Real Emissions from the City and Public Bus Fleets in Graz

J. de la Fuente[1], M. López[1], J. Toudert[1]*

[1] Technet, sostenibilidad en transporte, s.l. 28015 Madrid, Spain, josefina.fuente@technetsl.es

Abstract

Herein we present the on-road remote sensing emission measurement campaign carried out in Graz in May 2014, which comprised measurements of both the public bus fleet as well as the circulating fleet within the city. The major goal of the study was to provide real-emission data of both fleets, in order to determine their environmental state, contribution to air pollution and possible implementation of efficient mobility policies. Overall, the study comprised more than 11,600 unique vehicles (of which 142 corresponded to the bus fleet), for which emission values in grams of pollutant per kilogram of fuel burned have been determined.

Interestingly, the city fleet exhibits very low levels of emissions of particulate matter (PM), which currently constitute the city´s major problem as far as air quality is concerned. For the rest of pollutants, the behaviour of the fleet is similar to other European cities such as Zurich, but much lower emitting than those in Madrid or Barcelona.

The bus fleet was a well-maintained fleet, with lower levels of PM emissions and average CO and NO_x emissions compared to bus fleets in Barcelona and Madrid. However, higher HC emission levels were recorded from the Graz bus fleet.

After identification and repair of the 10 most emitting vehicles, considerable emission reductions for HC (77%) and CO (84%) were observed. This confirms the potential of the technology for the identification of High Emitters among the fleet and subsequent emission reductions.

Keywords: Real emissions, remote sensing (RSD), traffic emissions, on-road, real-world, vehicle specific power

A. Introduction

Clean air is considered to be a basic requirement of human health and well-being, but pollution continues to pose a significant threat to health worldwide. Thus, the presence of atmospheric pollutants above certain concentration limits, especially particulate matter (PM) and nitrogen oxides (NO_x), poses a severe risk to human health. In fact, several studies have identified a direct relationship between poor air quality, hospital stays and premature deaths (Lim et al., 2012; Raaschou-Nilsen et al., 2013; WHO, 2010; WHO, 2009; WHO 2005).

Within this context, road traffic is one of the main sources of atmospheric pollution: In 2010, road transport shares of emissions within the EU territory were around 58% for NO_x, 30% for CO, 22.5% for CO_2 and 18% for NMVOC (EEA/EU, 2012: ITF/OECD 2012). This is even more pronounced in urban areas, where road transport can account for up to 80% of total emissions (EEA/EU, 2103; Madrid Regional Authority, 2013). Therefore, controlling and reducing in-use emissions from motor vehicles is a priority target for EU Member States.

This control is currently regulated both by means of mostly very successful manufacturer required reductions in the certification emissions of new vehicles and by European laws (EC, 2000), which require vehicles to periodically pass emission tests (Periodical Test Inspections/Roadworthiness inspections) at regular intervals during their life-cycle. However, this system has proven to be inefficient for tackling the problem, mainly due to non-representativeness of real driving conditions (emissions are measured on parked vehicles, either idle or high-speed idle) and exclusion of several pollutants (such as nitrogen oxides-NO_x- or hydrocarbons –HC-).(CITA, 2011; Carslaw, 2011; Weiss, 2011).

Ultimately, despite all efforts from the EU and Member States to improve their air quality and reduce emissions from road transport, the objectives have not been reached so far (EEA, 2013-1), and hence further emission control and reduction systems must be found.

A perfect example of the above-mentioned air pollution problems is found in the city of Graz (Austria), which is considered one of the most polluted cities in Austria, with particulate matter (PM) levels that frequently exceed the EU-established legal limits (EEA, 2013-2; Spangl et al., 2013). Within the city, the transport sector is responsible for a large share (≈50%) of air pollution (Trimbacher et al., 2002; Heiden, et al., 2008), and hence control of emissions from this sector constitutes a priority for local and regional institutions. However, as stated before, current control systems have proven not to be sufficiently effective and hence additional methods have to be implemented.

