# **1** Black carbon, particle number concentration and nitrogen

2 oxide emission factors of random in-use vehicles

# 3 measured with the on-road chasing method

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#### 13 Abstract

14 The chasing method was used in an on-road measurement campaign, and emission factors 15 (EF) of black carbon (BC), particle number (PN) and nitrogen oxides (NO<sub>x</sub>) were determined 16 for 139 individual vehicles of different types encountered on the roads. The aggregated results provide EFs for BC, NO<sub>x</sub> and PN for three vehicle categories: goods vehicles, gasoline and 17 18 diesel passenger cars. This is the first on-road measurement study where BC EFs of numerous 19 individual diesel cars were determined in real-world driving conditions. We found good 20 agreement between EFs of goods vehicles determined in this campaign and the results of 21 previous studies that used either chasing or remote sensing measurement techniques. The 22 composition of the sampled car fleet determined from the national vehicle registry 23 information is reflective of Eurostat statistical data on the Slovenian and European vehicle 24 fleet. The median BC EF of diesel and gasoline cars that were in use for less than 5 years, 25 decreased by 60% and 47% from those in use for 5 - 10 years, respectively, the median NO<sub>x</sub> 26 and PN EFs, of goods vehicles that were in use for less than five years, decreased from those 27 in use for 5 - 10 years by 52% and 67%, respectively. Surprisingly, we found and increase of BC EFs in newer goods vehicle fleet compared to 5 - 10 year old one. The influence of 28

1 engine maximum power of the measured EFs showed an increase in NO<sub>x</sub> EF from least to more powerful vehicles with diesel engines. Finally a disproportionate contribution of high 2 3 emitters to the total emissions of the measured fleet was found; the top 25% of emitting diesel 4 cars contributed 63%, 47% and 61% of BC, NO<sub>x</sub> and PN emissions respectively. With the 5 combination of relatively simple on-road measurements with sophisticated post processing 6 individual vehicles EF can be determined and useful information about the fleet emissions can 7 be obtained by exactly representing vehicles which contribute disproportionally to vehicle 8 fleet emissions; and monitor how the numerous emission reduction approaches are reflected 9 in on-road driving conditions.

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## 11 **1 Introduction**

Traffic is a diverse and important source of air pollution and is complex to describe in terms 12 of per vehicle emissions. The amount of emitted pollutants depends on individual vehicle 13 parameters, the engine type and displacement, the type of exhaust after-treatment system, fuel 14 quality, maintenance status, traffic situations, topography, driver behavior and weather 15 conditions. Owing to the large number of variables, different statistical analyses and 16 17 measurement approaches have been employed in order to evaluate traffic emissions. These 18 vary in complexity in terms of describing traffic activity and emission factor (EF) determination. Franco et al. 2013, define EFs as different empirical functional relations of 19 emitted pollutants to the activity that causes them. Most standardized and robust EFs were 20 21 found to be produced in laboratories using dynamometer tests with prescribed driving cycles. 22 These tests can produce: (a) aggregated or bag results with respect to the mean speed or some 23 other kinematic parameter (e.g. mean acceleration) of a driving cycle; or (b) instantaneous emission data, where the emissions values measured can be related to recorded instantaneous 24 25 kinematic or engine covariates (Perrone et al., 2014). But the nature and conditions of the tests limits both the number of vehicles tested and the application to many on-road or so-26 27 called "real-world" conditions. In order to validate the emission model predictions and to compare their performance to actual vehicle emissions, "real-world" EF measurement 28 29 techniques have been developed (Franco et al., 2013). These employ different techniques for 30 measuring numerous vehicles in use in actual traffic situations: the measurements were 31 performed through the use of remote sensing next to the roads, following vehicles on the 32 roads, the use of on-board diagnostics data, or from data taken in tunnels (some of the first

such experiments may be found in Bishop et al., 1996; Hansen and Rosen, 1990; Weingartner
 et al., 1997).

3 The various "real-world" methods have been described as being less precise than the 4 dynamometer studies because the tests are not as repeatable as their dynamometer counterparts owing to the absence of standard cycles and the presence of additional 5 6 uncontrolled parameters introducing variability, such as environmental or traffic conditions, 7 driver behavior or highly transient operations (Franco et al., 2013). The on-road 8 measurements have some inherent drawbacks. Two possible shortcomings are that the 9 remote-sensing method can provide only a snapshot of the vehicle emissions and not how the 10 emissions vary during the trip (Franco et al., 2013) and that the on-road chasing method cannot be used in a dense traffic situations, where emissions from other vehicles' would 11 disturb the background measurements (Ježek et al., 2015; Wang et al., 2011). Their advantage 12 13 over laboratory measurements is that, over a short period of time, a large number of in-use 14 vehicles can be measured and a representative emission factor distribution for different vehicle categories can be obtained. Most of the previous on-road BC emission factor 15 measurements for individual vehicles were performed on diesel fueled trucks and on cars with 16 17 the spark ignition engine, henceforth referred to as gasoline cars (Ban-Weiss et al., 2009; Dallmann et al., 2011, 2012, 2014; Hansen and Rosen, 1990; Wang et al., 2011, 2012). Many 18 of these studies revealed that a small percentage of vehicles – the so-called super emitters; 19 20 contribute disproportionately to total vehicle emissions. Ban-Weiss et al., 2009, demonstrated 21 that 10% of the trucks contributed 40% of the BC and PN emissions. Wang et al., 2011, 22 showed that, in their measured fleet, 20% of the trucks contributed 50% of the carbon 23 monoxide (CO) and  $PN_{0.5}$  emissions, 60% of the  $PM_{0.5}$  (the particle number concentration – PN; and particulate mass concentration (PM) subscripts denote here the largest mobility 24 diameter [µm] of aerosol particles measured, in this case aerosol particles of 0.5 µm and 25 smaller) and over 70% of black carbon (BC) emissions. Bishop and Stedman, 2008, report the 26 27 same trend for nitrogen oxides (NO<sub>x</sub>), CO and hydrocarbons (HC). The advantage of 28 individual vehicle measurements over average fleet emission factors, as is often expressed by 29 dynamometer or portable emission measurement system (PEMS) studies, is the ability to detect and express the distribution of emissions from many vehicles as well as to identify 30 31 "super emitters" and their contributions within the vehicle population, serving as a basis for the implementation of improved emission data, more efficient abatement strategies and 32 33 monitoring of progress on controls.

1 The chasing method allows us to capture a range of EF from a single vehicle and to measure 2 the EF distribution rather than just a single value as is recorded with the stationary method. 3 Depending on engine operation state, each vehicle produces a range of EF with most values 4 around a representative value (median) and a long super emission tail - the comparison of the 5 chasing method and the stationary method can be found in Ježek et al. (2015). With a single stationary measurement we can capture only a single value of the vehicle's EF distribution 6 7 and several repetitions of a vehicle would be necessary to obtain that vehicles EF distribution. 8 We believe that using a single vehicles EF distribution measured in real driving conditions 9 and using the collective distribution of the vehicle fleet to model traffic emissions could 10 improve model predictions. Knowing the EF representative value and the super emission tails 11 allows quantifying the effect of potential abatement measures, e.g. how changing a driving regime would influence emissions at a certain section of the city. Previous studies using the 12 13 chasing method for EF measurements in real driving conditions were performed on fleets of 14 buses, light duty vehicles (LGV) with gasoline engines and heavy-goods vehicles (HGV) with 15 diesel engines (Canagaratna et al., 2004; Herndon et al., 2005; Schneider et al., 2008; Shorter 16 et al., 2005; Wang et al., 2011, 2012). Shorter et al., 2005, discuss the effectiveness of the 17 NO<sub>x</sub> emission reduction in different engine and exhaust system technologies, which had been introduced to the New York bus fleet. They found that NO<sub>x</sub> emissions from diesel and 18 19 Compressed Natural Gas (CNG) buses were comparable and that diesel hybrid electric buses 20 had approximately one-half the NO<sub>x</sub> emissions. They also found that in the group of diesel 21 buses equipped with continuously regenerating technology (CRT), nitrogen dioxide (NO<sub>2</sub>) represented a third of emitted NO<sub>x</sub>, while in non-CRT buses emissions, the percentage of 22 23 NO<sub>2</sub> was less than 10%. Similar NO<sub>2</sub> to NO<sub>x</sub> ratios were found by Carslaw and Rhys-Tyler, 24 2013, who used a remote sensing technique to measure the emissions of almost 70000 25 vehicles in United Kingdom (UK), where 30% of NO<sub>x</sub> were emitted as NO<sub>2</sub> by Enhanced Environmentally friendly Vehicles (EEV). The EEV is a recommended standard in the 26 27 European Union for HGVs with lower PM emission values than a Euro VI vehicle but the 28 same NO<sub>x</sub> standard as a Euro V.

