Færdselsstyrelsen

AVL

Plume Chasing
A way to detect high NO_x emitting vehicles

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Summary

Background and project aim

In recent years a number of trucks with a faulty or manipulated exhaust after treatments system have been detected in Europe. With the main motivation in environmental and public health, the Danish Road Traffic Authority in collaboration with the Danish Police are continuously developing methods to track down and prosecute operators of manipulated vehicles.

Since heavy-duty vehicles operating on roads in Denmark as well as the rest of Europe, are responsible for a significant part of the airborne emissions it is important to closely monitor changed behavior in the truck fleet. With the introduction of the Euro VI legislation [1], all new heavy-duty vehicles have been equipped with a selective catalytic reduction (SCR) system in order to reduce the exhaust emissions. This catalytic system works with a high efficiency in reducing the amount of nitrogen oxides (NO_x) in the exhaust. However, SCR systems are sensitive, require maintenance and use a consumable, called AdBlue®, to work properly.

A faulty or non-working system can result in emission levels 40 times higher in regards of NO_x compared to a healthy and working system. In accordance to the type approval it should therefore not be possible to operate the vehicle over longer distances when the system breaks down or AdBlue® is missing.

For operators of heavy-duty vehicles, this is estimated to induce costs of up to 2000 euro on a yearly basis. When major services are needed costs can be even higher. In the highly competitive European road transport market, it is therefore not surprising that a market has developed for solutions that override the trucks On-Board Diagnostics (OBD) systems, making it possible to operate the vehicle as if the systems were working.

These so-called defeat devices are cheap and easy to install. The driver can thereafter operate the vehicle with a non-functioning SCR, but without any restrains such as torque- or speed reductions.

Tracking down the devices has become an increasing and prioritized challenge for law enforcement (Danish Authority, personal communication, October 2019). As the systems are getting smaller, smarter and more sophisticated demands for instruments that make screening and fast detection possible has increased, supplementing traditional methods of detecting high emissions.

Thus, the performed study was arranged in order to screen the market for mobile remote sensing solutions and analyze their capability as a screening tool for possible future use by authorities. The objective of this work was to search for a system that allowed for fast screening of heavy-duty vehicles while driving, more specifically, plume chasing.

Studies Conducted

For this study, a literature review has been made, as well as a study of market available instruments. In addition, contacts have been established to experts in this field from universities, institutes and organizations worldwide.

An instrument has been sourced and practical tests have been conducted. In parallel a portable emission measurement system (PEMS) has been used as a reference to measure exhaust emission. The test has been done using trucks with working exhaust aftertreatment systems as well as manipulated ones.

For the practical tests the objective was to identify scenarios and situations which could be a possible source of false positive indications. In other words, a risk of identifying a healthy vehicle as a high emitter. This has been possible by combining the plume chasing results with the results from the in parallel conducted PEMS tests.

The study also attempts to establish the fundaments of a best practice by conducting test rounds on:

- Different vehicle configurations
- Different types of roads
- During different chasing speeds
- At alternating traffic density
- At different weather conditions

By request from the Danish police, the main focus was on highway traffic and semitrailer tractor combinations, which represents the setup for the majority of today's road transport in Europe [2].

Results

The results show that the acquired plume chasing instrument could detect low as well as high emitter. The measured emissions are in good correlation with the results from the PEMS measurements. This reduces the risk of false positive, due to instrument inaccuracy.

During dense traffic the accuracy of measuring a low emitter decrease. Nevertheless, the emissions of a manipulated and not functioning aftertreatment system are so much higher that it is possible to identify a high emitter even in more dense traffic.

Averaged emission results (2min interval) of a vehicle with a functioning exhaust aftertreatment system compared to non-functioning system did not overlap in any case.

Increased driving distance did in no case lead to wrong measurements, only to less measurements. However, the chasing could be performed with always ensuring the minimum safety distance. It was possible to acquire measurements on different vehicle configuration, a total vehicle length between 9,9m and ~25m was tested.

Conclusions

The study has shown the possibility of using a plume chasing device as a screening tool to detect high emitters during driving. Limitations to plume chasing during certain road layouts, traffic situations and speed variations have been identified.

With training and introduction to the instrument, an employee from an authority should be able to operate the device and perform plume chasing tests. A background training on emissions from heavy-duty trucks as well as engine management is recommended to understand the limitations of the use of the instrument.

However, there are several recommended improvements to simplify the usage and minimize the interaction with the operator.

Which are for example:

- Updated user interface with a clear indication for a "pass/fail" indication
- Automatic selection of the sampling side (left, right)
- Averaging results over a set time interval to minimize the risk for false positive
- Automatic detection of background concentration of NO_x and CO_2

To identify all training needs and required instrument improvements, an extended testing phase together with the Danish authorities is recommended.

Sammenfatning

Baggrund og projektets formål

I løbet af de seneste år er et voksende antal tunge køretøjer med fejlagtige eller manipulerede udstødningsefterbehandlingssystemer blevet afsløret i Europa. Med hovedfokus på for miljøbeskyttelse og folkesundhed udvikler Færdselsstyrelsen i samarbejde med Politiet løbende metoder til at afsløre operatører af manipulerede køretøjer.
Da tunge køretøjer på vejene i Danmark, såvel som i resten af Europa, er ansvarlige for en betydelig del af den luftbårne emission, er det vigtigt, nøje at overvåge udviklingen, når det kommer til tunge køretøjer. Med indførelsen af Euro VI-lovgivningen [1] er alle nye, tunge køretøjer udstyret med et selektivt katalytisk reduktionssystem (SCR) for at reducere udstødningsemissioner. Det katalytiske system fungerer effektivt, når det reducerer mængden af nitrogenoxider (NOx) i udstødningen. Dog er SCR-systemer avanceret udstyr som kræver vedligeholdelse og anvender et forbrugsstof, kaldet AdBlue® for at fungere korrekt.
Et manipuleret eller ikke-fungerende SCR-system kan resultere i emissionsniveauer, som har 40 gange højere NOx udledning, sammenlignet med et fungerende system. I henhold til typegodkendelse må det ikke være muligt at betjene køretøjet over længere afstande med et defekt SCR-system, eller hvor systemet mangler AdBlue®.
For operatører af tunge køretøjer anslås det at medføre omkostninger på op til 2000 euro årligt pr. køretøj at drive og vedligeholde et SCR-system. Når der skal udføres større service på et SCR-system, kan omkostningerne blive endnu højere. På det meget konkurrenceprægede europæiske transportmarked er det derfor ikke overraskende, at der er skabt et marked for løsninger, der tilsidesætter lastbilernes diagnosesystemer, så køretøjet kan betjenes med et uvirksomt SCR-system. Disse såkaldte manipulationsanordninger er billige og nemme at installere.
Afsløring af manipulation er en prioriteret opgave for kontrolmyndighederne. Efterhånden som karakteren af manipulation bliver mere sofistikeret, er der opstået et behov for instrumenter, som muliggør screening og hurtig detektion, og som kan supplere de traditionelle metoder til at detektere høje emissioner.

Den udførte undersøgelse er lavet med henblik på at screene markedet for såkaldte mobile remote sensing-løsninger for at analysere deres egnethed som et screeningsværktøj til eventuel fremtidig brug af myndighederne. Formålet med dette arbejde var at finde et system, der muliggjorde hurtig screening af tunge køretøjer under kørsel.

Udførte undersøgelser

Til denne undersøgelse er der foretaget en litteraturgennemgang samt en undersøgelse af tilgængelige instrumenter på markedet. Derudover er der blevet etableret kontakt til eksperter på området fra universiteter, institutter og organisationer over hele verden.

Til de praktiske test blev der anskaffet særligt udstyr til måling af NOx, som blev monteret på et køretøj. Referencemåling af emission fra udstødningen på de køretøjer, der blev anvendt som måleobjekter, er udført med et PEMS-system (Portable Emissions Measurement System).

Testen er udført ved måling på tunge køretøjer med fungerende, såvel som manipulerede udstødningsefterbehandlingssystemer.
For de praktiske tests har formålet været at finde scenarier og situationer, der kunne være en mulig kilde til 'falske positive' indikationer. Med andre ord, risikoen for at identificere et køretøj med et fungerende SCR-system som værende manipuleret.

Et formål med undersøgelsen har også været at etablere grundlæggende retningslinjer for anvendelse af udstyret, ved at gennemføre undersøgelser på og med:

- Forskellige køretøjskonfigurationer,
- Forskellige vejtyper,
- Ved forskellige hastigheder,
- Ved vekslende trafiktæthed,
- Under forskellige vejrforhold.

Efter anmodning fra det danske Politi har der været særligt fokus på motorvejstrafik samt sættevognstrækker og semitrailer kombinationer, hvilket repræsenterer størstedelen af vejtransport med tunge køretøjer i Europa [3].

Resultater

Resultaterne af undersøgelsen viser, at det erhvervede udstyr til mobil remote sensing kunne måle på køretøjer med lav såvel som høj emission af NOx. De målte emissioner korrelerer med resultaterne af PEMS-målingerne, og dermed reduceres risikoen for 'falske positiver' forårsaget af unøjagtigheder i instrumentet. Nøjagtigheden af målingerne falder for lavemitterende køretøjer i tæt trafik. Ikke desto mindre er emissionerne fra et manipuleret og ikke-fungerende efterbehandlingssystem så meget højere, at det er muligt at identificere et højt-emitterende køretøj, selv i mere tæt trafik. Undersøgelsen viste, at de gennemsnitlige målinger af emission over et 2 minutters interval for et køretøj med et velfungerende udstødningsefterbehandlingssystem, sammenlignet med et køretøj med et ikke-fungerende system, ikke overlappede i nogen tilfælde.

Forøgelse af køreafstanden førte ikke til unøjagtige målinger. Det påvirkede kun antallet af målepunkter.
Endvidere viste undersøgelsen, at den minimale sikkerhedsafstand til det køretøj, der måles på, altid kunne opretholdes.
Det var desuden muligt at få målinger på forskellige køretøjskonfigurationer med en samlet køretøjslængde mellem 9,9 m og 25 m.

Konklusion

Undersøgelsen har vist, at det er muligt at anvende det valgte mobil remote sensing-udstyr som et screeningsværktøj til at identificere køretøjer med høj emission af NOx under kørsel.
Begrænsningerne ved mobilt remote sensing-metoden ved visse vejtyper, trafiksituationer og variationer i hastighed er blevet identificeret.

Med kort introduktion i brug af instrumentet vil en medarbejder fra en myndighed være i stand til at betjene udstyret og udføre mobil remote sensing til screening af køretøjer. Det anbefales dog at udføre nogle forbedringer for at forenkle brugen og betjeningen for operatøren.

Det foreslås blandt andet følgende:

- Instrumentets brugergrænseflade skal tydeligt indikere, om målingen ligger under eller over grænseværdien
- Automatisk valg af prøvetagningsside (Skift mellem indsugning af udstødningsgasser i venstre eller højre side i forhold til placeringen af udstødningen på det køretøj der screenes)
- Gennemsnit af resultater over et defineret tidsinterval for at minimere risikoen for at få et falsk positiv
- Automatisk detektion af baggrundskoncentration af NOx og CO2

For bedst at kunne evaluere de resultater der opnås ved brug af mobil remote sensing, samt kende til de begrænsninger der er ved brug af remote sensing udstyret, anbefales det, at operatører modtager uddannelse i emissionsbegrænsende udstyr på tunge køretøjer.
For yderligere at undersøge mulighederne i systemet anbefales endvidere en udvidet testfase i samarbejde med de danske myndigheder.

Content

1 Introduction

This report presents the background and results of a project focused on investigating the usability and maturity of market available plume chasing devices. The project was carried out by AVL by appointment of the Danish Road Traffic Authority and conducted in quarter four of 2019.

Practical tests were carried out in the Stockholm area. The test environment were selected to be closely representative to Danish traffic and road condition.

The study serves to investigate the potential of market-available hardware solutions for daily use by the police forces of Denmark.

1.1 Motivation for study

In Europe, emissions from traffic and in particular heavy-duty trucks is a growing concern for human health as well as for the environmental impact. The Danish Road Traffic Authority has a history of performing investigative studies focused on emissions from heavy-duty vehicles [3] [4].

In recent years, interest have been growing on developing methods for detecting tampering with SCR systems installed on heavy-duty vehicles. As these cheating devices are getting more sophisticated, traditional investigative methods are no longer enough to track down and discover the devices. Therefore, emission measurement solutions, once seen as novelty, are now considered for law enforcement use. Furthermore, the Danish Road Traffic Authority has set up a team to consolidate and coordinate all studies focusing on truck emissions.

Plume chasing allows to screen vehicles during their normal driving pattern, without direct interaction with them. Furthermore, the emission measurements are not limited to a specific control point. This qualifies plume chasing to be a method as a screening device to identify high NO_x emitting vehicles while driving and select them for further investigations.

1.2 Activities

The project kick-off meeting was held in Odense, Denmark, on 11th of October 2019.

The first stage of the project was a state-of-the-art review. Thereafter, the work was focused on planning and setting up practical tests, finding collaboration partners, sourcing test vehicles and conducting interviews with the Danish Police. Practical tests were carried out during week 46 in 2019.

1.3 Organisation

AVL was granted the contract of conducting the study after biding on a letter of public procurement announced on the 11th of September 2019. Except from the project group from AVL, expert input has been sourced from industry leading companies as well as participating members from the Danish Authorities.

2 Background

Air quality control is a big challenge for many countries worldwide. In Europe, the transport sector contributed to 24,6% of carbon dioxide (CO_2) [5] and the road transport contributed to 39% of NO_x emissions [6] in 2017.

To reduce and minimize the emissions, the European Union (EU) has set emission limits that all vehicles need to comply with. This not only during type approval but also during normal use [1].

The following sections gives an overview of the emission legislation with a focus on the European Union, information on how and which emissions evolve from internal combustion engines, exhaust aftertreatment systems and emission measurement instruments.

2.1 Legislation

In 1992 Euro I for heavy-duty vehicles as well as Euro 1 for light-duty vehicles were introduced. Since then, the emission limits have significantly been decreased. The directives are typically stated as Euro 1 to Euro 6 for light-duty vehicles and with roman numbers (Euro I to Euro VI) for heavy-duty vehicles.

Figure 1 shows the maximal allowed NO_x emissions in mg/kWh for transient test cycles regarding heavy-duty vehicles. Besides lowering the emission levels, the test cycles were changed as well. From the European Transient Cycle (ETC) for Euro III to Euro V to the World Harmonized Transient Cycle (WHTC) for Euro VI.

