FLANDERS ENVIRONMENT AGENCY

Flanders State of the Art

Short Report

HDV (Heavy Duty Vehicles) NO_x emission measurement with "Plume Chasing" and subsequent inspection of high emitters

A study in Flanders (Belgium) November / December 2021

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Content

1 Summary

This report summarises the results of a project, applying the Airyx plume chasing measurement system, for detection of high emitter, heavy duty vehicles (HDV) in Flanders (Belgium) 23.11. – 08.12.2021 and the following inspection of the selected HDVs. The project was carried out as a collaboration between the Flanders environmental Agency, Vlabel Controle and Airyx. The study demonstrates that the emission inspection with plume chasing is well suited to efficiently identify individual defective and manipulated HDVs for further inspection.

Performed measurements:

For the emission measurements, the plume chasing, mobile remote sensing equipment supplied by Airyx, was installed in a vehicle from Vlabel controle (chapter 3.2). The new emission software directly indicates if the vehicle under examination, is a low, suspicious or high NO_x emitter. Thus, simple recommendations for further inspection are provided. Measurements were carried out by Vlabel controle following training by Airyx. Emission measurements could be successfully performed under all weather conditions, ranging from warm, sunny and calm to cold, rainy and windy conditions. No limitation on weather conditions for the plume chasing method could be observed. After a short measurement of 16 seconds in the plume (8 data points, where the CO_2 level was significantly above the prevailing CO_2 background) a first preliminary emission level is provided. If the emitter was identified and deemed to be low, the measurement was usually stopped after this preliminary result, in order to continue measuring on the next vehicle and thus vastly increasing the total number of tested HDVs. If the preliminary result indicated a suspicious or a high emitter, the measurements were typically continued for a longer period. An emission value is labelled as "valid" after 60 seconds sampling in the plume (representing 30 data points. However, often the vehicles were stopped for inspection before a valid value was derived. For a more reliable detection of these high emitters, this should be avoided in the future.

Investigated vehicles:

During the course of project, a total of 606 HDVs with corresponding NO_x emissions were investigated and for 594 of those, an emission value was derived (chapter 4). Measurements were performed on Belgium motorways in order to avoid problems resulting from cold SCR / cold engines of the inspected vehicles. 84% were identified as EURO VI, 14% EURO V and less than 2% belonged to the remaining EURO classes. The largest fraction was from Belgium (45%), followed by the Netherlands (12%), Poland (11%) and Romanian (8%) respectively. The remaining HDVs were mainly from other European countries.

Emissions of all vehicles:

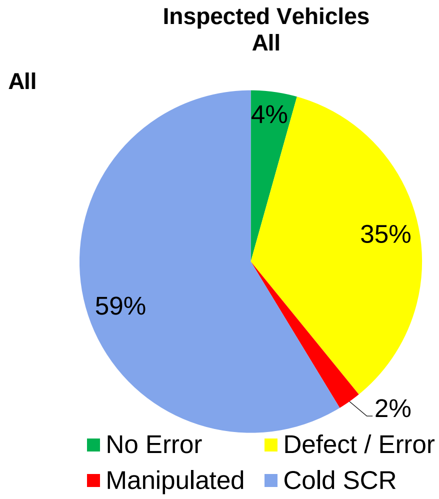
Similar to previous studies [1, 3, 6, 7, 8, 9, 10], the derived emission values were classified as low emitters if they were below a predefined limit (chapter 5). Different limits are applied for the different EURO classes (see Table 3). In this study, the HDVs with average emission limits above a basic limit, are further split into suspicious and if they are above a second even higher pre-defined limit, as high emitters. 17% of the HDVs were above the limits for suspicious or high emitters (11% and 6% respectively) which is higher than a recent study in Denmark with 9,7% [1]. Still the value is lower than in previous studies in Germany and Austria [3, 7, 8, 9, 10]. HDVs from Eastern European Union countries show a higher fraction of high and suspicious emitters in comparison to HDVs from central and western European

countries (chapter 5.6). This indicates a higher rate of defective and/or manipulated HDVs from these countries.

Vehicle inspections:

51 HDVs classified from the measurements as suspicious or high emitters were further inspected (only including HDV with available measurement data). The results of this inspection is classified into the following cases:

(1) no Error was found
(2) a Defect / Error was found
(3) a Manipulation was found
(4) a cold SCR (cold Engine) was identified as potential source for high emissions



(5)

Figure 1: Conclusion of the inspected HDVs for EURO V and VI. The percentage is relative to the inspected suspicious and high emitting HDV.

Beside the correctly identified “Defect / Error” and “Manipulated” cases, a large fraction is categorised as “Cold SCR” and a small group as “No Error”. No large difference was observed for EURO V & VI (see Figure 35). This statistic includes only inspected EURO V and EURO VI trucks and those classified as suspicious or high emitter.

Conclusions from the inspections are:

- the rate of HDVs with no Error found was very low (2 HDV). These were all EURO V HDVs with in one case a clear identified cold SCR (identified SCR warmup) and the other vehicle that had an additional refrigeration unit running on diesel, but without an emission cleaning system, likely responsible for the high emissions (chapter 7.1). Excluding these two HDV inspections, no EURO V and EURO VI HDV remain as “no Error” case thus resulting in a **0% false positive rate** or a **100% hit rate** in finding a high emitter with plume chasing.
- For 35% of inspected HDVs a defect or error was found
- For 2% (one vehicle) of inspected HDVs a manipulation was found, a very low value

- For 59% of inspected HDV a cold SCR / cold engine system was concluded as the reason for the high emissions. This is unusually high and is analysed in further detail in chapter 7.2 which results:
  - For 19% of the cold SCR classified cases, a clear warmup of the SCR was observed in the plume chasing data. This is a great advantage of the plume chasing method, that these warmup situations can be identified and thus avoid unnecessary inspections saving time for the inspectors. A better training of inspectors or improved software may be needed to avoid inspections of these HDV.
  - 26% show an instable emission value. This may indicate warm up and cool down of the SCR (Engine warm up problem) or an overseen error.
  - A large fraction of 30% show continuous high emissions over a long time. This is unexpected as a warmup of the SCR system, at least for some periods, is expected. This may also indicate that defect / manipulated systems are possibly overseen in the inspection which are often due to wrong indications of cold SCR systems. An extended inspection of these vehicles is recommended.
  - For 26% of these classified as “cold SCR” only very few emission measurement data points are available in order to give a reliable emission value and classification. Longer measurements are required.

When excluding from the statistics these vehicles which are not relevant in validating the plume chasing system (vehicles with clear SCR warmup, too few data points, diesel generator source)as they should not be inspected according to the instruction from Airyx manufacturer, the following statistic is derived:

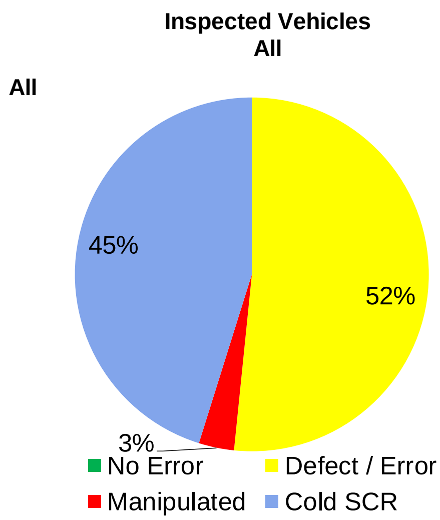


Figure 2: Conclusion of the inspected HDV for EURO V and VI excluding vehicles where the measurement system indicated a SCR warm up, emissions were low or too few data points were recorded. The percentage is relative to the inspected HDV.

In conclusion, the application of Airyx Plume Chasing measurement systems for NO_x can effectively support authorities in identifying high emitters caused by defective and/or manipulated HDVs. A big advantage is that the system is simple to operate and works under rainy and/or cold weather conditions. Even if cold SCR situations are reduced, the high rate of high emitters categorised as cold SCR should further be reduced. The system allows identifying many of these cold SCR from the data collected and thus avoiding unnecessary inspections. More investigations are required as to why such a high rate of cold SCRs are categorised in this study compared to other studies [2]. The upcoming question is, if these are undetected defects / manipulations in the inspection especially as many manipulations pretend the system a cold system. It could also be that the plume chasing measurement can be further improved to avoid a false classification. Currently an improved training of inspectors, in interpreting the plume chasing measurements, could already avoid many of the cases of a cold SCR causing a full unnecessary inspection.

2 Introduction

2.1 Background for the project

The Flanders Environmental Agency has, together with Vlabel Controle, made extensive efforts to control NOx emissions system used on heavy-duty vehicle (HDV). Airyx has developed the "Plume Chasing" measuring system for the identification of high emitters. This is already being used by the first authorities [1, 2]. This project is the first use of the Airyx "Plume Chasing" measurement system in Flanders, Belgium, and combination with heavy duty vehicle inspections by Vlabel Controle. This report summarises an extended study where the potential of the equipment was investigated for reliable high emitter HDV detection. For background information and technical introduction of the measurement method it is referred to other reports [1, 2]. The measurements and inspections were mainly performed along main high ways in Belgium, 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.

2.2 The content of the project

The two main objectives are: to share and increase competencies for people involved in the control effort and to evaluate the practical applicability of the plume chasing, mobile remote sensing equipment from Airyx. The project is carried out as a collaboration between the Flanders Environmental Agency, Vlabel Controle and Airyx. Airyx provided and installed the "Plume Chasing" NOx vehicle emission measurement system in a vehicle supplied by Vlabel Controle. A sufficient training of Vlabel Controle officers was provided in order to operate the equipment without on-site support from Airyx. Afterwards the authorities performed the measurements independently. The measurements were performed in a way so that the high emitters could be selected for further inspections by Vlabel Controle. Measurements were performed on the highways, but not being too close to typical HDV loading areas (like the harbour of Antwerp) in order to avoid cold engines / cold SCR with deactivated emission reduction systems.

The project brings together high emitter detection with the remote plume chasing method and further detailed inspections. One of the goals was to investigate if inspections can effectively be supported using this method.

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, 3, 4, 5, 6, 7] and 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. The current system is for NO_x (NO + NO_2) and NO_2 emissions. The application for particle emissions is under development.

The fundamental principle is, that the ratio between NO_x 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 NO_x and CO_2 (outside the investigated plume) need to be corrected for. Specific NO_x emissions (in g/kWh) are calculated from the measured ratio applying an estimated engine efficiency of 40% for the relationship between emitted CO_2 and engine power.

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 NO_x emission values of HDVs. The background concentration is retrieved from the recorded data from periods where no vehicle is monitored.

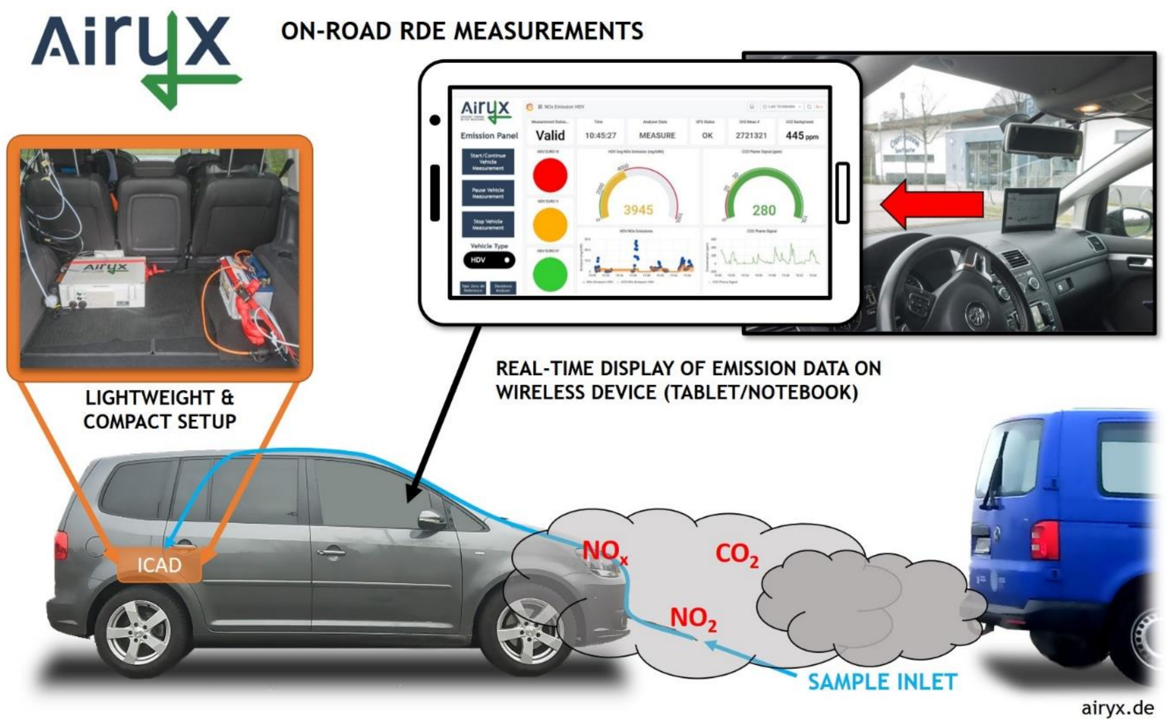


Figure 3: Basic sketch of plume chasing measurement principle from Airyx GmbH. The diluted exhaust gases are sampled and analysed. Different gases are measured with the ICAD instrument. From the ratio of the gases, emission factors of the followed vehicle are derived.

3.2 Chasing vehicle setup

Figure 4: Plume chasing installation on the Vlabel Controle vehicle (outside view). Two sampling inlets are combined to one sampling hose to the ICAD plume chasing instrument in the trunk.

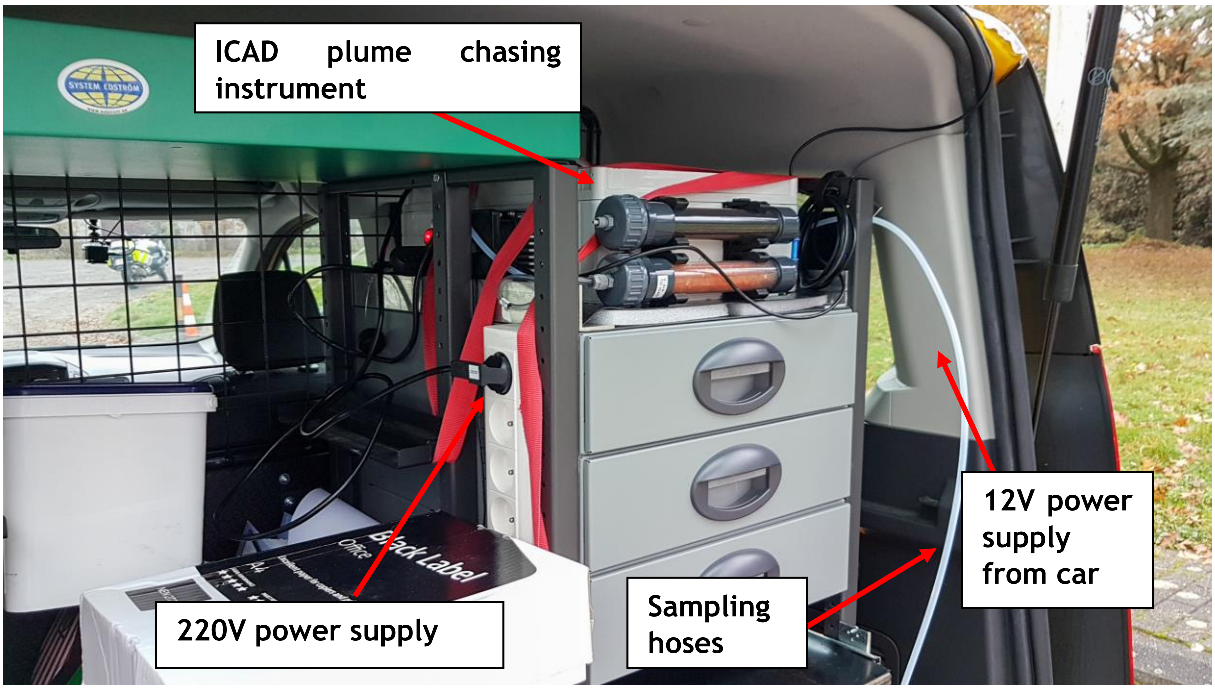


Figure 5: Plume chasing installation in the trunk of the Vlabel Controle vehicle. The sampling hose is guided through the cabin to the ICAD plume chasing instrument. The instrument is powered from the car 220V power system with UPS.

A Vlabel Controle passenger car used for inspection was used as the chasing vehicle. The setup could be installed within 1.5 hours.

Figure 4 shows the installation on the chasing vehicle. An aluminium construction mounted to the front bumper holds the sampling inlets. Two sampling inlets are installed on a flexible tubing to avoid injuries. Sampling hoses are made from 6mm PTFE. Similar to a previous study [1], both inlets are merged 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.

The sampling hose is going through the motor compartment inside the car (Figure 6) and then through the passenger cabin to the ICAD plume chasing instrument in the trunk. The total sampling hose length is ~6m.

The power consumption of the ICAD NO_x/CO_2 monitor is with 30W low enough to be operated directly from vehicle UPS system without the need to charge up batteries overnight. Figure 5 shows the installation inside the trunk.