Within this context, remote sensing offers an interesting addition for monitoring and controlling emissions from road transport, since it measures vehicle emissions under real-world driving conditions. The technology, which was originally developed in the late 1980´s in the University of Denver (Bishop et al., 1989), is capable of measuring individual vehicle exhaust concentration ratios of various pollutants and associating these values to a picture of the license plate, which allows for later analysis by vehicle category and other specifications.

Herein we present the results obtained in the remote sensing on-road emission measurement campaign conducted in Graz (Austria), in May 2014. The study was conducted by Technet (ISO17025 certified laboratory for the remote measurement of emissions from road traffic), and consisted of a characterization of the public Bus Fleet, which was further complemented with a measurement and awareness campaign of the city fleet.

B. Experimental Section

2.1. Remote Sensing Measurements

All measurements were carried out using a remote sensing device capable of measuring the ratios of individual vehicle tailpipe emissions of various pollutants (HC, CO, NO, PM) to carbon dioxide. The technology uses absorption spectroscopy techniques in order to precisely measure all pollutants from the vehicle exhaust. Background levels are continuously monitored, and the concentration ratios of the different pollutants are calculated from the attenuation of light produced at specific wavelengths when a vehicle´s plume crosses the light beam. Along with emission values, speed and acceleration of the vehicles are also measured, allowing estimation of the engine load at the time of the measurement. Additionally, a picture of the license plate is also recorded in order to obtain vehicle´s technical specifications. The device is periodically calibrated against a reference mixture of gas of known concentration ratios.

The measurements were conducted by Technet in May 2014 using a remote sensing commercial device (Accuscan-RSD4600) supplied by Environmental Systems Products, used according to the manufacturer´s operating procedures and those described previously in the literature (Carslaw et al., 2013; Carslaw et al., 2011).

2.2. Measurement sites

Measurements of the public bus fleet[1] were carried out at a single site, which exhibited slight positive slope (0.3°) to ensure that the vehicles were driven under sufficient engine load. The site was located at the entrance of the Bus Holding Graz garage. Vehicles were measured in the evening, after their usual routes, in order to assure absence of the so-called “cold-start effect”. Overall, a total of 718 valid registers were recorded, which corresponded to 142 unique vehicles.

Measurements of the city-fleet were carried out at various measurement sites, all of which exhibited a slight positive slope (0.5°-1.8°) and were distributed homogeneously throughout the city center. In total, the data set from the city fleet is composed of around 11,600 valid registrations for unique vehicles.

2.3. Data treatment

Initially, data were filtered in order to only analyze those records with valid emission measurements, valid speed/acceleration measurements and legible vehicle plate. Then, we selected those records for which Vehicle Specific Power (Jiménez-Palacios, 1998) values were maintained between 2 kW/ton and 30 kW/ton, in order to assure engine load and representativeness.

The remote sensing device provides emission values as a ratio of pollutant gas to exhaust CO_2. However, these ratios can be directly converted to fuel-specific emissions in grams of pollutant per kilogram of fuel and using carbon balance.

In this study, conversion of CO, HC and NO emissions to grams per kilogram were performed according to formulas previously described in the literature (Pockarel et al., 2002).

For NO_x, measured NO emission values in grams per kilogram of fuel burned are expressed as NO_2 equivalents according to the following equation (1):

$$[gNO_x/kg] = [gNO/kg] * 46/30 \qquad (1)$$

[1] Measured bus fleet corresponds to the fleet of the Bus Holding Graz, composed of 152 vehicles.

C. Results and discussion

3.1. Public-bus Fleet

A. Dataset

For 8 days, emissions from the public bus fleet of the city of Graz were measured. Measurements were conducted at the entrance of the Bus Holding Graz garage, when the vehicles returned from their usual daily routes. The number of valid records and unique vehicles per day of measurement, together with mean speed and vehicle specific power for each session are presented in the following table.

