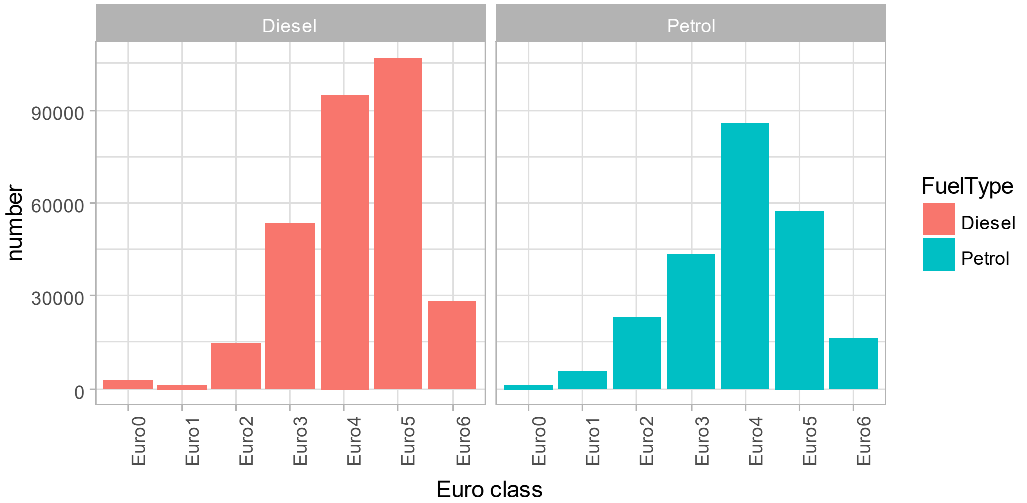

Figure 14. Numbers of petrol and diesel passenger cars used in the analysis.

Figure 15. Numbers of petrol and diesel passenger cars analysed split by Euro class and country of measurement.

Vehicle age distributions

The overall age distribution of vehicles is shown in Figure 16 for petrol and diesel passenger cars. Overall the data show that the age distribution for diesel cars is dominated by younger vehicles compared with petrol. These distributions are consistent with the more recent growth of diesel cars at the expense of petrol cars across Europe.

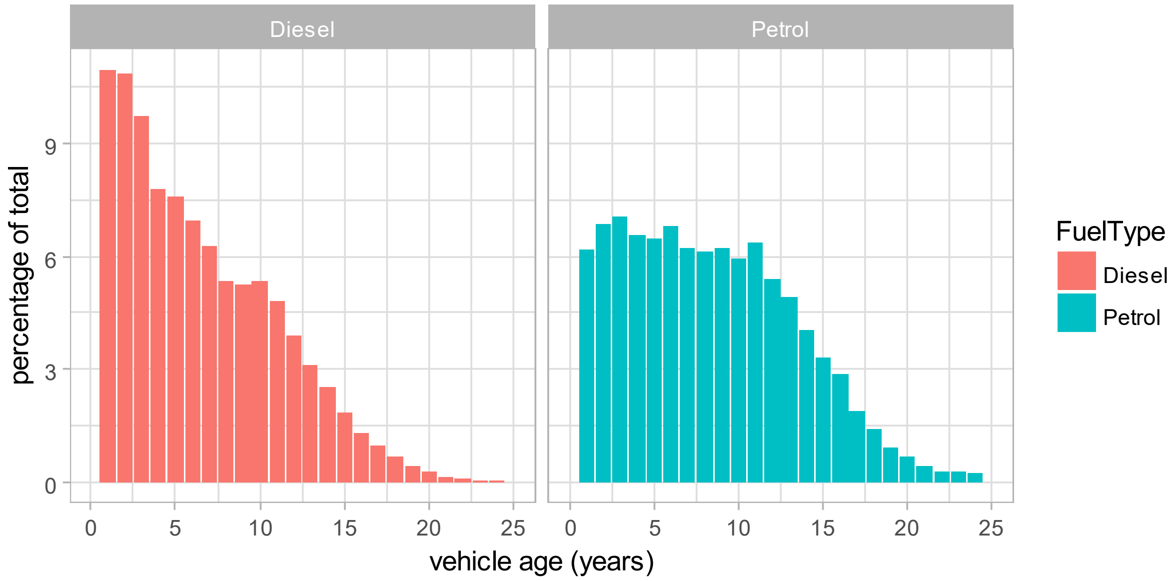

Figure 16. The distribution of vehicles ages in the CONOX database for diesel and petrol passenger cars.

Petrol passenger cars

Figure 17 shows the effect of vehicle age split by Euro class for emissions of CO. These data clearly show the general increase in emissions of CO as vehicles age. The effect is less apparent for older Euro classes from pre Euro through to Euro 3 as data are limited here. The data also show that ageing is important for emissions of CO, e.g. for Euro 5, nine year old vehicles emit over a factor of more than three than new vehicles. It should also be noted that older Euro classes are associated with much higher emissions of CO than more recent Euro classes. Overall, the results are consistent with expectations and show a clear deterioration effect (Figure 18).

In these plots, the age of the vehicle is effectively in intervals i.e. 0 to 1 year, 1 to 2 years old etc.

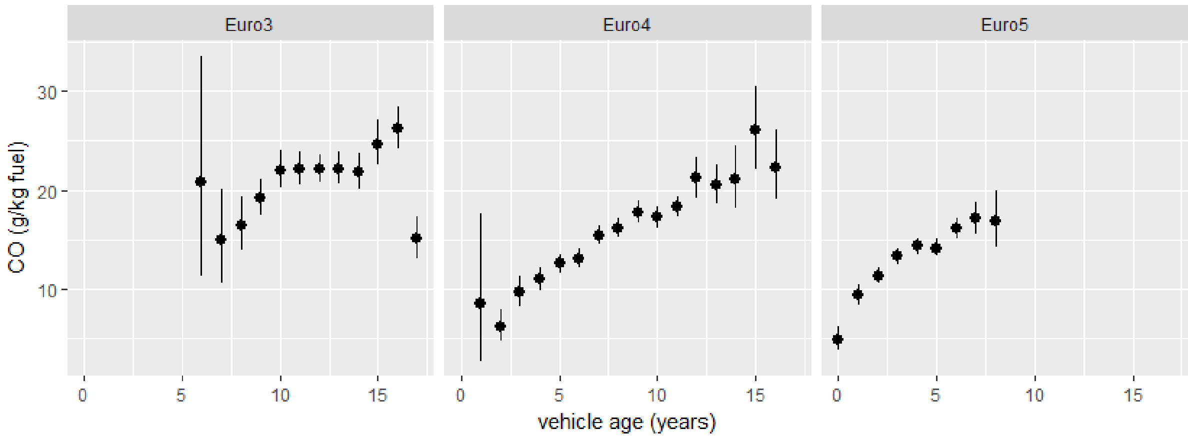

Figure 17. The effect of vehicle age for petrol passenger cars on emissions of CO, split by Euro class.

