NO_x RDE measurements with Plume Chasing - Validation, detection of high emitters and manipulated SCR systems

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Introduction

Vehicles, especially Diesel, are the most relevant NO_x ($NO + NO_2$) source in urban areas which cause large environmental problems. The EURO Norm define the allowed emissions (e.g. EURO VI since 1.1.2013 for vehicles >3.5t emission limit is 400mg/kWh). The best technology to achieve low NO_x emissions is the SCR (selective catalytic reduction), consuming AdBlue®. For vehicles above 3.5t (trucks and busses) all EURO VI and most EURO V use the SCR system. For vehicles below 3.5t, SCR systems become also widely used since EURO 6.

RDE (real driving emissions) can significantly vary from EURO Norm emissions in the lab. Thus RDE measurements have become an important topic in recent years to improve the true emissions on the road and not only in the lab. For vehicles above 3.5t RDE measurements have become mandatory but allow a higher emission with a conformity factor of 1.5 (resulting in 600mg/kWh). Typically, PEMS (portable emission measurement systems), installed on an individual vehicle are used to investigate RDE. But PEMS measurements are very expensive, time consuming and investigation of only very few individual vehicles are possible. They are thus not practical to investigate a large number of vehicles or even a complete fleet. On the other hand, remote sensing (RS) emission measurements are possible to investigate the emissions of a large quantity of passing vehicles. However, the measurement is a snap shot of the emission and not representative for an individual vehicle. Thus an individual high emitter cannot reliable be identified (see next chapter).

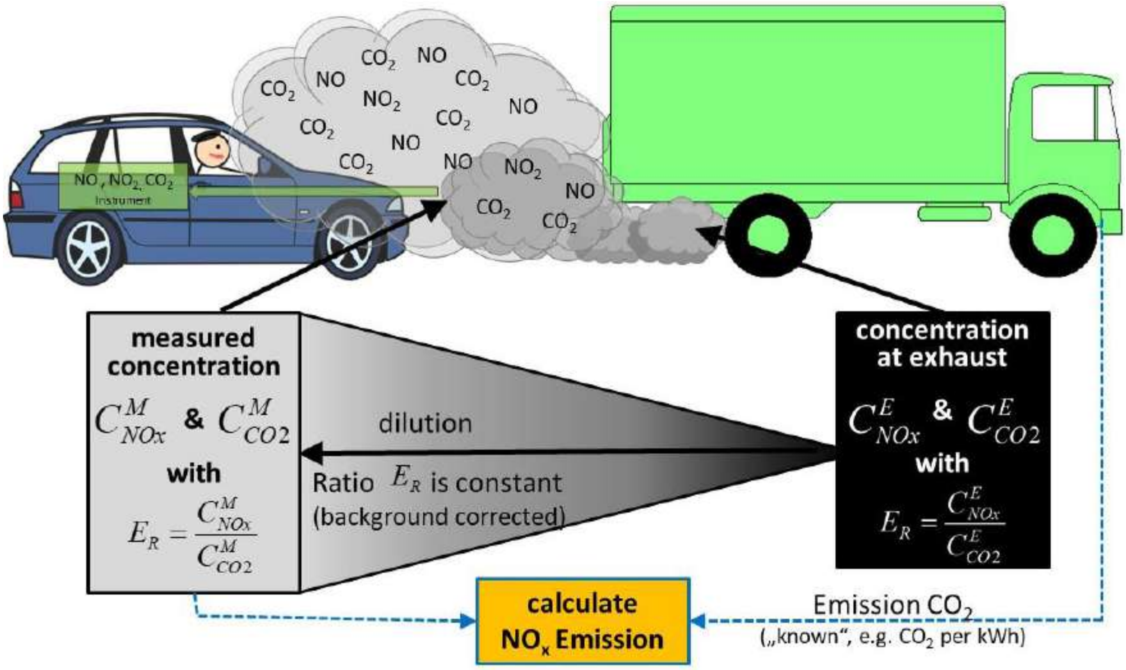


Figure 1: Plume Chasing measurement principle illustrated for NO_x. In a chasing vehicle the investigated pollutants (e.g. NO_x, PM) are measured together with CO_2. After correction of background concentration, the ratio of pollutant to CO_2 allow the calculation of the emission value with known CO_2 emission.

