No. C 387
Nov 2019

Study on the durability of European passenger car emission control systems utilizing remote sensing data

FINAL REPORT

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

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Imprint
Commissioned by: Federal Office for the Environment (FOEN), Air Pollution Control and Chemicals Division, CH-3003 Bern. The FOEN is an agency of the Federal Department of the Environment, Transport, Energy and Communications (DETEC).
Contractor: IVL Swedish Environmental Research Institute
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FOEN support: Harald Jenk **(**Air Pollution Control and Chemicals Division)
Note: This study/report was prepared under contract to the Federal Office for the Environment (FOEN). The contractor bears sole responsibility for the content.
Report number: C 387
ISBN: 978-91-7883-035-0
Edition Only available as PDF for individual printing

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This report has been reviewed and approved in accordance with IVL's audited and approved management system.

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Summary

1. This study analyses comprehensive remote sensing data to better understand deterioration effects from passenger cars on the emissions of NO_x (including NO_2), CO and hydrocarbons (HC).
2. Data from recent surveys at several European locations have been analysed including the data from the CONOX project[1]. The data are mostly from two instruments: the Opus 5000 RSD and the University of Denver FEAT instrument. The principal difference between these two instruments is that the FEAT has a separate spectrometer for NO_2 and is considered to produce more reliable measurements of NO_2 (and hence total NO_x) than the Opus instrument.
3. An important development has been the acquisition of vehicle mileage information from UK data for individual vehicles, and more recently from Sweden. This information provides a direct measure of mileage effects on vehicle emissions without the need to use vehicle age as a proxy for mileage.
4. Considering the whole CONOX database (almost 1 million vehicle measurements in total), mileage deterioration factors have been derived that show the change in emissions at 0, 50,000, 100,000 and 200,000 km for petrol and diesel cars. To quantify these changes, we have adopted a modelling approach based on Generalised Additive Models (GAMs) that also takes account of vehicle dynamics (using Vehicle Specific Power, VSP) and ambient conditions (through ambient temperature). The modelling aims to isolate the mileage deterioration effects separately from the influence of VSP and ambient temperature.
5. For emissions of CO and NO_x from petrol vehicles the data show increasing emissions with increased mileage, with earlier Euro standards showing more deterioration. The trends in HC with mileage are mixed, with Euro 3 and 4 vehicles showing a decrease in emissions with age. It should be noted however, that remote sensing instruments do not measure all hydrocarbon species and it is possible that the composition of HC changes with both Euro standard and mileage. This issue requires more investigation.
6. There is evidence that the emission of CO and HC increase as diesel passenger car mileage increases. The quantification of HC from Euro 6 vehicles by means of remote sensing is more uncertain. Emissions of NO_x from Euro 5 and 6 diesel vehicles show no obvious change as the vehicle mileage increases and there is limited evidence of an increase for Euro 3 and 4 vehicles at high mileages up to 200,000 km (However, see point 8 below).
7. The CONOX database has been analysed to consider also the mileage deterioration effects for individual manufacturers. Such an analysis is a strength of remote sensing data due to the large number of measurements available. The analysis does not indicate, for example, that any single manufacturer has vehicles that deteriorate in a significantly worse way than other manufacturers.

[1] Sjödin, Å., Borken-Kleefeld, J. Carslaw, D., Tate, J., Alt, G.-M., De la Fuente, J., Bernard, Y., Tietge, U., McClintock, P., Gentala, R., Vescio, N., Hausberger, S (2018) Real-driving emissions from diesel passenger cars measured by remote sensing and as compared with PEMS and chassis dynamometer measurements - CONOX Task 2 report. On behalf of the Federal Office of Environment, Switzerland, https://www.bafu.admin.ch/bafu/en/home/topics/air/publications-studies/studies.html

8. The emissions of NO_2 from diesel vehicles, as measured by the FEAT, tend to decrease as the vehicle mileage increases. This is an important finding given the importance of NO_2 emissions to ambient NO_2 concentrations close to major roads. The results also suggest that deterioration factors specifically for NO_2 (or the ratio of NO_2/NO_x) could usefully be considered in commonly used vehicle emission factor models. Emissions of NO_x from diesel vehicles show little evidence of change with increasing mileage for any Euro standard and are dissimilar to the patterns seen for HC or CO.
9. For the first time, it has been possible to measure the *same* vehicle over a 4- to 5-year period. Measurements made in London in 2013 were complemented with measurements at the same location in 2017/8. Over 1000 vehicles were measured at both time periods, which have been summarised into main Type Approval categories. While there is some evidence that total NO_x emissions were about 10-20% higher in 2017 for LDV diesels, it is considered the principal reason for this is related to differences in ambient temperature. During the measurement campaigns in 2017/8 ambient temperatures were about 10 °C lower than in 2013 (10 °C vs 20 °C).
10. Some care is needed when using vehicle age as a proxy for vehicle mileage. While there seems to be good agreement between the UK, Sweden and Switzerland (where we have data available) on the average relationship between vehicle age and mileage for petrol and diesel cars, there are limitations associated with the data. The mileage of a vehicle can vary substantially with vehicle age and the emissions data show low-mileage vehicles of any age frequently associated with low emissions. In other words, deteriorating emission performance appears principally driven by usage, not by age.
11. As the amount of remote sensing data increases, there will be additional opportunities to develop these analyses further. In particular, more investigation of the following issues would be worthwhile:
    a. A better understanding of the differences that can be introduced depending on the remote sensing instrument used and especially related to the measurement of NO_2.
    b. The change in emissions of ammonia (NH_3) as vehicle mileage increases.
    c. The further development and refinement of the CONOX database would be of substantial merit in this respect. There remain inconsistencies in how data are reported in different countries, which can make the analysis of the whole database challenging.

1 Introduction

This study makes use of data from the full CONOX database and a more recent subset of UK data. The CONOX database as described by Sjödin et al., 2018 has recently been updated to include additional data from Sweden, Switzerland and the UK from measurements made in 2017 and 2018.

The recent UK data has been analysed in more detail for two principal reasons. First, remote sensing measurements from 2017 onwards now include a measure of the vehicle mileage at the last annual MOT test (annual roadworthiness inspections). These data are highly valuable for the investigation of how vehicle deterioration affects vehicle emissions. Previous studies have used vehicle age as a proxy for vehicle mileage. The second benefit of some of the recent UK data is the use of the Denver University Fuel Efficiency Automobile Test (FEAT) instrument. The FEAT uses a dedicated spectrometer to measure NO_2, which leads to an improved measure of NO_2 emissions in vehicle exhaust. The latter benefit is important because it is suspected that as vehicles age, the amount of NO_2 they produce decreases. This effect is considered directly in the current report.

1.1 Measurements and data overview

Vehicle emission remote sensing data consists of short duration (snapshot) measurements of vehicle plumes. An individual measurement of the exhaust plume from a vehicle is not very informative and some form of data aggregation is needed to derive useful insight. The most common way of aggregating remote sensing data is to calculate the mean emission by some sort of categorical such as Euro classification or year of manufacture. Alternatively, continuous variables such as vehicle mileage can be 'binned' into intervals to produce categories. However, the binning process is rather arbitrary. For example, how wide should a bin be and how many measurements should there be in each bin?

In this report we use Generalized Additive Models (GAMs) to determine the relationships between the emission and mileage of a vehicle (Wood, 2008; 2003). The GAM approach is flexible and powerful and can be thought of as a 'data derived' method of establishing the relationship between two variables. One of the strengths of GAMs in the context of the analysis in this report is that relationships between variables can be non-linear. One of the principal benefits of using GAMs for the analysis of remote sensing data is that the data do not need to be aggregated in some way, e.g. by year, to establish relationships between variables.

In analysing the data on vehicle mileage, there is an important distinction between the analysis of data where vehicle mileage is recorded for individual vehicles and that which is derived based on the age of the vehicle. The former is potentially much more informative. For example, for the analysis of Euro 3 vehicles, measured mileage information generally spans a wide range of values from low to high values. However, age-derived mileages will generally span a much narrower range of mileages. If the 'youngest' Euro 3 vehicle is 10 years old, it will be assigned the average mileage based on a 10-year old car. In reality, 10-year cars will have a wide range of mileages (and potentially emissions) and this information is lost in age-derived mileages. This is one reason why we spent some time analysing the UK data where vehicle mileage is known for individual vehicles.

2 Vehicle fleet characteristics

2.1 Numbers of vehicles

Figure 1 shows the number of passenger cars in the updated CONOX database, categorised by country, fuel type and Euro emissions standard. The fraction of diesel passenger cars recorded in the UK and Sweden is roughly 50%, whilst around 71% of the measurements made in Spain are of diesel passenger cars. This contrasts to Switzerland, where much higher fractions of petrol passenger cars were observed (ca. 69%).

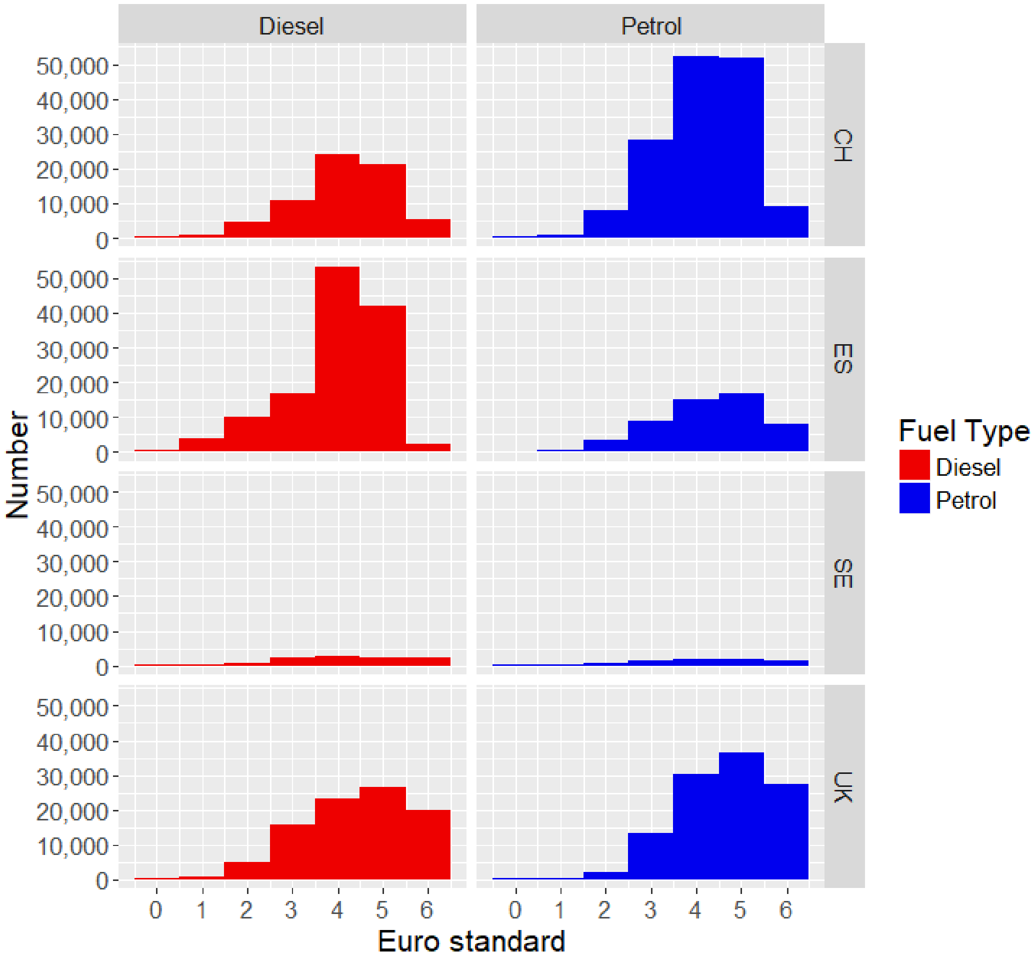

Figure 1. Numbers of diesel and petrol passenger cars in the updated CONOX database split by Euro class and country of measurement.

2.2 Vehicle mileage distribution

Remote sensing measurements for the recent UK and Sweden measurements (2017 onwards) now include a direct measure of the vehicle mileage at the last annual MOT test. The annual occurrence of MOT tests in the UK (once the vehicle is over 3 years old) means that the mileage is accurate to the nearest 12 months. In the updated European database presented in this study, there are 75,234 records available with vehicle mileage information; approximately 14% of the measurements come from Sweden, and around 86% from the UK. Figure 2 shows the distribution of vehicle mileage for diesel and petrol passenger cars in the UK and Sweden.

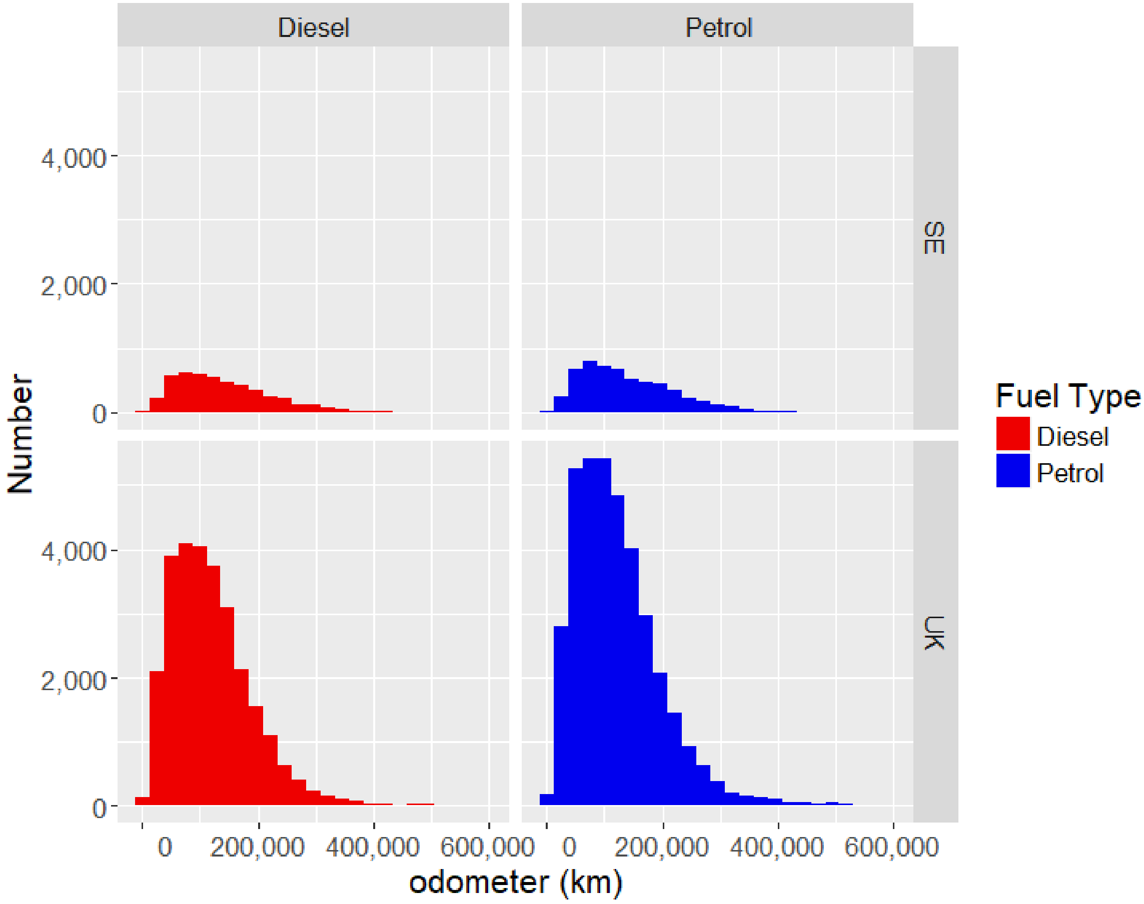

Figure 2. Distribution of vehicle mileage for diesel and petrol passenger cars measured in Sweden, 2016 and UK, 2017/2018.

2.3 Using vehicle age as a proxy for vehicle mileage

If a direct measurement of vehicle mileage from an annual roadworthiness inspection is not available, it is necessary to use vehicle age as a proxy for vehicle mileage. The age of the vehicle at the time of measurement is estimated by subtracting the model year of the vehicle from the measurement year. Figure 3 and 4 show an estimated vehicle mileage for petrol and diesel passenger cars, based on the country of measurement and the vehicle age.

