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On-road emission measurements in Sweden 2007-2015

Martin Jerksjö[1]

Abstract

In different studies reaching from 2007 through 2015 on-road emission measurements on heavy-duty buses and passenger cars have been conducted in Gothenburg, Sweden. Measurements of bus emissions have been carried out both from the roadside during real-world driving conditions with a remote sensing instrument, and during controlled driving conditions with both a remote sensing instrument and an Engine Exhaust Particle Sizer Spectrometer (EEPS).
All measured emissions (CO, HC and NO_X) from gasoline cars have continuously decreased from Euro 1 to Euro 6. Regarding diesel vehicles, emissions of nitrogen oxides from buses and passenger cars have not decreased significantly from the Euro 3 to the Euro 5 emission standard. A few diesel passenger cars and buses of the Euro 6 emission standard are included in the data set, which show a lower average emission of nitrogen oxides compared to Euro 5 vehicles. For buses a comparison between diesel and RME (Rapeseed Methyl Ester) was conducted. It was found that particle emissions from buses driving on 100% RME were 88% lower compared to emissions from buses fueled with conventional diesel.

Keys-words: (5 words) on-road emissions, heavy duty buses, passenger cars, NO_X, particles.

1 Introduction

This paper summarizes the on-road vehicle emission measurements conducted by means of remote sensing in Sweden between 2007 and 2015. The work was carried out within several different research projects, financed by the Swedish Transport Administration, Västtrafik (a public transport company serving Southwest Sweden) and the Foundation for IVL Swedish Environmental Research Institute (SIVL).

[1] IVL Swedish Environmental Research Institute, Aschebergsgatan 44, Gothenburg, Sweden

2 Background

In the summer of 2007, a series of remote sensing measurements were conducted in Gothenburg by means of the fourth generation of the Denver University FEAT instrument, the first remote sensor measuring NO_2 ("FEAT 4"). Apart from NO_2, this instrument measures CO, HC, opacity, NO, NH_3 and SO_2. This instrument has been described in detail earlier by e.g. Burgard *et al.* (2006). Measurements were carried out at four different sites, of which three had mixed traffic (with respect to vehicle categories), and the fourth site was a road operated by buses only. The main objective of the 2007 study was to measure on-road NO_X and NO_2 emissions for the first time in Sweden, and to gather on-road emission data in general for validation of the ARTEMIS/HBEFA emission models (Sjödin and Jerksjö, 2008). After the 2007 study (2010-2015), the main focus of the on-road emission/remote sensing studies in Sweden has been to measure emissions from heavy duty buses operating for public transport services. The main purpose of these measurements – carried out during controlled driving conditions – has been to screen the bus fleet for high-emitters, and to find out how reliable and useful remote sensing is for this purpose. Most of the measurements have been conducted with an RSD AccuScan RSD 3000 instrument, which measures HC, CO, NO and opacity, along with an EEPS (Engine Exhaust Particle Spectrometer) for particle measurements (number and mass divided by particle size). However, in the summer of 2014, the Denver University FEAT 4 instrument was hired by IVL again, both for the controlled measurements on buses and for a series of roadside measurements on mixed traffic. The measurements 2010-2015 have resulted in emission data for 218 unique buses, the roadside measurements in 2007 and 2014 excluded. Among the 218 buses, different Euro classes, model years, fuels, exhaust after-treatment systems, etc., are represented. The number of Euro VI buses measured was 15 (two methane fueled, nine RME fueled and four electrical hybrids fueled with RME). The measurements have been carried out at 17 different bus depots in Southwest Sweden, of which some has been visited more than once. The measurements with the FEAT 4 instrument were conducted at two of the bus operators and during a five day roadside measurement campaign. In this paper no analysis regarding high-emitters is presented, instead emissions from vehicles representing different Euro standards and operating on different fuels are compared.

3 Bus emissions during controlled driving conditions

Experimental

Emissions from the buses were measured during full throttle accelerations from stand still. Prior to the test, a warm-up route was driven, typically 5-10 minutes, to prevent cold engines. The length and driving conditions during the warm-up routes varied depending on where the buses were stationed. After being warmed up, the bus stops right before the instrument set-up. On a given signal it accelerates, passing the instruments and the emissions are measured. After the first measurement the bus turns to do a few more accelerations past the instruments until at least three valid measurements have been obtained. The aim has been to test ten buses at each bus garage; this is often accomplished during a workday including time for the set-up of instruments. The testing conditions are similar to conditions when buses accelerate in real-traffic, e.g. from a bus stop or a traffic light. This means that the measured emissions are representative for "stop and go" traffic normally occurring in city centers, but not for emissions during e.g. motorway driving.

The gaseous species have been measured using either of two different remote sensing instruments. Both instruments generate a light beam across the driving lane and measure concentration ratios of the pollutants to the concentration of CO2 by measuring absorption at certain wavelengths used for detecting each species. Relating pollutant concentrations to CO2 facilitates quantitative measurements of pollutant emissions despite not knowing the extent of exhaust gas dilution. Emissions measured by remote sensing are often expressed as ratios to CO2, or mass of pollutant per mass of fuel. In this report the latter is used.

Most measurements were performed with an AccuScan RSD-3000 instrument. One main drawback of this instrument is its inability to measure NO2 and therefore it only measures a part of the total NOx emissions. The NO2 / NOX-ratio varies between different manufacturers, emission standards and exhaust aftertreatment systems, and in some cases the total NOx emissions is dominated by NO, and primary emitted NO2 only contributes to a few percent. In other cases though, the shares of NO, and primary emitted NO2 are equal. If there is a good knowledge of NO2/NOx -ratios by certain exhaust aftertreatment systems etc., total NOx can be estimated by only measuring NO, but preferably both NO and NO2 should be measured. For measuring NO2 the Denver FEAT was used.

Both the AccuScan RSD-3000 and the Denver FEAT also measures opacity in the IR-range. This parameter gives an approximation of the particle emissions but it was not evaluated in this study since it is considered to be a too uncertain estimate of the particle emissions. Instead an EEPS (Engine Exhaust Particle Sizer Spectrometer, TSI Inc. Model 3090) was used. This instrument measures the number size distribution of particles in the range from 5.6 to 560 nm with a time resolution of 10 Hz. When estimating the particle mass, spherical particles with a density of 1 g cm-1 was assumed. The measured particle emissions were also related to CO2 as is the case for the gaseous species measured with the RSDs. CO2 concentrations used for relating to the particles measurements was measured using a non-dispersive infrared gas analyzer (LI-840A) with a time resolution of 1

Hz. The sampling of the particle and CO2 emissions was conducted by using an extractive sampling of the passing bus plumes, where the sample was continuously drawn through a cord-reinforced flexible conductive tubing. To prevent the influence of the ambient temperature on the measurement a thermodenuder (TD) was used in front of the EEPS (298K). Figure 1 shows a schematic of the experimental setup.

Today many buses use SCR (Selective Catalytic Reduction) systems for reducing nitrogen oxides. The efficiency of these is strongly dependent on the exhaust (catalyst) temperature. Since the temperature was not measured during these tests, it was not possible to determine if high NOX emissions from SCR-equipped buses was a consequence of low temperature or a malfunctioning SCR system.