Wang et al., 2011, measured the EF of BC, CO and  $PM_{0.5}$  on a fleet of 230 trucks and 57 buses in China, and identified "heavy emitters" in the road fleet. They found that 5% of the trucks contributed 50% of the BC emissions, and 20% of the trucks contributed 50% of the CO and  $PM_{0.5}$  emissions. Furthermore they found that the EFs of trucks registered outside Beijing were significantly higher than those that were subject to the stricter engine and fuel

1 quality standards enforced in Beijing. Because numerous trucks registered outside Beijing 2 operate in the Beijing area, restricting Beijing-registered truck emissions is not sufficient to 3 reduce traffic related pollution in the city. Their bus fleet measurements showed that replacement of older buses with newer buses (Euro IV and CNG) compared to their 4 5 predecessors (Euro II and Euro I) were indeed an effective way to reduce the emissions of the measured pollutants. In their follow up study (Wang et al., 2012), they employed the same 6 7 method on a fleet of 440 on-road trucks, measuring the EF of NO<sub>x</sub> and BC. They found that 8 the measures taken in Beijing were effective for the BC emissions of trucks that were from 9 that area, but they did not observe such a trend for NO<sub>x</sub> emissions.

10 An extensive on-road measurement study was performed in the UK by Carslaw and Rhys-11 Tyler, 2013. They employed a remote sensing technique to measure the emissions of NO, NO<sub>2</sub> and NH<sub>3</sub> on a fleet of almost 70000 individual vehicles which included also vans, 12 13 passenger cars with a compression ignition engine (henceforth referred to as diesel cars), and 14 gasoline cars. Matching these to vehicle registration data, they found that only gasoline fueled vehicles had shown an appreciable reduction in NO<sub>x</sub> emissions over the past 15–20 years, 15 16 whereas diesel fueled vehicles have not. They found that there was an influence of vehicle manufacturer for Euro 4/5 vehicles and that Euro 4/5 diesel vehicles with smaller 17 displacements emit less NO than those with larger displacements. According to the European 18 19 Automobile Manufacturers' Association (ACEA) the motorization in Europe is increasing for passenger cars and the commercial vehicle fleet - by about 50% in two decades (1990-20 2010). Fleet trends show that the percentage of diesel cars is also rising from about 30% in 21 22 2000 to about 60% in 2011, and that most popular passenger cars by segment are small and 23 lower medium cars which respectively represent 34.2% and 22.1% of all new cars sold in 24 Europe in 2011 (ACEA, 2012). A slightly smaller percentage of diesel cars (55%) was reported by the European Environment Agency (EEA, 2013a) who, in their report titled 25 "Monitoring CO<sub>2</sub> emissions from new passenger cars in the EU". They state that the average 26 car weight was at its highest in the last nine years, the average engine capacity had decreased 27 28 by 5% since 2007, and, despite of these changes, the improved vehicle technology has led to 29 greater fuel efficiency and lower average CO<sub>2</sub> emissions per kilometer travelled (EEA, 30 2013b). This report was based on data provided by the manufactures who were obliged to 31 measure CO<sub>2</sub> emissions using the type approved test cycle (NEDC) in laboratory conditions. 32 The statement was refuted by International Council on Clean Transportation in their 2013 33 white paper (Mock et al., 2013); in which they compared official and 'real-world' fuel

1 consumption and CO<sub>2</sub> values for cars in Europe and the United States. The report contained 2 and assessment of the results of several on-road driving datasets from various European 3 countries, where they found underestimation by type-approved measurements relative to on-4 road CO<sub>2</sub> emissions. Namely, in 2001, the discrepancy between the two had been below 10% and increased to around 25% by 2011, with 'real-world' emissions being higher than 5 emissions according to type-approval. The same report also clarifies that their analysis does 6 7 not suggest that manufacturers have done anything illegal. Instead it is suggested that the 8 NEDC was not appropriate to use for indicating fuel consumption as it was originally not 9 designed to measure this, nor was it designed to measure CO<sub>2</sub> emissions. Some features of the 10 test procedure can be exploited to influence test results, resulting in unrealistically low CO<sub>2</sub> 11 emission levels. These issues are being addressed by the United Nations through the development of a new vehicle test procedure, among other things (Mock et al., 2013). Based 12 13 on the limited availability of the data that were used in previous studies, we postulate that using on-road emission factors from a representative vehicle fleet could contribute 14 significantly to models' emission predictions. EF determination of a representative on-road 15 16 sample would include additional sources of variability which can be controlled in the 17 laboratory but not in real-world driving conditions.

BC, NO<sub>x</sub> and PN are emitted from internal combustion engines and negatively impact people's health. The three pollutants do not have the same formation process (Heywood, 1988; Kittelson et al., 2006). A more detailed description may be found in Supplementary material S1. It has been shown that increased BC concentrations are a better indicator of hazardous health effects of aerosol particle air pollution than the increase in the legislated particle mass concentrations (Janssen et al., 2012); and that it is after CO<sub>2</sub> the second most important contributor to global warming (Bond et al., 2013).

25 The research presented here is aimed to measure real-world BC EF of diesel cars, since there 26 was no previous research reporting BC EF of numerous diesel cars measured individually in real driving conditions. Gasoline cars and goods vehicles were included for comparison 27 purposes. We also measured vehicles' NOx and PN EFs due to their hazardous effects on 28 health and environment and for the comparison purposes to previous studies. We used the 29 30 chasing technique (Wang et al., 2011) and the running integration approach to calculate individual vehicles EF (Ježek et al., 2015), because it enables us to measure not only EFs of 31 32 numerous individual in-use vehicles, but also how their EFs change in time, giving us

individual vehicle's EF distribution. We analyze EF distribution within the vehicle category 1 2 by using the median EF value of individual vehicle's EF distribution and compare our results 3 to those of other chasing and remote sensing studies. We obtained registration information of 4 the chased vehicles to demonstrate the effects of vehicle age, vehicle maximum engine power, 5 the ratio of maximum power to vehicle size, and finally, the contribution of high emitters to 6 the total emissions of our measured fleet. We report the first on-road determination of BC, 7 NO<sub>x</sub> and PN EFs of passenger cars measured with the chasing method and the first BC EFs of 8 individual diesel cars measured in real driving conditions.

9

## 10 2 Methodology

11 We performed our measurements in December 2011 over the course of 7 days on Slovenian highways and regional roads, measuring predominantly the Slovenian vehicle fleet 12 13 (photographs from the measurement campaign are presented in Supplementary material Figure S1). Slovenia is a country positioned south of the Alps, next to the Adriatic and 14 opening to the Balkan and East European region. Slovenian highways are part of the V. 15 16 (Venice-Trieste/Koper-Ljubljana-Budapest-Kiev) X. and (Salzburg-Ljubljana-Zagreb-17 Belgrade-Thessaloniki) trans-European corridors and are thus an important connection 18 between central and east European states, especially for the transport of goods. As a result, 19 foreign vehicles were also encountered and measured in our campaign.