It should be noted that the UK mileage data is from the information collected from recent remote sensing surveys rather than being derived from national statistics as for Sweden and Switzerland. For petrol and diesel cars there is good agreement between the three countries shown in the plots up to vehicle ages of about 15 years. The data on older vehicles in general will be less reliable and more variable because there are fewer vehicles with very high mileages.

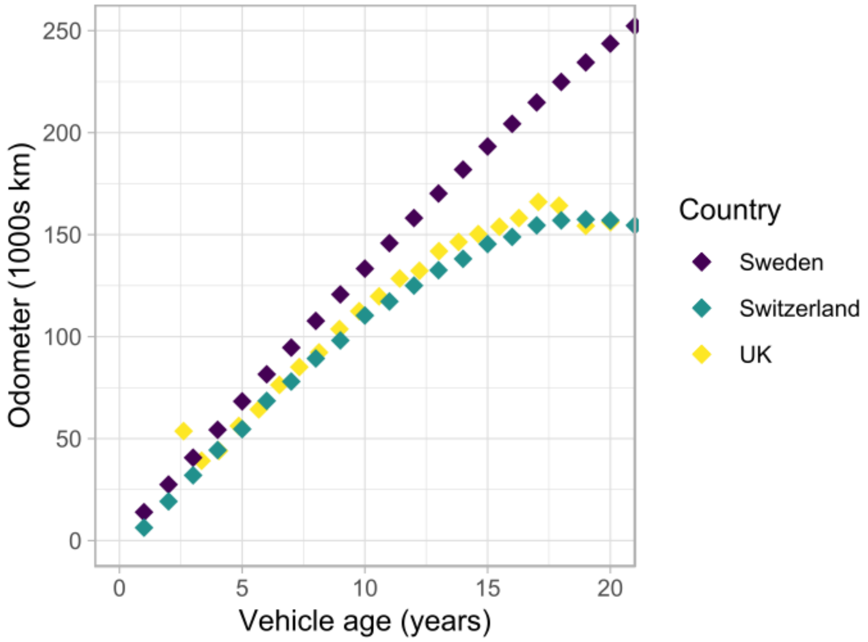

Figure 3. Estimate of vehicle mileage for petrol passenger cars, based on the country of measurement and the age of the vehicle.

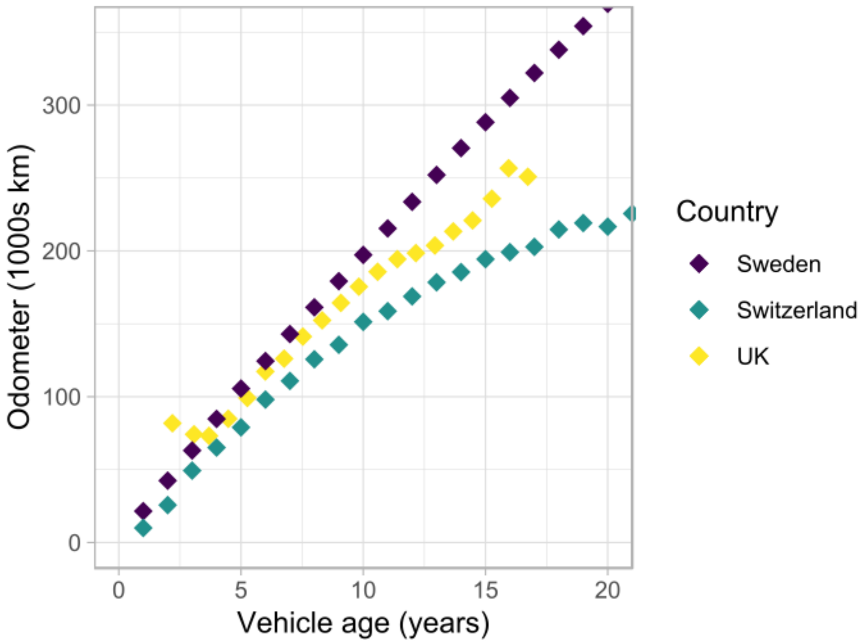

Figure 4. Estimate of vehicle mileage for diesel passenger cars, based on the country of measurement and the age of the vehicle.

While the relationships between vehicle age and mileage look 'well behaved' they do disguise a lot of potentially important variability. For example, taking a petrol car that is 10 years old would suggest a mean mileage of about 100,000 km. However, we find in the UK data that vehicles of this age can have vastly different mileages from <10,000 to > 500,000 km, as discussed below. This feature of the data is important when attempting to represent mileage-related vehicle emissions information, which can show different behaviours depending on whether observed mileage data is used for individual vehicles, or if proxy data is used based on mileage-age relationships.

The vehicle age-mileage relationships disguise a lot of variation. A vehicle of a particular age can be associated with a large range in mileage. To investigate the relationship further, quantile regression has been applied to determine how the median, 5 and 95th percentiles of mileage vary with vehicle age (Koenker, 2011; Koenker and Bassett, 1978). This analysis has been applied to passenger cars in the UK where actual individual vehicle mileage information is available.

For petrol cars (Figure 5) it shows for example that a 10 year old Euro 4 car has a median mileage of about 100,000 km but the range from 5th to 95th percentiles is from 50,000 to 200,000 km. Figure 6 shows for diesel cars that their mileages are higher than petrol and there is more evidence of a skewed relationship with a higher number of higher mileage vehicles for any particular age compared with petrol cars.

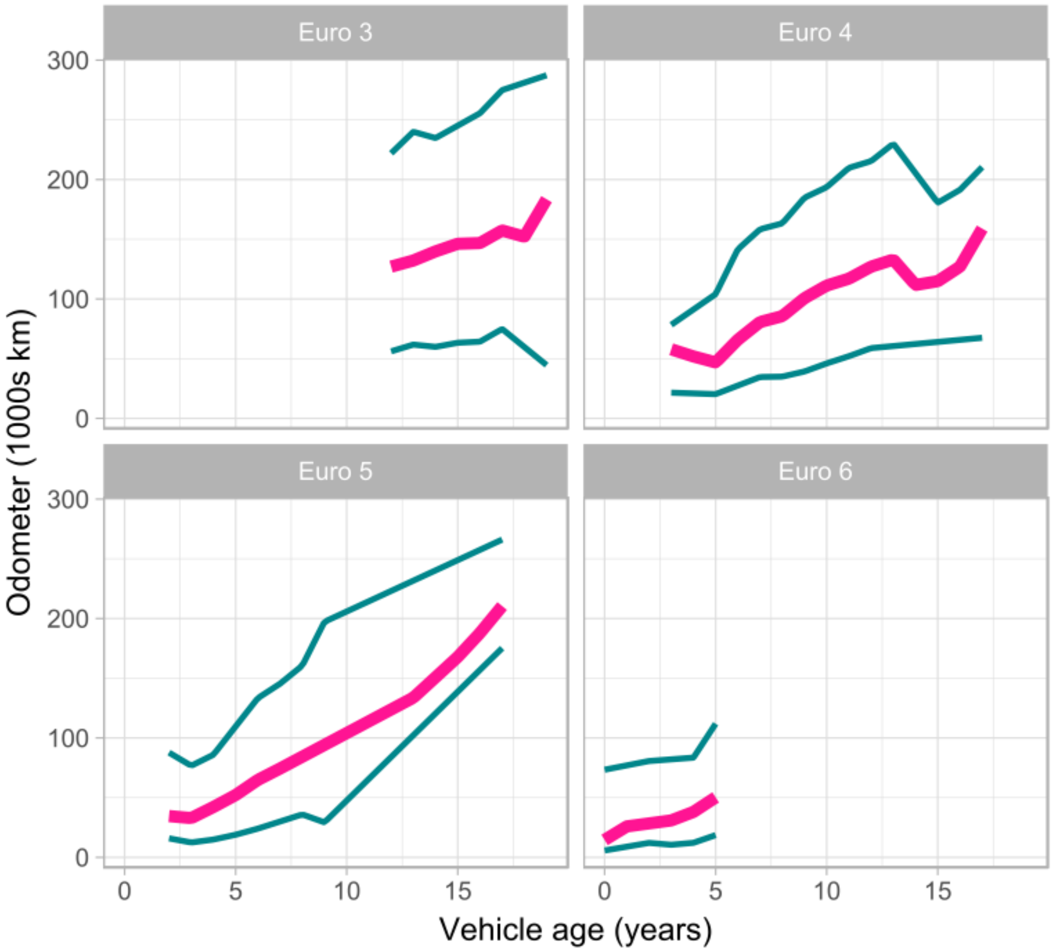

Figure 5. Variation of vehicle mileage with vehicle age for petrol passenger cars in the UK. The thick pink line shows the median value and the thinner green lines the 5th and 95th percentile values as determined by quantile regression.

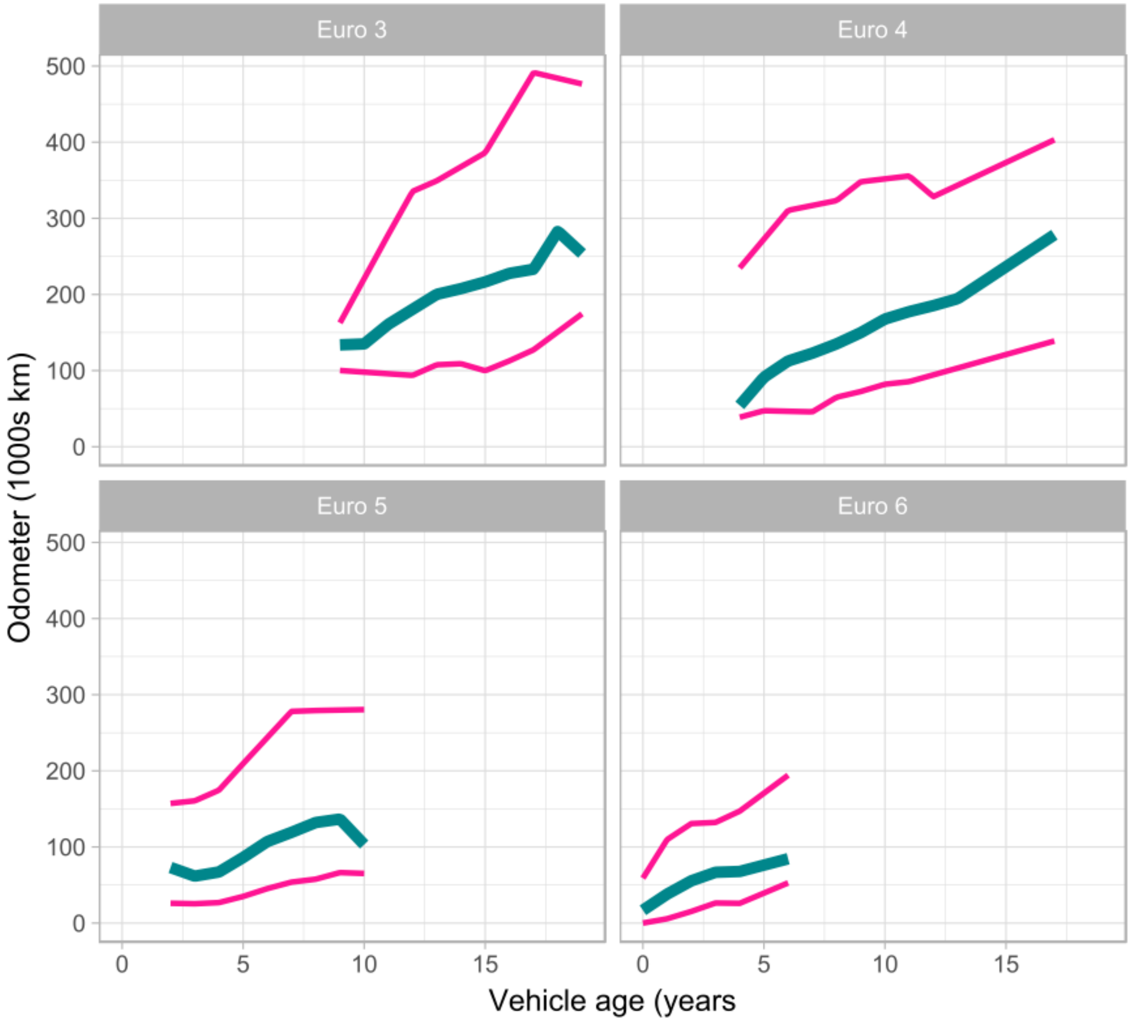

Figure 6. Variation of vehicle mileage with vehicle age for diesel passenger cars in the UK. The thick green line shows the median value and the thinner pink lines the 5th and 95th percentile values as determined by quantile regression.

3 Analysis of the updated database

3.1 Overview of petrol and diesel NOx emissions

Using the estimates of vehicle mileage shown in Figure 3 and 4, it is possible to assess the influence of mileage on emissions of NOx. As we did not obtain vehicle mileage by vehicle age data for Spain, these RS measurements have been excluded from the analysis and we focus instead on data from Sweden, Switzerland and the UK. We first perform the analysis for petrol cars as the usefulness of RS data for determining their deterioration has been proven already (Bishop and Stedman, 2008; Borken-Kleefeld and Chen, 2015); then we transfer the same method to diesel cars.

Figure 7 clearly shows that NOx emissions increase with increasing mileage for Euro 3 and 4 petrol cars. For Euro 5 cars there appear two regimes: Roughly stable emissions up to about 150,000 km, followed by a very steep increase in the emission rate from then onwards. There are too few data for Euro 6 cars with mileages above 100,000 km and thus no evidence of relevant deterioration.

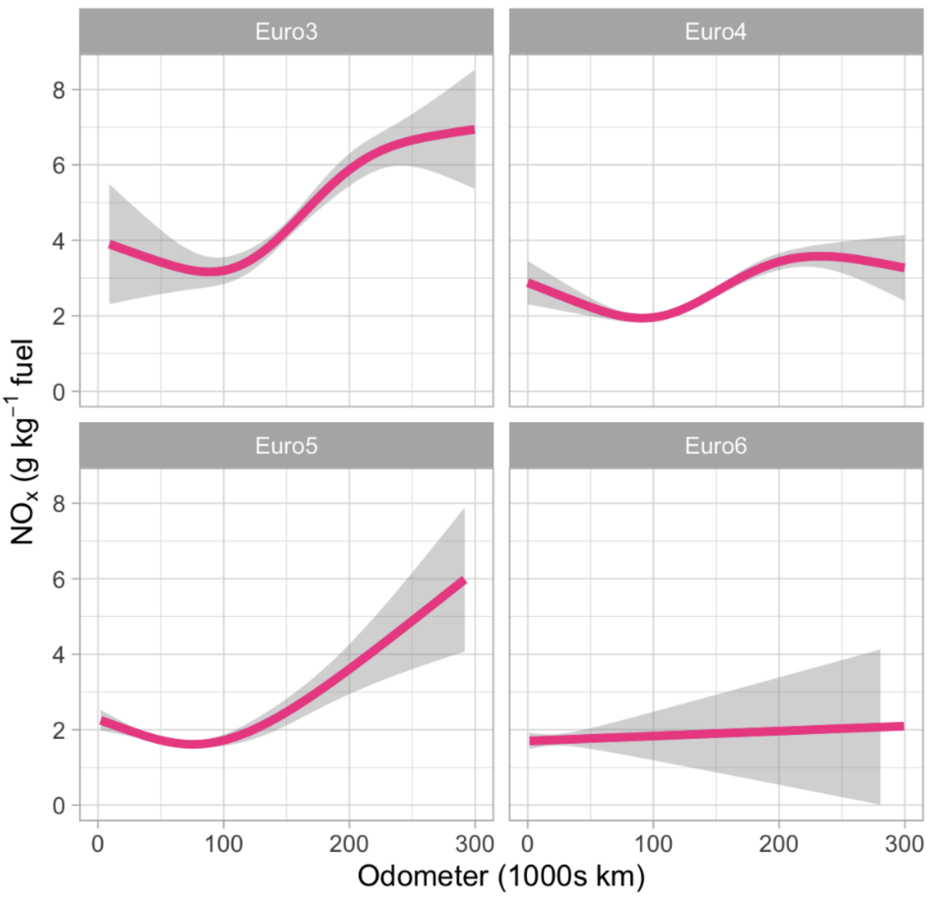

Figure 7. NOx emissions from petrol passenger cars, split by Euro standard. The smooth lines show the results of fitting a GAM to the data.