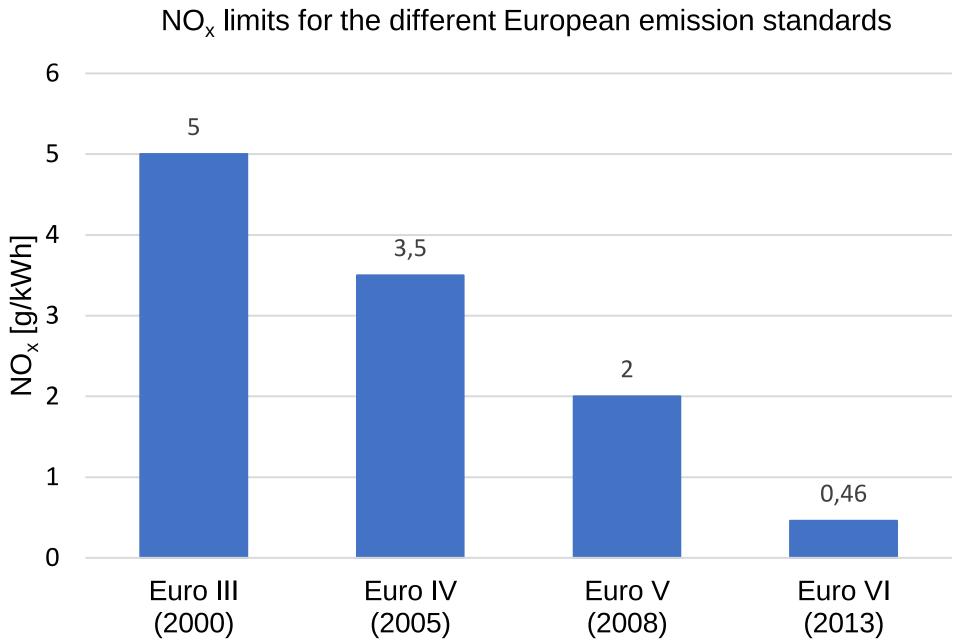

Figure 1 Comparison of NO_x limits for Euro III to Euro VI together with implementation date. The emission limits rapidly decreased with a big step from Euro V to Euro VI [7].

With the introduction of Commission Regulation 582/2011 it became mandatory to demonstrate the in-service conformity (ISC) of vehicles upon type approval. In the ISC tests the vehicles are driven in their normal driving pattern as well as payload. These tests are performed using a portable emission measurement system (PEMS). In section 2.4.1 the measurement system is further explained. The allowed emission limits for in-service conformity (ISC) are based on the emission limits for the World Harmonized Transient Cycle (WHTC) and a defined conformity factor. The ISC-Limit is calculated by multiplying the WHTC limit with the conformity factor.

Table 1 Euro VI emission limits together with ISC-Limits for heavy-duty vehicles

Component	Limit test cycle WHTC	Conformity-factor	ISC Limit
NOx	460 [mg/kWh]	1.5	690 [mg/kWh]
HC	160 [mg/kWh]	1.5	240 [mg/kWh]
CO	4000 [mg/kWh]	1.5	6000 [mg/kWh]
PM	10 [mg/kWh]	-	-
PN	$6*10^{11}$ [#/kWh]	-	-

2.2 Input from customer

Through discussion during meetings with the Danish Road Traffic Authority and interviews with the Danish Police it was clear that the focus for the plume chasing would be on highway testing and especially on vehicles of the category N3. These are vehicles that are designed for the carriage of goods and exceed a maximum mass of 12 tons. The investigation on how the testing would be conducted, which vehicles would be suitable, and the selection of the testing routes was therefore performed with the consideration that the focus is on highway testing. To see the capabilities of plume chasing, but also challenging scenarios, some rural sections were included in the testing. In addition, the testing was also conducted on the drive towards the highway entrance as well as during warm up in urban driving.

2.3 Emissions

In a complete combustion with ambient air, the exhaust contains carbon dioxide (CO_2), water (H_2O), nitrogen (N_2) and oxygen (O_2). In reality, there are other harmful emissions like carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides like NO and NO_2 (NO_x), particles and others. [8]

2.3.1 NO_x

The main concern regarding emissions for diesel engines are nitrogen oxides (NO_x). There are three major chemical mechanism that produce NO_x: thermal or Zeldovich mechanism, prompt or Fenimore mechanism, and the combustion of fuel-bound nitrogen. The Zeldovich mechanism is the most significant one for internal combustion engines, in which Nitric Oxide (NO) is formed in high-temperature burned gases behind the flame front [8]. The percentage of NO in NO_x is around 60-90%. The equations 1, 2 and 3 below show the formation of NO.

$$O + N_2 \rightleftharpoons \mathrm{NO} + N \quad (1)$$

$$N + O_2 \rightleftharpoons \mathrm{NO} + O \quad (2)$$

$$N + OH \rightleftharpoons \mathrm{NO} + H \quad (3)$$

2.3.2 Exhaust aftertreatment system

As mentioned in 2.1, the emission limits were continuously reduced. Fulfilling the requirements and being below the allowed limits is, especially for NO_x, a challenging task. Over the years exhaust aftertreatment systems (EATS) were improved and new technologies developed. A modern EATS usually consists of four components:

- Diesel Oxidation Catalyst (DOC)
- Diesel Particulate Filter (DPF)
- Selective Catalyst Reduction (SCR) catalyst
- Ammonia Slip Catalyst (ASC)

Sometimes there is an exhaust gas recirculation (EGR) system installed as well. Figure 2 shows schematically the setup and arrangement of the components of an exhaust aftertreatment system of a modern Euro VI truck. In reality, the different components are often together in a one-box design.

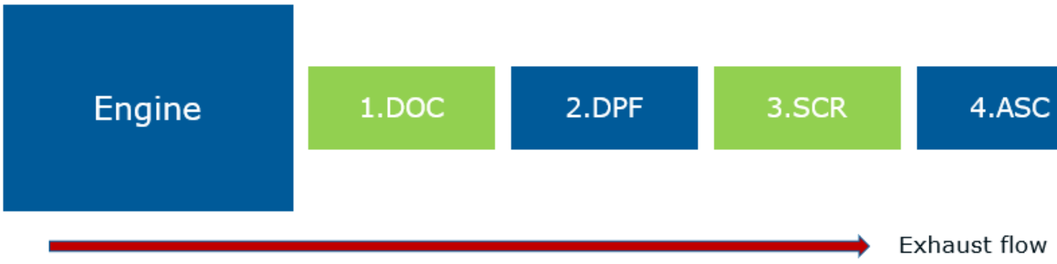

Figure 2 Schematic drawing of an exhaust aftertreatment system (EATS) setup and the arrangement of the single components in the exhaust stream

The most crucial component for reducing NO_x emissions is the SCR, it can have a conversion ratio of above 98%. The SCR system uses ammonia to turn nitrogen oxides (NO_x) to nitrogen gas (N_2) and water (H_2O). Due to the toxicity of ammonia, it is not directly stored on the vehicle and instead formed from an aqueous urea solution called AdBlue®. This solution is injected before the SCR catalyst and ammonia is formed through a twostep process. The equation can be seen below. Temperatures above 180°C are typically required. [1]

$$(NH_2)2CO \longrightarrow NH_3 + HNCO\ (Thermolyse) \tag{4}$$

$$HNCO + H_2O \longrightarrow NH_3 + CO_2\ (Hydrolyse) \tag{5}$$

NO_x is then reduced to N_2 and H_2O through the following equations. Equation 6 and 7 are the dominant one. At low temperatures (< 250°C) the reaction in equation 7 is dominant but is most efficient with a ratio of NO_2/NO_x of 50%. Therefore, a diesel oxidation catalyst is installed upstream of the SCR to oxidize NO to NO_2. [9]

$$4NO + O_2 + 4NH_3 \longrightarrow 4N_2 + 4H_2O \qquad (6)$$

$$NO + NO_2 + 2NH_3 \longrightarrow 2N_2 + 3H_2O \qquad (7)$$

$$6NO_2 + 8NH_3 \longrightarrow 7N_2 + 12H_2O \qquad (8)$$

As described, for an SCR, AdBlue® is consumed and the consumption is around 4-6% of fuel consumption by volume.

2.3.3 AdBlue Emulators

Fault codes in the emission control system, reagent levels below a certain limit or low reagent quality cause the vehicle to trigger first a low-level inducement system with reduced engine torque and severe inducement system with a reduced vehicle speed to 20km/h (*creep mode*) [10].

To avoid maintenance costs for SCR systems or avoid adding AdBlue®, a larger market has evolved for so-called AdBlue emulators. These AdBlue emulators send a false signal to the engine emission control, confirming to the system that the exhaust after treatment system is working properly and preventing from going into *creep mode*.

These devices are often well hidden and difficult to detect. A comprehensive survey of AdBlue emulators market availability, different types of emulators and control methods has been conducted by [3]. AdBlue emulators can be divided into OBD installations, CAN installations, Passive components and software solutions (Reprogramming). Figure 3 gives an overview of these four main types. The ingenuity and sophistication of AdBlue emulators has evolved significantly over the years and the further they are developed, the more difficult they become to detect.

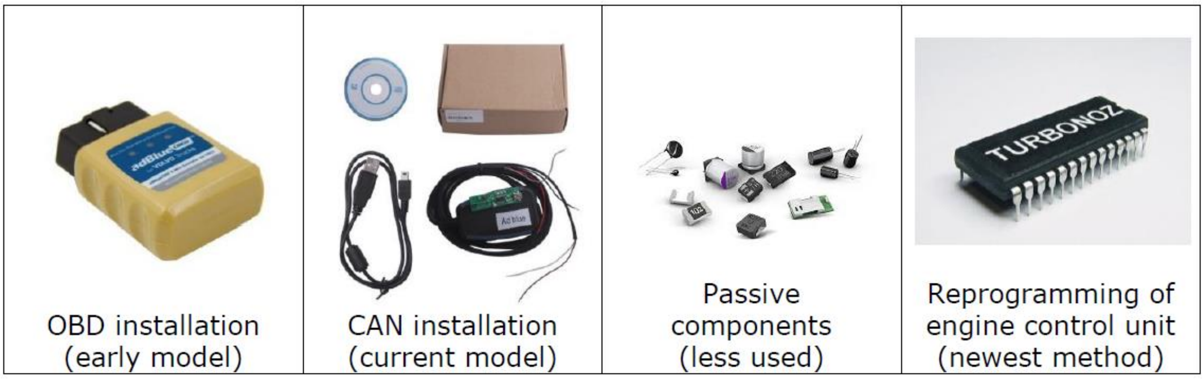

Figure 3 Overview of the four main types of AdBlue Emulators [3]

As written in 2.3.2 the efficiency of a well-functioning SCR systems can be above 98%. Manipulating the SCR system has therefore a high impact on the NO_x emissions. 30 times higher emission compared to a functioning SCR is not uncommon during an In-Service Conformity test. Roadside inspections in Denmark, Germany, Switzerland and Norway have shown that driving with a manipulated vehicle is not an uncommon practice [3].
Knowing this, the motivation behind detecting and finding AdBlue emulators is strong.

As AdBlue emulators are getting smaller and more sophisticated it becomes more challenging to find them. Besides the difficulties of physically finding a hidden AdBlue emulator installed somewhere on a vehicle, there is the big challenge of detecting manipulated vehicles during driving.

2.4 Instruments

Different mobile instruments have been developed to measure emissions during real driving. In the following, the different instruments are briefly explained.

2.4.1 PEMS

A portable emission measurement system (PEMS) is a relatively small measurement system that is used for mobile emission measurements for Light-Duty, Heavy-Duty as well as Non-Road Mobile machinery. With the Commission Regulation 582/2011 coming in force, it became mandatory for truck manufactures to demonstrate the in-service conformity for their new type approved vehicles. The testing shall be repeated at least every two years over the useful life period which is 700.000km or 7 years for a heavy-duty vehicle of the category N3.

AVL is, among others, a manufacturer of PEMS equipment. The setup of different systems is similar. The instrument for passenger cars is either mounted on the tow hook or in the trunk. For heavy duty vehicles it is usually installed in the truck box or in a purpose-built trailer. An exhaust flow meter (EFM) is fit after the original exhaust pipe to measure the exhaust mass flow and be able to calculate mass emissions. Sampling points are installed after the EFM and transport exhaust gases through heated lines to the PEMS instrument.

To calculate the emission factors in g/kWh it is necessary to read out data from the vehicle to be able to calculate the work. An OBD reader, reads out the needed signals from the vehicle through the OBDII connection. In addition to the PEMS equipment and EFM there are also ambient sensors for temperature, humidity and pressure installed as well as a GPS antenna. Batteries or generators are usually used to provide sufficient power to the equipment. Figure 4 shows a PEMS equipment installed on a passenger car and Figure 5 shows the whole setup for a heavy-duty vehicle.

Figure 4 AVL PEMS equipment installed on the tow hook of a passenger car. Typical setup during a Real-Driving Emission (RDE) test

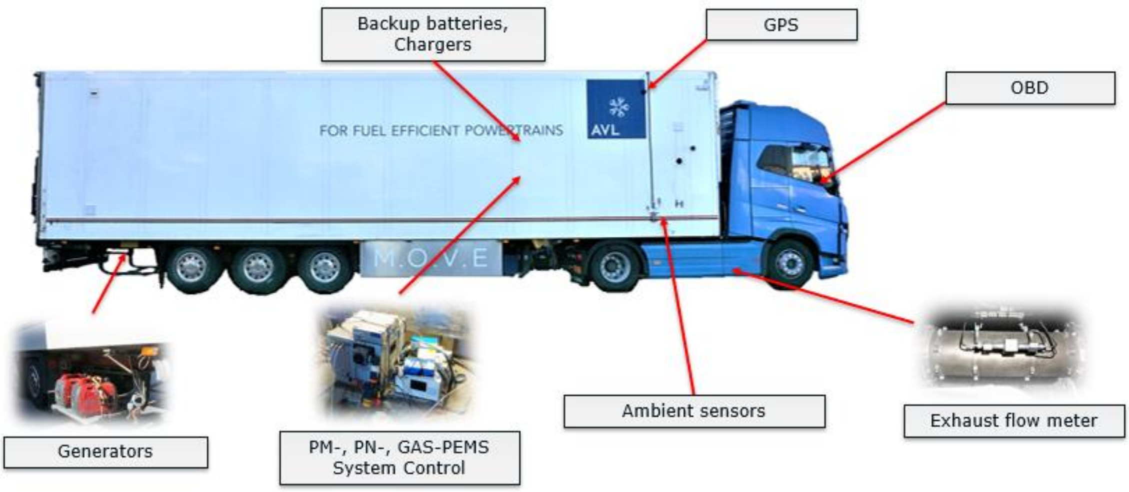

Figure 5 Overview of the PEMS equipment installation on a heavy-duty vehicle for an In-Service Conformity test. Showing the different components and their placement on the vehicle

The benefit of PEMS over traditionally used test bed testing is that emissions are measured on-road. Besides that, there is the cost effectiveness and the relative fast installation.