To fill the gap between PEMS and RS, we apply and further develop the new Plume Chasing method (Figure 1). It allows to investigate reliable the emission of individual vehicles with a lower demand than PEMS. Main applications are the real driving emissions of a vehicle fleet to indicate high emitters. For example, public busses can be studied to derive the high emitters which need to be repaired or exchanged. Also the reliable detection of high emitters due to a malfunction in the emission cleaning system or even manipulation are possible. We here present validation studies of the Plume Chasing method and different applications.

Requirements for individual vehicle emission measurements

The emission regulation defines the maximum allowed emission averaged over a complete test cycle. On a short time scale the emissions can vary significantly from its average value, not only due to varying engine power (or fuel consumption), but also in the ratio to CO_2. The main reason is the strong fluctuation of emissions and needed regulations of the emission cleaning system leading to a variability of the emission reduction. Thus also a correct working EURO VI or V truck can on short time show emission values of a EURO III or II truck. Different studies show that NO_x RDE of EURO V show on short periods large variability, also significantly above the EURO Emission norm (e.g. TNO 2014, TNO, 2016). But lower variability and average emissions below the EURO Norm are found on the highway where more constant driving conditions are found (Kleinebrahm, 2008; TNO 2014, TNO, 2016). EURO VI trucks show typically emission values with lower variability and they better agree to the EURO Norm (e.g. TNO 2014, TNO, 2016).

The statistical variance (and thus accuracy) of the emission ratio in dependence of the averaging time is shown in Figure 2 for two trucks derived with PEMS. Note this is the statistical variance, individual emission values can vary even more. The derived short term emission values are compared with the average emission of a complete test cycle. A short averaging like for RS measurements (left end of the plot, yellow shaded area) feature a large deviation and thus a large error on the investigated emission. Different colour lines indicate two different trucks one EURO V and one EURO II and also measurements at different road sections or exclusion of cold start. Trucks without SCR systems like the EURO II show a lower variability like expected. Emissions vary less at relative constant driving conditions like on a highway. Blue shaded area indicate the typical averaging period for plume chasing (3 to 10 minutes) for each investigated vehicle.