The corresponding relationships between vehicle mileage and NOx emissions for diesel cars are plotted in Figure 8. There is an increase of the emission rate for Euro 3 cars up to 200,000 km. Much older cars seem to have lower emissions again. A slight increase of the emission rate can also be seen for Euro 4 cars up to about 180,000 km mileage, followed by a stagnation or even slight decrease with higher mileages. No clear trends can be determined for Euro 5 or Euro 6 cars.

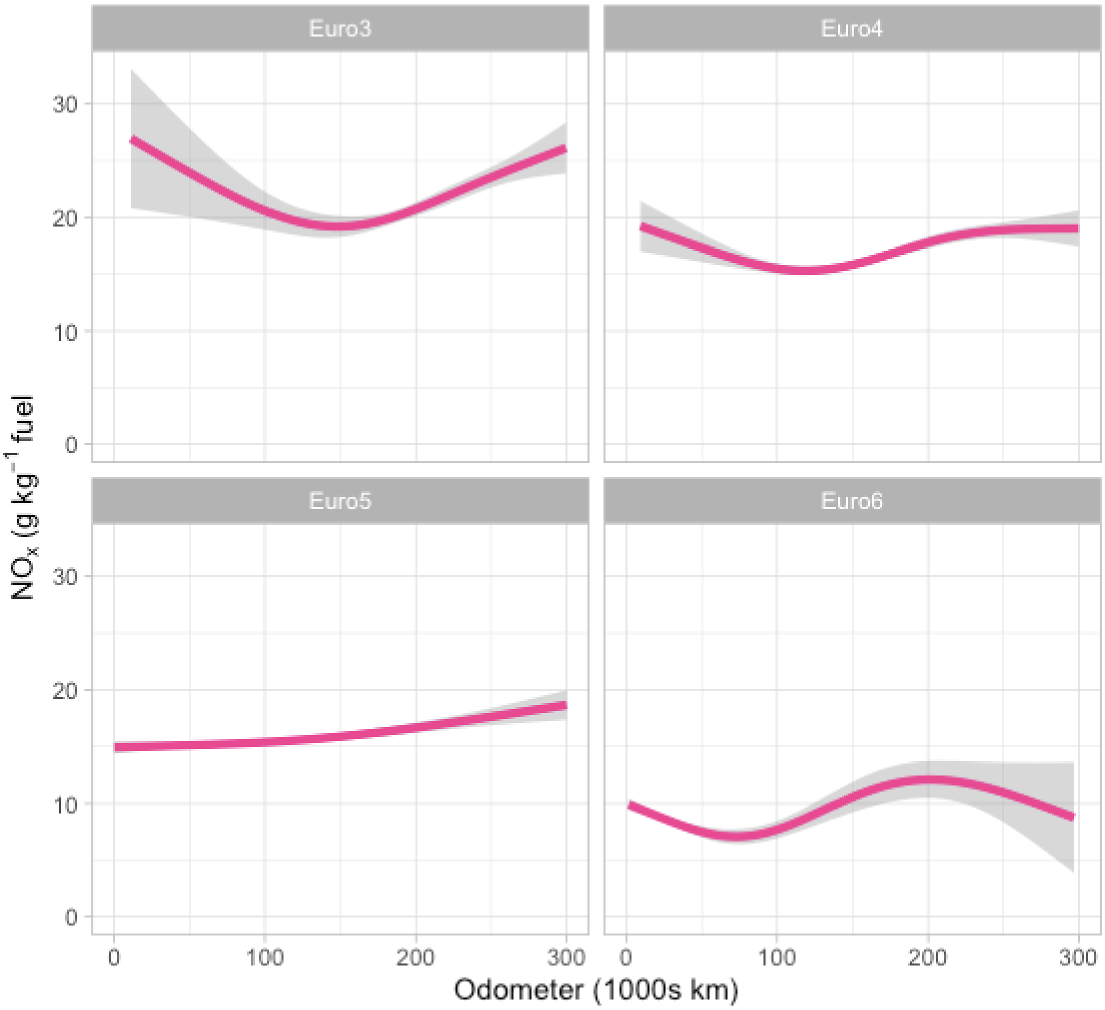

Figure 8. NOx emissions from diesel passenger cars, split by Euro standard. The smooth lines show the results of fitting a GAM to the data.

3.2 Emission deterioration factors

The CONOX data have been analysed to derive scaling factors that show how emissions from vehicles change relative to a base value of new vehicles, i.e. with zero mileage. The emission measurements are not only dependent on vehicle mileage but can also be affected by the vehicle operating and environmental conditions. For vehicle emission remote sensing data, the most appropriate metric to account for vehicle operating conditions is Vehicle Specific Power (VSP), which is a measure of the instantaneous power demand of a vehicle at the time of measurement. Some emissions of pollutants are also known to vary by ambient temperature.

While it is possible to filter data to certain ranges of VSP and ambient temperature to ensure consistency across many different measurement locations, this can be wasteful because potentially large amounts of data might be removed. It can be important to undertake some sort of data filtering because individual measurement locations can have very different characteristics, e.g. are located on a relatively steep slope where vehicle power demand is high; furthermore, measurements were made in different seasons and hence under colder and warmer ambient temperatures. This is known to affect notably NOx emissions from more recent diesel cars. An alternative approach is to use a statistical model to 'account' for the influence of VSP and ambient temperature. In this respect, the GAM can provide a measure of the effect of mileage that is independent of the influence of VSP or ambient temperature.

For each pollutant, we modelled the relationship between mileage and emission separately for each Euro standard using a GAM. This model was then used to predict the emissions at specific odometer values of 0, 50k, 100k and 200k km, together with the 95% confidence interval in the predicted value. The predictions have been made at fixed values of VSP (8 kW/t and ambient temperature of 20 °C, close to the overall mean values in CONOX). To establish factors, the predicted values were scaled to their value at 50,000 km. The GAM used was in the form

$$E = s(Odometer) + s(VSP) + s(T)$$

Where E is the emission in g kg^{-1} fuel, *Odometer* is the vehicle mileage in km, VSP is the Vehicle Specific Power and T is the ambient temperature in °C. The s in the equation above represents a smooth function.

In this relative formulation the deterioration rates become directly comparable - applicable - to deterioration rates derived from emission measurements in different units, e.g. gram pollutant per km driven.

3.2.1 Deterioration factors for petrol cars

The deterioration factors with mileage for petrol cars from the GAM analysis are shown in Figure 9 and demonstrate for CO that emissions progressively increase through 50k to 200k km. There is a similar pattern for NOx with lower increases up to 100k km. HC emissions show a mixed response with Euro3 and Euro 4 vehicles showing some evidence of a decrease with mileage. It is not known why HC emissions decrease, but HC emissions are more uncertain to model, as shown by the wider error bars relative to NOx and CO and are more affected by taking account of other influences such as VSP and ambient temperature. It is possible that remote sensing also detects contributions from evaporative emissions but the extent to which this is important is not known.

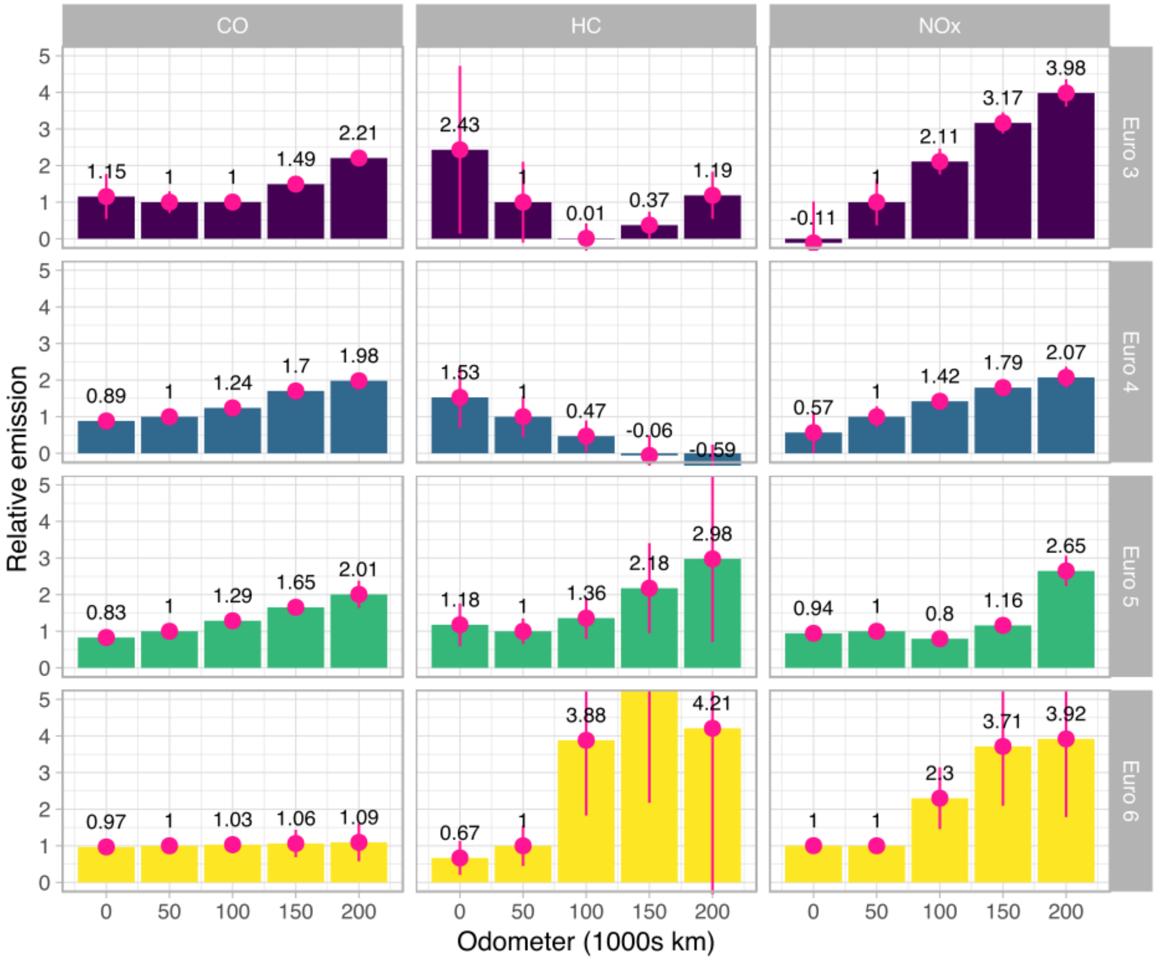

Figure 9. Mileage scaling values for petrol cars by Euro standard and pollutant. Emissions are scaled to equal one at 0 km and all data are normalised to 20° C ambient temperature and a VSP of 8 kW/t.

Broadly speaking, CO and NOx readings increase with mileage as to be expected from deterioration of the catalytic converter. At least for Euro 3 and Euro 4 cars the decrease of the HC emission rate is incompatible with this. However, HC is also mixed bag of various substances. The remote sensing devices are tuned to broad-band absorption of certain HC-bonds; their readings are then scaled up by a fixed factor to estimate total HC in the exhaust. We can speculate that the composition of the different HC changes with an ageing catalyst, and that therefore a fixed scaling factor is inappropriate. In any case, we suggest not to use the deterioration results for HC until further investigations have been made but focus on NOx and CO emission rates.

For NOx deterioration we determine higher deterioration that is clearly above the legal durability requirements and above deterioration factors determined earlier. Importantly a limit for deterioration up to a certain mileage threshold is not found; this assumption taken in HBEFA (as well as COPERT and the EEA Guidebook) is refuted by the long-term remote sensing data. For Euro 5 and Euro 6 cars these are the first on-road deterioration factors at all. If the surprisingly high deterioration rate for latest gasoline cars is confirmed, then their in-use emission levels appear to exceed significantly the legislated limit values.

The picture is a bit different for deterioration of the CO emission rate: We derive higher deterioration rates than previously assumed for Euro 4 and Euro 6 cars (preliminary), but lower deterioration rates for Euro 3 and Euro 5 cars. Euro 3 cars are the oldest in our sample and therefore we have hardly cars with low mileage. In consequence, the emission rate at low mileage does not provide a firm base for a deterioration factor. As a proxy, however, is the change rate e.g. for every 50,000 km that we used for Table 1. It indicates a doubling of the emission rate between 50,000 and 100,000 km, and another doubling until 200,000 km.

We suggest considering deterioration factors derived in this study when updating emission factor models. The functional forms can be provided upon request.

3.2.2 Summary: Petrol emission deterioration factors

Here we compare the results of this analysis with earlier work by Borken-Kleefeld and Chen (2015) and come up with suggestions for revised emission deterioration factors as a function of vehicle mileage. A few comments on the proposed deterioration factors:

- There are only few records for brand new vehicles or vehicles with low mileage in any Remote sensing campaign, as very new vehicles only make up a very small share of the fleet. Hence, on the basis of our data we cannot robustly determine an emission factor at 0 mileage.
- Likely, the share of vehicles with mileages above 200,000 kilometres is small. In addition, there is an unknown sampling effect, meaning that those cars surviving to this high mileage do not have the same characteristics as the fleet average car at 50,000 km, say. Therefore, we do not suggest deterioration factors for mileages higher than 200,000 km based on our sample(s). However, a continued degradation or possible stagnation might be taken as an indication for the further development of the emission rate.
- In our campaigns we have hardly seen evidence for a high or increasing rate of individual high emitters. It rather appears that degradation of the emission control equipment happens gradually across the fleet. The GAM analysis employed above does not prescribe or elucidate a specific function form by itself. Traditionally a linear rate of increase has been assumed. We do not see strong evidence in our data against this hypothesis and we can support it for its simplicity.

The suggested revised emission deterioration factors for petrol cars have been compiled in Table 1.

Table 1. Illustrative deterioration factors for petrol cars for 50,000, 100,000 and 200,000 km cumulated mileage. CONOX data, normalised for 20°C ambient temperature and 8 kW/t VSP.

Cumulated mileage	50k NOx	100k NOx	200k NOx	50k CO	100k CO	200k CO
	Euro 1			**Euro 1**		
Durability req.						
HBEFA/COPERT[e]	1.06	1.76	2.04	1.11	1.63	1.85
RS-ZH (2000-2013)[d]	**1.35**	**1.85**	**3.4**	**1.25**	**1.55**	**2.4**
	Euro 2			**Euro 2**		
Durability req.						
HBEFA/COPERT[e]	1.06	1.76	2.04	1.11	1.63	1.85
RS-ZH (2000-2013)[d]	**1.35**	**1.75**	**3.1**	**1.15**	**1.35**	**1.85**
	Euro 3			**Euro 3**		
Durability req.		1.2[a]			1.2[a]	
HBEFA/COPERT[e]	1.07	1.17	1.28[b]	1.06	1.20	1.37[b]
RS-ZH (2000-2013)[d]	1.2	1.5	2.15	1.15	1.3	1.65
RS CONOX (2011-18)	1	2	4	1	1	2.2
Proposal from RS data	**1.00**	**1.63**	**2.90**	**1**	**1**	**2**
	Euro 4			**Euro 4**		
Durability req.		1.2			1.2	
HBEFA/COPERT[e]	1.07	1.17	1.28[b]	1.25/1.05	1.5/1.1	1.75[b]1.2[b]
RS-ZH (2000-2013)[d]	1.15	1.4	1.9	1.25	1.5	2.25
RS CONOX (2011-18)	1	1.4	2.1	1	1.25	2
Proposal from RS data	**1.00**	**1.50**	**2.00**	**1**	**1.5**	**2**
	Euro 5			**Euro 5**		
Durability req.			1.6[c]			1.5[c]
RS CONOX (2011-18)	1	1	2.65	1	1.3	2
Proposal from RS data	**1**	**1 up to 125k**	**2.5**	**1**	**1.3**	**2**

a: Requirement up to 80,000 km. b: Assumed deterioration factor from 160,000 km onwards. c: Requirement up to 160,000 km. d: Borken-Kleefeld & Chen 2015. *e: Average over engine size and urban-rural driving.

3.2.3 Deterioration factors for diesel cars

The deterioration factors with mileage for diesel cars from the GAM analysis are shown in Figure 10. These results show that CO emissions tend to increase with increasing mileage for Euro 4 to Euro 6. The decrease seen for Euro 3 vehicles is difficult to understand – but the uncertainties in the model for these vehicles is higher. Emissions of NOx are notable for any lack of significant change with mileage. Emissions of HC increase with mileage for Euro 3 to 5 vehicles. The HC emissions for Euro 6 vehicles is highly uncertain, which may reflect the very low emissions from these vehicles, or even other effects such as LNT regeneration.