Table 1: Number of records, valid records, unique vehicles, mean speed and mean VSP per day of measurement

Day of Measurement	No. valid records[a]	No. unique vehicles	Mean Speed[b] (Km/h)	Mean VSP[b] (kW/t)
1	21	8	18.6 ± 2.2	4.3 ± 1.0
2	126	46	15.8 ± 3.2	5.0 ± 2.6
3	12	2	16.5 ± 1.8	3.7 ± 0.8
4	71	42	16.5 ± 3.8	5.2 ± 2.3
5	193	68	16.7 ± 3.6	7.2 ± 4.2
6	132	55	17.0 ± 3.0	4.1 ± 1.6
7	74	34	17.0 ± 4.1	5.1 ± 2.4
8	89	36	17.6 ± 4.0	5.0 ± 1.8
Total/average	718	142	16.8	5.3

[a] Refers to records with valid emission measurements, valid speed/acceleration measurements, legible license plate and VSP values between 2-30kW/t. [b] Errors expressed as the standard deviations from the site means

Overall, 718 valid records were registered throughout the measurement campaign, which corresponded to 142 unique vehicles. On average, vehicles were driven at a mean speed of 17 km/h, with a VSP value of 5 kW/t.

B. Average emissions

Vehicle information for analysis and processing of data was obtained from the bus-fleet owner (Bus Holding Graz). Unfortunately, only overall data of the fleet (*i.e.* No. of buses, fuel type and No. of buses per EuroStandard) was provided. Therefore, an analysis of the evolution of emission values with model year or a more exhaustive analysis by vehicle age could not be executed. However, taking into account that all vehicles were diesel-fuelled buses, we were able to obtain the corresponding emission factors in grams of pollutant per kg of fuel burned as described in the previous section (*2.3 Data Treatment*).

Figure 1 and Table 2 show average emissions for the bus fleets in Graz and other European cities:

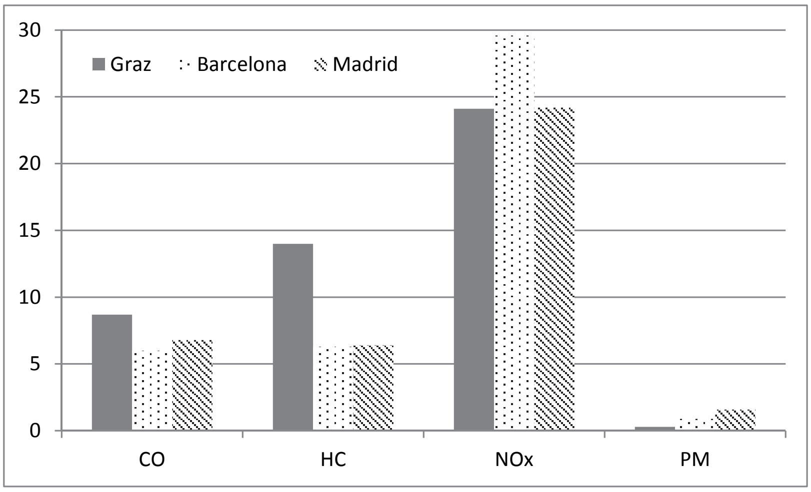

Figure 1: Average emission values for different European bus-fleets. NO_x values correspond to gNO_2/kg calculated from the measured gNO/kg

Table 2: Average emission values for different European bus-fleets[a]

Fleet	gCO/kg	gHC/kg	gNO/kg[b]	gNO_x/kg[c]	PM (g/kg)
Graz	8.7 ± 1.7	14.0 ± 1.3	15.6 ± 0.9	24.1 ± 1.4	0.28 ± 0.07
Barcelona	6.0 ± 1.2	6.3 ± 0.9	19.3 ± 1.3	29.6 ± 1.9	0.9 ± 0.1
Madrid	6.8 ± 0.6	6.4 ± 0.3	15.8 ± 0.4	24.2 ± 0.7	1.6 ± 0.1

[a] Errors expressed as 95% confidence intervals calculated from the daily means. [b]Grams of NO. [c]Grams of NO_2 (conversion of the measured gNO/kg into gNO_2/kg of fuel equivalents).