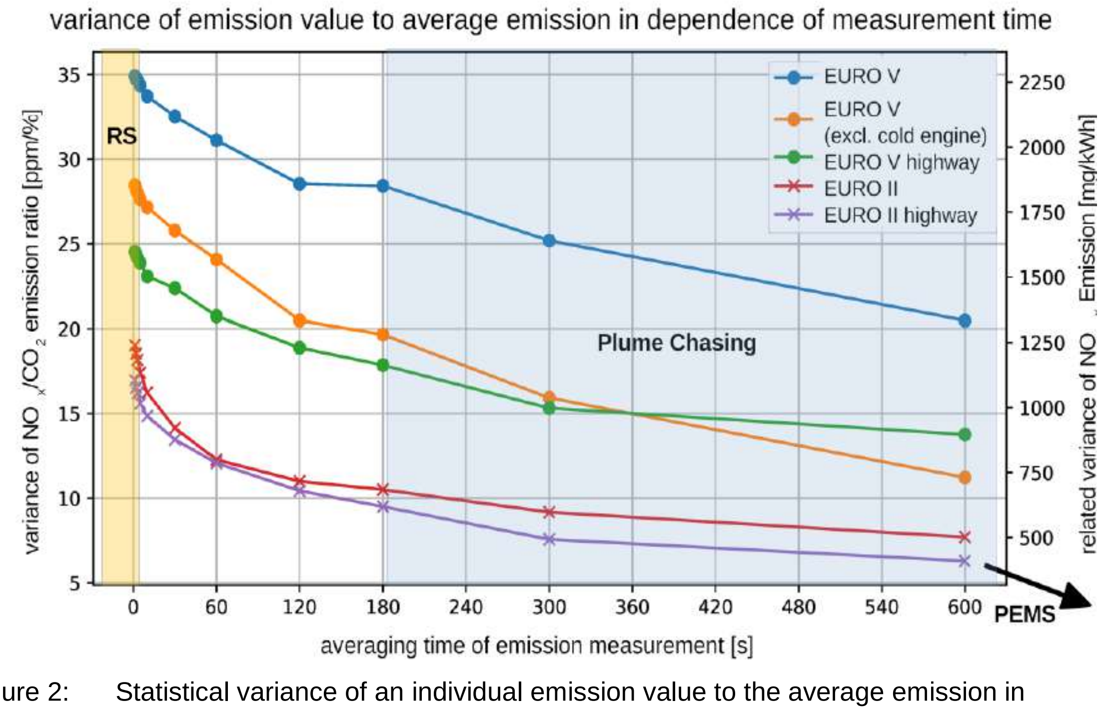


Figure 2: Statistical variance of an individual emission value to the average emission in dependence of the averaging time of the value for a EURO V and EURO II truck.

That mean to derive a reliable emission value of an individual vehicle the measurement has to average over a representative period and should be performed at driving condition with relative constant conditions like on the highway. For example, to identify a EURO V truck with a defective emission system, and thus on average higher emissions, the derived emission value should have an accuracy of typ. 1000mg/kWh. For a measurement on the highway (green curve in Figure 2) this requires a measurement over 300s (=5min). A snap shot measurement of the emission, like done with RS technique, does not fulfil these criteria. Plume Chasing can easily measure over several minutes and even on the highway to achieve these accuracies.

Plume Chasing

Plume Chasing measurements (sometimes also called sniffer car) is based on a gas observation in the diluted emission plume of the investigated vehicle. A chasing car samples air in the diluted plume behind the investigated vehicle (Chui et al., 2016; see Figure 1) and analyse the gas sample. Due to dilution of the air, the observed concentrations do not provide a direct emission value and additional the measurement of a reference gas is required. The reference gas is CO_2. It's emission value is well defined over the fuel consumption. The calculation of emissions (emission ratios) is similar to the well-established Remote Sensing (RS) technique, by using the ratio of the desired trace gas or particle to the CO_2 (Bishop and Stedman, 1996). First the measured concentrations are corrected by its background level outside the plume. Afterwards the ratio E_R of the pollutant to CO_2, e.g. NO_x / CO_2, is derived. The ratio E_R is constant in the plume, directly at the exhaust pipe or few meters behind the vehicle, as all gases have the same dilution. With strong dilution the concentrations cannot sufficiently be separated from the background any more. Thus we define a threshold of 30ppm CO_2 above background concentration to indicate sampling inside the emission plume. Measurements at lower concentration are not used for the emission calculation. From sensitivity studies we observed this 30ppm as best compromise. A higher threshold would reduce the amount of valid measurement points, but no significantly difference in the average emission ratio for an individual vehicle was found. If even lower threshold would be chosen we observe a change in the observed emission ratio, likely as than other emission from other vehicles more influence the measurements. Background concentrations needed for the data analysis are taken automatically from the measurement time series as in between the vehicle regularly show low emissions (concentrations are than similar to background levels) or we observe the background before approaching the vehicle or while overtaking. In practice the algorithm searches the data point with lowest CO_2 concentration while measuring a vehicle plus a time window of 2 minutes. The CO_2 and NO_x concentration during this time are used as background value. But it needs to be considered that changing different background concentrations need to be considered or excluded. Therefore, we exclude measurements in tunnels and treat measurements on different road times separately (e.g. a country road separated from a high way). Also other background measurements are possible (e.g. measurement background concentration over a separate inlet, different selection of background concentration), but extensive investigations show, that the selection of the correct background only minor influence the derived emission value and is thus not critical (Roth, 2018). However, plume sampling can still be optimised to measure higher concentrations of the emission, as than the error of the background correction plays a minor role and influence of other vehicle emissions can be reduced. Optimising the sampling for plume changing is thus still topic of current investigations.

