Short Report

Emission measurements with "Plume chasing" and subsequent inspection of Heavy Duty Vehicle (HDV) high emitters

A study in Slovakia September / October 2023

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Content

1 Summary

This report summarises the results of a project, applying the Airyx plume chasing measurement system to investigate NO_x and particle emissions of Heavy Duty Vehicles (HDVs), Light Commercial Vehicles (LCVs) and Passenger Cars (PCs) in Slovakia between 05th September and 5th October 2023. The focus was on HDVs where high emitters were identified. For a few days, identified high emitting HDVs were stopped by the police for further inspection. The inspections were supported by technical experts using OBD inspection tool (W.EASY DETECTIVE). The project was carried out as a collaboration between the International Council on Clean Transportation, TU Graz, Airyx, ISA UK Ltd and TSA spol. s r.o. and Wabcowürth for inspections. The study shows that emission inspection with plume chasing is well suited for efficiently obtaining precise emission values for NO_x and particles (Black Carbon (BC) and Particle Number (PN)) from individual vehicles. It allows to reliably identify high emitters due to defective and manipulated emission systems. For HDVs this could be proven with the performed inspections.

Performed measurements:

For the emission measurements, the plume chasing, mobile remote sensing equipment supplied by Airyx, was installed in vehicles from the partners in Slovakia (chapter 3.2). In addition to the normal equipment also two instruments from the TUG for measuring particles were installed and implemented in the real time emission software from Airyx. The emission software directly indicates if the vehicle under examination, is a low, suspicious, or high NO_x emitter. The average particle emissions are also displayed. Thus, simple recommendations for further inspection are provided. Emission measurements could be successfully performed under all weather conditions, ranging from warm, sunny and calm to rainy and windy conditions. No limitation on weather conditions for the plume chasing method could be observed.

Investigated vehicles:

During the project, a total of 2941 vehicles with corresponding NO_x and particle emissions were investigated. For 2547 of the vehicles a valid emission value was derived (chapter 4). 1889 of them were HDVs (1625 measured in Slovakia, 135 in Germany and 129 in Czechia), 16 buses, 449 PCs, 191 LCVs and 2 motorcycles. Measurements were performed on Slovak motorways as well as under urban and suburban conditions. HDVs, PCs and LCVs were mainly measured on motorways. While only 3% of the HDVs were measured on urban and suburban roads, the share was higher for PCs (46%) and LCVs (28%). 72% of the HDVs were identified as Euro VI, 20% Euro V and less than 8% belonged to the remaining Euro emission standards. The largest fraction of HDVs was from Slovakia (56%), followed by Poland (22%) and Czechia (7%) respectively. 51% of the PCs and 64% of the LCVs were identified as Euro 6, 22% and 21% as Euro 5, 18% and 9% as Euro 4 and less than 10% and 7% belonged to the remaining Euro emission standards. Nearly all investigated PCs and LCVs were from Slovakia.

Emissions of all vehicles:

Average NOx emission values could be derived for 1625 HDVs, 449 PCs and 191 LCVs measured in Slovakia. Average non-volatile PN (>23nm) emission values were determined for 539 HDVs, 119 PCs and 44 LCVs. Furthermore, average BC emission values for 899 HDVs, 310 PCs and 162 LCVs were obtained. The lower number of PN and BC emission values is due to a breakdown of the measurement vehicle (in a replacement car only NO_x measurements could be performed) and a defect PN instrument at the end of the campaign.

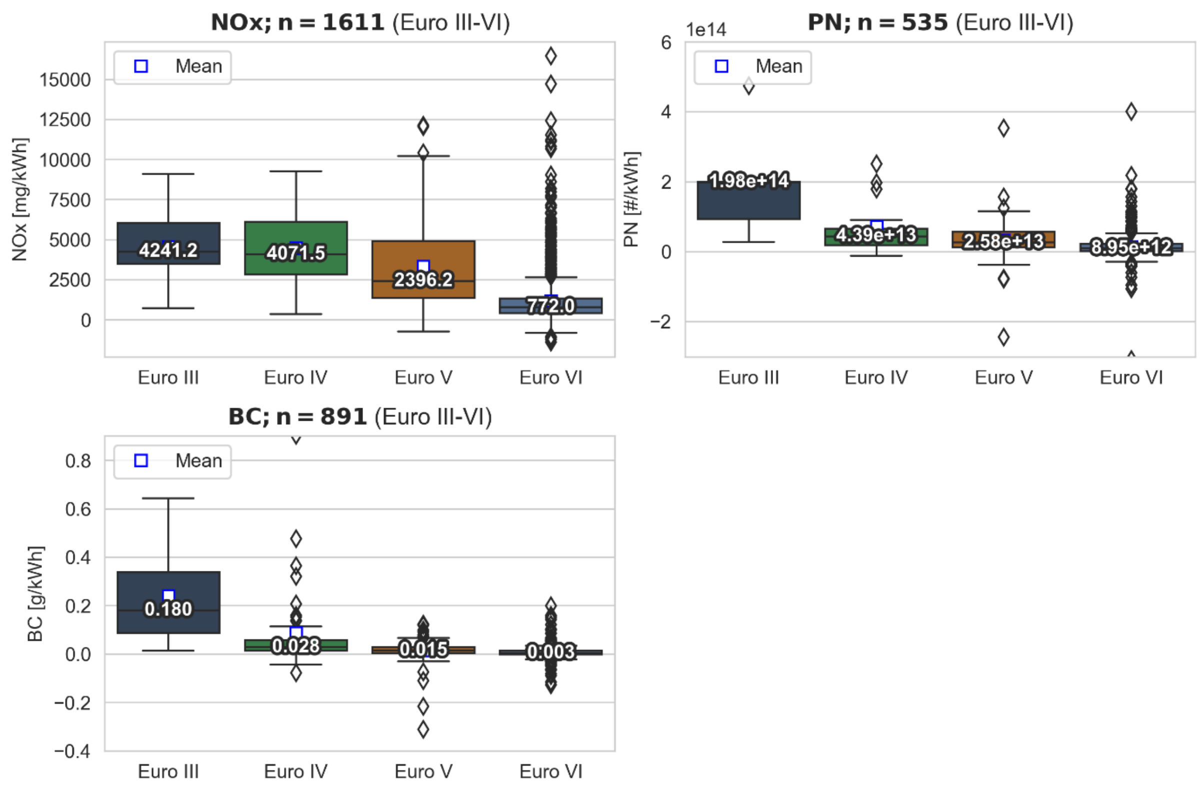

Figure 1: Distribution of average NO_x, non-volatile PN (>23nm) and BC emissions of Euro III to Euro VI HDVs, measured in Slovakia. HDVs below Euro III are excluded, as well as HDVs with unspecified Euro classes. The numbers in the plots represent the medians.

Like in previous studies [2, 4, 5, 6, 7, 9, 10, 11, 12], the derived NO_x emission values were classified as low emitters if they were below a predefined limit (chapter 5). Different limits are applied for the different Euro emission standards (see Table 3). In this study, the HDVs with an average NO_x emission limit above a basic limit, are further split into suspicious and if they are above a second even higher pre-defined limit, as high emitters. 34% of the HDVs were above the limits for suspicious or high NO_x emitters (16% and 18% respectively). This value is similar to a recent study in Czechia [4]. For particles, such classifications were not applied in this study because a definition of thresholds for high emitters under such real driving measurement conditions still needs to be derived.

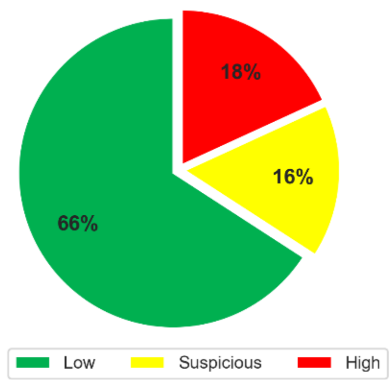

Figure 2: Statistics of NO_x emission classification of all measured HDVs (all countries and all Euro emission standards).

Vehicle inspections:

28 of the HDVs classified from the measurements as suspicious or high emitters were further inspected. These are not all vehicles flagged as suspicious or high emitters (about 5%). The results of this inspection is classified into the following cases:

(1) no Error was found
(2) a Defect / Error found
(3) a Manipulation found
(4) a cold SCR / cold Engine with inactive SCR system
(5) Software issue found

The statistic excludes one inspected vehicle that was older than Euro V.

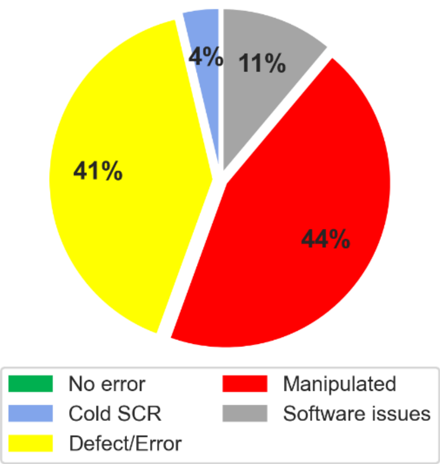

Figure 3: Conclusion of the inspected HDVs for Euro V and VI. The percentage is relative to the inspected suspicious and high emitting HDV.

Conclusions from the inspections are:

- For 41% of the inspected HDVs a defect or error was found.
- For 44% a manipulation of the emission system was proven.
- For 4% of inspected HDV a cold SCR / cold engine system was concluded as the reason for the high emissions.
- For 11% a software issue was found due to a missing mandatory OE software update.
- No HDV is classified as “No Error”. That means that no HDV was wrongly classified from the Plume Chasing measurement.

It should be noted that it is often difficult to distinguish between a defect and a manipulation. A defective system might be manipulated to allow the vehicle to continue driving. With inspection tools, the defect is easier to find than the manipulation.

In conclusion, the measurement of PN and BC emissions could be successfully integrated in the Airyx Plume chasing measurement system and average PN and BC emission factors could be calculated in real time in parallel with the NO_x emission values. The Airyx Plume chasing measurement system could support authorities in identifying high emitters caused by defective and/or manipulated vehicles. A major advantage is that, compared to other remote emission sensing techniques, no permits are required for the studies and the system is simple to operate, making the studies easy to carry out. It also works in rainy and/or cold weather conditions.

2 Introduction

2.1 Background for the project

Airyx has developed the "Plume chasing" measuring system for the identification of high emitters. The system has already been used by authorities in Denmark, Belgium, and Czechia [2, 4, 5, 6]. This project is the first use of the Airyx "Plume chasing" measurement system in Slovakia. This report summarises the extended study in which the plume chasing equipment was extended for particle measurements (Black Carbon (BC) and Particle Number (PN)) and the live evaluation of particle measurements was integrated into the Airyx system for the first time. The measurements and inspections of heavy duty vehicles (HDVs) were mainly performed along main highways in Slovakia, in order to have a large proportion of fully working emission reduction systems on the HDVs after warm-up and avoiding high emissions due to cold engines / cold SCR. Not only HDVs were measured but also light duty vehicles (LDVs) such as light commercial vehicles (LCVs) and passenger cars (PCs). Those vehicles were mainly measured in urban and suburban areas. Further background information and a technical introduction of the measurement method can be found in other reports [2, 5].

2.2 The content of the project

The two main objectives are: to conduct vehicle emission measurements of NO_x as well as particles (BC and PN) for HDVs and LDVs and to share and increase competencies for people involved in the control effort like local police and inspectors. The project is carried out as a collaboration between International Council on Clean Transportation, TUG and Airyx. Organisation and executional phase were carried out in collaboration with ISA UK Ltd and TSA spol. s r.o. Airyx provided and installed the "Plume chasing" NO_x vehicle emission measurement system in a vehicle supplied by partners in Slovakia. The particle instruments were installed by TUG. The police inspections of identified high emitting HDVs were supported by technical experts using OBD inspection tool (W.EASY DETECTIVE). We'd like to express our special thanks to companies MotoJas s.r.o., Nitra and IQ Cars, Piešťany for their cordial approach and providing a valuable service background. Before the campaign a new software by Airyx was developed to integrate the particle instruments such that NO_x, NO_2 and Particle emission factors could be derived in real time during real driving conditions. Focus was on HDVs on highways, but also LCVs and PCs in urban and suburban environments were investigated.

The project combines the detection of high / suspicious emitters with the remote plume chasing method and further detailed inspections of HDVs by the Slovakian police. The focus was on HDV inspections, as inspection tools and enforcement methods are available for these vehicles.

3 Method

The plume chasing measurement system from Airyx is used in this study. The method is described in detail in other reports [1, 2, 7, 8, 11, 13]. We refer here only to the general principle and differences to previous studies.

3.1 Basic principle

Plume chasing measurements are performed by following a vehicle and measuring in the diluted exhaust plume, enabling the calculations of its emissions. So far, the system was for NO_x (NO + NO_2) and NO_2 emissions. For this study particle measurements (BC and non-volatile PN with a cut off diameter of 23nm) were included for the first time with one real time data analysis software.