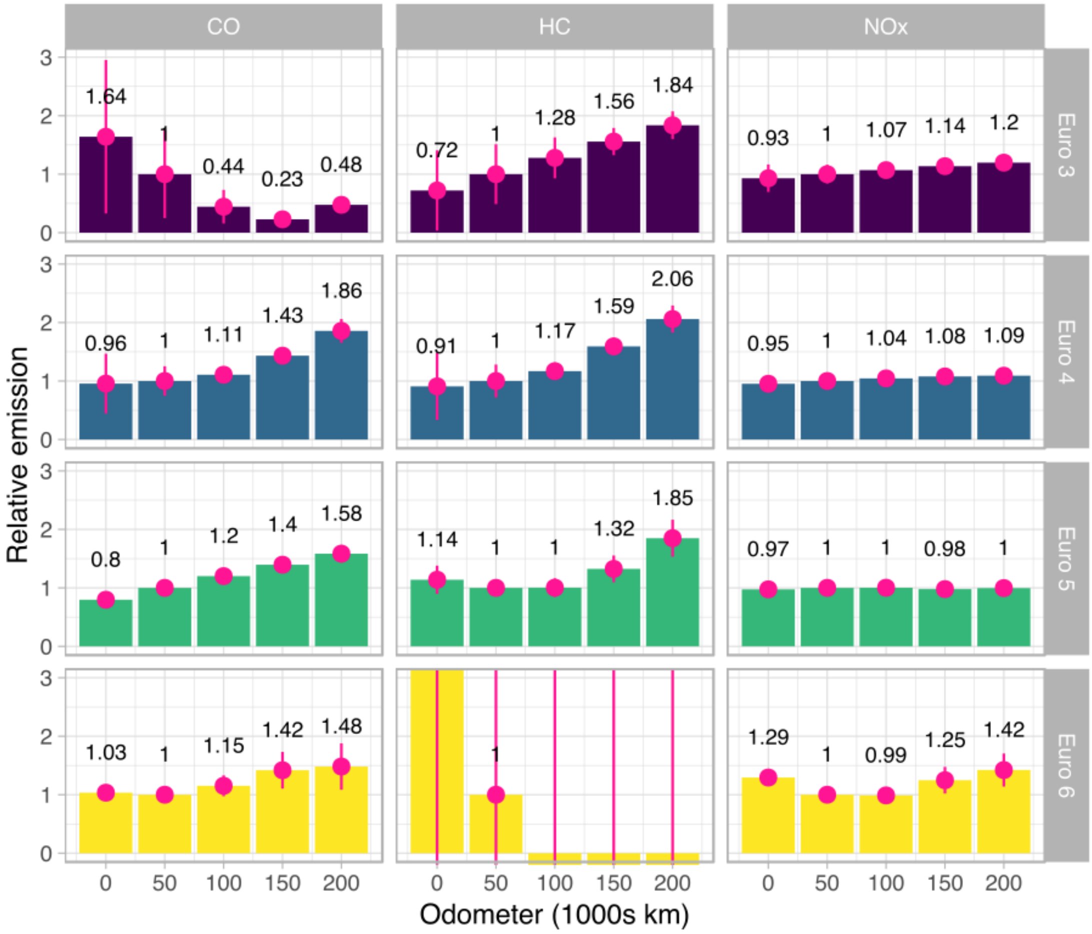

Figure 10. Mileage scaling values for diesel cars by Euro status and pollutant. Emissions are scaled to equal one at 0 km and all data are normalised to 20° C ambient temperature and a VSP of 8 kW/t.

For diesel cars we find increasing emission rates with higher vehicle mileages for all pollutants (NOx, CO and HC) and essentially all Euro stages. The only exceptions are CO emissions for the (old) Euro 3 cars and HC emissions for the (most recent) Euro 6 cars. For CO it is likely related to unreliable values for the early Euro 3 cars, of which only few were actually measured. The HC emissions from Euro 6 diesel cars are rather low and therefore not reliably measured. We therefore disregard both in the following summary (Table 2). For NOx we confirm a small deterioration and that is more than assumed in the legislation. Yet overall the emission rate is rather stable over the lifetime mileage. CO emissions exhibit a clear increase with mileage and much higher than has previously been assumed or measured. CO emissions from much used diesel cars can reach the level of petrol cars' emissions.

3.2.4 Summary: Diesel emission deterioration factors

Here we compare the results of this analysis with earlier work by Chen and Borken-Kleefeld (2016) and come up with suggestions for revised emission deterioration factors as a function of vehicle mileage. A few comments on the proposed deterioration factors:

- There are only few records for brand new vehicles or vehicles with low mileage in any Remote sensing campaign, as very new vehicles only make up a very small share of the fleet. Hence, on the basis of our data we cannot robustly determine an emission factor at 0 mileage.
- Likely, the share of vehicles with mileages above 200,000 kilometres is small. In addition, there is an unknown sampling effect, meaning that those cars surviving to this high mileage do not have the same characteristics as the fleet average car at 50,000 km, say. Therefore, we do not suggest deterioration factors for mileages higher than 200,000 km based on our sample(s). However, a continued degradation or possible stagnation might be taken as an indication for the further development of the emission rate.
- In our campaigns we have hardly seen evidence for a high or increasing rate of individual high emitters. It rather appears that degradation of the emission control equipment happens gradually across the fleet. The GAM analysis employed above does not prescribe or elucidate a specific function form by itself. Traditionally a linear rate of increase has been assumed. We do not see strong evidence in our data against this hypothesis and we can support it for its simplicity.

So far, no deterioration has been assumed for diesel cars. Hence, the data presented in this study suggests some important updates, notably for older and high mileage diesel cars.

The suggested revised emission deterioration factors for diesel cars have been compiled in Table 2.

Table 2. Illustrative deterioration factors for diesel cars for 50,000, 100,000 and 200,000 km cumulated mileage. CONOX data, normalised for 20°C ambient temperature and 8 kW/t VSP.

cumulated mileage	**50k NOx**	**100k NOx**	**200k NOx**	**50k CO**	**100k CO**	**200k CO**
	Euro 1			**Euro 1**		
Durability req.		1[a,e]			1.1[a]	
RS-ZH (2000-2013)[d]	**1***	**1***	**1***	**1**	**1**	**1**
	Euro 2			**Euro 2**		
Durability req.						
RS-ZH (2000-2013)[d]	**1***	**1***	**1.25***	**1**	**1**	**1**
	Euro 3			**Euro 3**		
Durability req.		1[a,e]			1.1[a]	
RS-ZH (2000-2013)[d]	1.06*	1.125*	1.25*			
RS CONOx (2011-18)	1	1.07	1.2			
RS proposal	**1.00**	**1.05**	**1.20**	**1**	**1**	**1**
	Euro 4			**Euro 4**		
Durability req.		1[e]			1.1	
RS-ZH (2000-2013)[d]	1	1	1	1	1	1
RS CONOx (2011-18)	1.0	1.04	1.09	1.0	1.1	1.9
RS proposal	**1.00**	**1.03**	**1.06**	**1.00**	**1.00**	**1.30**
	Euro 5			**Euro 5**		
Durability req.			1.1[c,e]			1.5[c]
RS CONOx (2011-18)	1.0	1.0	1.0	1	1.2	1.6
RS proposal	**1.00**	**1.00**	**1.03**	**1.00**	**1.00**	**1.30**

a: Requirement up to 80,000 km. c: Requirement up to 160,000 km. d: Chen & Borken-Kleefeld 2016. e: For NOx alone and NOx+HC.

4 Analysis of UK data – petrol cars

The results presented in this section combine the Opus and FEAT data into a single data set, except for a consideration of NO_2 where the FEAT is considered separately. The reason to consider the results from the FEAT separately for NO_2 is that we believe the data to be more robust because the FEAT instrument has a dedicated spectrometer for NO_2. The focus of this section is to show the relationships between actual (rather than derived) vehicle mileage and emission. Unlike the analysis of the CONOX database deterioration factors, no account is taken to the influence of VSP or ambient temperature using of statistical modelling.

4.1 Emissions of CO

The change in emissions with mileage for CO is shown in Figure 11 for Euro 3 to 6 petrol cars. The trends from Euro 3 to 6 show behaviour in line with expectations. First, the absolute emissions of CO decrease from Euro 3 to Euro 6. Second, there is evidence that the slope between CO and mileage is steeper for earlier Euro standards. One interesting and potentially important finding is that low mileage early Euro class vehicles (e.g. Euro 3 and 4) can be relatively low-emitting. So, while the Euro standard is important, the mileage of the vehicle can be more important, e.g. high mileage (~300,000 km) vehicles from Euro 3 to 5 all have relatively high emissions.

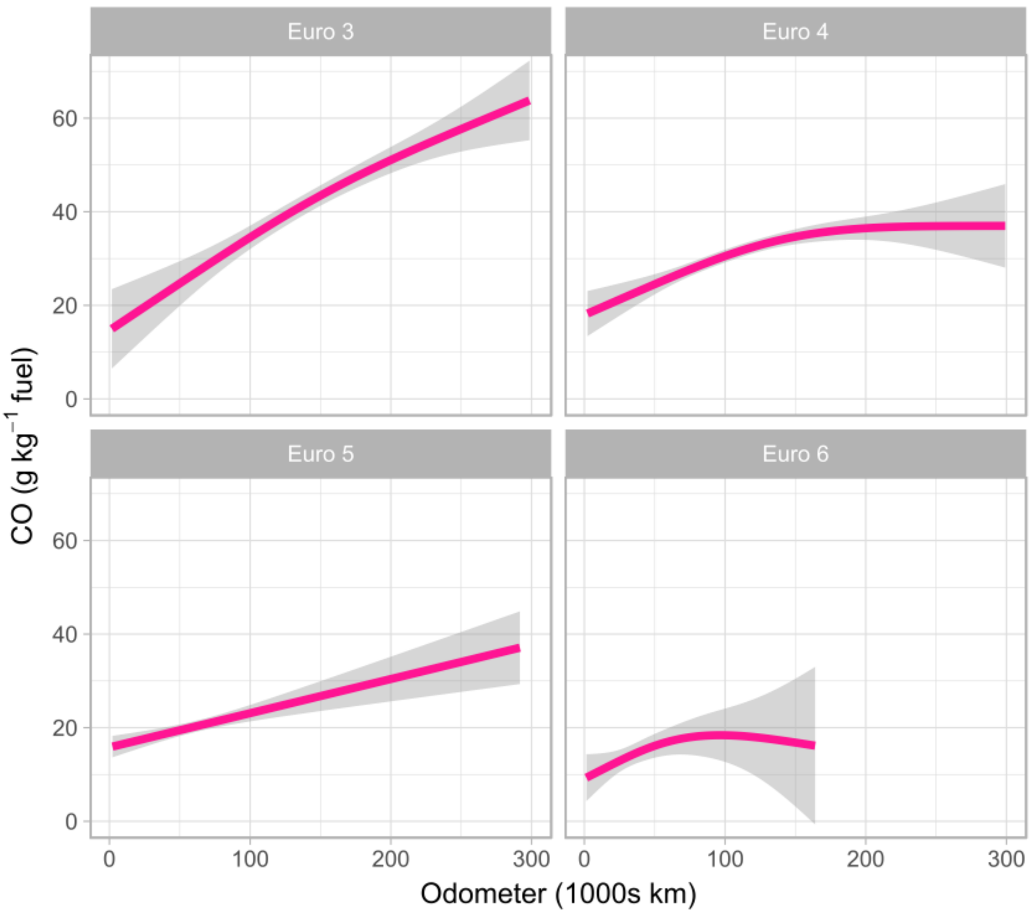

Figure 11. CO emissions (g kg-1 fuel) vs vehicle mileage for UK petrol passenger cars, split by Euro standard. The smooth lines show the results of fitting a GAM to the data.

4.2 Emissions of HC

The emissions for HC show less clear patterns relative to CO and in fact show some evidence of decreasing emissions with vehicle age (Figure 12). It is difficult to understand the reasons for this behaviour, but it should be recognised that the remote sensing instruments are calibrated using propane as representative of a wider group of hydrocarbons and some assumptions are made about the 'missing' HC mass. It is possible therefore, that changes in HC composition could affect the measurements.

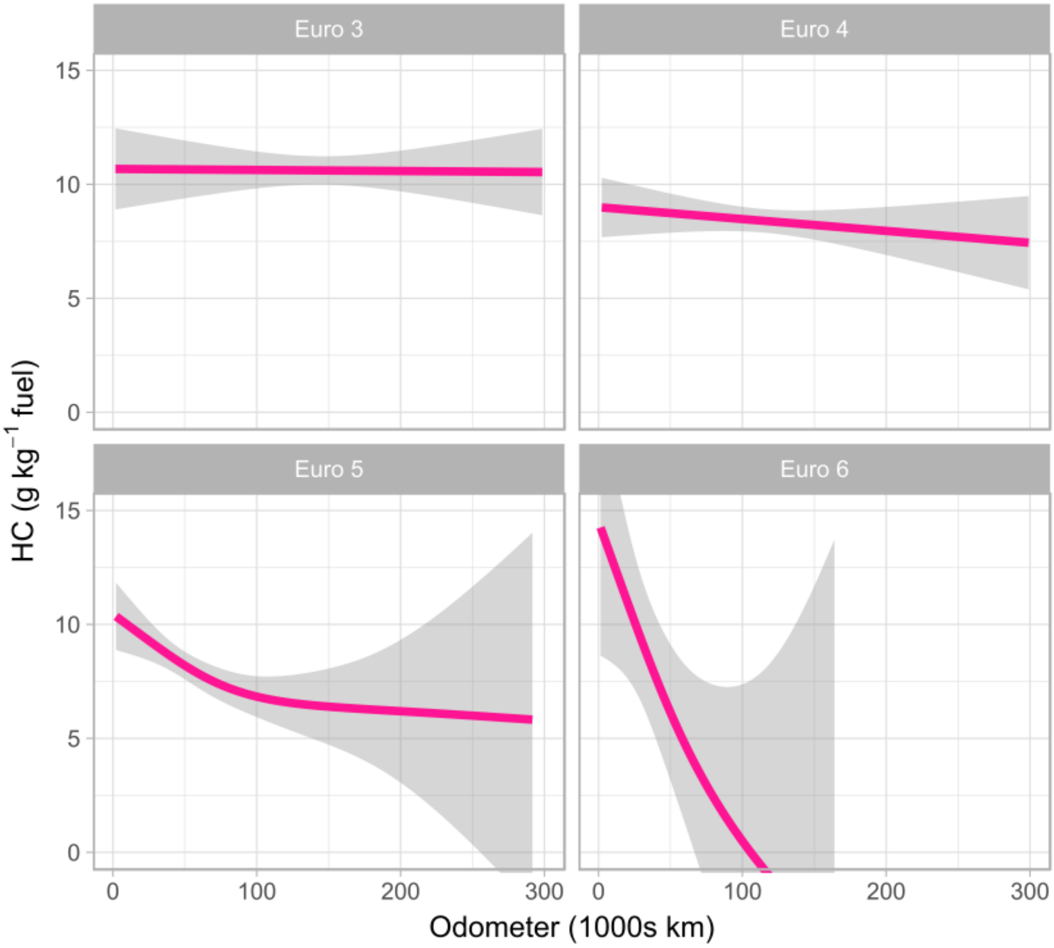

Figure 12. HC emissions as a function of vehicle mileage for petrol passenger cars, split by Euro standard. The smooth lines show the results of fitting a GAM to the data.

4.3 Emissions of NO

We specifically consider NO emissions separate from total NOx to avoid any issue of the detection of NO_2 using the Opus instrument. The behaviour with mileage is similar in behaviour to emissions of CO, i.e. highest emissions for older Euro standards and steepest gradient with mileage (Figure 13). These results show that low mileage petrol Euro 3 cars can have substantially lower emissions than high mileage Euro 3 petrol cars (about a factor of four). It is interesting to note that for all Euro standards, low mileage vehicles can have very low emissions. As of now, there are insufficient numbers of Euro 6 cars to robustly understand any high mileage effects - and no evidence yet of any deterioration for emissions of NO.