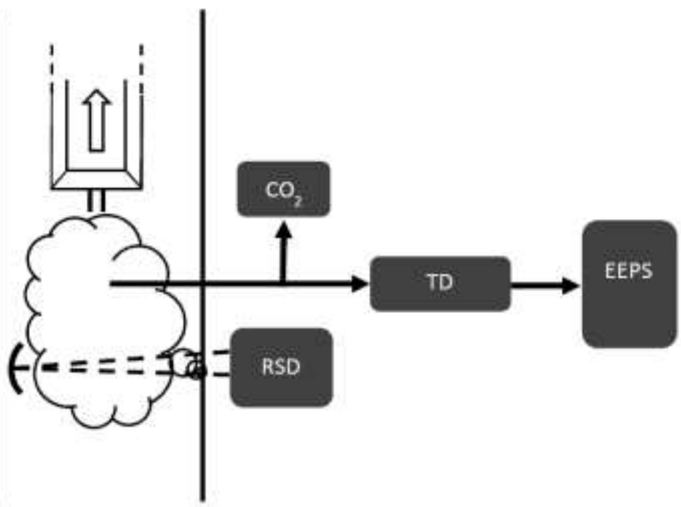

Figure 1. Schematic of the experimental set-up used (Hallquist *et al.* 2013).

4 Results

Most of the measurements of nitrogen oxides during full throttle acceleration in the studies conducted from 2010 to 2015 were done with the AccuScan RSD 3000, which does not measure NO_2. The total NO_2 emission have instead been estimated by using general NO_2/NO_X ratios from the HBEFA road emission model (HBEFA, 2016) or ratios estimated by IVL from measurements with the Denver FEAT. Since the NO_2 part in most cases is approximations, some of the figures in this paper instead present measured NO (as NO_2 equivalents). In general, median emission values of e.g. different Euro standards are presented. This will give a value more representative of the Euro standard compared to the mean, since the mean may be affected by high-emitters. However, in some cases the averages are presented with a 95% confidence interval. All measured emission factors are expressed as mass of pollutant per kg fuel burnt and are notated as EF_{NO}, EF_{PM} etc.

In total 218 unique buses were measured at the depots during the period 2010-2015. Fifteen of the buses were measured twice and one was measured three times during the six year period. The emission standard of the tested buses ranged from Euro II to Euro VI. Some of the tested Euro V diesel buses were in the Swedish vehicle register referred to as EEV. According to Västtrafik, and in some cases the bus operator, these buses were specified to comply with the Euro V standard, but not the EEV standard. Since it was not clear how to classify these vehicles all diesel buses referred to as EEV in the register is referred to as Euro V vehicles in this paper. Also different techniques for reducing NO_X and particles are represented among the buses. Information about the Euro standard and exhaust aftertreatment systems was obtained from the bus operators or Västtrafik. Some of the information from the operators did show up to be wrong during the data evaluation, especially regarding information on the presence of particle reduction systems for Euro IV and Euro V buses. However, most of this incorrect information could be corrected by contacting the vehicle manufacturers. All manufacturers also have their own implementation of the aftertreatment system that differs from the other brands, even though they are similar. This is important to bear in mind since the emissions will depend not only on the technique but also on bus/engine manufacturer. Table 1 shows a summary of all the measured buses with respect to fuel type, Euro class and technology. Also the measured mean and median emissions of NO_X (EF_{NOx}) and PM (EF_{PM}) are presented. Information about the fuel was obtained from the bus operators. Some buses, mostly Euro V and Euro VI, were fueled with 100% RME (Rapeseed Methyl Ester). When it comes to diesel there may be a mix of different low blends of RME and HVO (Hydrotreated Vegetable Oil). Since IVL does not have this detailed information all low blends are termed as diesel.

Table 1. Number of tested buses and EF_{NOx} and EF_{PM} by fuel, Euro standard and exhaust aftertreatment system. HEV = Hybrid electric vehicle, DF = dual fuel (diesel and methane). Dual fuel buses where operated on diesel when tested.

Fuel	Euro std.	Technology	#*	#**	EF_{NOX}			EF_{PM}		
					Median	Mean	95% CI	Median	Mean	95% CI
Diesel	E II		2	2	22	22	69	819	259	2325
Diesel	E III		11	7	12	14	6	1571	1794	668
Diesel	E III	DPF	17	16	13	16	5	188	229	134
Diesel	E III	SCR+DPF	5	4	22	26	19	6	507	1360
Diesel	E III	EGR+DPF	1	1		18			61	
Diesel	E IV	SCR	4	4	10	13	21	222	746	1746
Diesel	E IV	EGR	12	12	14	15	7	*650*	1151	719
Diesel	E V	SCR	42	42	22	27	6	257	301	66
Diesel	E V***	SCR+DPF	4	4	20	21	9	1	1	2
Diesel	E V	EGR+DPF	5	5	11	13	8	36	54	62
Diesel (HEV)	E V	SCR	7	7	30	27	1	41	45	23
RME	E III	SCR+DPF	2	2	38	38	4		68	
RME	E IV	SCR	6	6	40	39	24	233	268	262
RME	E IV	EGR	2	2	13	13	16	72	72	197
RME	E V	SCR	23	22	38	38	7	28	59	26
RME	E V	EGR+DPF	7	7	10	10	5	61	64	35
RME (HEV)	E V	SCR	10	10	42	39	11	19	21	9
RME (DF)	E V	SCR	10	10	36	35	2	77	82	7
RME	E VI	EGR+SCR	9	9	4	4	2	1	2	2
RME (HEV)	E VI	EGR+SCR	4	4	7	13	24	1	1	1
Methane	EEV		50	46	0	30	11	8	23	13
Methane	E VI		2	2	0.45	0.45	0.32	2	2	17
Total			**235**	**224**						

* In this column every bus that were tested two or three times are counted two or three times respectively.

** In this column every bus that were tested two or three times and not have changed from diesel to RME are counted only once. Six of the buses were tested both on diesel and RME, hence these buses are included twice in this column.

*** mini buses

NO_X emissions by Euro standard

Measured EF_{NOx} from all buses are shown in Figure 2, together with the median values of each Euro class/technology. The figure shows that there is no decrease in NO_X emissions going from Euro III to Euro V for the conditions valid in the controlled measurements. As is seen in Figure 2, buses equipped with an SCR-catalyst have approximately twice the emissions of their EGR equivalents. This is most likely due the SCR not operating at optimal conditions during the tests. The tested Euro VI (diesel) buses though, use both SCR and EGR and the measured NO_X emissions from these buses were several times lower than the emissions from the Euro V buses, and did not show any sign of significant increases in NO_X even after longer periods of stand still. When it comes to methane powered buses, the very high median emissions are due to some groups of buses emitting high amounts of NO_X.