The fundamental principle is, that the ratio between pollutant and CO_2 does not change, no matter how much the exhaust gas is diluted, and thus independent if measured directly at the exhaust or 50m behind the vehicle. Background concentrations of pollutant and CO_2 (outside the investigated plume) need to be corrected for. Emissions can be derived as ratios NO_x/CO_2, BC/CO_2 or PN/CO_2. Specific pollutant emissions (in g/kWh or #/kWh) are calculated for HDVs from the measured ratio applying an estimated engine efficiency of 40% for the relationship between emitted CO_2 and engine power. For LDVs the specific pollutant emissions are calculated in g/kgfuel or #/kgfuel applying a carbon mass fraction in fuel of 0.86 for petrol and diesel.

A valid plume signal is defined by a CO_2 signal of min. 30ppm above the background concentration. Only these valid data points are used to derive pollutant emission values. The background concentration is retrieved from the recorded data from periods where no plume is measured.

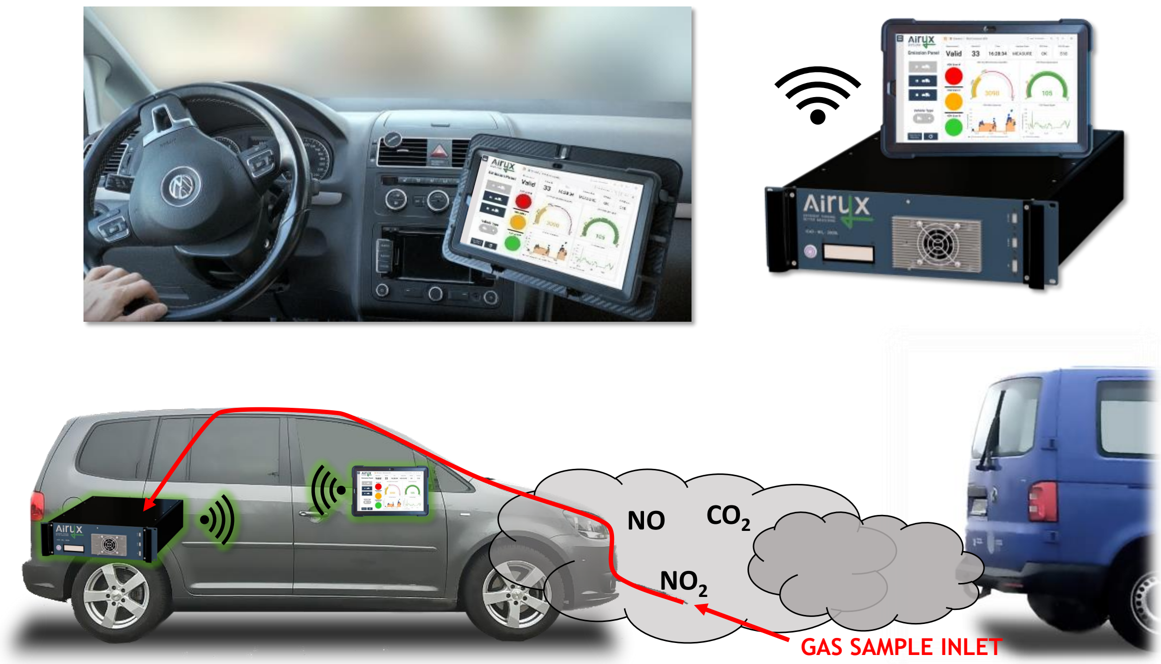

Figure 4: Basic sketch of plume chasing measurement principle from Airyx GmbH. The diluted exhaust gases are sampled and analysed. Different gases are measured with the ICAD-NOx-200DE instrument (NO2, NOx, CO2) and particles are measured with (not shown in this illustration) Black Carbon Tracker (BC) from TUG and AVL DiTEST Counter (PN). From the ratio of the gases and particles, emission factors of the followed vehicle are derived.

3.2 Instruments

The Plume Chasing setup had different instruments for particle and gas measurements installed. ICAD-NOx-200DE (ICAD) instruments were used to measure NO_x, NO_2 and CO_2, a Black Carbon Tracker (BCT) [3] for BC and a AVL DiTEST Counter (Counter) [14] for PN (Table 1).

Parameter	Instrument	Measurement range	Time Resolution	Accuracy (1 σ)
NO_x, NO_2	ICAD-NOx-200DE (ICAD)	0 … 5000 ppb	2 s	0.4 ppb
CO_2	ICAD-NOx-200DE (ICAD)	0 …2000 ppm	2 s	5 ppm
BC	Black Carbon Tracker (BCT)	0 … 3 mg m^{-3}	1 s	1 µg/m^3
PN (non-volatile, >23nm)	AVL DiTEST Counter	0 … 5 · 10^6 # cm^{-3}	1 s	±1000 # cm^{-3}

Table 1: Instruments used for the Plume Chasing setup.

3.3 Chasing vehicle setup

Three different passenger cars were used as chasing vehicles (see Figure 5 and Figure 6). In all three plume chasing vehicles an ICAD instrument was installed to measure NO_x, NO_2 and CO_2. For the particle measurements a BCT and a Counter were installed in ChasingVeh2 and also in ChasingVeh1 for the trip from Germany to Slovakia.

Figure 5: Plume chasing installation on ChasingVeh2 (outside view). The measurement probe system features two sampling inlets which are combined to one sampling hose to the ICAD plume chasing instrument, Counter, and BCT in the trunk.

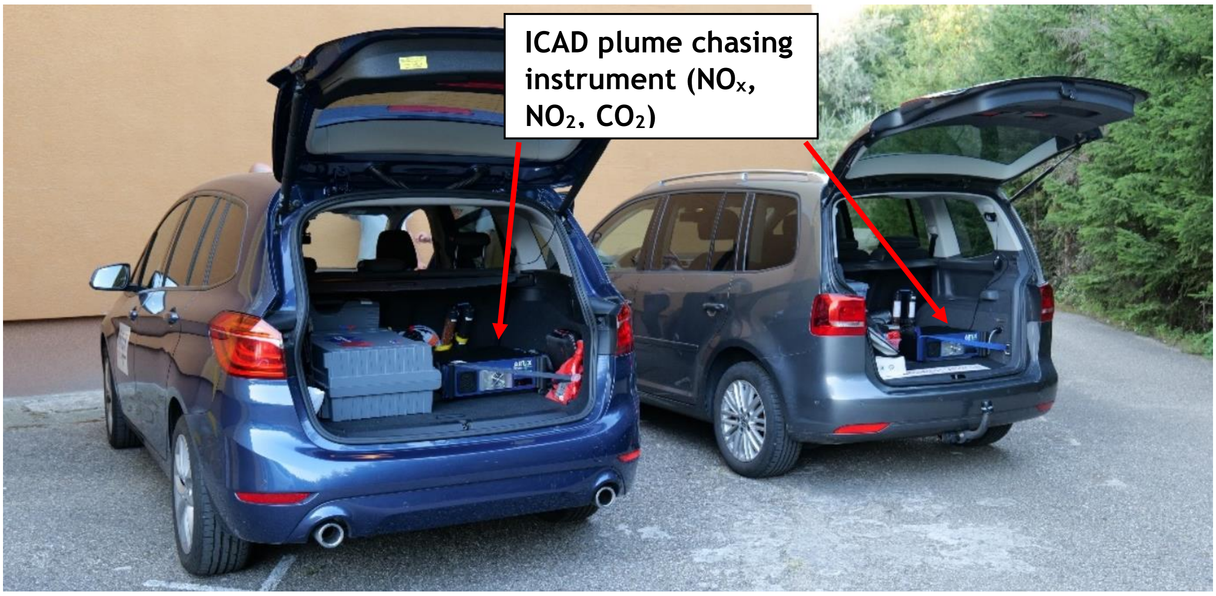

Figure 6: ChasingVeh1 (right) and ChasingVeh3 (left) with the ICAD instrument installed in the trunk.

The three chasing vehicles were not in use simultaneously, but were temporarily in use as a replacement due to a breakdown of the main ChasingVeh2.

Figure 5 shows the principle of the installation of the inlets on the plume chasing vehicles. A measurement probe system is mounted to the front bumper including the sampling inlets. The two sampling inlets are installed on a flexible tubing to avoid injuries. Sampling hoses are made from 8mm Tygon tubing with low particle losses which merge to one sampling line. This allows a more reliable measurement of the plume independent of the exhaust location of the monitored vehicle and as well as meteorological effects like side winds. Few centimetres after the measurement probe system, the sample tubing splits into an 8mm Tygon tubing for the particle instruments and a 6mm PTFE tubing for the ICAD NO_x, NO_2, CO_2 instrument. This should reduce losses in the tubing but still allow the measurement of the same plume with all instruments.

The sampling hose is going through the motor compartment inside the car and then through the passenger cabin to the ICAD plume chasing instrument/BCT/Counter in the trunk. The total sampling hose length is ~6m. A water and insect trap, as well as a cyclone which filtered out coarse particles larger than 1um was installed upstream to the particle instruments to protect the equipment from water and large particles (see Figure 7).

To be able to run the system with the particle instruments for the whole day without recharging, three batteries were installed in the lower compartment of ChasingVeh2 (see Figure 8). In the other two Plume chasing vehicles one 12V battery was sufficient as the ICAD NO_x/CO_2 monitor has only a power consumption of 30W. Figure 6 shows the installation inside the trunks of ChasingVeh1 and 3.

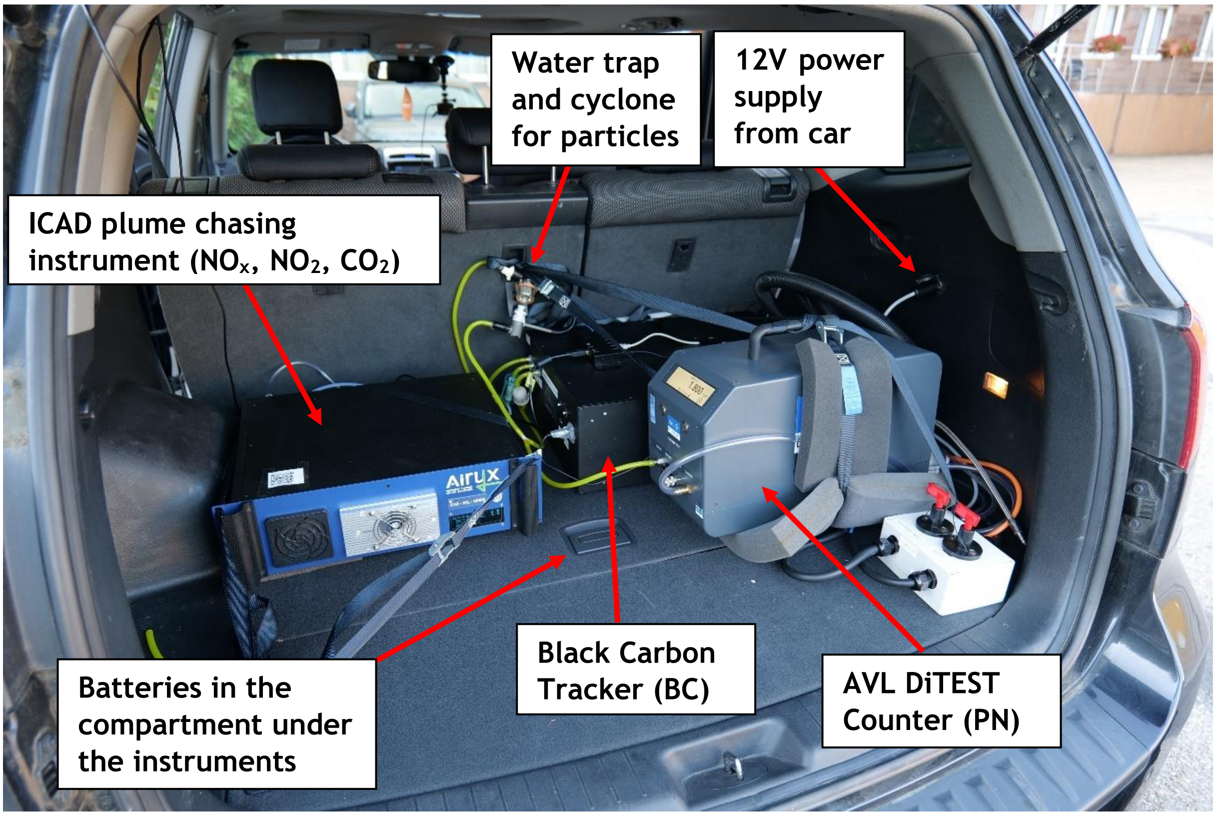

Figure 7: Plume chasing installation in the trunk of ChasingVeh 2. The sampling hose is guided through the cabin to the instruments. The instrument is powered from three batteries.

