Real driving exhaust gas emissions from trucks and vans when engine is cooling off in urban areas

Report – Real Driving Emission in Copenhagen

PEMS Project

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On behalf of

Ministry of Environment and Food of Denmark – Environmental Protection Agency

ECM

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Content

1. List of Abbreviation

AdBlue	Trade name of urea-water mixture (for reduction of NOx)
CF	Conformity factor (CF) for a given emission
CO	Carbon monoxide
CO_2	Carbon dioxide
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
EGT	Exhaust Gas Temperature
EURO VI	EU emission standards for Heavy-duty engines and vehicles
Euro 6	EU emission standards for Light-duty vehicles
FC	Fuel consumption
KBA	Kraftfahrt-Budesamt
NO_X	Nitrogen oxides
NOx-Index	mg NOx per gram CO_2
OBD	On-Board Diagnosis
PEMS	Portable Emission Measurement System
PM	Particle Mass
PN	Particle Number
RDE	Real Driving Emissions
STA	Swedish Transport Agency
SCR	Selective Catalytic Reduction
PN	Particle number
PTI	Periodical Technical Inspection
WHTC	Worldwide harmonized Heavy-duty vehicles Test Cycle
WHTP	Worldwide harmonized Heavy-duty vehicles Test Procedures
WLTC	Worldwide harmonized Light-duty vehicles Test Cycle
WLTP	Worldwide harmonized Light-duty vehicles Test Procedures

Disclaimer

The reader should note that the report only covers 4 tested vehicles and thus the statistical data is small. However. The results and conclusions are based on a limited number of tests and conditions. The results and conclusions are valid only for the specific vehicles (individual) included in these tests. The study does not say who a vehicle brand performs.

2. Summary

On behalf of Ministry of Environment of Denmark – Environmental Protection Agency, EXIS together with ECM and Applus Denmark, have carried out a project named Real driving exhaust gas emissions from trucks and vans when engine is cooling off in urban areas.

The main questions to which this work would provide answers were:

- Assess real driving emissions from vehicles delivering goods in urban areas
- Find out under which conditions the SCR-system (aftertreatment system for reducing NOx emissions) is functioning and not functioning with respect to engine load, engine temperature, SCR-efficiency, driving condition, outdoor temperature, and load/weight of the vehicle

In this study three (3) heavy duty trucks and one (1) delivery van have been tested with respect to a number of emissions parameters and the function of the exhaust gas aftertreatment system. All vehicles were diesel-powered, which are often used for goods transport because they are powerful in combination with relatively low fuel consumption. The disadvantage of this type of engine has traditionally been particles and NOx (oxides of nitrogen) emissions. Particles are normally not a problem when diesel particle filters (DPF´s) are used. Other exhaust emissions such as HC and CO are not a problem when catalysts are being used as these components are easily oxidized in the oxygen-rich environment in the exhaust gas of diesel-powered vehicles.

All tests have been performed at the PTI station of Applus Denmark in Hvidovre Copenhagen. A test route (about 50 km) simulating a vehicle exiting the highway and then delivering goods with 6 stops in Copenhagen city area was driven with all the vehicles. A SEMS-system named EZ-PEMS from ECM was used in combination with a particle number (PN) and particle mass (PM) instrument with the brand PPS-M by Pegasor, Finland.

Modern vehicles use a reducing agent (urea, AdBlue) that is added to the exhaust gases and it reacts with NOx in the SCR-system (Selective Catalytic Reduction). This is a highly effective way to reduce NOx emissions. For this concept to work with highest efficiency, it is required that the exhaust system have a certain minimum temperature. If, above it, NOx is reduced very effectively, but below, the flow of reducing agents must be shut off (e.g., to avoid excessive emissions of urea and creating deposits in the exhaust system) and this results in increased NOx emissions. When the vehicles are driven on highway, the NOx emissions are low and after entering the city area a decrease in temperature and efficiency of the aftertreatment system can be seen. This does not always, or automatically, mean that the emissions are high, and the vehicles may be able to do the full test route without significant increase in NOx emissions. The main parameter is how warm the temperature of the aftertreatment system and how well it can preserve heat during stops. In heavy traffic and several unplanned stops a big increase in NOx can sometimes be seen and it corresponds to loss of temperature in the aftertreatment system. The larger the engine is (in relation to the vehicle size), the bigger the problem seems to be, but the two major factors for how well the SCR system works is the how long periods a vehicle is standing still during a route and how often those stops occur.