Figure 3 shows EF_{NO} for methane powered buses by manufacturer (M1-M4), model year and age of the vehicle when tested. In a complete analysis of the emission behavior from the different manufacturers there are even more parameters that should be considered, e.g. different models from the same manufacturer, kilometers driven and maintenance. The differences between models from the same manufacturer did not show any significant differences, and this information was chosen not to be included in the analysis. When it comes to driven kilometers, IVL did get information about only a few of the buses and no information at all about when the buses were serviced. Emissions of NO from two of the manufacturers (M3 and M4) were low regardless of vehicle age (median 1.5 g kg $fuel^{-1}$ and 4.9 g kg $fuel^{-1}$). M2 showed a bit higher median emission (20 g kg $fuel^{-1}$) compared to M3 and M4, also two really high emitters were identified from M2. The highest median emission was measured from manufacturer M1 (67 g kg $fuel^{-1}$), and the variation in NO-emissions between the different individual buses within this brand was relatively large. Also, all the buses from M1 were owned by the same operator which may have an influence on the emissions, e.g. that all the buses have higher yearly driving distances than other buses and that the maintenance scheme differed from other operators. However, the reason for these differences between manufacturers was not further investigated.

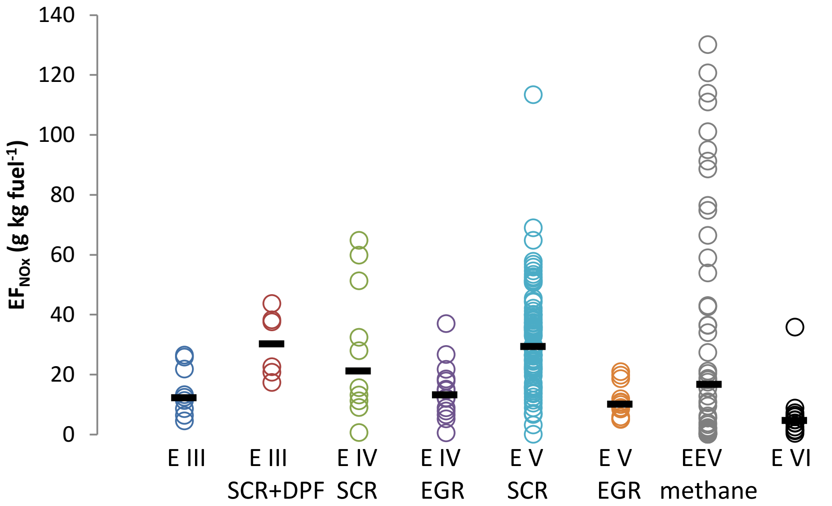

Figure 2. Measured EF_{NOX} from all buses by Euro standard and aftertreatment system (circles) and median EF_{NOX} (black lines).

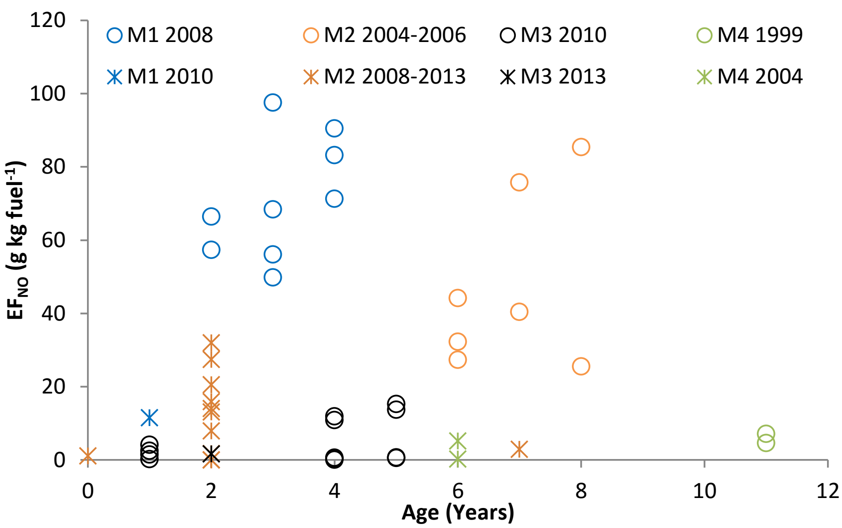

Figure 3. EF_{NO} from methane powered buses by manufacturer, model year and age.

Particle emissions by Euro standard

In Figure 4 the particle emissions (by mass) for all the tested buses are shown. There is a large variation in emissions between different classes but also within the Euro classes. Euro III (without DPF) and IV (EGR) have the highest median EF_{PM} (1571 and 649 mg kg fuel^{-1} respectively) and the EEV (methane fueled) and the Euro VI buses the lowest (8 and 1 mg kg fuel^{-1} respectively).

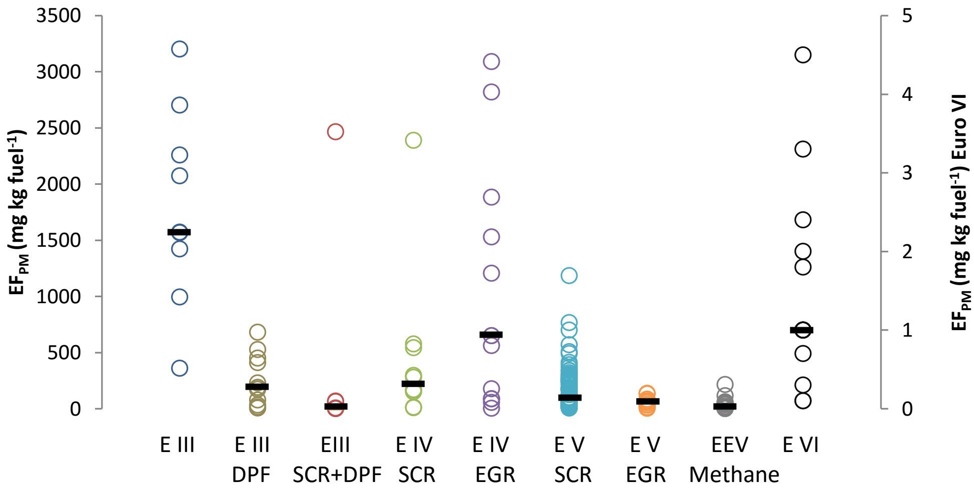

Figure 4. Measured EF_{PM} from all buses by Euro standard/aftertreatment system (circles) and median EF_{PM} (black lines). The secondary axis is for Euro VI.

Buses equipped with diesel particulate filter (DPF) are emitting significantly less particle mass compared to similar buses without DPF as is illustrated in Figure 5 for Euro III buses. The median EF_{PM} with DPF is 188 mg kg fuel^{-1} and the median EF_{PM} without 1571 mg kg fuel^{-1}, respectively. The reason for high masses for some buses equipped with DPF may be malfunction of the DPF.

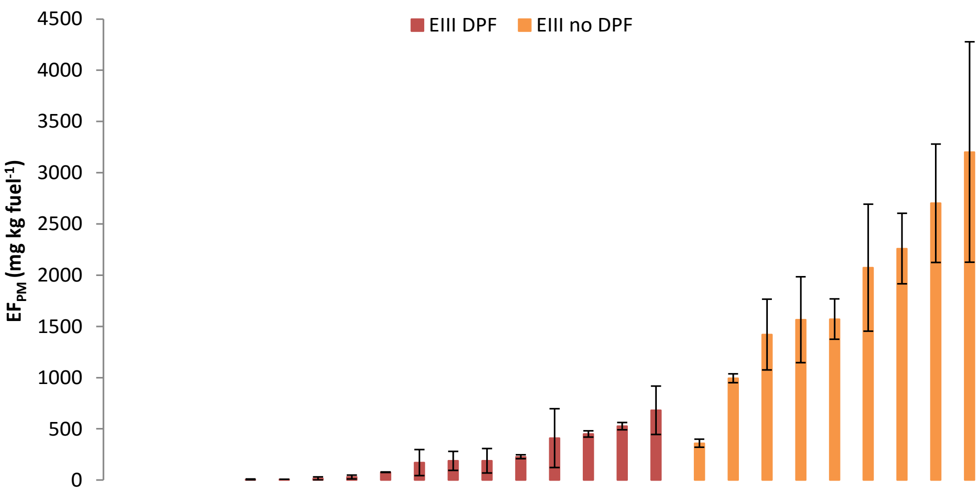

Figure 5. EF_{PM} of Euro III buses equipped with (red) and without DPF (orange). Stated errors are at the statistical 95% confidence level.