20 In EF analysis we included any vehicle which emissions and background concentrations we 21 could capture without interference of other on-road vehicles (vehicles that would drive in 22 front of the chased vehicle). The inclusion of the measurement in further analysis was 23 determined on-road and confirmed with video recordings of each chase. For most vehicles we measured the background concentrations before and after the chase, in few instances we used 24 25 only one - measured before or after the chase. On average each chase lasted for two minutes 26 and a half, with the shortest chase lasting for 47 s and the longest for 396 s. The travelling 27 speed was changing within each chasing episode but for most trucks it was between 80 and 90 28 km/h and for cars it was between 100 and 130 km/h. In the final analysis we excluded 10 cars 29 because we could not obtain registration information needed to categorize them as a diesel or 30 a gasoline car.

The mobile measurement platform used for the on-road chasing measurements is described in detail in Ježek et al., 2015. We used instruments with high time resolution (1 to 10 s) the

Carbocap GMP343 (Vaisala) to measure  $CO_2$ , the Aethalometer AE33 prototype version  $\beta$ 1 2 (Aerosol d.o.o.), the Fast Mobility Particle Sizer (TSI), for the on-road campaign we added 3 also a Nitric Oxide Monitor and an NO<sub>2</sub> converter (models 410 and 401, 2B Technologies). 4 For the Nitric Oxide Monitor the sampling line was a Teflon tube, while for the rest we used static-dissipative tubing. The instrumental details and measurement uncertainties are 5 summarized in Table 1. The Aethalometer data was compensated for the loading effect using 6 7 the Drinovec et al. (2015) compensation algorithm. While the size distribution of the exhaust 8 particles change with the engine operation (Ježek et al. 2015; Sharma et al., 2005), a fact that 9 might have implication in the context of the health effects of exhaust particles, Rayleigh-Debye-Gans theory (Sorensen, 2001; an example of such calculation can be found in Kim et 10 11 al., 2015) predicts the mass absorption cross-section independent of the size distribution of 12 the fractal aggregates. This is consistent with the near-road observations by Ning et al. (2013).

## 13 **2.1 Emission factor calculation**

We calculated the emission factor as the pollutant (P) per kg of fuel consumed, assuming the equal dilution of all emitted pollutants and complete combustion of the fuel, where almost all the carbon in the fuel is oxidized to CO<sub>2</sub> (Ban-Weiss et al., 2009; Dallmann et al., 2011; Hansen and Rosen, 1990), the fuel consumption can be estimated by measuring the CO<sub>2</sub> emissions.

$$EF_{P} = \frac{\int_{tj}^{ti} (P_{tj} - P_{ti}) dt}{a \cdot \int_{tj}^{ti} (CO_{2 tj} - CO_{2 ti}) dt} \cdot w_{c}$$
(1)

19 The coefficient *a* in denominator represents the mass ratio between C and CO<sub>2</sub>: a = 12:44 =0.2727; thus converting the mass concentration of  $CO_2$  in Eq. (1) to units of mass 20 concentration of C (mg C per m<sup>-3</sup>). The carbon fraction in fuel w<sub>c</sub> for both gasoline and diesel 21 22 was set to 0.86 (Huss et al., 2013). The subscripts *ti* and *tj* denote the time of the beginning and end of integration step, respectively. NO<sub>x</sub> was treated as NO<sub>2</sub> equivalent with molar mass 23 46 g mol<sup>-1</sup> (USEPA, 2010; Wang et al., 2012). We used the running integration approach with 24 the 10 s integration step, to obtain individual vehicle's time dependent EF, and thus its EF 25 distribution. From the distribution we calculated the median value and used it as the 26 27 representative EF value for the investigated vehicle.

1 The running integration approach is described in more detail in Ježek et al., 2015, where the 2 chasing method has been tested on contemporary cars in controlled conditions. The results of the two integration approaches - the bulk integration from the beginning and to the end of the 3 4 chase (Wang et al., 2011) and running integration, have already been compared in Ježek et al., 5 2015. Here we again perform the comparison on a larger number of measured vehicles. The regressions between the two methods for all three investigated pollutants (BC, NO<sub>x</sub> and PN) 6 7 are presented in Figure 1. For all three pollutants the Pearson's r' coefficient was at least 0.97, 8 all three intercepts were close to zero. The bulk integration method gives somewhat larger 9 EFs than the running integration for BC and PN, while the slope is very close to unity for NO<sub>x</sub>. Whilst BC and PN bulk integration overestimated the median EF by 9% and 14% 10 11 respectively, the bulk integration for NO<sub>x</sub> EF underestimated the median EFs by 2%. The 12 slight underestimation of bulk NO<sub>x</sub> EFs was probably because the instrument for NO<sub>x</sub> 13 measurements had lower time resolution (10 s) than other instruments (1 or 2 s), thus super 14 emission peaks were not as clearly resolved as they were for BC and PN.

The uncertainty of the median value, which we here use as the representative EF value for a 15 16 single vehicle, was estimated to be -24/+26 % (Ježek et al., 2015). This uncertainty is reduced when calculating the fleet EF distribution. The uncertainty of the single measurement depends 17 18 on the measured CO<sub>2</sub> and its signal to noise ratio (Ježek et al., 2015). We constrain the 19 calculation of the time evolving EF when CO<sub>2</sub> values are low by using a 10 s integrating time interval instead of shorter intervals. This smooths out the high engine emission peaks, which 20 are already smoothed out by travelling through the exhaust system and the atmosphere to the 21 measurement instruments (Ajtay et al., 2005), and constrains the calculation error, yet keeping 22 23 the calculated median value unchanged. The dilution does not affect the measurements of the 24 single vehicle EF as long as the CO<sub>2</sub> increase is above the limit reported in Ježek et al. (2015). 25 We show this in a comparison between a PEMS measurement and a chasing determination of EF (Figure S2, data from Ježek et al., 2015). The impact of limited number of vehicles was 26 investigated by Ban-Weiss et al. (2009), where they show that sampling  $\geq$  30 trucks should be 27 28 a large enough sample.

29

## **2.2 Vehicle classification and fleet description**

2 We collected license plate numbers and gained more information on the measured vehicles 3 from their registration certificates. The data provided by the Slovenian Ministry of 4 Infrastructure and Spatial Planning; contained information about each vehicle category 5 according to the Directive 2001/116/EC (2002), the fuel used, the date the vehicle first 6 entered into service, curb weight, engine displacement and the maximum net power, where 7 the maximum net power is defined as the maximum value of the net power measured at full 8 engine load (UNECE Regulation No 85, 2013) and the curb weight is the weight of the 9 vehicle without the driver or any other additional load (Regulation No. 540/2014 of the 10 European parliament, 2014).

11 For 2011 (the year our measurement study was conducted) we used the Eurostat vehicle fleet 12 statistics (for Europe and Slovenia); Slovenian National Interoperability (NIO) portal 13 (http://nio.gov.si/), where we gained detailed information on Slovenian car fleet; and 14 compared them to our measured fleet. The Eurostat statistics for cars in Europe include countries that reported not only the total number of cars but also the information on which 15 16 fuel they used and their respective engine displacements (the countries included are listed in the Supplementary material S2). Of the 207185950 passenger cars in-use, 61% used gasoline 17 18 fuels and 34% used diesel.

19 Our vehicle classification to categories was based on that of vehicle registration information, 20 according to the Commission Directive 2001/116/EC (European Communities, 2002). In 21 Europe vehicles with more than four wheels are organized according their purpose to 22 categories M, N and O, on the first level. Category M includes vehicles for the transport of 23 passengers, category N comprises commercial vehicles for the transport of goods, and 24 category O includes trailers (and semi-trailers). Further categorization of category M pertains 25 to the number of passenger seats and the vehicle's maximum allowed weight, whereas the N and O categories are further segmented regarding to the vehicle's maximum allowed weight. 26 27 This classification, with further sub categories, is then, among other things, also used for 28 prescribing emission standards to new vehicles. Passenger cars (category M1) and light 29 commercial vehicles weighing less than 1305 kg (category N1-I) have the same emission 30 standards, even though the corresponding Euro 1 and Euro 2 standards came into force in 31 different years. Light commercial vehicles have two more categories of Emission standards: 32 N1-II (1305 – 1760 kg); and N1-III (> 1760) together with N2 (light commercial vehicles 33 with a maximum mass exceeding 3500 kg but below 12000 kg). Depending on the vehicle's 34 use, the same vehicle can be registered as an M1 or N1. Similar categorization is used in the Eurostat data. There are also many other classifications of vehicles, that depend mostly on the
 purpose of their use.