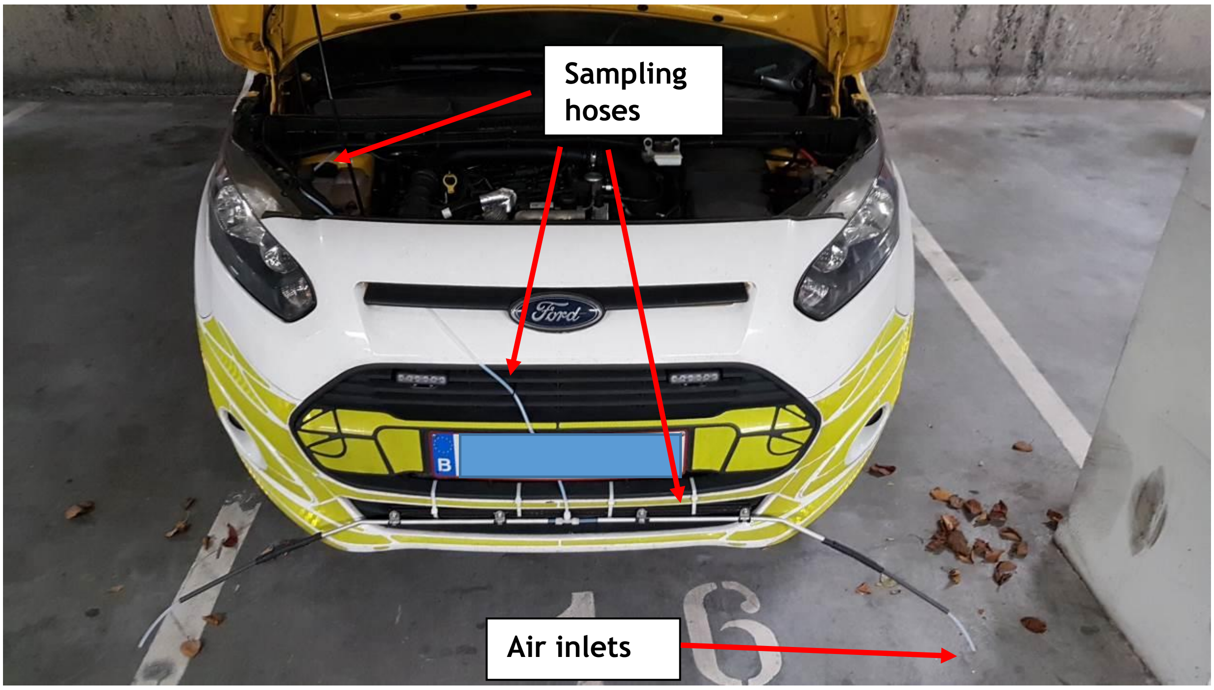


Figure 6: Sampling hose installation on the front of the plume chasing vehicle. The sampling hose is guided from the front through the motor compartment inside the cabin. In the cabin it is below the floor mat.

Figure 7: 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 temporarily used for additional documentation, but most of the time in this study it was not operated. 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. This is also working as the user interface (Figure 7), via WiFi to the ICAD. 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 3.3.

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 8.

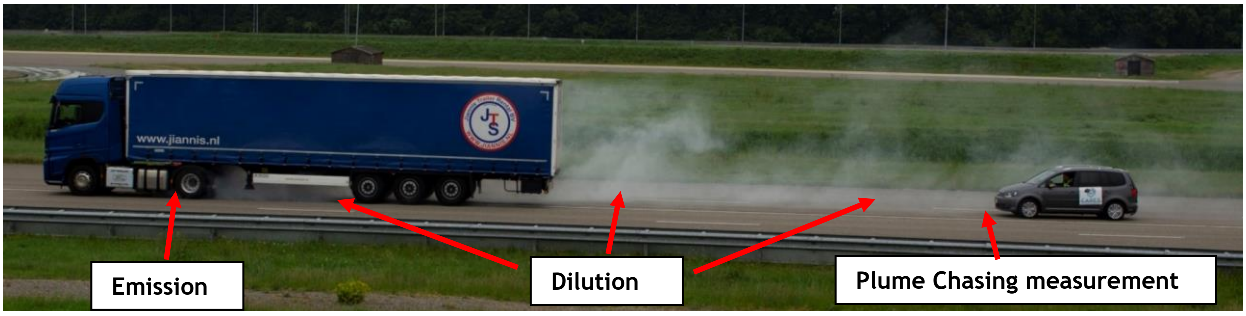


Figure 8: Illustration of plume chasing measurement configuration. The emitted exhaust gases are diluted. The plume chasing vehicle measures the gases in the diluted plume. Exhaust gases visualised in this picture with white smoke.

3.3 Emission software v2.0

The new plume chasing emission software v2.0 developed in the EU CARES project (https://cares-project.eu/) was applied in this study. It also containing improvements suggested from previous studies [1, 2]:

- It provides a clear indication of high / suspicious / low emitter cases (for classification limits see chapter 5.1)
- The emission values are from the sampling simultaneously on the left and right side.
- The software derives the background concentration of NO_x and CO_2 automatically and corrects the measurement in the emission plume accordingly.
- An average emission value is directly calculated between pressing “Start” and “Stop” for an individual emission measurement and averaged over the duration of the measurement.

The new display is described in Figure 9. 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 indicating “Acquiring” the first emission data are averaged. A “Prelim.” = preliminary result is provided after the first 8 valid data points (16 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 emission value is simply illustrated by a three step traffic light. Each light is for a EURO VI, V and IV and different due to different emission limits. The three colours indicate clearly “high” (red) emitter, “suspicious” (orange) and “low” (green) emitter and thus make easy decisions for further inspections.

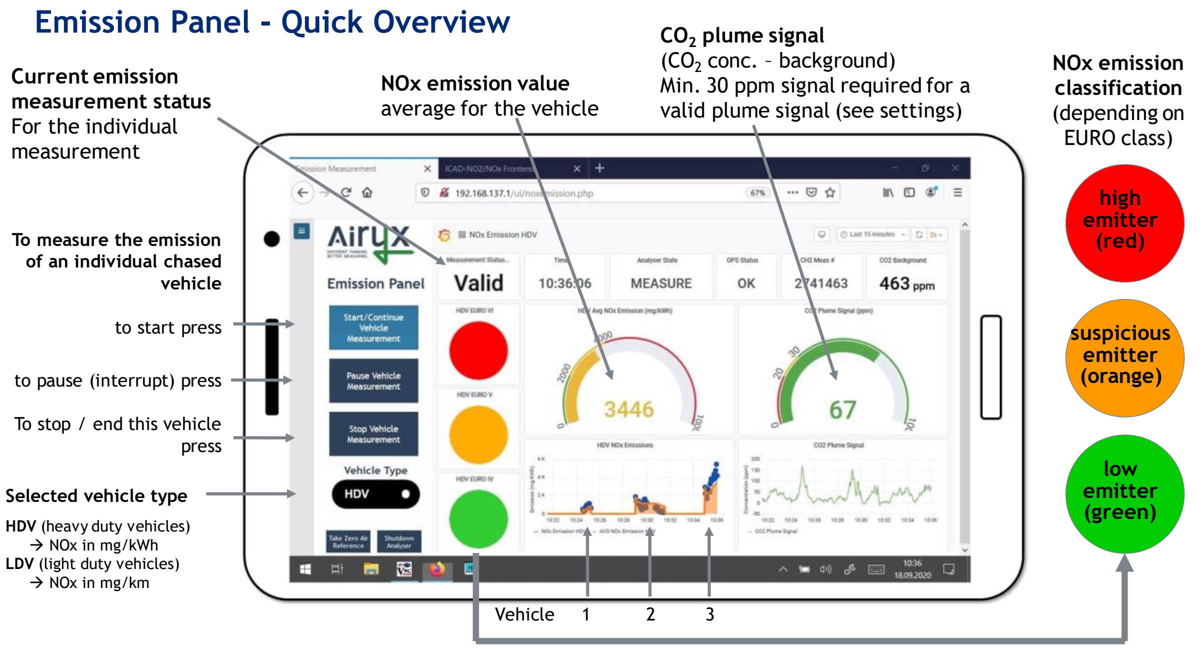


Figure 9: Explanation of the emission display as visualised during the measurement.

The fast indication of a preliminary result should help to focus on the high and suspicious emitters while the measurement of a preliminary low emitter may be aborted.

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

3.4 Time and Location of Measurements

The measurements were performed in Belgium between 23rd November and 8th December 2021 by Vlabel Controle officers. The investigations were done mainly on highways and partly on larger rural roads (see Figure 10). This should reduce the amount of cold engines / cold SCR as vehicles are further away from parking places and have already run for some time. Additionally, the constant driving on highways should allow relative stable emissions and operation of emission reduction systems.

Measurements were performed on 15 days. Weather conditions were very different ranging from warm, sunny and calm to cold and rainy. During all weather conditions plume chasing emission measurements were performed successfully. No difficulties were observed during stronger rain what is a large advantage in comparison to other measurement methods.

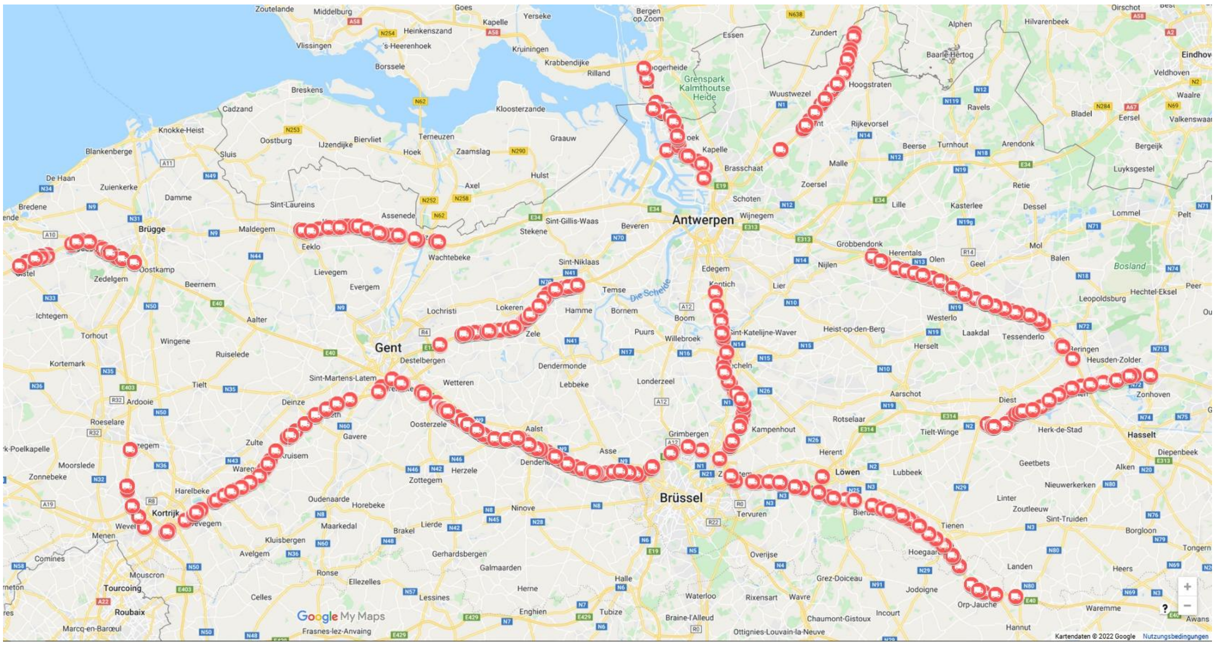


Figure 10: Map with location of measured HDV during the study.

3.5 Performing emission measurements

The Vlabel Controle officers performing the measurements and followed inspections were trained in a three-day workshop by Airyx in theory, installation and measurements (Figure 11).

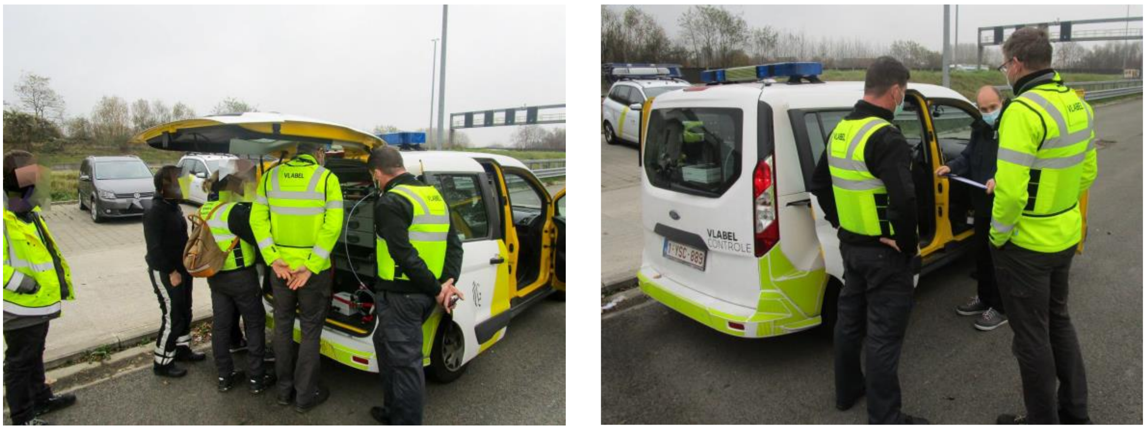


Figure 11: Practical training of the plume chasing measurement system to Vlabel controle inspectors.

The plume chasing car was operated by Vlabel controle, following different HDV as indicated in Figure 12. As the plume chasing vehicle was a Vlabel controle vehicle it could directly stop the trucks. Additional other Vlabel controle inspectors with other cars or motorbikes accompanied the measurement and often performed the HDV inspection. Thus more HDV could be investigated with plume chasing measurement vehicle while other Vlabel control officers performed the inspection.

Figure 12: Picture inside the plume chasing vehicle during measurements.

When the plume chasing car was behind a HDV 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 8 valid data points (= 16 seconds) a preliminary emission value is indicated. If this indicated a low emitter (<1200mg/kWh for EURO VI), the measurement was, in most cases stopped as it can be expected that this HDV 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 longer measurement is needed to avoid a false positive e.g. due to a cold engine or a specific short term engine state. However, many HDV stopped for inspection were measured less that the required 30 data points. This may have a significant influence on the reliable identification of the high emitter and will be investigated separately.

The measurement of an individual HDV was stopped by pressing "Stop", and the HDV was overtaken to record vehicle type, number plate and thus derive the EURO classification (from tables).

From the emission classification and the EURO class of the HDV it was then decided if the HDV was inspected by Vlabel Controle. The inspection was often performed by a different team of inspectors. Thus, the plume chasing car could directly continue to investigate further HDVs. Due to logistical reasons, not all HDVs with suspicious or high emission level could be inspected.

3.6 Inspections

Inspections were performed by Vlabel Controle. Inspection tools (e.g. from Wabco Würth) were applied to identify the reason for the high emission level. This report does not include an assessment of the quality of the inspection. The results are used for statistical analysis, and are discussed with the measurement results.

4 Statistics measured HDV

In total, emission measurements for 606 HDV were performed. Measurements with less than 8 valid data points (<16 seconds), or where no information for the HDV was obtained, are excluded. For some measured HDV the start and stop were not applied correctly and a clear assignment of data to a HDV is not possible. These vehicles were also excluded. Data for 594 HDV could be used for the following statistics.

4.1 Emission EURO classes

The largest fraction of the HDVs are, with 84%, the EURO VI vehicles. 14% are EURO V and less than 2 % (9 HDVs) are older vehicles. Of 578, and thus almost all HDVs, a EURO class could be estimated.

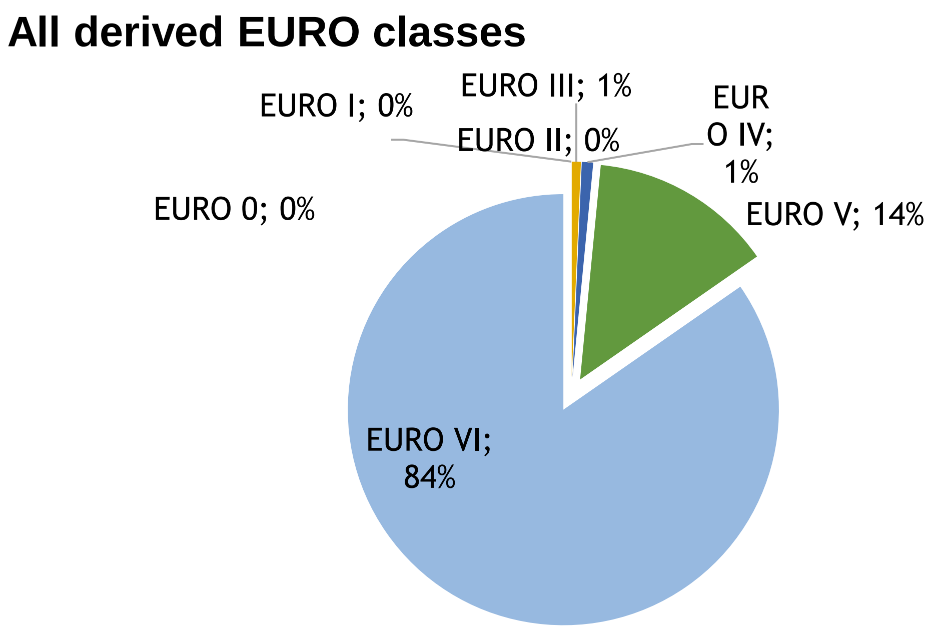


Figure 13: Distribution of EURO emission class between the measured HDVs in percent.