Although relatively fast compared to test bed testing, it still requires modifications to exhaust system and installation of equipment on the vehicle. The idea of mobile NO_x screening would be without any direct interaction with the vehicle. This makes PEMS not suitable to conduct the testing. In this study, the PEMS is used to define the current state of the tested vehicle, in regards of emission levels and to see if the vehicle complies with the limits allowed for In-Service Conformity.

2.4.2 Plume Chasing

Plume chasing testing is performed by following a vehicle and measuring the exhaust plume, enabling the calculations of its emissions. The fundamental principal is that the ratio between CO_2 and NO_x does not change, no matter how much the exhaust is diluted. From the ratio it is then possible to calculate the specific emissions in g/kWh. The setup of the plume chasing is further reviewed in section 4.5.

3 State-of-the-art review

A literature study was conducted to review the current state-of-the-art of plume chasing. Therefore, different journals, papers and reports have been studied.

3.1 Survey of collaboration partners

For this study, AVL needed to collaborate with researchers and experts in plume chasing testing and evaluation. Part of the project was therefore to find a suitable collaboration partner.

Four institutes have been identified as having experience in the field of plume chasing:

- The Hongkong University of Science and Technology [11]
- Tampere University Finland [12] [13] [14]
- Korea Institute of Machine and Materials [15] [16]
- University of Heidelberg [17] [17] [18] [19]

According to the studies performed the main conclusion was that the first three institutes have instruments focused to research only. This implies rather complex installations in laboratory vehicles with controlled ambient conditions and high power consumption. Given this, they were not considered as products that could easily be implemented for this study.

From the University of Heidelberg, a spin-off company called Airyx GmbH was founded. This company has further developed a plume chasing analyzer, and their measuring device is designed as a small and mobile equipment, with easier installation and practical to operate. In general, the instrument is well developed and commercially available.

Thus, it was decided to collaborate with Airyx GmbH for the evaluation of plume chasing equipment and methods.

4 Method

In the beginning of this chapter the vehicles that were tested are described. Further on, the routes where the tests were conducted are explained. Afterwards the plume chasing instrument as well as the chasing vehicle are described.

4.1 Test vehicles

Two standard market trucks were used for the practical trials. Vehicle 1 was a Volvo FH 500 (2018), vehicle 2 was a Scania R440 (2014). Both trucks are presented in detail in sections 4.1.1 and 4.1.2. During the plume chasing tests both trucks were tested with PEMS equipment to validate exhaust emissions.

In order to fit the exhaust flow meter, the tailpipes of the trucks were modified. This is common practice during PEMS tests and does not affect the exhaust emissions.

4.1.1 Vehicle 1

Table 2 Overview of technical data of vehicle 1

Make and Model	Volvo FH 500 (6x2)
Model Year	2018
Emission Standard	Euro VI
Vehicle Category	N3, (Tractor)
Engine	13L, 375 kW
Fuel	Diesel (Market Fuel)
After Treatment System	EGR, DOC, DPF, SCR, ASC
Mileage	46 294 km
Weight during testing	32 000 kg
Vehicle Length	~18 m (including semitrailer)

Figure 6 Vehicle 1 - Volvo FH 500 Tractor and coupled testing trailer. Vehicle was followed in this configuration during the plume chasing.

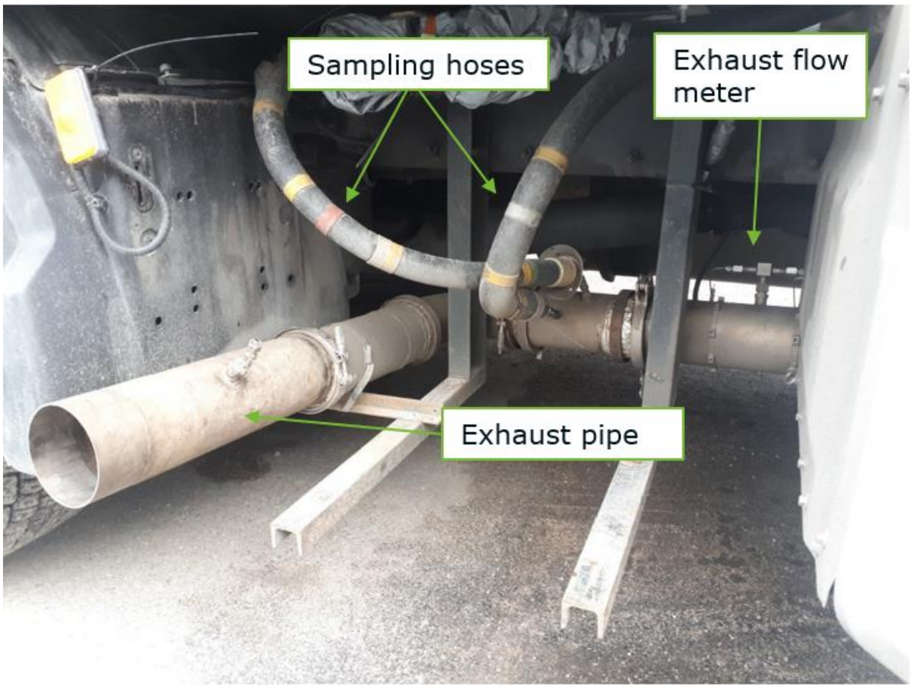

Figure 7 Vehicle 1- exhaust tailpipe configuration with the installed exhaust flow meter. This shows the typical setup that is used for a PEMS test on a heavy-duty vehicle.

In order to fit the exhaust flow meter and leave the required pipe length after the exhaust sampling points, a 90-degree and a straight pipe were installed downstream of the EFM. This resulted in the tailpipe discharge on the right-hand side of the vehicle.

4.1.2 Vehicle 2

Table 3 Overview vehicle 2

Make and Model	Scania R440 (6x2)
Model Year	2014
Emission Standard	Euro V, Retrofitted EATS
Vehicle Category	N3, (Rigid)
Engine	13L, 324kW
After Treatment System	Retrofitted SCR, DPF
Fuel	Diesel (Market Fuel)
Mileage	63 708 km
Weight during testing	20 500 kg
Vehicle Length	9,9 m

Figure 8 Vehicle 2 - equipped with PEMS equipment and chasing vehicle with plume chasing equipped parked behind. Picture was taking during a short stop along the testing route.

The Scania R440 was equipped with a retrofitted EATS. The truck should in this case then be compliant with the EU Stage VI legislation in regards of emissions. However, the injection system for AdBlue® was not functioning, resulting in high emissions, similar to a manipulated vehicle. Figure 9 shows the exhaust configuration during the PEMS and plume chasing testing.

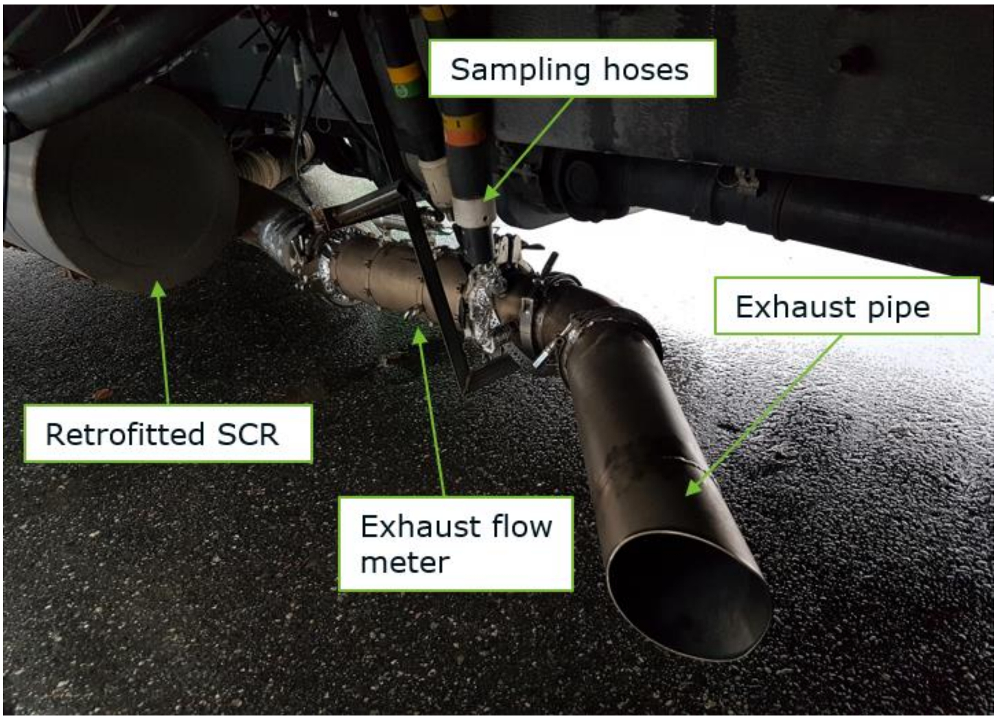

Figure 9 Vehicle 2- configuration and routing of the retrofitted after treatment system. Picture shows the retrofitted SCR as well as the exhaust flow meter that is required for the PEMS testing.

4.2 Manipulation

In order to simulate a faulty, tampered or possibly manipulated after treatment system the urea tank of vehicle 1 was emptied and flushed prior to filling it with clean water. This was done after the testing with the functioning SCR was performed. The truck ECU will then recognise the urea concentration as substandard (below 32,5% (m/m)). Depending on the year of the type approval, the fault code will be triggered either by comparing engine out to tailpipe NO_x emission or by a urea quality sensor in the AdBlue® tank. Regardless, according to the legislation, the driver will then be noticed. This will give the opportunity to operate the truck for some hours prior to torque reduction setting in. Typically, 10 hours of continuous driving is possible before reduction in speed or torque occurs.

4.3 Test routes

The plume chasing instrument was tested for usability on a variety of road types and driving situations in order to test how traffic density, chasing velocity, road layout and other parameters affects the quality of the measurement.

The plume chasing measurements were focused on highway driving scenarios. However, the testing was not limited to highway and the routes included some rural and urban scenarios as well.

The tests were therefore performed during and in close connection to driving situations where it is known that it is difficult to fulfil the emission legislation limits.

These included:

- Chasing directly after entering motorway, which means high engine load with not fully heated engine and exhaust system
- Chasing in dense traffic
- Chasing on winding rural roads
- Testing after 45 minutes of standstill on motorway, simulating a mandatory 45 min break

Tests were performed in order to stress the truck's after-treatment system, to detect the worst-case situations for a functioning system and to determine the risks for false-positive situations.

Different parts of motorway road 73 (Nynäsvägen) were used for most parts of the testing campaign. Figure 10 presents an overview of the test route.

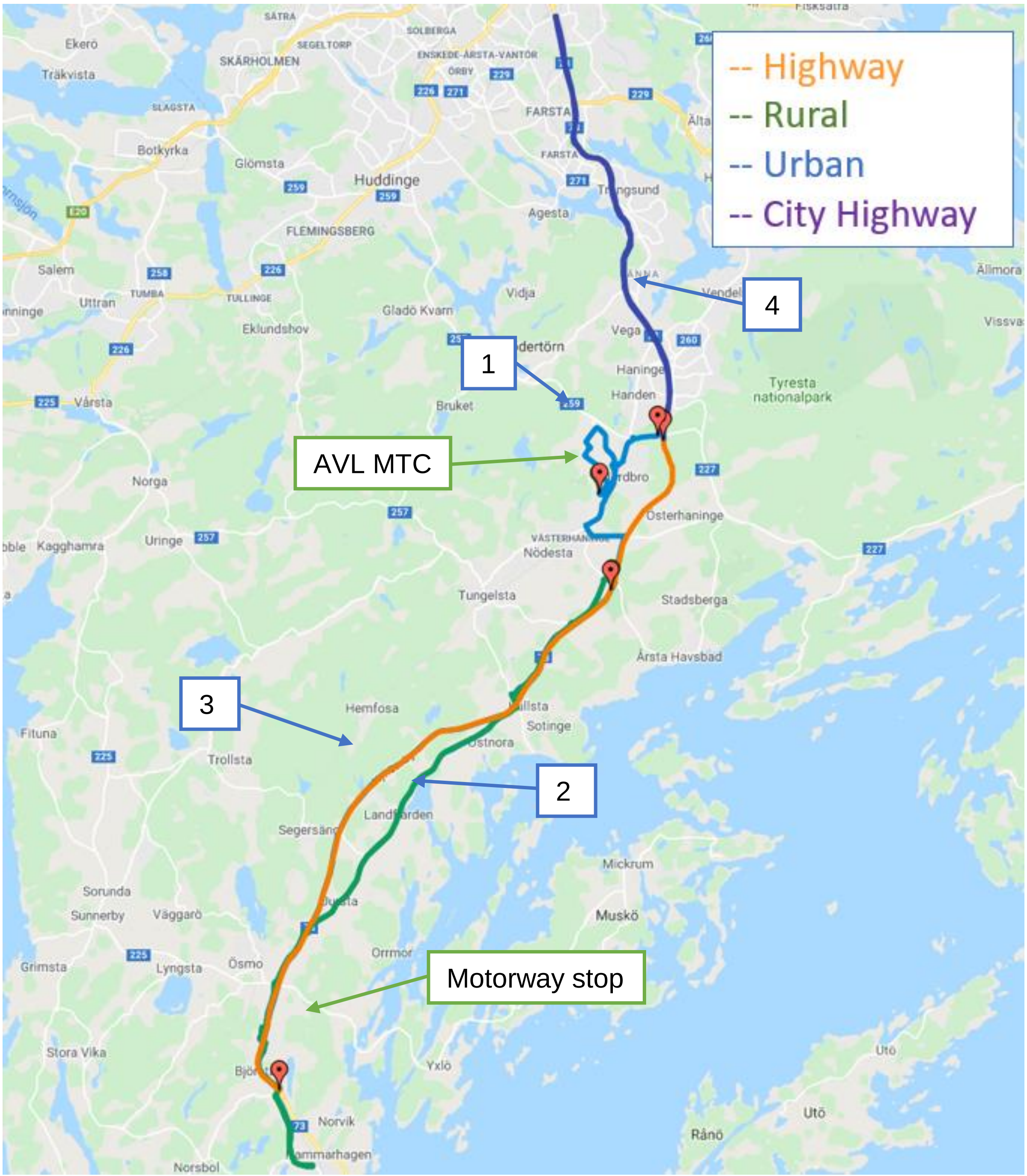

Figure 10 Overview of the test route, with color coded sections. 1) Urban, 2) Rural, 3) Highway, 4) City Highway.

In the following are the different sections of the route further explained. The number at the beginning of each paragraph is corresponding to the number of the section shown in Figure 10.

1) Test was started at AVL MTC site and followed by 10-15 minutes long warm-up section though industrial/urban area. Figure 11 shows part of the warmup section. The warm-up serves to establish a correct working temperature of the engine as well as aftertreatment system. Typically, exhaust emissions at engine coolant temperatures below 70°C are considered non-representative.

Figure 11 Typical vehicle arrangement outside AVL prior to the plume chasing test start. Vehicle 1 and chase vehicle depicted as example.