We set up three main categories: diesel cars, gasoline cars and goods vehicles. In the gasoline cars category we included only M1 vehicles with spark ignition engines; in diesel cars category we included M1 cars with compression ignition engine and light goods vehicles categorized as N1; other vehicles categorized as N2, N3, M2 or M3 were all in the goods vehicle category. The categorization is summarized in Table 2, where it is also indicated how it overlaps with the classification in Directive 2001/116/EC.

9 For some heavy goods vehicles, buses and light goods vehicles, we were unable to obtain the 10 vehicle verification data (foreign vehicles and vehicles for which we were unable to note their 11 license plates). These vehicles were only included in the results when more detailed 12 information (age, engine displacement or power) about the vehicle was not needed and the 13 vehicle's category could be determined solely from their visual appearance. Thus, we kept the 14 heavy goods vehicles and vans for which we did not have registration information but could 15 categorize them as N1, N2 or N3, based on their appearance.

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#### 17 **3** Emission factor measurement results

Our total vehicle fleet sample was 139 vehicles; it consisted of 75 passenger cars (M1) of which 51 were diesel and 24 gasoline cars; 6 buses (M3); 1 mini bus (M2); 26 light goods vehicles, of which 17 were category N1 and 8 were category N2; and 32 heavy goods vehicles (N3). We were unable to obtain the registry data for 2 buses, 4 of the light goods vehicles (2 categorized as N1 and 2 as N2), and 15 of the heavy goods vehicles (N3). The fleet sample is summarized in Table 2.

24 We compared our measured fleet composition on the vehicles' age and size with the 25 information on the Slovenian and European vehicle fleet statistics (section 3.1). We present 26 our results as BC, PN and NO<sub>x</sub> EF distributions for the vehicle categories and compare them 27 to results of other similar studies in section 3.2. We further demonstrate how the EFs of each 28 group depend on their age, by grouping them according to years when EURO3 and EURO 4 29 standards became effective. Even though the purpose of use is indeed important when 30 classifying vehicles; but with such categorization the mechanical features may be overlooked. 31 A single car (for example Renault Kangoo or similar) can be classified as a personal vehicle

or a light goods vehicle. To see how mechanical and physical features of the vehicles affect the emissions, we disregarded the purpose based categorizations and observed the effect of engine maximum net power, and the ratio between engine maximum net power and vehicle mass in section 3.4. In section 3.5 we present the contribution of high emitters to the sampled fleet cumulative emissions.

## 6 3.1 Comparison of sampled vehicle fleet and Eurostat data

7 The fleet sample size determines the representativeness of the measured fleet. According to 8 Ban-Weis et al. (2009), about  $\geq$  30 trucks should be a large enough sample (presuming that 9 the sampling was indeed random) for the sample mean to equally likely to fall below or above 10 the sample mean. Our category samples were larger than the above threshold for diesel cars and goods vehicles, and very close to the threshold for gasoline cars. This makes us confident 11 12 that the sample is large enough to be representative of the on-road fleet during the approximate period of the campaign on East-West and North-South trans-European corridors 13 14 V and X. In order to establish the relationship of our data as representative of the Slovenian 15 and the average European fleet, we used Eurostat data to compare the size and age 16 composition of the three investigated vehicle fleets.

In section 3.1.1 we show a comparison between the European, Slovenian and the campaign passenger car fleets (only M1 vehicles) according to the fuel used, engine displacement and age, and in section 3.1.2 the composition of goods vehicle fleets (N1, N2 and N3) according to their size and age.

#### 21 3.1.1 Passenger cars

22 From Table 3 we can see that the combination of cars in the European and Slovenian fleets 23 are very similar. The percentage of diesel and gasoline cars in the European fleet is 34% and 24 61%, while the Slovenian fleet has 36% and 63% of diesel and gasoline cars, respectively. The engine displacements of diesel or gasoline engines are similar. Both fleets show that most 25 gasoline cars have engine displacements smaller than 1400 cm<sup>3</sup> (49% and 61% for European 26 27 and Slovenian fleet respectively) and that only a small portion of gasoline cars have an engine 28 displacement larger than 2000 cm<sup>3</sup> (7% and 3% for the European and Slovenian fleets, respectively). Most diesel powered cars have an engine displacement in the size range of 1400 29

to 2000 cm<sup>3</sup> (76% and 79% respectively); the fewest have an engine displacement smaller
than 1400 cm<sup>3</sup> (5% and 4% respectively).

3 The gasoline and diesel car engine displacement segregation of the campaign fleet is 4 representative of the European and Slovenian fleets, where, again most gasoline cars (50%) had engine displacements smaller than 1400 cm<sup>3</sup>, followed by 42% of cars with engine 5 displacements in the range of 1400 to 1999 cm<sup>3</sup> and the fewest gasoline cars had engine 6 displacements larger than 2000 cm<sup>3</sup> (8%). For diesel cars, the share was - as in the European 7 and Slovenian fleets - largest for 1400 to 1999 cm<sup>3</sup> sized engines (75%), followed by 25% of 8 diesel cars with engine displacements larger than 2000 cm<sup>3</sup>. We did not encounter any diesel 9 cars with engine displacements smaller than 1400 cm<sup>3</sup>. 10

European and Slovenian car fleet statistics also compare well if segregated by the age of the passenger cars. From Table 4 we can see that the two have almost the same percentage in all four age groups set by Eurostat; the largest difference between them is only 6%. Most passenger cars in both fleets were in use for 10 years or more (42% and 39% for the European and Slovenian fleets respectively), followed by the group of cars that was in use for between 5 and 10 years (28% and 34% respectively), almost 20% were in use for between 2 and 5 years and about 10% were in use for less than 2 years.

18 Our total measured passenger car fleet consisted of somewhat more cars in the ages of 2 to 10 19 years, and fewer vehicles that were over 10 years than were in the Slovenian and European fleets. Using the NIO database we separated Slovenian diesel and gasoline car fleet using 10, 20 21 5 and 2 years in use as delimiters. In Table 4 we can see that we get almost the same percentages in all bins for both diesel and gasoline cars in our measured fleet and the 22 23 Slovenian car fleet. But because, unlike in European or Slovenian fleet, there were more diesel than gasoline cars in our fleet, and because half of gasoline cars were older than 10 24 25 years and only 18% of diesel cars were in that age group, the age of our total fleet does not 26 match the Slovenian or European total car fleet age distribution.

During our measurements, our prime focus were diesel cars, because they are commonly found in Slovenia and Europe and are the most problematic with regard to emissions of BC and NO<sub>x</sub>. We used gasoline cars for the control and heavy goods vehicles for comparison to previous studies that used similar techniques. There are therefore a greater percentage of cars powered by diesel (68%) than gasoline (32%) in the fleet of this study than there are in Europe or Slovenia in general and therefore the age of our total passenger car fleet does not 1 match the total Slovenian nor European passenger car age groups. By analyzing the age 2 distribution within diesel and gasoline cars separately we have shown that our two 3 subcategories do indeed match the Slovenian fleet from which we sampled from and are thus 4 representative for the Slovenian vehicle fleet, and most likely also for the European car fleet, 5 as the two are very similar.

#### 6 **3.1.2 Goods vehicles**

The goods vehicles are much more versatile in their purpose and hence the mass they have to carry and power they have to produce. We were able to get the registration information for many of the sampled vehicles (28 out of 47) to identify the technical differences between the vehicles. Below, we show the representativeness of the Slovenian fleet for Europe. Our sample seems big enough to be representative, given the previously published criteria (Ban-Weis et al., 2009).