Emission norm	No#	percentage
EURO 0-II	0	0%
EURO V	81	13,80%
EURO VI	497	84,67%
Sum	587	

Table 1: EURO class of measured HDVs

4.2 Country of origin

For 580 HDVs, a country of origin was read from the number plate. In some cases, the number plate could not be read. The largest group are from Belgium (45%) followed by the Netherlands (12%), Poland (11%), Romania (8%) and Latvia (5%).

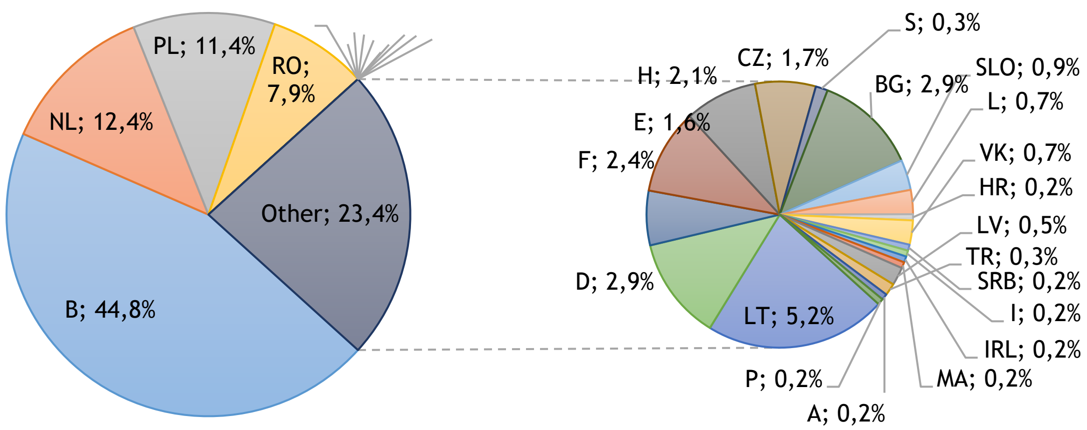


Figure 14: Distribution of origin for the measured HDVs in percent.

origin HDV (sorted by percentage)	No#	percentage
B	260	44,8%
NL	72	12,4%
PL	66	11,4%
RO	46	7,9%
LT	30	5,2%
D	17	2,9%
BG	17	2,9%
F	14	2,4%
H	12	2,1%
CZ	10	1,7%
E	9	1,6%
SLO	5	0,9%
L	4	0,7%
VK	4	0,7%
LV	3	0,5%
S	2	0,3%

TR	2	0,3%
HR	1	0,2%
SRB	1	0,2%
I	1	0,2%
IRL	1	0,2%
MA	1	0,2%
A	1	0,2%
P	1	0,2%
Sum	**580**	100%

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

4.3 Ratio of "preliminary" and "valid" measurements

A "valid" emission value is based on measurement of 30 data points equivalent to 60 seconds of data (see chapter 3.3). It is indicated by the software as a "valid" and thus reliable emission value. A shorter measurement with a min. of 8 data points = 16 seconds of data, still provides an emission value and is indicated as "prelim." = preliminary emission value. If a suspicious or high emission is observed, collection of data for a "valid" measurement is recommended as a low emitter can also show high emissions for a short period. This avoids wrong classification (false positives) due to emission variation.

For a low emitter a preliminary measurement is expected to be sufficient. The percentage of preliminary measurements is with 74% high as a large fraction of HDV showed low emission values and measurements were stopped before a valid value was achieved. If not otherwise stated, the results from the preliminary plus the valid measurements are used in the following analysis.

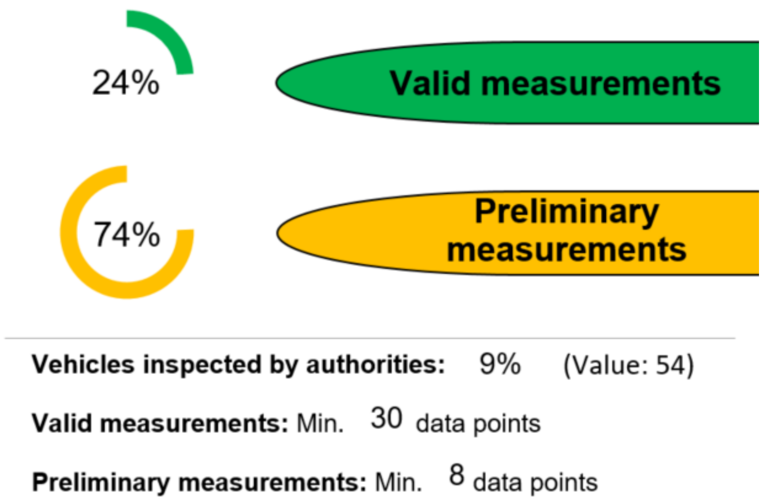


Figure 15: Ratio of measurements with a "preliminary" emission value (min. 8 data points) and a "valid" emission value (min. 30 data points = 60 s).

4.4 Ratio of "preliminary" and "valid" measurements of inspected HDVs

While it is strongly recommended to measure an HDV with a suspicious or high emission until a "valid" result is derived, many inspected HDVs have only a preliminary result. For 35 inspected HDVs, a valid measurement is derived and for 16 only a preliminary measurement result. Two inspected HDV had even no sufficient data for a preliminary result and were excluded from the following statistics.

4.5 HDV brands

A mixture of different common HDV brands was investigated.

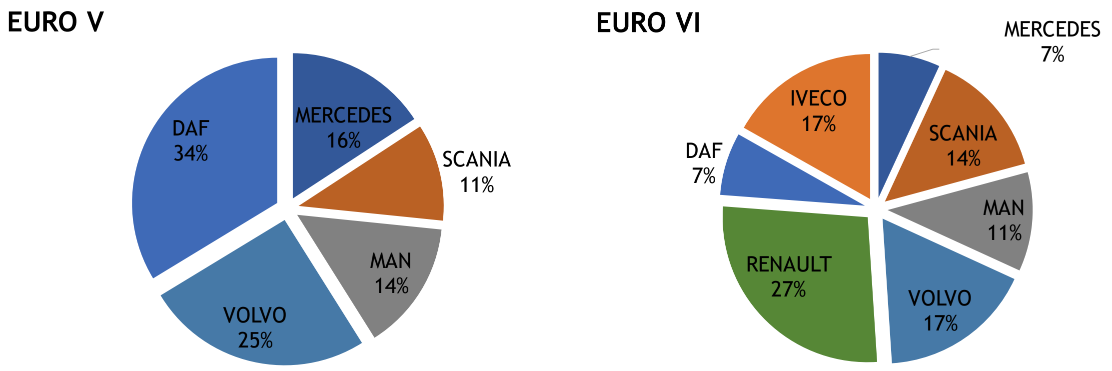


Figure 16: Ratio of HDV brands for EURO V and EURO VI.

5 Emission values

5.1 Classification of emission limits

To identify a suspicious or a high emitter a margin to the EURO norm emission limit is added. The limits are adapted from the recent study in Denmark 2020 [1].

	EURO III	EURO IV	EURO V	EURO VI
Classification	mg/kWh	mg/kWh	mg/kWh	mg/kWh
low	≤6000	≤4500	≤2500	≤1200
suspicious	>6000	>4500	>2500	>1200
high	>7000	>5500	>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.

5.2 Emission statistics

The derived emission values of each HDV are classified according to chapter 5.1. 83% are classified as low emitters. 11% of HDVs are found to be suspicious, and 6% clearly as high emitters. The ratio of suspicious and high emitters is almost 50% lower than in previous studies in Germany and Austria [3, 6, 7, 8, 9, 10]. This may be due to a change in the vehicle fleet, more inspections, different regulations or local variations.

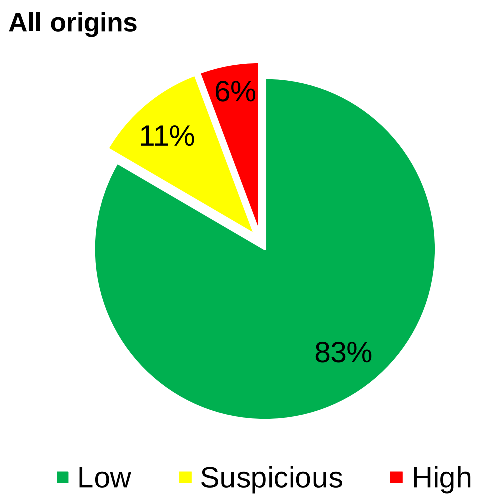


Figure 17: Statistics of emission classification of all measured HDV (all countries and all EURO classes).

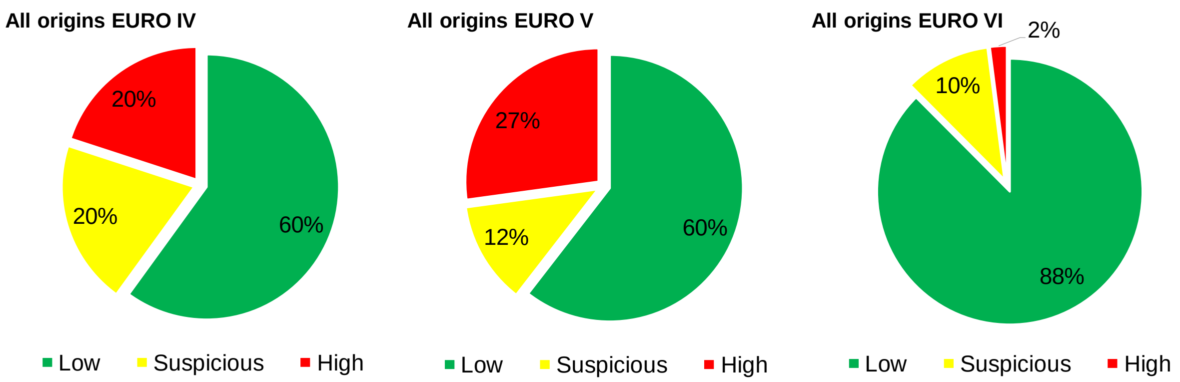


Figure 18: Statistics of emission classification separated for the EURO class.

Emission statistics	EURO III	EURO IV	EURO V	EURO VI	All
low	3	3	49	428	483
suspicious	1	1	10	51	63
high	0	1	22	10	33
low [%]	75%	60%	60%	88%	83%
suspicious [%]	25%	20%	12%	10%	11%
high [%]	0%	20%	27%	2%	6%

Table 4: Statistics of emission classification. First total numbers, and below in percent.

The separation for the different EURO classes indicate lowest ratio of suspicious and high emitters for EURO VI. EURO IV and EURO III should be investigated with caution, as the number of measured HDVs is low (Table 4) and these are quite old HDVs with high mileage where the emission system may not work properly any more.

The ratio of suspicious and high emitters for EURO V is significantly higher than for EURO VI.

5.3 Analysis by country – Belgium

Same analysis like in chapter 5.2 is performed only for the HDVs from Belgium. 254 measured HDVs are in this group. Slightly lower suspicious and high emitters for EURO VI but slightly higher amounts for EURO V are observed. This may be caused by a higher probability of the EURO V being 'cold engines' as these are more often used for local short distance transports than foreign EURO V HDV.

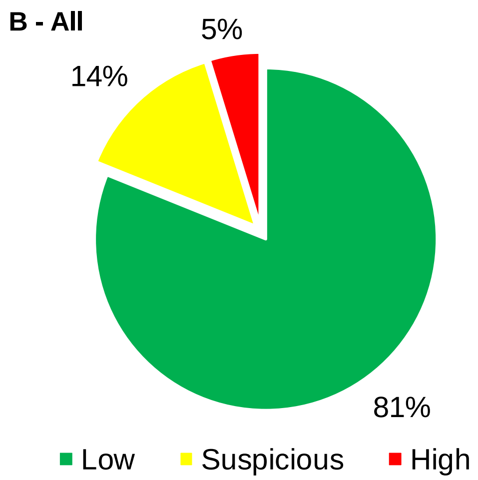


Figure 19: Statistics of emission classification only for Belgium HDV.

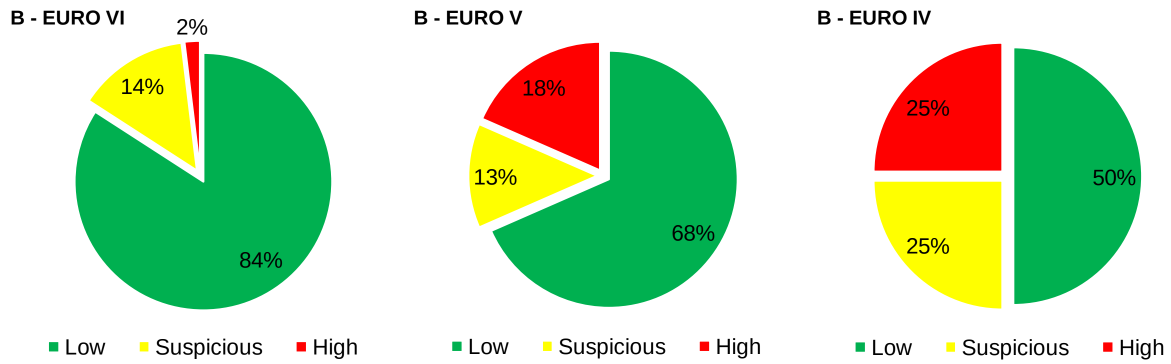


Figure 20: Statistics of emission classification separated for the EURO class only for HDV from Belgium.

5.4 Analysis by country – Netherland

Same analysis like in chapter 5.2 is performed only for the HDVs from the Netherlands (72 HDVs in all) For the 7 measured EURO V HDVs, 4 (57%) are classified as high emitters. This is a much higher ratio than for most other countries.

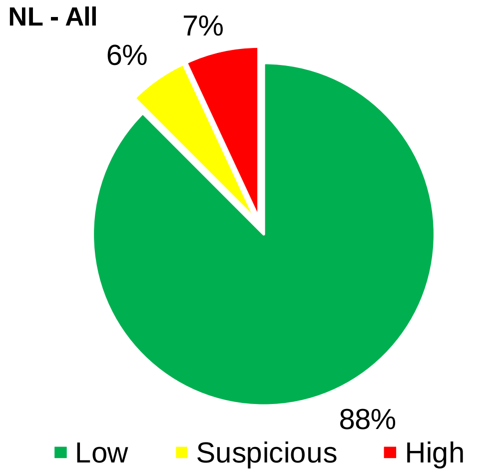


Figure 21: Statistics of emission classification only for HDV from Netherland.

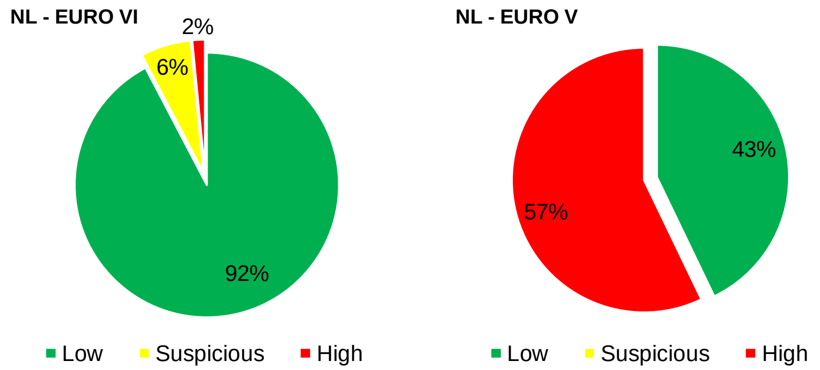


Figure 22: Statistics of emission classification separated for the EURO class only for HDV from Netherland.

5.5 Analysis by country – Poland

Same analysis as in chapter 5.2 is performed only for the HDVs from Poland (65 HDV). Here, a very low rate of high emitters is observed. For EURO VI (57) class, no high emitters and only a few (2) suspicious emitters were found.

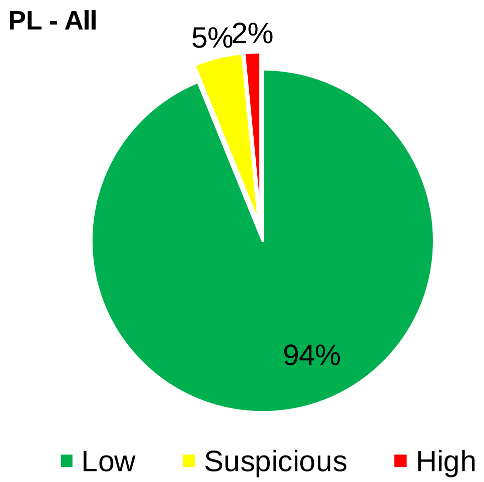


Figure 23: Statistics of emission classification only for HDVs from Poland.