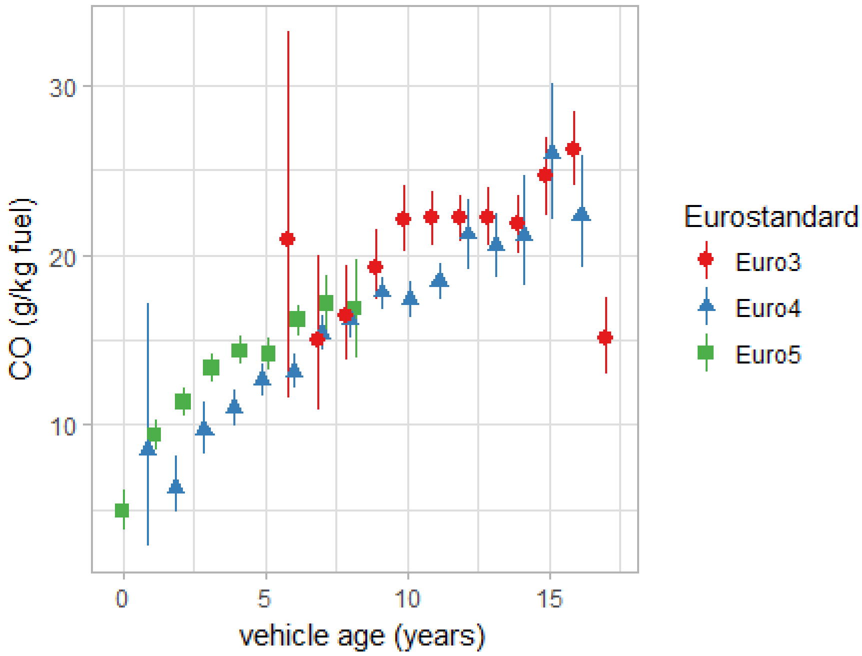

Figure 18. The effect of vehicle age for petrol passenger cars on emissions of CO, split by Euro class.

The emissions of NO for petrol cars are shown in Figures 19 and 20. Compared with the emissions of CO shown in Figure 18, the variations of NO with age are much more variable for different Euro classes. For example, for Euro 3 and 4 vehicles, increasing vehicle age tends to be associated with gradually increasing emissions of NO. In contrast, Euro 5 vehicle emissions of NO appear to *decrease* with increasing vehicle age. The underlying reasons for this behaviour are not known and need further investigation.

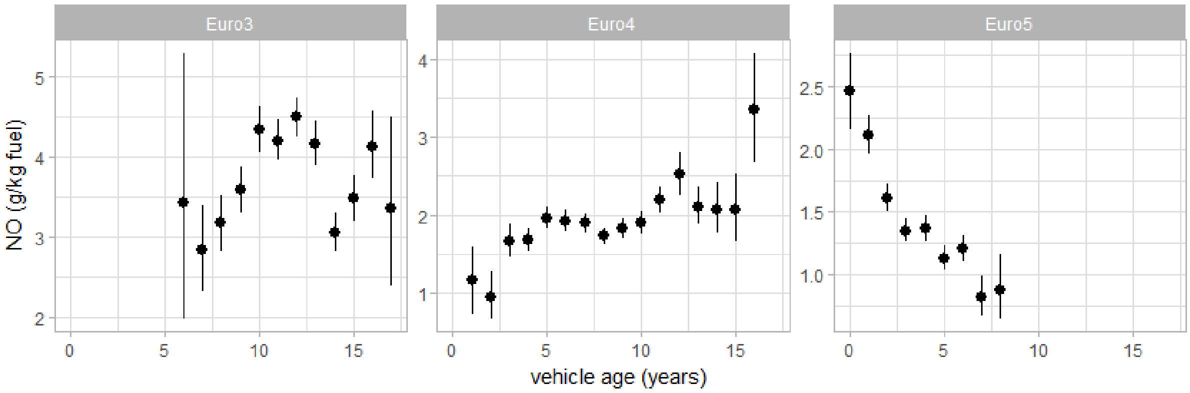

Figure 19. The effect of vehicle age for petrol passenger cars on emissions of NO, split by Euro class.

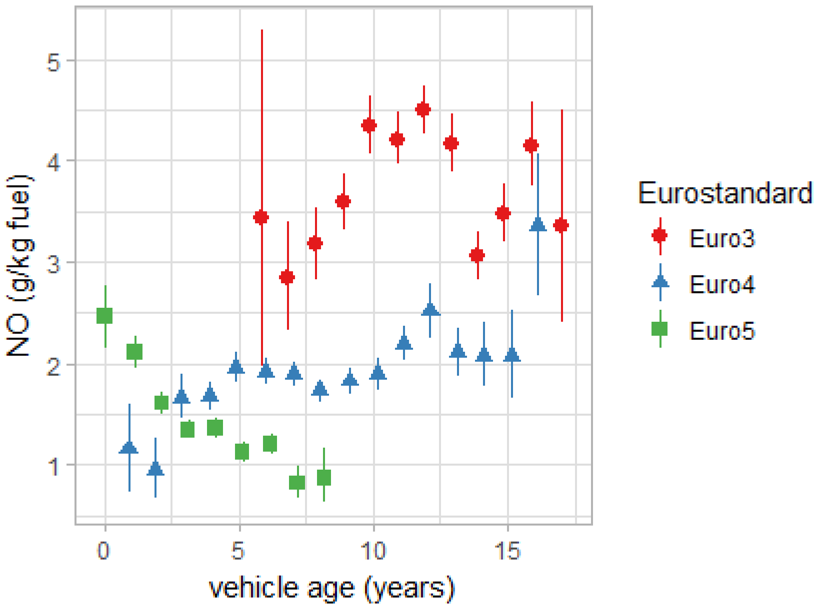

Figure 20. The effect of vehicle age for petrol passenger cars on emissions of NO, split by Euro class.

