Færdselsstyrelsen

EVALUERING

af plume chasing-teknologien som led i udvælgelsen af køretøjer til vejsidesyn

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Plume Chasing – Evaluation

In 2020 the Danish Road traffic authority had an external consultant that carried out a project called *Heavy-duty vehicle (HDV) NOx emission measured with mobile remote sensing (plume chasing) and subsequent inspection of high emitters* (Pöhler, 2021). During this project, the Plume chasing equipment was tested for 10 days on the Danish highways and the results from the test perioded were evaluated. The evaluation resulted in an emission level for the NO_x emission for the heavy-duty vehicles.

The project was so successful, that the Danish Road traffic authority purchased two plume chasing systems that in the fall of 2021 were mounted on two of the inspector vehicles.

Based on the experience gained with the equipment this report should evaluate the use of the plume chasing equipment with a focus on the following subjects:

- Share of the vehicles in the three categories: normal, suspicious and high emitters. The definitions are from (Pöhler, 2021)
- Share of cold, defect, or manipulated vehicles in the high emitting group
- Emission level as a function of the brand/manufacture (EURO norm VI)
- Emission level as a function of mileage and age of the vehicle (EURO norm VI)
- Emission level and if the vehicle has any other errors in the initial roadside inspection

The majority of the vehicles that are used for cross-border transportation through Denmark are EURO VI vehicles. Hence, part of the evaluation is focused on EURO VI.

Dansk Resume

I 2021 gennemførte en ekstern konsulent et projekt for Færdselsstyrelsen kaldet *Heavy duty vehicle (HDV) NO_x emission measurement with mobile remote sensing (plume chasing) and subsequent inspection of high emitters* (Pöhler, 2021).

I projektet blev Plume Chasing-udstyret afprøvet på motorvejen i Danmark i 10 dage. Resultatet viste, at udstyret kan anvendes til at finde køretøjer, der har fejl på det emissionsbegrænsende udstyr.

Dette projekt var så succesfuldt, at Færdselsstyrelsen indkøbte to plume chasing systemer som er blevet installeret på to af styrelsens inspektørbiler.

Denne rapport skal analysere hvordan udstyret er blevet anvendt gennem de første 6 måneder i forbindelse med vejsidesyn i Danmark samt følgende punkter:

- Andelen af køretøjer i de tre kategorier: normal, mistænkelig og høj udledende, som er defineret i NO_x projektet.
- Andelen af kold/defekt/manipuleret i den højtudledende gruppe.
- Udledning afhængig af antal kørte km samt alder af køretøjet for EURO VI
- Udledning afhængig af fabrikat for EURO VI
- Udledning og om køretøjet har andre fejl ved det indledede vejsidesyn.

Projektet er afgrænset til EURO VI lastbiler over 12 tons, da disse i udstrakt grad anvendes til grænseoverskridende transport.

Rapporten belyser, ud over de ovennævnte punkter, den europæiske lovgivning på området, hvordan udstyret er monteret på Færdselsstyrelsen inspektør bil samt en række konklusioner og herefter anbefalinger inden for områderne.

Da EURO-normen for alle de køretøjer, der er målt gennem de første 6 måneder, ikke er kendt, er grænseværdierne for normal, mistænkelig og høj udledende defineret på baggrund af undersøgelserne gennemført i (Pöhler, 2021). Dette er der nærmere redegjort for i rapporten.

Andelen af køretøjer i de tre førnævnte kategorier, som er defineret i (Pöhler, 2021), er 67% normalt, 21% mistænkelige samt 12% højudledende køretøjer. Dette er fastlagt ud fra 1106 målinger, som er gennemført fra september 2021 til februar 2022.

Undersøgelsen har vist, at 11% af lastbilerne i den højtudledende gruppe var mistænkt for at være manipuleret, mens de resterende 89% var defekte og blev sendt til ekstraordinært syn.

Analysen af resultaterne fra de 10 dages fokuseret kontrol med plume chasing viste, at lastbiler, der er ældre end 3 år samt har kørt mere end 350.000 km, begynder at få fejl på de emissionsbegrænsende udstyr.

Resultaterne er også blevet analyseret i forhold til emissionen ud fra de forskellige fabrikater. Analysen indikere ikke sammenhæng mellem udledningen og fabrikat. Det skal noteres, at datagrundlaget til denne analyse er yderst begrænset.

Analysen af resultaterne demonstrerede ikke nogen sammenhæng mellem højt udledende køretøjer og andre fejl på køretøjet.

I nærværende projekt er den europæiske lovgivning på området afdækket. Hovedkonklusionerne fra denne analyse er:

- Holdbarheden af det emissionsbegrænsende system er fastsat til 7 år eller 700.000 km afhængigt af hvad der kommer først for N3 med en masse over 16 tons.

- Det emissionsbegrænsende udstyr skal være aktivt når følgende betingelser er opfyldt:
  - Omgivelsestemperaturen skal være mellem -7°C og 35°C
  - Højden skal være under 1600 m over havniveau.
  - Kølevæsketemperaturen skal være over 70°C

- Reglerne for typegodkendelse har fastsat et emissionsniveau for NO_x fra 2013 til udgangen af 2016 på 900 mg/kWh, herefter skal alle køretøjer overholde 460 mg/kWh

- On-Board diagnose (OBD) systemet skal indtil udgangen af 2017 reagere, når udledningen er over 1500 mg/kWh, herefter skal reagere, når udledningen er over 1200 mg/kWh

Analysen af både resultaterne fra plume chasing kampagnen sammenholdt med analysen af lovgivningen har ledt til følgende anbefalinger:

- Der er et bekymrende antal lastbiler med høj udledning i Danmark. Derfor anbefales det, at der forsat er fokus på det emissionsbegrænsende udstyr ved vejsidesyn. Herunder, anbefales det at alle inspektørbilerne i Færdselsstyrelsen udstyres med et plume chasing system.

- Grænsen på 1200 mg/kWh for plume chasing fastholdes for EURO VI køretøjer.

- Alle køretøjer, der standses ved vejsidekontrol undersøges med OBD udstyr uafhængigt af målingen fra plume chasing.

- EURO VI køretøjer der ved målingen med plume chasing har en udledning over 2200 mg/kWh, skal kaldes til syn såfremt nedenstående betingelser er opfyldt:
  - Kølevæsketemperaturen er over 70°C
  - Omgivelsestemperaturen er mellem -7°C og 35°C

- At der på EU-niveau arbejdes for en metode, der i forbindelse med periodesyn kan fastslå, om det emissionsbegrænsende system er velfungerende

- At informere køretøjsfabrikanterne samt mekanikkerne, om holdbarheden af det emissionsbegrænsende system.

- At der på EU-niveau arbejdes for at skærpe grænsen for, hvornår OBD-systemet skal reagere og dermed kravet for, hvornår MIL lampen tændes og Chaufføren dermed bliver opmærksom på at lastbilen har en høj udledning.

- At der på EU-niveau arbejdes for at udvide det temperatur område hvor det emissionsbegrænsende system er aktivt. Temperaturen for kølevæsken er i dag fastsat til 70°C i direktiv (EU No 582/2011, 2011).

- At de nuværende plume chasing grænser for mistænkelige og højudledende køretøjer for EURO V ændres fra 2.500 mg/kWh og 3.500 mg/kWh til 4.500 mg/kWh og 7.000 mg/kWh, grundet alder på køretøjerne der overstiger deres holdbarhedskrav samt de oprindelige krav til køretøjerne.

Alle anbefalingerne er yderligere underbygget i rapporten.

Færdselsstyrelsen

Content

Legislation for EURO VI HDV

The EU regulation 595/2009 (EC No 595/2009, 2009) defines the emission level for the EURO VI vehicles. The EU regulation has been implemented by the EU regulation 582/2011 (EU No 582/2011, 2011) on implementing and amending Regulation (EC) No 595/2009. The following sections highlight some of the regulation for the NO_x emission system.

Durability

According to the EU regulation (EC No 595/2009, 2009) the durability of the emission system shall limit the tailpipe emission for a minimum of 700.000 km or 7 years whichever comes first for an N3 vehicle with a maximum technically permissible mass exceeding 16 tons.

Active NO_x system

The NO_x emission system should according to the legislation[1] be active under the following conditions:

- Temperatures between -7°C and 35°C
- Altitudes below 1600 m above sea level
- Coolant temperature above 70°C.

Hence, if all the above conditions are fulfilled the emission system should reduce the NOx emission level.

Limits for NOx emission.

The EU regulation (EC No 595/2009, 2009) sets a limit for the NO_x emission to 460 mg/kWh for a WHTC cycle. This limit is valid for vehicles that are type approved after 31 December 2012 and from 31 December 2013 for all new vehicles. However, it is possible to register a vehicle that does not meet the emissions limit for 18 months after the above dates.

During a transition period, the NO_x emission limit was 900 mg/kWh[2]. This is the limit for new type approvals until 31 December 2015 and 31 December 2016 for all vehicles.