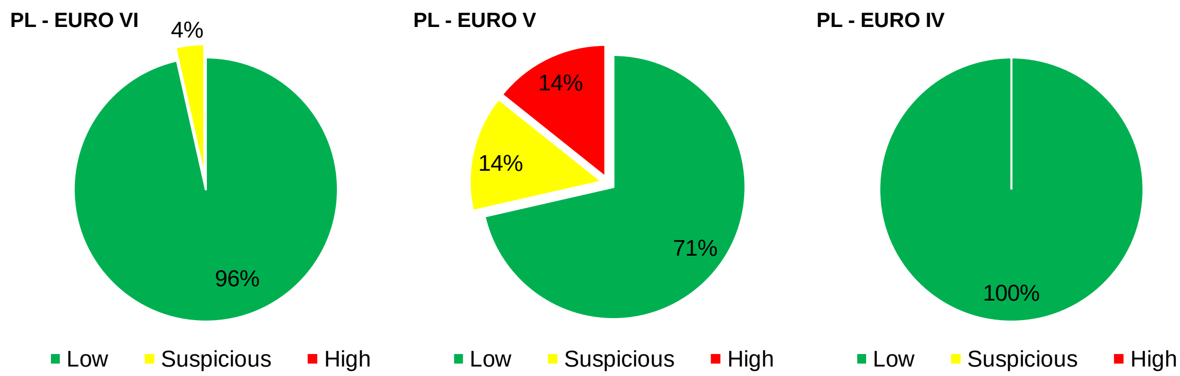


Figure 24: Statistics of emission classification separated for the EURO class only for HDV from Poland.

5.6 Analysis by country –eastern European countries: RO, BG, H, SLO, HR, LT, LV, MA

Same analysis as in chapter 5.2 was performed for the HDVs from the eastern European countries. As each group is too small to perform its own sufficient statistic, the countries are treated as one group with, in total 133 measured vehicles. A much higher rate of high emitters is found indicating that HDVs from these countries are much more often affected by defects and manipulations. Table 5 shows that this high rate is not due to a low sample size, but was found for many HDVs.

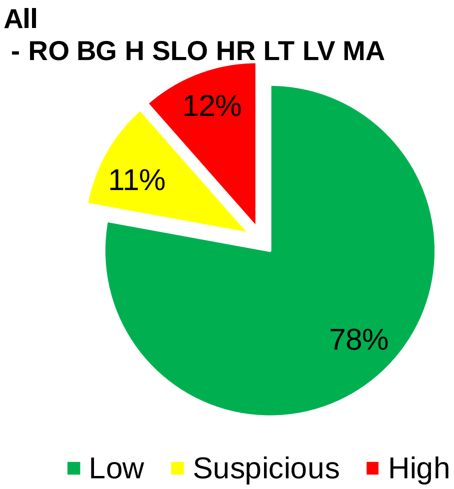


Figure 25: Statistics of emission classification for the sum of the eastern European countries: RO, BG, H, SLO, HR, LT, LV.

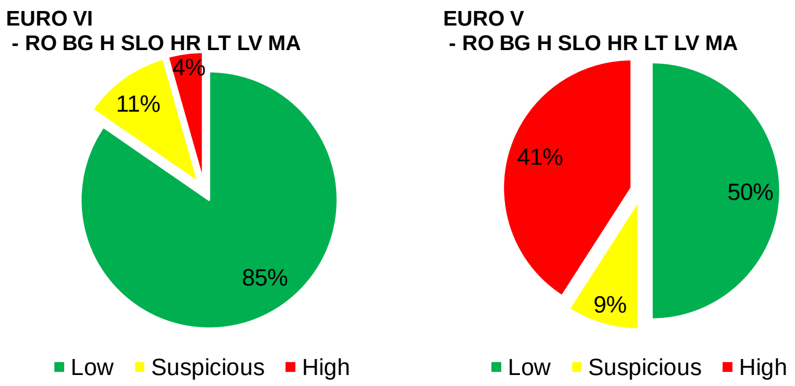


Figure 26: Statistics of emission classification separated by the EURO class again for the sum of the eastern European countries: RO, BG, H, SLO, HR, LT, LV.

Emission statistics - eastern Europe	EURO III	EURO IV	EURO V	EURO VI	All
low	0	0	11	77	88
suspicious	0	0	2	10	12
high	0	0	9	4	13
low [%]	-	-	50%	85%	78%
suspicious [%]	-	-	9%	11%	11%
high [%]	-	-	41%	4%	12%

Table 5: Statistics of emission classification only for the sum of the eastern European countries: RO, BG, H, SLO, HR, LT, LV. First total numbers, and below in percent.

The higher amount of high emitters in this group is in agreement to previous studies [1, 8].

5.7 Analysis by country –central & western European countries: B, NL, Pl, D, L, F, E, CZ

The same analysis as in chapter 5.6 was performed for the HDVs of the western and central European countries. This group is made as a comparison to the eastern European group. It has in total a comparable low amount of high and suspicious emitters. Table 5 shows that this lower rate is not due to a low sample size, but was found for very many HDV.

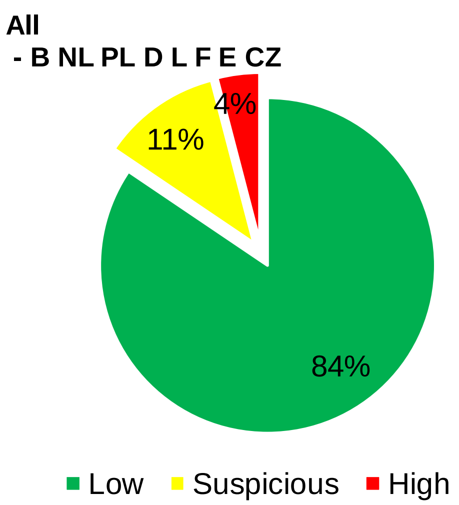


Figure 27: Statistics of emission classification only for the sum of the western and central European countries: B, NL, Pl, D, L, F, E, CZ.

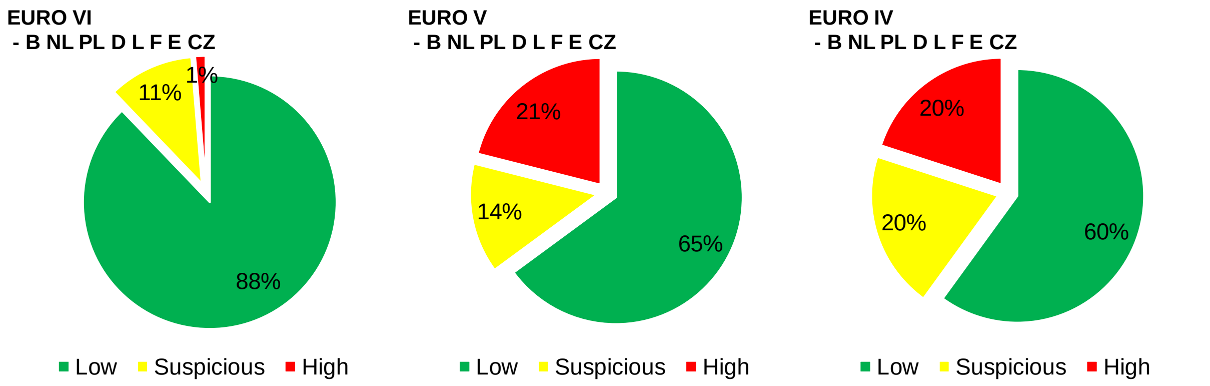


Figure 28: Statistics of emission classification separated by the EURO class and for the sum of the western and central European countries: B, NL, Pl, D, L, F, E, CZ.

Emission statistics - western & central Europe	EURO III	EURO IV	EURO V	EURO VI	All
low	3	3	37	332	375
suspicious	1	1	8	41	51
high	0	1	12	5	18
low [%]	75%	60%	65%	88%	84%
suspicious [%]	25%	20%	14%	11%	11%
high [%]	0%	20%	21%	1%	4%

Table 6: Statistics of emission classification only for the sum of the eastern European countries: RO, BG, H, SLO, HR, LT, LV. First total numbers, and below in percent.

5.8 Histograms of emissions

To study the distribution of the emission values, histograms are shown in Figure 29, Figure 30 and Figure 31. Clearly most of the HDVs show low emissions below 1000mg/kWh. Still a significant fraction of HDV with values above 3000mg/kWh is observed.

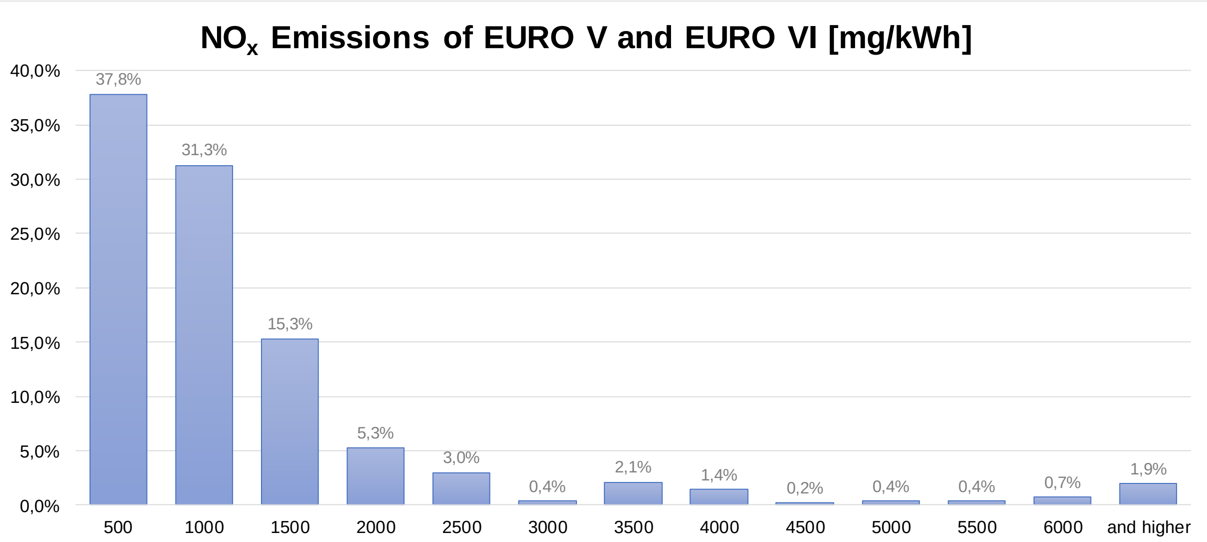


Figure 29: Histogram of observed emissions for all HDV.

When studying HDVs of type EURO VI only, generally lower emission values are observed (Figure 30). A large fraction is within the EURO Norm for real driving emissions (RDE) of 690mg/kWh. Most HDVs are still within 1200mg/kWh.

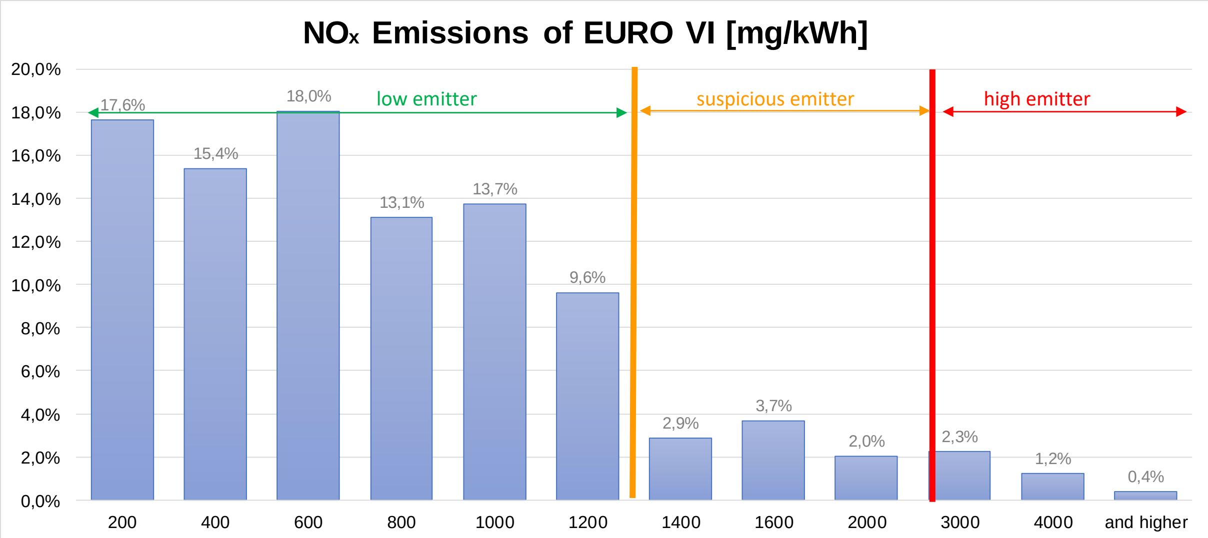


Figure 30: Histogram of observed emissions for EURO VI HDVs.

A similar plot only for the EURO V is shown in Figure 31. The distribution indicates a strong decrease above 3500mg/kWh. However, EURO V HDVs are more affected by cold engines which may cause high emissions even for correct working HDV.

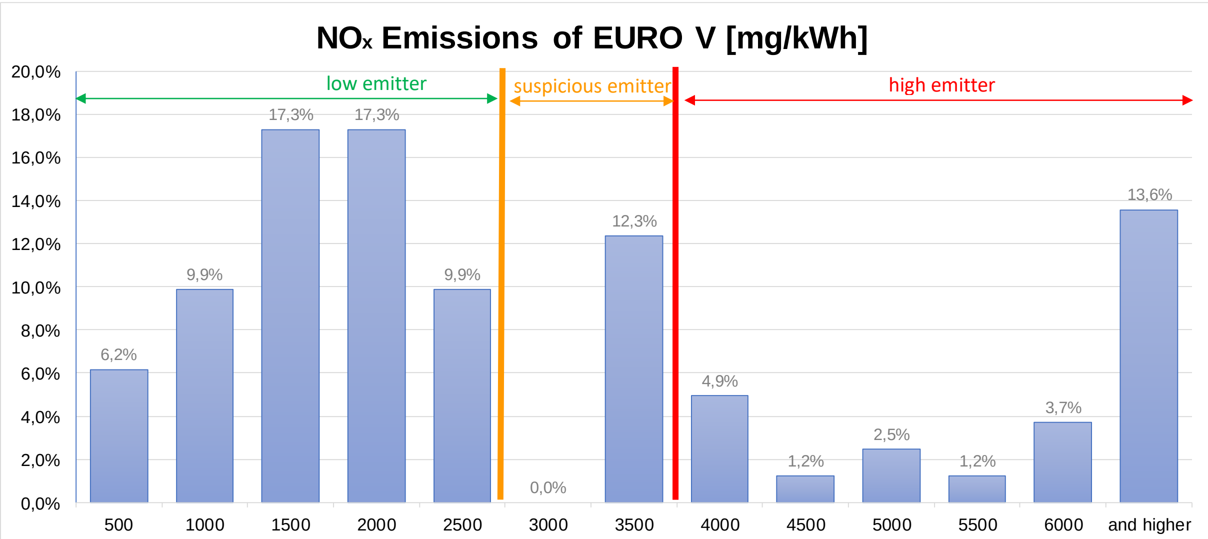


Figure 31: Histogram of observed emissions for EURO V HDV.

6 Inspections

In total 48 HDVs were inspected by VLABEL Controls where emission data are available and which feature high or suspicious emission levels. More than these 51 HDV were inspected, but the other had to be skipped for the statistics. Four inspected HDV were skipped in this report as no or not sufficient emission measurement data were recorded for an emission classification. Further three were EURO IV, and are not further included as they do not have a SCR or similar emission reduction system. Other four inspected EURO V and VI HDV were classified as low emitters where no defect or manipulation was found like expected. To avoid confusion these are also excluded in the following statistics.

For 15 out of 48 inspected EURO V and VI HDV (31%) 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 logistical reasons. However, it needs to be considered that the emission values of these 15 HDVs has a higher uncertainties and conclusions should be made with caution.

6.1 Emissions of inspected HDV

The emission classification of the inspected HDV is shown below. HDVs classified as low emitters, were partly investigated. The reason is that some were just identified as older HDV after they were stopped for inspection and are thus classified for the older EURO class as a low emitter. Also, in some cases where the emission were close to the emission limit, an inspection was decided upon nevertheless.

	EURO III	EURO IV	EURO V	EURO VI	sum
low	0	1	1	3	5
suspicious	0	1	9	14	24
high	0	1	19	6	26
sum	**0**	**3**	**29**	**23**	**55**
low [%]	-	33%	3%	13%	9%
suspicious [%]	-	33%	31%	61%	44%
high [%]	-	33%	66%	26%	47%

Table 7: Emission classification of the inspected HDV.

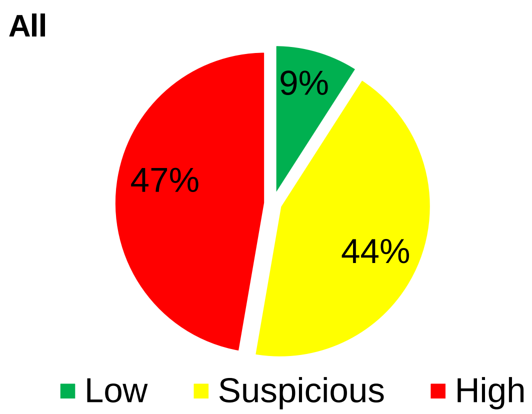


Figure 32: Emission classification of the inspected HDV.