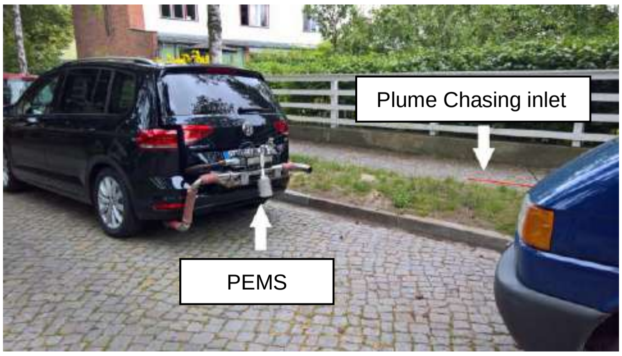
If emissions of other vehicles dilute into the investigated emission plume a measurement error arises according to its proportion. This is especially a problem in dense stop and go traffic with multiple driving rows. Emissions of a vehicle driving in front of the investigated vehicle has only a minor influence of up to 10%. This is typically uncritical, but can in extreme cases (e.g. very high emitter in front of a low emitter) cause significant measurement errors with an overestimated emission up to a factor of two. It is thus obvious that Plume Chasing cannot achieve the accuracy of PEMS.

From the emission ratio E_R an emission factor of the pollutant, e.g. E_{NOx}, can be calculated using the known CO_2 emission E_{CO2}. For vehicles >3.5t (trucks and busses) E_{CO2} per kWh is needed to calculate the emission per kWh. E_{CO2} can be estimated over the engine efficiency and the carbon content of diesel. We apply an engine efficiency of 40%, which is a very optimistic energy efficiency of a truck and corresponds to a best case emission calculation (lower efficiency result in higher emission factor). For vehicles <3.5t (cars) E_{CO2} per km is needed to calculate the emission per km. E_{CO2} is measured or estimated from data bases (HBEFA). This estimation may introduce errors of 20% which are still lower than typical emission variations.

Figure 3: Mobile ICAD NOx instrument of Airyx GmbH used for Plume chasing. The instrument fits in the easily in any car boot.

We apply a IR CO_2 Sensor and a ICAD-NO_x instrument from Airyx GmbH for our plume chasing studies. In the ICAD NO is converted to NO_2 so that all NO_x is in the form of NO_2. Afterwards it is optically measured by its characteristic differential absorption features which has the large advantage to avoid interferences with other emitted gases. The measurement with 2 seconds time resolution has an accuracy of ~0.5ppb. The used instruments feature perfect mobile performance with high time resolution, high accuracy, large measurement range and low power consumption and are thus ideal for this application.

Validation



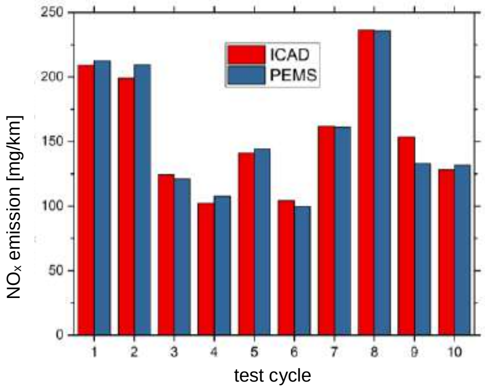


Figure 4: Validation measurements of Plume Chasing (ICAD instrument) with PEMS for EURO 6 passenger diesel cars. Emissions were compared over a test cycle of 31km. The NO_x emissions derived for each cycle are compared for the two instruments (right plot).

We performed several different validation campaigns of NO_x emissions derived with Plume Chasing vs. PEMS for passenger cars (vehicles <3.5t) as well as trucks (vehicle > 3.5t). General a good correlation can be observed.Figure 4 show the measurement for two different EURO 6 passenger cars over a real driving test cycle of 31km in urban and suburban area (Krufczik, 2017). PEMS and Plume Chasing (ICAD instrument) derive for each test a very similar NO_x emission with an agreement typical of ~5% (10mg/km). The variation between the test cycle is due to a variation of the emission, but observed by both techniques. In cycle 9 (Figure 4 right plot) Plume Chasing observes a higher emission caused by a disturbance from an old diesel van with very high emissions driving a long distance in front of the investigated car.