The data also reveal there are clear differences in ageing effects dependent on the country being considered, as shown in Figure 21. When plotted in this way the UK measurements tend to show higher emissions of NO and stronger effects due to deterioration. There can be speculation on different fleet mix or inspection and maintenance practices between the countries, but this cannot be decided without further analysis.

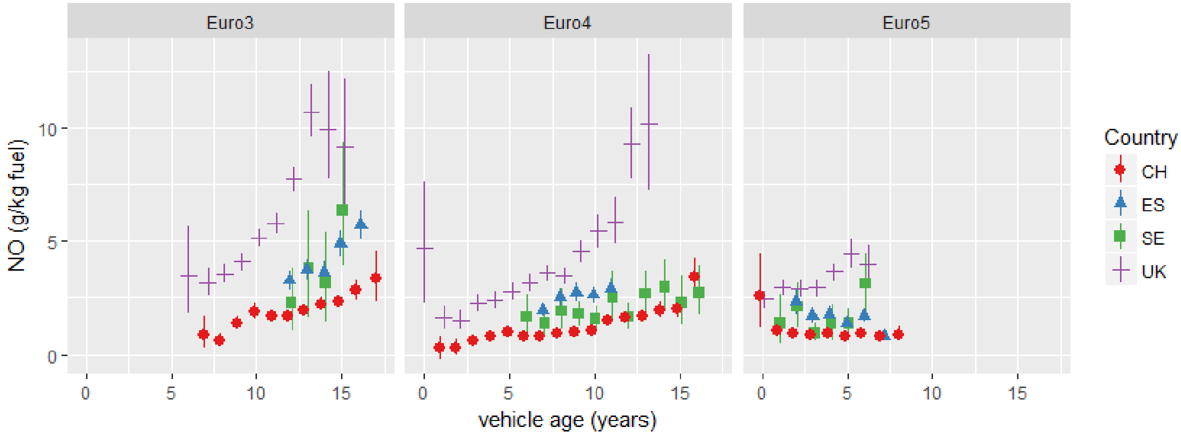

Figure 21. Effect of vehicle age on emissions of NO split by country.

Diesel passenger cars

Emissions of CO

Emissions of CO from diesel vehicles are generally considered to be low relative to petrol vehicles. Nevertheless, there is clear evidence that the emissions increase with vehicle age (Figures 22 and 23) – perhaps due to deterioration of the DOC on vehicles. Nonetheless, diesel cars of 10 years or older do not have a higher CO emission rate than new petrol cars.

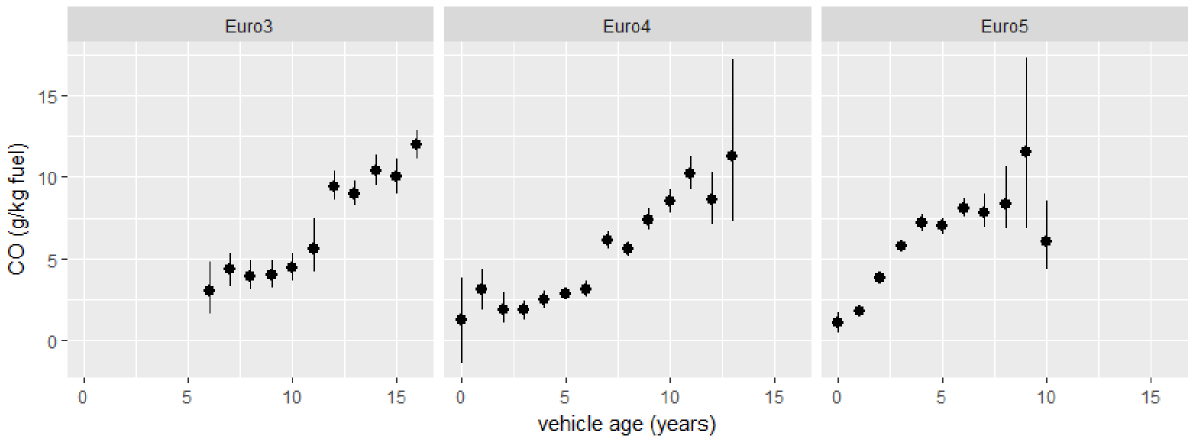

Figure 22. The effect of vehicle age for diesel passenger cars on emissions of CO, split by Euro class.

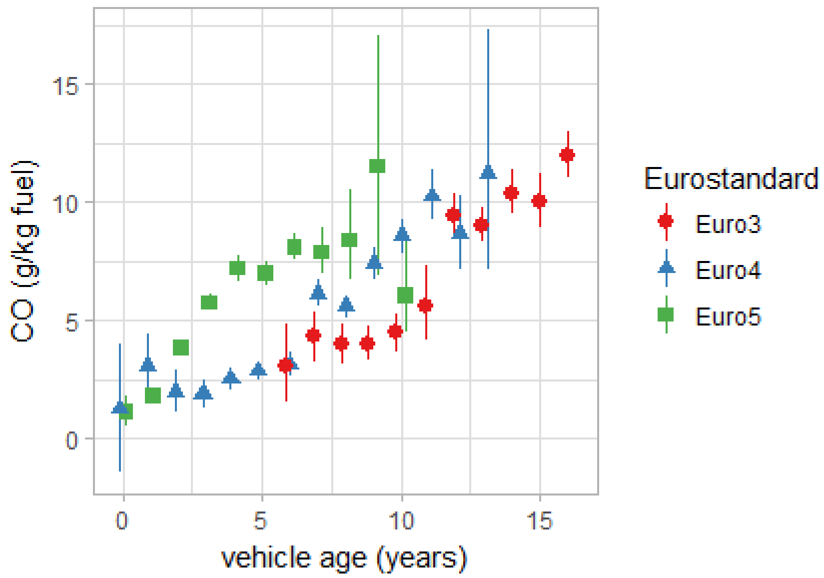

Figure 23. The effect of vehicle age for diesel passenger cars on emissions of CO, split by Euro class.

Emissions of NO

The change in emissions of NO with vehicle age is mixed across the countries (Figure 24) There is a clearly increasing trend for Euro 3 cars with age, but inconclusive developments for Euro 4 cars. In the case of Euro 5 cars, the emission rate seems to increase with age in Switzerland and the UK, while it appears decreasing in Sweden. This needs to be analysed in more detail to understand the underlying reasons.