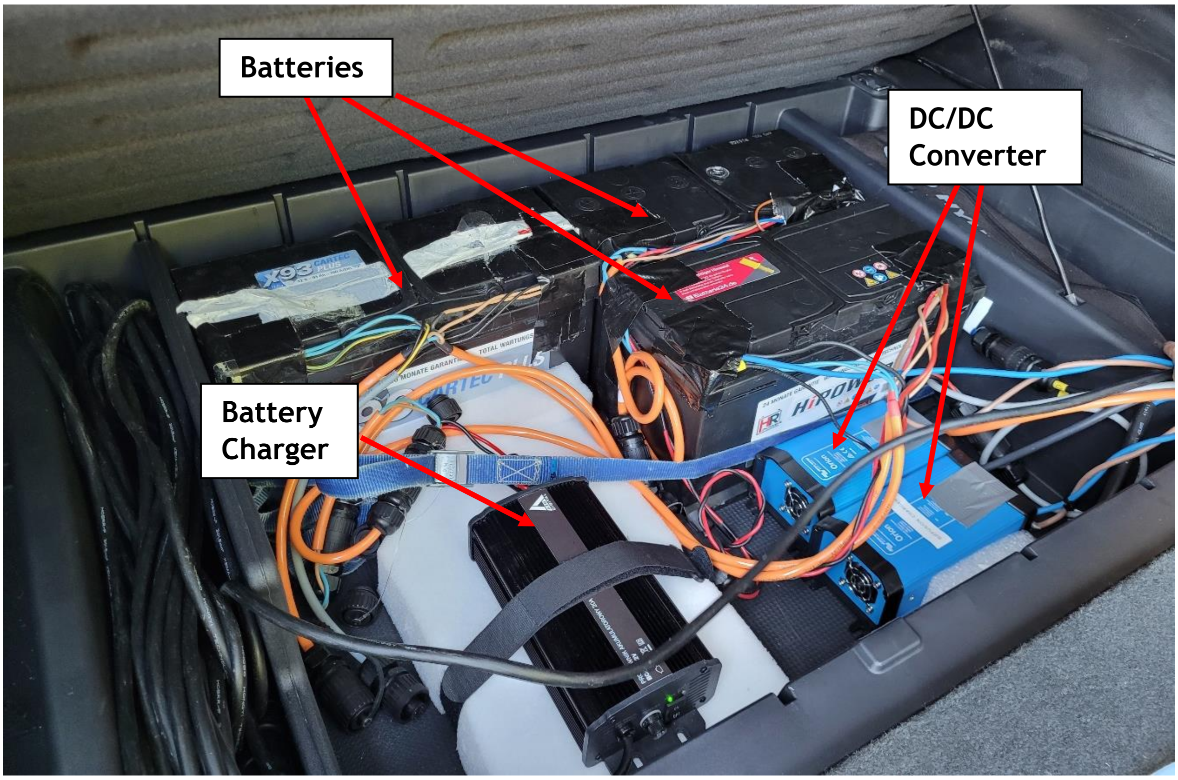

Figure 8: Battery installation in the trunk of the plume chasing vehicle. The two DC/DC Converter provide the needed 24V for the Counter and BCT.

Figure 9: Display installation in the cockpit. A tablet is used to display the real time data and is connected via WiFi to the ICAD instrument. It allows operation and visualisation.

A GPS records the measurement locations and driving speed but is not necessarily needed for the measurements. A dashboard camera was used for additional documentation. By using the pictures, it is possible to check the measurement circumstances and other traffic conditions. The camera is not needed for the real time data analysis.

To visualise the emission results during the Plume chasing measurement, a display (tablet) is installed in the cockpit and is also used as interface to the ICAD connected via WIFI to the instrument (Figure 9). Also, other laptops and tablets could connect to the ICAD at the same time, so that multiple users can directly see the current measurements. Details on the display and user interface are described in section 3.4.

The ICAD instrument has a start-up time of ~1min. At colder temperatures, it may need up to 15min to heat up to the minimum temperature of 25°C before measurements start.

The measurement configuration of an inspected HDV with the chasing vehicle in the exhaust plume is illustrated in Figure 10.

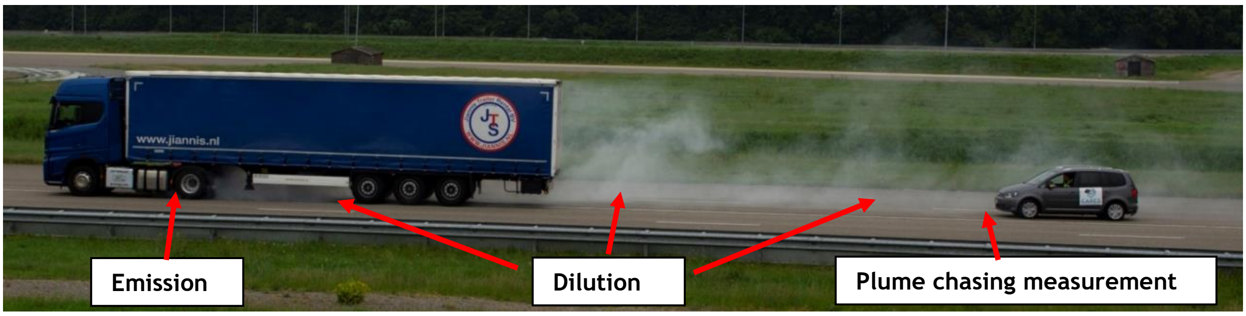

Figure 10: Illustration of plume chasing measurement configuration. The emitted exhaust gases are diluted. The plume chasing vehicle measures the gases in the diluted plume. Exhaust gases visualised in this picture with white smoke.

3.4 Emission software v3.5

A new plume chasing emission software v3.5 was applied in this study now also integrating the visualisation of particle measurements. The emission display is shown in Figure 11. It provides a simple operation during emission measurements with display of the most relevant parameters. Measurements of an individual vehicle are started with pressing “Start”. The “Measurement Status” indicate the status, first showing “Acquiring” indicating that the first emission data are averaged. A “Prelim.” = preliminary result is provided after the first 5 valid data points (10 seconds of data). If sufficient data points are collected (30 data points = 60 seconds) a “Valid” status is indicated. The measurement of an individual vehicle is ended by pressing “Stop”. The classification of the average NO_x emission value is simply illustrated by a three-step traffic light. The three colours indicate clearly “high” (red) emitter, “suspicious” (orange) and “low” (green) NO_x emitter and thus provide necessary information for further inspections. There are three different lights visible. One for Euro VI, one for Euro V and the third one for Euro IV vehicles, all with different emission limits. The fast indication of a preliminary result should help to focus on the high and suspicious emitters if used as screening tool for inspection authorities. If a preliminary result indicates a low emitter, the measurement is typically aborted but still used in the data. This helps to utilize the available measurement time for reliable high emitter identification.

The time series of the Counter and BCT measurements (PN and BC) together with their average values are shown in the lower right window of Figure 11.

For each individually measured vehicle the average emission values are saved in a daily file for the statistics performed in this report.

Figure 11: Explanation of the emission display as visualised during the measurement.

3.5 Time and Location of Measurements

The measurements were performed in Slovakia between 5th September and 5th October 2023. The investigations of HDVs were mainly done on highways, those of LDVs also partly on urban and suburban roads (see Figure 12). The constant driving on highways should allow relative stable emissions and operation of emission reduction systems.

Measurements were performed on 18 days. The weather was most of the time warm and sunny (~20°C), some days were also colder and rainy. During all weather conditions plume chasing emission measurements were performed successfully. No difficulties were observed during stronger rain (a large advantage in comparison to other emission measurement methods).

Figure 12: Map with location of measured vehicles during the study.

3.6 Measurement procedure with inspections

The plume chasing vehicle was measuring different vehicles. When the plume chasing car was behind a vehicle the measurement was started by pressing "Start". The CO_2 plume signal indicated if a sufficient signal from the exhaust plume is detected. Only data points measured with min. 30ppm CO_2 above the derived background are considered by the software as being valid signals = valid data points. During some driving situations, no emission plume is present like deceleration, downhill or with strong side winds. The chasing vehicle followed until a sufficient signal was collected. After the first 5 valid data points (= 10 seconds) a preliminary emission value is indicated. If this indicated a low emitter (<1200mg/kWh for Euro VI HDV), the measurement was, in most cases stopped as it can be expected that this vehicle will be a low emitter. If the emission value indicated a suspicious or high emitter, the measurement was continued until a valid emission value (30 valid data points = 60 seconds) is achieved. The measurement of an individual vehicle was stopped by pressing "Stop". In case of measuring a HDV, after the measurement the vehicle was overtaken to record vehicle type, number plate and Euro emission standard (from signs or front face of HDV). For LCV and PC, the data was documented from the rear.

On days when inspections of identified high-emitting HDVs by the police were possible, an identified high or suspicious emitter (according to its Euro emission standard) was reported to the police by phone. The Slovak police stopped then those vehicles and performed an inspection. Dedicated inspection tools (e.g., from Wabcowürth) were applied to identify the reason for the high emission level. Due to traffic conditions, logistical and safety reasons, not all HDVs with suspicious or high emission level could be inspected. Efficiency could be significantly increased if the measurement vehicle was also the police car, stopping the high emitter for inspection.

Some of the stopped vehicles for inspection were measured less than the required 30 data points. This can have a significant influence on the reliable identification of the high emitters as the longer measurement is needed to avoid a false positive result e.g., due to a cold engine or a specific short term engine state.

Figure 13: Introduction of the plume chasing measurement system to Slovak police and inspection of an HDV.

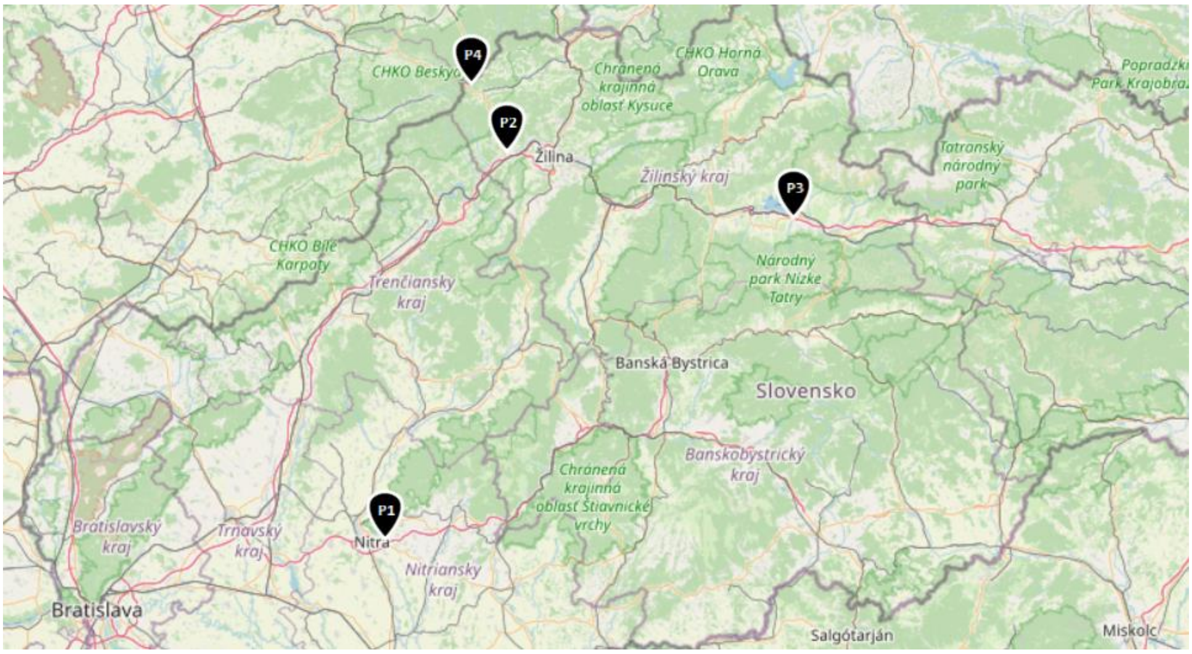

Figure 14: Location of checkpoints for police inspections.

There were four different check points (P1-P4) for police inspections throughout the campaign (see Figure 14). At inspection point P1 two police cars were waiting just before the exit to the inspection point at the highway and escort the HDV reported by the plume chasing vehicle. At P2 and P3 there was only one police vehicle available. It was following the chasing vehicle all the time and started to escort the HDV (only in direction of the fixed measurement point) after they were classified as high or suspicious emitters. This procedure results in less cases where the HDV left the highway or stopped for a break in between the measurement and the location where the police car was waiting. P4 was a checkpoint close to the border of Czechia. It was a narrow street and all HDVs going this direction had to pass this checkpoint. High emitters were waved out by one police man when passing the checkpoint. At this point HDVs were checked also for different other things like load or breaks. Disadvantage was that after one hour of inspections the amount of HDVs traveling in the direction of the inspection point decreased significantly as truck drivers trying to avoid police inspections (drivers spread the information immediately after the first inspections start).

4 Vehicle statistics

Emission measurements for 2941 vehicles were performed in this study. Measurements with less than 5 valid data points (<10 seconds), with a contaminated plume from a high emitter in front, or where no information (euro emission standard, fuel type, data inconsistency…) for the vehicles was obtained, are excluded. Thus, valid emission measurements from 2547 vehicles could be used for the analysis.

In total, plume chase data of 1889 HDVs, 16 buses, 449 Passenger Cars (PCs), 2 motorcycles and 191 Light Commercial Vehicles (LCVs) could be retrieved (see Figure 15). From the 1889 HDVs, 264 were measured on the way from Germany through Czechia to Slovakia and back. If not other mentioned for the further HDV analysis, only the HDVs in Slovakia are considered.