13 Eurostat does not report the number of heavy goods vehicles as N1, N2 and N3, rather it reports the number of lorries (defined as: rigid road motor vehicle designed, exclusively or 14 15 primarily, to carry goods) by their load capacity (defined as: maximum weight of goods declared permissible by the competent authority of the country of registration of the vehicle). 16 17 The data thus includes vehicles with a gross weight of not more than 3500 kg but excludes tow trucks. From Table 5 we can see that lorries with load capacity less than 1500 kg are most 18 19 numerous in both Slovenian and European fleet and that the vehicles with load capacity over 10000 kg are fewest. With Table 5 and 20

21 Table 6 (where we report Eurostat data for the European and Slovenian fleet), we demonstrate 22 that the Slovenian vehicle fleet from which we sampled the most vehicles from is representative of European average both regarding the size segregation and vehicle age. We 23 24 could not make an indirect comparison of Eurostat data to our sample fleet because we did not 25 get the load capacity reported for most of our measured vehicles, and because the number of 26 license plates we could collect was low. Nonetheless, we used the NIO database and found that in the Slovenian fleet there were 72% of N3 goods vehicles weighing less than 12000 kg 27 that were not road tractors or special purpose vehicles, while in our fleet there were 57% of 28 29 such vehicles. We binned the vehicles according to their age: those that were in use for less than 10 years, 5 to 10, and less than 5 years. The Slovenian fleet consisted of 38%, 38% and 30 31 24% vehicles in each categories, respectively, while the measured vehicles consisted of 21%,

50% and 29% respectively. Here the size of the sample was only 14 vehicles for which we
had registry information. The discrepancy is larger because of the larger diversity in vehicle
size among the goods vehicles than for personal cars, and because our sample size is small.

## 4 3.2 Emission factors distributions and comparison to other studies

5 We determined EFs of different type vehicles, grouped them into three categories: gasoline cars, diesel cars and goods vehicles (as described in section 2.2.), and present their BC, NO<sub>x</sub> 6 and PN EF distributions in Figure 2. Because the formation paths for the three pollutants 7 8 differ (see section Supplementary material S1) and technological solutions for the three 9 vehicle categories differ, also their EF distributions show different tendencies. The median BC EF for diesel cars  $(0.79 \text{ g kg}^{-1})$  is the highest of the three vehicle groups, followed by 10 goods vehicles (median 0.47 g kg<sup>-1</sup>), and gasoline cars (0.28 g kg<sup>-1</sup>), where also the lowest BC 11 EFs are to be found. The median of  $NO_x$  EF distribution is highest for goods vehicles (27.71 g 12 kg<sup>-1</sup>), followed by diesel cars (15.43 g kg<sup>-1</sup>), and again lowest for gasoline cars (6.34 g kg<sup>-1</sup>). 13 We can observe similar trend with PN EF distribution - highest median value for goods 14 vehicles (11.49  $10^{15}$  kg<sup>-1</sup>), followed by diesel cars (4.4  $10^{15}$  kg<sup>-1</sup>), and gasoline cars (1.95  $10^{15}$ 15 kg<sup>-1</sup>). The shapes of the PN distributions are different from the shapes of the NO<sub>x</sub> EF 16 17 distributions. NO<sub>x</sub> EF distributions have the narrowest range of the three investigated 18 pollutants for all three vehicle groups, while PN EF distributions are broad and in the case of goods vehicles even bimodal. They would remain bimodal even if buses and light goods 19 20 vehicles (N2) would be excluded from the analysis.

21 In Table 7 we compare the results of our study to other chasing and remote sensing studies 22 that measured the same species (Ban-Weiss et al., 2009; Carslaw and Rhys-Tyler, 2013; 23 Dallmann et al., 2011; Hudda et al., 2013; Schneider et al., 2008; Shorter et al., 2005; Wang et al., 2011, 2012). Remote sensing studies were included because good agreement between 24 25 the results of the remote sensing and chasing techniques was found by Ježek et al., 2015, where it has been shown that with multiple measurements of the same vehicle with the 26 27 stationary method, we can obtain a similar distribution as when measuring the same vehicle with the chasing method, and that the median value, of both techniques, is similar. We did not 28 29 compare our results to other study types such as tunnel measurements, chassis dynamometer 30 tests or measurements with portable emission measurement systems, as they have already 31 been discussed in other studies (e.g. Shorter et al., 2005; Wang et al., 2012).

The BC EF median of goods vehicles we measured  $(0.47 \text{ g kg}^{-1})$  is similar to the mean value 1 2 of HGV fleet reported by Dallmann et al. in their 2011 study after additional emission control was implemented (0.49 g kg<sup>-1</sup>); compares well to the results of Wang et al., 2012, for HGVs 3 from the Beijing area  $(0.40 \text{ g kg}^{-1})$ , where there are also more strict emission control standards 4 5 implemented as compared to surrounding provinces; and to the results of Hudda et al. 2013, who report 0.41 g kg<sup>-1</sup> BC EF for high cargo route in California (I-710). While BC EFs of 6 7 these studies (including ours) agree, NO<sub>x</sub> EFs do not. While NO<sub>x</sub> EFs were high in the 8 Chinese study (47.3 and 40 g kg<sup>-1</sup> for Beijing and Chongqing respectively), they were much lower in the two US studies (~ 15 g kg<sup>-1</sup>). The lower EF for the US studies may be due to a 9 10 different mix of vehicles due to promotion of the purchase of newer vehicles. The median value of the NO<sub>x</sub> EF distribution (27.7 g kg<sup>-1</sup>) observed for goods vehicles lies closer to the 11 average HDV fleet value reported by Dallmann et al., 2011, before the active replacement rule 12 13 was implemented (25.9 g kg<sup>-1</sup>), and to the results of another US study (Shorter et al., 2005) where they report NO<sub>x</sub> EF for buses equipped with CRT (27.8 g kg<sup>-1</sup>). The two European 14 15 studies (Carslaw and Rhys-Tyler, 2013; Schneider et al., 2008) report similar NO<sub>x</sub> EF for different vehicle types - while Schneider et al., 2008, measured 18 trucks in Germany by 16 17 chasing them on the road, and report NO<sub>x</sub> EF of their measured fleet to be 18 g kg<sup>-1</sup>. Carslaw and Rhys-Tyler, 2013, report similar values 18.9 g kg<sup>-1</sup> for vans (N1), but much higher for 18 goods vehicles (average of HGV: 37.88 g kg<sup>-1</sup>). The reason only BC or NO<sub>x</sub> EF between our 19 20 measured fleet and other studies match may be related to the different age of the investigated 21 vehicle fleets. We will address this again in section 3.3, where we investigate the dependency of the determined EFs to vehicle age in their respective category. 22

The NO<sub>x</sub> EF values of the gasoline and diesel cars in this campaign (6.3 and 15.4 g kg<sup>-1</sup> 23 24 respectively) coincide with those reported by Carslaw and Rhys-Tyler 2013 (5.6 and 17.1 g kg<sup>-1</sup> respectively). The median NO<sub>x</sub> EF of gasoline cars in this campaign is slightly lower than 25 that reported by the EEA (8.7 g kg<sup>-1</sup>) in Tier I approach of their guide book (EEA, 2013c); 26 while those of diesel cars and LDV in this campaign are slightly higher than the NO<sub>x</sub> EFs in 27 the aforementioned guide book (13.0 g kg<sup>-1</sup>). The goods vehicles NO<sub>x</sub> EFs (27.7 g kg<sup>-1</sup>) from 28 29 this campaign agree with those reported by Shorter et al., 2005, for CRT (CRT stands for continuous regenerating technology) equipped buses (27.8 g kg<sup>-1</sup>); and to HGV NO<sub>x</sub> EFs 30 (25.9 g kg<sup>-1</sup>) reported by Dallmann et al., 2011, for HGV emissions before vehicles had to be 31 32 retrofitted with additional exhaust after-treatment devices. The NO<sub>x</sub> EFs of goods vehicles 33 measured in the present campaign are lower than HGV NO<sub>x</sub> EFs reported by Wang et al.,

2012, (40.0 g kg<sup>-1</sup> and 47.3 g kg<sup>-1</sup>), who used the same measurement method; lower than 1 Carslaw and Rhys-Tyler, 2013, (39.8g kg<sup>-1</sup>) who used a stationary remote sensing method; 2 and lower than HGV EF reported by EEA (33.4 g kg<sup>-1</sup>). This may indicate either that our 3 4 goods vehicles sample emitted less per unit of fuel; or that the measurement techniques used, 5 produce different results. We have shown in Figure 1 how using two different integration approaches yields in up to 16% different results. Some differences between the studies may 6 7 arise from using the average value for representation of the vehicle categories EF instead of 8 the median, which is not as strongly influenced by super emitters as the average.