From analysis of Table 2, it is clear that the bus fleet in Graz presents similar emission levels for CO and NO as those from Madrid or Barcelona, but emits considerably more HC and exhibits much lower levels of PM.

Thus, the bus fleet in Graz seems to be much cleaner in terms of PM emissions than the rest of the fleets in Europe. This is especially important in the case of Graz, provided its long-known problems with legal ambient PM-levels surpassing (EEA, 2013-2; Spangl et al., 2013).

In order to have a better feeling of the environmental state of the fleet, we decided to compare its mean emissions to the type approval limit values (EC, 2000). For this purpose, limit values in grams of pollutant per km over the homologation driving cycle (EST) are converted to grams of pollutant per kg fuel burned using a diesel efficiency of 0.26 l/kW-h (Volvo Truck Corporation, 2003).

Figure 2 shows mean emission values for the bus fleet (grey bars), together with Euro III (black lines) and Euro III EEV (grey lines) type approval limit values. Selection of Euro III and Euro EEV standards was made because the bus Graz fleet is composed mainly of Euro III (93 vehicles) and Euro EEV (57 vehicles) buses.

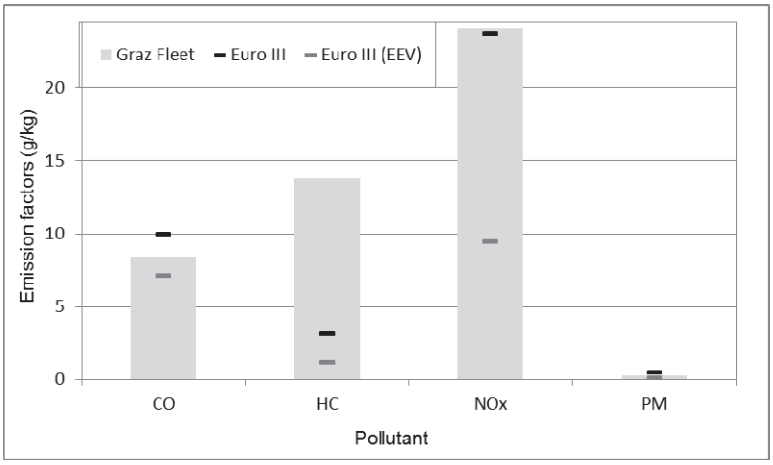

Figure 2: Mean emission values for Graz bus fleet and type approval limit values for Euro III and Euro III EEV. (NO_x = grams NO_2 obtained from conversion of gNO/kg)

The previous figure shows what we had already envisioned from comparison to other European bus fleets: overall, the Graz bus fleet seems to be clean, but it exhibits considerably high emission values for HC. In fact, mean emission factors for HC surpass both Euro III as well as Euro III EEV type approval limit values. For the rest of pollutants, mean emission factors are between both type approval limit values.

C. High emitter identification

Once the fleet had been characterized, we then turned our attention to the most emitting vehicles.

Several studies have shown the potential of Remote Sensing for the identification of High Emitters among fleets (USEPA, 1996; BAR, 2001). According to previous reports, these vehicles constitute a small portion of the fleet, but can provide a considerable share of global emissions, since the vast majority of vehicles have very low emission levels (Bishop et al., 1996; Bishop et al., 2000; Bishop et al., 2008; Zhang et al., 1995; Sjödin et al., 1997).

Within this context, we decided to test the potential of an RSD-program to reduce the emissions from the fleet through identification (and ulterior repair) of the most emitting vehicles.

In order to do this, we decided to tackle the 10 most emitting vehicles in the Graz bus fleet. With this task in mind, we first selected those vehicles for which more than one measurement had been recorded during the measuring campaign (90 vehicles). From this sub-fleet, the 15% most emitting vehicles per pollutant were selected, rendering a list of 32 high emitting vehicles. Out of these, the highest emitting vehicles were identified by choosing those buses that surpassed the established thresholds for at least 2 pollutants. This provided a list with the 10 most emitting buses among the fleet, which were used for our study.