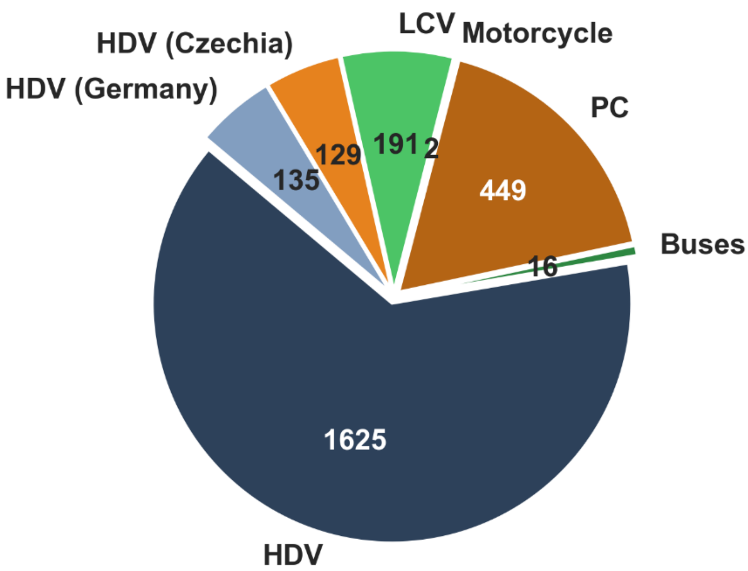

Figure 15: Distribution of vehicle categories of valid chases. In total, 2547 valid plume chases were performed. Indicated vehicles are measure in Slovakia if not labelled otherwise.

All measured HDVs in Germany or Czechia are measured on highways. The road type of the other vehicle categories is shown in Figure 16. Most of the Slovakian HDVs are measured on highways (97%), whereas 30% and 17% of the PCs and 12% and 16% of the LCVs are measured under urban and suburban conditions respectively.

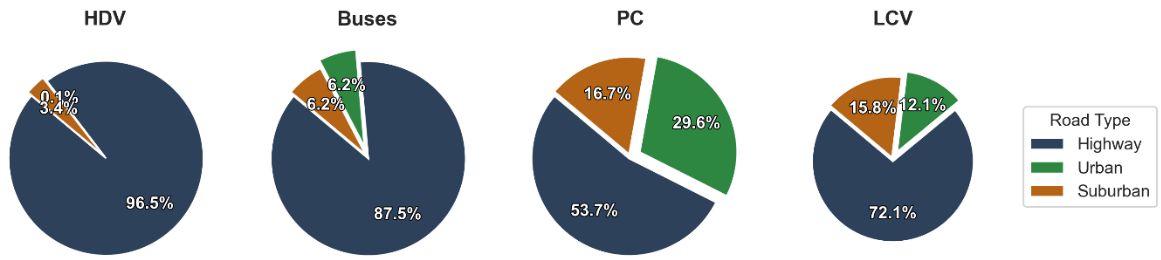

Figure 16: Road type of measured HDVs, Buses, PCs and LCVs.

4.1 HDVs

4.1.1 Euro emission standard

Most of the HDVs (72%) measured in Slovakia are Euro VI vehicles (Figure 17). 20% are Euro V vehicles and less than 8 % are Euro IV or below. For 1618 (>99% of the measured individual HDVs), a Euro emission standard could be classified.

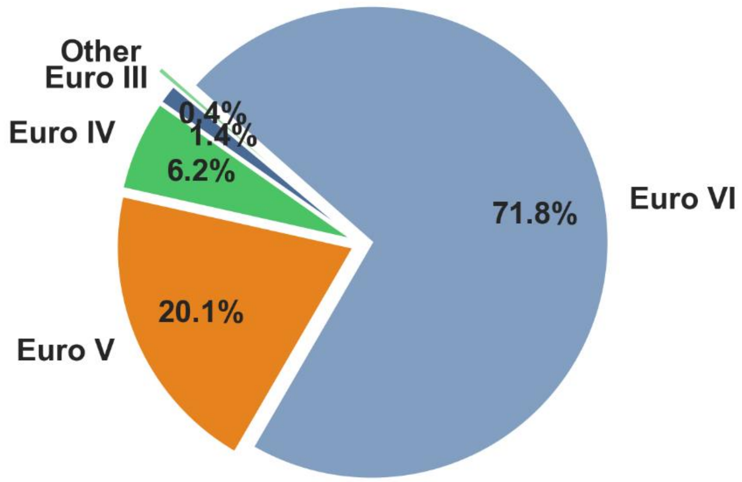

Figure 17: Distribution of Euro emission standard between the measured HDVs in percent.

4.1.2 Country of origin

For 1623 HDVs, a country of origin was read from the number plate. The largest group is from Slovakia (56%) followed by Poland (22%) and Czechia (7%) (Figure 18). Next are HDVs from Hungary, Romania, Slovenia with already less than 60 vehicles each (Table 2).

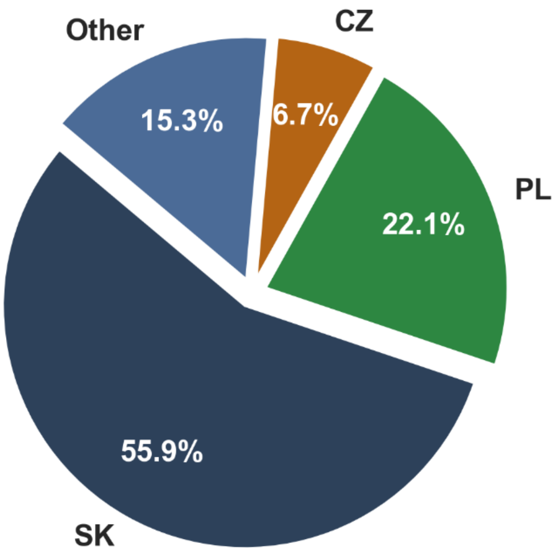

Figure 18: Distribution of origin for the measured HDVs in percent.

origin HDV (sorted by percentage)	No#	percentage
SK	910	56.0%
PL	358	22.0%
CZ	109	6.7%
H	53	3.3%
RO	36	2.2%
SLO	28	1.8%
TR	21	1.3%
UA	20	1.3%
SRB	19	1.2%
HR	17	1.1%
LT	10	0.6%
A	10	0.6%
BG	8	0.5%
MK	6	0.4%
P	5	0.3%
BIH	4	0.3%
GE	3	0.2%
D	2	0.1%
NL	1	0.1%
S	1	0.1%
RO	1	0.1%
GR	1	0.1%
F	1	0.1%
UK	1	0.1%
Sum	1631	100%

Table 2: Country of origin of measured HDV. The country indicated is from the truck not the trailer.

4.1.3 Brands

For 1596 HDVs, a brand could be identified and was logged (Figure 19). A mixture of all common brands was investigated. The three most common brands on Slovak highways are Scania, Volvo and Mercedes for Euro VI HDVs. For Euro V vehicles, Volvo, MAN and Scania. Only a few Euro VI HDVs were measured from the brands Ford, Tatra, Avia and Mitsubishi (<1.6% each).

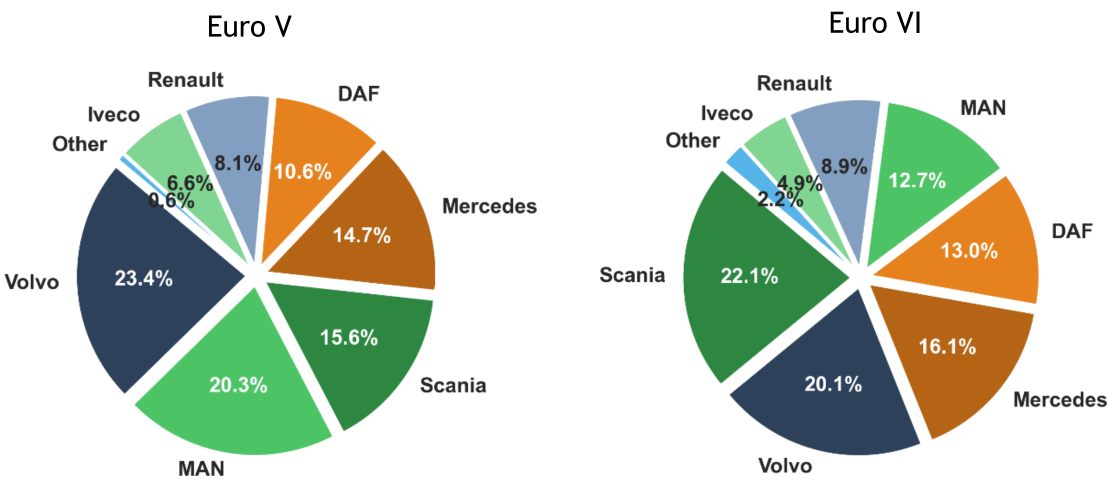

Figure 19: Ratio of HDV brands for Euro V and Euro VI.

4.2 Passenger cars (PC)

449 valid measurements of PCs were investigated. Technical vehicle information from data base (databasevozidiel.sk), including Euro emission standards and vehicle make, is available for 365 PCs (81% of the measured individual PCs). 62.2% are diesel PCs, 35.1% petrol and 2.8% LPG.

4.2.1 Euro emission standard

Most of the PCs (51%) measured are Euro 6a - 6d vehicles (Figure 20). 22% are Euro 5, 18% Euro 4 and less than 10% are older vehicles. For 422 (>93% of the measured individual PCs), a Euro emission standard could be classified.

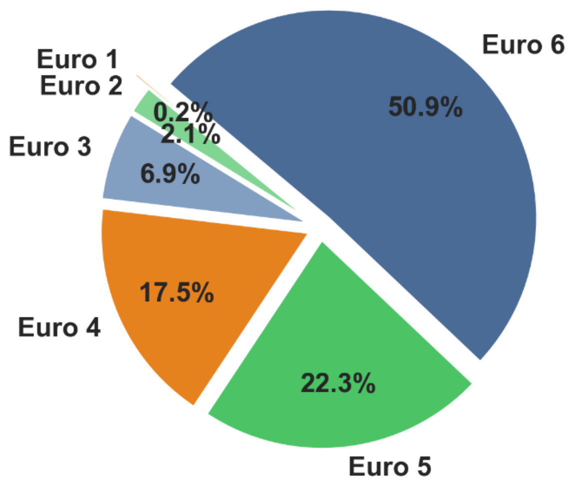

Figure 20: Distribution of Euro emission standard between the measured PCs in percent.

4.2.2 Brands

For 431 PCs, a brand could be identified. A mixture of all common brands was investigated. The two most common brands are Skoda and VW with a share of over 40% for Euro 5 PCs and a share of over 30% for Euro 6 PCs (Figure 21).

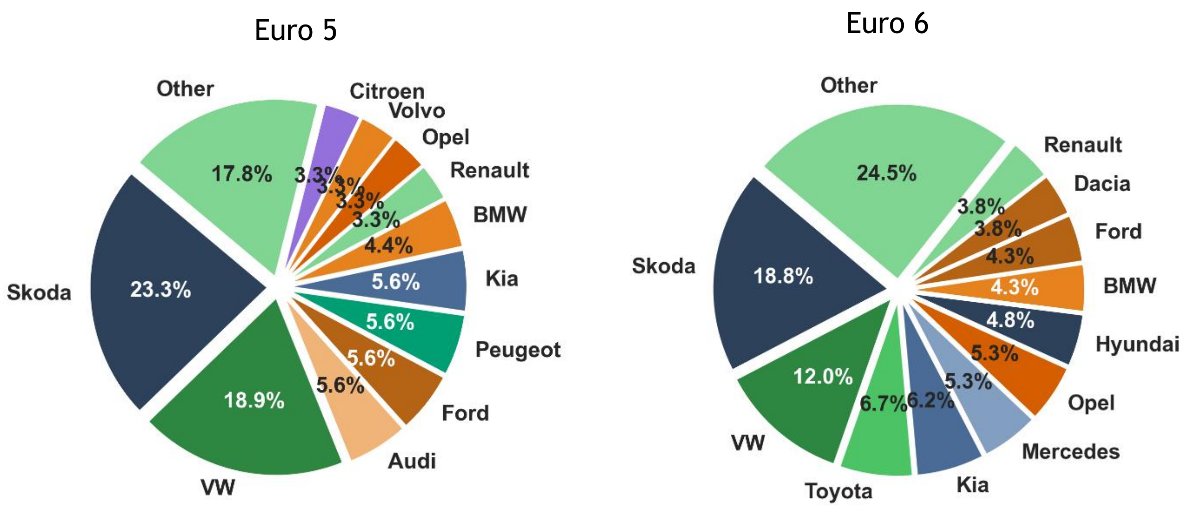

Figure 21: Ratio of PC brands for Euro 5 and Euro 6.

4.3 Light Commercial Vehicles (LCVs)

191 LCVs were investigated. For 132 of them (69% of the measured individual LCVs) the technical vehicle information, including the Euro emission standard and the make of the vehicle, was available. Almost all (97.7%) of the LCVs in the study are diesel-powered.

4.3.1 Euro emission standard

Most of the LCVs (64%) measured are Euro 6 vehicles (Figure 22). 21% are Euro 5 and less than 16% are Euro 4 and below. For 180 (>94% of the measured individual LCVs), a Euro emission standard could be classified.