9 The weight a truck engine has to pull can change drastically from an unloaded truck to twice 10 or three times its unloaded mass, therefore we would expect its emissions would also change a 11 lot more than we would expect them to change with a passenger car. This is one more variable 12 that would be difficult to monitor under controlled condition protocols.

HGV PN EF from Ban-Weiss et al., 2009, (4.7 10<sup>15</sup> kg<sup>-1</sup>) and from the study of Hudda et al., 13 2013, (4.2 and  $5.2 \cdot 10^{15} \text{ kg}^{-1}$ ) coincide with those of here presented diesel cars PN EFs 14 (4.4·10<sup>15</sup> kg<sup>-1</sup>); and Schneider et al., 2008, PN EF (8.3·10<sup>15</sup> kg<sup>-1</sup>) lie closer to our goods 15 vehicle PN EF median (11.49.10<sup>15</sup> kg<sup>-1</sup>). The PN EF is most difficult to determine and 16 compare because it depends on the measurement instrument and sampling conditions. Our 17 18 measurements were conducted while chasing vehicles on highways and regional roads in 19 winter, while others measured EF with remote sensing method at the end of a tunnel in 20 summer. Each study used different measurement instruments with different particle size 21 measurement range.

## 22 **3.3 Emission factors and vehicle age**

23 In this section we have further broken down each of our four vehicle groups to three age 24 subgroups: less than 5 years; 5 to 10 years; and 10 or more years in use. We wanted to 25 observe if newer vehicles showed an improvement in their emissions per unit of fuel burned. 26 The 5 and 10 year limits should roughly separate vehicles in three groups that comply with either the entry of Euro standards 4 or 5 (less than 5 year old vehicles), Euro standard 3 (5-27 10 year old vehicles), and Euro 2, 1 or pre-Euro vehicles (over 10 year old group). A clear 28 29 separation between vehicles compliant Euro standards cannot be made based solely on the 30 date the vehicle was put in use, because an improved vehicle may be put on the market before 31 the date when the new standard is enforced, or a vehicle that is compliant to the old standard 1 may still be put to use one year after the new standard enforcement date (2001/116/EC 2 European Communities, 2002). The vehicle age should reflect not only the deterioration of 3 the engine and exhaust system, but also the technological advances made in engines and 4 exhaust systems over the years due to stricter emission standards.

5 The results show some improvement for the three investigated pollutants (Figure 3 and S3). 6 For BC EFs the improvement is most evident for less than 5 year old diesel cars, where we can see a 60% drop in median values from 5-10 year old diesel cars to those with age less 7 8 than 5 years. This reduction most probably reflects the impacts of regulations to reduce the 9 PM vehicle emissions from Euro 3 to Euro 4 by 50%. The reduction was probably achieved with the increased use of diesel particle filters (DPF); which are commonly used in the post 10 Euro 5 cars. We can also observe a 55% decrease in median BC EF of gasoline cars from the 11 oldest (10 or older) to the newest group (5 years or less). These vehicles are less critical 12 regarding PM emission as diesel cars, whereas due to increased PM and especially PN 13 14 emissions of direct injection gasoline cars both are limited in recent Euro emission standards. 15 Our results show that compared to newest diesel cars category the gasoline cars have lower 16 BC EF medians in all three age groups. We can observe a 41% decrease in BC EF median from goods vehicles older than 10 years to the 5-10 year category. Worryingly, the newest 17 goods vehicles median BC EF increased by 34% in comparison to the 5-10 year old group. 18 Emission standards from Euro III to Euro IV for goods vehicles demanded PM emissions (in 19 g kW<sup>-1</sup>h<sup>-1</sup>) to reduce 5 fold. Unlike with passenger cars, the emission reduction of goods 20 vehicles was achieved with SCR not with (DPF), and thus the soot emissions were not limited 21 22 as efficiently.

In Figure 3 (and S3) we observed a 67% decrease in goods vehicles PN EFs (in  $10^{15}$  kg<sup>-1</sup>) from 5—10 year old vehicles to those that were in use for less than 5 years. This may indicate that either more agglomerated soot particles were being emitted or emissions of some of the particulate precursors had been reduced. Median PN EFs reduced by 67% from the oldest to the newest diesel car group. For gasoline cars the PN EFs varied the most within individual age group, where individual vehicles with high emissions skewed the distribution.

In Figure 3 (and S3) we can observe the gradual decrease of NO<sub>x</sub> EFs from gasoline cars to diesel cars to goods vehicles, as it is also shown in Figure 2, where also vehicles for which we did not get more detailed information were included. Goods vehicle NO<sub>x</sub> EFs are showing an appreciable decrease in average and median values from oldest to newest age group (50% and

1 70% respectively), which we postulate is due to increased use of SCR in newer post Euro V 2 vehicles, which can effectively reduce NO<sub>x</sub> emissions. When separated by age, we can see 3 that now both NO<sub>x</sub> and BC EF correlate better to some of the previously published studies 4 (Table 7). The 10 year or older goods vehicles (BC and NO<sub>x</sub> EF respectively 0.7 g kg<sup>-1</sup>, 43.95 g kg<sup>-1</sup>, please see Figure 3 and S3) relate better with Wang et al., 2012, Chongqing EFs; and 5 our less than 5 year old goods vehicles (median BC and NO<sub>x</sub> EF, respectively 0.55 g kg<sup>-1</sup>, 6 13.37 g kg<sup>-1</sup>) relate better with the most recent situation reported in the US for high cargo 7 8 route in California (I-710) by Hudda et al., 2013.

- 9 Diesel cars' maximum NO<sub>x</sub> EFs increased in the newest group but the median of the group decreased by 24% in comparison to 5-10 year old diesel cars. NOx emission standards for 10 11 diesel and gasoline cars were introduced with the Euro 3 standard. We could observe a reduction of gasoline car median NO<sub>x</sub> EF from those in use for over 10 years to those in use 12 13 for 5—10 years. At this time the use of the three way catalysts was common in the market and 14 according to our results efficient in reducing NO<sub>x</sub> emissions. The median did not reduce 15 further for diesel cars that were in use for less than 5 years but the average value did. The decrease of emissions is smaller than we would expect it to be according the newer European 16 17 emission standards. We postulate that this is because the emissions of Euro 5 diesel cars were achieved with DPF, not including de-NO<sub>x</sub> devices, in such instances driving that would be 18 more aggressive than NEDC would not reflect more stringent NO<sub>x</sub> Euro emission standards in 19 20 real-world driving. In the study of Carslaw and Rhys-Tyler, 2013, they found a satisfactory 21 reduction of average NO<sub>x</sub> EF only for gasoline cars but not for diesel cars.
- Carslaw and Rhys-Tyler found an influence of vehicle manufacturer on  $NO_x$  EFs for Euro 4/5; this could potentially explain the skewed  $NO_x$  EF distribution observed in our fleet, if some of the manufacturers would be disproportionally represented. However, Carslaw and Rhys-Tyler did not reveal the brands that produce lower EF values; and our sample size is too small compared to the number of manufacturers for us to consider debating such trends in our fleet.
- The reason the EF distributions are skewed and some an order of magnitude higher than the rest may be because, at the time of our measurements, these cars were somehow compromised, – e.g. not well maintained, or frequently operating in transient conditions that favored high pollutant emissions. On-road measurements of individual in-use vehicle fleet can provide useful information about the fleet emissions by exactly including such vehicles.