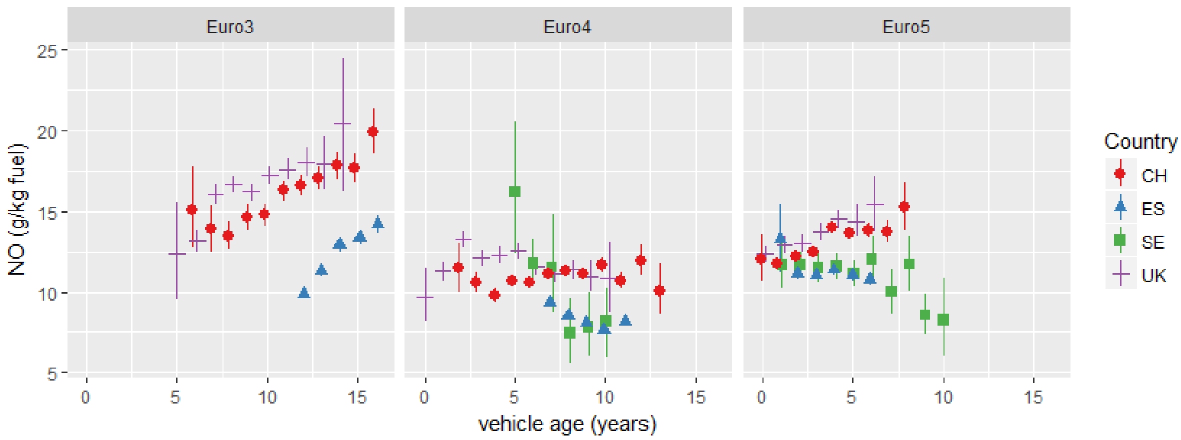

Figure 24. The effect of vehicle age for diesel passenger cars on emissions of NO, split by Euro class and country.

Emissions of particulate matter

Remote sensing instruments can provide an indication of particulate matter (PM) emissions through UV measurements at around 250 nm, which has been shown to provide a good measure of diesel particulate emissions. The plots in Figures 25 and 26 show that there is evidence that as diesel cars age their emissions of PM increase. However, for Euro 5 vehicles (that will have DPF) the emissions are much lower than for Euro 3 or 4 vehicles. There is evidence though that as Euro 5 vehicles age the PM emissions increase and there is consistency across the different countries considered.

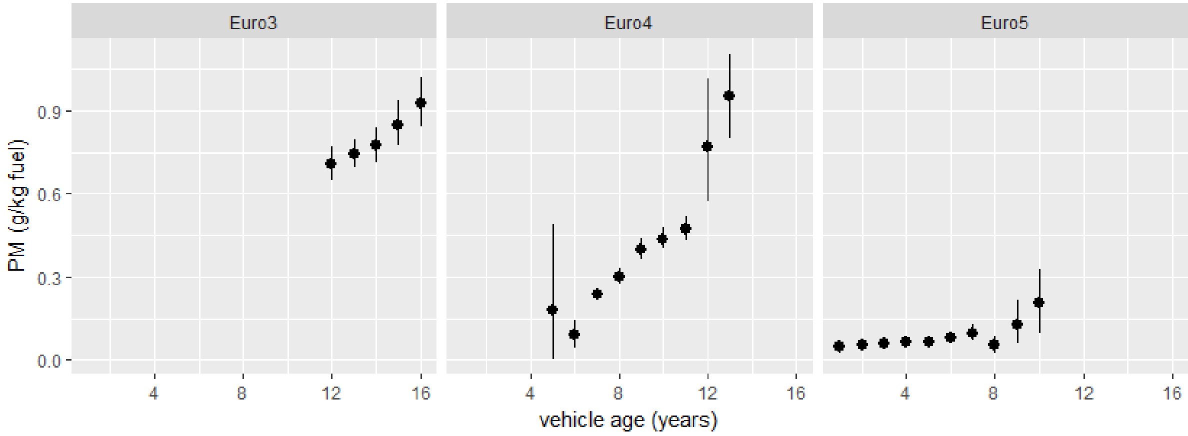

Figure 25. The effect of vehicle age for diesel passenger cars on emissions of PM, split by Euro class.

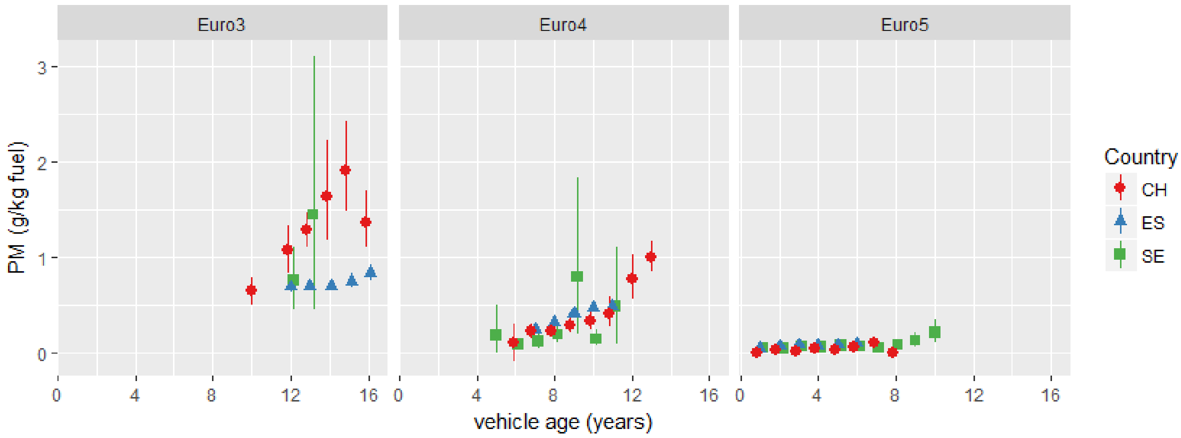

Figure 26. The effect of vehicle age for diesel passenger cars on emissions of PM, split by Euro class.

Emissions of NO by most popular model in each country

With a large database such as CONOX, there are opportunities to disaggregate the data in many ways. This section provides some examples of considering the deterioration of vehicles split by fuel type, Euro standard and most popular engine displacement in each country.

For each country, the vehicle models were ranked in terms of their numbers and the top three chosen for further analysis. This type of analysis is illustrative and can be refined and further developed. In particular, a more comprehensive treatment of sample size and uncertainties is required when partitioning the data to this extent.

Euro 4 petrol

The results shown in Figure 27 show that overall emissions of NO tend to increase as a vehicle ages across all countries. However, the results also indicate that the deterioration appears to be worse in the UK than in other countries, the reasons for which need to be investigated further. Some manufacturers seem to share the same trend, e.g. the Volkswagen models in Switzerland and the Vauxhall models in the UK.