Buses corresponding to the Euro V standard were the most frequently tested. In Figure 6, all the Euro V buses are shown and subdivided depending on fuel and NO_X abatement technology. For SCR buses the median EF_{PM} was higher for diesel buses compared to RME fueled buses. For the EGR buses the median EF_{PM} was very similar between the different fuel types, 36 and 61 mg kg fuel-1, respectively. However, these buses were equipped with DPF. Additionally, for the RME buses, the median EF_{PM} was similar for the EGR+DPF and SCR technologies (61 and 28 mg kg $fuel^{-1}$, respectively).

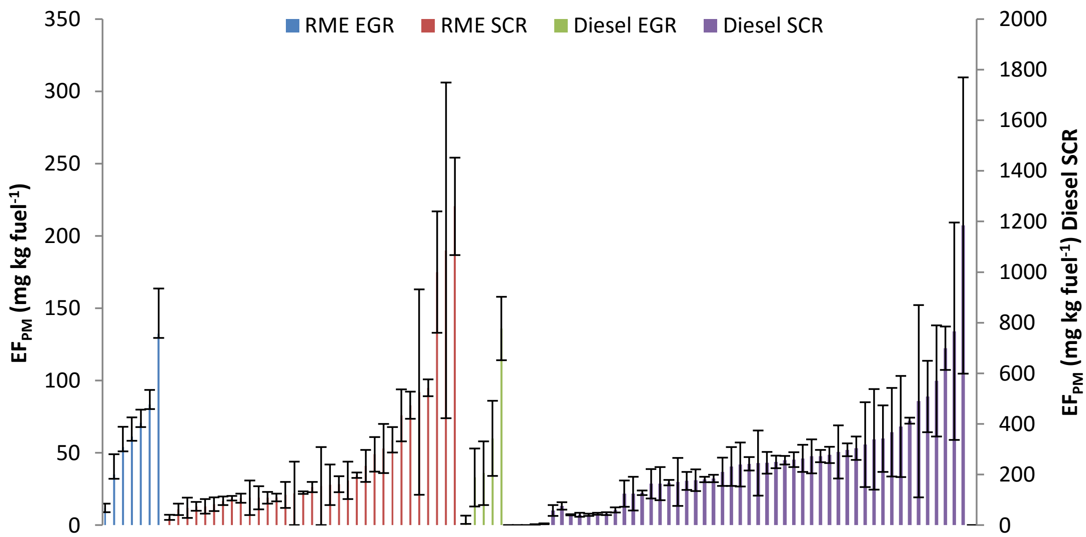

Figure 6. EF_{PM} of the tested Euro V buses with respect to fuel and NO_X abatement technology. The secondary y-axis is for Diesel SCR buses. Stated errors are at the statistical 95% confidence level.

Particle and NO_X emissions from diesel vs RME fueled buses

Among the tested diesel buses there was a mixture between buses fueled with conventional (low blended) diesel and buses fueled with 100% RME. This enabled an analysis of differences in emissions depending on the type of fuel. To minimize the number of parameters other than the fuel that may influence the emissions, only Euro V buses with SCR from one manufacturer were considered. However, different models from this manufacturer were included. When it comes to particle mass, the median emission from RME fueled buses was 88% lower than the median for buses fueled with low-blended diesel (30 mg kg $fuel^{-1}$ and 249 mg kg $fuel^{-1}$, respectively), see Figure 7. The particle emissions from the RME fueled buses were generally low, <100 mg kg $fuel^{-1}$, whereas the scatter for diesel fueled buses was much larger, ranging from 41 to 1200 mg kg $fuel^{-1}$.

Any differences in NO_X-emissions between the fuels are not as a clear as for particle mass, Figure 8. This is in line with expectations as the NO_X reduction system (SCR) is dependent on parameters such as the exhaust temperature which was not controlled in this study. However, the median NO_X emission from buses fueled with low blended diesel was 35% higher than for RME fueled buses (25 g kg fuel^{-1} and 33 g kg fuel^{-1}, respectively). Still it is not possible to determine if the measured difference in this study is fuel dependent, or if it is a consequence of different exhaust gas temperatures of the tested buses. Most likely it is an effect of both fuel and temperature.

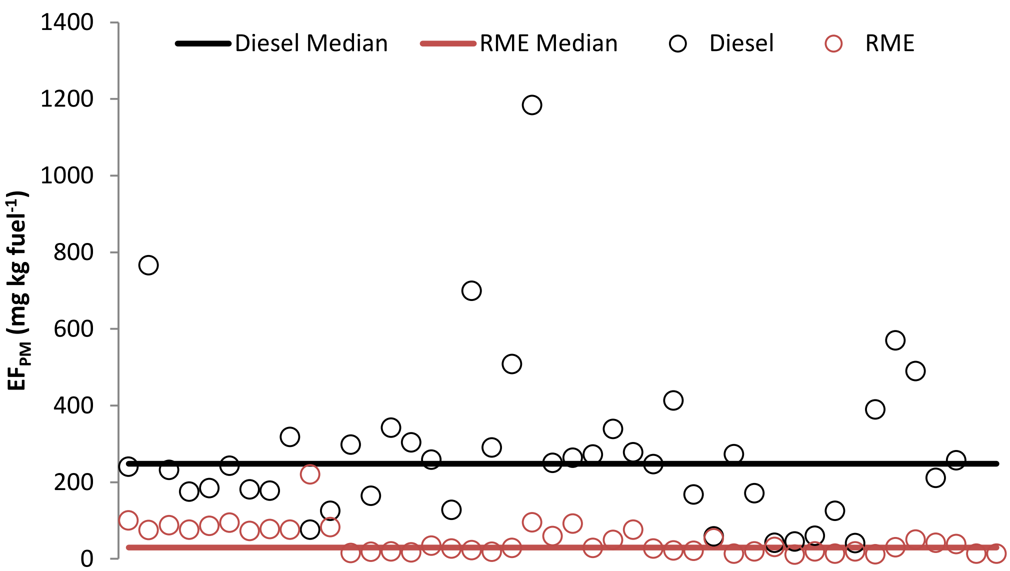

Figure 7. Median EF_{PM} for Euro V busses running on RME (red symbols) and diesel (black symbols).