2) After the warm-up the driving continued on rural roads. This section tested the method and instrument on winding roads, presented in Figure 12. During this part, plume chasing was conducted with varying distance between chased and chasing vehicle. Speed limit on this section varied from 60-90km/h.

Figure 12 Part of the rural route section. Picture is shown as an example but represents the typical layout of the rural route sections.

3) In order to simulate the mandatory break after 4,5 hours of continuous driving, a 45 minutes long standstill was performed. The place that was used for the standstill is just before the highway entrance and can be seen in Figure 13. Trucks entering the highway with a cooled down engine were identified as source for potential false-positive during plume chasing measurements.

Figure 13 Truck stop at motorway entering ramp in Älgviken used to simulate 45min mandatory break.

3) After the stop, the driving continued in highway velocity. The highway section was quite long, and the plume chasing test was performed on varying distance to the

vehicle in front. The highway selected has typically low traffic density, thus the potential interference from surrounding traffic was low, presented in Figure 14.

Figure 14 Swedish National Road 73 (Väg 73) During typical traffic density.

4) Closer to Stockholm City the highway transited into City-close highway conditions, where the traffic density increased significantly compared to the highway section, presented in Figure 15.

The interference from surrounding traffic on the measurements is not only limited to exhaust interference. There is also risk for other vehicles overtaking the chased vehicle and thus interfering with the ongoing measurement.

Figure 15 Motorway section closer to Stockholm city implicates dense traffic. More of a challenging section during plume chasing due to interference with other vehicles.

The selected test route was designed to present a wide variety of traffic conditions, chasing speeds and surrounding factors. Testing at lower speeds was not performed. Due to the lack of drag, the exhaust plume is not properly directed in a laminar flow to the back of the truck. A summary of testing points and associated speeds can be found in Table 4.

Table 4 Summary of test scenarios

Type of test	Velocity [km/h]	Route used	Note
Rural driving	~ 70	Nynäsvägen (old stretch)	
Motorway, after stop	~ 80	Road 73 (exit Älgviken)	
Motorway, driving	~ 80	Road 73 (North)	
City highway	~ 60	Road 73 close to Stockholm	Varying speed

4.4 Weather conditions

The tests were performed under weather conditions typical for late Swedish autumn. Temperatures varied between 3-9° C and tests were performed in rain as well as in dry conditions. Detailed weather conditions are presented further in Table 5.

During the test conducted in rain and on wet road surface, significant amount of splash from the road surface was experienced. This did not seem to affect the ability to detect the exhaust plume.

Table 5 Consolidated weather data presented as test averages for tests 1 – 4.

Test nr.	Avg. Temp	Avg. Hum	Wind	Weather observation
1	7,9 °C	82 %	6 m/s	Fog, slightly wet road surface
2	6,8 °C	97 %	3 m/s	Overcast, slight rain
3	3,9 °C	93 %	1 m/s	Overcast, no rain
4	5,8 °C	91 %	3 m/s	Overcast, rain, wet road surface

In addition, Figure 16 presents time resolved temperature and humidity data for the four tests.

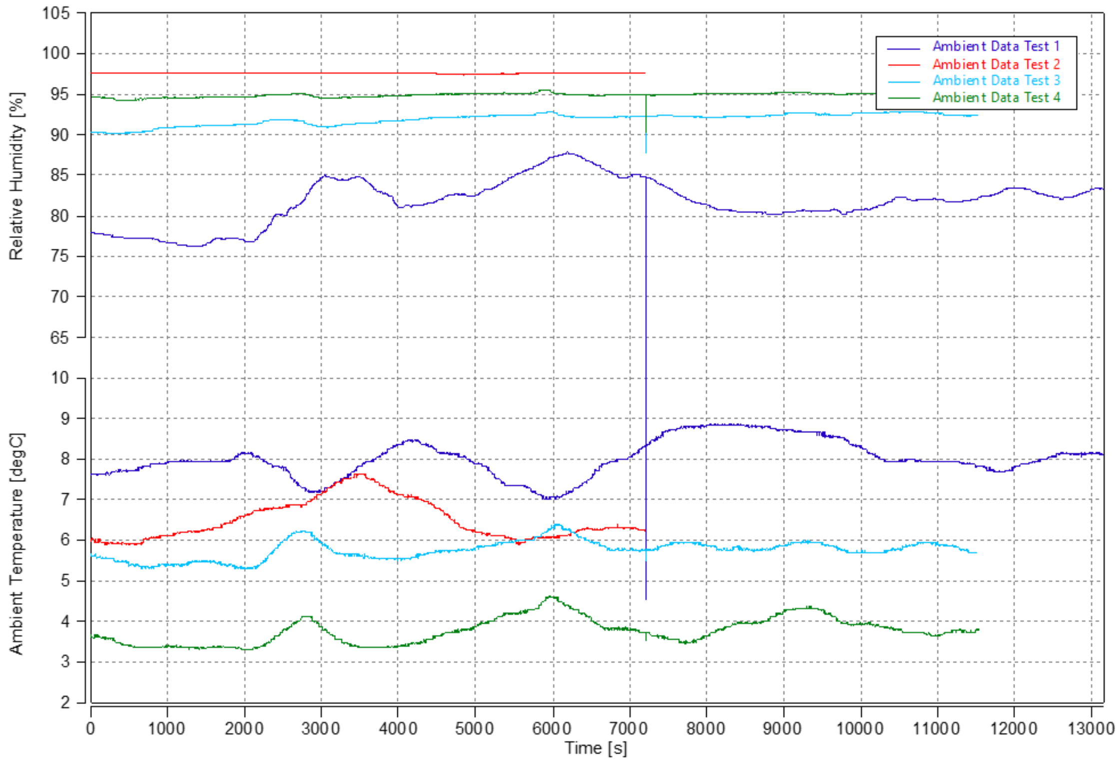

Figure 16 Graphic presentation of temperature and humidity during the plume chasing testing. These measurements were acquired from the ambient sensors on vehicle 1 and 2. The line at 7200s is due to a periodic zero check of the measurement equipment.

4.5 Plume Chasing

A collaboration for the plume chasing activities was made with Airyx GmbH. The following section gives an introduction to the setup and functionality of the plume chasing instrument itself. How the instrument was set up and installed for this testing campaign is explained in section 4.6. Figure 17 shows the instrument model that was used during the testing campaign, named ICAD NO_2/NO_x/NO Monitor.

Figure 17 Airyx ICAD NO_2/NO_x/NO Monitor [20]. This instrument model was used for the plume chasing

ICAD stands for Iterative Cavity Enhanced DOAS which is a new measurement system that was developed by the University of Heidelberg. The NO_2 concentration is defined by spectral absorption. A pump creates a flow of 0,5 to 2l/min and samples the air through a PTFE hose into the measurement cell. Since only NO_2 can be measured in the measuring cell, NO is converted to NO_2 by oxidizing NO with Ozone (O_3) that is generated in an internal ozone generator. A modified K30-FR CO_2 sensor from SenseAir is used to measure the CO_2 concentration in the sampled air. The sensor uses an Infrared absorption of CO_2 to define the CO_2 concentration. The sampling air is filtered, and the atmospheric pressure, humidity and temperature are defined to improve the measurement accuracy. As explained in section 2.4.2, the ratio between CO_2 and NO_x is independent of the dilution of the exhaust. The background concentration of NO_x and CO_2 is measured periodically so it can be deducted from the concentration measured in the plume (see equation 9).

$$R = \frac{E_{NOx}}{E_{CO2}} = \frac{\Delta C_{NOx}}{\Delta C_{CO2}} = \frac{C_{NOx} - C_{NOx,Background}}{C_{CO2} - C_{CO2,Background}} \tag{9}$$

By assuming an engine efficiency of μ=40% and a density of $\rho_{Diesel} = 0.84 kg/l$ it is possible to make a good estimation on the performed work in kWh through the CO_2 emissions. This allows calculation of the specific emissions of NO_x in mg/kWh.

A more in-depth explanation on how the emissions are calculated in the plume chasing can be found in [18]. A schematic overview of the calculation of the emissions is shown in Figure 18. The emission factors are only calculated when the CO_2 emissions are 30ppm above the CO_2 background concentration. This ensures that the calculated NO_x emissions are actually from the followed vehicle. Depending on traffic situation and environmental influences the background concentration changes during the testing. The background concentration is, at the time of the conducted tests, manually input in the software. The concentration, when not measuring in the plume, is observed and if needed the changed background concentration input in the software.

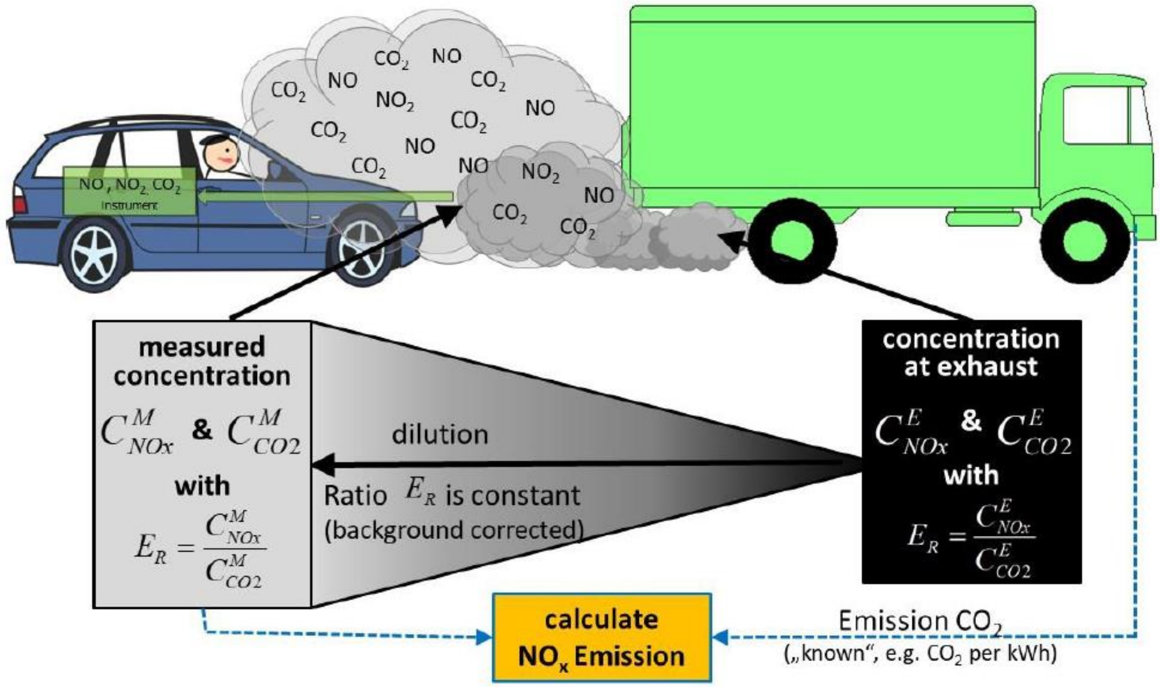

Figure 18 Principal of calculating the NO_x emissions in the diluted plume [2]. Showing the fundamental of plume chasing that the ratio between NO_x and CO_2 is constant.

Figure 19 shows the flow scheme and a detailed visualisation of the instrument.

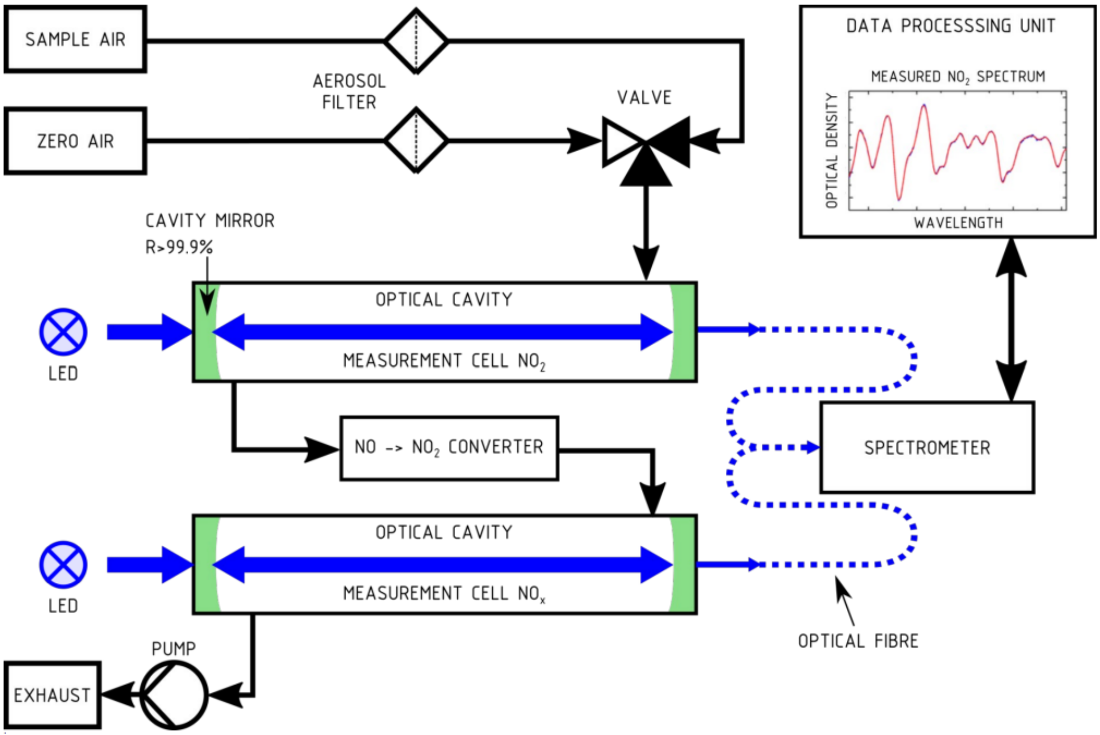

Figure 19 Flow scheme and measurement principle of the ICAD NO2/NOx/NO Monitor.

The properties of the instrument are presented in Table 6.

Table 6 Typical properties of Airyx ICAD Monitor

Typical properties	
Start-up time	< 1 min
Operating temperature range	-10 – 45°C
Power consumption	< 30W, 12V
Sample flow	0.5 – 2l/min
Data communication	LAN/WLAN
Computer system	Internal embedded PC
Weight	< 10 kg
Measurement range	0 – 5000ppb
Size	12” x 16” x 5”

During testing, the measurement data can be displayed on a tablet. Figure 20 shows how the user interface looks during a test. On the left site of the figure is the panel where the background levels are entered. On the top side are GPS position, time and measurement points noted. Below that are the CO_2 and NO_x concentration display and if the CO_2 emissions are 30ppm above the background concentration, the specific NO_x emissions [mg/kWh] are calculated and visualized. The colour indication was pre-set from Airyx GmbH, and do not reflect thresholds for manipulated vehicles. Below that are line graphs for CO_2 and NO_x concentration and a scatter graph for visualizing the specific NO_x emissions.