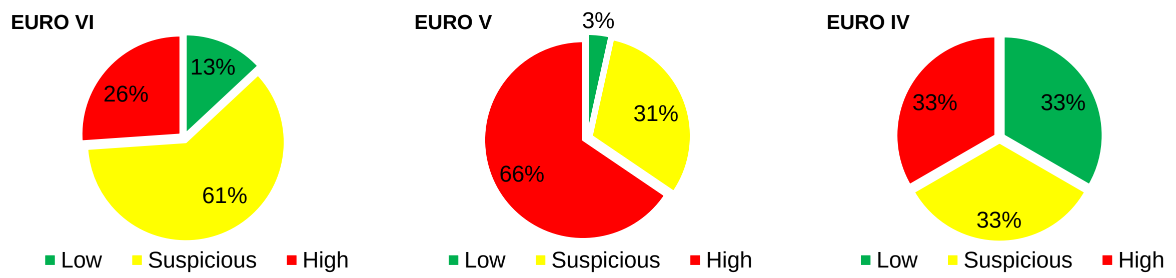


Figure 33: Emission classification of the inspected HDV for EURO VI, EURO V and EURO IV.

6.2 Conclusions inspections

In this chapter the conclusion of the inspected HDVs is summarised. Here all inspected HDVs are included independently of whether the measurement indicated a high or suspicious emitter. Also, if not otherwise stated, all inspections are included independent if only a short preliminary emission measurement was performed before or a longer valid measurement.

Four categories are separated:

(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

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 48 inspected HDV), as older HDVs are allowed to have higher emissions and there is only limited possibilities for inspection of the emission system.

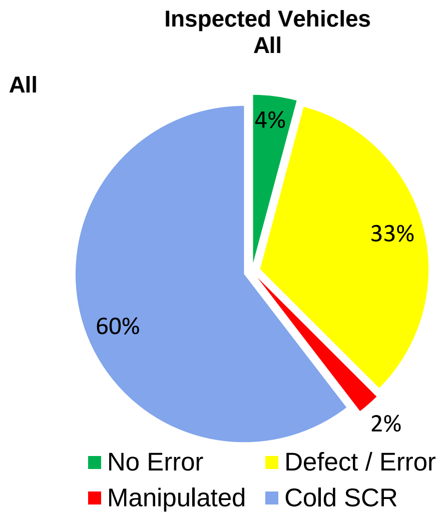


Figure 34: Conclusion of the inspected HDV for EURO V and VI. The percentage is relative to the inspected HDV.

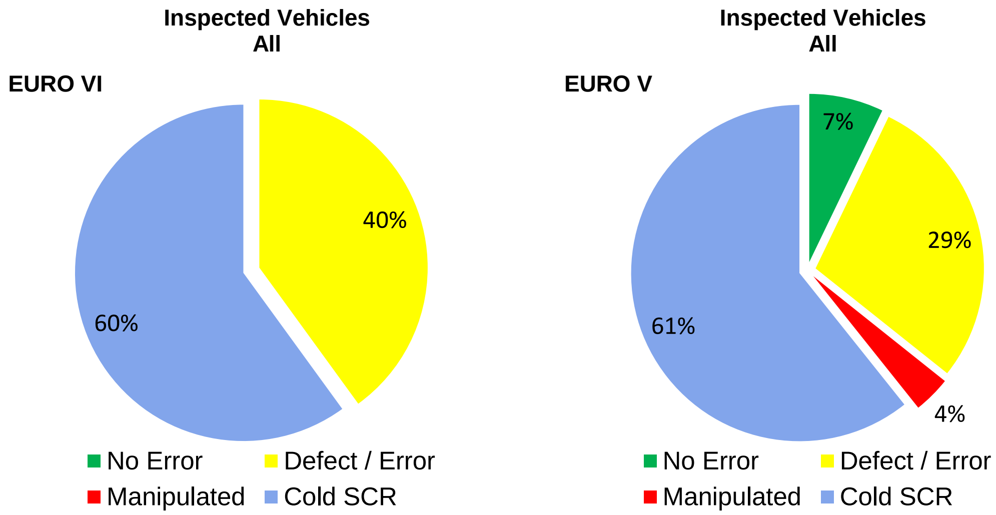


Figure 35: Conclusion of the inspected HDV, left for EURO VI and right for EURO V.

From Figure 34 and Figure 35 it can be seen that a “Cold SCR” are classified for most inspected HDV. This is unexpected, as the measuring location was on highways (see chapter 3.4), far from typical loading areas and thus the the engine and SCR has enough time to warmup. Even more surprisingly is, that the high rate of cold SCR was also classified for EURO VI where SCR systems warmup very quickly. This will further be analysed in chapter 7.2.

For 33% (29% for Euro V, 40% for Euro VI) of the inspected HDVs a defect or error in the emission system was found. The rate is very similar for EURO V and VI. Only for 2% a manipulation of the emission system was proven (one EURO V HDV) an unexpected low value and will be analysed also in chapter 7.2.

Two HDV (4%) are classified as “No Error”. Further detailed analysis (chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**) show that one had a clear SCR warmup and was than likely warm during the inspection and one with a diesel running fridge likely causing the high NO_x emissions. That means that actually no HDV was wrongly classified and one HDV should actually not be inspected.

Inspection	EURO V	EURO VI	All (EURO V + VI)
No Error	2	0	2
Defect / Error	8	8	16
Manipulation	1	0	1
Cold SCR	17	12	29
No Error [%]	7%	0%	4%
Defect / Error [%]	29%	35%	33%
Manipulation [%]	4%	0%	2%
Cold SCR [%]	61%	60%	60%

Table 8: Result of inspections. First the total numbers are given and below the percentage.

6.2.1 Conclusion of inspections for HDVs with a fully valid measurement

For 31% (15 out of 48) of the inspected EURO V and VI HDVs, only a preliminary emission measurement (see chapter 3.5) with the plume chasing device was made before the HDV was stopped for inspection. That mean the derived emission value and the classification are more inaccurate for these HDV. Here it is analysed if this has an influence on the inspection statistics. By comparing Figure 34 with Figure 36 it can be observed that no mayor differences are found. It is thus unlikely the reason for the high rate of classified “Cold SCR” or the two HDV with “No Error” .

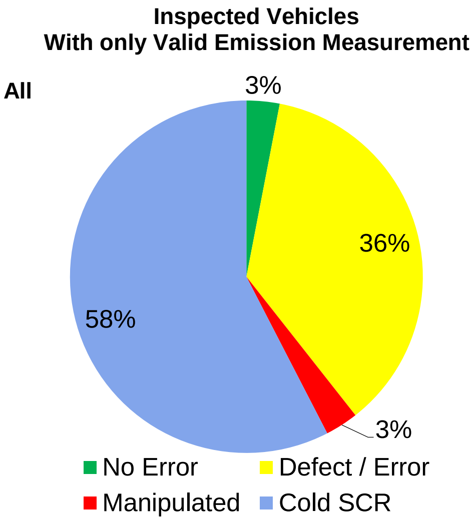


Figure 36: Similar to Figure 34 but only for HDV where a valid emission measurement was made before.

6.2.2 Conclusion of inspections only for the high emitters

If analysing the inspection results only for these HDV where the measurement indicate them as high emitters (excluding inspected suspicious and low emitters) a better agreement to identification of defects and manipulations is expected.. However Figure 37 show no major difference to Figure 34. Also 2 HDVs classified as having “No Error” remain (9%). These two HDVs, are either older vehicle or running a diesel powered fridge. These will be further analysed in chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**).

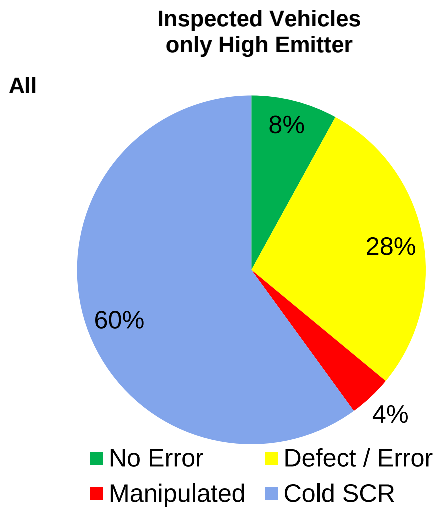


Figure 37: Similar to Figure 34 but selected for only the classified high emitters.

6.3 Inspections eastern European countries: RO, BG, H, SLO, HR, LT, LV, MA

The emission measurements observed between eastern European countries (RO, BG, H, SLO, HR, LT, LV, MA) show much higher rates of high and suspicious HDV emissions than for other origins (chapter 5.6 in comparison to 5.7). It would be expected that the rate of defective and manipulated HDV would be higher in this group in comparison to Figure 34, as only these two factors can explain the increase in the observed emission statistics between the different countries seen in chapter 5.6 in comparison to 5.7 (HDV from different countries use similar HDV).

Even more the rate of "Cold SCR" should be lower for foreign HDV, as they work less often on short range (regional) transports where engine and SCR are more likely not warmed up. However, this can not be observed in the statistics shown in Figure 38. Calculating to absolute numbers of all HDV the values mean that 13,8% of HDV in this group feature suspicious and high emissions due to cold SCR. This is much higher than for the western European country (chapter 6.4), opposite to what would be expected, and also a very high number for highway driving. This unexpected rates indicate, at least partly, wrong classifications of "Cold SCR".

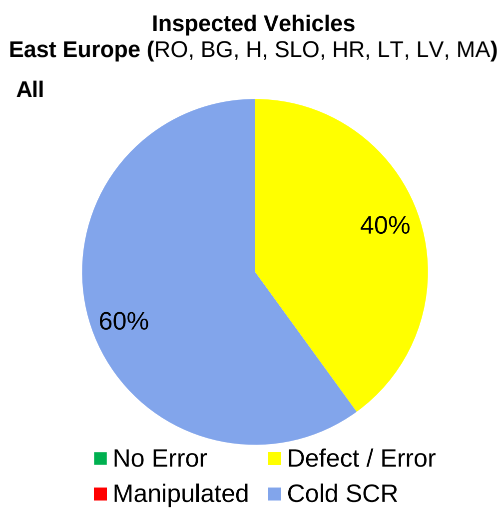


Figure 38: Similar to Figure 34 but only for vehicles from eastern Europe: RO, BG, H, SLO, HR, LT, LV, MA.

6.4 Inspections central & western European countries: B, NL, Pl, D, L, F, E, CZ

Similar to chapter 6.3 here, inspection conclusions are analysed for central and western European countries: B, NL, Pl, D, L, F, E, CZ. No major difference to Figure 34 and Figure 38 is observed. However, this would mean that in this group (using data from chapter 5.7) absolutely 9,75% of HDVs show suspicious or high emissions due to a cold SCR system. This is much more than would be expected on highways and also indicate problems in the “Cold SCR” identification.

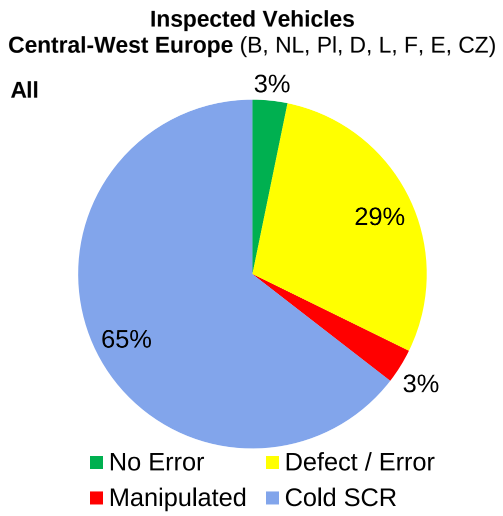


Figure 39: Similar to Figure 34 but only for vehicles from central & western Europe: B, NL, Pl, D, L, F, E, CZ.

7 Analysis of individual inspected vehicles

In this chapter, the individually inspected HDVs are further discussed, especially, with respect to vehicles that are classified as having a “Cold SCR” or “No Error”. We focus mainly on vehicles measured, for which sufficient data points from the plume chasing system are available.

7.1 Inspected vehicles with “No Error”

For the two HDV classified as “No Error” in the inspection a clear exclusion as a high emitter is found below. This means all these vehicles are not identified as “false positives”.

Old EURO IV without SCR systems and HDV with measured low emission value are already excluded as these were expected to have “No Error”. Inspected HDV with no or to few measurement data for a preliminary emission classification were also removed from the statistic.

For the two HDV remaining in the statistics, the deeper analysis result follows:

One showed a clear SCR warmup (similar to chapter 7.2.1) in the measurement data. At the point of inspection the SCR system was than warm and the inspection did not show a cold SCR system anymore. A better identification of these warmup processes would avoid inspection of these HDV’s.

The second HDV in this group had a diesel powered refrigeration unit, very likely leading to the high emissions observed (chapter 7.1.1).

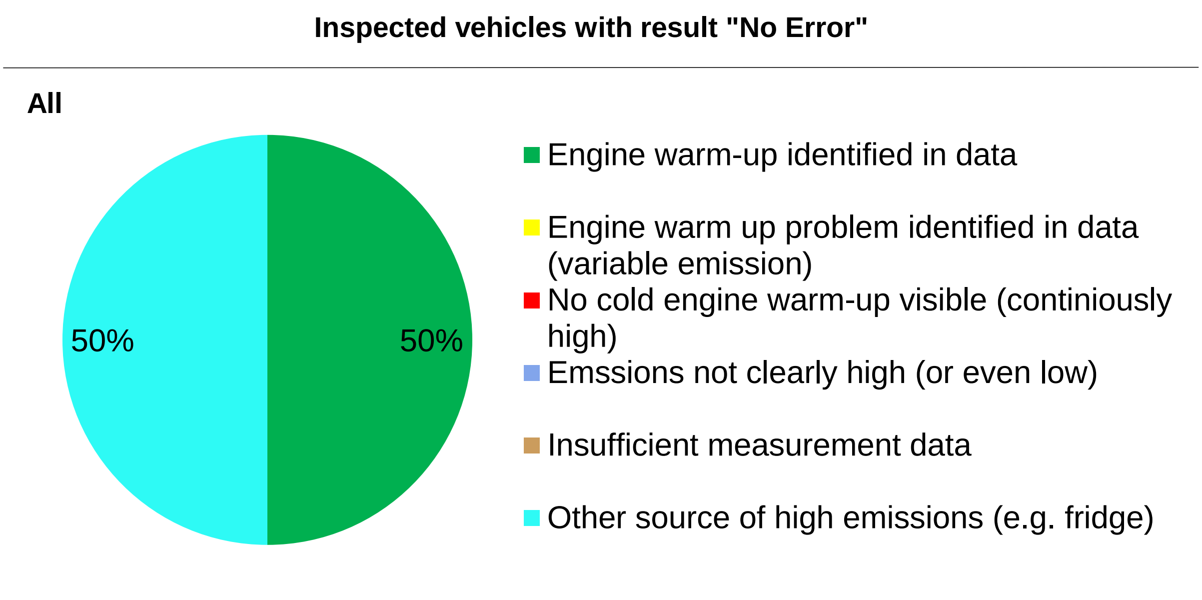


Figure 40: Emission data analysis of HDV classified as “No Error”. For all HDV an exclusion is found.

7.1.1 HDV with diesel powered fridge

One of the high emitting HDV showed emission values above 15.000mg/kWh (Figure 41), and had a diesel powered fridge. The inspection did not show an error or manipulation of the truck. Most likely the diesel running fridge was operated without any after treatment system and thus responsible for the high NO_x emissions.