In another study we investigated how good Plume Chasing can also capture short term emission variations like measured with PEMS (Reber, 2018). Figure 5 show one example of pulsed accelerations. We achieve best correlation for small and moderate speeds and distance to the vehicle up to 25m. For larger distance and high driving speed of min. 80km/h often only 30% of the measurements are in the emission plume. This directly result in larger error of short term emission values up to 25%. The result show that at good measurement conditions with small vehicle distance and moderate speed Plume Chasing can observe short term emission variations with time resolutions of ~10s. But data also show that short measurements are more affected by disturbances from other vehicles that this is the case for the average value.

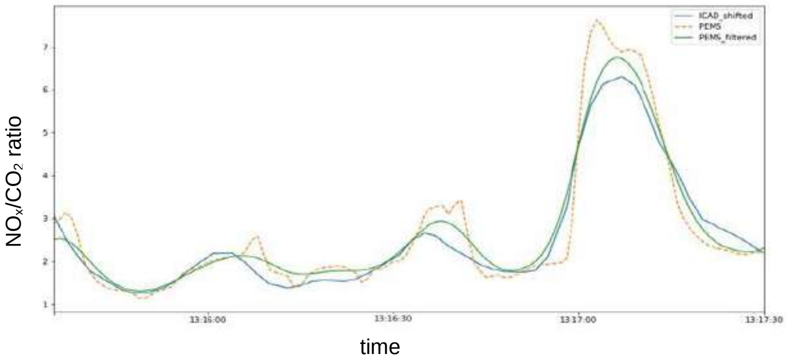


Figure 5: Validation measurements of Plume Chasing (ICAD instrument) with PEMS for short term emission variations during incremental acceleration. We average the PEMS data over 10s (filtered) and shift to get agreement with Plume Chasing.

Beside validations with cars also extensive validation studies for truck NO_x emissions were performed for BAFU (Bundesamt für Umwelt, Switzerland) together with EMPA (Switzerland) (Roth, 2018). The emissions of 3 test trucks ranging from EURO II with high emissions, EURO V (moderate emission) to EURO VI (low emissions). The goal was to investigate how reliable Plume Chasing can separate high from low emitters at different conditions. This would allow to detect defective or manipulated emission cleaning systems of EURO V and EURO VI trucks. Unfortunately, the PEMS measurement in the study did not derive realistic emission values. They were over long distances unrealistic 0mg/kWh. Thus only a comparison of EURO II and V was possible. An example of a EURO V is shown in Figure 6 where different road sections with very different driving behaviour and traffic load are included.

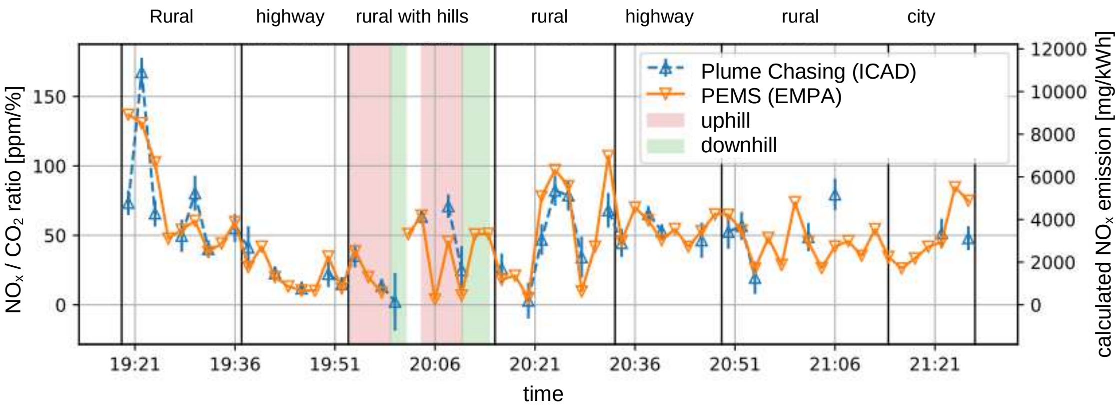


Figure 6: Validation measurements of Plume Chasing (ICAD instrument) with PEMS of a EURO V truck over different road sections. Compared are 2-minute average emission ratios.