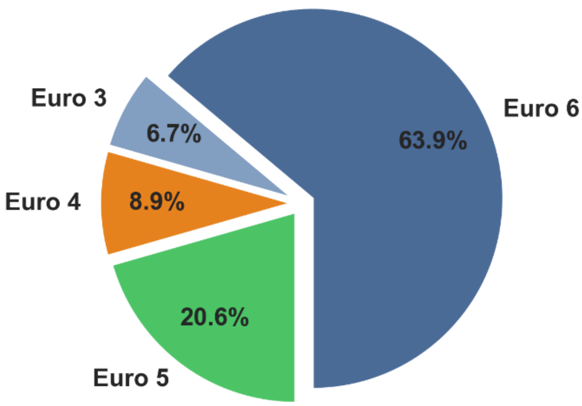

Figure 22: Distribution of Euro emission standard between the measured LCVs in percent.

4.3.2 Brands

For all LCVs a brand could be identified. A mixture of all common brands was investigated. The three most common brands are Fiat, Renault and Peugeot for Euro 5 and Euro 6 LCVs (Figure 23).

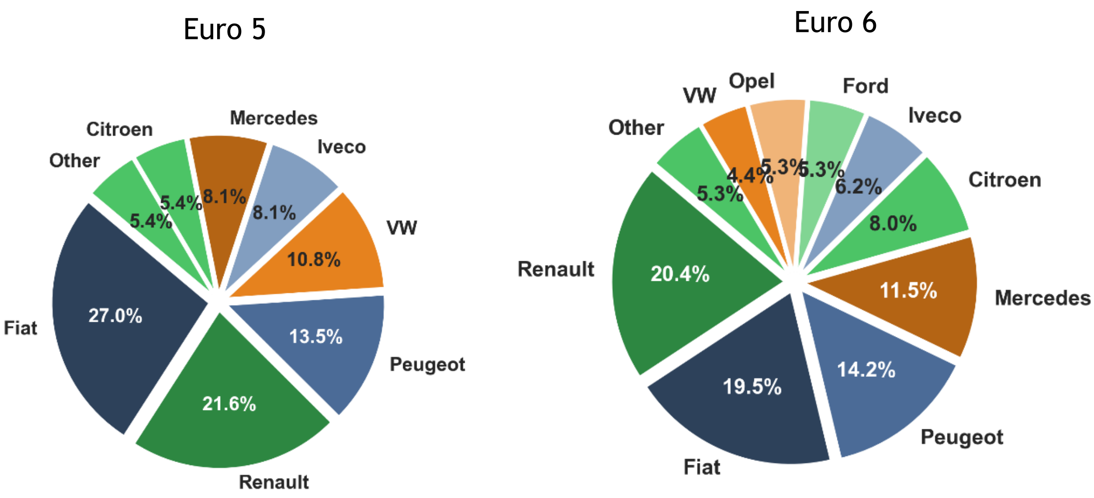

Figure 23: Ratio of LCV brands for Euro 5 and Euro 6.

5 Emission values

5.1 HDVs

5.1.1 NO_x, PN and BC emissions

The NO_x, PN and BC emissions of HDVs measured by the Plume Chasing method for different Euro emission standards can be found in Figure 24. The median emissions of all species are decreasing with increasing Euro emission standard. NOx emissions decrease significantly from 2411mg/kWh for Euro V to 770mg/kWh for Euro VI HDVs. The PN and BC emissions show a 65% and 79% decrease of emissions from Euro V to Euro VI HDVs with the obligatory introduction of diesel particle filters.

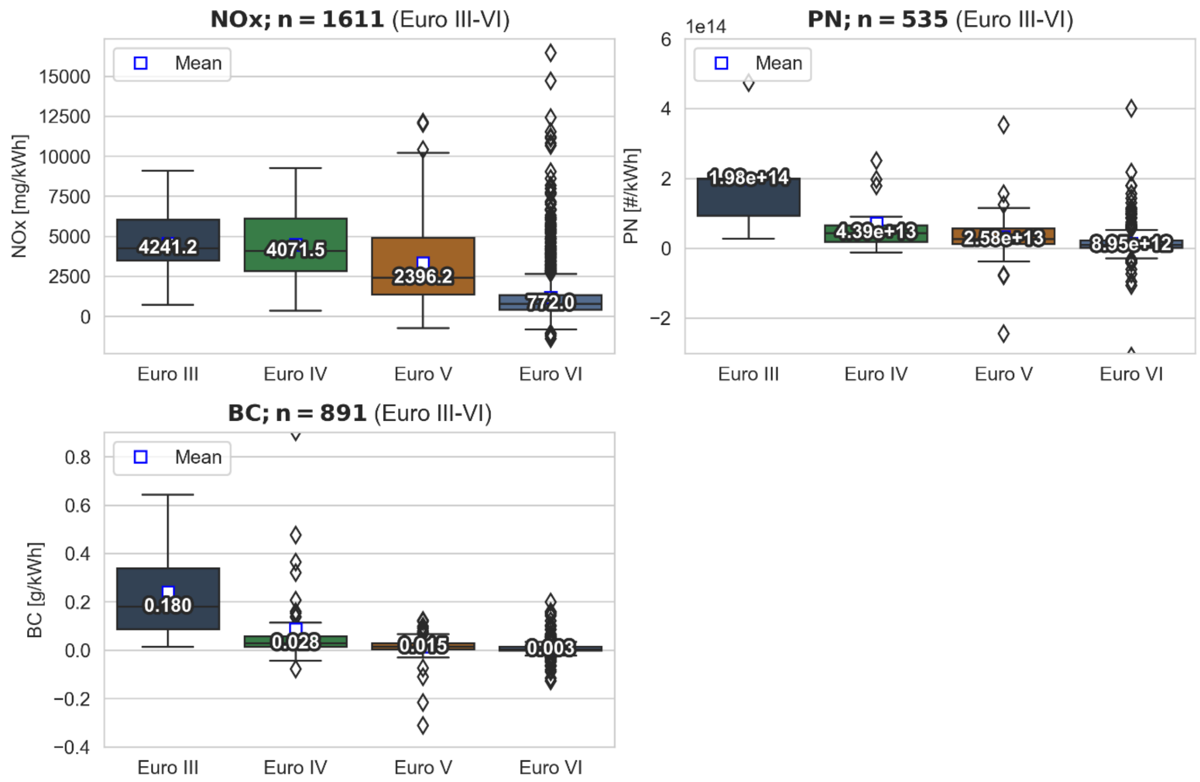

Figure 24: Distribution of average NOx, non-volatile PN (>23nm) and BC emissions of Euro III to Euro VI HDVs, measured in Slovakia. HDVs below Euro III are excluded, as well as HDVs with unspecified Euro classes. The numbers in the plots represent the medians.

The NO_x, PN and BC emissions for different brands (Volvo, MAN, Scania, Mercedes and DAF) can be found in Figure 25 for Euro V and in Figure 26 for Euro VI HDVs. It should be noted that the number of HDVs measured per brand is low, especially for Euro V, so no statistically robust conclusion can be drawn.

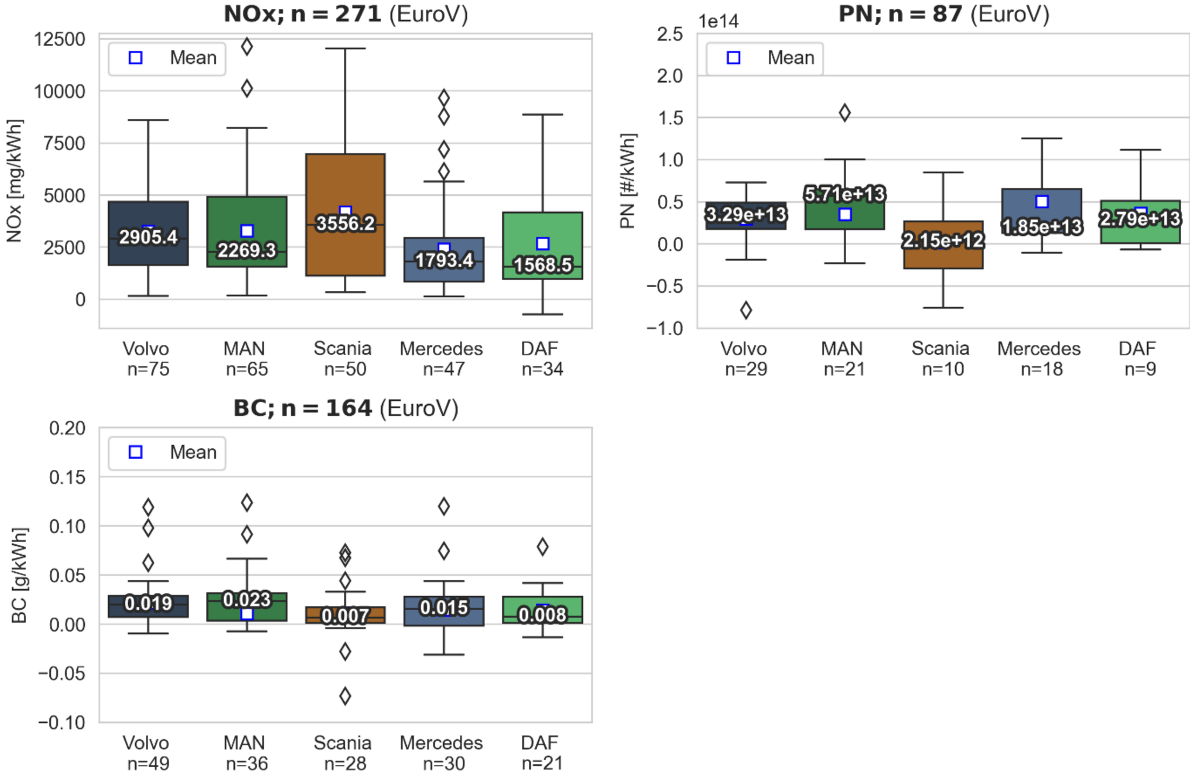

Figure 25: Distribution of average NOx, non-volatile PN (>23nm) and BC emissions of Euro V HDVs by brand, measured in Slovakia. The numbers in the plots represent the medians.

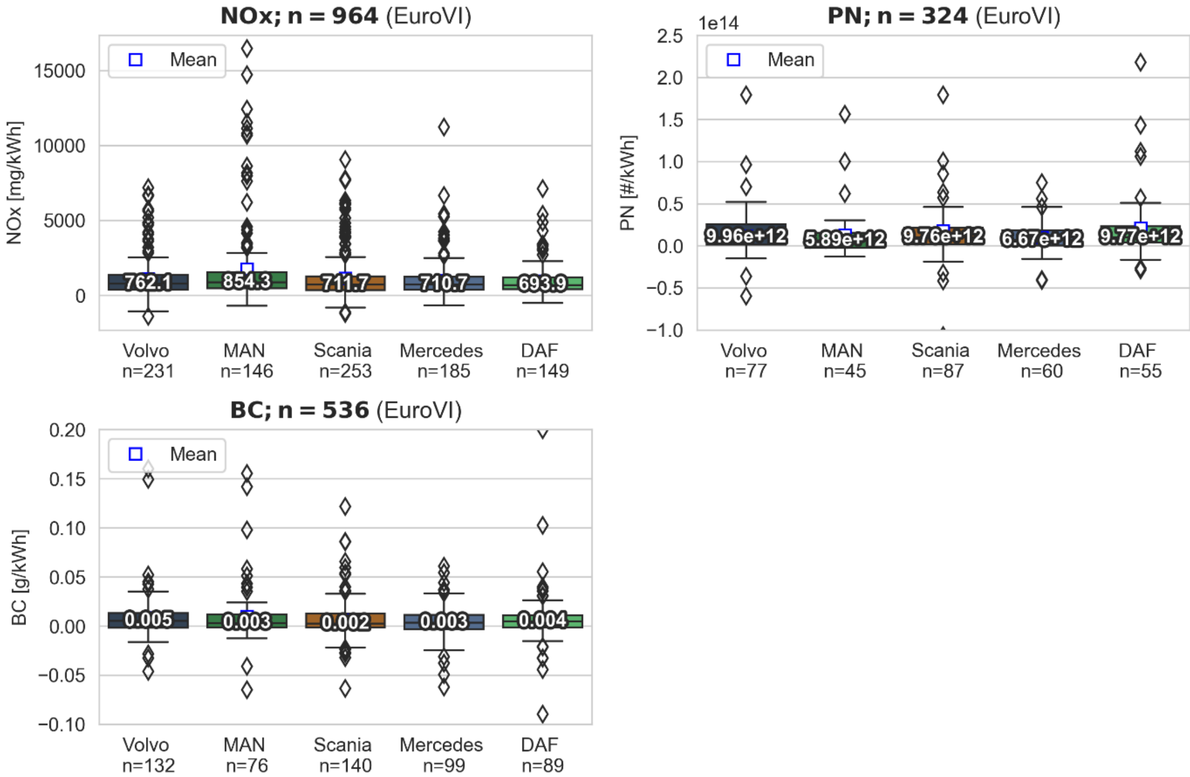

Figure 26: Distribution of average NOx, non-volatile PN (>23nm) and BC emissions of Euro VI HDVs by brand, measured in Slovakia. The numbers in the plots represent the medians.

5.1.2 Classification of emission limits NO_x

To identify a suspicious or a high emitter a margin to the Euro emission standard limit is added. The limits were derived from plume chasing emission measurements combined with inspections [6]. The margin does not only include the variability of the emission system, but also measurement uncertainties due to e.g. other emission plumes.