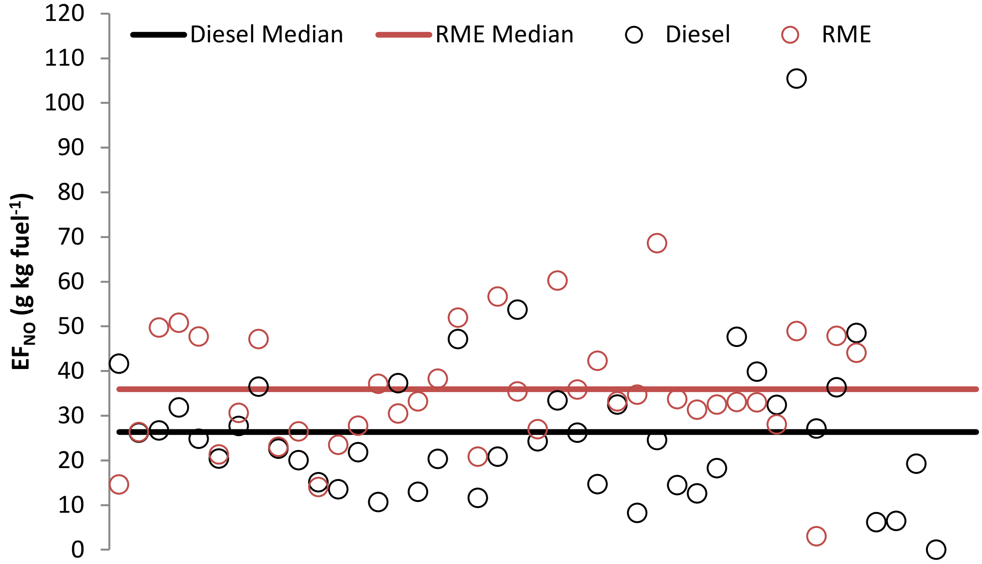

Figure 8. Median EF_{NO} for Euro V busses running on RME (red symbols) and diesel (black symbols).

Emissions from buses tested both on diesel and 100% RME

Seventeen of the buses were analyzed more than once, with one year or more between each occasion. For six of these buses (here named B1, B2, B3, B4, B5 and B6) there was a fuel switch from diesel to RME between the two occasions the bus was tested, and both a decrease (B1, B2 and B3) and an increase (B4, B5 and B6) in EF_{PM} when running on RME compared to diesel were observed. The emission standard of B1, B4 and B6 was Euro IV and Euro V for B2, B3 and B5.

B1 was converted to be operated on 100% RME in 2014. Also the particulate filter was washed in March 2015 (four months before the measurements). The lower emissions in 2015 compared to 2010 may be a consequence of both the conversion to RME and/or the newly washed particulate filter. Both B2 and B3 were converted to be operated by 100% RME and the particle emissions were significantly lower in 2015 compared to 2012 (Figure 9). Common for these buses is that the combustion conditions were similar (i.e. small difference in EF_{CO}) at both occasions the bus was tested, indicating a general reduction in EF_{PM} when running on RME compared to diesel (Figure 9).

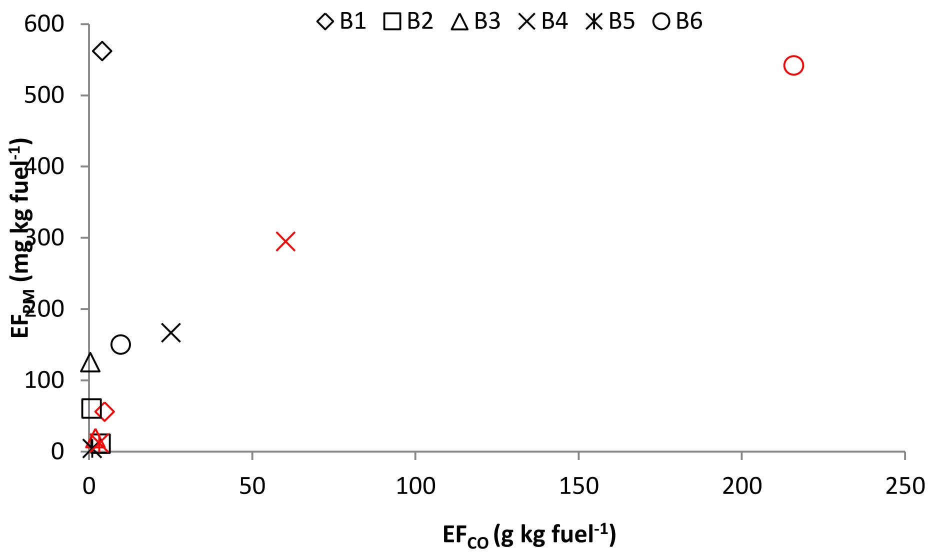

Figure 9. EF_{PM} for buses that have been tested at multiple years and where there has been a fuel switch (red symbols are EF_{PM} when fueled with RME).

For B4, B5 and B6 the particle emissions were higher when running on RME compared to diesel. B4 was converted to RME operation sometime between 2011 and 2015, and B11 was converted sometime between 2014 and 2015. However, for B4 and B6 also the EF_{CO} was much higher when running on RME (Figure 9), indicating a more incomplete combustion, hence favoring soot formation. It is therefore difficult to distinguish between impact of fuel and impact of different combustion conditions on the emissions.

B5 was converted to RME operation sometime between 2010 and 2015. There was a slight increase in particle mass emitted when running on RME, and also the CO emission increased somewhat. However, the CO emission was much lower compared to B4 and B6. Additionally, B5 was equipped with a DPF, so another possibility for the increase in particle mass emitted, besides fuel and combustion conditions, is the performance of the DPF.

For three of the buses (B2, B3 and B6) the measured difference in EF_{NO} was statistically significant (Figure 10). B2 and B3 showed an increase of NO emissions when fueled with RME compared to diesel, whereas B6 showed the opposite trend. B6 did even show a significant increase of EF_{PM} and EF_{CO}, but the reason for the lower NOx emission is hard to determine without knowing more about the bus/engine. Since it was equipped with an SCR catalyst it may just be a consequence of better operating conditions of the catalyst at the second measurement occasion.

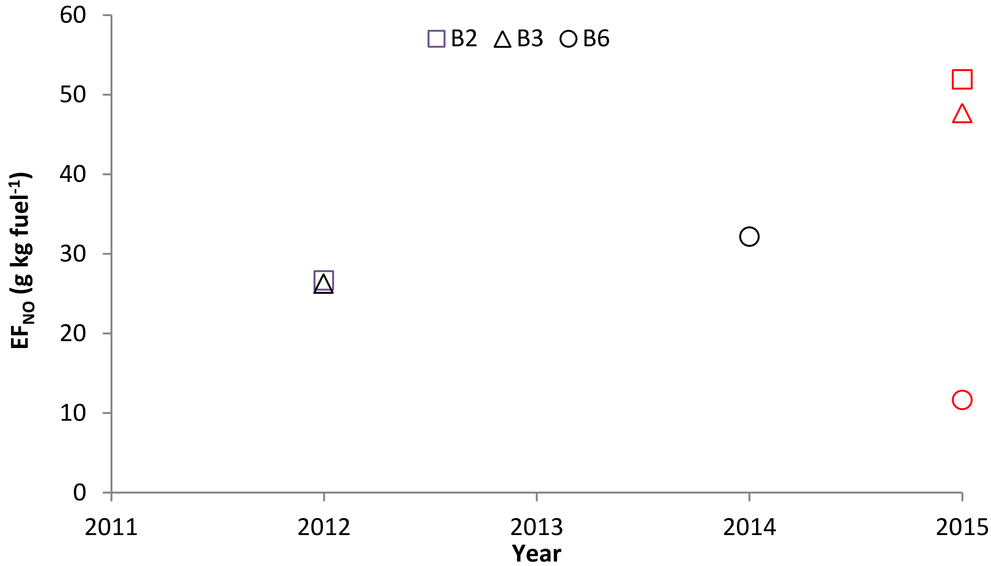

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Figure 10. EF_{NO} for buses that have been tested at multiple years and where there has been a fuel switch (red symbols are EF_{NO} when fueled with RME).