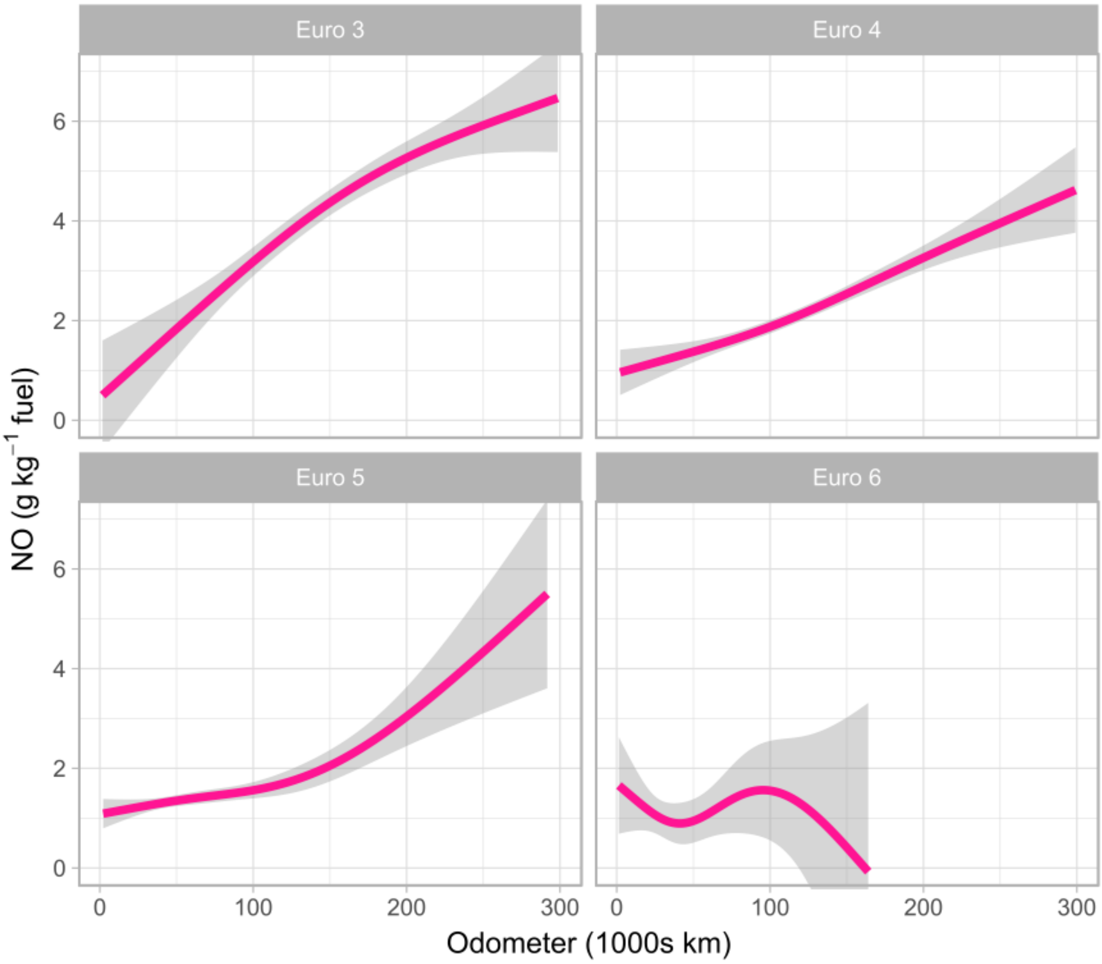

Figure 13. NO emissions as a function of vehicle mileage for petrol passenger cars, split by Euro standard. The smooth lines show the results of fitting a GAM to the data.

4.4 Emissions of NO_2

Emissions of NO_2 from petrol cars are very low, as shown by Figure 14, based on FEAT measurements. We find no relationship with vehicle mileage and the emission of NO_2.

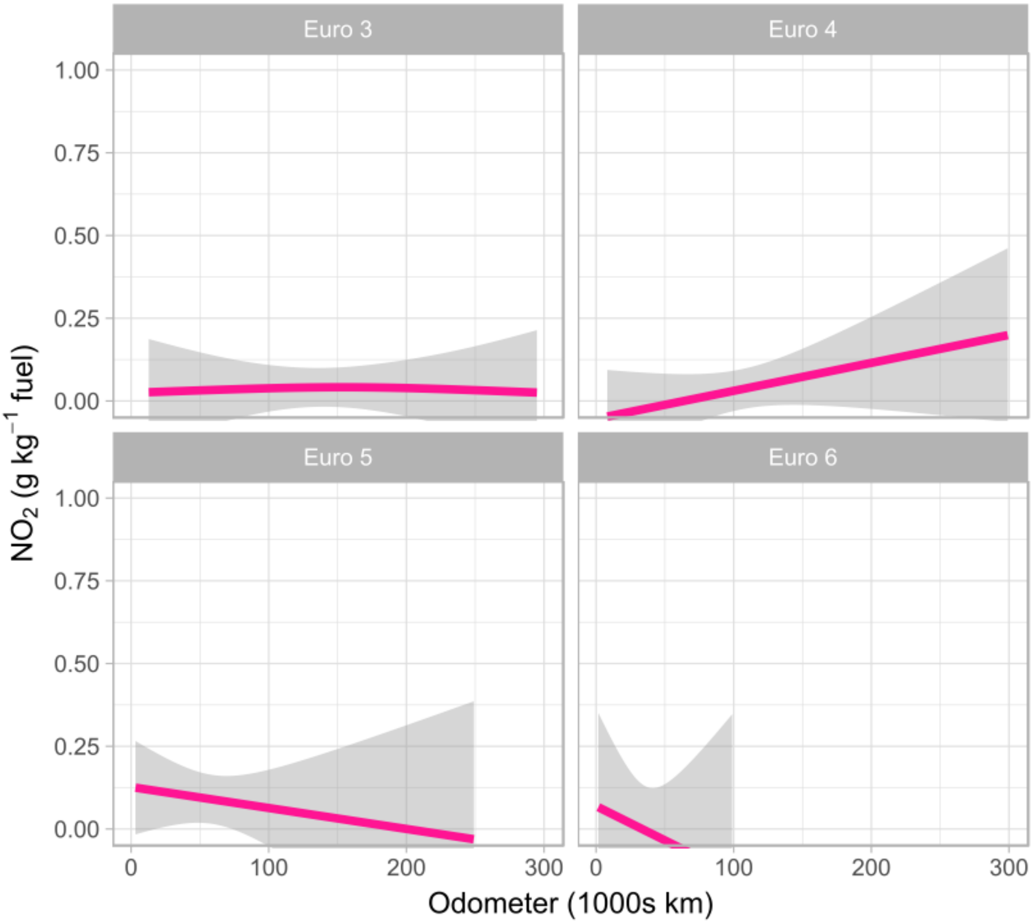

Figure 14. NO_2 emissions as a function of vehicle mileage for petrol passenger cars, split by Euro standard. Data from FEAT instrument only. The smooth lines show the results of fitting a GAM to the data.

4.5 Emissions of NO_x

NOx emissions from petrol cars show evidence of increasing emissions with vehicle mileage and with older Euro standards (Figure 15). There is a stronger relationship between mileage and emissions for older Euro standards. An important finding is that low mileage petrol cars (regardless of Euro standard) are associated with low emissions.

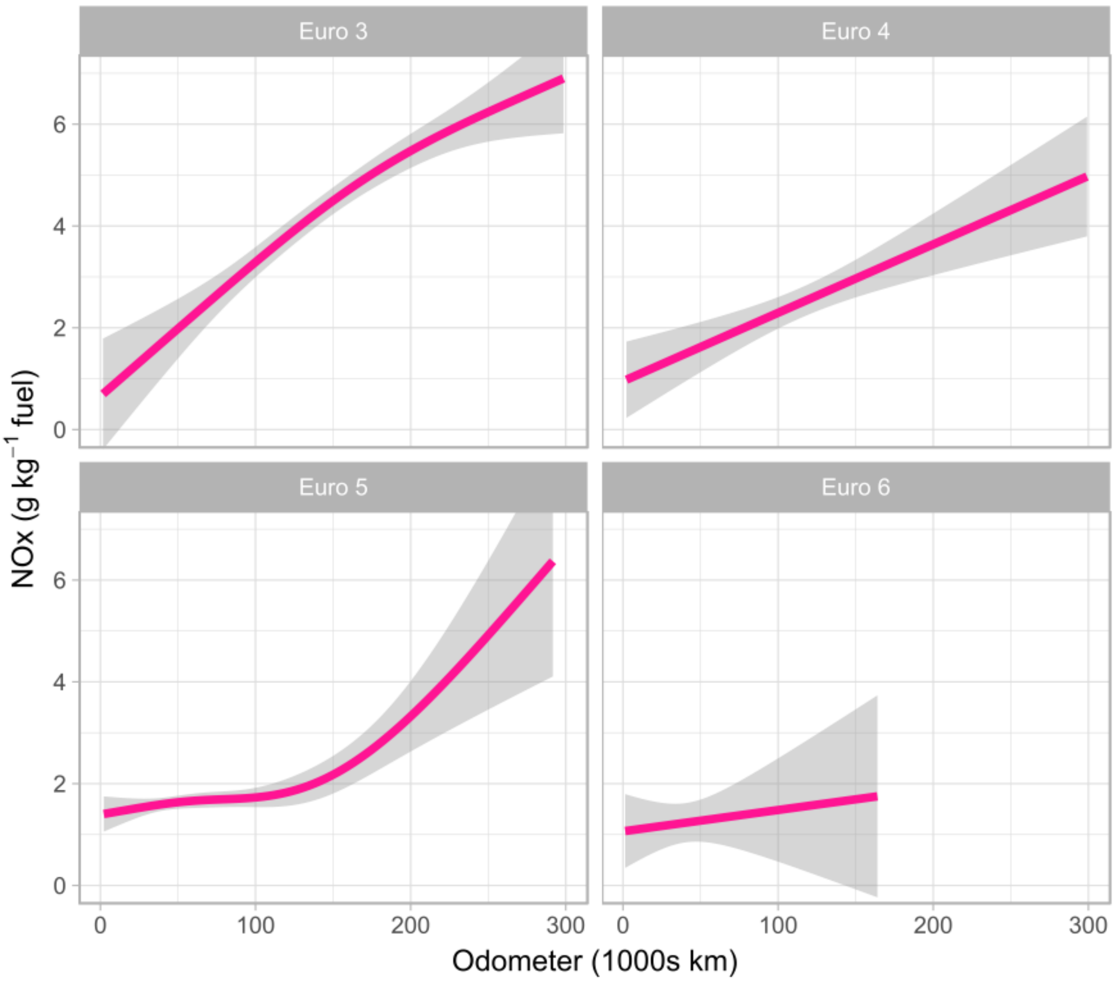

Figure 15. NOx emissions as a function of vehicle mileage for petrol passenger cars, split by Euro standard. The smooth lines show the results of fitting a GAM to the data.

5 Analysis of UK data – diesel cars

5.1 Emissions of CO

Emissions of CO show some evidence of increasing with vehicle mileage for earlier Euro standard vehicles (Figure 16). The evidence overall is weaker than that for petrol cars, considered in section 4.1. Note that the emissions of CO from diesel cars are also lower than for petrol cars.

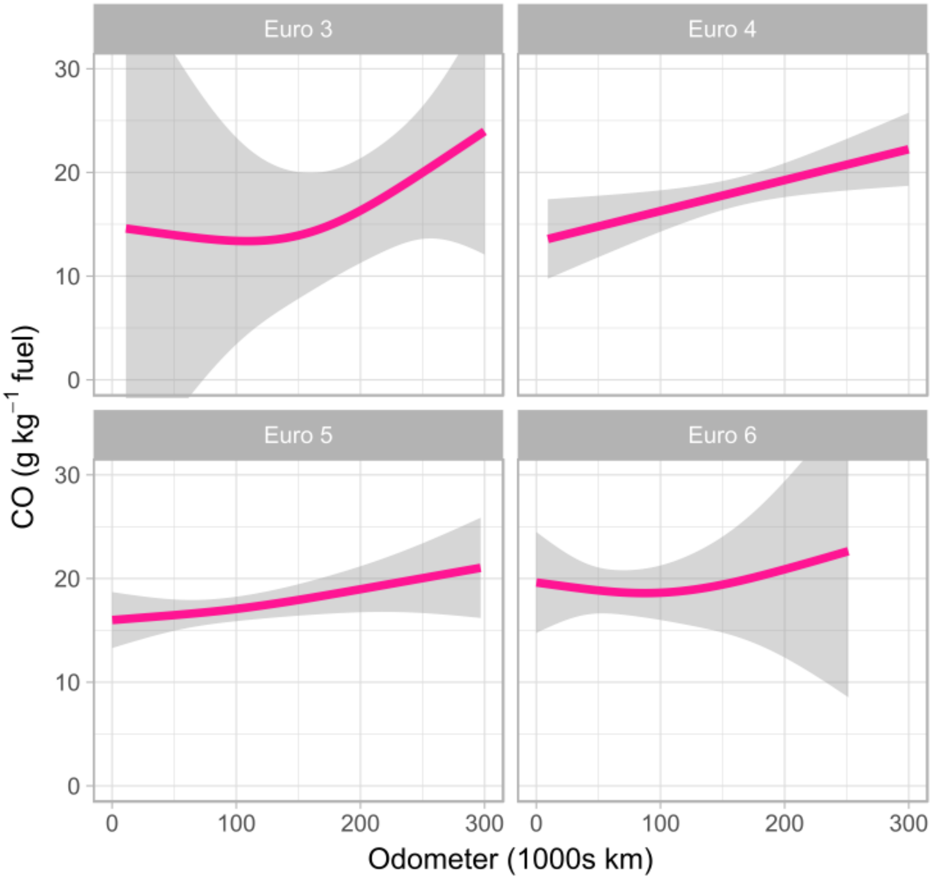

Figure 16. CO emissions as a function of vehicle mileage for diesel passenger cars, split by Euro standard. The smooth lines show the results of fitting a GAM to the data.

5.2 Emissions of HC

Emissions of HC from diesel cars show mixed results, as shown in Figure 17. Overall the data suggest there is not strong evidence that HC emissions increase with vehicle mileage.

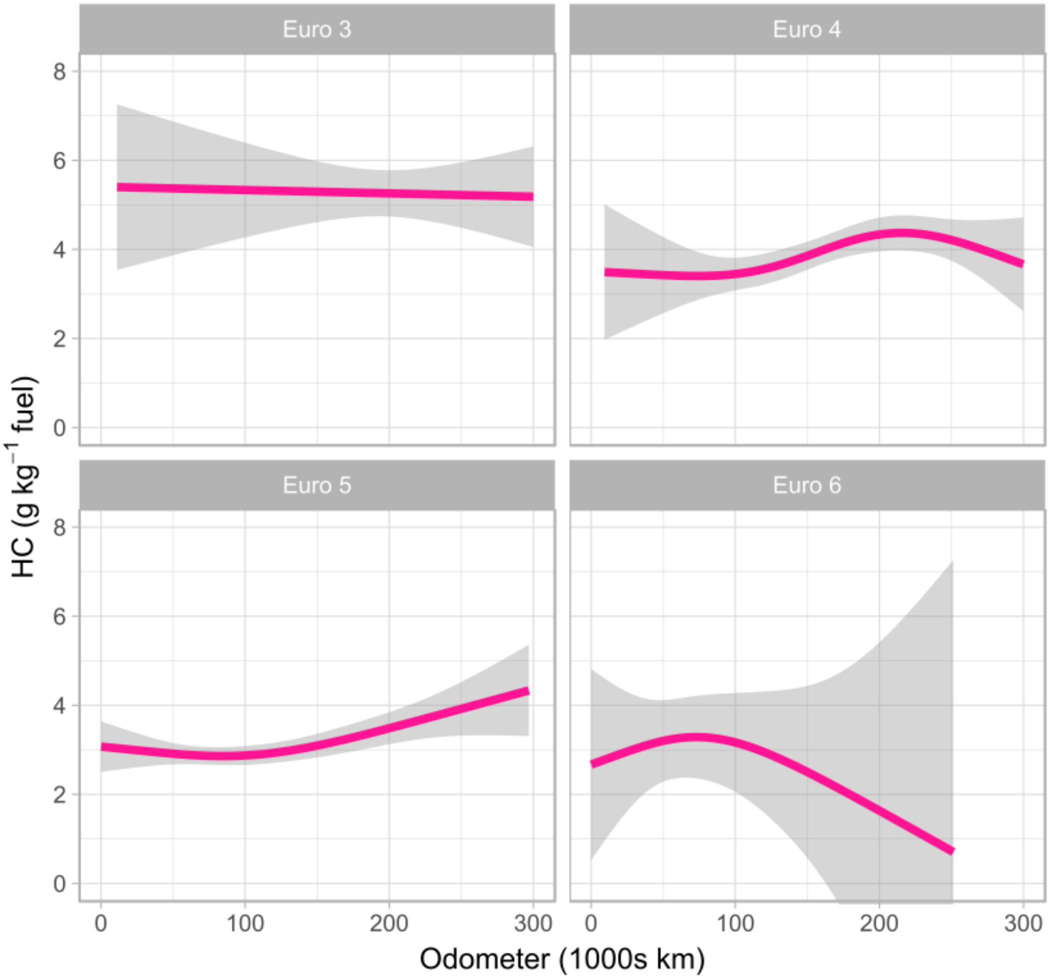

Figure 17. HC emissions as a function of vehicle mileage for diesel passenger cars, split by Euro standard. The smooth lines show the results of fitting a GAM to the data.