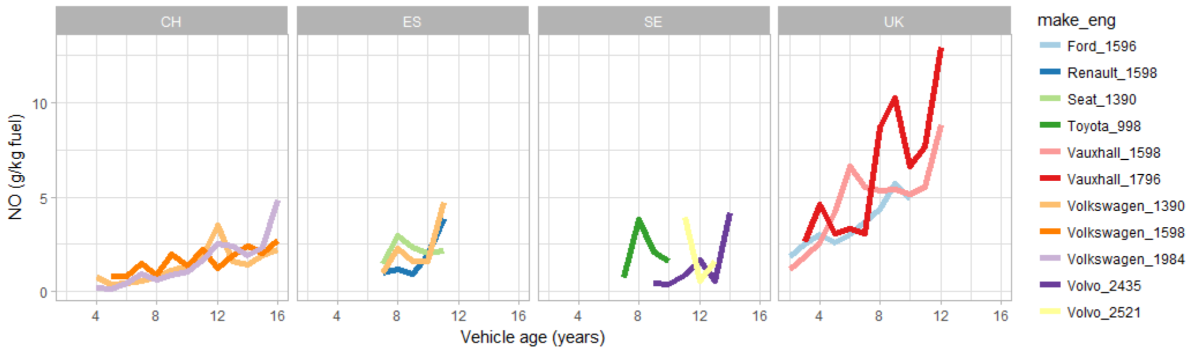

Figure 27. The effect of vehicle age for Euro 4 petrol passenger cars on emissions of NO, split by the three most popular model vehicles in each country. The legend provides information on the manufacturer and engine size in cc.

Euro 5 petrol

For Euro 5 petrol vehicles, the deterioration of NO emissions is not as great as for Euro 4 vehicles, which is expected (Figure 28). However, the results again show the UK vehicles exhibit more deterioration in NO emissions than other countries. One hypothesis is that this could be manufacturer specific.

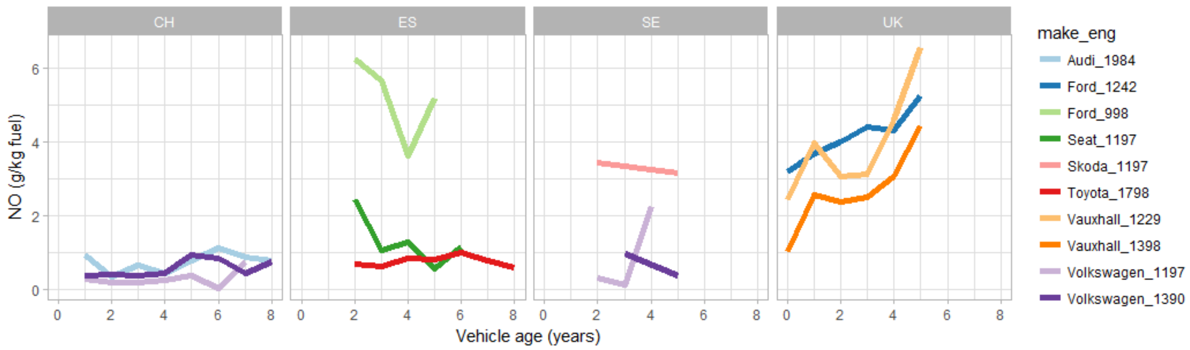

Figure 28. The effect of vehicle age for Euro 5 petrol passenger cars on emissions of NO, split by the three most popular model vehicles in each country. The legend provides information on the manufacturer and engine size in cc.

Euro 4 diesel

The results for Euro 4 diesel cars are rather mixed across the different counties, showing no obvious pattern of deterioration (Figure 29), in line with earlier findings (Chen and Borken-Kleefeld 2016). On average however, the vehicles models in the UK tend to have higher NO emissions than in other countries but the pattern of change with vehicle age is inconsistent i.e. with emissions either increasing or decreasing with vehicle age. Note that the data from Sweden should be considered with caution because of smaller sample sizes.

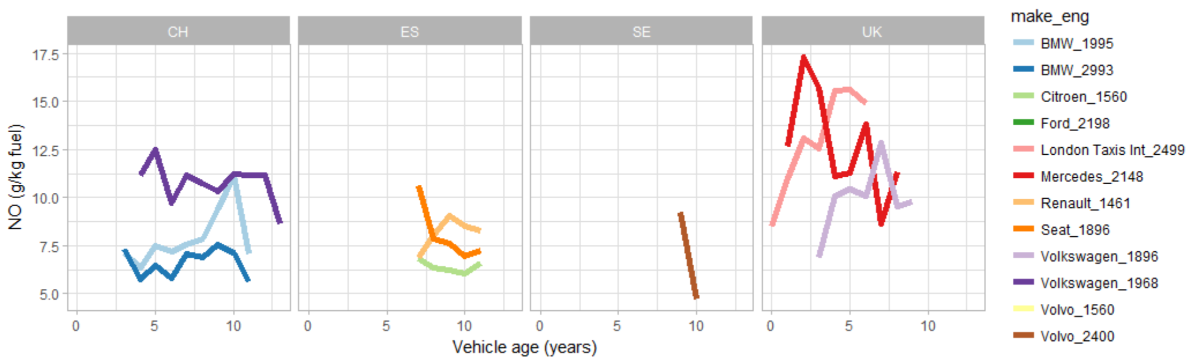

Figure 29. The effect of vehicle age for Euro 4 diesel passenger cars on emissions of NO, split by the three most popular model vehicles in each country. The legend provides information on the manufacturer and engine size in cc.

Euro 5 diesel

For Euro 5 diesel cars the Swiss data suggests emissions of NO deteriorate within the first five year of vehicle life but there are no clear patterns of deterioration for vehicle models in other countries (Figure 30). In the UK for example, all three model vehicles show no clear change in emissions with age. In Sweden, the Volvo with the 1560 cc engine actually has much higher emissions for relatively young vehicles and about a factor of 3-4 less NO emissions for vehicles > 5 years old. Such variations warrant further investigation to explore the underlying reasons for the changes observed.