OBD limits

The emission system is monitored by an On-board diagnostic (OBD) system. The system has to monitor the emission level of the vehicle. The NO_x OBD limit for the EURO VI is 1500 mg/kWh until 31 December 2016. After this date the OBD limit is 1200 mg/kWh. This is defined in (EU No 582/2011, 2011).
Hence, if the OBD system measures the NO_x emission to more than 1200 mg/kWh or 1500 mg/kWh a counter is activated, and the frequency of the error is recorded. When the frequency is above a threshold the malfunction indicator light (MIL) indicator is activated and the driver becomes aware of the problem with the vehicle.
It is first at this stage the driver of the vehicle becomes aware of the problem and can act on the higher emission.

Periodical technical inspection

The EU Directive (EU No 2014/45) sets the technical requirements for the periodical technical inspection (PTI) of the vehicles. The periodic roadworthiness tests of vehicles used on public roads has two ways of inspecting the emission system for diesel-driven EURO VI vehicles. The inspection methods are visual inspection and opacity measurements. However, none of these methods can be used to determine if the emission system can reduce NO_x as specified by the

[1] (EU No 582/2011, 2011) Annex XIII section 2.3.2
[2] (EU No 582/2011, 2011)Annex XIII section 7.1.1.1

legislation. Because the emission level is not visual, nor does it influence an opacity measurement.
According to the EU Directive (EU No 2014/45) OBD testing has to be part of the PTI from 20 of May 2023[3]. However, it is not directly required as part of PTI to control the emission system with OBD-equipment.

Data acquisition

The data for the study is obtained by plume chasing. The method is described in (Pöhler, 2021). The equipment has been mounted in two of the inspection vehicles at the Danish Road traffic authority. The inspection vehicle is noted in Figure 1.

Figure 1: The vehicle with the plume chasing equipment mounted. The image to the left shows the sample inlet. There are two sample inlets one on each side in the front of the car. The image to the right shows the analyzer mounted in the back of the car.

Two sample inlets are installed on each side in front of the car. The sample hoses are made from PTFE (Polytetrafluorethylene) typing with a diameter of 6mm. The sample lines are merged into one sample line that is led into the ICAD analyzer.
During the measurement with the plume chasing equipment, a tablet is used to visualize the emission level. The tablet is mounted on the dashboard of the vehicle. This is noted in Figure 2.
The software that is used is described in the previous report (Pöhler, 2021).

Figure 2: The tablet that is used to show the plume chasing measurement during the drive.

[3] (EU No 2014/45) Annex III section 14, implementation is determied by article 22 section 1.

The data for the estimation of the number of vehicles in the normal, suspicions, and high emitting group and for estimating the distribution of cold, defect and, manipulated in the high emitting group are obtained from September 2021 and until March 2022. During this period 1106 vehicles have been measured. The length of the measurement is defined as more than 15 measurement points. One measurement point is 1 sec where the CO_2 content of the plume signal is above 30 ppm. Therefore, the result from the study gives a good estimate for the share of high emitting vehicles in Denmark.

Share of vehicles in the three categories normal, suspicious, and high emitters.

In the report from (Pöhler, 2021) the limit of emission and the measurement time was defined. The proposed limits and measurement time are summarized in Table 1.

Table 1: The emission limits for EURO V and EURO VI vehicles (Pöhler, 2021).

Classification	EURO V	EURO VI
Suspicious [mg/kWh]	>2500	>1200
High [mg/kWh]	>3500	>2200
Measurement duration for an emission classification of a high or suspicious emitter	60 s	
Measurement duration to exclude a high emitter	15 s	

As noticed from the table the emission limits are dependent on the EURO classification of the vehicle. However, the EURO classification of the vehicle is only noticed if the vehicle is stopped for inspection. Hence, it is not possible to divide the data into EURO classification and then the classify the emission as Normal, suspicious, and high. Measurements below the limit values are considered to be normal functioning vehicles.

However, it is possible to conclude from the table that vehicles with an emission below 1200 mg/kWh are normal emitting vehicles because that is common for both EURO V and EURO VI. For vehicles between 1200 mg/kWh and 3500 mg/kWh, the emission is suspicious until the EURO classification of the vehicle has been determined and vehicles that have an emission above 3500 mg/kWh will be high emitters independent of the EURO classification.
Table 2 gives an overview of the emission limits that are independent of the EURO classification.

Table 2: Emission limits independent of the EURO classification

Classification	Emission limit
Normal [mg/kWh]	<1200
Suspicious [mg/kWh]	>1200 and <3500
High [mg(kWh]	>3500

From September 2021 until March 2022, 1106 vehicles were controlled by plume chasing and the distribution of the vehicles in the three categories are noted in Table 2. The distribution of vehicles is noted in Figure 3.

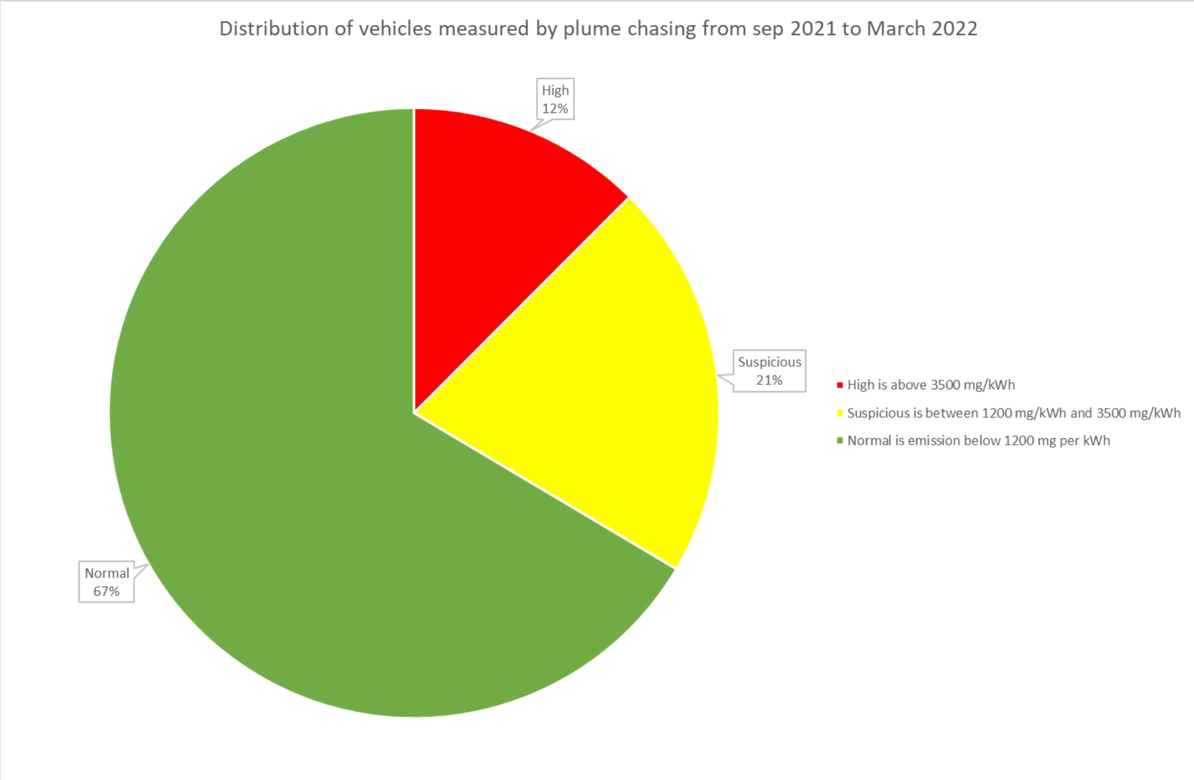

Figure 3: The distribution of Heavy-duty vehicles in the three categories normal, suspicious, and high. Where the emission from normal is below 1200 mg/kWh, suspicious emission level is between 1200 and 3500 mg/kWh, and high is an emission level above 3500 mg/kWh.

As noticed from the figure 67% of the vehicle were below the plume chasing emission limit for EURO VI. The vehicle in the suspicious group is 21% and the high emitters are 12%.

In the project (Pöhler, 2021) 9.7% of the vehicles were suspicious or high emitters. So, the number of high emitters in this study is a factor 3 higher than in the previous project. However, the number of high emitters also covers normal emitting EURO V vehicles. Hence the factor of 3 can be caused by EURO V vehicles in the data and not by and increasing number of defect or manipulated vehicles.

Share of cold, defect, or manipulated in the high emitting group.

The high and suspicious emitting vehicles from the period September 2021 until March 2022 were subjected to a roadside inspection.
During the roadside inspection the technical condition of vehicle is inspected according to the EU directive 2014/47EU. During the technical inspection the on-board diagnostics for the vehicle was read out and analyzed for errors.
The roadside inspection revealed that the number of vehicles that were defective was 89% and the number of vehicles that were suspected of being manipulated was 11%. Figure 4 illustrates this.