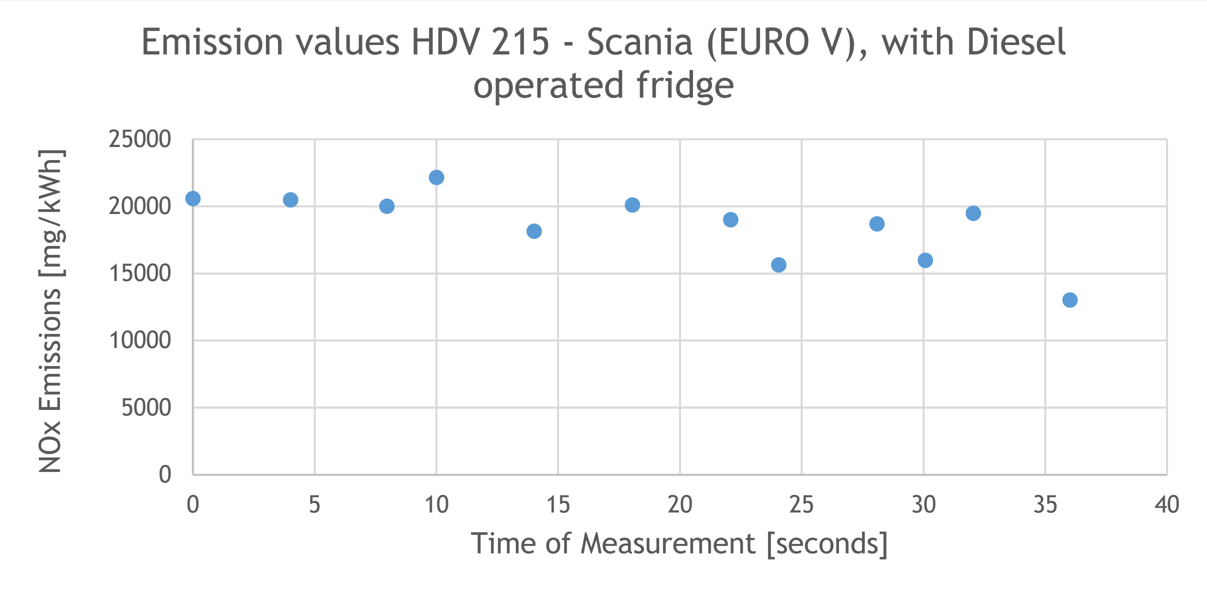
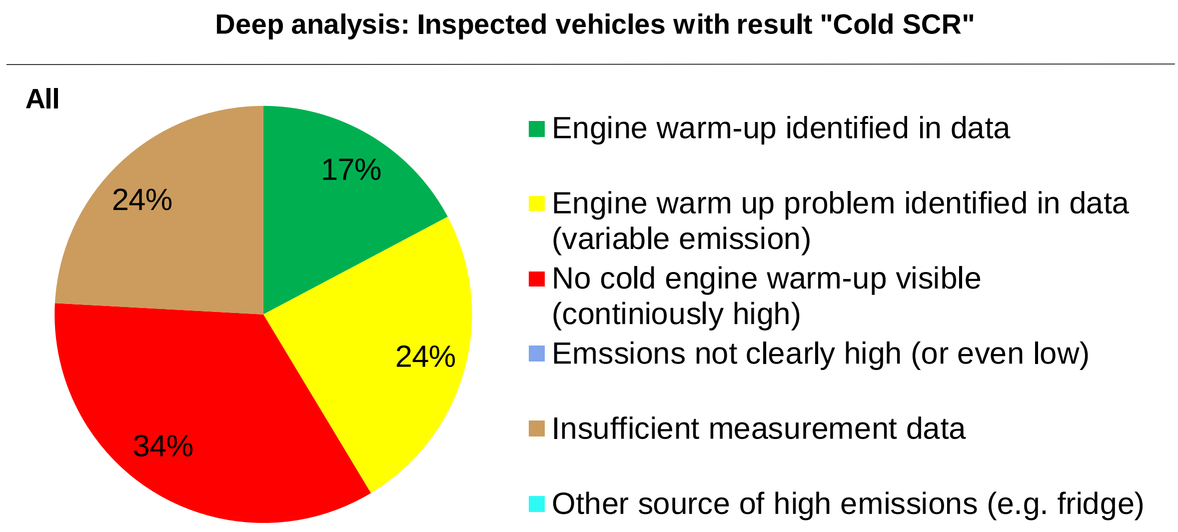


Figure 41: Time series of NOx emission factor for measured HDV no 215 (EURO V), where a fridge running on diesel was identified as the source.

7.2 Inspected HDV with "Cold SCR" (cold engines)

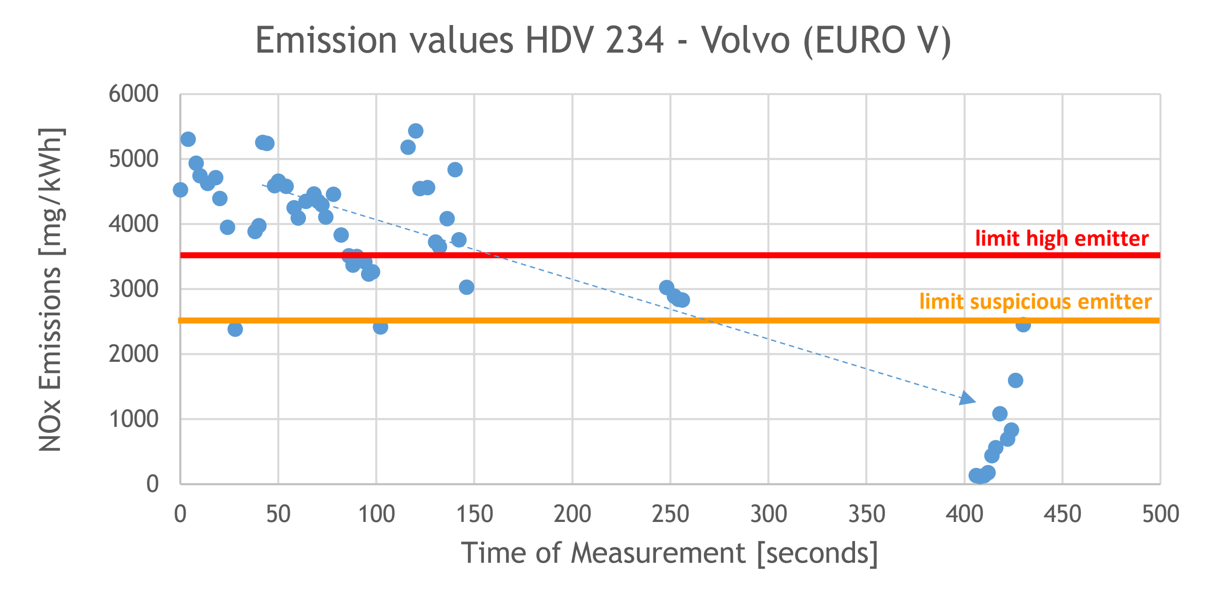
For the large fraction of vehicles classified as having a "cold SCR" in the inspection the situation is more complex. Several of these HDVs, showed a clear warmup (see chapter 7.2.1 and 7.2.3). So already the measurement data indicate a cold SCR and these vehicles should be measured longer or not be stopped for inspection. Others HDV in this group show a variable emission indicating, an unstable emission system, as known for older EURO V under low load (chapter 0) but it seems that this can sometimes also be observed for EURO VI (chapter 7.2.4). A significant fraction of HDVs show a very constant high emission (chapter 7.2.5 and 7.2.6). A possible wrong classification during the inspection might be an explanation. For example, a manipulation pretends a cold SCR simply due to a manipulation of the temperature sensor. It is one of the simplest manipulation methods. As a results the SCR system will not work. During the inspection one might then see these lower, manipulated SCR temperatures, but they are wrong. Extensive experience is needed to identify these wrong temperature values as a manipulation in order not to classify them as “Cold SCR”, but “manipulated”, cases.

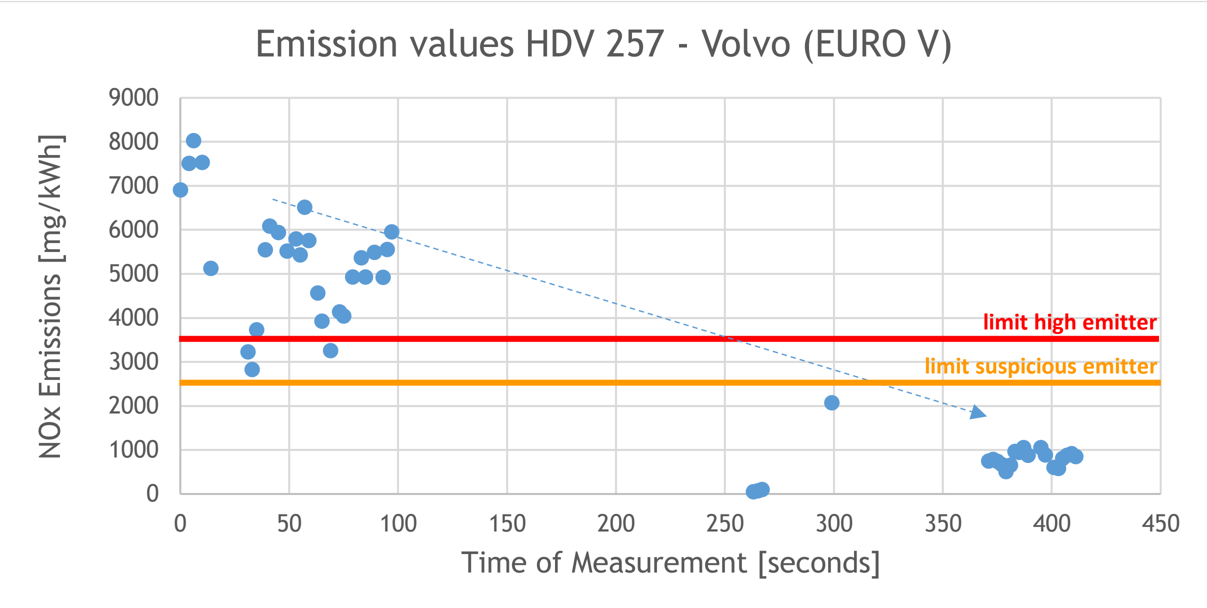


Cold engines and cold SCR result in a deactivated SCR emission reduction system and thus high NO_x emissions. When the engine warms up, the SCR should turn on and result in a strong reduction of the emissions. It is also well known, that some EURO V HDVs have, at lower load, problems warming up the SCR system [1]. This can be found for few EURO V with large engines and low load. However, it is unexpected that a large fraction of vehicles show no SCR warmup when their emission systems are working correctly.

7.2.1 EURO V SCR warmup

When the engine and the SCR system are leaving the warmup state, it starts to operate nominally and emissions decrease. This can also be observed in some of the measured HDVs which were inspected (Figure 42). The measurement data already indicated a warmup and for the inspectors it should be clear that for such inspected vehicles a cold SCR during a warm up can be expected. It may need a better clarification and training for inspectors to avoid inspections of such vehicles in the future.


Emission values HDV 234 - Volvo (EURO V)
NOx Emissions [mg/kWh]
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
250
300
350
400
450
500
Time of Measurement [seconds]
limit high emitter
limit suspicious emitter


Emission values HDV 257 - Volvo (EURO V)
NOx Emissions [mg/kWh]
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
50
100
150
200
250
300
350
400
450
Time of Measurement [seconds]
limit high emitter
limit suspicious emitter

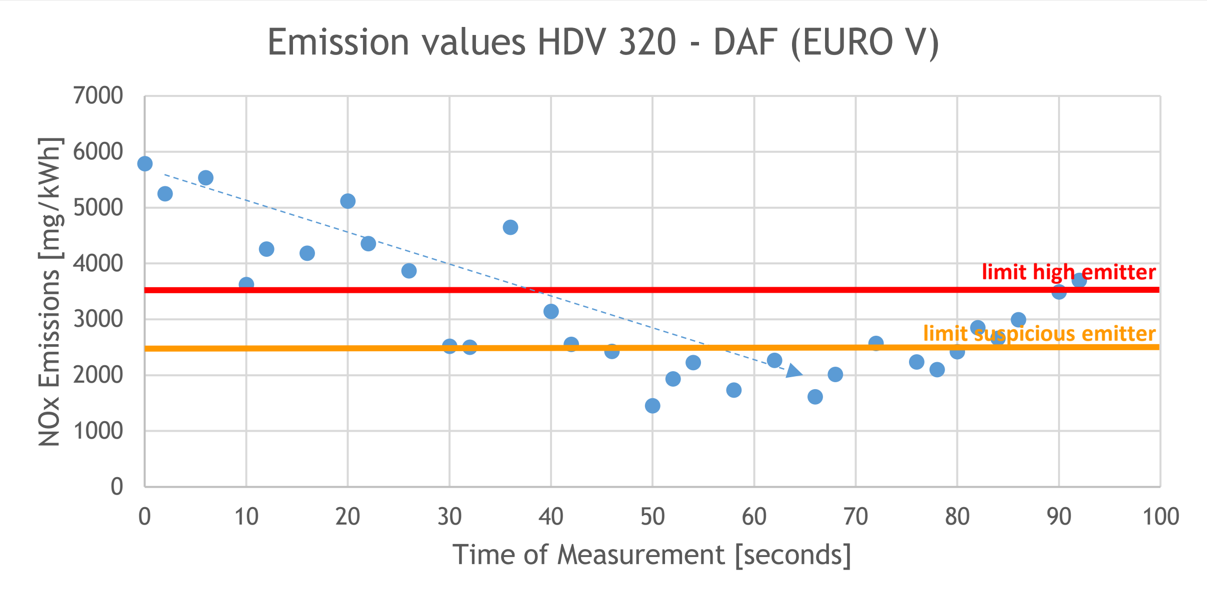
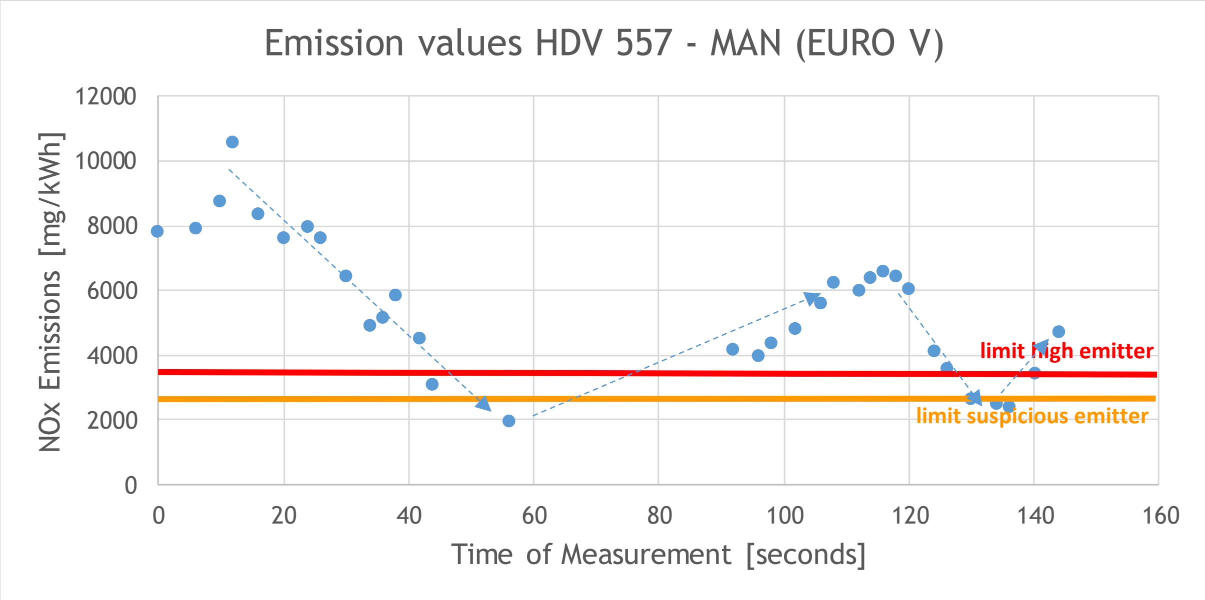


Figure 42: Time series of NOx emission factor for selected EURO V HDV where a warmup can be identified. These vehicles were classified in the inspection as cold SCR.

7.2.2 Variable EURO V emission due to insufficient SCR warmup

HDVs where the SCR / engines do not quickly warmup are easily misinterpreted as high emitters and selected for an inspection. Even if this is observed in the inspection, the goal is to identify these cases beforehand and thus avoid an inspection.

The high emissions arise due to a cold SCR system of the HDV which does not warm up as the engine load is too low (e.g. no load) or the engine and emission system is oversized. The emission system would work if the HDV is fully loaded, but will not reach sufficient working temperature if it is nearly empty, driving slightly downhill or having just recently started to drive. This will occur more often for local transport than for long range transport and thus in this study more likely to be from HDVs from Belgium.