After identification, these 10 vehicles were sent for repairs, which according to information from the owner company mainly consisted on filter changes. Once repaired, emissions from these vehicles were measured again in order to quantify their emissions and determine whether they had been reduced or not.

Table 3 lists the mean emission values for each of these ten high emitters before and after repair, whereas the corresponding differences (i.e., achieved emission reduction) are presented in Table 4.

Table 3: Average emission values for the 10 most emitting vehicles before and after repair

	Mean emissions before repair (g/kg)				Mean emissions after repair (g/kg)			
BUS	CO	HC	NO_x[a]	PM	CO	HC	NO_x[a]	PM
1	9.40	16.22	37.30	0.69	1.34	7.32	29.73	0.66
2	23.81	55.75	32.91	-1.54	1.09	6.10	26.50	0.63
3	10.27	22.36	26.26	0.61	8.12	4.15	49.00	0.85
4	11.55	29.67	28.23	-0.60	2.02	9.22	19.71	2.02
5	5.06	6.31	34.11	1.16	0.25	2.25	25.38	0.87
6	16.05	29.44	27.65	-0.29	2.97	6.14	25.40	1.17
7	22.36	37.06	30.98	0.46	3.37	7.23	29.69	0.76
8	12.79	29.38	34.49	0.27	0.39	8.54	25.67	0.71
9	9.75	22.92	29.73	0.76	1.38	7.68	25.10	1.16
10	14.60	30.62	26.73	0.18	1.64	6.09	25.24	0.68
Avg	13.7	27.9	30.7	0.2	2.2	6.6	27.9	1.0

[a]Grams of NO_2 (conversion of the measured gNO/kg into gNO_2/kg of fuel equivalents). Negative readings are an indication of instrument noise around zero and are retained in the data set so as not to upwardly bias the mean results.

Table 4: Emission reductions for 10 most emitting vehicles after repair

BUS	Emission reductions[a] (g/kg)				Emission reductions[b] (%)			
	CO	HC	NO_x[c]	PM	CO	HC	NO_x[c]	PM
1	8.06	8.90	7.57	0.03	86%	55%	20%	5%
2	22.72	49.64	6.41	-2.18	95%	89%	19%	-141%
3	2.14	18.20	-22.74	-0.24	21%	81%	-87%	-39%
4	9.53	20.46	8.52	-2.62	83%	69%	30%	-434%
5	4.81	4.06	8.73	0.29	95%	64%	26%	25%
6	13.07	23.30	2.25	-1.46	81%	79%	8%	-498%
7	18.99	29.83	1.29	-0.30	85%	81%	4%	-65%
8	12.40	20.84	8.82	-0.44	97%	71%	26%	-160%
9	8.37	15.24	4.63	-0.40	86%	66%	16%	-52%
10	12.96	24.53	1.48	-0.49	89%	80%	6%	-267%
Avg.	11.4	21.3	2.8	-0.8	84%	77%	9%	----

*[a]Reduction=[before-after]; [b]Reduction(%)=([before-after]/[before])*100; [c]Grams of NO_2 (conversion of the measured gNO/kg into gNO_2/kg of fuel equivalents).*

From Table 3 and 4, several important conclusions are drawn:

- For all selected buses, considerable emission reductions for HC (77%) and CO (84%) are observed after repairs.

  In order to assure the statistical significance of these differences, the mean emission values of these 10 vehicles before and after repair (taking into account their corresponding errors) were compared. Through comparison, it was observed that the difference between both averages was in fact larger than their 95% confidence intervals (i.e., confidence intervals do not overlap), meaning that the reductions we observed are statistically significant.

  In our opinion, these reductions could be explained in terms of exhaust back pressure (Jääskeäinen, H., 2007): Before filter changing, accumulation of soot in the diesel particle filters would generate high exhaust back pressure, implying high HC and CO emissions, together with high engine loads and temperatures. After replacing the old filters with new ones, exhaust back pressure would be considerably reduced, and hence emissions lowered.