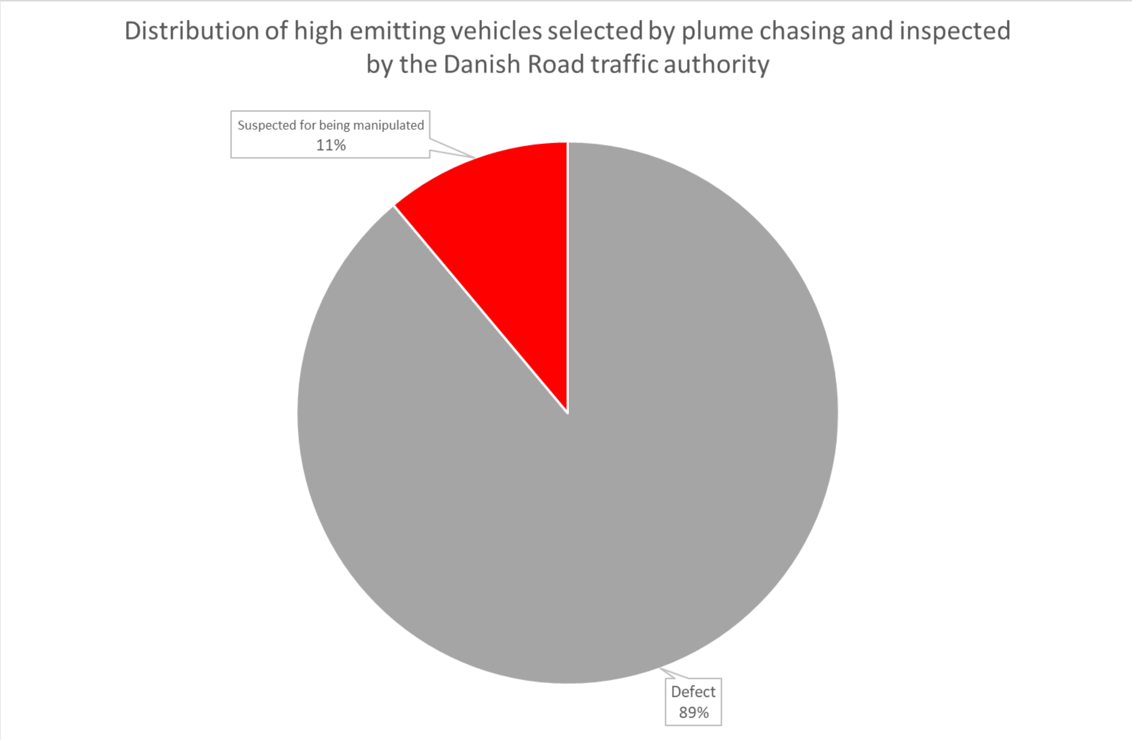

Figure 4: The distribution of high emitting vehicles selected by plume chasing.

The suspicious or manipulated group is the vehicles that The Danish Road traffic authority suspects are manipulated. However, it is not part of the roadside inspection to determine if the vehicle is manipulated. If The Danish Road Traffic Authority suspects that the vehicle is manipulated, then the vehicle is reported to the police.

Exhaust Emission level as a function of mileage and age of the vehicle (EURO VI).

During the weeks 9 and 11, 82 EURO VI vehicles were inspected after a valid plume measurement. The vehicles were randomly chosen during the two weeks and all vehicles that had a valid plume measurement was stopped.
The inspection method is the same method as used from September 2021 and forward. However, the OBD data was analysis after the inspection to verify the conclusion from the roadside inspection.

An emission measurement is valid after the plume measurement was continued for 60 sec (30 datapoints). Plume is present if the CO_2 signal is min 30 ppm above background concentration. Hence, the measuring time during the 2 weeks of focused plume chasing was longer than the normal plume chasing time.

As part of the analysis of the OBD system the state of the emission system was determined. The emission system was categorized with inspiration from the plume chasing project in 2020 (Pöhler, 2021). The emission systems were categorized in three categories

- Normal: well-functioning emission system
- Cold: a vehicle that haven't reached operational state
- Defect: a vehicle with a mal-functioning emission system this category also contains the manipulated vehicles.

The analysis does not differ between defect and manipulated because it is not the focus for the Danish Road traffic authority to prosecute the owners of the vehicles. If the OBD analysis on the road shows that the vehicle might by manipulated the police is contacted and they will decide if the owner should be prosecuted.

The emission level as a function of age is noticed in Figure 5. The emission level as a function of the total mileage for the vehicles is noted in Figure 6.
The share of normal is 77% (64 vehicles), defect is 22% (18 vehicles) and cold is 1% (1 vehicle).

Each blue dot represents a vehicle with an emission system that is categorized as normal. Each grey dot represents a vehicle that have a defect emission system. The orange dot represents a vehicle with a cold emissions system. The green line is the plume chasing emission level for a well-functioning exhaust system. The red line is the plume chasing emission level for a high emitter. In between the green and the red line is the emission level suspicious. The orange line is the type approval limit for the vehicles according to the section OBD limits.

The classification of the emission system is based on the analysis of the OBD system and does not consider other errors on the vehicles. If the emission system is classified as defect and the emission level is below the plume chasing line, then the classification is based in the analysis of errors in the OBD system.

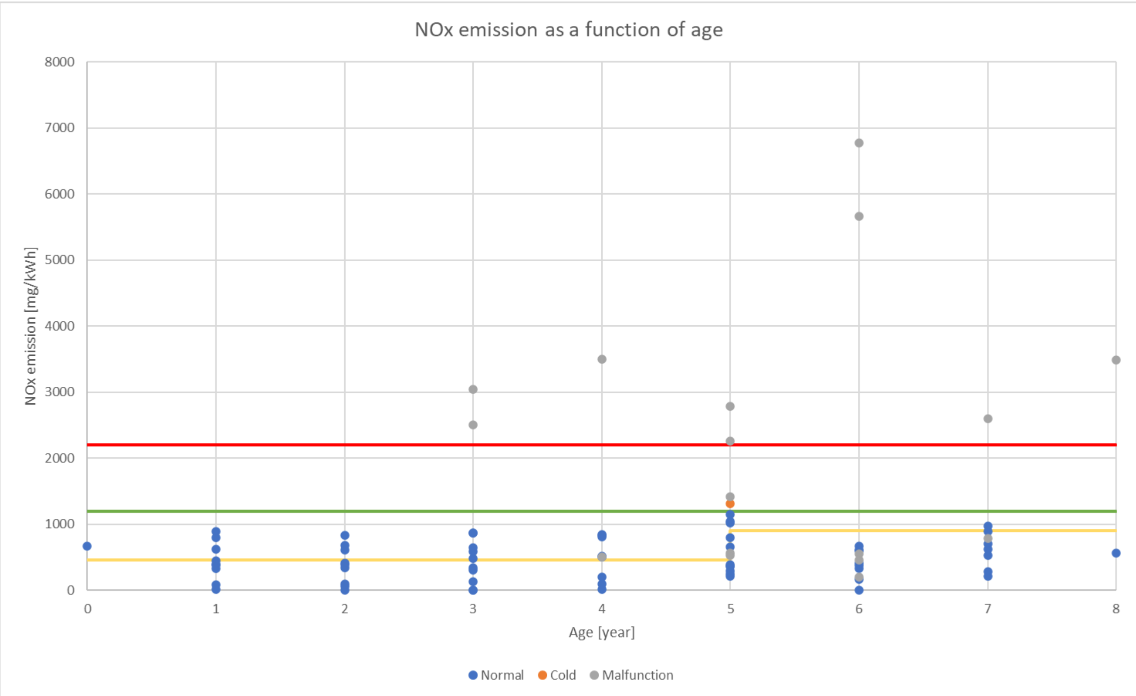

Figure 5: NO_x emission level as a function of age for vehicles of EURO VI classification.

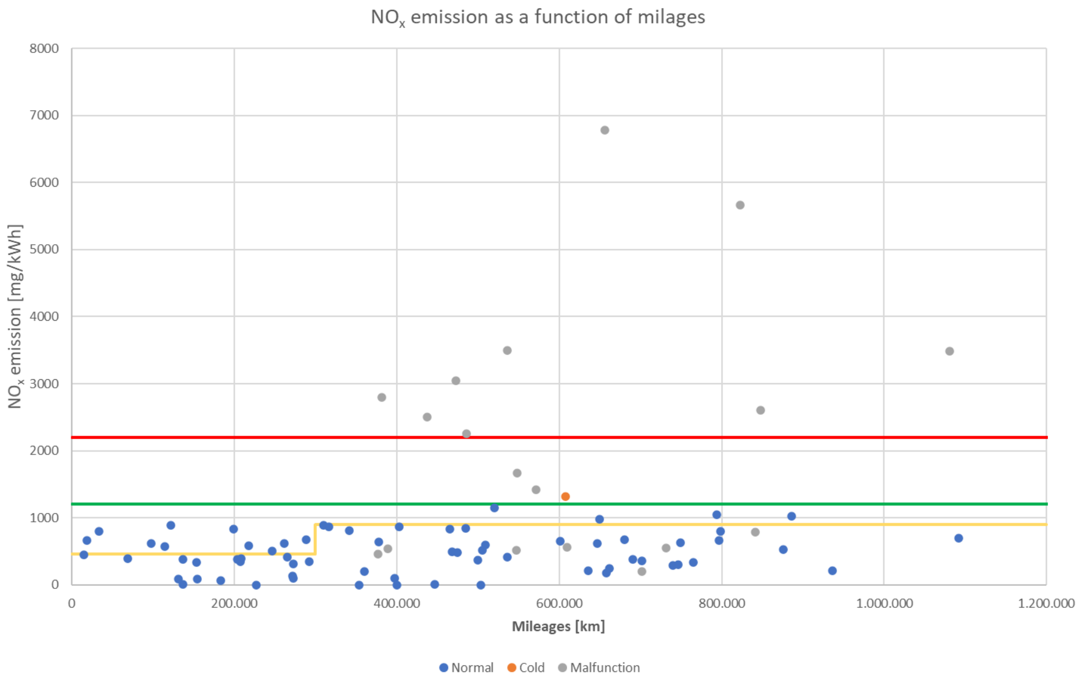

Figure 6: The NO_x emission level as a function of the total mileage in km of the vehicle.