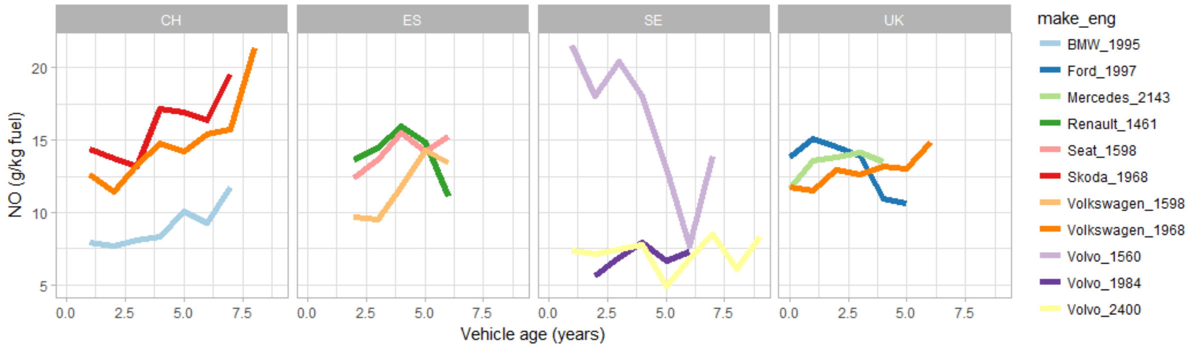

Figure 30. The effect of vehicle age for Euro 5 diesel passenger cars on emissions of NO, split by the three most popular model vehicles in each country. The legend provides information on the manufacturer and engine size in cc.

Limitations and recommended next steps

There is considerable scope for more detailed analyses than are considered here. These include:

- Work to understand the differences between countries, vehicle operating conditions and ambient temperatures. The differences between countries will be driven by both differences in vehicle fleets but also different approaches to inspection and maintenance.
- Conversion of change behaviour with vehicle age to vehicle mileage to allow better cross-comparison between countries.
- More work is required on the CONOX database to calculate robust NOx emissions, which is currently being undertaken. Further analysis will therefore present the deterioration effects on total NOx rather than just NO, as currently considered.
- Importantly, comparison with emission model (COPERT, HBEFA) approaches and their respective assumptions for estimating the effect of vehicle deterioration on emissions of CO, HC, NOx and particulate matter. For instance, the current European Guidebook on emission inventories, the COPERT model and to some extent also the HBEFA model still assume zero or a slight deterioration of NO_X for all diesel vehicles (EEA 2013; Katsis, Ntziachristos, and Mellios 2012; Keller et al. 2017).
- An improved understanding of how the ratio of NO2/NOx changes as vehicles age. Limited analysis of the UK fleet using the University of Denver (FEAT) instrument suggests that as vehicles age, the ratio of NO2/NOx tends to decrease (Carslaw et al. 2016; Grange et al. 2017). However, more work is required to understand these effects more.
- The evidence for the robustness of DPF on Euro 5 and Euro 6 diesel passenger cars. Remote sensing data clearly shows a major reduction in PM emissions with the introduction of DPF on Euro 5 passenger cars. A key question is the long-term robustness of DPF and how deterioration (or indeed DPF removal) affects emissions on PM.
- Further work is required to calculate the uncertainties related to the deterioration of specific model vehicles from individual countries. It might for example be better to consider 'manufacturer family' emissions e.g. grouping a specific engine size across the VW Group (Volkswagen, Audi, Skoda and Seat). Such aggregation would boost the sample sizes and reduce the associated uncertainties.
- As the CONOX database continues to grow, there will be enhanced opportunities for the deeper analysis of the data, e.g. the deterioration rates from light commercial vehicles, trucks and buses; or to what extent deterioration affect the whole fleet in the same way or certain manufacturers or even models specifically. Try to distinguish between general deterioration of the engine tuning and the emission after-treatment system on the one hand and the increase of broken (or tampered) vehicles (high-emitters) on the other hand.
- Re-assess the influence of old, deteriorated vehicles on the resulting air quality in the light of the new information in ageing behaviour.

Temperature dependence of diesel passenger cars' NO_X emissions

Since remote sensing always measures emissions during ambient conditions, it represents an ideal tool to study the impact of ambient temperature on emissions, both for hot and cold engines (although remote sensing measurements are mostly carried out on warmed-up engines). Based on CONOX data (more than 200,000 remote sensing measurements on diesel passenger cars), Figure 31 reveals the ambient temperature dependence, in the range from just above zero to about +35 degrees, of real-world NO_X emissions from Euro 5 diesel passenger cars. A similar plot is presented in Figure 32, representing recently conducted measurements in the UK (Carslaw, 2017). Clearly, NO_X emissions from hot diesel Euro 5 passenger cars increase with decreasing temperature. It is also interesting to note that NO_X emissions reach a minimum in the temperature range where the type approval test is carried out (20-25 C), and then increase with increasing temperature.

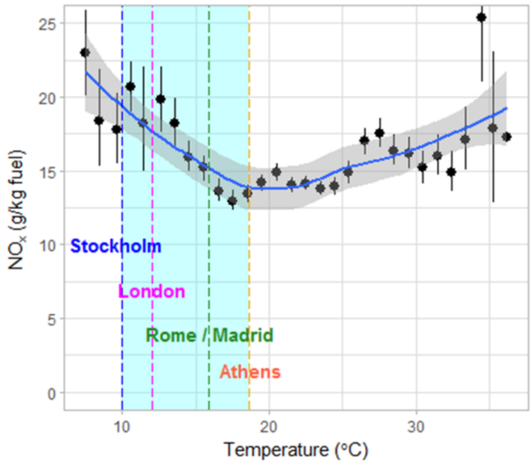

Figure 31. NO_X emissions (in g/kg fuel) for Euro 5 diesel passenger cars as measured by remote sensing vs ambient temperature (CONOX data, ≈200,000 records).

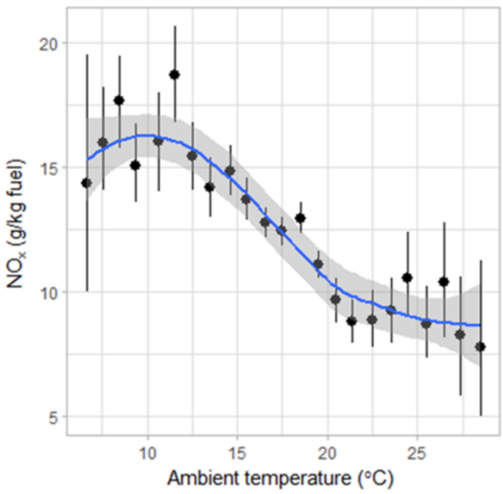

Figure 32. NO_X emissions (in g/kg fuel) for Euro 5 diesel passenger cars as measured by remote sensing vs ambient temperature (UK data 2017 (Carslaw, 2017)).