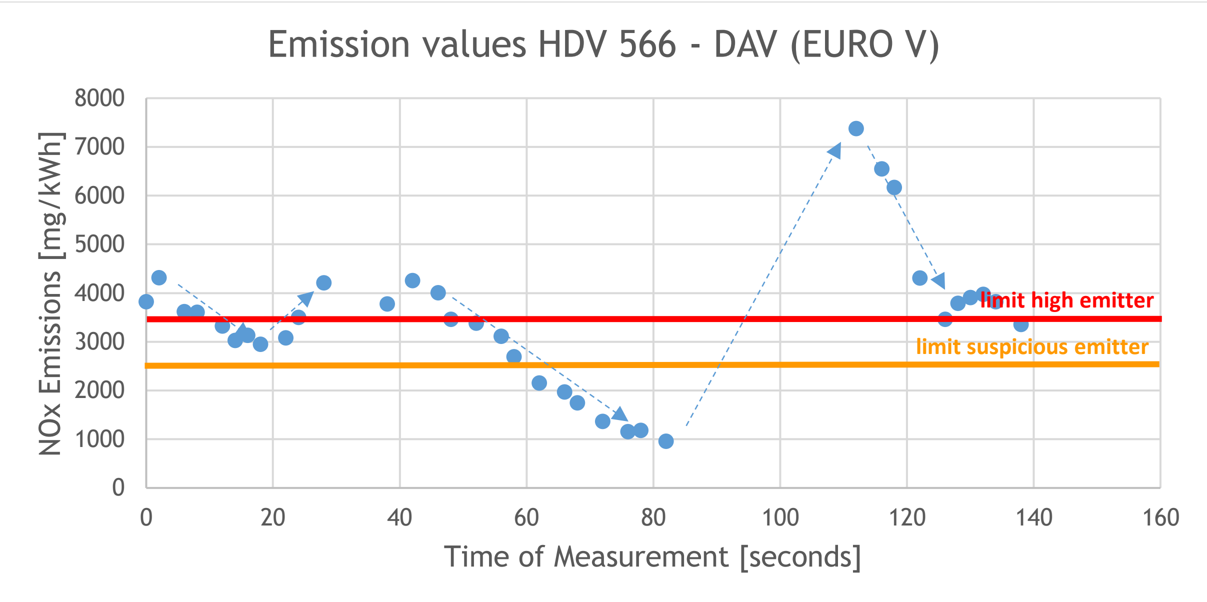
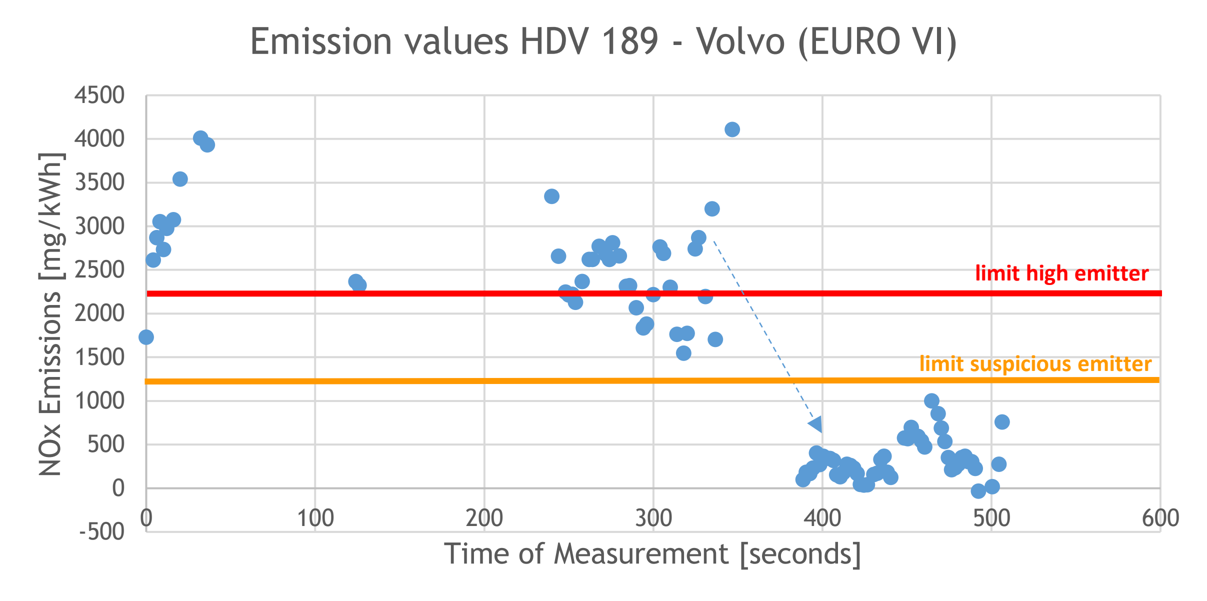


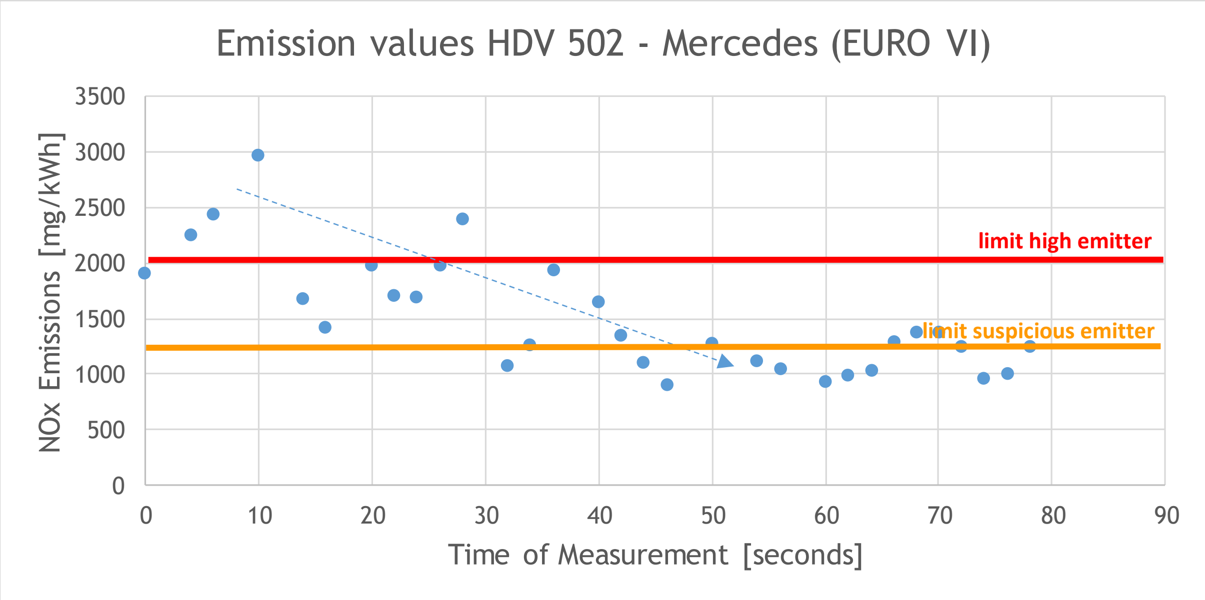
Figure 43: Time series of NOx emission factor for selected EURO V HDV where a strong fluctuation of emissions is observed likely caused by insufficient warmup of the engine / SCR system.

It can be seen that these HDVs reach for some periods a lower emission value, but the SCR is not working continuously. The variability in the emission value may indicate such insufficient SCR warmup.

7.2.3 EURO VI SCR warmup

For EURO VI HDVs a warmup is less often observed, as the systems typically warmup much quicker and are already warm when the vehicles are on the highway. Examples of observed EURO VI warmup can be found in the following Figure 43. Here the measurements already indicate a clear warmup of a cold SCR and inspections could be avoided as they would likely only result in a "Cold SCR".





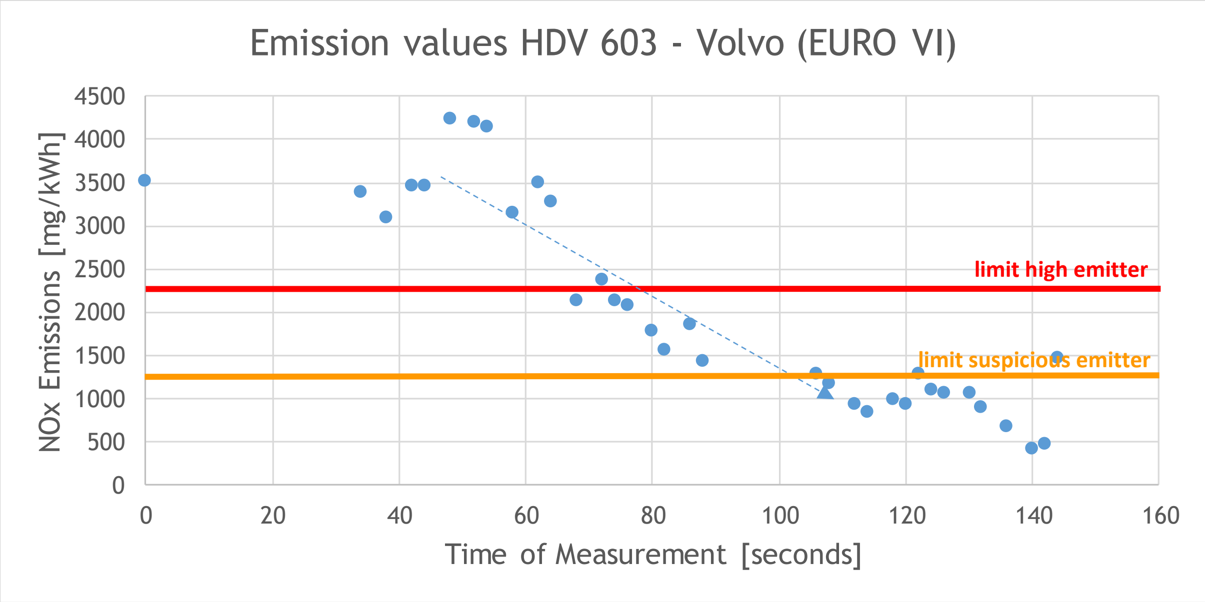
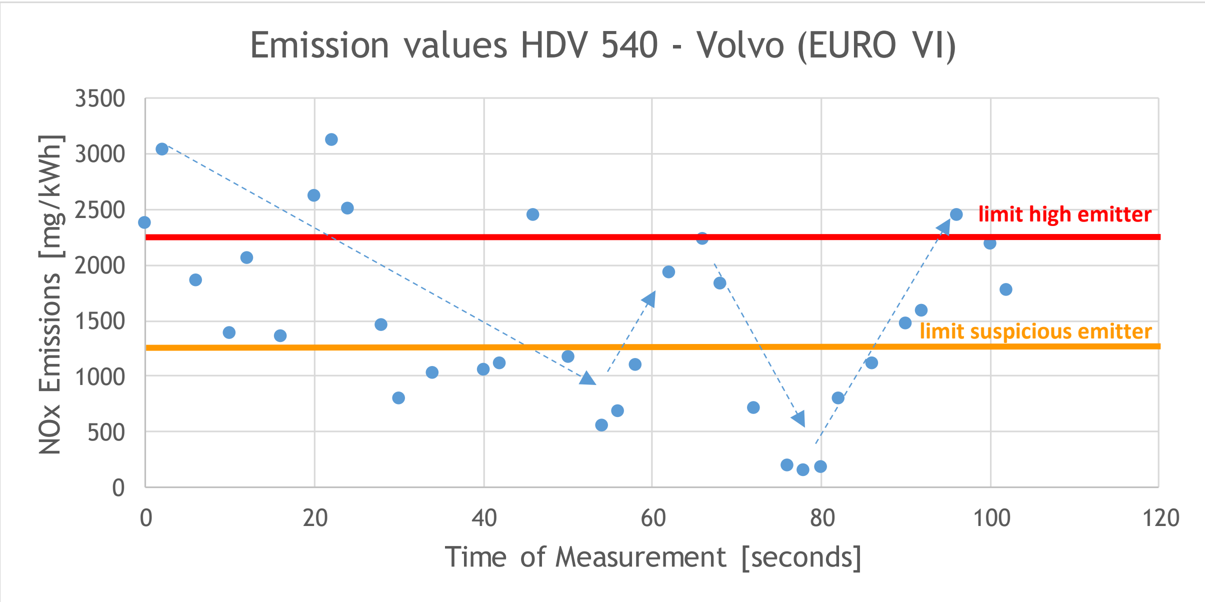


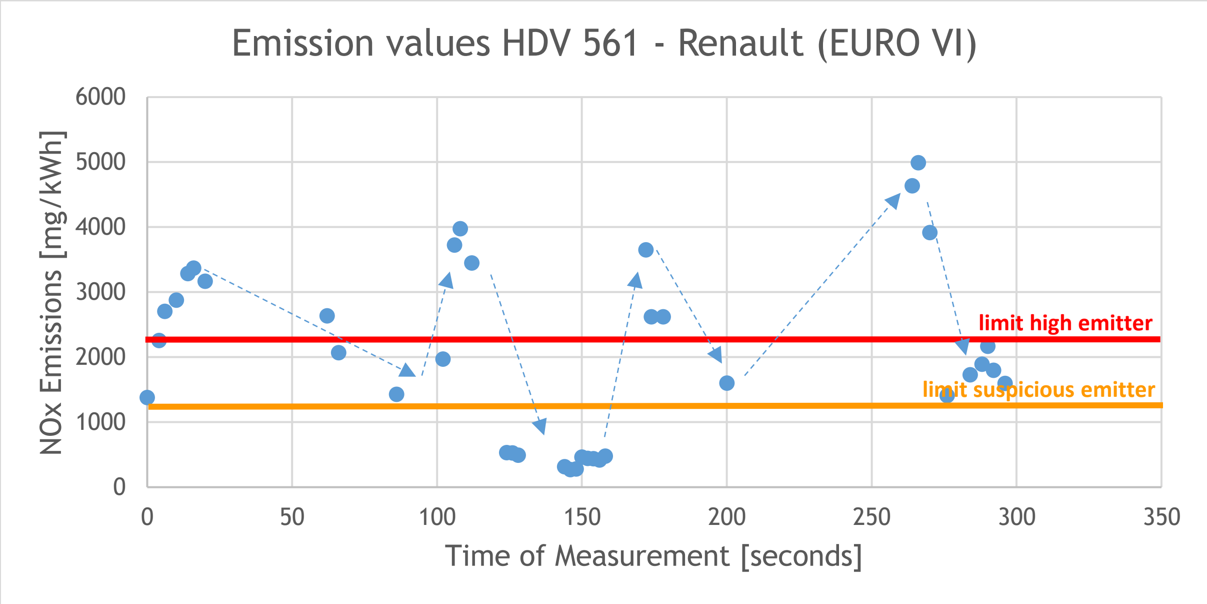
Figure 44: Time series of NOx emission factor for selected EURO VI HDV where a warmup can be identified. These vehicles were classified in the inspection as cold SCR.

For the HDV 189 in Figure 44 the SCR warm up started very late after the measurement. Such a long engine and SCR warm up are unusual for EURO VI, especially when the vehicle has already been driving beforehand on the highway. No further documentation on the driving history of the HDV is available to make further conclusions here.

7.2.4 Variable EURO VI emission due to insufficient SCR warmup

Similar to chapter 7.2.2 for EURO VI. Insufficient SCR warmup is largely unexpected for EURO VI vehicles, but seems to be, nevertheless sometimes a reason for temporary high emissions. More details on the vehicle, its load and the inspection parameter are needed to evaluate the reason of high emissions for these vehicles.





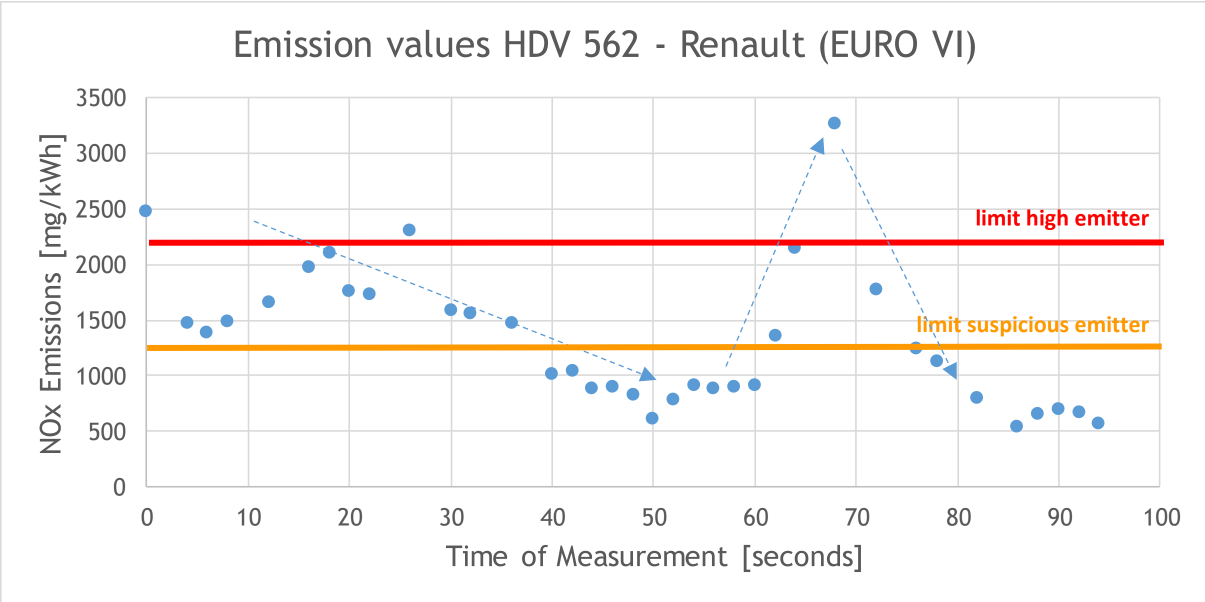
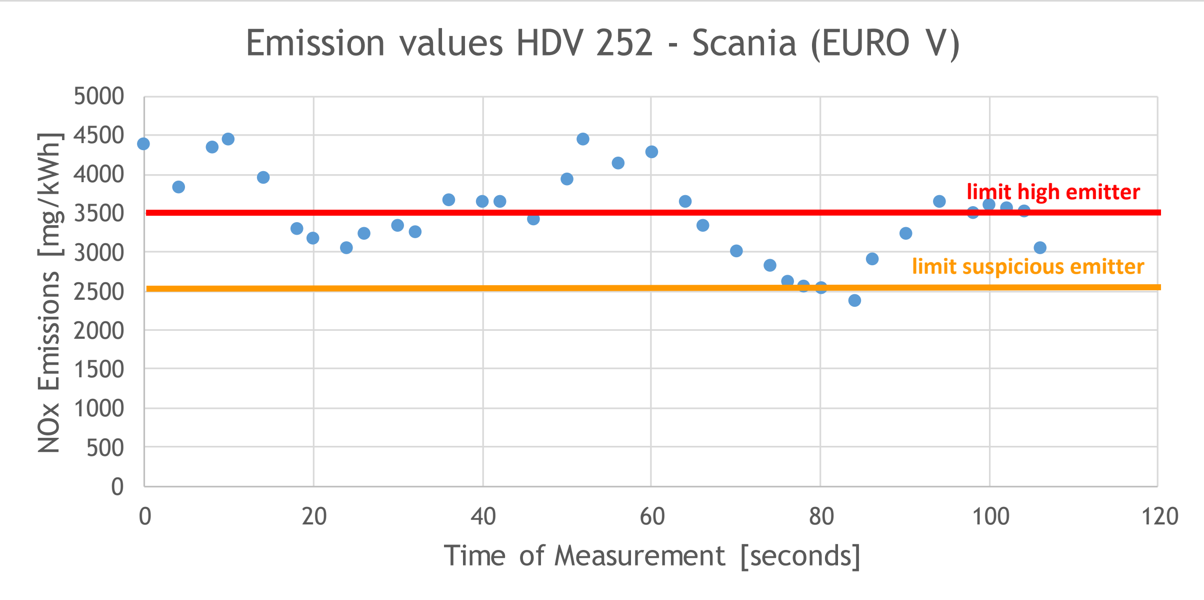