As noticed from the figures, the emission level from the vehicles with well-functioning (blue dots) are all below the limit from the former plume chasing project (Pöhler, 2021). However, seven of the vehicles that had a mal-functioning emission system had an emission below the limit. Common for the seven vehicles is that they are more than 3 years old and driven more than 350.000 km.
The share of vehicles below 350.000 km are 29 vehicles of which all have a well-functioning emission system with a normal emission level. Above 350.000 km there are 53 vehicles of which 18 or 34% of the vehicles above 350.000 km is defect, 34 or 64% of the vehicles above 350.000 km is normal and 1 is cold.

It is therefore noticed that the emission systems start to malfunction after the age of three years or more than 350.000 km whichever comes first. In the analysis there are no vehicle below 3 years that have a milage above 350.000 km.

When an emission system is malfunctioning or defective the dosing of AdBlue is reduced or stopped. When the dosing of AdBlue is reduced or stops the exhaust emission level of NO_x rises. The emission system can be repaired so the emission level can be reduced again.

However, a natural aging of the catalytic material in the exhaust system will occur during the lifetime of the vehicle. When the catalyst ages the reduction of NO_x will decrease hence it is expected that older or vehicles with high mileage will have a higher NO_x emission due to the aging of the catalyst. The aging of the catalyst is at present time irreversible, and the only option is to replace the catalytic material.

Revision of errors on high emitters.

As part of the roadside inspection during week 9 and 11, the vehicles were subjected to investigation by OBD. The OBD data from only the high emitters have been reviewed to determine why they are high emitters and if the driver is aware of the problem with the emission system.

The revision showed that the majority of the drivers knew of the errors with the vehicles. Due to the MIL indication lamp was on. However, in the case of one vehicle, the driver is unaware of the problem with the emission system. The error with the emission system was detected for the first time 12 days before the vehicle was inspected by the roadside inspector. Hence, the vehicle has been a high emitter for 12 days and the OBD system has not informed the driver of a problem during this period. The driver has not been informed because the frequency counter for the error is still below the threshold for activation of the malfunction indicator light (MIL) indicator.

Emission level as a function of manufacture of the Heavy-duty truck (HDV).

As part of the plume chasing evaluation where the data accusation was carried out in week 9 and 11, it is interesting to see if the evaluation indicates that the emission is dependent on the manufacture or brand of the heavy-duty vehicle.

The distribution of EURO VI vehicles on manufacturers registered in The Danish Motor vehicle register (DMR) in Denmark are as shown in Table 3 according to www.*bilstatistik.dk*

Table 3: The distribution of vehicles among the seven larges brands

Number	Brand	Number of vehicles	
		Number	Share
1	Scania	8.350	28,23%
2	Volvo	8.184	27,67%
3	Mercedes-Benz	5.485	18,54%
4	MAN	4.293	14,51%
5	Iveco	1.564	5,29%
6	DAF	950	3,21%
7	Renault	504	1,70%
Total including minor brands		29.581	

In the following analysis, the top four manufacturers and DAF will be included in the analysis of the exhaust as a function of manufacture. The top four manufacturers are Scania, Volvo, Mercedes-Benz, and MAN these have been selected because they are the heavy-duty vehicles with the highest frequency on the Danish roads. DAF was selected because this manufacturer is very popular in other European countries. The manufacturers that have been selected is covering approximately 90% of the heavy-duty vehicles registered in Denmark.

The NO_x emission as a function of mileage and age for the five manufacturers is noted in Figure 7 to Figure 16.

Common for all the manufacturers is that the emission level for a well-functioning emission system is below the 1200 mg/kWh limit.

The data for the different manufacturers are very limited, therefore it is difficult to conclude any trends for the emission strategy with regards to the durability of each of the manufacturers. The result indicates that MAN vehicles that have driven more than 350.000 km have a higher frequency of malfunctioning compared to the other manufacturers.

However, due to the very limited data material it is not possible to assess if it is a trend or if the emission system has a design error or arbitrary.

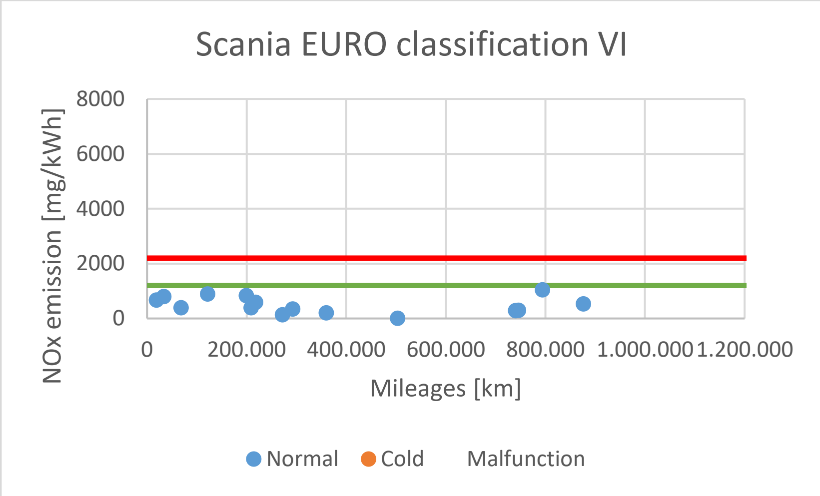

Figure 7: The NOₓ emission as a function of mileage for Scania EURO VI vehicles

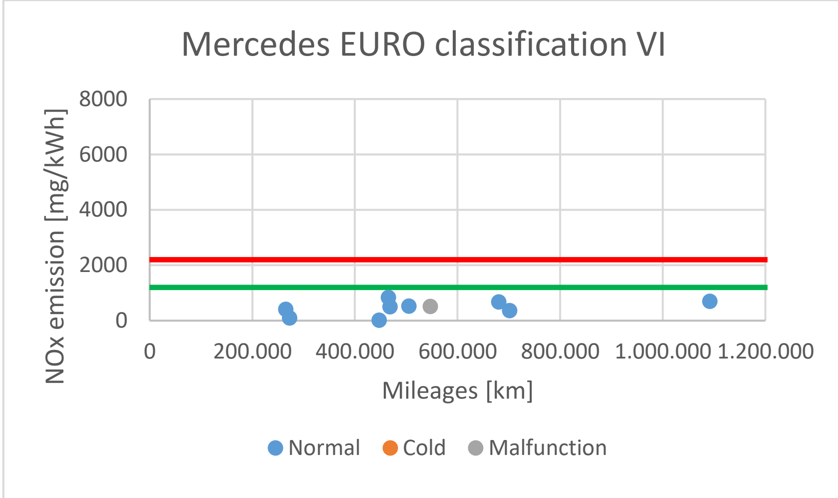

Figure 8: The NO_x emission as a function of mileage for Mercedes EURO VI vehicles.