	Euro III	Euro IV	Euro V	Euro VI
Classification	mg/kWh	mg/kWh	mg/kWh	mg/kWh
low	≤6000	≤4000	≤2500	≤1200
suspicious	>6000	>4000	>2500	>1200
high	>7000	>5000	>3500	>2200
Euro emission limit	≤5000	≤3500	≤2000	≤460
RDE conformity factor	-	-	-	1,5
Euro RDE emission limit	-	-	-	≤690

Table 3: Defined thresholds for emission classification used in this study.

5.1.3 Emission statistics NO_x

The derived emission values of each HDV are classified according to chapter 5.1.2. 66% are classified as low emitters. 16% of HDVs are found to be suspicious, and 18% clearly as high emitters (Figure 27). The ratio of suspicious and high emitters is similar to a previous study in Czechia [4].

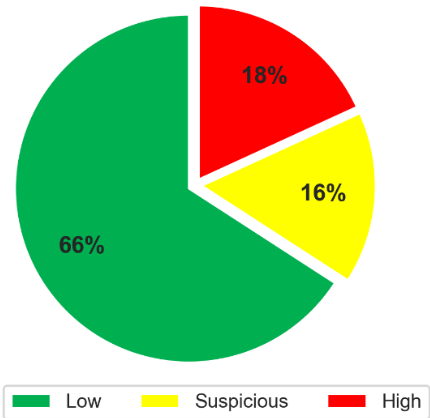

Figure 27: Statistics of NO_x emission classification of all measured HDVs (all countries and all Euro emission standards).

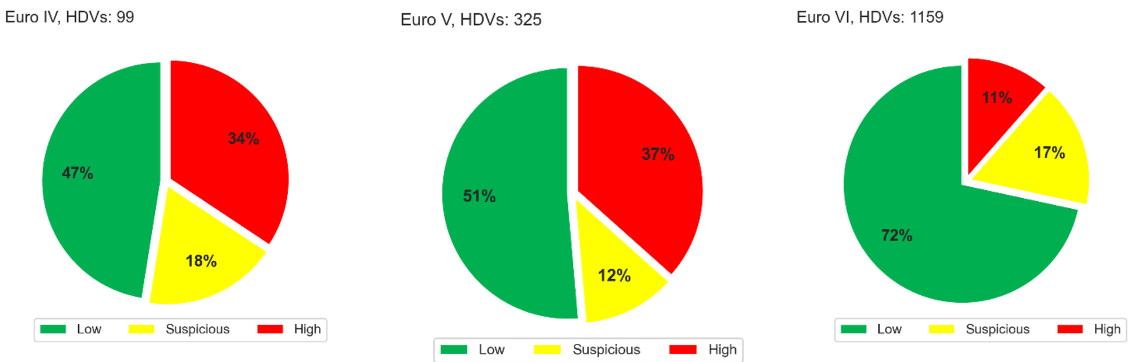

Figure 28: Statistics of NO_x emission classification separated by Euro emission standard.

The separation for the different Euro emission standards indicates lowest ratio of suspicious and high emitters for Euro VI. Euro IV should be investigated with caution, as these are quite old HDVs with high mileage where the emission system may not work properly anymore due to normal aging. This is due to the fact that for EURO IV and V manufacturers only need to demonstrate emission limit compliance for a lifetime of 500.000km or 7 years (EU Effective 2005.10/2006.10, for Euro VI this is 700.000km or 7 years). During normal technical inspection, the NO_x emission reduction system is not tested, so it is possible that a degraded emission reduction system will not be detected.

The ratio of suspicious and high emitters for Euro V is significantly higher than for Euro VI (Figure 28). A plausible reason is that newer vehicles have less often a defective emission system and most likely they are not manipulated as long as they are under warranty of the manufacturer. Additionally, leased trucks are typical new EURO VI models which are unlikely to be manipulated by the operators.

5.1.4 Comparison with measurements on German and Czech highways

Same analysis like in chapter 5.1.1 and chapter 5.1.3 is performed for the HDVs measured on the way to Slovakia on German and Czech highways. 135 HDVs were measured on German highways and 129 on Czech highways (Figure 15).

The NO_x, BC and PN emissions of HDVs measured on German and Czech highways can be found for different Euro emission standards in Figure 29. Compared to the average emissions measured in Slovakia (also shown in Figure 29 for a better comparison), the average emissions in Germany are lower for Euro V and VI HDVs for all species. For Euro IV they are higher, but as only one Euro IV HDV is measured in Germany this number is not representative. In Czechia the median emissions are for NO_x and PN higher than in Germany (more than twice as high) and also higher than in Slovakia (up to 50% higher). No BC measurements were performed on Czech highways.

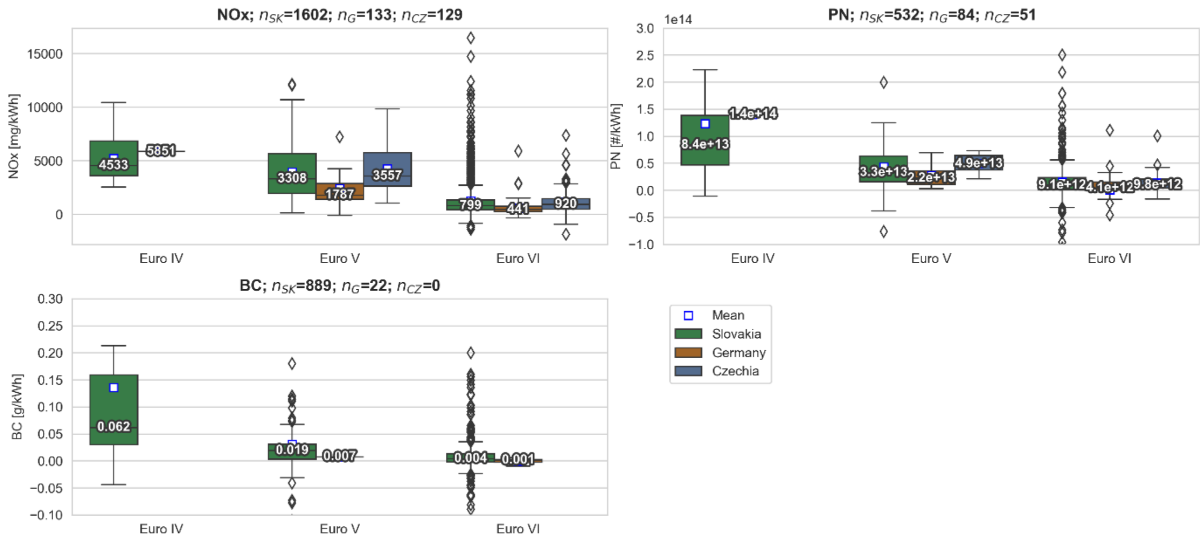

Figure 29: Distribution of average NOx, non-volatile PN (>23nm) and BC emissions of Euro IV to Euro VI HDVs, measured on Slovakian, German and Czech highways. The numbers in the plots represent the medians.

The ratio of suspicious and high emitters is 8% for trucks on German highways (Figure 30). On Czech highways, the ratio of suspicious and high emitters is similar to Slovakia at 41% (Figure 30). The proportion of suspicious emitters on Czech highways (21%) is even slightly higher than on Slovakian highways (16%). The large differences show that the rate of high and suspicious emitters is very different from country to country.

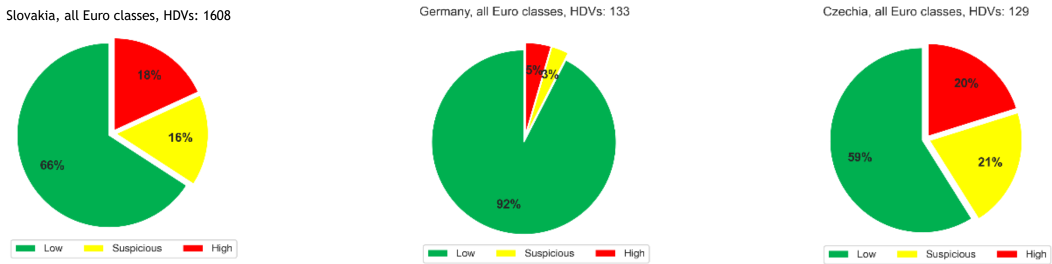

Figure 30: Statistics of NO_x emission classification for EURO V plus EURO VI HDVs measured on Slovakian, German and Czech highways. Note the small statistical quantity of vehicles in Czechia and Germany.

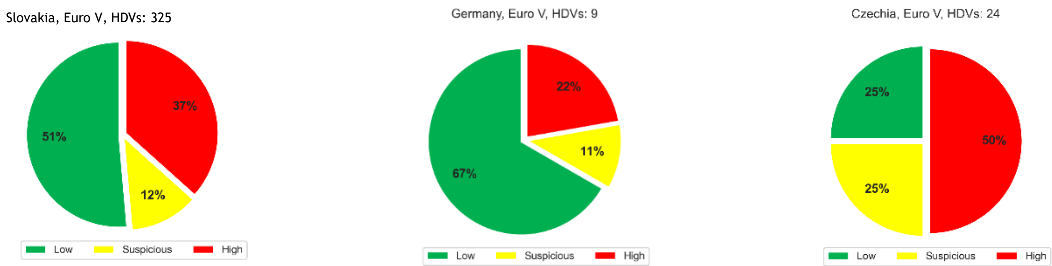

Figure 31: Statistics of NO_x emission classification for Euro V HDVs measured on Slovakian, German and Czech highways. Note the small statistical quantity of vehicles in Czechia and Germany.

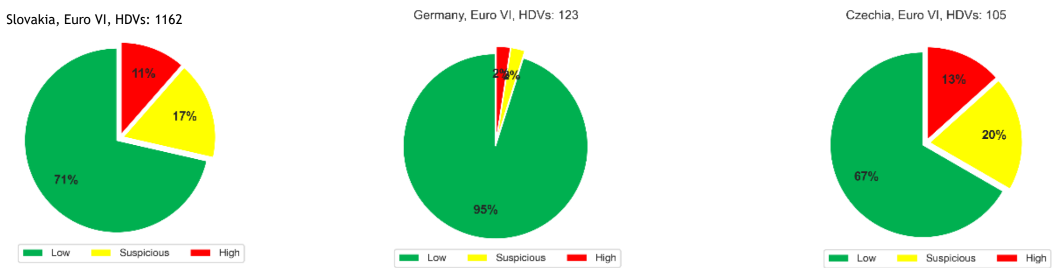

Figure 32: Statistics of NO_x emission classification for Euro VI HDVs measured on Slovakian, German and Czech highways. Note the small statistical quantity of vehicles in Czechia and Germany.

To investigate this further, the rate of high and suspicious emitters divided by country of origin is shown in Figure 33 for the 6 most represented countries. HDVs from Slovakian, German and Czech highways and all euro emission standards are included.

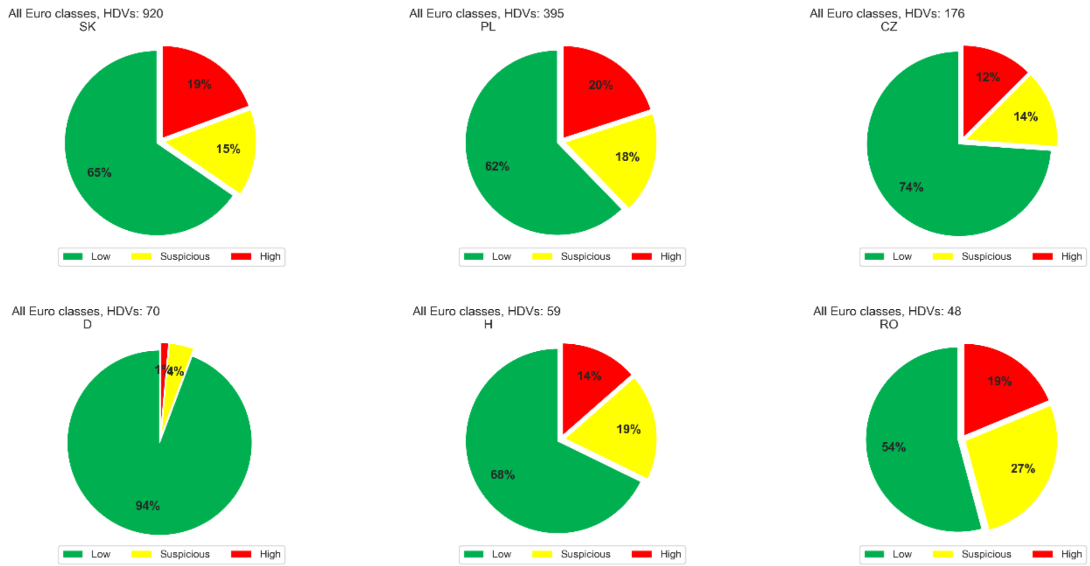

Figure 33: Statistics of NO_x emission classification for HDVs measured on Slovakian, German and Czech highways with different countries of origin: Slovakia (SK), Poland (PL), Czechia (CZ), Germany (D), Hungary (H) and Romania (RO). Note that all euro emission standards are included.

5.1.5 Histograms of NO_x emissions

To study the distribution of the NO_x emission values, histograms are shown in Figure 34. Some of the HDVs show low emissions below 1000mg/kWh. A significant fraction of HDVs with values above 3000mg/kWh is observed. Especially a large fraction of Euro V HDVs (~19%) had very high emissions above 6000mg/kWh. Those vehicles often contaminated the plume of up to two HDVs behind them if they were driving in close distance to each other. The contaminated vehicles were counted as invalid measurements.