Compared are emissions ratios of NO_x/CO_2 averaged over 2 minutes raging up to 160ppm/% (correspond to 12.000mg/kWh). If the signal of the plume was to week for the plume chasing method (less than 30ppm CO_2 above background) no emission value is derived. A good agreement between the two methods is observed, even if measurement conditions were difficult at dense highways, hilly roads and even urban sections. Over all truck measurements a correlation of R=0.88 is achieved with slope of 0,83 (lower emissions with plume chasing). Especially for the EURO II PEMS derives higher emission values. Reasons can be uncertainties in the Plume Chasing method or interferences of the PEMS technique. Best agreement was achieved on rural roads and uphill (R=0,91 and R=0,93 respectively) and also good agreement on highways (R=0,89). For a measurement over several minutes an agreement of 100mg/kWh can be achieved.

All validation studies show that Plume Chasing can derive NO_x emission values relatively simple and reliable, but not with accuracies like PEMS. No significant overestimation was observed. Thus it can be used to simple investigate emission of individual vehicles and to identify high emitters. They also show that PEMS can feature problems and observe wrong emission values which need to be further investigated.

Study emissions of a public bus fleet

We analysed the emissions of public busses in few German cities. Examples are shown in Figure 7 for the city of Reutlingen and Figure 8 for Heidelberg. Real emissions of the busses are often unknown and thus it is not precisely known how much the public busses contribute to total NO_x emissions and NO_2 air pollution problems in the city.

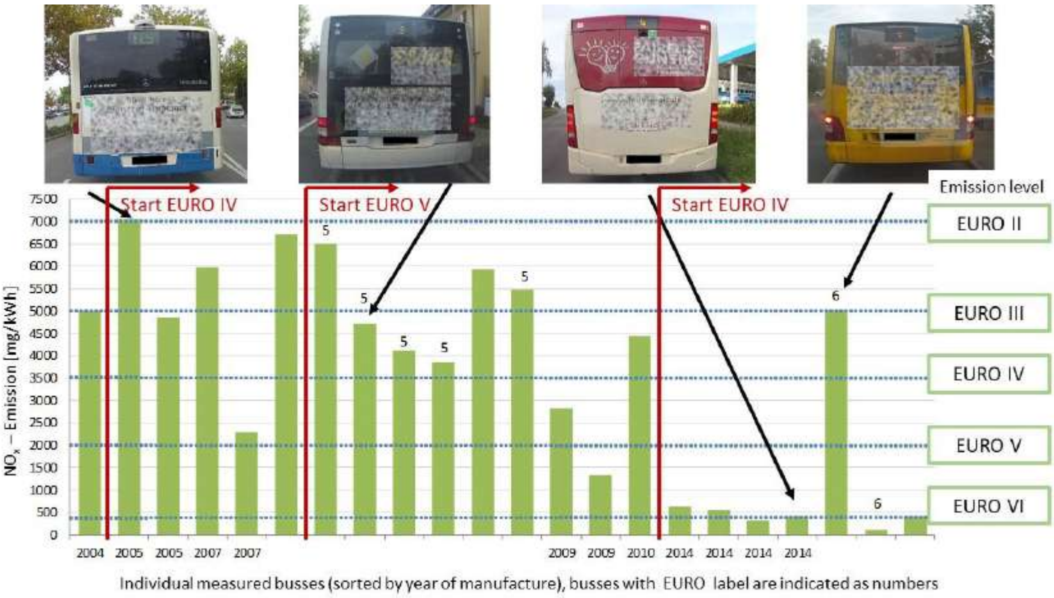


Figure 7: Public bus NO_x emissions in Reutlingen. Each column represents an individual bus, sorted by year of construction. If precise construction date or EURO class are known, they are indicated. Dotted lines indicate the EURO emission Norm.