- For NO_x, a mean reduction of 9% emissions per vehicle was also observed, which seemed reasonable and could also be explained in terms of exhaust back pressures, since this have a strong influence on engine temperature and load, which in turn also influence NO_x emissions.

  However, quite surprisingly, one of the buses exhibited a considerable increase in NO_x emissions after repair. In order to find an explanation for this, we went back to the data and observed that VSP values for this vehicle were considerably different for measurements before and after repair. Thus, the vehicle was measured at an average VSP of 2.2±0.2 kW/t before repair, whereas the load was considerably increased for measurements after repair (12.4±2.4 kW/t). Provided that NO_x emissions steadily increase with increasing VSP, the increase in NO_x emissions for this vehicle could be explained in these terms.

- Finally, if we look at PM values for all vehicles, a consistent increase of emissions is observed for almost all buses after filter change (except for two).

  Although these differences cannot be considered significant (emission values are very low, and basically lie below the detection limit, within the instrument´s noise range), this increase could be explained if one turns to filter efficiency. It is a widespread knowledge that filter efficiency considerably improves with increasing accumulation of soot in the filters. Hence, before replacement, filter efficiency would be high due to soot accumulation, whereas this efficiency would be reduced when the filters were replaced with new ones (where no soot accumulation is present), and PM emissions would subsequently increase.

In summary, considerable emission reductions for HC (77%) and CO (84%) have been achieved, whereas only moderate reductions were observed for NO_x (9%). PM results cannot be considered significant in this case.

We then analysed the contribution of these individual reductions to the overall emissions of the fleet. For doing this, we calculated overall emissions from the fleet (by adding up all measured emissions), and determined the share that the achieved reductions implied (Table5).

Table 5: Global fleet emissions, overall reductions and contribution of reduction to global emissions from the fleet

Pollutant	Fleet emissions[a]	Overall reduction[b]	Contribution[c]
gCO/kg	685.6±5.8	113.0±6.2	16%
gHC/kg	1252.6±8.4	215±12	17%
gNO_x/kg[d]	2058±11	26.9±9.4	1%

[a]Sum of all emissions from unique vehicles; [b]Sum of all reductions from table 4; [c]Contribution=[reduction]/[fleetEmissions]. [a,b,c] Standard errors expressed as standard deviations of the sums. [d] Grams of NO_2 (conversion of the measured gNO/kg into gNO_2/kg of fuel equivalents)

Hence, by identifying and repairing only the 10 most emitting vehicles within the fleet, moderate reductions of the overall emissions of the fleet (16%CO, 17% HC and 1% NO_x) have been achieved.

All in all, this study has served as proof that RSD technology can in fact be very practical for reducing emissions from the fleet by acting upon a very small portion of it. Therefore, it can generate great benefits with very low disturbance.

3.2. City Fleet

A. Dataset

During 5 weeks, emissions from the circulating fleet in the city of Graz were measured at mainly 4 different sites (previously described in section *2.2 Measurement sites*). Altogether, more than 11,600 records of unique vehicles have been registered.

Table 6 lists the number of records, valid records, mean speed and vehicle specific power for each site

Table 6: Number of records, valid records, unique vehicles, mean speed and mean VSP per measurement site

Measurement site	No. of records	No. valid records[a]	No. unique vehicles	Mean Speed[b] (Km/h)	Mean VSP[b] (kW/t)
1	10604	6756	5723	23.9 ± 7.4	5.5 ± 4.2
2	2041	1337	1026	28.0 ± 7.1	5.8 ± 4.0
3	9230	6697	2868	25.2 ± 7.2	3.5 ± 2.8
4	5638	1433	396	38 ± 11	7.6 ± 5.7
5[c]	9825	3385	1667	31 ± 11	6.3 ± 4.3
Total/Average	37338	19608	11680	26.1	5.2

[a] Refers to records with valid emission measurements, valid speed/acceleration measurements, legible license plate and positive VSP. [b] Deviation expressed as standard errors from the mean. [c] Various sites. Individually, these did not constitute optimum RSD sites, but altogether they served for obtaining further data.