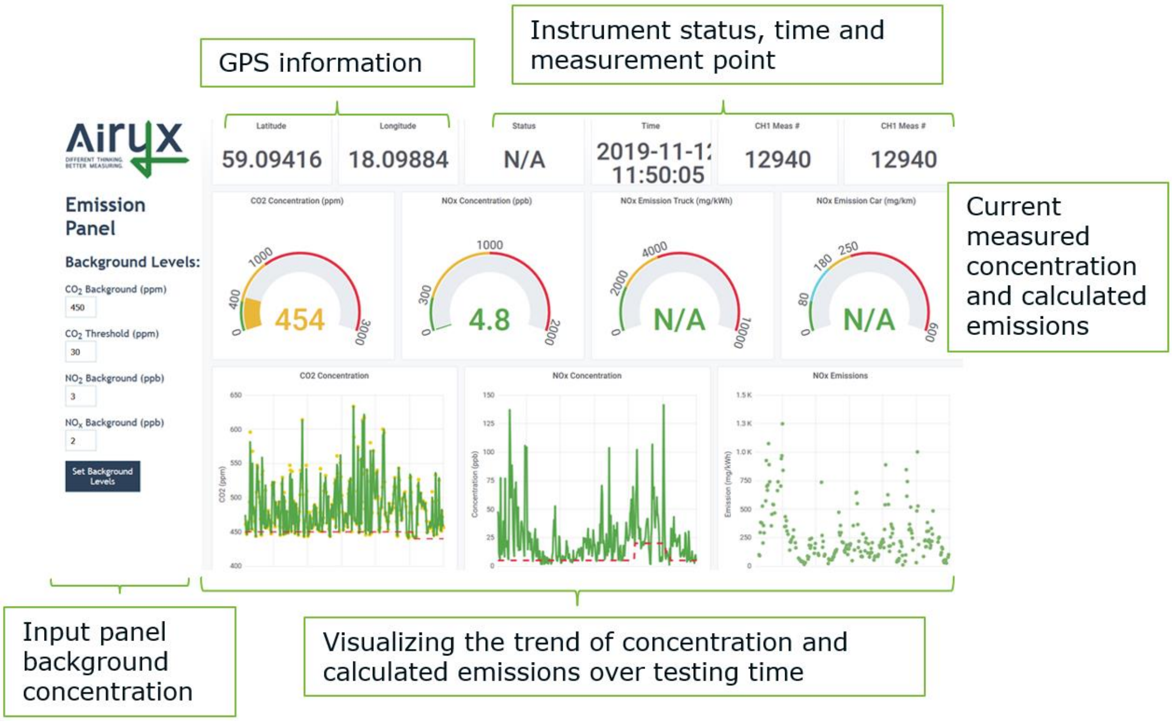

Figure 20 User interface of the instrument during testing

4.6 Chasing vehicle

A Volvo V60 was used as a chasing vehicle. The plume chasing instrument was installed and secured in the trunk. As shown in Table 6 the power consumption of the instrument is low enough to use the 12V outlet of the vehicle. To avoid voltage drops and to have a backup when the vehicle is switched off a battery was used. Figure 21 shows the vehicle rigged for testing.

To identify possible influences of wind and to be able to correlate them to the measurements, an anemometer with an internal GPS was mounted on the roof. This is not required for regular plume chasing measurements.

A dashboard camera is mainly used when looking at the collected data after the test. By using the pictures, it is possible to correlate influences from other traffic on the measurement results. The camera is not needed for the real time data and is only used for further post processing and investigations after the testing is completed.

In the front of the vehicle an aluminium construction was fixed to the front bumper. The tubes at the end of the construction are shaped in a way that they are sticking out to the front of the vehicle. Having them too close could cause interference with the boundary layer that is created in front of the chase vehicle.

Figure 21 Chasing vehicle equipped with plume chasing equipment

Figure 22 shows the equipment mounted in the vehicle trunk. There are two PTFE sampling hoses mounted on the vehicle, one going out to the left and one going out to the right side. These two hoses are then guided to the inside of the vehicle. Where, the hoses are connected to a valve before entering the measurement instrument

Depending on the exhaust configuration of the chased vehicle the sampling point is changed to either the left or the right side. When approaching a vehicle from behind, it is usually not possible to know if the exhaust is on the left or the right side. By the time of the testing the selection of sampling point (left or right) had to be chosen manually.

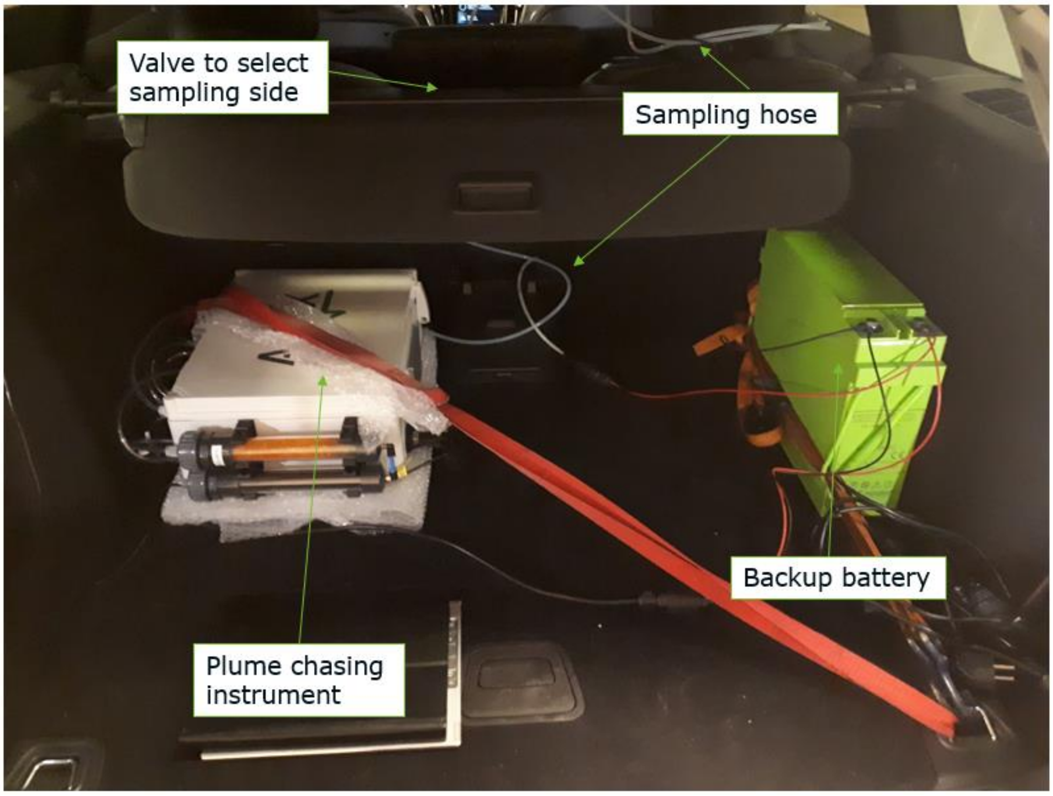

Figure 22 Installed plume chasing instrument in the trunk of the chasing vehicle. Picture shows the instrument, backup battery as well as sampling line and power connection. The valve to select the sampling side is fixed on the back seats.

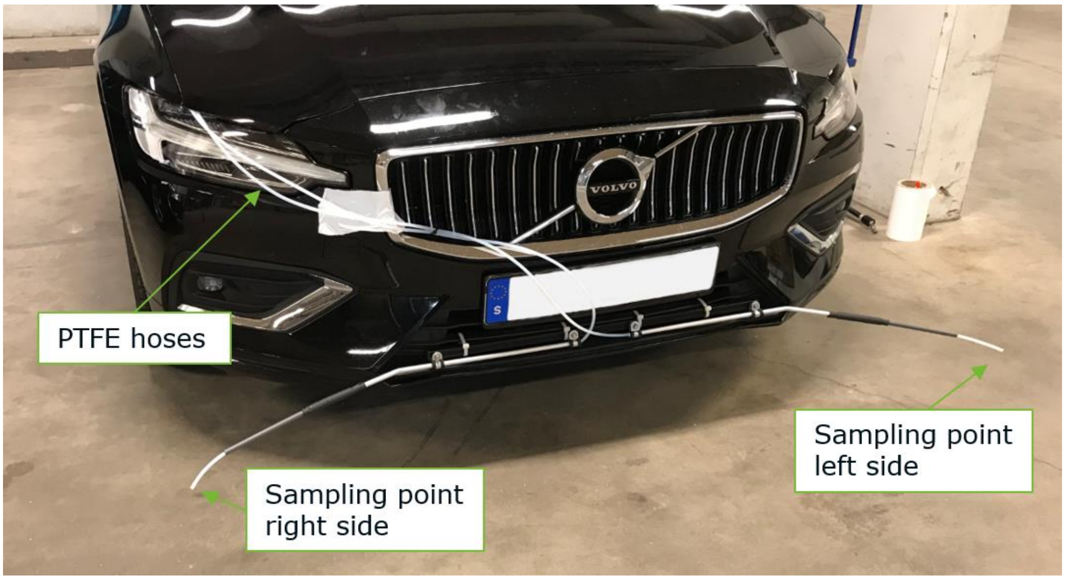

Figure 23 Detailed look of the sampling points/sampling hoses

5 Results

This section starts with a description of the identified practicability aspects of the plume chasing instrument. Afterwards, the results from the plume chasing are presented, continuing with the effects of different following distances and concludes with the economical results.

5.1 Practicability

The light weight and the small dimension of the instrument is a big advantage. This allows to transport and carry the instrument by one person.

During the testing week it did not come to any breakdowns or problems with the instrument which creates the impression that the instrument can so far be seen as reliable. The low power consumption allows to use the on-board power supply of the chasing vehicle and does not require any other external power supply. With having the vehicle and therefore the instrument in a garage overnight (temperature was around 21°C) the startup time of the instrument was within few minutes (~2-4min).

The current setup requires a manual selection of the sampling side, this would require that the valve is installed in a reachable distance from the front passenger seat. The current user interface requires background emission knowledge as well as observing of the measured emission during chasing. The sampling probes would be quite vulnerable if the chasing vehicle would be parked in public places and would catch attention from civilians. Either probes with automatic retraction or allowing the easily detach them would be suggested.

5.2 Plume chasing results

The following part describes the results from the practical tests. Starting with vehicle 1 in the healthy state, continuing with vehicle 2 and finishing with the results of vehicle 1 in the manipulated state. In this context, healthy means that the exhaust aftertreatment was in fully functioning condition. Further on, there is comparison between three testing results, as well as the results from different following distances.

Generally, the main focus for this testing campaign was not to compare the accuracy to PEMS. However, it is vital that the results are reasonable in comparison and that there is no risk of having a false positive result due to instrument inaccuracy. Therefore, a comparison between the plume chasing data and the collected PEMS data was performed and can be found in section 5.3.

5.2.1 Vehicle 1 – healthy

The first test for Vehicle 1 was performed in a healthy state. The test started with a warmup consisting of urban driving, followed by a rural section. The different sections and type of routes are explained in section 4.3.

Chasing the vehicle on a rural part can be challenging especially on winding roads. Due to the exhaust configuration, going out to the right, you would ideally drive a bit further to the right side of the road which might be a potential risk. Nevertheless, it is possible to measure the plume, but with difficulties for longer consecutive acquisition.

On the highway it is easier to maintain sampling in the plume and therefore obtain longer periods of continuous data. Since there are fairly straight roads, it is less difficult to maintain a constant position with regards to speed and distance in relation to the chased vehicle.

After driving on the rural and highway section, the testing was continued on a city-close highway part with more dense traffic. This was challenging due to exhaust interference from other vehicles. Noise dampening walls in parts of the highway and high buildings on the sides tend to collect emissions, possibly raising background emissions levels locally. These factors create interferences with the measured emissions from the chased vehicle. Figure 24 shows a screenshot of the display showing the online data.

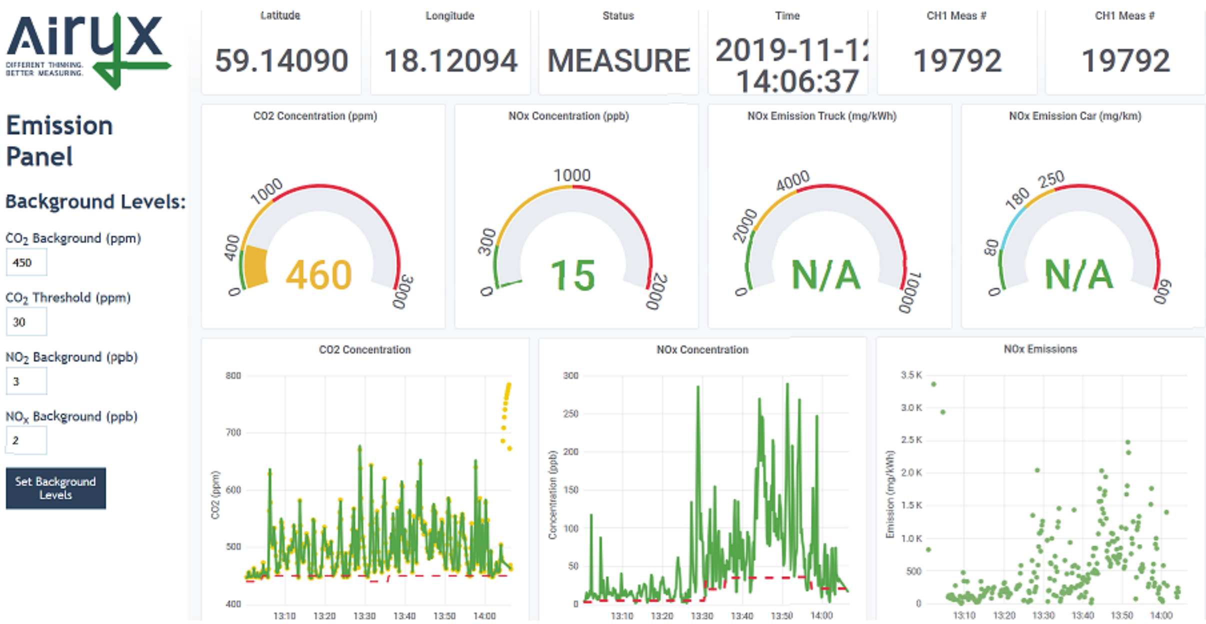

Figure 24 Online values (live) of vehicle 1 in healthy state during rural and highway driving. Emissions stay on a relatively constant level below the allowed emission limit but increase during the city highway section due to interference.

Figure 25 shows a detailed view of the calculated specific emission. The values are presented live, during the actual testing and calculated from the raw data. There are outliers, but these are only single values and most data points are in the expected range.