5.3 Emissions of NO

NO emissions gradually increase with vehicle mileage for diesel passenger cars for all Euro standards except Euro 3, as shown in Figure 18. Note that increase may not indicate an increase in total NOx (see later).

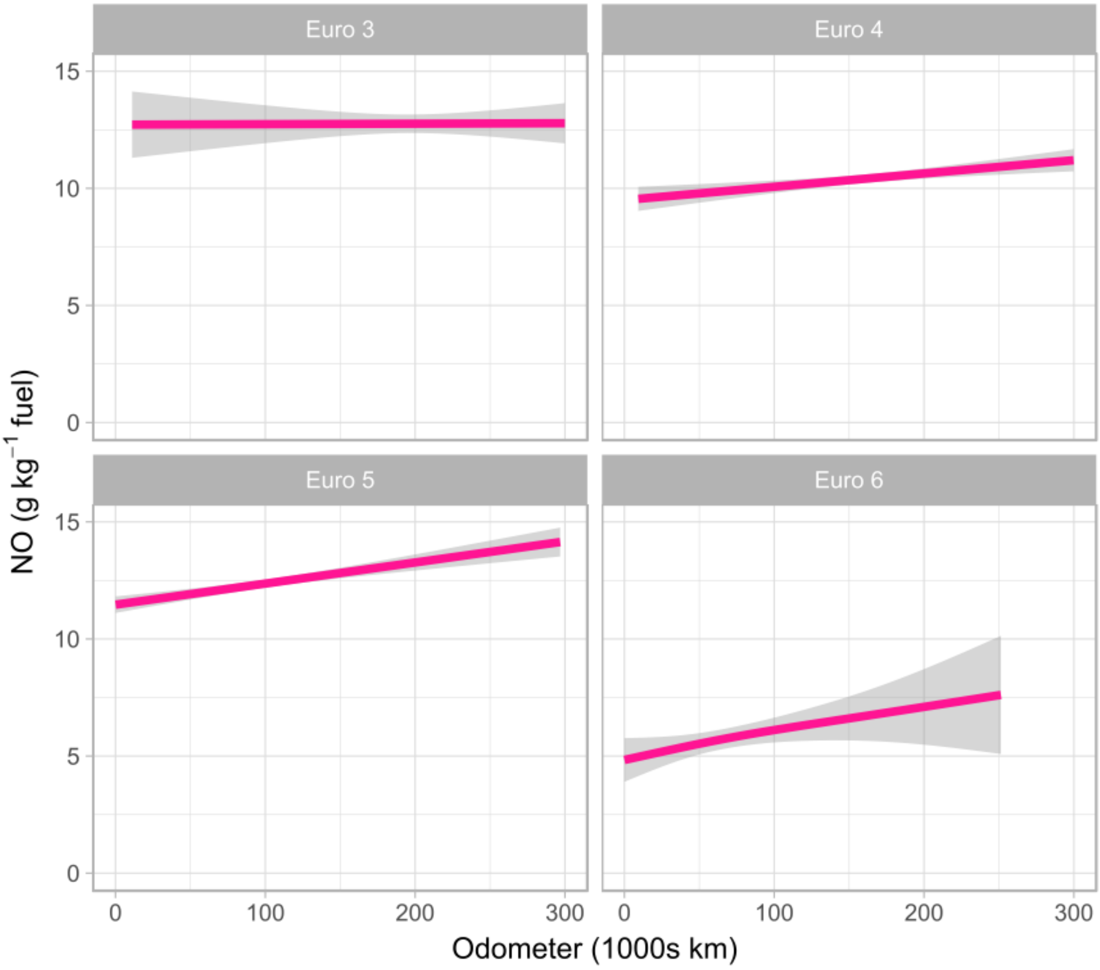

Figure 18. NO emissions as a function of vehicle mileage for diesel passenger cars, split by Euro standard. The smooth lines show the results of fitting a GAM to the data.

5.4 Emissions of NO_2

The emission of NO_2 has been specifically considered using the FEAT instrument. The results shown in Figure 19 indicate that as the vehicle mileage increases the amount of NO_2 produced decreases. This is an important finding because of the role that directly emitted NO_2 has close to roads in the ambient environment.

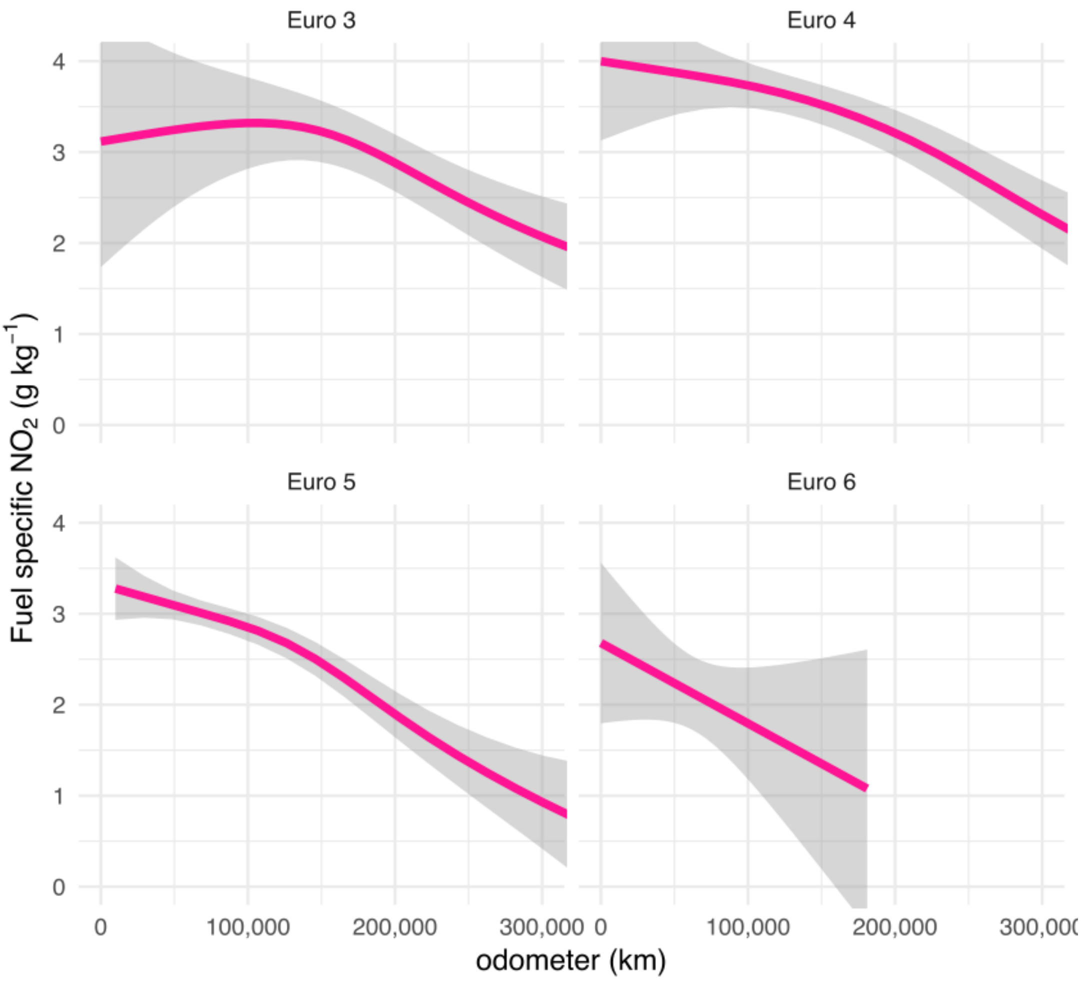

Figure 19. NO_2 emissions as a function of vehicle mileage for diesel passenger cars, split by Euro standard.

5.5 Emissions of NOx

Both the Opus and FEAT instruments show that emissions of NO tend to increase with vehicle mileage (see Figure 20). For the reasons discussed earlier, it is believed the FEAT measurements will be more robust than the Opus measurements because of the NO_2 measurement. The Opus instrument tends to show higher NO_2 emissions for earlier Euro standard vehicles e.g. Euro 3. The likely reason is that older diesel vehicles will have elevated HC emissions and the Opus instrument is detecting the HC as NO_2. Nevertheless, the overall pattern of change shown in Figure 20 does not indicate that emissions of NOx are strongly dependent on mileage.

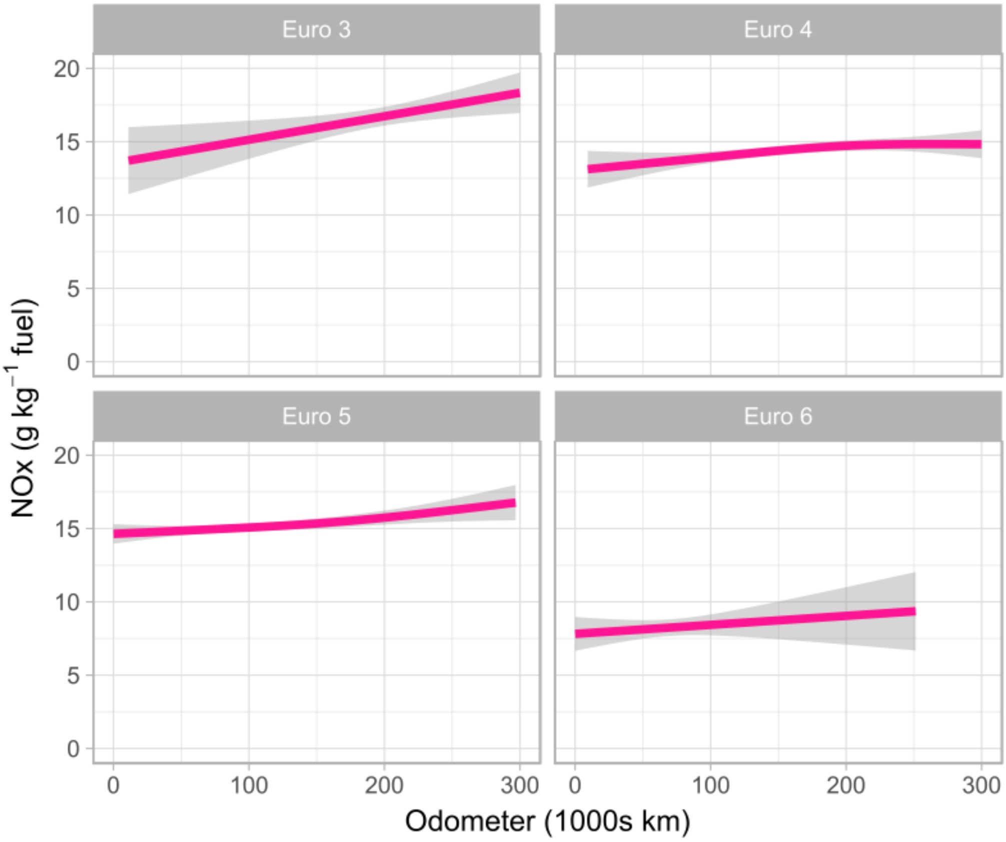

Figure 20. NOx emissions as a function of vehicle mileage for diesel passenger cars, split by Euro standard.

5.6 Fraction NO_2 in NOx

The preceding analysis considered measurements made during 2017/2018. However, it is also valuable to compare the NO_2/NOx ratio for that campaign with earlier work at the same location in west London on Putney Hill (Carslaw et al., 2015). During the 2013 campaign, 4,358 Euro 5 diesel PC were measured during June and July. The NO_2/NOx ratio for Euro 5 diesel PC in 2013 was 25.5% on average. Five years later, the ratio had decreased to 15.6%. An absolute reduction in the NO_2/NOx of 10% over 5 years is substantial and provides further evidence that as the mileage of a diesel PC increases, the NO_2/NOx ratio decreases.

5.7 Same vehicle analysis

The London 2017/2018 measurements made at the Putney Hill site were made in an identical location to the London 2013 measurements. Furthermore, the instrument used in both cases was the DU FEAT. These measurements provide an opportunity to consider whether the same vehicle was measured during both campaigns based on its vehicle registration number. The analysis to date showed that there were about 1,100 measurements made in 2017/2018 that corresponded to the same vehicle measured in 2013 (577 unique vehicles). While the number of repeat measurements of the same vehicle is too low for a specific analysis, when grouped by fuel type, Type Approval category and Euro status, it was possible to compare the difference in emissions of NOx over the 4 to 5-year period.

The plot below (Figure 21) shows the results for the 2013-2017/8 comparison, with the dashed line representing the 1:1 relationship for diesel vehicles. Overall, there is a good relationship between the measurements made in 2013 and 2017. For light duty diesel cars and vans there is some evidence that emissions are higher for the 2017 measurements compared with those in 2013. However, it is likely that much of this difference is due to differences in ambient temperature. On average, the 2013 data were collected in ambient temperatures of 20°C, whereas the mean temperature during the 2017 campaign was 10°C. It is encouraging however, that there is good consistency in the results shown in Figure 21 and Figure 22.

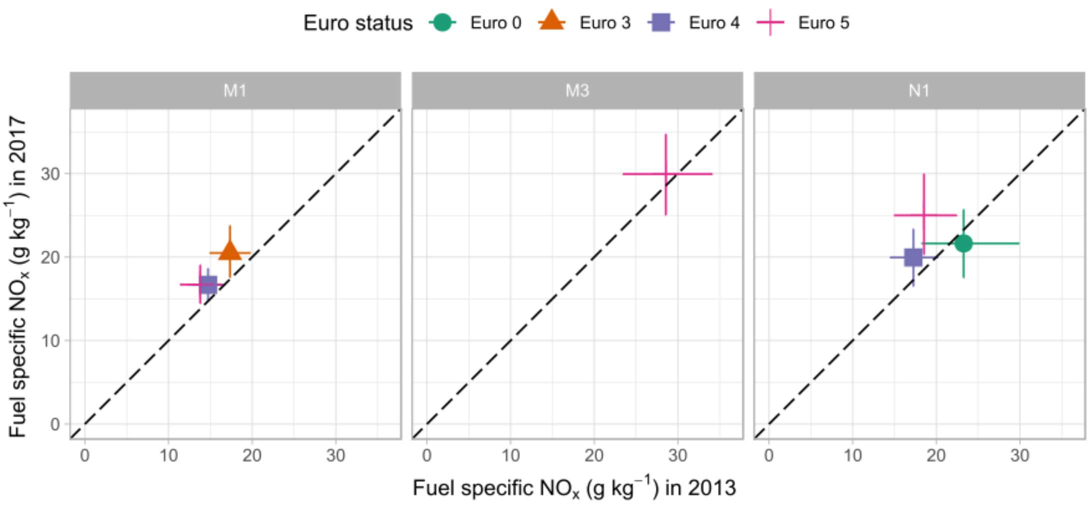

Figure 21. Summary emissions of NOx showing the relationship between emissions of the same vehicles measured at the same location in 2013 and 2017/2018 for diesel vehicles. Each panel shows the Type Approval category.

The relatively high emissions from Euro 2 petrol cars (~8 g/kg NOx) is very similar in each year, showing that further deterioration does not seem to have occurred over the intervening years, as shown in Figure 22. Within the uncertainty of the measurements, there is no difference between 2013 and 2017 results.