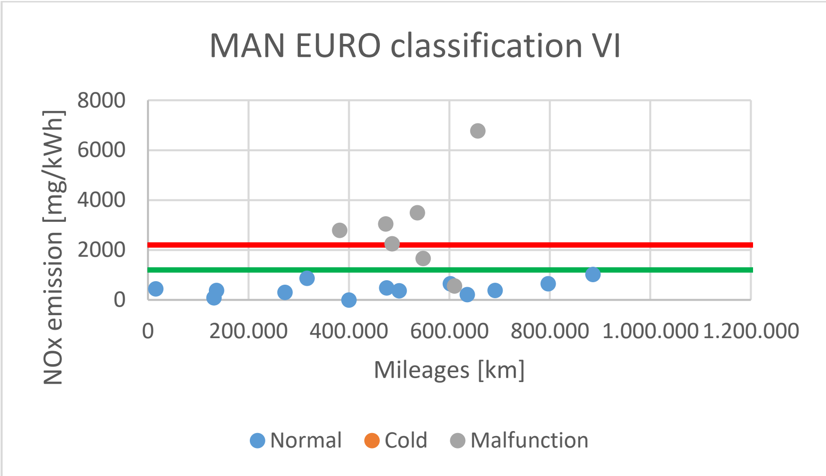

Figure 9: The NO_x emission as a function of mileage for MAN EURO VI vehicles

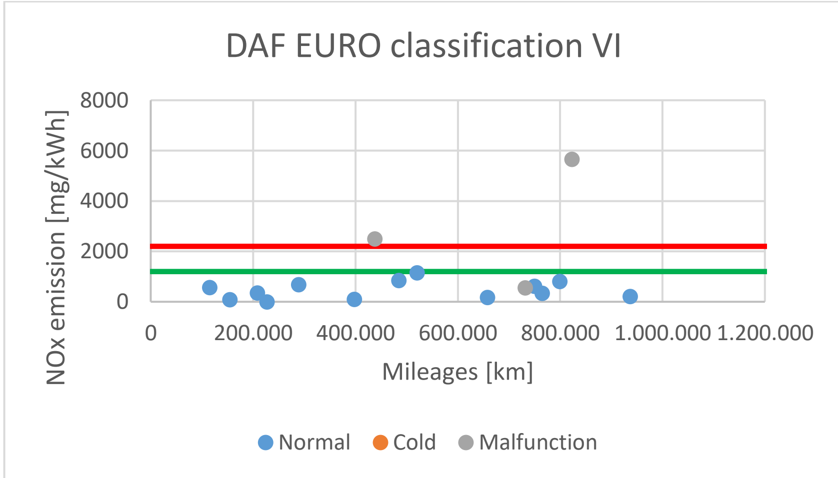

Figure 10: The NO_x emission as a function of mileage for DAF EURO VI vehicles

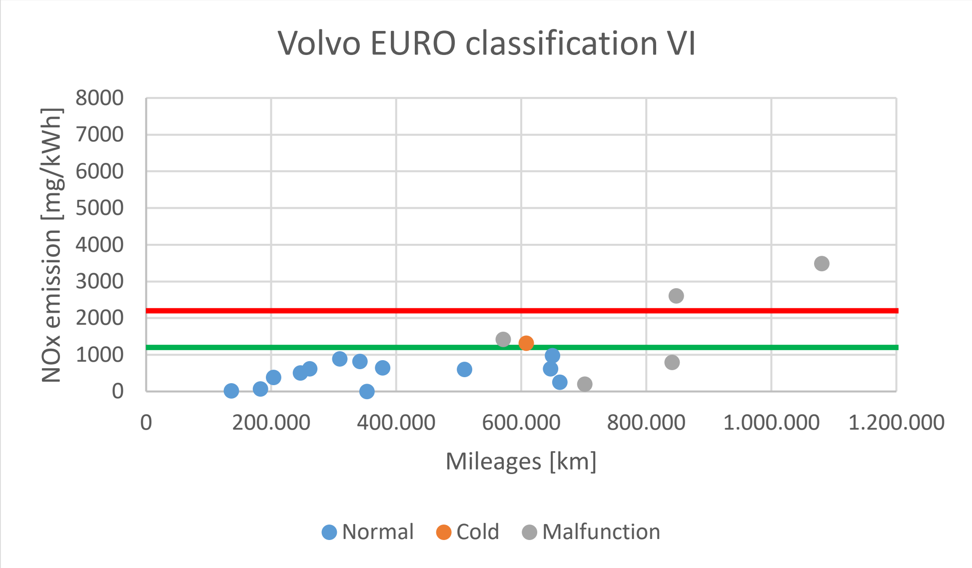

Figure 11: The NO_x emission as a function of mileage for Volvo EURO VI vehicles

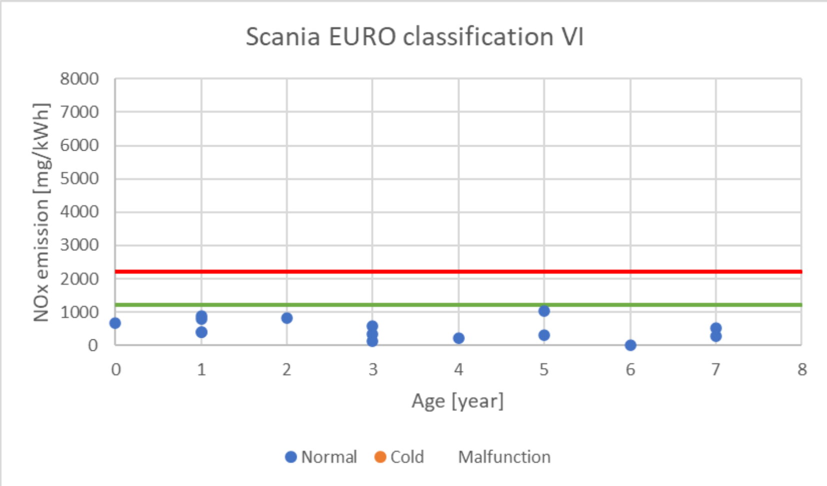

Figure 12: NO_x emission as a function of age for Scania EURO VI

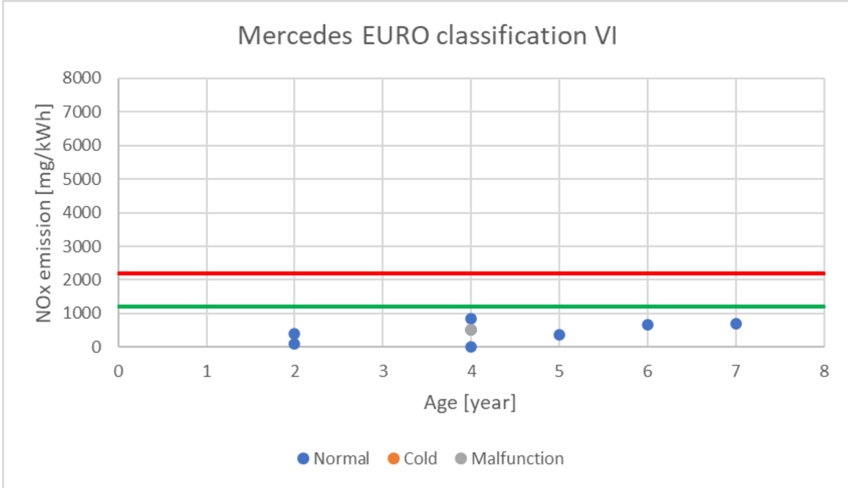

Figure 13: NO_x emission as a function of age for Mercedes EURO VI

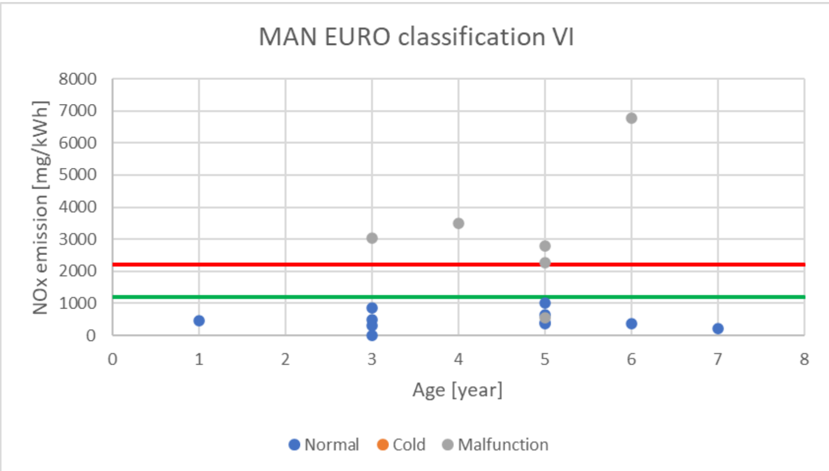

Figure 14: NO_x emission as a function of age for MAN EURO VI

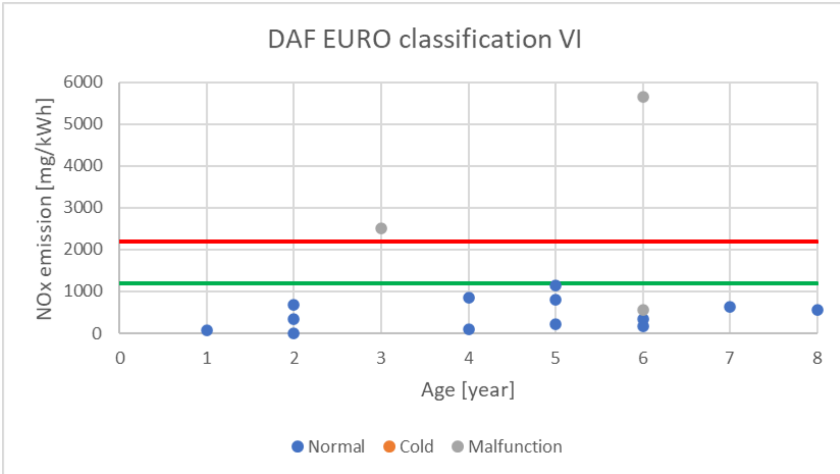

Figure 15: NO_x emission as a function of age for DAF EURO VI

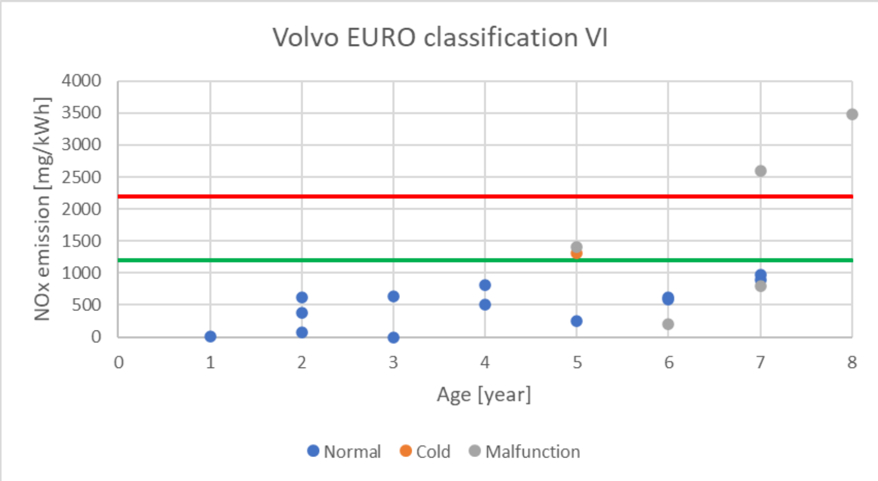

Figure 16: NO_x emission as a function of age for Volvo EURO VI

Conclusion – Evaluation of the plume chasing methodology for roadside inspection

The plume chasing equipment has been used as part of the selection tools for approximately 6 months in Denmark. During this time the NO_x emission level of more than 1000 vehicles has been measured.
During the 6 months it was confirmed that the measuring time for a high emitter is longer than the measuring time for a low emitter. This is in line with the recommendations in (Pöhler, 2021).