It can be seen, that the emissions are higher in the beginning of the test. This is expected since the exhaust temperature is low and therefore the temperature in the SCR is below the working temperature. After around 15min, when entering the rural section, the exhaust temperature has increased to above 250 °C and, subsequently, the NO_x emissions decrease significantly.

The standstill period was approximately 45 min with the engine turned off. The stop simulates the mandatory stop after 4.5 hrs of driving. The parking spot was on the highway entering ramp and the data point in this period are the measured values from passing vehicles. The emissions do not increase significantly after the stop. This indicates that the engine as well as the exhaust after treatment have kept a quite high temperature. The acquired temperature signals from the EFM confirm that the exhaust temperature quickly reaches a temperature of 250 °C and higher (see Figure 25).

During the city-close highway part there are a lot of disturbances from the surrounding traffic. However, this would not be a reason for the emissions from the vehicle to increase in this part. From the PEMS data it can be seen that the emissions stay on a similar level as during the highway and rural part before. Therefore, the seen increase of emissions is likely from surrounding vehicles contributing to the measurements.

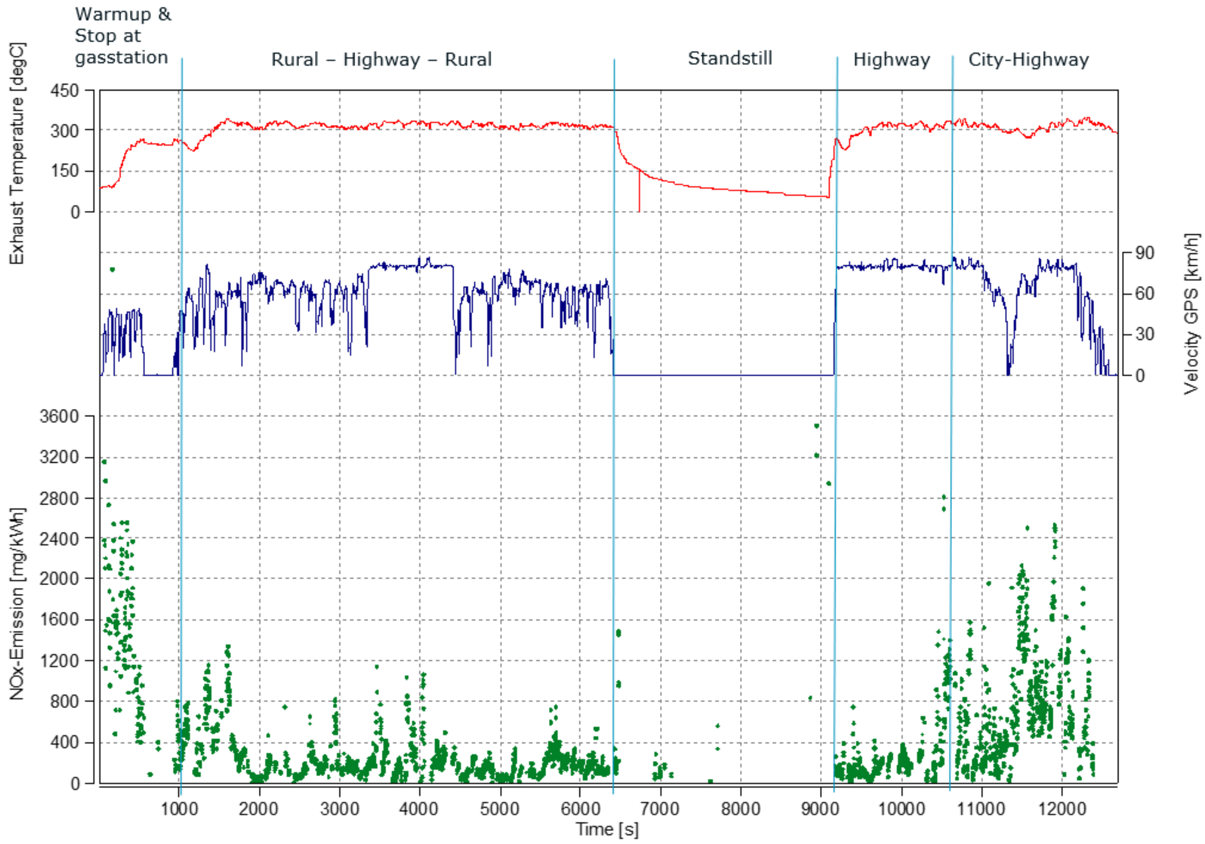

Figure 25 Vehicle 1 - NO_x emission as presented live during testing. The figure shows the data from the whole test including a 45min standstill close to a highway entrance. The exhaust temperature and GPS velocity signals were recorded from the PEMS equipment.

5.2.2 Vehicle 2

As seen in section 4.1.2, Vehicle 2 is a rigid vehicle that is shorter compared to Vehicle 1 (9,9m compared to ~18m). Therefore, the distance between exhaust pipe and chasing vehicle is shorter as well. Furthermore, the exhaust pipe exits to the left side and approximately face backwards with 45°. The route was identical compared to the one driven with vehicle 1. Figure 26 shows a screenshot of the display during the actual testing. The color coding is pre-set in the software and should not be used as a pass/fail indication of the EU limits.

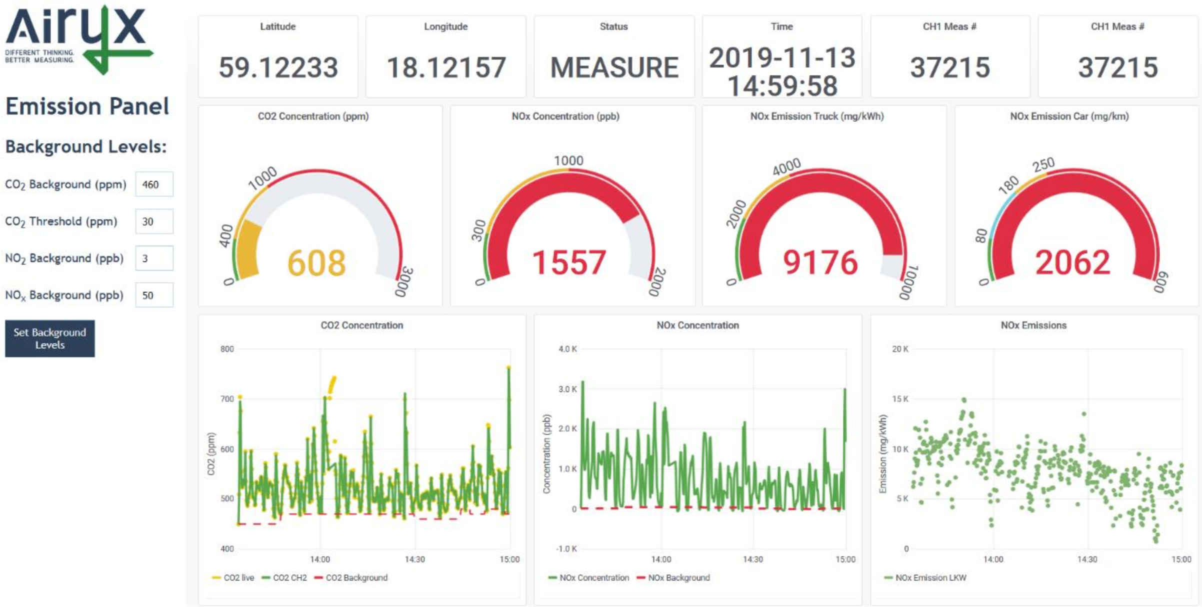

Figure 26 Online values of vehicle 2 of rural and highway driving. The measured emissions clearly indicate that the vehicle has high emissions, significantly above the limit (see scatter plot).

Figure 27 shows a detailed look on the calculated NO_x emissions. The emissions do not decrease as they did for vehicle 1. The reason for this is the nonfunctioning urea injection.

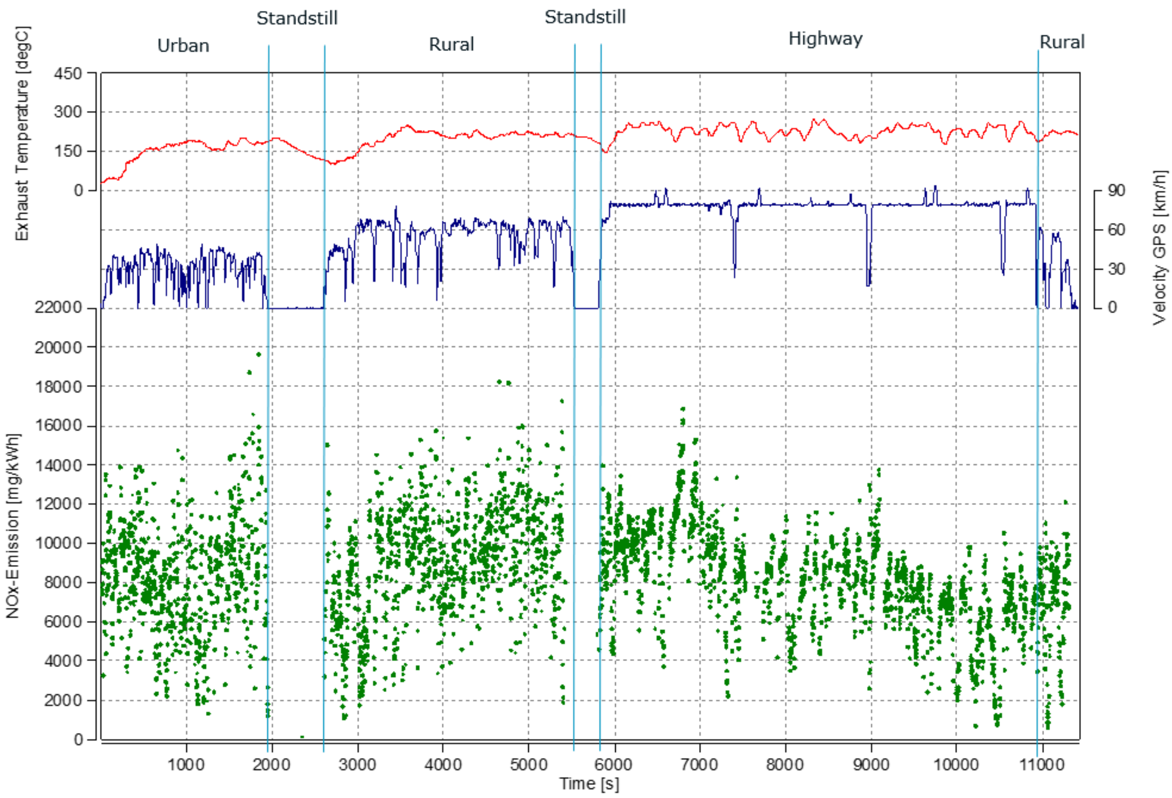

Figure 27 Vehicle 2 - NO_x emission as presented live during testing. The picture shows the emission during the whole test. The measurements were performed on an In-Service Conformity compliant route with urban, rural and highway section. Driven on identical sections as for vehicle 1.

5.2.3 Vehicle 1 - manipulated

Vehicle 1 was manipulated, as described in 2.3.3, and then tested on identical route sections as for the first test. Figure 28 shows a screenshot of the display during testing.

Figure 28 Vehicle 1, manipulated, highway section.

During the start of the test, it is likely that there was some AdBlue® left in the system and a buffer in the SCR itself. In Figure 29 it can be seen that after some minutes, the emissions start to rise as the SCR is at this stage nonfunctioning.

There is a clearly visible difference between the city highway section of the test with “vehicle 1 – manipulated” compared to “vehicle 1 – healthy”. Even though there can be interferences with other vehicles and other emissions, the emissions from a vehicle that is manipulated are still significantly higher. This allows to detect a high emitter even in more dense traffic, where interference influence the measurements.

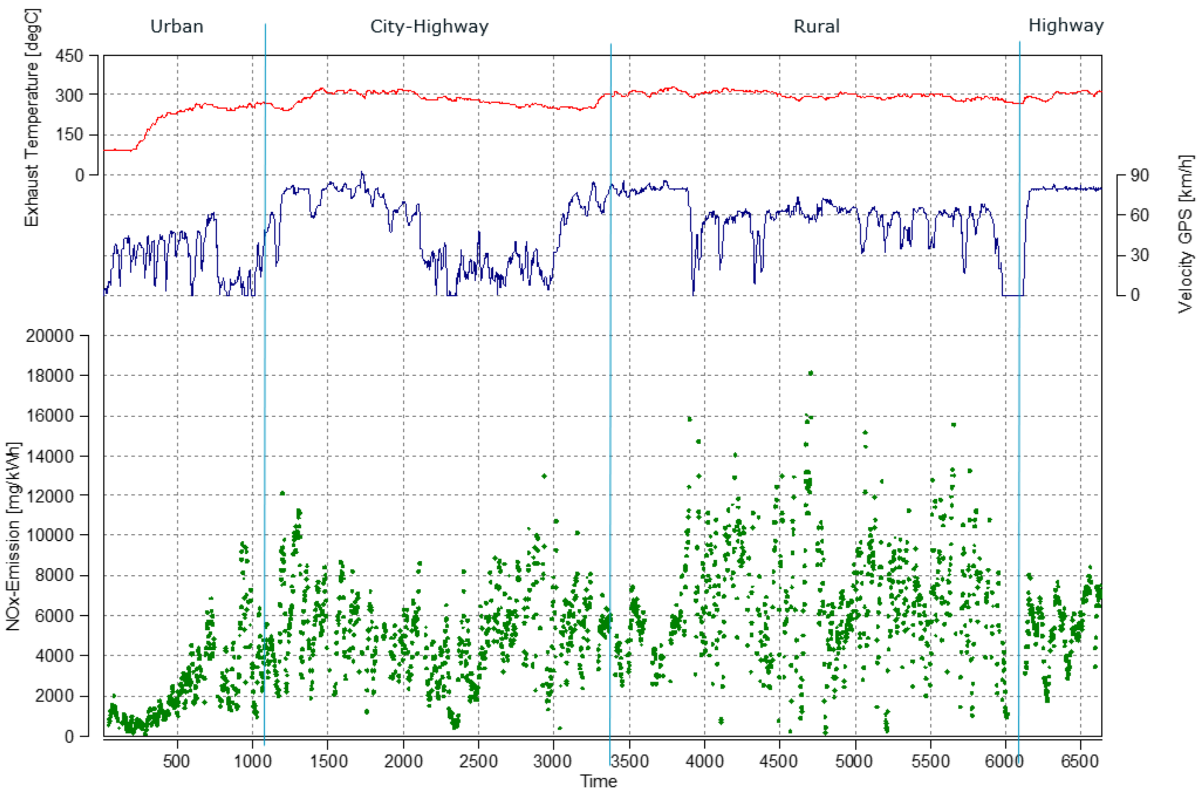

Figure 29 Vehicle 1 (manipulated) - NO_x emission as presented live during testing. NO_x emissions are clearly higher compared to the test during the healthy state.