# 3.4 Emission factors according to maximum net engine power and 2 maximum net engine power to vehicle weight ratio

3 In addition to the information about the vehicle engine type, their category and the date of 4 first use, the registration database also provided information about the engine's maximum net 5 power and vehicle curb weight. We present in this section the EFs sorted according to the 6 engine maximum net power and the ratio of engine's maximum net power to vehicle's curb 7 weight. Here, we do not use the same vehicle groups as in the previous subchapter. Rather we 8 separated the vehicles to gasoline and diesel engines and then further according to different 9 size bins for both engine maximum net power and maximum net power to weight ratio. The 10 sizes of the bins were determined in a way that a single bin size would not include a 11 disproportionally large number of vehicles and that each bin would have enough vehicles for 12 a statistical presentation. There are also some gaps between the adjacent bins; this is because there were no vehicles in that range. The results are shown in Figure 4 and S4. 13

When EF are sorted by vehicle's engine maximum net power, we can see that diesel engines in the lowest maximum net power bin (less than 70 kW) feature highest median BC EFs and that the more powerful diesel engines feature lower BC EFs. The trend is reversed for  $NO_x$ EF, where more powerful larger vehicles feature higher  $NO_x$  EF. There is an exception for  $NO_x$  EF in the least powerful diesel group, which feature relatively high  $NO_x$  EF compared to the adjacent engine power bins.

20 The ratio of maximum engine power to vehicle curb weight can give a rough estimate of the 21 engine load under which the vehicle has to operate in normal driving conditions. Large trucks 22 have high vehicle mass but low maximum net power to vehicle mass ratio. Smaller vehicles 23 have smaller mass but higher maximum net power to vehicle mass ratios, and for the smallest vehicles the ratio again decreases. A vehicle with lower maximum net power to mass ratio 24 25 driven in similar driving conditions and with a similar driver behavior would have its engine 26 operating at higher loads leading to higher in-cylinder temperatures. Operation at higher in-27 cylinder temperatures would result in more thermic NO<sub>x</sub>. This trend in NO<sub>x</sub> can be observed in Figure 4 and S4 for both diesel and gasoline engines, where we can see that vehicles with 28 29 low power to mass ratio produce higher NO<sub>x</sub> EF and vehicles with high power to mass ratio 30 produce lower NO<sub>x</sub> EF. For BC and PN EF the trend is not as clear as it is for NO<sub>x</sub>, it could be 31 described as a gradual increase of EF from low to high power to mass ratios but in the highest power to mass ratio bin the median BC and PN EF drop. 32

We separated the gasoline vehicles into two groups for each observed parameter. The differences between gasoline vehicle categories are difficult to observe. We postulate this is because we were only operating with cars and the change in the vehicle mass and mass to power ratio was smaller than it was for the vehicles with diesel engines which included trucks.

## 6 3.5 Contribution of high emitters to the measured fleet

The contribution of high emitters to the measured vehicle fleet was calculated as cumulative 7 8 emissions. To exclude large differences in fuel consumption between trucks and cars, we 9 calculated high emitter contribution separately for goods vehicles, gasoline cars and diesel 10 cars. The cumulative emission distribution of our vehicle fleet were calculated for vehicles from highest to lowest emitters as it was previously done in similar studies (Ban-Weiss et al., 11 12 2009; Dallmann et al., 2012; Wang et al., 2011, 2012). The results in Figure 5 show that 25% of highest emitting vehicles in each vehicle category produce 50 to 65% of BC emissions, 47 13 to 55% of NO<sub>x</sub> emissions and 61 - 87% of PN emissions. The high contributions of super 14 emitters are the statistical cause of the non-symmetrical distributions and are responsible for 15 16 the mismatch between the median and the average EF values. Excluding high emitting vehicles or improving their emission rates by retrofitting them with additional after treatment 17 18 devices, such as was the case in Port of Oakland, US, (Dallmann et al., 2011) can decrease 19 traffic emissions.

20

#### 21 4 Conclusions

During the measurement campaign the BC, PN and NO<sub>x</sub> EFs for 139 different vehicles were 22 successfully determined. The sample fleet statistics was compared to Eurostat data for 23 24 Slovenia and Europe. An excellent agreement between the composition of the average 25 European and Slovenian car fleet, and the car sample fleet sampled in this campaign was 26 found. The main results of this research are the first reported on-road BC EF for diesel cars, and first BC, PN and NO<sub>x</sub> EF for passenger cars measured with the on-road chasing 27 28 technique. In order to compare the results of this study to previous ones, EFs of goods 29 vehicles were also determined. EF distributions for BC, PN and NO<sub>x</sub> were presented for three 30 vehicle groups: diesel cars, gasoline cars and goods vehicles. Differences between the EF 31 frequency distributions of the three vehicle categories for all three investigated pollutants were observed, the most important being the highest median BC EF value of diesel cars, and
 an increase in NO<sub>x</sub> EFs from the least powerful to more powerful diesel vehicles.

The results of this study were compared to the results of previous studies that used similar methods. The median BC EFs for the diesel cars (0.79 g kg<sup>-1</sup>) determined in this study is similar to the HGV EFs mean reported by Dallmann et al., 2011; and Wang et al., 2012, where vehicles were subject to less strict emission regulations. Goods vehicles BC EF median determined here resembles the EFs determined for vehicles subject to stricter emission standards. The goods vehicle median NO<sub>x</sub> EF reported in this study resembles those determined by Dallmann et al., 2011; and Shorter et al., 2005.

10 The median BC EF value of newer diesel and gasoline cars (less than 5 years) is lower than the value for the older car categories. For the goods vehicles it lies between the medians of the 11 12 two older goods vehicles groups. Contrary to BC EF, goods vehicles showed a significant 73% decrease in the NO<sub>x</sub> EF median values from vehicles that were in use for over 10 to 13 14 those in use for less than 5 years. We postulate this is because different after-treatment approaches were used for passenger cars and goods vehicles. PN EF median values decreased 15 16 for vehicles in use for less than 5 years in all three vehicle groups compared to older ones, but unfortunately the span of PN EFs of goods vehicles and gasoline cars increased. We attribute 17 18 the decreases to advances made in engine operation and exhaust after treatment devices.

19 The contribution of highly emitting vehicles was calculated and, as in previous studies (e.g. 20 Ban-Weiss et al., 2009; Wang et al., 2015, and Wang et al., 2012), a small number of vehicles 21 (25%) was found to disproportionately contribute to the total fleet emissions (47% to 87%). 22 The exclusion of high emitters by retrofitting old vehicles with after-treatment devices and 23 encouraging the sale of new vehicles through the exchange of older vehicles, has shown to be an effective measure to reduce vehicle emission rates (Dallmann et al., 2011) locally. 24 25 Unfortunately, the older vehicles might be sold in countries beyond the reach of the EU regulations, and would still have a negative impact on air quality and the climate elsewhere. 26

The methodology used in this study is a relatively simple and efficient approach for monitoring emissions of the in-use vehicle fleet, and investigating the effectiveness of emission reduction measures (also shown in Dallmann et al., 2011; and Wang et al., 2011). Real-world measurements are important because individual vehicle emissions depend not only on the vehicle type approval at the time it is put on the market, but are also on their maintenance and the driving conditions. 1

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- 28
- 29

- 1 Table 1. Measurement instruments, their time resolutions, sampling flows and measurement
- 2 uncertainties.