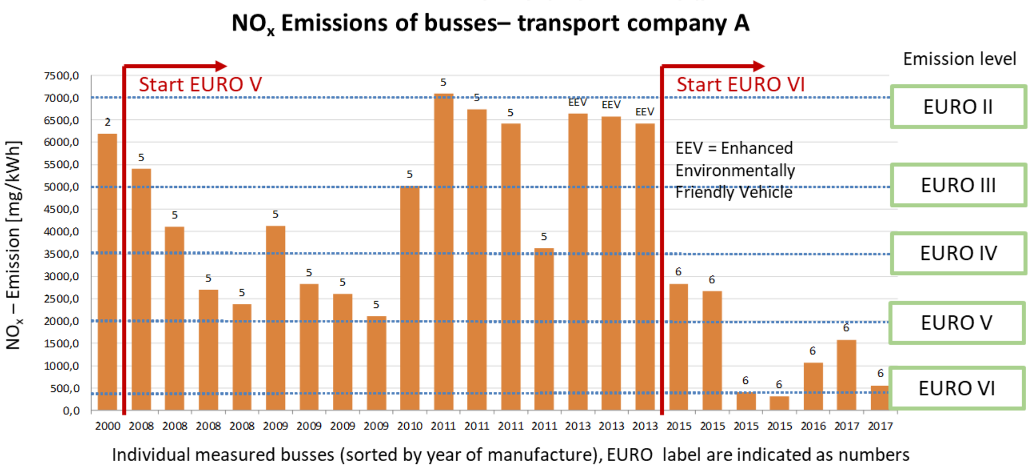


Figure 8: Public bus NO_x emissions in Heidelberg (similar to Figure 7) of one specific transport company where bus data are provided.

Figure 7 and Figure 8 show that real driving emissions in the city up to EURO V are much higher than the EURO emission norm which is related to the old emission test procedure. Interesting is that even newer EURO V – EEV (Enhanced Environmental Friendly) busses show often the highest emission value up to 7000mg/kWh (EURO II level). A significant reduction can be observed for EURO VI busses (on average 663mg/kWh), often even below the EORO VI emission norm. The reason for this improvement are stronger emission test procedures introduced for EURO VI including real driving emissions. Few individual EURO VI busses feature much higher emissions (see Figure 7) indicating a defective emission system. Also some older EURO VI seem to feature higher emissions (see Figure 8) indicating a degradation of the SCR system. These studies demonstrate that investigations of the public bus fleet allow cities to perform decisions on the fleet to effectively reduce its emission. For example, we estimate that the NO_x bus emissions in Heidelberg could be reduced by 80% if all busses with emissions above 2000mg/kWh are upgraded or exchanged to EURO 6 level with real driving emissions observed in the study.

Truck emission studies – identification of manipulated emission systems

For truck emissions we focus on the identification of high emitters due to manipulated or defective SCR systems. So called AdBlue® emulators simply switch off the SCR systems to save AdBlue® consumption (up to 2000€/year), but also to avoid an expensive maintenance exchange of the SCR system. As a result, truck emissions increase significantly. AdBlue® emulators are already available for 25€ and are easy to install. There are two kinds, hardware and software emulators. Hardware emulators are a small electronic which is installed in the truck. They can be located at positions which are difficult to reach (below the trailer) and thus they are difficult to find in a control. The software emulators are a manipulated engine software which is uploaded to the truck and popular for EURO VI trucks. There is no physical modification of the truck. So far it is not possible to detect these emulators. Modern emulators have many features which additionally make it difficult to detect them, e.g. emission reduction is applied only above a certain speed so that detection requires a higher driving speed. Additionally, AdBlue® consumption arise even if it is much lower. Also optional DPF or EGR manipulation is possible. Current controls focus on the observation a physical hardware emulator. It is obvious that only a small portion of the hardware emulators are found due to its small size, and no possibilities to observe software emulators. Thus official numbers of manipulations arising from these controls (1-3%) underestimate the number of manipulated trucks.