5.2.4 Chasing distance

The plume chasing measurements were always conducted with allowing the minimum safety distance. On urban and rural driving, the distance varied due to traffic situation, road changes and speed. During highway driving the active cruise control (ACC) was used to ensure a constant distance. The distance in the ACC was chosen to be either on 1 or 3, on a scale from 1 to 5. Distance 1 was ~20m, distance 2 ~30m. When increasing the distance, the measured concentration decreases and eventually it is not possible to measure in the plume anymore. However, it is still possible to measure with an increased distance, but with less measurements. Nevertheless, with a decreased concentration there will not be wrong measurements, only less. When driving with a set distance 1 on the ACC, the requirements for the minimum safety distance are fulfilled and it will not feel unsafe.

5.2.5 Comparison between vehicles

Even vehicles with a fully functioning exhaust aftertreatment system can emit emissions outside of the emission limits for shorter periods. One risk is therefore to detect a low emitter as a high emitter and vice versa. Therefore, a comparison was performed with vehicle 1 – healthy, vehicle 1 - manipulated state and vehicle 2. For the comparison, the single values were averaged over an interval of 2min. The datapoints where split for highway and rural. The diagrams display the total average value of the intervals. The lower end of the error bar represents the datapoint with the lowest emissions over an interval of 2 min. The upper end of the error bar corresponds to the interval with the highest emissions also over an interval of 2 min.

The average values are as follows:

- Vehicle 1 (healthy): 270mg/kWh
- Vehicle 1 (manipulated): 7223 mg/kWh
- Vehicle 2 (defect SCR): 10273 mg/kWh.

The error bars from vehicle 1 – healthy do not in any case overlap with the error bars from vehicle 1 – manipulated or vehicle 2. Neither in the rural part nor in the highway part. Through this it can be concluded that the risk of detecting a low emitter as a high emitter is very low. However, these are averaged values and single values can overlap. Therefore, the emission trend needs to be observed, which allows to approximate what the average value would be.

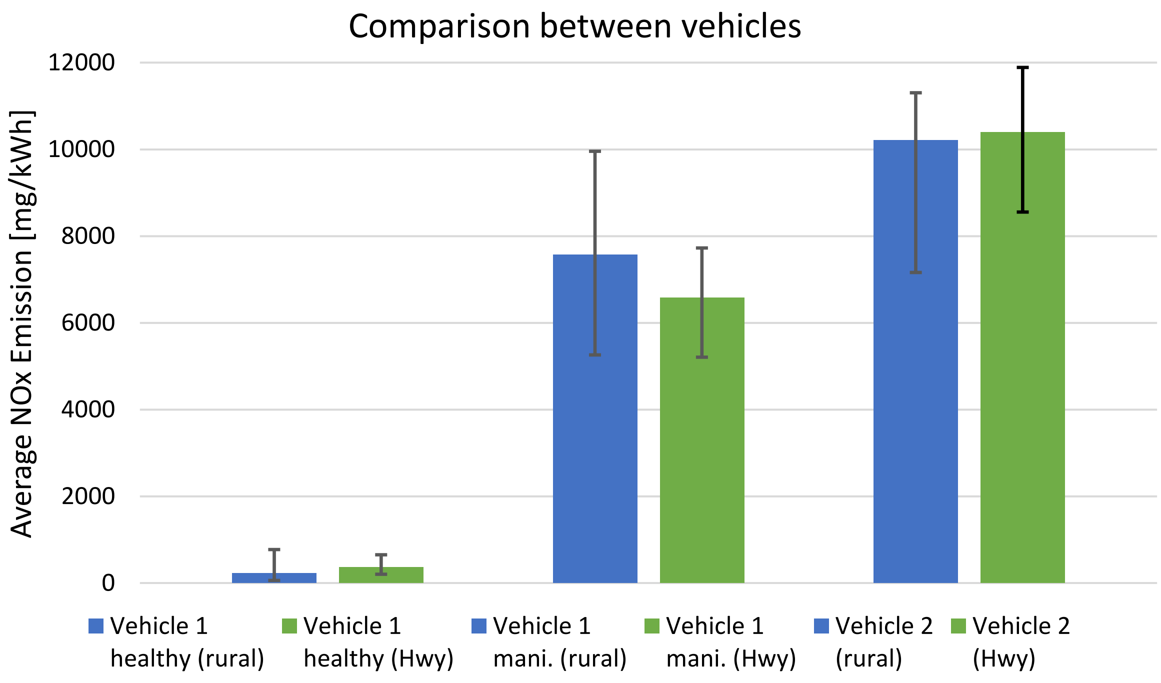

Figure 30 Comparison of Vehicle 1 (healthy), Vehicle 1 (manipulated) and Vehicle 2. Presenting average results with a min and max value that show that the average emissions for a 2 min interval do not overlap in any case between a healthy and a manipulated vehicle.

Another comparison between vehicle 1 – healthy and vehicle 1 – manipulated was performed with the online values that are presented during the testing. The results can be seen in Figure 31. A big difference can be seen in emission levels and only some single values do overlap. This again shows that the risk of detecting a low emitter as a high emitter and vice versa is minimal.

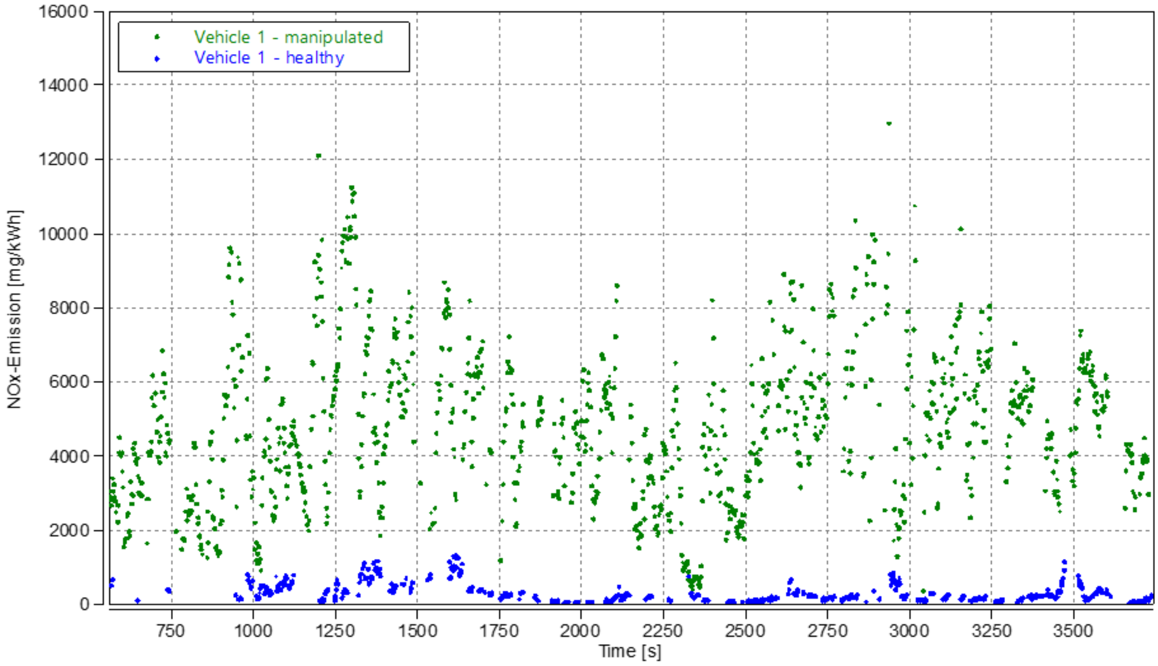

Figure 31 Comparison of NOx emission between Vehicle 1 with a functioning SCR and Vehicle 1 manipulated. The difference in NOx level can be seen and only single values overlap.

5.2.6 Testing further vehicles

Besides measuring vehicle 1 and 2 that were tested in parallel with PEMS, a study of other trucks on the road was performed. While driving down the highway, trucks were randomly selected, followed, the best sampling point side identified, and the emissions measured through plume chasing. These tests presented extra challenges.

- The drivers of the trucks were unaware of the plume chasing and the driver therefore behaves more unpredictable.
- The exhaust configuration was unknown and sampling point side where chosen while conducting the test.
- Truck service history and driving history prior the measurement was unknown.

The time required to approach a vehicle, find the exhaust plume, select the correct sampling side and start taking measurements is generally longer than the measurement time that is needed to be able to identify if the vehicle is a high or low emitter.

After conducted measurement, the vehicle was overtaken, and the Euro class determined through the registration plate. Besides measuring vehicles that were of a similar configuration as vehicle 1 and vehicle 2 (see section 4.1), a rigid truck trailer combination with around 25m total length was measured. Despite the length, it was possible to determine the emissions. Figure 33 and Figure 34 show pictures taken during testing.

The testing performed resembled a real chasing situation. The measurement results were observed and identified if the vehicle was a high or low emitter. Assumptions of the Euro class were made from the emission results and compared to the actual Euro class, that could be identified when passing the vehicle and noting the license plate. However, it also becomes clear that it is hard to establish the Euro class just by the vehicles. Access to truck data, such as a traffic register is a valuable tool and should be considered as a complement to the plume chasing for further activities.

Figure 32 shows the measured NO_x emissions during testing. The results from the five trucks presented are all from randomly selected vehicles. As it can be seen the results for truck 1 and 2 are well in line with the Euro class. Truck 3 and 5 are slightly higher than the allowed emission limits for EU VI. However, the sampling time was short (between 3 and 9min), and it was not clear where the truck has entered the highway. It was unknown for how long the truck was driven before the measurements were taken and therefore unknown if the exhaust aftertreatment has reached its working temperature. Truck 4 was followed from a highway entrance. It is therefore likely that the exhaust temperature was still low and that the aftertreatment system had not reached its working temperature. Nevertheless, even after 10min of driving on the highway, the results were above the allowed limit.

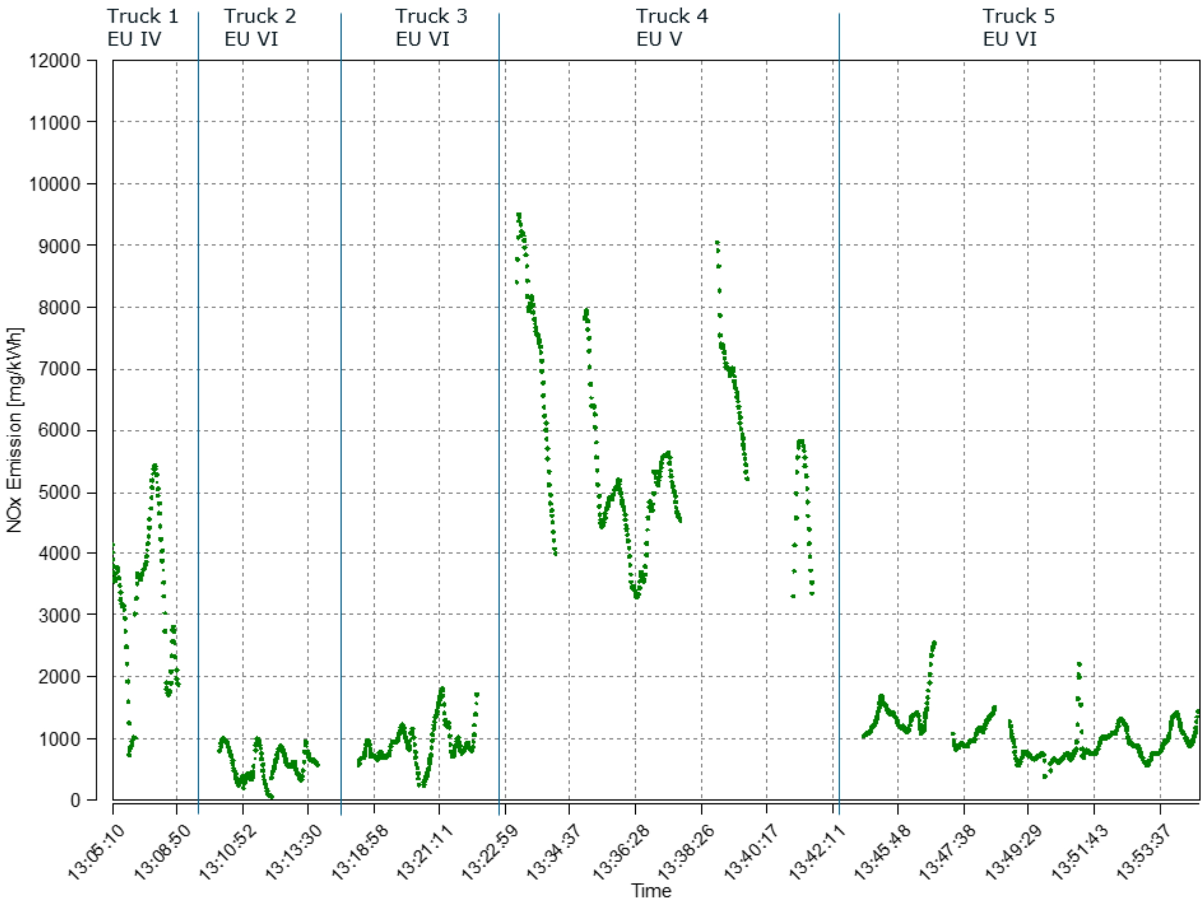

Figure 32 NOx emission as presented live during testing of randomly selected vehicles. All five trucks presented here were randomly selected. Truck 1, 2, 3 and 5 are in line with the expected emission and not significantly above. Truck 4 shows higher values.

Figure 33 Random selected truck being measured. Rigid tow truck (~12m)

Figure 34 Random selected truck being measured. Tractor-trailer combination (18m)

5.3 Comparison Plume chasing to PEMS

A comparison between the results from plume chasing and PEMS was performed. This serves to identify the risk for false positive, due to measurement inaccuracy or the method of plume chasing itself.

The data used for the comparison was post-processed where a spectral data analysis on all data-points was performed. The NO_x and CO_2 signals where time shifted and the NO_x signal smoothened. Only data points were considered when measuring behind the truck, other points were ignored (e.g. when a car was in between).

The background concentration was defined through an algorithm and when the CO_2 concentration was 20 ppm above, the NO_x and CO_2 concentration are used. If a time period contains more than 30 % data points, all NO_x and CO_2 concentrations are averaged, and the ratio NO_x/CO_2 calculated. From the ratio, the specific NO_x emission [mg/kWh] is calculated assuming a 40 % engine efficiency.

The PEMS data was time aligned with the plume chasing data and then averaged with the same intervals as the plume chasing data.

The data points were averaged with intervals of 30 s, 1 min, 2 min and 5 min. The shorter an interval becomes the higher is the impact of a time offset. A longer interval reduces the impact of a possible time offset and reduces the impact of non-representative datapoints. However, it is more difficult to see rapid changes in emission behavior in long intervals.