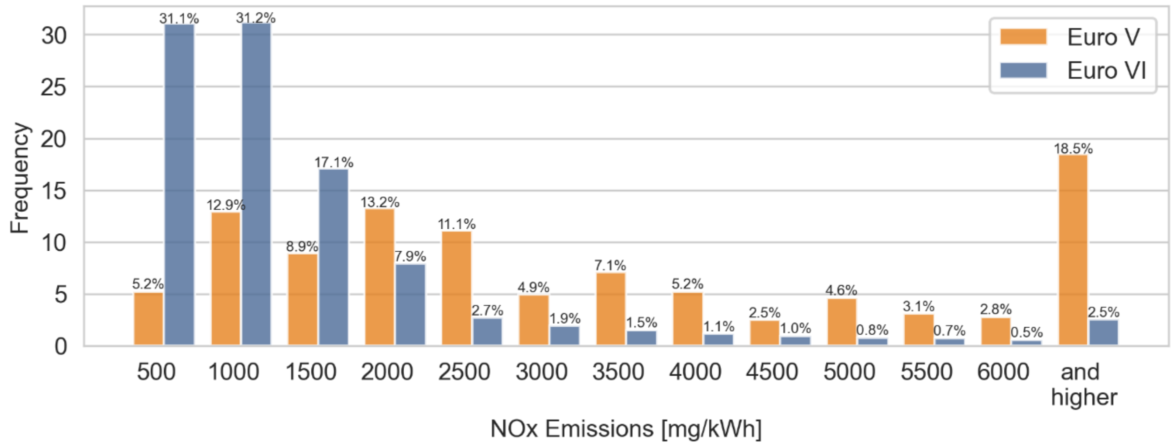

Figure 34: Histogram of observed NO_x emissions for Euro V and Euro VI HDVs.

5.1.6 Histograms of BC emissions

To study the distribution of the BC emission values, histograms are shown in Figure 35. We compare the BC emission values with the emission limit for PM, of which BC is a fraction. Some of the HDVs show low BC emissions below 10mg/kWh. A significant fraction of Euro VI HDVs has values above the Euro VI emission standard of 10mg/kWh. The same is observed for Euro V HDVs and the Euro V emission standard of 20mg/kWh. A significant fraction of Euro V HDVs (~6%) has very high emissions above 60mg/kWh. Those vehicles are not necessarily the same as the high NO_x emitters (Figure 36).

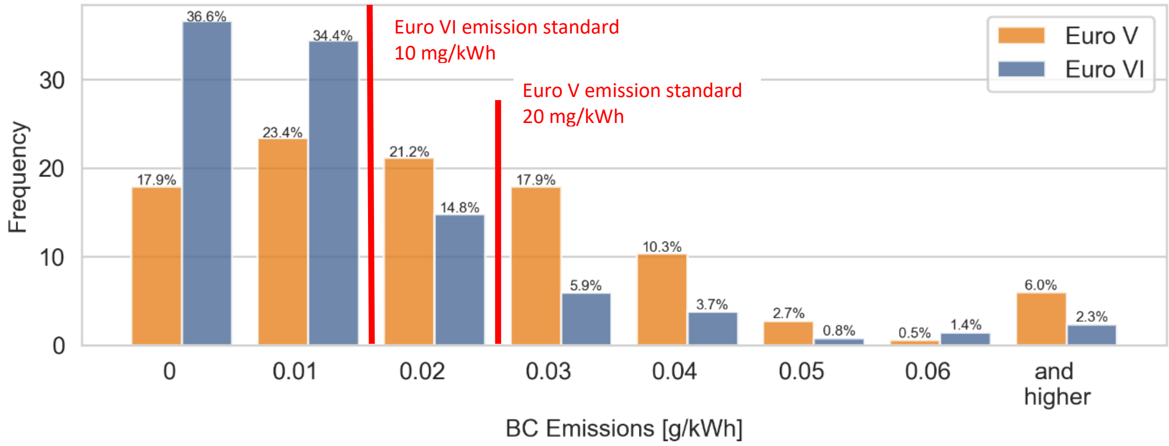

Figure 35: Histogram of observed BC emissions for Euro V and Euro VI HDVs.

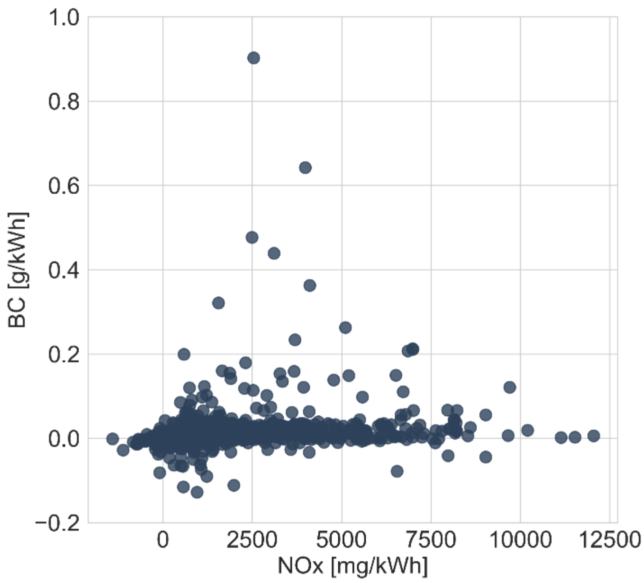

Figure 36: BC vs. NOx emissions for all measured HDVs.

5.1.7 Histograms of PN emissions

To study the distribution of the PN emission values, histograms are shown in Figure 37. Only very few (~23%) of the Euro VI HDVs show emissions below the Euro VI emission standard of $6{\cdot}10^{11}$ #/kWh. As for NO_x and BC especially a significant fraction (~22%) of Euro V vehicles shows very high PN emissions above $6{\cdot}10^{13}$#/kWh. In contrast to NO_x and PM, there is no emission limit for PN for HDVs that are Euro V or lower. High PN emissions often correlate with high BC emissions (Figure 38).

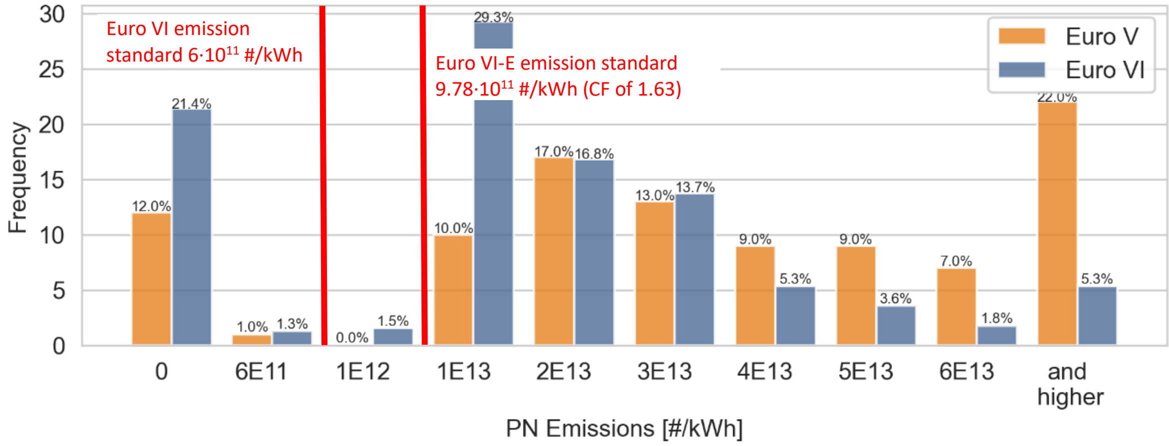

Figure 37: Histogram of observed PN emissions for Euro V and Euro VI HDVs.

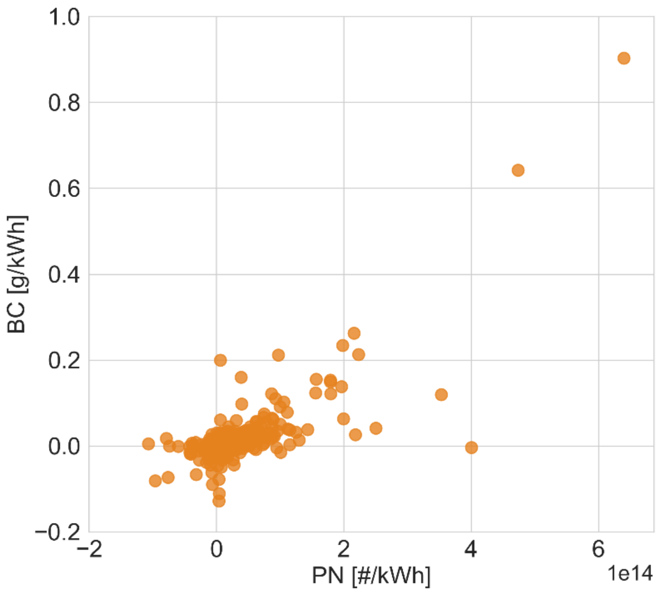

Figure 38: BC vs. PN emissions for all measured HDVs.

5.2 Passenger cars

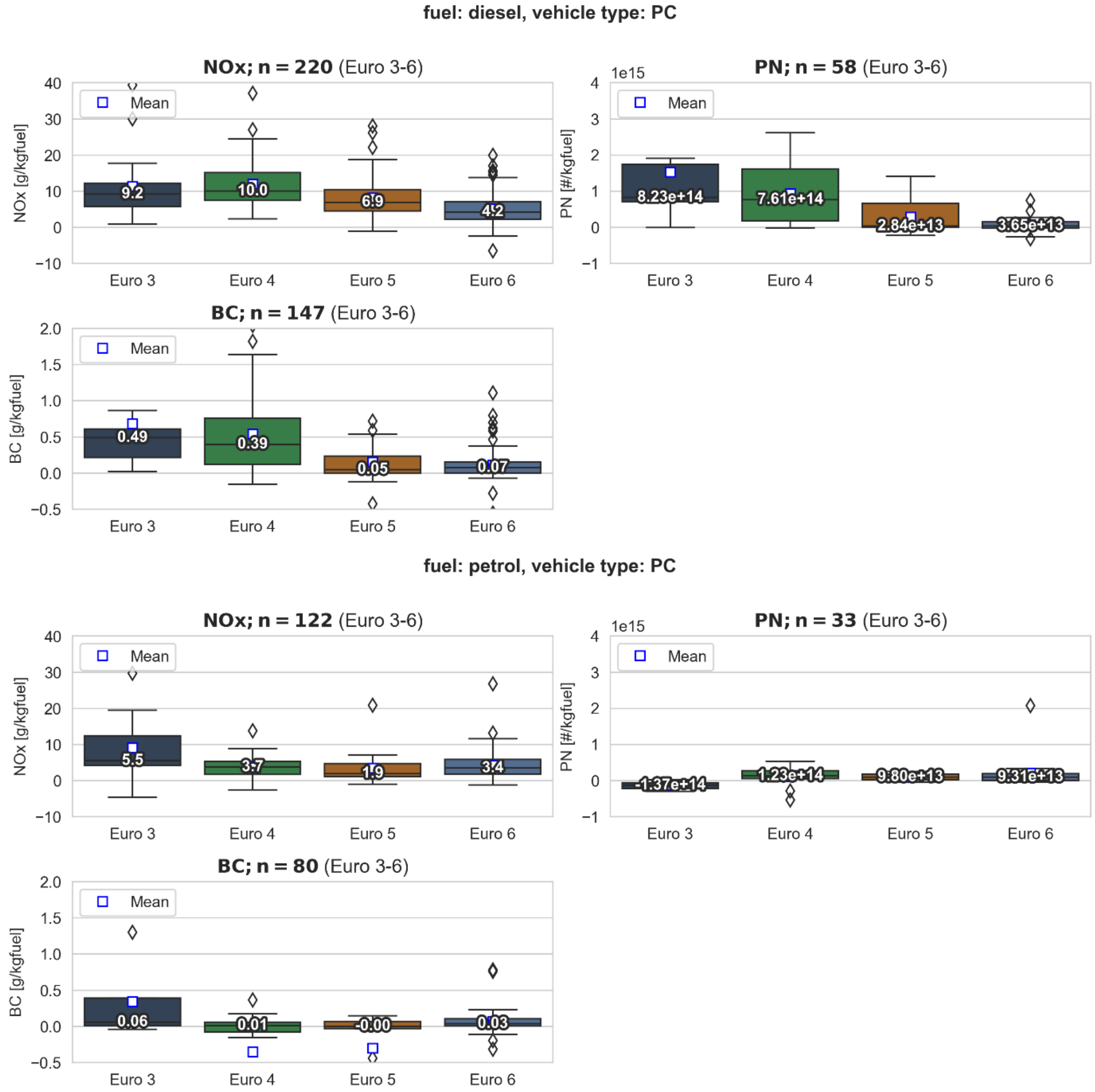

Figure 39: Distribution of average NOx, PN and BC emissions of Euro 3 to Euro 6 PCs (diesel top and petrol bottom), measured in Slovakia. Note the small statistical quantity of PN measurements. The numbers in the plots represent the medians.