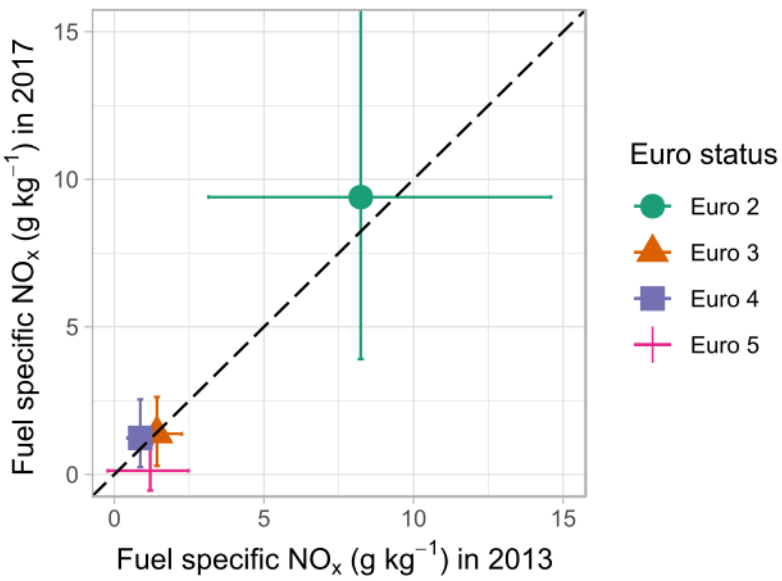

Figure 22. Summary emissions of NOx showing the relationship between emissions of the same vehicles measured at the same location in 2013 and 2017/2018 for petrol vehicles.

6 Analysis of petrol passenger cars by manufacturer

One of the potential benefits of remote sensing data is that it provides much more detailed information on the vehicles being analysed. This section considers the variation in emissions by manufacture 'families'. These manufacturer groupings have been defined by the ICCT and provide a way of grouping the same engine used across a range of individual manufacturers (Bernard et al., 2018). While the aggregation by Bernard et al., (2018) attempts to match nominally similar engines by their size, in this section we only consider the differences by the most popular manufacturers. The purpose of the analysis is to demonstrate the potential for remote sensing data to provide more detailed information on deterioration than would be possible using data from either laboratory or PEMS measurements.

Considering the whole CONOX database provides a considerable amount of data, which also allows the data to be filtered in different ways. Of principal interest is filtering for similar vehicle power demand using VSP and ambient temperature. However, tests using different filtering did not reveal substantially different behaviour in the emissions compared with using the whole unfiltered database. We have therefore not filtered the data in the proceeding analysis but acknowledge it could be useful in some situations in future work.

In the proceeding analysis we consider the six most populous vehicle manufacturers for each Euro standard and filter to ensure at least 20 measurements in any one vehicle mileage interval.

6.1 Emissions of NO

There is a clear increase in emissions of NO with mileage for Euro 3 and Euro 4 vehicles but a large variation by individual manufacturer as seen by Figure 23.

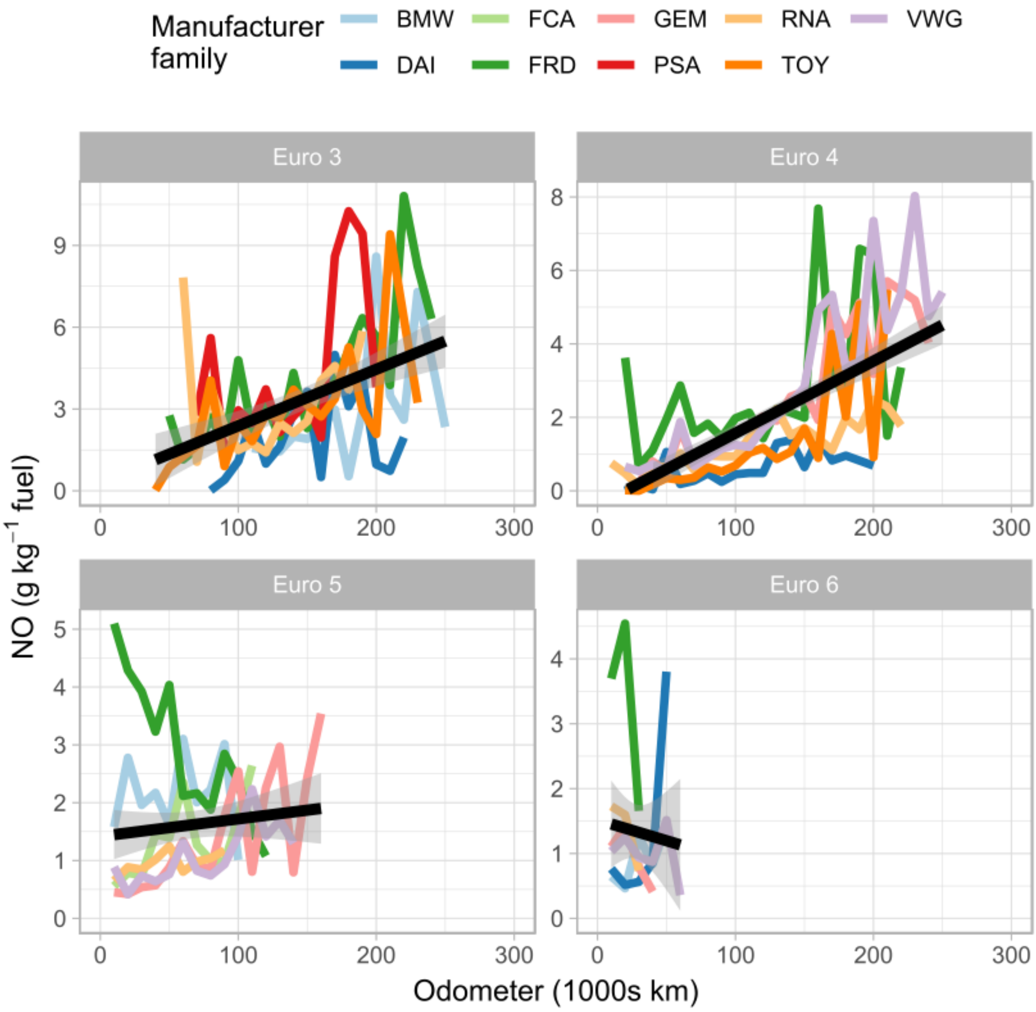

Figure 23. The effect of vehicle mileage on emissions of NO for petrol passenger cars across Europe, split by the six most popular manufacturer groups for each Euro class. The black smooth lines show the results of fitting a GAM to the data and the legend provides information on the manufacturer group.

6.2 Emissions of NOx

Emissions of NOx from petrol cars follow a similar pattern to NO as shown in Figure 24, where there is again a large variation between individual manufacturers.

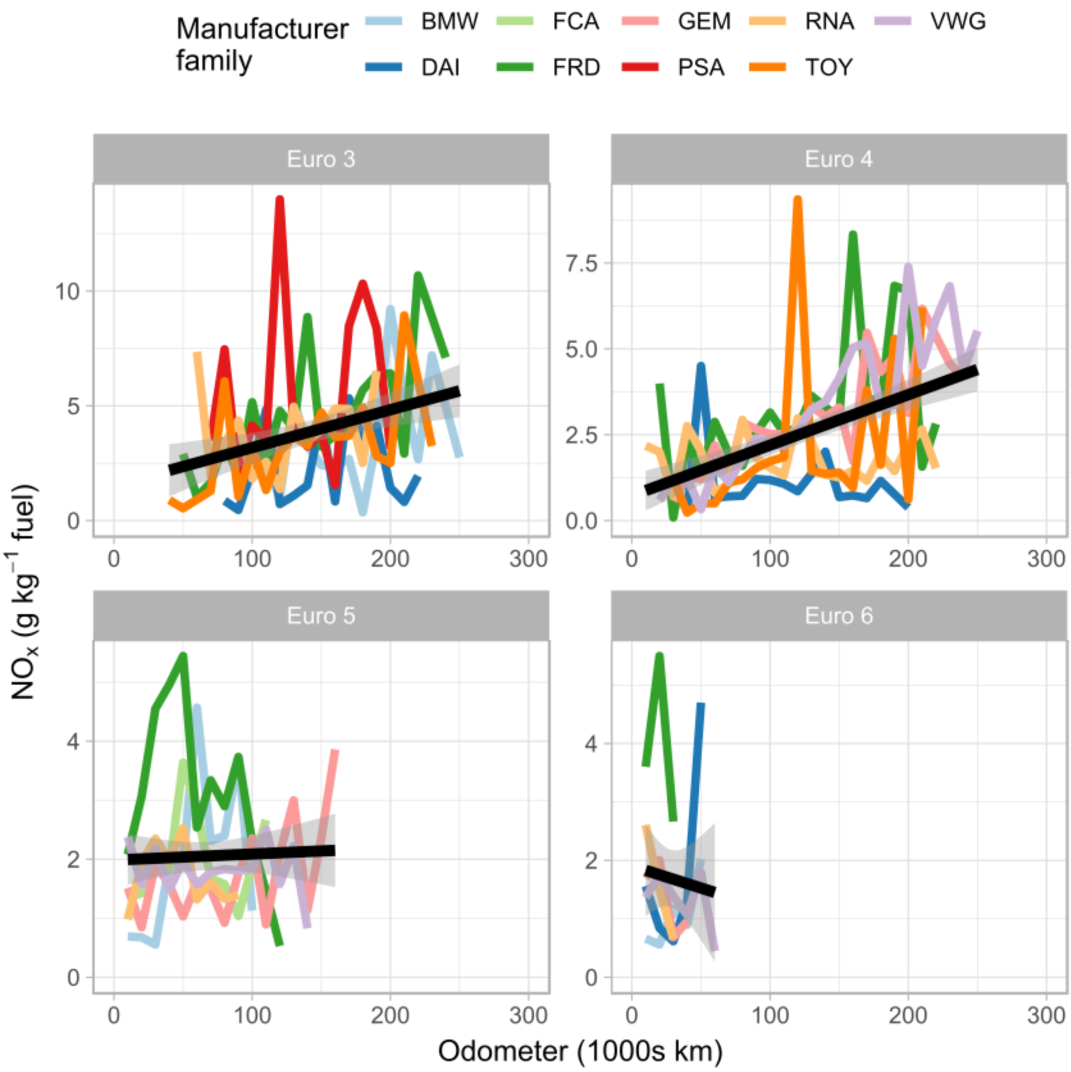

Figure 24. The effect of vehicle mileage on emissions of NOx for petrol passenger cars across Europe, split by the six most popular manufacturer groups for each Euro class. The black smooth lines show the results of fitting a GAM to the data and the legend provides information on the manufacturer group.

6.3 Emissions of CO

The results for CO show there is a wide variation in emissions vs. mileage depending on the vehicle manufacturer considered, as shown in Figure 25. Overall however, the aggregate trend (shown by the black line) shows increasing emissions of CO with vehicle mileage (except for Euro 6, which has very little data).

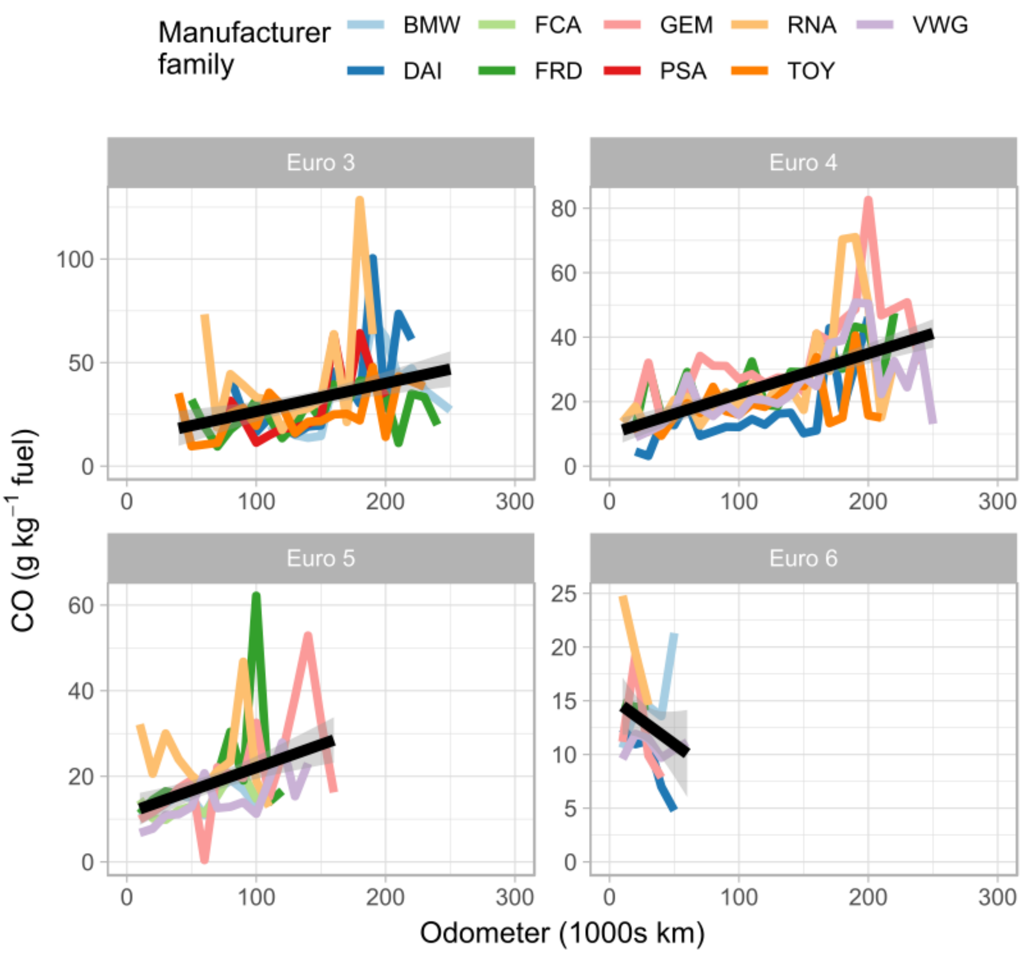

Figure 25. The effect of vehicle mileage on emissions of CO for petrol passenger cars across Europe, split by the six most popular manufacturer groups for each Euro class. The black smooth lines show the results of fitting a GAM to the data and the legend provides information on the manufacturer group.

6.4 Emissions of HC

As for CO emissions, the results for HC show there is a wide variation in emissions vs. mileage depending on the vehicle manufacturer considered, as shown in Figure 26. Overall however, the aggregate trend (shown by the black line) shows increasing emissions of HC with vehicle mileage.

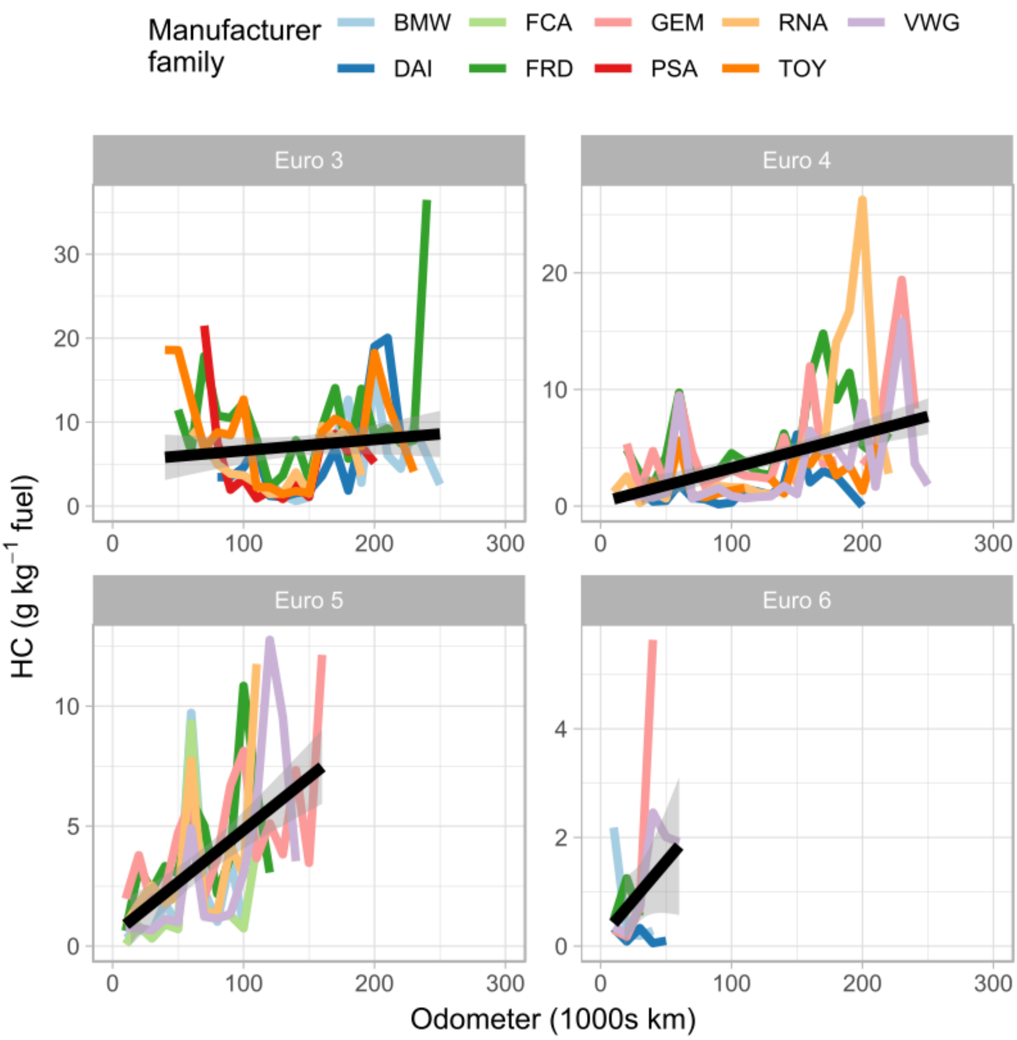

Figure 26. The effect of vehicle age on emissions of HC for petrol passenger cars across Europe, split by the six most popular manufacturer groups for each Euro class. The black smooth lines show the results of fitting a GAM to the data and the legend provides information on the manufacturer group.