Instrumentation	Species measured	Time resolution	Instrument flow	Measurement uncertainty
Mobile platform (A)				
Carbocap GMP343 (Vaisala)	$CO_2$	2 s	7 l/min	3 ppm
Aethalometer AE33 (Aerosol d.o.o.)	BC	1 s	7 l/min	30 ng/m <sup>3</sup>
FMPS* (TSI)	PN	1 s	10 l/min	± 10 to 20%**
Nitric Oxide Monitor and an NO <sub>2</sub>	NO <sub>x</sub>	10 s	0.7 l/min	1.5 ppb
converter (models 410 and 401 of 2B				
Technologies)				

\* Particle size range 5.6 – 560 nm

\*\* The uncertainty of PN measurements is calculated for each particle size stage and varies within different stages. It is dependent on the measurement conditions and PN concentrations.

3

4 Table 2. Number of vehicle types in the sampled fleet, according their assigned categories.

Category	Vehicle type	2001/116/EC	# in our fleet sample	# missing registry information
Gasoline cars	Gasoline cars	M1	24	
Diesel cars	Diesel cars	M1	51	
	Light goods vehicles 1	N1	17	2
Goods vehicles	Light goods vehicles 2	N2	8	2
	Mini buss	M2	1	
	Buses	M3	6	2
	Heavy goods vehicles	N3	32	15

5

- 6 Table 3. Passenger car fleets according the fuel used and engine displacement at the end of the
- 7 year 2011.

		Gasoline			Diesel				
				From				From	
			Less	1400			Less	1400	
			than	to	2000		than	to	2000
		Of	1400	1999	cm <sup>3</sup> or	Of	1400	1999	cm <sup>3</sup> or
Fleet	Total	total	cm <sup>3</sup>	cm <sup>3</sup>	over	total	cm <sup>3</sup>	cm <sup>3</sup>	over
Europe	207185950	61%	49%	44%	7%	34%	5%	76%	19%
Slovenia	1089335*	63%	61%	37%	3%	36%	4%	79%	17%
Our fleet	75	32%	50%	42%	8%	68%	0%	75%	25%

\*The Slovenian fleet in Eurostat (total vehicles 1066490) slightly differs from the NIO database, which is reported in this table, but overall reports almost the same percentages of the vehicle composition.

		10 years or	From 5 to 10	From 5 to 2	Less than 2
		over	years	years	years
Europe	Total	42%	28%	19%	11%
Slovenia	Total	39%	34%	18%	9%
	Gasoline	50%	25%	15%	9%
	Diesel	18%	48%	23%	11%
This study	Total	27%	47%	29%	7%
	Gasoline	50%	25%	17%	8%
	Diesel	16%	49%	29%	6%

1 Table 4. Passenger car fleets according to their age, at the end of the year 2011.

2

3 Table 5. Statistics on lorries size in 2011 for Europe and Slovenia.

	total	Less than 1500	From 1500 to 4999 kg	From 5000 to 9999 kg	10000 kg or over
Europe*	17994007	79%	14%	3%	4%
Slovenia	75508	71%	14%	7%	8%

4

5 Table 6. Statistics on lorries age in year 2011 for Europe and Slovenia.

				From 5	
		Less than	From 2	to 10	10 years
	total	2 years	to 5 years	years	or over
Europe	17995713	10%	20%	26%	43%
Slovenia	75508	11%	25%	32%	32%

6

Study	Study type	Vehicle type	EF BC (g kg <sup>-1</sup> )	EF PN (10 <sup>15</sup> kg <sup>-1</sup> )	$EF NO_X (g kg^{-1})$
Shorter, 2005	Chasing <sup>a</sup>	Diesel buses			34.5 (8.1 – 117.1)
		CRT			27.8 (±6.3)
Schneider, 2008	Chasing <sup>b</sup>	HGV	0.22±0.14	8.3±5.8	18±14
Ban–Weiss, 2009	Remote s. <sup>a</sup>	HGV	1.7 (0.1 - 20)	4.7 (0.2 - 40)	
Dallmann,	Remote s. <sup>d</sup>	HGV (2009)	$1.07 \pm 0.18$		25.9 ± 1.8
2011		HGV (2010)	$0.49 \pm 0.08$		15.4 ± 0.9
Dallmann, 2013	Remote s. <sup>d</sup>	HGV	0.62 ± 0.17		
Hudda, 2013	Mobile	LDG	$0.07 \pm 0.05$	0.43 ± 0.26	3.8 ± 1.4
		HDD I-710	0.41 ± 0.21	4.2 ± 3.4	15 ± 9.2
		HDD freeways	$1.33 \pm 0.33$	5.2 ± 3.1	16 ± 10
Wang, 2012	Chasing <sup>c</sup>	HGV Beijing	0.4 (0.2-0.8)		47.3 (38.1 - 62.5)
		HGV Chongqing	1.1 (0.7-1.6)		40.0 (31.7-48.1)
Carslaw and	Remote s. <sup>e</sup>	Gasoline cars			5.6 (1.6 - 28.1)
Rhys-Tyler, 2013		Diesel cars			16.37 (15.7 – 21.6)
		Van (N1)			18.9 (17.6-24.7)
		HGV (all)			39.8 (36.7 - 50.6)
EEA, 2013c	Emission	Gasoline cars			8.73 (4.48–29.89)
	inventory	Diesel cars			12.96 (11.2–13.88)
		LGV			14.91 (13.36–18.43)
		HGV			33.37 (28.34–28.29)
This study	Chasing <sup>c</sup>	Gasoline cars	0.28 (0.15-0.46)	1.95 (1.08-4.88)	6.34 (3.77-10.6)
		Diesel cars	0.79 (0.36-1.36)	4.4 (2.62-9.03)	15.43 (8.82-22.63)
		Goods vehicles	0.47 (0.24-0.72)	11.49 (2.55-19.76)	27.71 (17.89-38.24)
		LGV (N2)	0.64 (0.37-0.96)	16.8 (8.22-19.01)	23.16 (17.89-27.46)
		Buses	0.4 (0.24-0.65)	9.99 (1.91-19.23)	55.88 (39.09-55.9)

## 1 Table 7 Comparison of EF with other similar on-road studies.

<sup>a</sup> mean (range); <sup>b</sup> mean  $\pm$  standard deviation; <sup>c</sup> median (1<sup>st</sup> and 3<sup>rd</sup> quartile); <sup>d</sup> mean  $\pm$  95% confidence interval; <sup>e</sup> emission ratios from Carslaw and Rhys-Tyler, 2013, paper were converted to EFs using the same molecular weights and carbon fraction as in formula 1, for HGV we the average of both HGV groups they report HGV(3.5-12t) and HGV(>12t); presented are average values for all Euro standards in a group, in parenthesis are the smallest and largest mean value of emission standards.





Figure 1. Comparison of two integration approaches to calculate individual vehicle's emission factor (EF). With the bulk integration the EF is calculated by integrating the plum from the

- 5 beginning to the end of the chase; the median EF is calculated with the running integration
- 6 approach with 10s integration windows, from the EF distribution the median value is then
- 7 calculated.



1

2 Figure 2. Black carbon (BC), particle number concentration (PN) and NO<sub>x</sub> emission factor

3 (EF) distributions for gasoline and diesel cars, light and heavy goods vehicles. Note the EF

4 logarithmic scale.

5

![](_page_32_Figure_0.jpeg)

1

Figure 3. BC and NOx EF according to different vehicle categories and age group subcategories: gasoline passenger cars (GC, blue), diesel passenger cars (DC, black), and goods vehicles (GV, red). Note the EF logarithmic scale; same figure in linear scale can be found in Supplementary material – Figure S3.

![](_page_33_Figure_0.jpeg)

Figure 4. BC and NOx EFs according engine power (left) and size (right); red boxes present
gasoline engines (GE) and black boxes present all diesel engines (DE) regardless of their
vehicle category. Note the EFs are on logarithmic scale; same figure in linear scale can be
found in Supplementary material – Figure S4.

![](_page_34_Figure_0.jpeg)

Figure 5. Cumulative distribution of all vehicles emissions. Fractions of vehicles are
distributed from highest to lowest emitting vehicles. The result shows that 10% of vehicles
contribute about a half of total BC and NO<sub>x</sub> emissions.