During week 9 and 11 all vehicles that were measured were inspected. It was found that all EURO VI vehicles with an emission level, after a valid plume chasing measurement, above 1200 mg/kWh had a mal-functioning emission system. However, 7 vehicles or approximately 39% of the malfunctioning vehicles had a NO_x emission below 1200 mg/kWh.

The plume chasing system has during the period been very successful as a selection tool for high emitters with the current limit of 1200 mg/kWh. All the vehicles that have been detected as high emitters either had an error on the emission system or were suspected to have been manipulated and subsequently handed over to the Police.

The present study has shown that if a EURO VI vehicle emits more than 1200 mg/kWh then it is very likely that the emission system is malfunctioning. However, the data is very limited in the span between 1200 and 2200 mg/kWh. The 2200 mg/kWh is the limit for proposed by (Pöhler, 2021) for high emitting EURO VI vehicles. So, until more data in the span between 1200 mg/kWh and 2200 mg/kWh is obtained it is recommended that EURO VI vehicles that emits more than 2200 mg/kWh measured by plume chasing is called for a technical inspection in the country of origin. If the following conditions are fulfilled, the coolant temperature for the vehicle must be above 70°C, the temperature of the soundings has to be between -7°C and 35°C and the altitude below 1600 m above sea level.

The results showed that for EURO VI vehicles with an emission level above 1200 mg/kWh all had a malfunctioning emission system.
Hence, it could be a valid limit for the emission system in connection with Periodical technical inspection (PTI).

However, below 1200 mg/kWh is approximately 10% of the normal emitting vehicles had a malfunctioning emission system. It is therefore recommended that all vehicles independent of the emission level are inspected as part of the roadside inspection by use of OBD to reveal that the emission system is well functioning.

It has been noted among the police and the inspectors that the number of manipulated vehicles in Denmark has decreased from the beginning of 2018 until now. However, this is not supported by data.
The decrease in the number of manipulated vehicles can be caused by a change in the legislation, with much higher sanctions and a change in the enforcement strategy.

The analysis of the data did not indicate that there is a correlation between high emitters and other visual errors on the inspected vehicles (light, tires, suspension, breaks, etc.).

In general, the evaluation shows that a concerning number of vehicles that are driving, with a defective emission system. The two weeks of focused plume chasing showed that 21% of the vehicles had a malfunctioning emission system.
Therefore, it is assessed that the focus on this issue during a roadside inspection should continue.

Recommendations for roadside inspections:

- Due to the concerning number of vehicles with a high emission due to a defect emission system it is recommended to keep the focus on the emission system in connection with roadside inspection. Hereunder, it is recommended to equip all inspection vehicles with a plume chasing system.
- Keep the emission limits for EURO VI of 1200 mg/kWh for plume chasing
- All vehicles that are stopped for roadside inspection should be investigated by OBD.
- A standard procedure for the roadside inspection of the vehicle with OBD should be developed.
- EURO VI vehicles that emits more than 2200 mg/kWh and fulfill the following conditions should be called for a technical inspection in the country of origin.
    - Coolant temperature above 70°C
    - Surrounding temperature between -7°C and 35°C
    - The altitude of the measurement was conducted below 1600 m above sea-level

Conclusion – durability of the emission system

The analysis showed that the emission system starts to malfunction after 350.000 km or 3 years whichever comes first. After this age or mileage, the roadside inspectors start to find errors in the emission system.

Figure 17 shows the distribution of age for heavy duty vehicles in Denmark. While Figure 18 shows the mileage as a function of age registered as part of regular PTI. The error bars show the standard deviation for mileage. From the figures it is noted that it is very unlikely that vehicles can drive more than 350.000 km in less than 3 to 4 years.
So, vehicles that are more than three years should undergo a thorough inspection of the emission system as part of the ordinary PTI.

In Denmark approximately 60% of the fleet is more than 3 years old and approximately 86% of the current European fleet is older than three years (ACEA, n.d.). Hence, the issue with the malfunctioning emission system and thereby a higher NO_x emission can be a factor throughout Europe.

Due to the very limited data material, it is not possible to assess if is the durability of the emission system is a common trend or if the emission system has a design error.

Recommendations for the durability of the emission system:

- On the EU level it is recommended to develop a method for ensuring the functionality of the emission system in connection with PTI. The method could be based on both OBD and on emission measurement.
- Inform the manufacturers and the workshops about the durability of the emission system

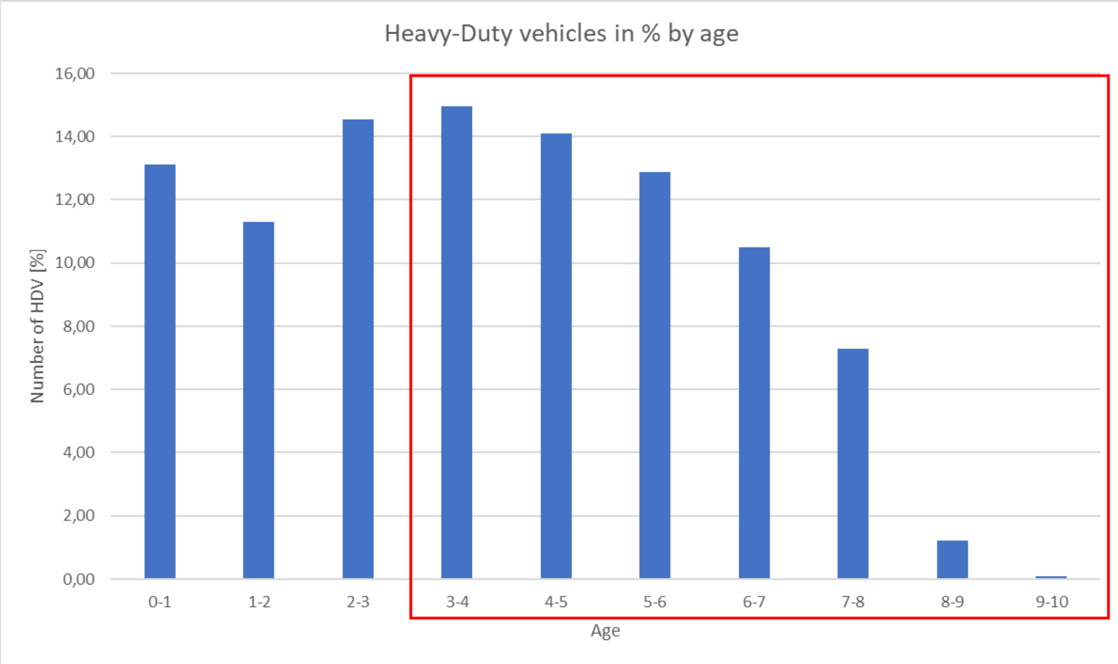

Figure 17: Heavy-duty vehicles in Denmark sorted by age at last PTI. The red box marks the HDV that are more than 3 years old and therefore are more likely to have an error on the emission system.

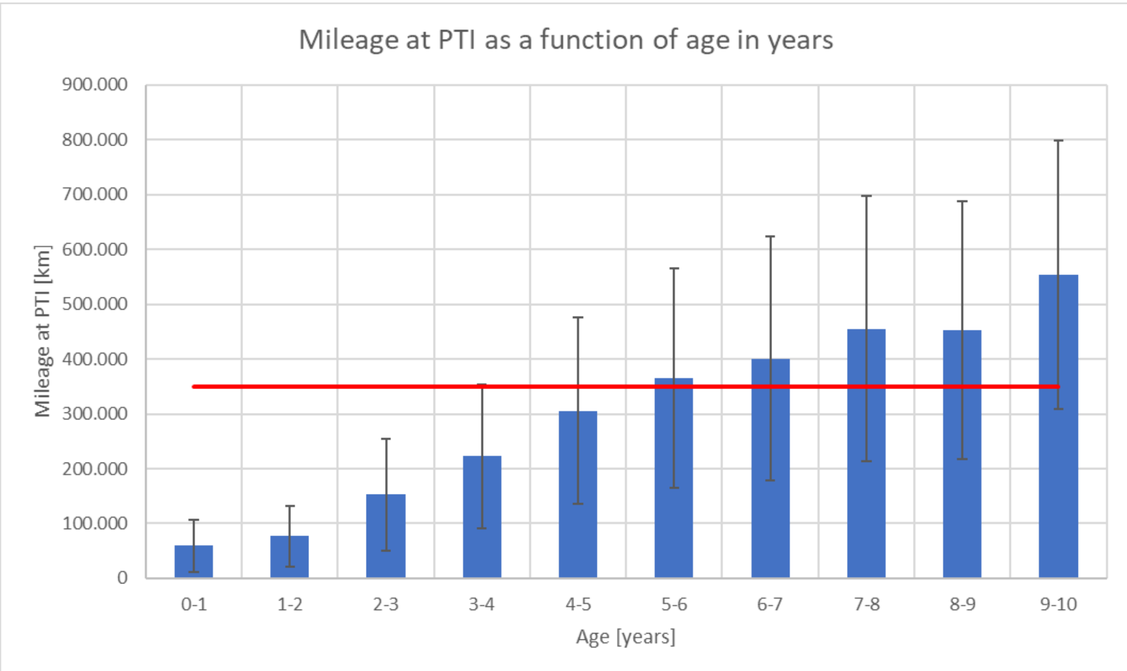

Figure 18: Mileage as a function of age registered as part of regular PTI. The error bars show the standard deviation for mileage. The red line shows the limit of 350.000 km where the emission system starts to fail.