7 Analysis of diesel passenger cars by manufacturer

7.1 Emissions of NO

The emissions of NO show little obvious pattern for the different manufacturer families, as shown in Figure 27 and little evidence of any change with vehicle mileage, consistent with the overall analysis of the CONOX database.

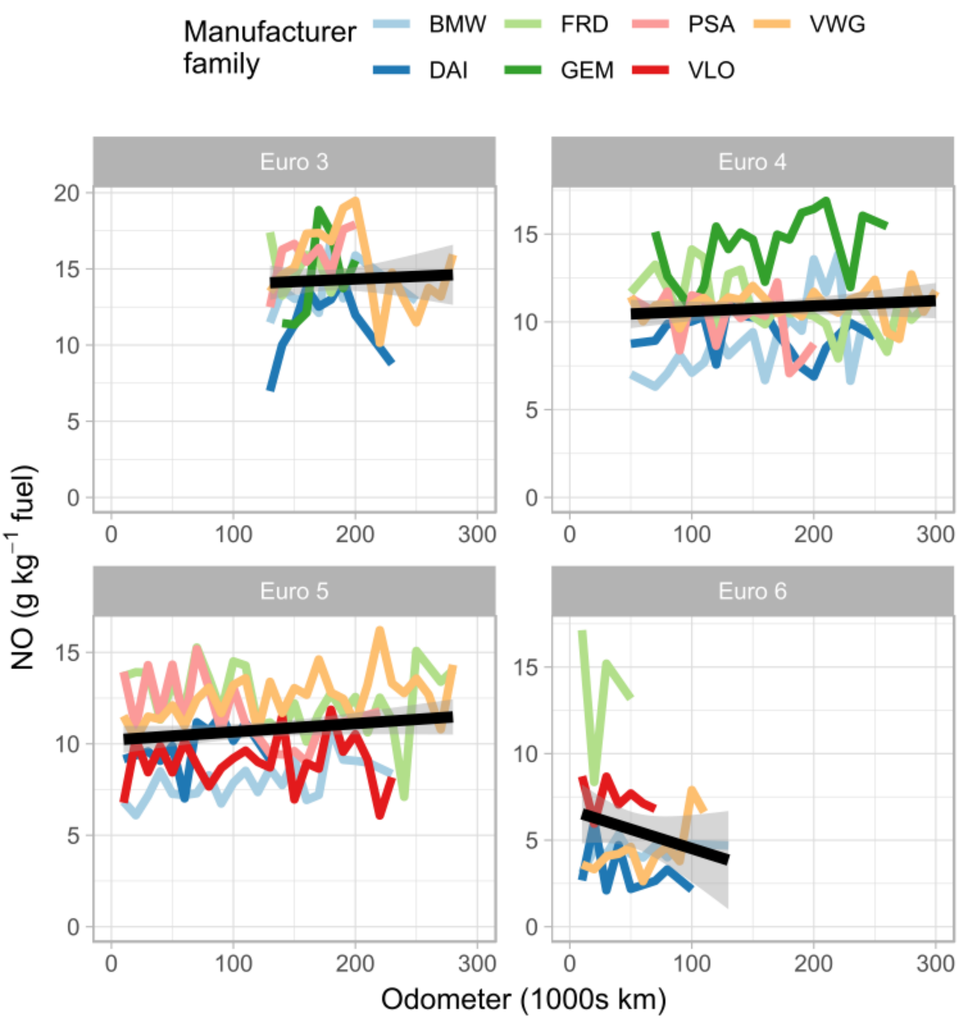

Figure 27. The effect of vehicle mileage on emissions of NO for diesel passenger cars across Europe, split by the six most popular manufacturer groups for each Euro class. The black smooth lines show the results of fitting a GAM to the data and the legend provides information on the manufacturer group and engine size in cc.

7.2 Emissions of NOx

Similar to the emissions of NO, there is limited evidence of much change in diesel NOx emissions with mileage, as shown in Figure 28.

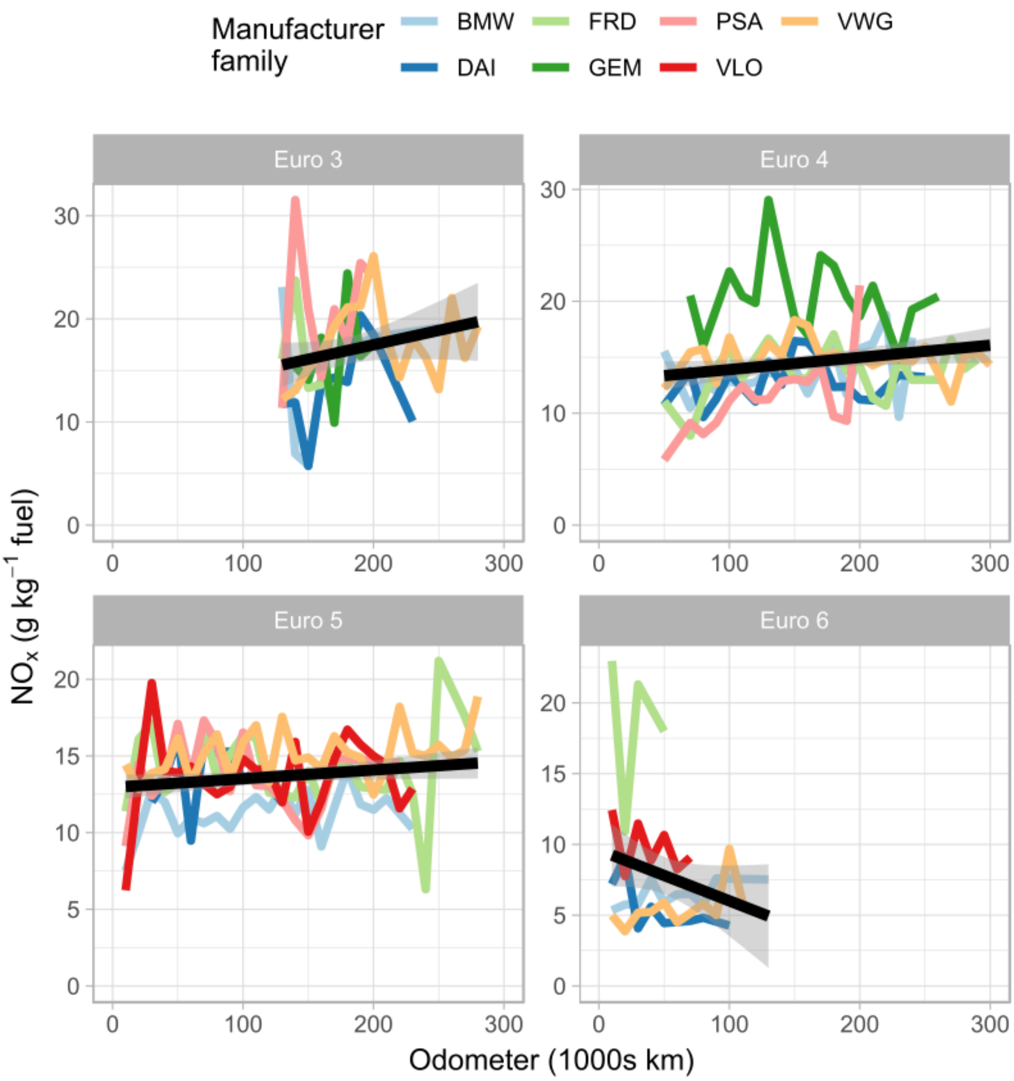

Figure 28. The effect of vehicle mileage on emissions of NOx for diesel passenger cars across Europe, split by the six most popular manufacturer groups for each Euro class. The black smooth lines show the results of fitting a GAM to the data and the legend provides information on the manufacturer group.

7.3 Emissions of CO

The data indicate that CO emissions from diesel cars for the most populous vehicle models tend to increase with vehicle mileage – shown in Figure 29. There is however a wide variation in the emissions depending on the vehicle being considered.

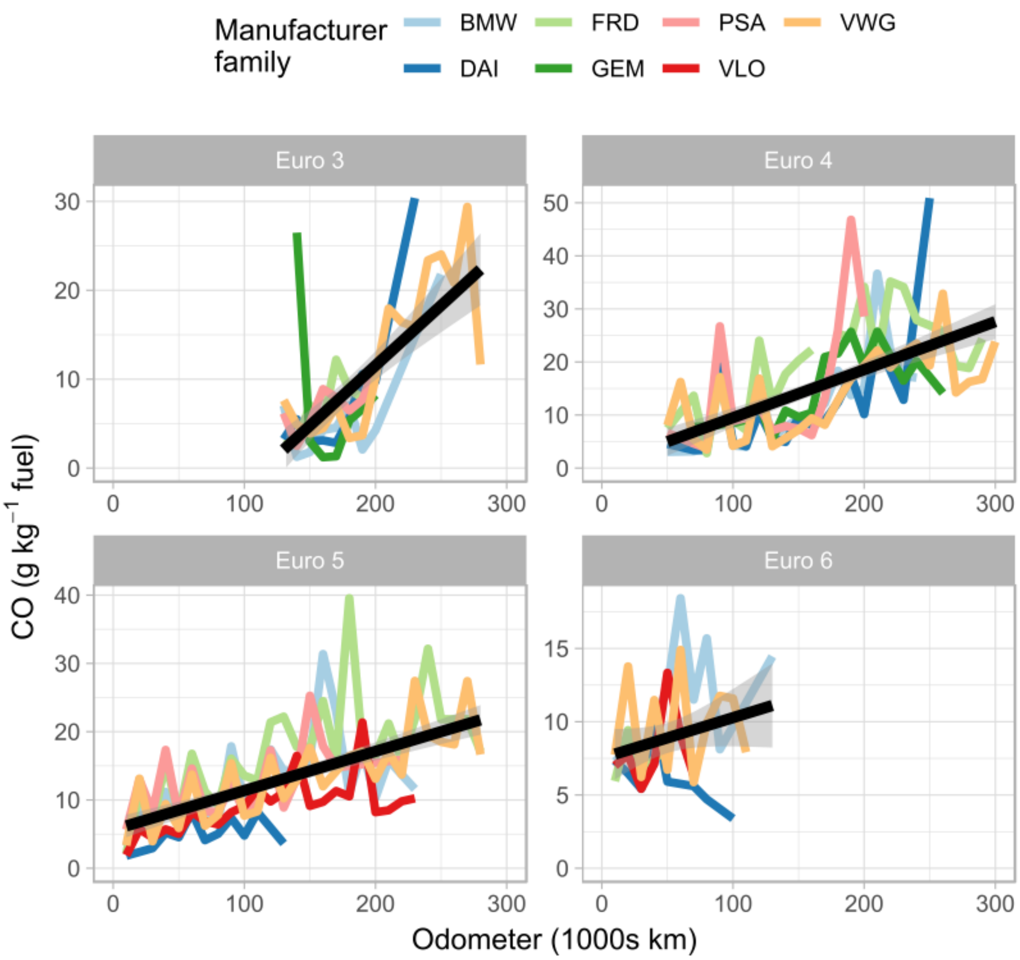

Figure 29. The effect of vehicle mileage on emissions of CO for diesel passenger cars across Europe, split by the six most popular manufacturer groups for each Euro class. The black smooth lines show the results of fitting a GAM to the data and the legend provides information on the manufacturer group.

7.4 Emissions of HC

As for CO emissions, the data indicate that HC emissions from diesel cars for the most populous vehicle models tend to increase with vehicle mileage (Figure 30), however with a wide variation in the emissions depending on the vehicle being considered.

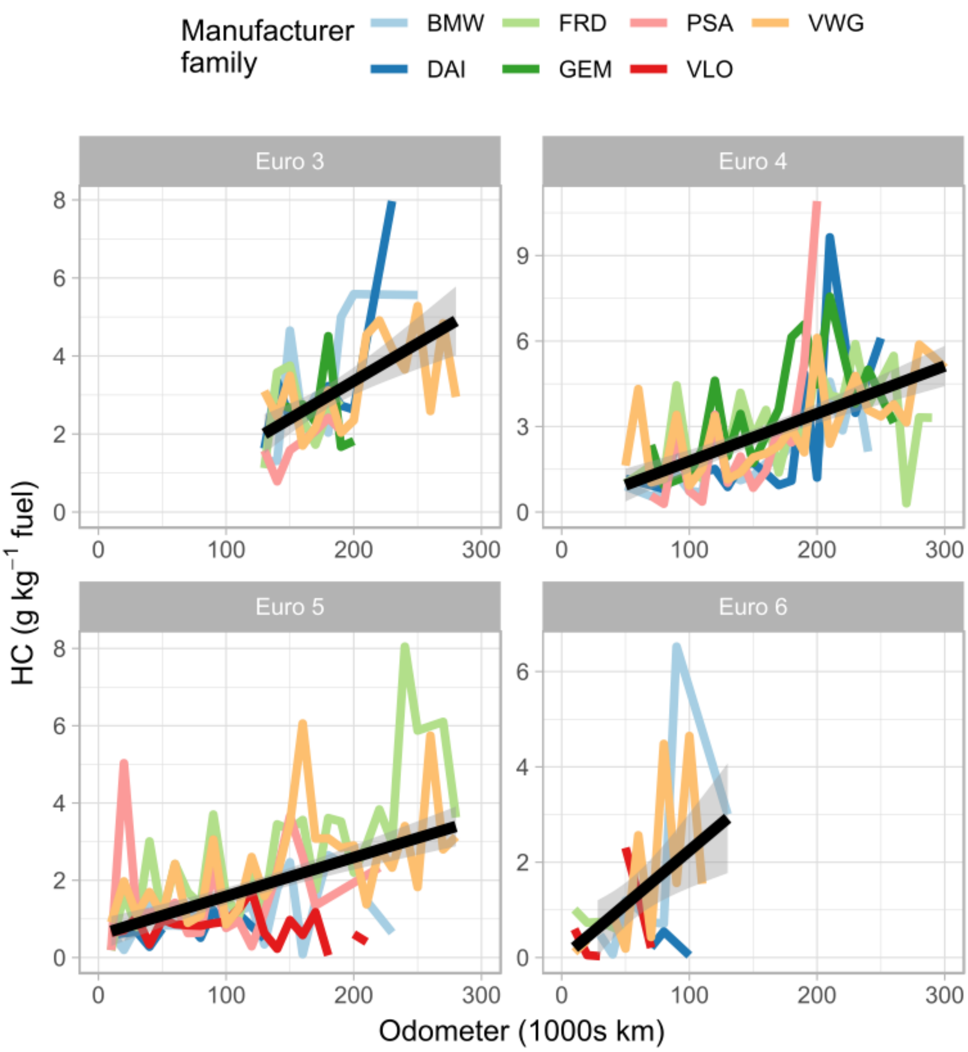

Figure 30. The effect of vehicle mileage on emissions of HC for diesel passenger cars across Europe, split by the six most popular manufacturer groups for each Euro class. The black smooth lines show the results of fitting a GAM to the data and the legend provides information on the manufacturer group.

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