Conclusions

This study, representing Task 2 of the CONOX project, ultimately pooled and analysed hundreds of thousands of real driving emission data from remote sensing measurements carried out on various locations across Europe in four countries (Spain, Sweden, Switzerland and United Kingdom) between the years 2011 and 2017.

Although remote sensing has a an apparent limitation in the snapshot character of its emission measurement principle, this study has proven that this can largely be overcome by its feature of being able to provide large number of measurements in a short time and at a low cost. Thus, it represents an efficient "big data" provision tool, enabling various kinds of statistical analyses on real-world emission data, which is normally not feasible with emission data collected by means of conventional emission measurement methods (e.g. chassis dynamometer and PEMS tests).

Other important features of remote sensing are:

- Measuring exhaust emissions during drive-by.
- Contactless (=remotely), without vehicle preparation and the chances for the passing vehicle to detect that an emission test is taking place being practically negligible (as opposed to the situation for conventional tests as revealed in "dieselgate").
- Real-life "average" vehicles (no preselection).
- With natural driver (not a trained test driver).
- In real traffic (no bench, no track).
- Under ambient conditions (not lab conditions).
- Random, as passing by (no scripted test).
- Fleet average weighted by model, mileage & age.
- Wide range of driving and ambient conditions.

More specifically the results from the analysis carried out in this study are:

- Average NO_x emissions from diesel passenger cars (by Euro standard, make, brand, model, engine family, etc.) as measured by remote sensing agree well with corresponding emissions measured on-board vehicles, e.g. by means of PEMS, thus remote sensing has been proven as a powerful tool for market surveillance and for complementing conventional test methods aiming at capturing real driving emissions.

- With help of remote sensing all top selling models can be measured. Despite large efforts and resources spent on PEMS tests in the past, these did not cover the market sufficiently, and high NO_x emitters were effectively escaping the tests.

- The real-world NO_x emissions from diesel passenger cars remain virtually unchanged by the EU emission legislation from Euro 1 through Euro 5, meaning that in real-world driving the average European diesel Euro 5 car emits 5-6 times more NO_x in excess of the Euro 5 standard.

- Euro 6 diesel passenger cars emit on average about half as much NO_X as Euro 5 diesel cars, still the Euro 6 diesel cars emit on average about five times more NO_X in excess of the Euro 6 standard.

- The introduction of effective DPFs (diesel particulate filters) along with the Euro 5 emission standard has effectively reduced the real-world emissions of particulate matter from Euro 5 and 6 diesel passenger cars down to very low levels.

- The remote sensing data analysis has yielded new knowledge and insights as regards the phenomena of emissions deterioration for diesel and petrol passenger cars, and further work on this topic is recommended.

- Real-world NO_X emissions from Euro 5 diesel passenger cars operating with hot engines show a clear dependence of ambient temperature, with emissions increasing strongly with decreasing ambient temperature below 20 degrees, and increasing again with increasing ambient temperature above 25 degrees.

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Appendix 1. List of database parameters with descriptions

DATABASE PARAMETER NAME	PARAMETER DESCRIPTION
VehiclePassageID	Filled in automatically when data are imported into the database
PassageTime	Time of vehicle passages according to the RSD
SessionID	Filled in automatically when sessions are registered in the database via the website interface
VehicleCategoryID	Vehicle category code according to the "Lists" spreadsheet in the database Excel upload form
VehicleCategory	Filled in automatically when VehicleCategoryID is inserted
FuelTypeID	Fuel type code according to the "Lists" spreadsheet in the database Excel upload form
FuelType	Filled in automatically when FuelTypeID is inserted
EmissionStandardID	Emission standard code according to the "Lists" spreadsheet in the database Excel upload form
EmissionStandard	Filled in automatically when EmissionStandardID is inserted
AbatementTechID	Abatement technology code according to the "Lists" spreadsheet in the database Excel upload form
AbatementTech	Filled in automatically when AbatementTechID is inserted
VehicleMakeCodeID	Vehicle make code according to the "Lists" spreadsheet in the database Excel upload form
VehicleMake	Filled in automatically when AbatementTechID is inserted
S/A flag	RSD speed and acceleration measurement valid flag (V=valid, x= unvalid)
Speed mph	Measured vehicle speed by the RSD - in miles per hour
Accel mphpersec	Measured vehicle acceleration by the RSD - in miles per hour per second
Speed kph	Measured vehicle speed by the RSD - in miles per hour
Accel kphpersec	Measured vehicle acceleration by the RSD - in miles per hour per second
VSP	Vehicle specific power caclulated by the RSD from speed and acceleration and US default data
VSPStatus	VSP valid flag (V=valid, x=unvalid)
ValidPlumePoints	Number of valid CO2 measurements by the RSD in the exhaust plume

Average_CO2	The average column density for CO2 along the RSD beam during the measurement
Max_CO2	The maximum column density for CO2 along the RSD beam during the measurement
Percent_CO	Tailpipe concentration of CO in volume percent derived from the RSD measurements
Percent_CO2	Tailpipe concentration of CO2 in volume percent derived from the RSD measurements
PPM_HC_Propane	Tailpipe concentration of HC expressed in ppm propane units derived from the RSD measurements
PPM_HC_Hexane	Tailpipe concentration of HC expressed in ppm hexane units derived from the RSD measurements
PPM_NO	Tailpipe concentration of NO in ppm derived from the RSD measurements
PPM_NO2	Tailpipe concentration of NO2 in ppm derived from the RSD measurements
PPM_NH3	Tailpipe concentration of NH3 in ppm derived from the RSD measurements
UV_Smoke	Tailpipe concentration of smoke derived from the RSD measurements in the UV range
IR_Smoke	Tailpipe concentration of smoke derived from the RSD measurements in the IR range
Ratio_CO_CO2	CO/CO2-ratio by volume derived from the RSD measurements
Ratio_HC_CO2	HC/CO2-ratio by volume derived from the RSD measurements
Ratio_NO_CO2	NO/CO2-ratio by volume derived from the RSD measurements
Ratio_NO2_CO2	NO2/CO2-ratio by volume derived from the RSD measurements
Ratio_NH3_CO2	NH3/CO2-ratio by volume derived from the RSD measurements
AmbientTemperature	Air temperature as measured by the RSD
BarometricPressure	Air barometric pressure as measured by the RSD
Humidity	Air humidity temperature as measured by the RSD
CO_gpkg	CO emission in grams per kg fuel burned
CO2_gpkg	CO2 emission in grams per kg fuel burned
HC_gpkg	HC emission in grams per kg fuel burned
NO_gpkg	NO emission in grams per kg fuel burned (as NO2)
NO2_gpkg	NO2 emission in grams per kg fuel burned
NOx_gpkg	NOx emission in grams per kg fuel burned (as NO2)
NH3_gpkg	NH3 emission in grams per kg fuel burned
UV_Smoke_gpkg	Smoke (PM) emission in grams per kg fuel burned according to the RSD measurements in the UV range
IR_Smoke_gpkg	Smoke (PM) emission in grams per kg fuel burned according to the RSD measurements in the IR range