After analyzing the different interval length, the 2 min interval was chosen to be used for the comparison. This time period gives the best trade-off between minimizing an effect of a possible time offsets, having enough datapoints in the interval, and still seeing differences in the emissions. A more in-depth study on the averaging intervals has been conducted in the report “Remote RDE Messtechnik Validierung [18]. This report has shown that the 2 min interval give the best correlation between PEMS and plume chasing.

The averaged intervals are presented Figure 35 to Figure 37.

Figure 35 presents the results from Vehicle 1 in the healthy state with a functioning SCR. Both results follow the same trend, high emissions in the beginning during the warmup/industrial section and stable emissions below 400 mg/kWh in most cases. From the exhaust temperature it can be seen that the emissions decrease when the exhaust temperature reaches around 300°C. As described in 5.2.1 the increasing emissions during the city highway part is due to disturbance from other vehicles. The PEMS results stay at the same level as during the highway and rural sections before. Overall there are no big discrepancies between the plume chasing and PEMS results.

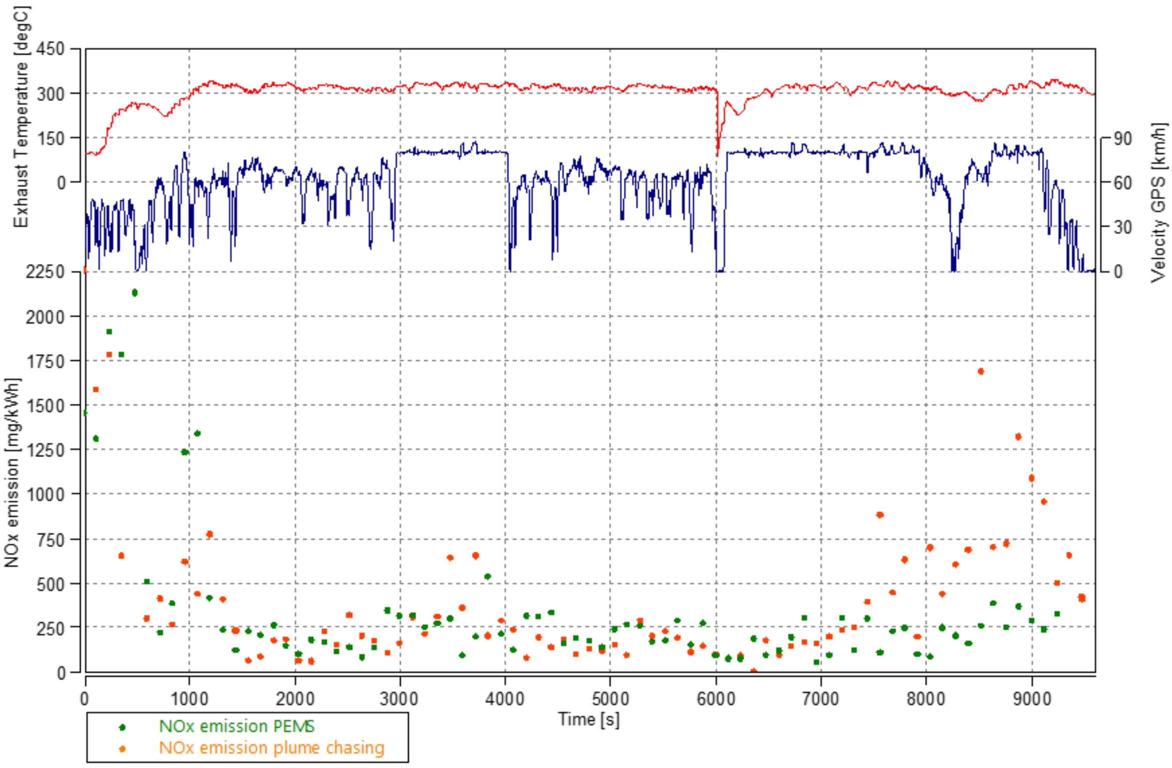

Figure 35 Vehicle 1 - healthy, 2 min averaged NOx emissions. The picture shows a good correlation between PEMS and plume chasing with bigger differences during more dense traffic on a city highway section. The scale of the y-axis is from 0-2250 mg/kWh.

Figure 36 presents the 2 min averaged NO_x results from vehicle 1 in the manipulated state. In section 5.2.3 it was described that it took a while until the NO_x emission started to rise, due to left AdBlue® in the system. The PEMS results follow the same pattern. From approximately datapoint 10, the emissions stay on a level significantly above the allowed limit. The PEMS and plume chasing results are, as during the test with vehicle 1 in healthy state, in line.

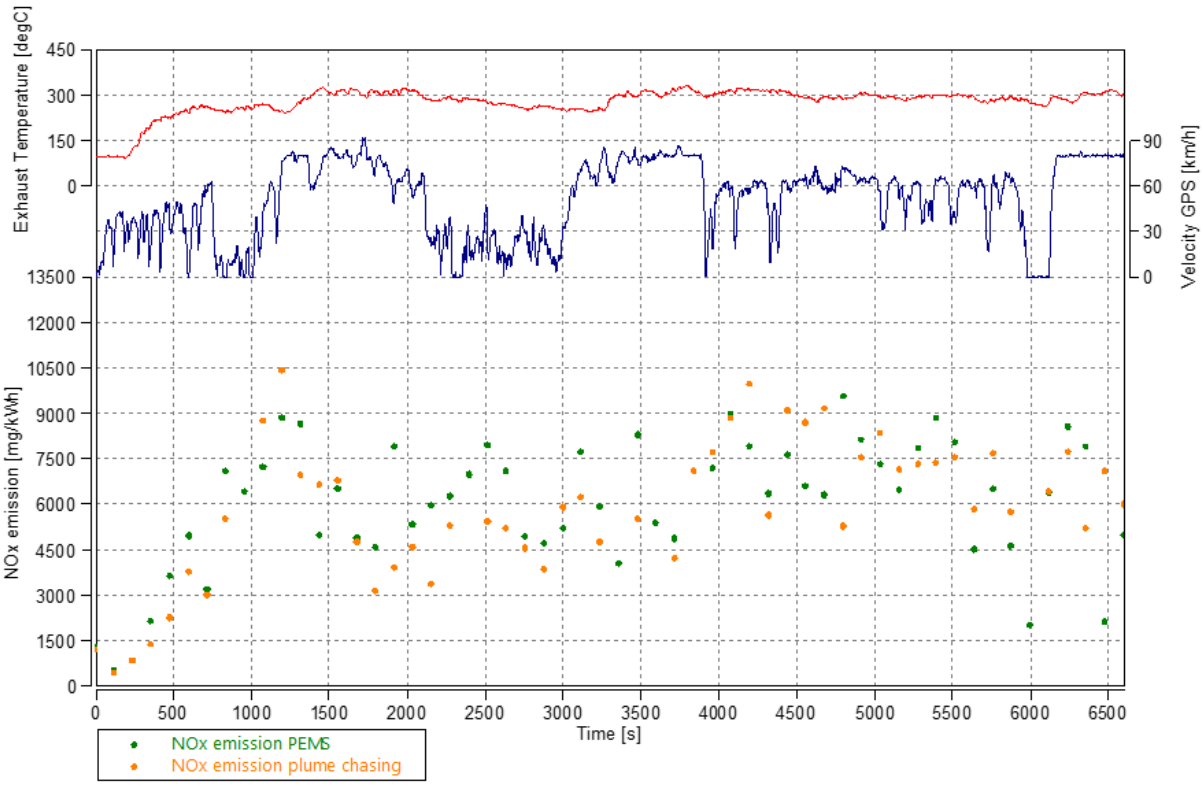

Figure 36 Vehicle 1 - manipulated, 2 min averaged NOx emissions. The emissions increase in about 20min from a low emitter to a high emitter. This is probably due to some urea left in the SCR system. The scale of the y-axis is from 0-16000 mg/kWh.

Figure 37 presents the 2 min averaged NO_x results from vehicle 2 in the manipulated state. The emissions are for both PEMS and plume chasing on a level above the emission limit and stay on that level throughout the whole test. The emissions are between 5000 and 12000 mg/kWh for both measurement devices.

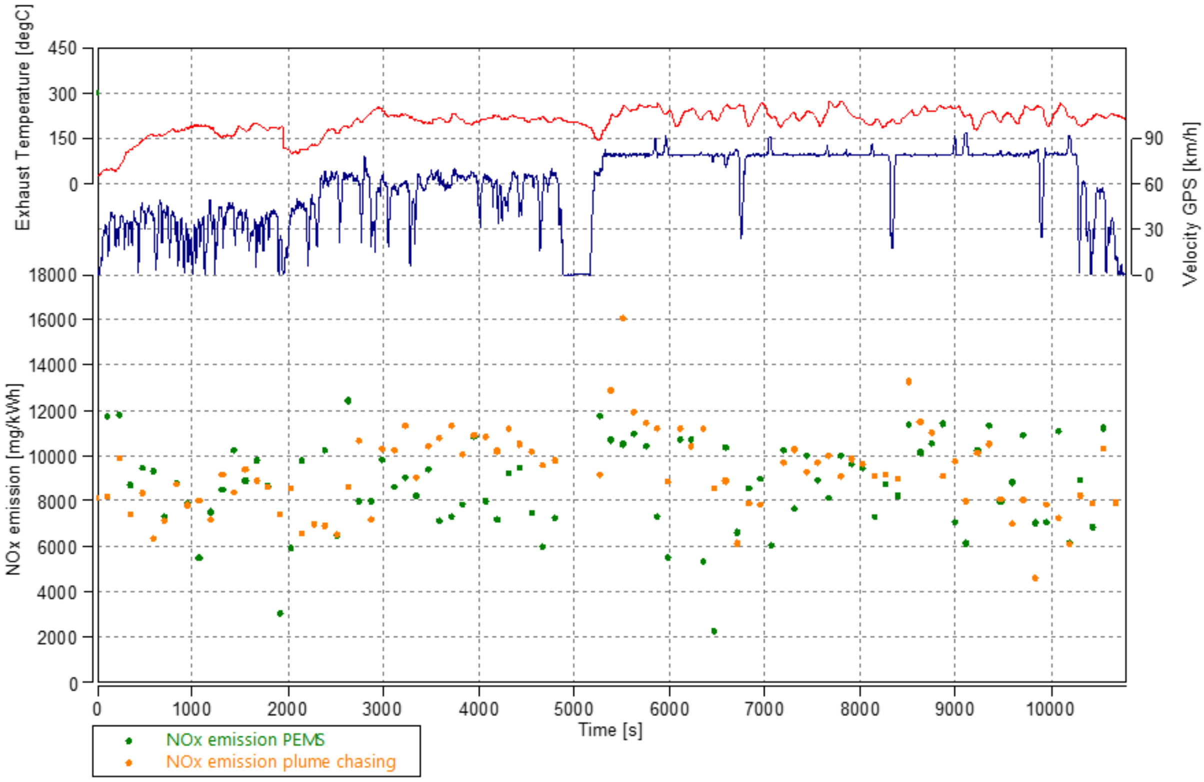

Figure 37 Vehicle 2, 2 min averaged NO_x emissions. Showing the emissions are constantly on a high level with a good correlation between PEMS and plume chasing. The scale of the y-axis is from 0-30000 mg/kWh.

5.4 Economics

Prices for the complete plume chasing instrument with installation on the vehicle, testing of the installed equipment as well as training, is currently between 45.000 to 60.000 €. The price may vary depending on the acquired setup, extent and scope of the training as well as complexity of installation.

Besides this, there are yearly maintenance costs of approximately 3.000 € for filter changes, service and calibration. (Dr. D. Pöhler, personal communication, January 2020)

These costs are based on the assumption that the instrument is used for an average of eight hours per week and that the service is performed by the manufacturer.

Additional to the costs that are directly correlated to the instrument, come the costs for personnel. Training and introduction will take around 2 to 3 days. This may change depending on the extent and therefore length of the training.

The instrument is small enough to fit in a regular trunk (see dimensions in section 4.5). Therefore, it is assumed that an already available vehicle will be used as a chasing vehicle.

Operation costs should be based on the assumption that the plume chasing will be performed by two people. One to drive the chasing vehicle and one to observe the measured emissions.

Besides purchasing an instrument, there is the possibility of renting the equipment or purchasing the measurements as a service.

6 Conclusion and Discussion

This study evaluated the plume chasing method for detecting high NO_x emitters among commercial vehicles. Research was performed to understand the needs of the intended end-user and to know the state-of-the-art.

The performed study shows that the plume chasing method works as a tool to get a first indication of vehicle emissions. The findings suggest that the correspondence to more well-established measurement methods, such as PEMS measurements, is sufficient for the intended use. Furthermore, the instrument tested is easy to fit in a standard police van due to its small dimensions, weight and power consumption.

The recommended chasing period stipulated by the manufacturer is 2 minutes. This is with the perspective of achieving the most accurate measurements. However, the results from the study indicate that a shorter chasing period (15-20s) is sufficient to collect valid data for the intended use. As another conclusion from the chasing period, the time it takes to find the plume is usually more time consuming then the actual measurements. Detecting a suspicious vehicle, positioning on the road with suitable distance can take more time than measuring the plume for the target vehicle.

Highlights from the study include:

- The method appears tolerant to driving differences such as speed variations, road curvature and differences in distance to the chased vehicle to certain amount
- The measurements are not sensitive to weather such as rain, moderate wind or fog in any particular extent.
- The method can detect a not functioning SCR system without a high risk of false positive detection.
- The tested instrument was easy to handle and to install in the chase vehicle.

According to the performed study, the analyzer used and provided by Airyx GmbH was the most well developed and market ready system available at the time of testing. However, some areas of improvement were noticed:

- The software should be developed to better suit the needs and capabilities when the instrument is operated by an authority. The interface should then give a clear indication from a “pass/fail” perspective.
- Sampling probe (right or left) is at this point chosen manually by a valve. This should be automatically controlled.
- Automatic detection of background NO_x and CO_2 levels is needed in order to make the instrument more user friendly.
- Implementing an averaging window would assure a higher measurement accuracy and further minimize the risk of false/positive

Plume chasing is a promising method for detecting high NO_x emitting vehicles during on-road testing. The validation of the equipment shows good reliability and correlation for the intended purpose. The recommended updates are with the main purpose of simplifying the handling. Together with other procedures, the method shows a good potential to be used for detecting manipulated or faulty SCR systems during on-road inspections.

7 Recommendations for future activities

Subjects for further study:

- Financial perspectives need to be evaluated. It needs to be identified how much time and therefore money is saved when using plume chasing to identify possible manipulated vehicles. Then a comparison can be made to the previous methods.
- Further develop a best practice methodology for handling, usage and limitations of the instrument.
- Based on the findings in this study the recommendation is to arrange an extended study to investigate the possibilities of implementation together with Danish Authorities and Danish Police. The recommendation is to purchase or rent one analyzer unit and install in a Police car in order to evaluate the further usability.

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