The NO_x, PN and BC emissions of PCs measured by the Plume Chasing method for different Euro emission standards can be found in Figure 39. The emissions are separated by fuel type (at the top: diesel, at the bottom: petrol).

The average emissions of diesel PCs decrease as the Euro emission standard increases from Euro 3 to Euro 5. There are no major differences between Euro 5 and Euro 6 emissions, except for NO_x, which is around 30% lower for Euro 6 PCs.

For petrol PCs, there are no major differences between the different Euro emission standards, especially for PN and BC emissions. NO_x emissions decrease with increasing Euro emission standards from 5.5g/kgfuel for Euro 3 to 1.9g/kgfuel for Euro 5 and increase again by 70% for Euro 6 petrol PCs. This might be due to a small number of vehicles contributing to the statistics of Euro 3 to 5 petrol PCs (<21).

5.3 Light commercial vehicles

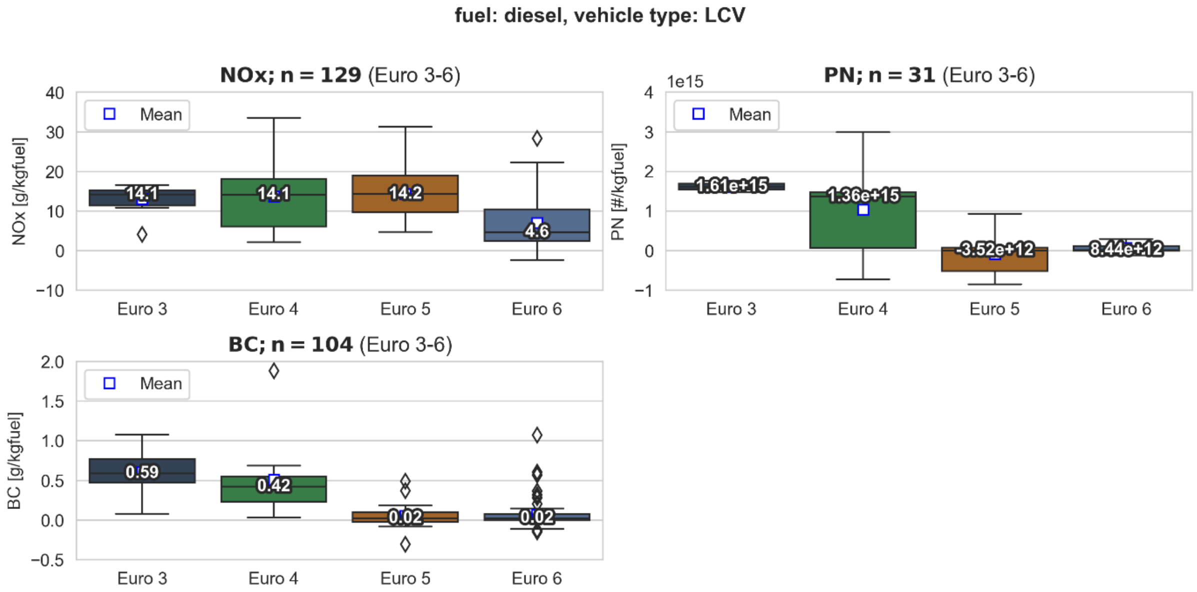

Figure 40: Distribution of average NOx, PN and BC emissions of Euro 3 to Euro 6 LCVs (diesel), measured in Slovakia. Note the small statistical quantity of PN measurements. The numbers in the plots represent the medians.

The NO_x, PN and BC emissions of LCVs measured by the Plume Chasing method for different Euro emission standards can be found in Figure 40. Median NO_x emissions decrease significantly from Euro 5 to Euro 6 LCVs (from 14.2g/kgfuel to 4.6g/kgfuel). This is also the case for BC from Euro 4 to Euro 5 LCVs (from 0.42g/kgfuel to 0.02g/kgfuel) and for PN (from $13.6 \cdot 10^{14}$#/kgfuel to $0.04 \cdot 10^{14}$#/kgfuel).

5.4 Summary

An overview of all median emission values can be found in Table 4.

Table 4: Overview of median emission values.

		Euro 3/III	Euro 4/IV	Euro 5/V	Euro 6/VI
HDV	NO_x [mg/kWh]	4241	4102	2411	770
	BC [mg/kWh]	180	28	14	3
	PN [#/kWh] $\cdot 10^{13}$	19.8	4.4	2.6	0.9
PC (petrol)	NO_x [g/kgfuel]	5.5	3.7	1.9	3.4
	BC [g/kgfuel]	0.06	0.01	0.0	0.03
	PN [#/kgfuel] $\cdot 10^{13}$	-13.7	12.3	9.8	9.3
PC (diesel)	NO_x [g/kgfuel]	9.2	10.0	6.9	4.2
	BC [g/kgfuel]	0.49	0.39	0.05	0.07
	PN [#/kgfuel] $\cdot 10^{13}$	82.3	76.1	2.8	3.7
LCV	NO_x [g/kgfuel]	14.1	14.1	14.2	4.6
	BC [g/kgfuel]	0.59	0.42	0.02	0.02
	PN [#/kgfuel] $\cdot 10^{13}$	161	136	-0.4	0.8

6 HDV Inspections

In total 28 HDVs identified as high or suspicious emitters were inspected by the police. These are about 5% of the HDVs flagged as suspicious or high emitters. One of the inspected HDVs was Euro IV, 13 Euro V and 14 Euro VI. The Euro IV vehicle is not further included as it does not have a SCR or similar emission reduction system.

For 16 out of 28 inspected Euro V and VI HDV (50%) only a shorter preliminary emission measurement was achieved (less than 30 data points equivalent to less than 60 seconds data) before the HDV was stopped. A longer measurement was sometimes not possible due to traffic conditions, logistical and safety reasons. However, it needs to be considered that the emission values of these 16 HDVs have a higher uncertainty and conclusions should be made with caution.

3 out of the 28 inspected HDVs were classified as suspicious emitters, the rest as high emitters.

The findings of the inspections are separated in five categories:

(1) no Error found
(2) a Defect / Error found
(3) a Manipulation found (emulator, software, temp. sensor, NO_x sensor de-activation)
(4) a cold SCR / cold Engine with inactive SCR system
(5) Software issue found

The “Cold SCR” indicates, not an error of the measurement and of the HDV, high emissions were caused by an SCR emission reduction system in an inactive state. However, it is an unwanted feature when defective and manipulated HDV should be identified.

Multiple conclusions for one HDV are avoided, even if this would in principle be possible. In the following analysis the focus is on Euro V and Euro VI HDVs (in total 27 inspected HDVs), as older HDVs are allowed to have higher emissions and there are only limited possibilities for inspections of the emission system.

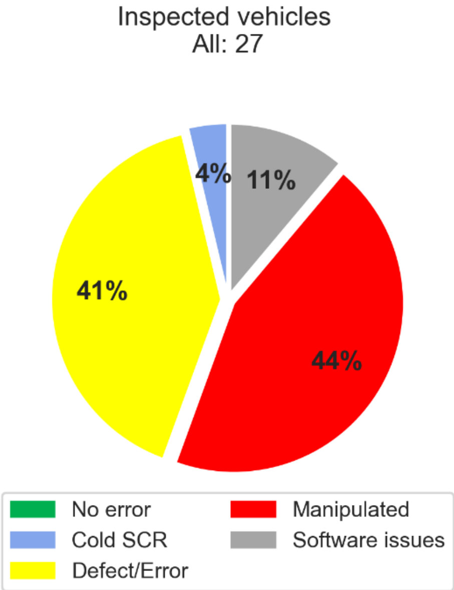

Figure 41: Conclusion of the inspected HDV for Euro V and VI. The percentage is relative to the inspected HDV.

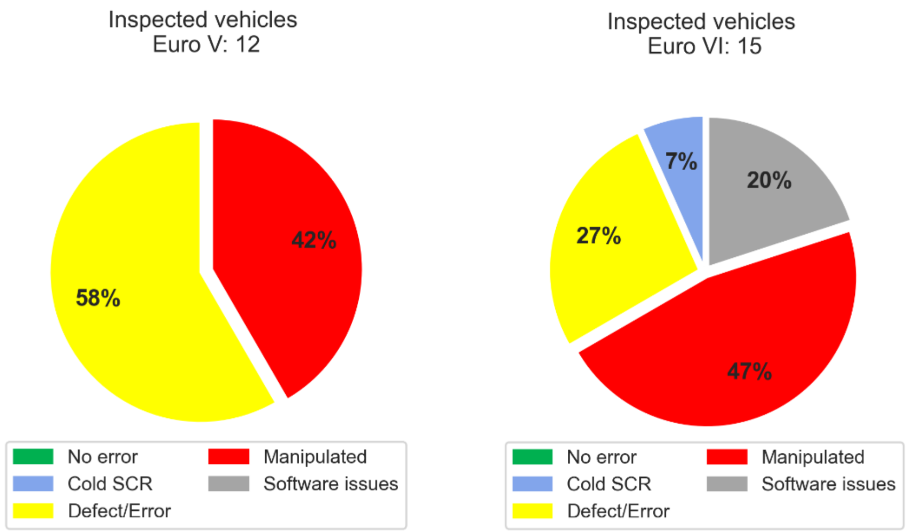

Figure 42: Conclusion of the inspected HDV, left for Euro V and right for Euro VI.

For 41% (58% for Euro V, 27% for Euro VI) of the inspected HDVs a defect or error in the emission system was found (Figure 41, Figure 42). For 44% a manipulation of the emission system was proven (42% for Euro V, 47% for Euro VI). The rate is similar for Euro V and VI. It should be noted that a defect can also be a manipulation. A defect is documented if an error in the OBD system was found, e.g. due to a flashing Malfunction Indicator Lamp. Normally a defect will force the truck driver to go to a workshop for repair, otherwise the engine power will be reduced. Often this engine power reduction is manipulated, but it is not easy to prove. The HDV than drives for a long time with a defective emission system.

For only 4% of the inspected HDVs (one vehicle) a cold SCR/cold engine system was concluded as the reason for the high emissions. 11% showed a manufacturer issue due to a missing mandatory OE software update. No HDV is classified as “No Error”. That means that no HDV was wrongly classified.

If analysing the inspection results only for the high emitters (excluding suspicious emitters) a better agreement to identification of defects and manipulations is expected. This is also observed in Figure 43 (right). The HDV with the cold SCR was only a suspicious emitter.

Old Euro IV without SCR systems are already excluded as these were expected to have “No Error”.

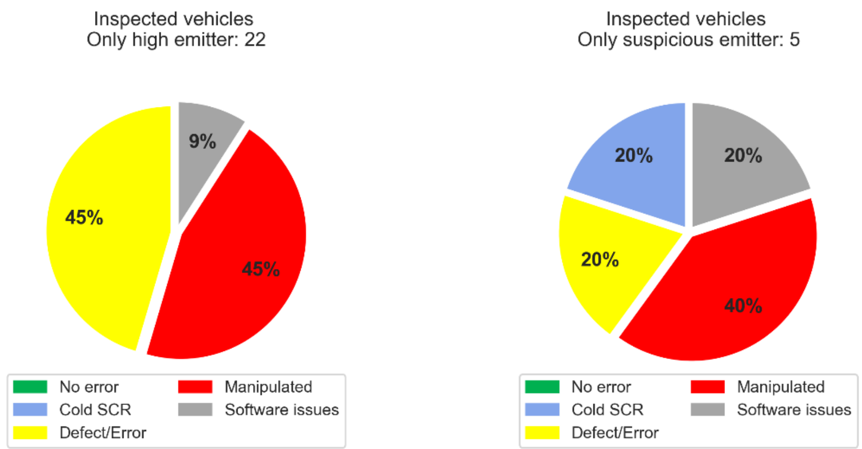

Figure 43: Conclusion of the inspected HDVs, left for only the classified high emitters and right for only the classified suspicious emitters.

7 Recommendations for technical improvements

The two particle instruments (AVL DiTEST Counter and Black Carbon Tracker) for measuring PN and BC could be successfully integrated in the Plume Chasing system. The evaluation and display of emission factors worked well in real time. The robustness of the two used particle instruments to vibrations must be investigated further. During the measurement campaign, regular errors of the Counter were observed during stronger vibrations and at the end of the campaign the Counter was defect. The BCT worked fine throughout the campaign but as it uses fragile plastic parts, it had a defect after shipping. These parts could cause problems in the long run and should as well be improved further for the mobile use. The BCT had a long warm up time (60 minutes) and as a work around the instrument was not switched off over night to avoid long start-up time in the morning. A better temperature regulation is needed. The 24V operation of the instrument was working, but required a more complex setup. A 12V operation would be preferred.

It is recommended that a cyclone is used also for future campaigns to avoid clogging of the particle system with dust and to separate large particles to avoid measurement artefacts. This also applies to the water trap to protect the instrumentation from water. For emissions with a high volatile content, such as very old vehicles, a catalytic stripper could be recommended to ensure that only solid particles are measured to enhance comparison with the emission standard.

Thresholds of low/suspicious/high emitters for PN and BC still need to be defined for HDVs/LDVs. The classification of the average PN and BC emission value can then be simply illustrated by a three-step traffic light as it exists for the average NO_x emissions. Thus, simple recommendations for further inspections of particle filters can be provided for enforcement (e.g., police).

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