Overall, 19,608 valid records were registered throughout the measurement campaign, which corresponded to 11,685 unique vehicles. On average, vehicles were driven at a mean speed of 26 km/h, with VSP value of approximately 5 kW/t.

Additionally, the measurement study was further complemented with an awareness campaign, consisting on showing the drivers the level of emissions of their vehicles in real time. For this purpose, a “smart sign” was deployed at measurement sites for 2 weeks (Figure 2).

Figure 2: Smart Sign installed in the city of Graz for awareness purposes

B. Preliminary data analysis

Up to now, vehicle technical information for analysis and processing of data has not been provided by the city of Graz, and hence a proper, thorough analysis of the records cannot be executed.

However, average emission factors in grams of pollutant per kg of fuel burned for the fleet, together with those recorded by similar campaigns in other European Cities (Chen, Y. et al., 2014; Technet, 2008-2011) are presented in Table 7.

Table 7: Average emission values for different European fleets [a]

Fleet	gCO/kg	gHC/kg	gNO/kg[b]	gNO_x/kg[c]	gPM/kg
Graz	15.8 ± 1.1	3.2 ± 0.2	5.0 ± 0.1	7.7 ± 0.2	0.46 ± 0.02
Zurich	15.1 ± 0.1	0.71 ± 0.01	----	6.02 ± 0.02	----
Madrid	20.9 ± 0.9	4.8 ± 0.2	7.4 ± 0.1	11.2 ± 0.1	1.18 ± 0.02
Barcelona	18.4 ± 0.7	6.5 ± 0.2	8.2 ± 0.1	12.4 ± 0.1	1.19 ± 0.02

[a]*Errors expressed as 95% confidence intervals calculated from standard deviations of the means.* [b] *Grams of NO.*
[c]*Grams of NO_2 (conversion of the measured gNO/kg into gNO_2/kg of fuel equivalents).*

By comparison of average emission values from Table 6, it can be clearly deduced that the environmental state of the Graz fleet is comparable to that in Zurich (except for HC values), but cleaner than the ones in Madrid or Barcelona. This is probably closely related to the higher environmental-awareness of administrations and population both in Austria and Switzerland as compared to Spain.

Similarly to what was observed for the bus fleet, the fleet in Graz emits very low levels of PM, which again is surprising considering the on-going problems that the city has had for surpassing legal limits (EEA, 2013-2; Spangl et al., 2013). This seems to point to a smaller contribution from traffic than what is commonly believed among experts and institutions (Trimbacher et al., 2002; Heiden et al., 2008).

If we now look at the emission distribution of the fleet for various pollutants, our data indicate that the 5% most emitting vehicles are responsible for up to 61% of the global emissions of the fleet. Hence, potentially, if these vehicles were identified and sent for repairs, considerable emission reductions for the global fleet could be achieved.

Table 8: Cut-points and emission share of the 5% most emitting vehicles

Cut-points (g pollutant/kg fuel)				Emission Contribution (%)			
CO	HC	NO_x[a]	PM	CO	HC	NO_x[a]	PM
82.6	14.9	29.0	2.56	61%	42%	24%	37%

[a]Grams of NO_2 (conversion of the measured gNO/kg into gNO_2/kg of fuel equivalents)

D. Conclusions

In summary, the present study shows the unique opportunities that RSD technology offers, not only in terms of providing massive amounts of real-emission data in a short period of time, but also for identifying high emitters among the fleet and achieving subsequent reductions of the overall emissions.

Our data have shown that the circulating fleet in the city of Graz behaves similarly to other European fleets for most gaseous pollutants, but exhibits considerably lower levels of PM. This is especially important, since it points to a lesser contribution of road transport to the ongoing problems of the city in terms of complying with PM legal limits.

The measurement and identification campaign executed in the bus fleet has proven the potential of the technology for reducing overall emissions from the fleet through identification and repair of a small share of vehicles.

Further analysis of the obtained data is currently underway, and will be complemented once technical data for measured vehicles is provided.

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