On-road measurements

Buses

This section presents NO_X emissions and NO_2/NO_X ratios measured from the roadside with the Denver FEAT in 2014. For comparison, measured NO_2/NO_X ratios are compared to ratios measured during the controlled acceleration measurements and also to ratios from the HBEFA model.

The by far most frequent emission standard measured among the buses from the roadside was Euro V (this was also the case with the controlled measurements at the bus depots). Among the measured Euro V buses one manufacturer was dominating. There were also three other manufacturers that were represented to an extent that an analysis of differences in NO_X between the brands was considered possible. This is interesting since different manufacturers may use different versions of exhaust aftertreatment systems that may result in e.g. different levels of emitted NO_X and NO_2/ NO_X ratios. It is also interesting to compare NO_X emissions measured from the roadside with measured emissions from the controlled acceleration measurements.

Table 2 presents measured NO_X emissions together with information on emission standard, NO_X reducing technology, manufacturer and number of measurements. Comparing emissions from the SCR equipped Euro V buses (M1 and M2) show that the differences in median and average NO_X emissions are quite large. However the number of measurements of M2 is low and this is reflected in the confidence interval. If comparing to the measured NOx during the controlled acceleration measurements from the same manufacturers, the difference is similar to what is observed from the roadside which may indicate lower on-road NO_X emissions from M2 compared to M1. The NO_2/ NO_X ratio between M1 and M2 are similar though.

The EGR equipped buses (M3 and M4) shows similar levels of NO_X emissions but the average NO_2/ NO_X ratio differs greatly (5 vs 41%). One possible reason may be due to different techniques used for particle reduction, but this could not be confirmed during this study.

Only two unique Euro VI buses were measured from the roadside (total 6 measurements) and the NO_X emissions were low, similar to the observations from the controlled measurements during acceleration. The NO_2/ NO_X ratio was measured to 29% from roadside and 22% during the controlled measurements. It should be noted though that this is a ratio of two low averages based on a small number of measurements which makes the ratio uncertain.

Table 2. EF_{NOX} emissions (g kg fuel^{-1}) measured from the roadside and NO_2 share of NO_X measured during the controlled acceleration measurements, from the roadside and ratios taken from the HBEFA model.

Euro Standard	**Technol.**	**Brand**	**#**	**#**	**EF_{NOx}**			**NO2/NO_X**		
			(total)	(unique)	Median	Average	95 % CI	Roadside	Controlled	HBEFA
E III	-	Mix	10	7	43	42	7	5%	-	7% (30%)
E V / EEV	SCR	M1	246	116	41	43	3	2%	1%	7% (25%)
E V	SCR	M2	8	4	26	29	19	2%	-	7% (25%)
E V / EEV	EGR	M3	173	79	20	25	2	5%	-	21% (25%)
E V	EGR	M4	19	13	21	21	4	41%	-	21% (25%)
E VI	SCR+EGR	M1	6	2	1	2	3	22%	29%	-

Passenger cars

The roadside measurement campaigns in 2007 and 2014 resulted together in 20 000 valid measurements on passenger cars. This is a quite low number compared to many other similar remote sensing studies from which data have been published. Still our results are similar to those presented in e.g. Carslaw *et al.* (2013) and Borken-Kleefeld and Chen (2013), which indicates that the amount of data is still sufficient to use for some analyses, even though the uncertainties in the means in some cases are high.

All figures in this section are presented as average emissions by Euro class with error bars showing the 95% confidence interval of the mean. Pre-Euro 1 vehicles are divided into three groups, Pre-Euro cars with a three way catalyst, vehicles of model year 87-88 where there is a mix of vehicles with and without three-way catalysts, and Pre-Euro which only includes cars without three-way catalysts. Only vehicles with a measured vehicle specific power between 2.5 and 22.5 are included.

Figure 11 - 14 show emission trends of CO, HC, NO_X and NH_3 from pre-Euro to Euro 6 for gasoline passenger cars. Other remote sensing studies of European passenger car emissions, e.g. Carslaw *et al.* (2013) and Borken-Kleefeld and Chen (2013), have shown that these emissions have decreased for every new Euro standard from Euro 1 through Euro 5. Carslaw *et al.* (2013) have also shown that ammonia from gasoline cars is predominantly emitted from the first model years that were equipped with three-way catalysts. Then the emissions have decreased through the emission standards to be at approximately the same level for Euro 6 vehicles as for pre-Euro non-catalyst vehicles. Results from Carslaw *et al.* (2013) and Borken-Kleefeld *and Chen* (2013) also clearly show that when it comes to diesel cars newer cars emit about the same level of NO_X that new cars did 20 years ago. Data from the measurements in Gothenburg in 2007 and 2014 show the same trends. Moreover, when comparing average emissions by Euro standard between the 2007 and 2014 measurements, the NO_X emissions seem to have increased within the same emission standard. If analyzing NO ad NO_2 separately it shows that NO has increased and at the same time NO_2 has decreased, also leading to a decreased NO_2/NO_X ratio. The reason for the increase in NO_X and at the same time lower NO_2/NO_X comparing the measurements in 2007 with 2014 is not clear. Some of it may be attributed to the uncertainty due to a relatively low number of measurements. But it may also be deactivation of the diesel catalyst which causes deterioration of the NO_X reduction performance and the ability to produce NO_2.This may also be the reason for the difference between the 2007 Gothenburg measurements and data presented in Carslaw (2013). Other differences between the measurements in Sweden and the UK may be a different mix of engine sizes. In Carslaw (2013b) the NO_2/NO_X-ratios for diesel cars are presented separately for <2 liter engines and >2 liter engines. This shows a higher NO_2 share for the larger

engines in a certain VSP range with a maximum of about 47% for Euro 4 cars with low VSP. The diesel vehicles measured had an average cylinder volume of 2.3 l and 2.2 l for Euro 3 and Euro 4 vehicles respectively in 2007. In 2014 the averages were 2.3 l and 2.1 l. Another difference may be a possibly higher share of Euro 3 vehicles with DPF in Sweden compared to the UK.

Figure 4 shows that the NO_2/NO_X ratio measured in 2007 increased from about 15% for Euro 2 cars to about 47% for Euro 3 cars and 56% for Euro 4 cars. The increase from Euro 2 to Euro 3 is due to the introduction of diesel oxidation catalysts (DOC) in Euro 3 vehicles. Some Euro 4 cars were equipped with DOC + diesel particulate filter (DPF) which may explain the higher NO_2/NO_X ratio from Euro 4 compared to Euro 3, Carslaw *et al*. 2016. Data presented in Carslaw *et al.* (2013) also show this stepwise increase of the NO_2/NO_X ratio from Euro 2 to Euro 4.