Conclusion – legislation

As noted in the section *Legislation for EURO VI HDV* the type-approval limit was decreased from 900 mg/kWh[4] to 460 mg/kWh. The change was implemented so all vehicles after 1st of January 2017 should live up to the decreased emission level. Hence, it is expected to see a decrease in the NO_x emission from the vehicle due to the change in the type-approval limit.

Figure 19 shows the distribution of vehicles below the OBD limit of 1200 mg/kWh measured in week 9 and 11. The orange line denotes the type-approval limit for EURO VI heavy-duty vehicles.

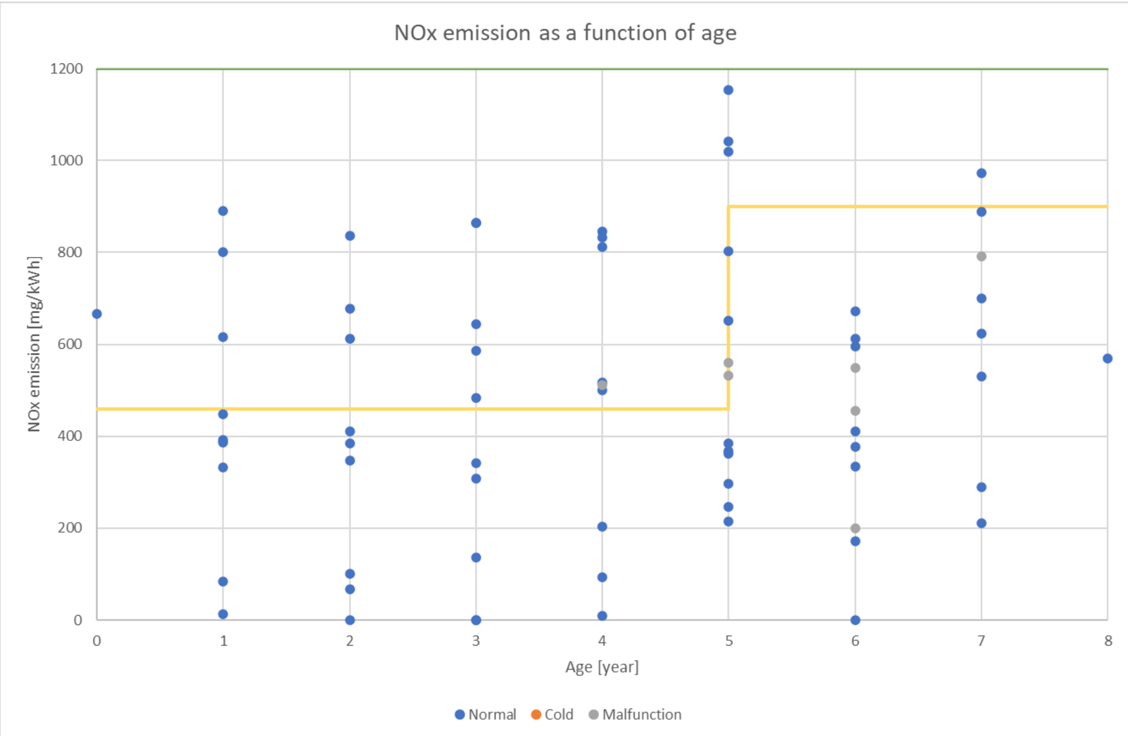

Figure 19: The emission level as a function of age. The orange line denotes the type approval limit for EURO VI vehicles. The blue dots represent each the emission level of a vehicle where the emission system is well-functioning. The gray dots represent each the emission level of a vehicle with a mal functioning emission system.

The figures do not show the expected decrease in the emission level due to the change in the type-approval legislation. This could indicate that the limit controlling the emission level when the vehicle is in use is the OBD limit that for EURO VI vehicles is set to 1200 mg/kWh and 1500 mg/kWh for vehicles approved before 31 December 2016.

Recommendation for the legislation

- At the EU-level work toward decreasing the OBD limit in the legislation (EU No 582/2011, 2011).

[4] (EU No 582/2011, 2011)Annex XIII section 7.1.1.1

Conclusion – payload and the legislation.

In the project (Færdselstyrelsen , 2021) from 2021 "*The effect of payload on the temperature of the SCR system"* conducted by the Danish Road traffic authority, it was concluded that when a heavy-duty vehicle was driving without payload the emission system was not activated during ordinary driving. This was especially pronounced with heavy-duty vehicles without a payload and high engine power. In the project, it was concluded that the temperature of the emission system could not reach a sufficiently high temperature to reach operating conditions. Hence the emission level for the vehicle was high during the entire trip. The projects concludes that the temperature of the emission system was too low to initiate the NO_x reduction reaction.

However, the *Active NOx system* section reports that the legislation for the emission system states that the coolant temperature have to be above 70°C before the NO_x reduction have to be initiated.

The temperature of the coolant system is in at least for one of the vehicles tested in the project (Færdselstyrelsen , 2021) from 2021 "*The effect of payload on the temperature of the SCR system"* were below 70°C. Hence, the emission system was inactive because the coolant temperature was below 70°C and not as assumed in the report that the emission system did not reach a sufficient operation temperature

When a vehicle with high engine power and low or no payload drives under normal conditions on a highway, they do not necessarily reach the point where the coolant temperature gets above 70°C hence the emission system is not active.

The report *Plume Chasing A way to detect high NO_x emitting vehicles* (AVL, 2020) it is stated that the emission from an inactive emission system can be up to 40 times higher than when the system is well functioning. Hence, an inactive emission system due to a low engine temperature can have an emission of NO_x that is 40 times higher than when the engine temperature is above 70°C.

Recommendations for the payload and the legislation

- At the EU-level, work toward broaden working conditions for the emission system.

Review - EURO V HDV

In the report from (Pöhler, 2021) the plume chasing limit of emission level was set at 2.500 mg/kWh for suspicious and 3.500 mg/kWh for high emitting vehicles.

However, during week 9 of focused data collection, it became obvious that the number of EURO V vehicles on the Danish highways was very limited and the emission level from the vehicles was very varying, noted from Figure 20. During the first week 13 vehicles were measured, and the dispersion of the vehicles was very large, ranging from approximately 800 mg/kWh to above 10.000 mg/kWh.
The EURO V vehicles are more than 10 years. Due to the high dispersion and the age of the vehicles EURO V vehicles were omitted from the main part of the analysis. This section only highlights the most important part of the NO_x emission of the legislation, very limited plume chasing data, and the conclusion and recommendation for the EURO V vehicles based on the very limited data obtained only during week 9 in 2022.

Legislation – EURO V

The EU directive (EU No 2005/55, 2005) implements the EU legislation for the EURO V HDV. The parts of the legislation that are reviewed are the same as for EURO VI, the coolant temperature, the durability, the OBD limit and when the system is active.

The durability of the emission system, for vehicles of category N3 with a maximum technical permissible mass exceeding 16 tons, is set to 500.000 km or 7 years which comes first. So, all the EURO V vehicles that are active today have passed the durability limit from the manufacturer.

The limits for when the emission system has to be active have been changed during the EURO V classification. Table 4 gives an overview of the parameters that has to be fulfilled before the emission system have to be active.

Table 4: Overview of when the emission system has to be active for a EURO V HDV

	Coolant temperature	Outdoor temperature	Sea level
2005	70 to 100 °C	10 to 30 °C	Below 1000 m
1 of Jan. 2006	70 to 100 °C	6 to 30 °C	Below 1000 m
1 of Jan. 2008	70 to 100 °C	2 to 30 °C	Below 1000 m

The type-approval limit for the EURO V HDV is 2000 mg/kWh both for the ESC (European stationary cycle) and the ETC (European Transient cycle) (EU No 2005/55, 2005).

The limit for when the OBD system has to notify the driver of a problem is 7000 mg/kWh. So above this limit, the OBD system has to activate the MIL.

Results from plume chasing for EURO V

During the first week of plume chasing EURO V vehicles were included in the study. The state of the emission system was analyzed by OBD in a similar matter as the analysis of the EURO VI vehicles.