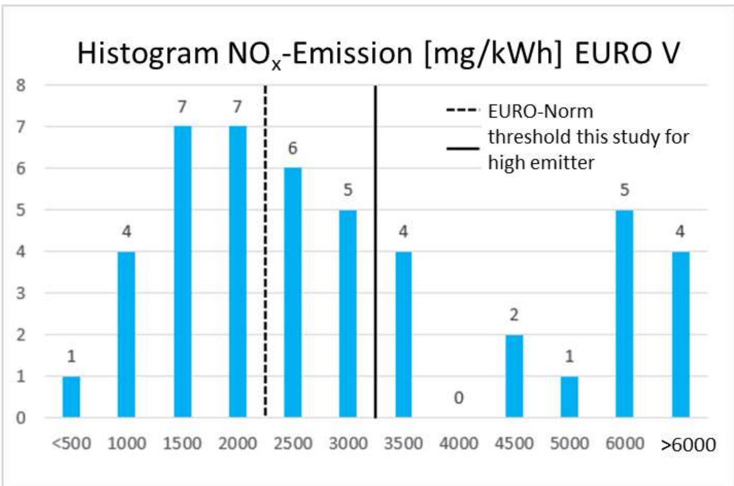


Figure 9: Histogram of observed EURO V truck emissions in Austria, 2018.

With Plume Chasing we can reliable identify high emitters and thus quantify the amount of potentially manipulated trucks. In the last years we performed studies in Germany (254 trucks), Austria (215 trucks) and Switzerland (39 trucks) mainly performed on high ways. Due to warm engine and relative constant driving behaviour, reliable emission measurements can be observed (see Figure 2, TNO 2014; TNO 2016). On the other hand, this mean that at such driving conditions a high emission over several minutes cannot be explained with an engine effect, but mainly due to a defective of manipulated emission system. As threshold for such a high emitter we use the EURO Norm emission value + a tolerance of 1000mg/kWh (resulting in 3000mg/kWh for a EURO V, 1400mg/kWh for a EURO VI).

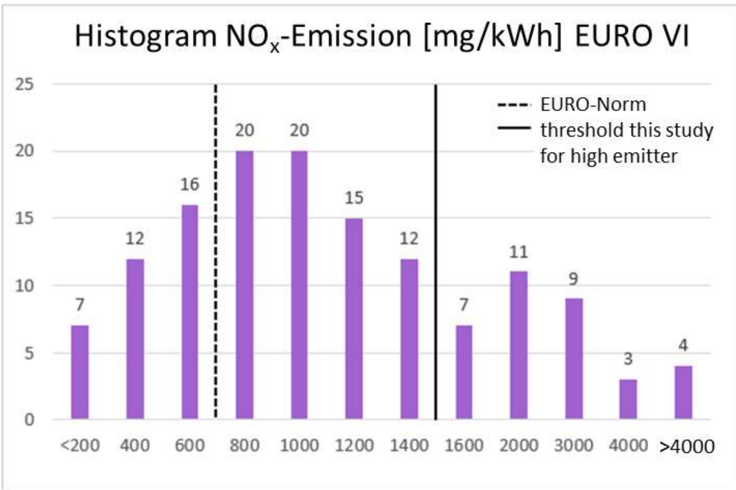


Figure 10: Histogram of observed EURO VI truck emissions in Austria, 2018

Figure 9 and Figure 10 show the histogram of observed emissions for the study in Austria 2018. A good separation between low and high emitters is visible. Many trucks show consistently high emissions and use potentially AdBlue® emulators. These trucks originate mostly from east and south Europe. Up to 35% of EURO V trucks are affected and up to 25% of EURO VI trucks (Table 1). It clearly shows that also EURO VI trucks are often manipulated. The higher percentage in Austria may be due to a different truck fleet or to an increase in manipulations. The percentage is much higher than for controls due to the mentioned difficult observation. Plume Chasing is probably currently the most reliable method to easily and reliable identify these individual high emitters. We also observe a correlation of the high emitters with transport agencies. In the study in Austria few suspicious trucks could also be investigated in a police control. For half of these trucks a suspicious electronic device like a hardware emulator could be observed or errors in the SCR system. The later could also originate from an emulator. The large amount of high truck emitters has a significant impact of total NO_x Emissions of the transport sector.

Table 1: Percentage of observed high emitting trucks with potentially manipulated SCR emission systems.

Percentage of high emitters	EURO V	EURO VI
Germany, 2016		
German trucks	0%	6.9%
non German trucks	26%	19%
Austria, 2018	35%	25%

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