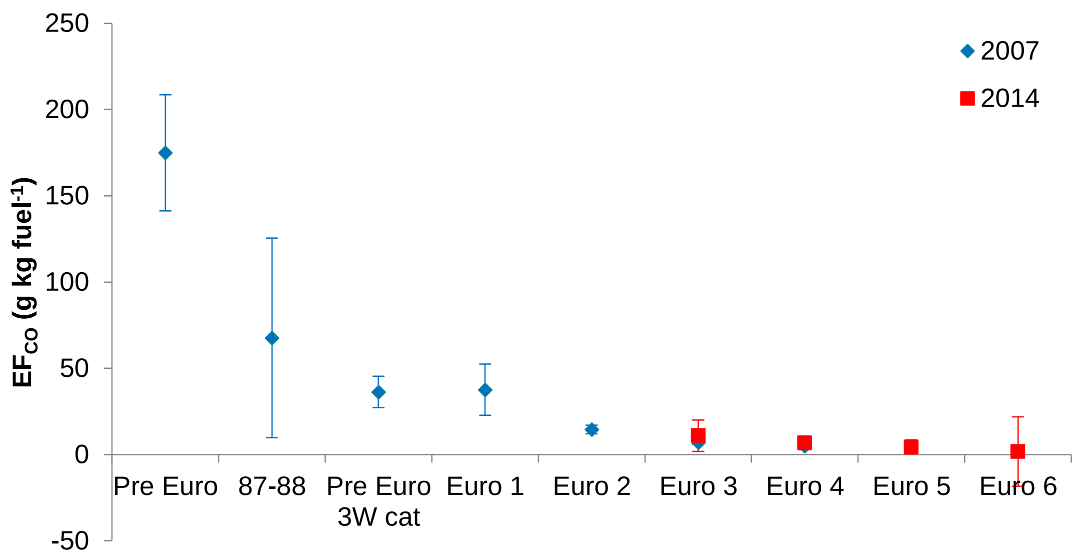

Figure 11. CO emissions from gasoline cars as measured in Gothenburg 2007 and 2014.

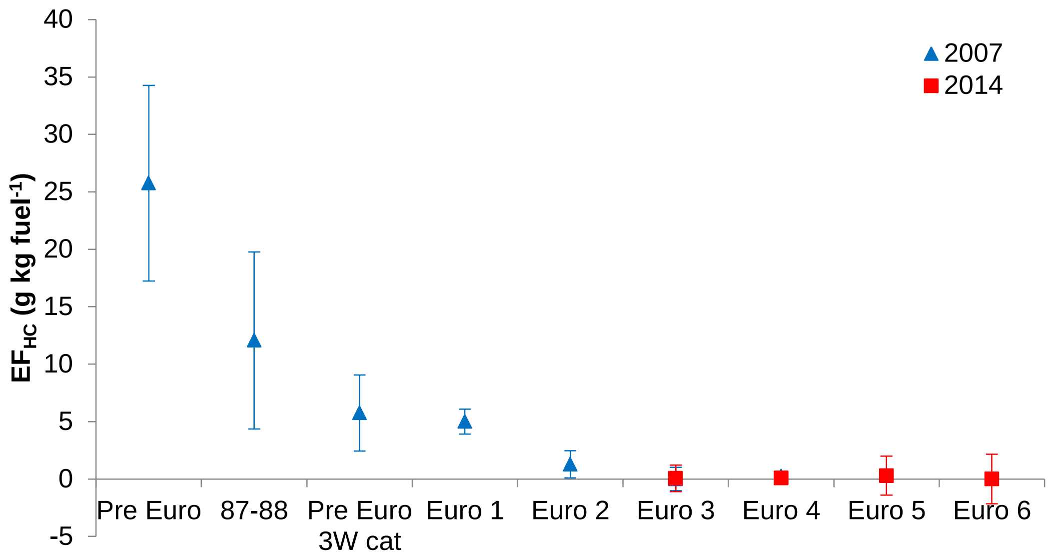

Figure 12. HC emissions from gasoline cars as measured in Gothenburg 2007 and 2014.

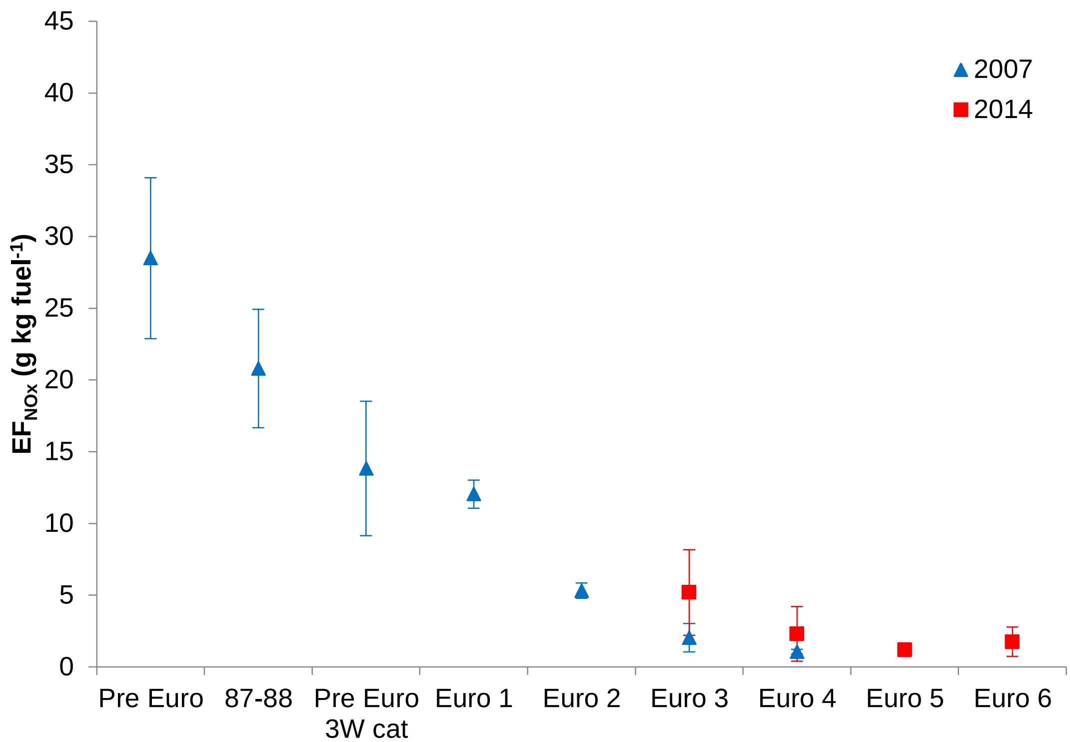

Figure 13. NO_X emissions from gasoline cars as measured in Gothenburg 2007 and 2014.