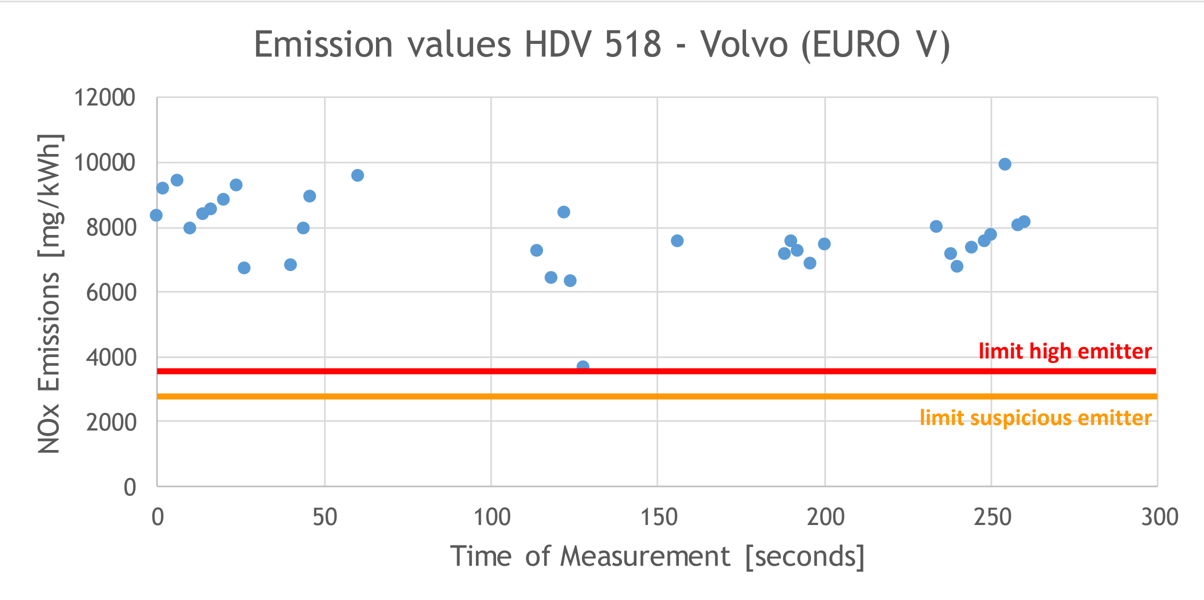
Figure 45: Time series of NOx emission factor for selected EURO VI HDV where a strong fluctuation of emissions is observed likely caused by insufficient warmup of the engine / SCR system.

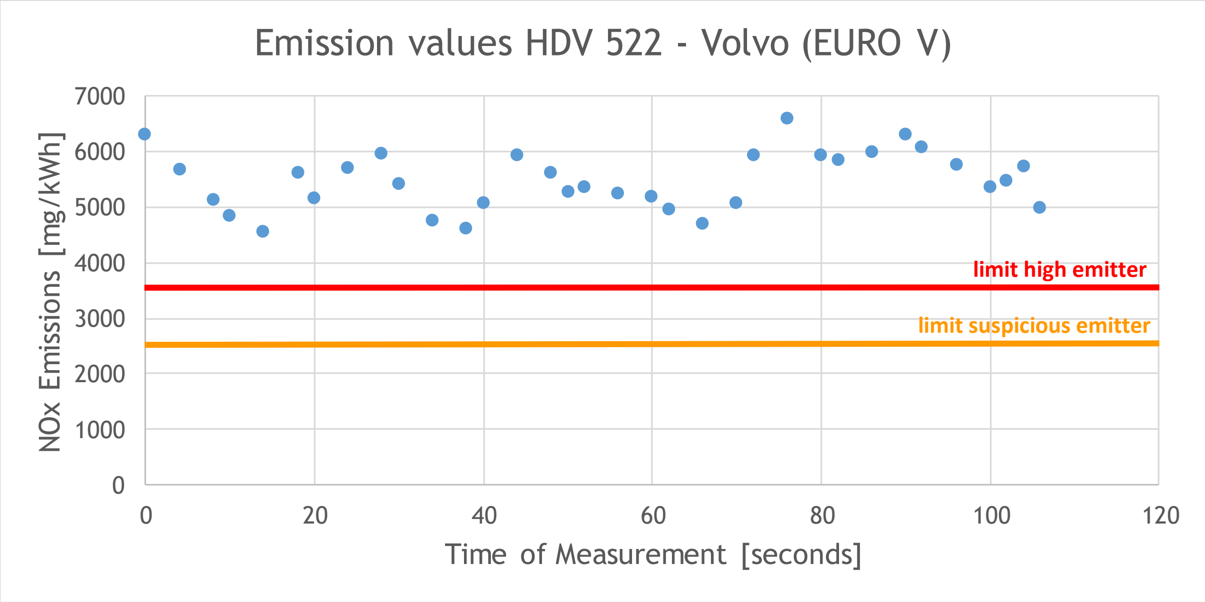
7.2.5 EURO V where measurement data disagree with "cold SCR" classification

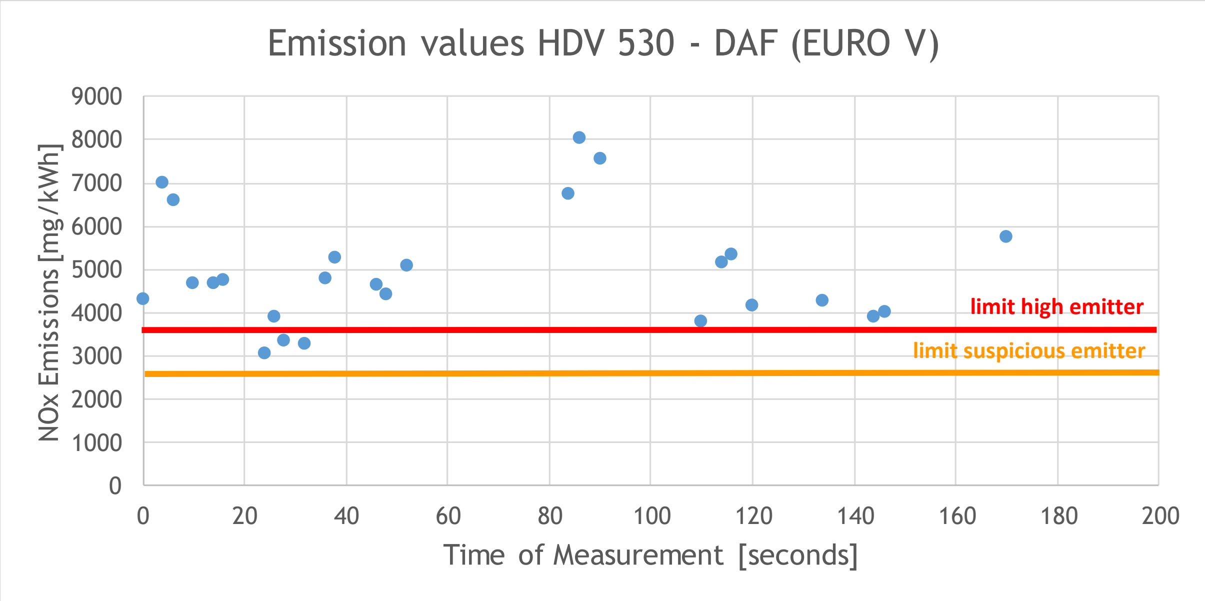
The most challenging group are vehicles which show high emissions without any indication of an SCR warmup, but where the inspection concluded a cold SCR. These vehicles could have the same problem with SCR warmup as shown in chapter 7.2.2 and 7.2.4, that mean vehicles which have problems for the SCR system, to warm up at all. The inspections did not record if these vehicles where driving empty resulting in low engine load, which could be a reason. However, here no period with a working or partly working SCR system could be observed. Examples of the emission values for such vehicles are given in the following Figure 46. The constant high emission value may well indicate that the cause is more likely to be due to a defect or a manipulation which was not found. Common emulators are on the market which pretend a cold SCR being present in order to cause the AdBlue metering system to turn off. This may lead to such inspection results.

More detailed inspections are needed in the future to better characterise such vehicles and exclude any kind of defect or manipulation.






Emission values HDV 522 - Volvo (EURO V)
NOx Emissions [mg/kWh]
7000
6000
5000
4000
3000
2000
1000
0
0
20
40
60
80
100
120
Time of Measurement [seconds]
limit high emitter
limit suspicious emitter


Emission values HDV 530 - DAF (EURO V)
NOx Emissions [mg/kWh]
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
20
40
60
80
100
120
140
160
180
200
Time of Measurement [seconds]
limit high emitter
limit suspicious emitter

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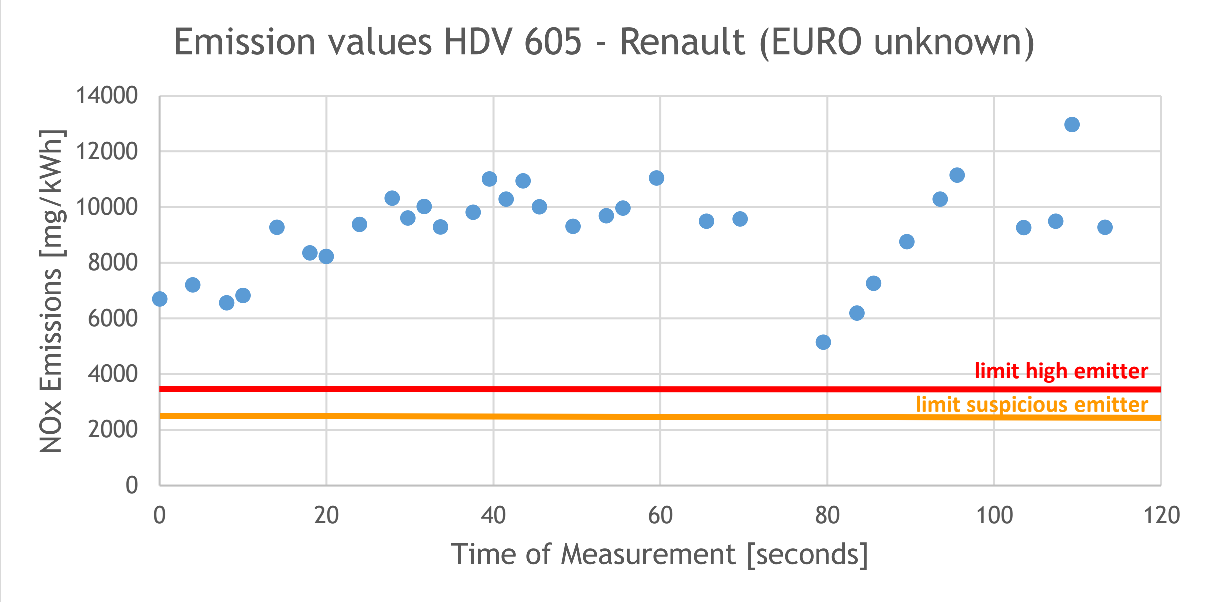

Figure 46: Time series of NOx emission factor for selected EURO V HDV where a continuous high emissions is observed and inspection concluded a cold SCR system.

7.2.6 EURO VI where measurement data disagree with "cold SCR" classification

Similar to chapter 7.2.5 also one inspected EURO VI vehicle was categorised as having a cold SCR from the inspection and showed continuously high NO_x emissions. As EURO VI HDV require a better SCR warmup management to fulfil the regulations, it is very unlikely that a vehicle showing no warmup with a reduction in NO_x emissions over several minutes. Especially when the vehicle had already been driving before on the highway. A more detailed inspection is highly recommended for such vehicles. It is very unlikely that this vehicle has no defect or manipulation.

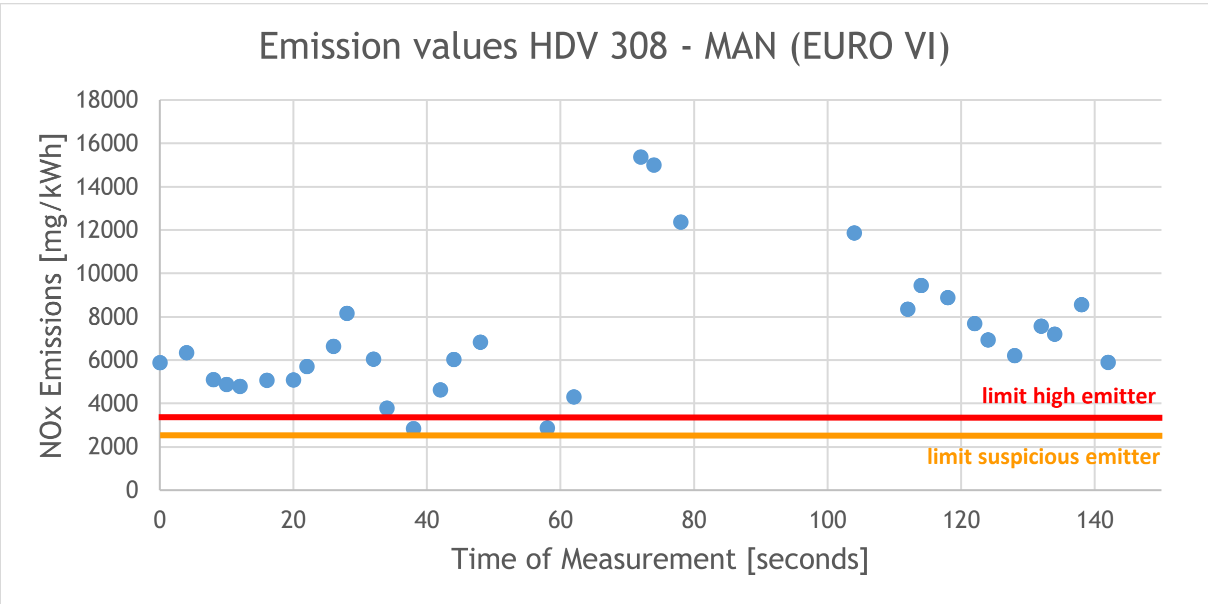

Figure 47: Time series of NOx emission factor for a selected EURO VI HDV where a continuous high emissions is observed and inspection concluded a cold SCR system.

7.3 Corrected inspection statistics

In chapter 7.1 and 7.2 it is explained that several of the inspected vehicles are not relevant for the statistics in identifying reliably defective and manipulated HDV with the plume chasing method. If we remove the following inspected HDVs from the statistics:

- With low emission values /emission values below the defined thresholds (chapter5.1)
- With a clear SCR warmup in the measurement data
- With other high emitting NO_x source like a diesel running fridge
- With too few data points to give a reliable (valid) emission classification

HDV with instable emission values e.g. due to insufficient SCR warmup are not removed, as the reason is not absolutely clear. 34 inspected HDV remain for the statistics (Figure 48).

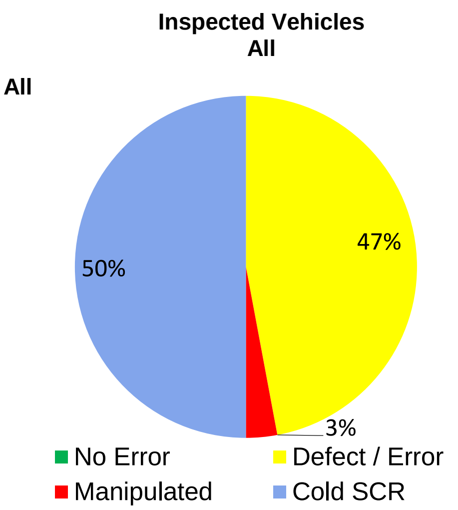

Figure 48: Conclusion of the inspected HDV for EURO V and VI excluding vehicles irrelevant for the statistics. The percentage is relative to the inspected HDV.

The group of defective vehicles increases now to 47%. Still 50% are classified as “Cold SCR”, indicating that still more work is needed in the inspection of these vehicles. Also the rate is still much higher than in other similar studies [2].

8 References

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[10] Pöhler und Engel (2019), Bestimmung von realen Lkw NOX-Emissionen (Real Driving Emissions) und hohen Emittern auf deutschen Autobahnen, Final report, Institute of Environmental Physics, University of Heidelberg.