The analysis is noted in Figure 20. The figures show the emission level as a function of mileage. The color of the dots represents the results of the analysis of the OBD data from each of the vehicles. The red line marks the current limit of 3500 mg/kWh for high emitters for plume chasing while the orange line marks when the OBD system has to activate the MIL indicator in the vehicle.

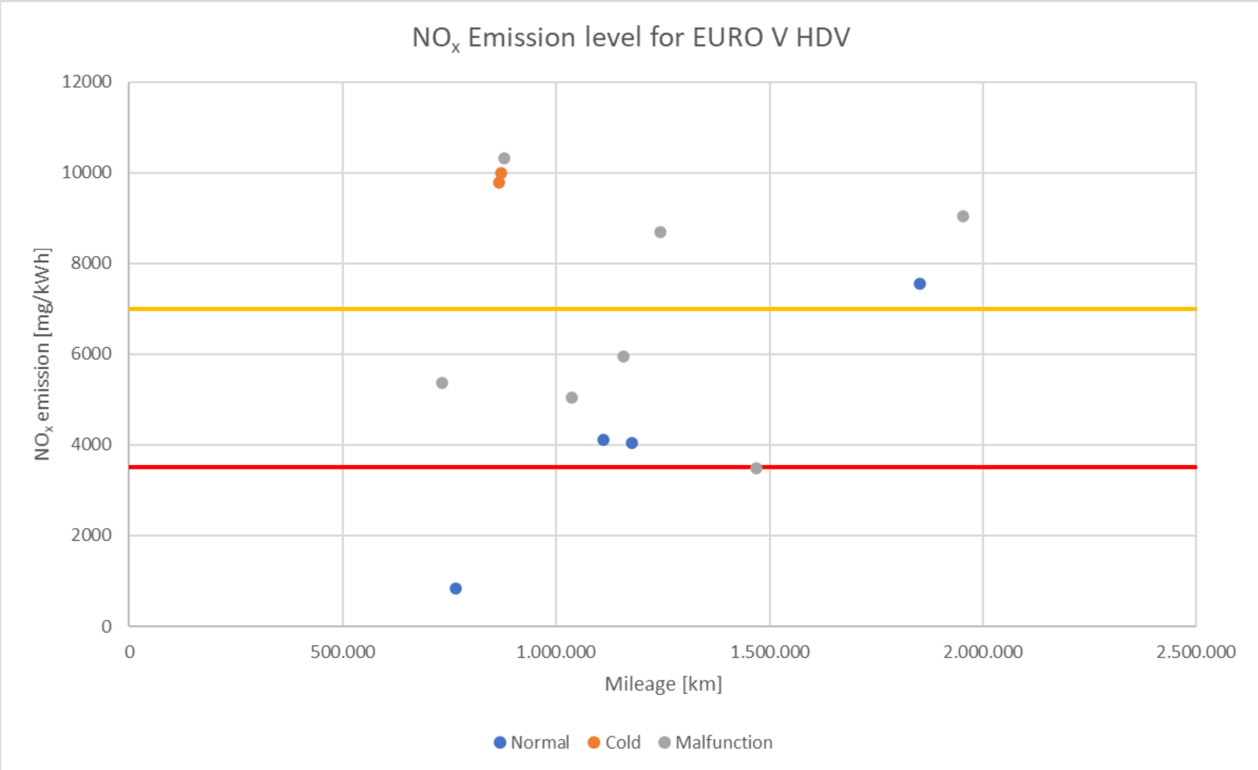

Figure 20: Plume chasing results for EURO V vehicles. The dots represent the average emission level for each vehicle. The color of the dot represents the outcome of the analysis of the OBD data. The orange line is the limit for when the OBD system activates the MIL. The red line is the current limit for the emission level measured by plume chasing.

The figures show that the emission level for the EURO V vehicles is fluctuating. Of the 13 vehicles that were measured only one vehicle had an emission level below the high emitting limit for plume chasing for the EURO V.
On four or 31% of the vehicles, the emission system was well functioning and therefore classified as normal. On 2 or 15% of the vehicles, the emission system was cold and on the rest 7 or 54% of the vehicles the emission system was defective or potentially manipulated.

Conclusion – EURO V

The data material for the EURO V vehicles is limited to only 13 vehicles. However, the emission level for the 13 vehicles is very different. Furthermore, it was noticed that the current emission level for the plume chasing is very low. The current limit was based on 55 measured vehicles. Based on the data and the review of the legislation, the limits for the plume chasing equipment it is recommended that the high emitting limit for plume chasing is reached so the probability of a da mal-functioning vehicle is higher. Hence, the enforcement is focused on the malfunctioning vehicles.

Recommendation – EURO V

- EURO V is changed to above 4500 mg/kWh it is suspicious and above 7000 mg/kWh is a high emitter.

Reference

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Færdselstyrelsen . (2021). *The effect of the payload on the temperature of the SCR system.*

Pöhler, D. (2021). *Report: Heavy Duty Vehicle (HDV) NO_x emission measurement with mobile remote sensing (plume chasing) and subsequent inspection of high emissters.* Germany: AiryX.

Review by external parties

The evaluation is carried out by Færdselsstyrelsen and have been reviewed by

Dr Denis Pöhler, Co-Founder & CEO of AiryX, who notes:

The presented study is the largest continuous data set of HDV emissions (more than 1000 vehicles) observed with plume chasing in Europe. The amount of investigated vehicles provides a reliable statistic of the amount of high and suspicious HDV emitters. It is an important contribution to evaluate this problem further. The percentage of the suspicious and high emitting HDV is similar to other studies in Europe, but significantly higher to the previous study in Denmark. The reason should be further investigated. The 100% hit rate of the plume chasing instrument to identify a defective or suspicious / manipulated system is absolutely satisfying. It proves that this system can reliable be applied by authorities to pre-select the problematic high emitting HDV for further inspections.
Especially important is the presented combination of the plume chasing emission measurement with extensive vehicle inspections. Inspecting not only high emitters, but all vehicles, provides the first comprehensive dataset of emissions versus vehicle state. Such investigations are very costly due to the high effort. To my knowledge such data are not available yet, what make this data set unique. It should be noted, that such data are urgently needed to connect measurements of high emissions of HDV with vehicle conditions, and this not for single vehicles like done so far, but on a large statistical basis. The clear correlation of larger amount of malfunctioning emission systems for EURO VI vehicles with higher mileage indicate, that these vehicles should be more in the focus of emission measurements, inspections and further legislation.
10% of the "normal" emitting EURO VI HDV still show malfunctions in the inspection. This is also an important finding. First it indicates, that the short measurement of "normal" emitters of 15s may not be sufficient and malfunctions are not always detected with this setting by plume chasing. Longer measurement periods also for "normal" emitting vehicles should be evaluated. Second, malfunctions may under some conditions not lead to high emissions.
The findings for the EURO V with very high emissions for most inspected vehicles is different to previous studies but need to be evaluated with care due to the small amount of vehicles. The high mileage of these vehicles during the study may be an explanation. Further investigations are needed to understand if a general problem exist for the old EURO V HDV.
In conclusion this study demonstrate that plume chasing is a good tool to identify high and suspicious emitting HDV. The amount of these vehicles is relatively high (up to 33%), and investigation and inspections of these vehicles is important.

Katja Asmussen, Special Consultant at the Danish Environmental Protection ministry.

Eduard Fernández, Executive Director, CITA (International Motor Vehicle Inspection Committee), who notes:

This report is the result of a very solid work aiming to tackle the difficult issue of tampering. Tampering is a problem challenging to foresee and manage exclusively from a technical perspective because it also involves the users' behavior. It requires and holistic approach involving at least approval, roadside inspection, periodical inspection, control of the trade of defeating devices and enforcement.

Tampering happens because it is easy to conduct and difficult to detect. European standards of emissions have significantly increased the requirements for new vehicles with the series Euro V and VI. Unfortunately, those updates never included provisions consistent enough to prevent tampering or facilitate its detection. For instance, the Type 2 test described in the homologations regulations never was adapted to Euro V or Euro VI.

That definition of the Type 2 test has a tremendous impact on how to check the vehicle during its life and becomes the test referred to in the Directives 2014/45/EU and 2014/47/EU, limiting its efficiency.

That lack of perspective from the vehicle approval side obliges stakeholders to take onerous and complex initiatives like the one described in this report. Another action in the same direction is the implementation of Particle Number – PN counting in periodical and roadside inspections to detect the fraudulent removal of particle traps.

It is strongly recommended that this report becomes a subject of reflection for rule-makers to better coordinate the technical requirements for vehicles with a whole-life perspective. Besides introducing requirements to make tampering more difficult to commit, it is also necessary for vehicle approval to provide tools to facilitate its detection, namely:

- *Reference values of what to expect from a vehicle. As previously mentioned, the Type 2 test in the approval needs to evolve to cope with the current requirements. This is particularly important in the case of NO_x because of the complexity in the management of the anti-NO_x systems.*
- *The possibility to check whether the software installed in the vehicle is the proper one.*
- *Access to sensors readings to check that the information they provide to the vehicle ECU(s) is the right one.*
- *Access to actuators to check whether they are operative or not.*


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