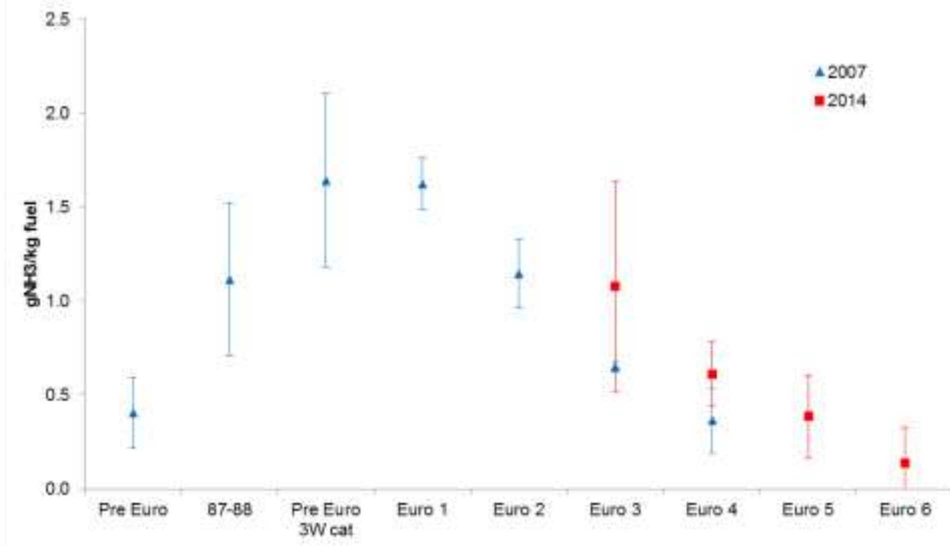

Figure 14. NH_3 emissions from diesel cars as measured in Gothenburg 2007 and 2014.

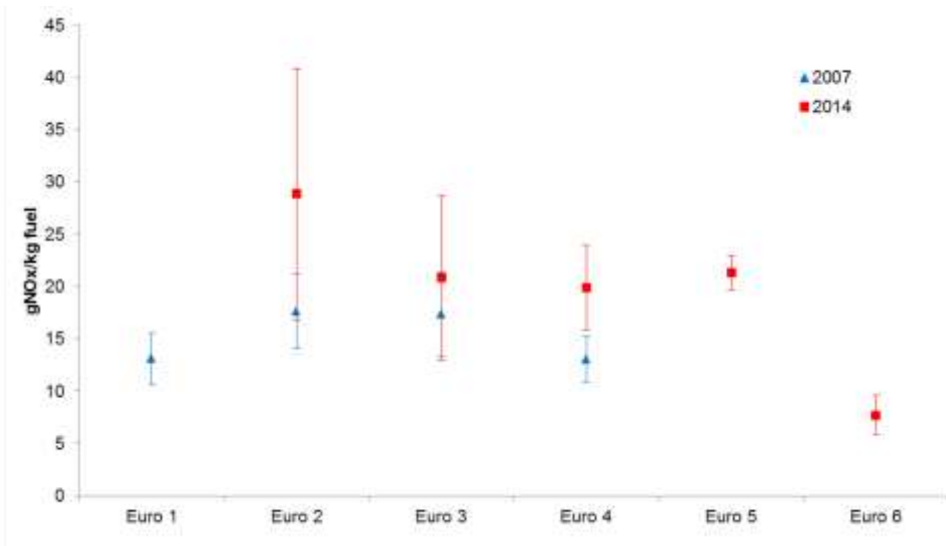

Figure 15. NO_X emissions from diesel cars as measured in Gothenburg 2007 and 2014.

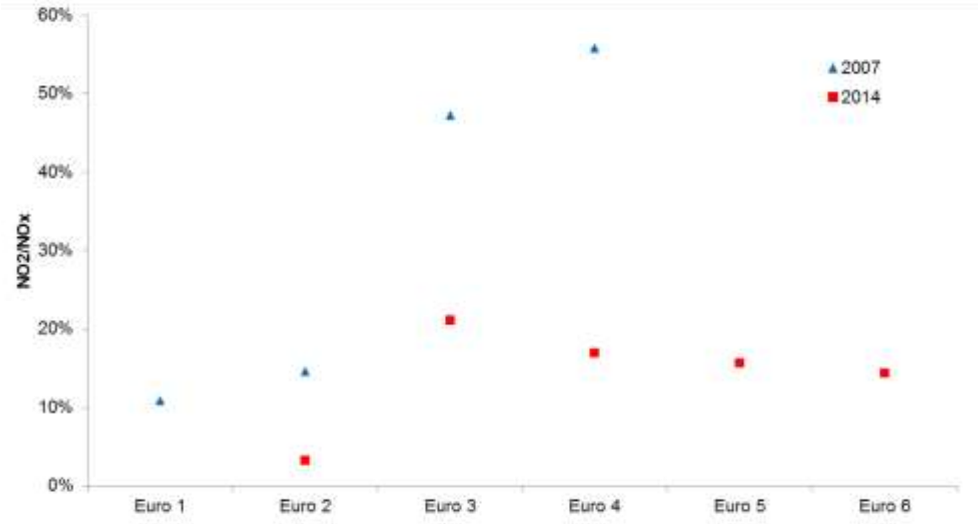

Figure 16. NO_2/NO_X ratio in exhausts from diesel cars as measured in Gothenburg 2007 and 2014.

5 Conclusion

During 2007-2015 on-road emission measurements by means of remote sensing were conducted in Sweden, mainly on heavy-duty buses and passenger cars. The number of measured vehicles in the studies is relatively small compared to other similar studies in Europe and the United States. However, the Swedish data shows comparable results with other studies. What differs from most other published studies on roadside emission measurements, is the use of an Engine Exhaust Particle Sizer Spectrometer for measuring particle mass and number (of which only particle mass has been presented in this paper) on heavy-duty buses. These measurements have shown differences in emission behavior between different emission standards and emission reduction technologies. More over the roadside measurements on passenger cars in 2007 were probably the first of its kind in Europe including NO_2. The following measurement in 2014 enabled an analysis of changes in NO and NO_2 emissions from diesel passenger by emission standard over a seven year period (2007 to 2014).

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References

[1] Burgard D.A, Bishop G. A., Stadtmuller R. S., Dalton T. R. Stedman D. H., Spectroscopy Applied to On-Road Mobile Source Emissions, Applied Specrtoscopy 2006 May; 60(5): 135A-148A

[2] Carslaw D. C., Murrells, T. P., Andersson J. & Keenan M., (2016) : Have vehicle emissions of primary NO2 peaked ? Faraday Discuss, Advance Article, DOI 10.1039/C5FD00162E

[3] Carslaw D. C. & Rhys-Tyler, G., (2013): New insights from comprehensive on-road measurements of NOX, NO2 and NH3 from vehicle emission remote sensing in London, Atmospheric Environment 81 (2013) 339-347

[4] Carslaw D. C. & Rhys-Tyler, G., (2013b): Remote sensing of NO2 exhaust emissions from road vehicles – A report to the City of London Corporation and London Borough of Ealing, , DEFRA Project Reference 332c2011 (City of London Corporation), 334c2011 (London Borough of Ealing)

[5] Chen Y., Borken-Kleefeld J., (2013): Real-driving emissions from cars and light commercial veicles – Results from 13 years remote sensing at Zurich/CH, Atmospheric Environment 88 (2014) 157-164

[6] Hallquist Å. M., Jerksjö M., Fallgren H., Westerlund J. & Sjödin Å., (2013): Particle and gaseous emissions from individual diesel and CNG buses, Atmos. Chem. Phys., 13, 5337-5350

[7] HBEFA (2016), www.hbefa.net