E_VSP_kW/t	Vehicle specific power in kW per tonne calculated from the RSD measurements by means of the CONOX methodology
E_FuelRate_g/s	Vehicle fuel rate in grams per second calculated from the measurements by means of the CONOX methodology
E_CO2_g/s	CO2 mass emissions in grams per second calculated from the RSD measurements by means of the CONOX methodology
E_CO_g/s	CO mass emissions in grams per second calculated from the RSD measurements by means of the CONOX methodology
E_HC_g/s	HC mass emissions in grams per second calculated from the RSD measurements by means of the CONOX methodology
E_NO_as NO2_g/s	NO mass emissions in grams per second as NO2 calculated from the RSD measurements by means of the CONOX methodology
E_NO2_g/s	NO2 mass emissions in grams per second calculated from the RSD measurements by means of the CONOX methodology
E_PM_g/s	PM mass emissions in grams per second calculated from the RSD measurements by means of the CONOX methodology
CalFactor_CO	RSD calibration factor for CO
CalFactor_CO2	RSD calibration factor for CO2
CalFactor_HC	RSD calibration factor for HC
ValidPlumePoints_CO	Number of valid CO measurements by the RSD in the exhaust plume
ValidPlumePoints_HC	Number of valid HC measurements by the RSD in the exhaust plume
ValidPlumePoints_NO	Number of valid NO measurements by the RSD in the exhaust plume
ValidPlumePoints_NO2	Number of valid NO2 measurements by the RSD in the exhaust plume
ValidPlumePoints_NH3	Number of valid NH3 measurements by the RSD in the exhaust plume
CO_Valid	RSD CO measurement valid flag (V=valid, x= unvalid)
CO2_Valid	RSD CO2 measurement valid flag (V=valid, x= unvalid)
IR_HC_Valid	RSD HC measurement valid flag (V=valid, x= unvalid)
NO_Valid	RSD NO measurement valid flag (V=valid, x= unvalid)
NO2_Valid	RSD NO2 measurement valid flag (V=valid, x= unvalid)
NH3_Valid	RSD NH3 measurement valid flag (V=valid, x= unvalid)
UV_Smoke_Valid	RSD UV smoke measurement valid flag (V=valid, x= unvalid)
NO2 measured or estimated	Filled in automatically when campaign or session is registered in the database (1=measured, 2=estimated)
LICENCE	The license plate number of the measured vehicle
VIN/CHASSIS NUMBER	Vehicle identification number - in Sweden also called chassis number

GROUP NUMBER	Number code which relates to the make, model and model year of the vehicle - we might omit this from the DB
MODEL NAME	EU vehicle classification - M1, N1, N2, N3, etc.
VEHICLE DESCRIPTION	Parameter in the Swedish national vehicle register giving the make of the vehicle and sometimes also the model
TRADE DESIGNATION	Parameter in the Swedish national vehicle register giving the model of the vehicle and sometimes also the make
MODEL YEAR	Model year of the vehicle
MONTH OF MANUFACTURE	Year and month of manufacture of the vehicle
DATE OF REGISTRATION	Date when the vehicle was registered in the vehicle register
DISPLACEMENT_cm3	Engine displacement volume in cm3
CURB WEIGHT_kg	Curb weight of the vehicle in kg
TOTAL WEIGHT_kg	Total weight (maximum allowed weight) of the vehicle in kg
POWER_FUEL1_kW	Engine power of the vehicle in kW
WIDTH_mm	Vehicle width in mm
HEIGHT_mm	Vehicle height in mm
LENGTH_mm	Vehicle length in mm
CERT_CO2_gkm_MIXED	Certified CO2 emission in grams per km in mixed driving - value often (always?) lacking in the Swedish vehicle register
CERT_CO2_gkm_RURALMOTORWAY	Certified CO2 emission in grams per km in rural or motorway driving - value often (always?) lacking in the Swedish vehicle register
CERT_CO2_gkm_URBAN	Certified CO2 emission in grams per km in urban driving - value often (always?) lacking in the Swedish vehicle register
CERT_FUELCONSUMPTION_MIXED_lp100km	Certified fuel consumption emission in grams per km in mixed driving
CERT_FUELCONSUMPTION_RURALMOTORWAY_lp100km	Certified fuel consumption emission in grams per km in rural or motorway driving - value often (always?) lacking in the Swedish vehicle register
CERT_FUELCONSUMPTION_URBAN_lp100km	Certified fuel consumption emission in grams per km in urban driving - value often (always?) lacking in the Swedish vehicle register
CO2_FUELCONSUMPTION_DrivingcycleID	Driving cycle ID - value often/always lacking in the Swedish vehicle register
VehicleInformation Date	Date when the vehicle register was updated
Mileage_km	Odometer reading of the vehicle in km when the vehicle was last inspected at an inspection station
Inspection date	Date when the vehicle was last inspected at an inspection station
VehiclePassageComments	Comments during vehicle passage in the RSD measurements
Segment	Vehicle segment according to ICCT segmentation

On-road mass	On-road mass according to CONOX definition
FF_R0_N/t	Parameter to be inserted into the fuel flow equation developed by Stefan Hausberger
FF_R1_(Ns/m)/t	Parameter to be inserted into the fuel flow equation developed by Stefan Hausberger
FF_cw*A_m2/t	Parameter to be inserted into the fuel flow equation developed by Stefan Hausberger
FF_coeff_A	Parameter to be inserted into the fuel flow equation developed by Stefan Hausberger
FF_coeff_B	Parameter to be inserted into the fuel flow equation developed by Stefan Hausberger
FF_coeff_C	Parameter to be inserted into the fuel flow equation developed by Stefan Hausberger
FF_flag	Valid flag for fuel flow (V=valid, x=unvalid)

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