One of the conclusions is that it takes longer time to warm-up and cool-down a heavy-duty vehicle engine (and the exhaust gas aftertreatment system) compared to a smaller vehicle. This means, as for example that it is more important to shut off the engine during stops from a small vehicle compared with a heavy-duty truck. It may be a good idea to use different maximum allowed time on idling for light and heavy-duty vehicles. As an example, it could be 2 minutes for light duty- and 10 minutes for heavy duty trucks.

The particle number emissions during all tests were low unless the DPF was regenerating, which is has to do from time to time. All tested vehicle seems to be a factor of 100 under the limit values and the exhaust gas contain fewer particles per cm^3 than the ambient city air.

3. Dansk Resumé

På vegne af Miljøministeriet – Miljøstyrelsen har EXIS sammen med ECM og Applus Danmark udført et projekt kaldet Emissioner af udstødningsgas ved virkelige kørselsforhold fra lastbiler og varebiler i forbindelse med motorafkøling i byområder.

De vigtigste spørgsmål, som dette arbejde skal give svar på:

- Vurdere emissioner ved virkelige kørselsforhold fra køretøjer, der udbringer varer i byområder
- Finde ud af, under hvilke forhold SCR-systemet (efterbehandlingssystem til reduktion af NOx-emissioner) fungerer og ikke fungerer, hvad angår motorens belastning, motorens temperatur, SCR-effektivitet, kørselsforhold, udendørs temperatur og køretøjets last/vægt

I dette forsøg er tre (3) tunge lastbiler og en (1) varebil blevet testet for en række emissionsparametre, og for hvordan systemet til efterbehandling af udstødningsgas fungerer. Alle køretøjer var dieseldrevne, som det ofte bruges ved varetransport, fordi de er motorstærke og samtidig har et forholdsvist lavt brændstofforbrug. Ulemperne ved denne motortype har traditionelt været partikler og emissioner af NOx (kvælstofoxider). Partikler plejer ikke at være et problem, hvis der bruges dieselpartikelfiltre (DPF'er). Andre udstødningsemissioner såsom HC og CO er ikke et problem, hvis der bruges katalysatorer, fordi disse komponenter nemt oxideres i de oxygen-rige omgivelser i udstødningsgassen fra dieseldrevne køretøjer.

Alle disse test er blevet gennemført på PTI-stationen hos Applus Danmark i Hvidovre ved København. Alle køretøjerne kørte en testrute (cirka 50 km), som simulerede et køretøj, der kører fra på motorvejen for at bringe varer ud med 6 stop i indre by i København. Et SEMS-system kaldet EZ-PEMS fra ECM blev brugt sammen med et instrument til måling af partikelantal (PN) og partikelmasse (PM) af mærket PPS-M fra Pegasor, Finland.

Moderne køretøjer anvender et reduktionsmiddel (urea, AdBlue), som tilføjes udstødningsystemet, og det reagerer med NOx i SCR-systemet (selektiv katalytisk reduktion). Det er en yderst effektiv måde til at reducere NOx-emissioner på. For at dette koncept kan fungere med størst mulig effektivitet, skal udstødningsgasserne have en vis minimumstemperatur. Hvis de er over minimumstemperaturen, reduceres NOx meget effektivt, men hvis de er under den, skal der lukkes for tilstrømningen af reduktionsmidler (fx for at undgå for store emissioner af urea og dannelse af aflejringer i udstødningssystemet), og det resulterer i øgede NOx-emissioner. Så længe køretøjerne kører på motorvejen, er NOx-emissionerne lave, men når de kører ind mod indre by, kan der ses et fald i temperaturen og efterbehandlingssystemets effektivitet. Det betyder ikke, at emissionerne altid eller automatisk bliver høje, og køretøjerne kan foretage hele testruten, uden der sker en væsentlig stigning i NOx-emissioner. Det vigtigste parameter er, hvor varmt temperaturen i efterbehandlingssystemet er, og hvor godt det kan holde på varmen i løbet af stop. I tæt trafik og ved flere uplanlagte stop kan der undertiden ses en stor stigning i NOx, og det hænger sammen faldet i temperaturen i efterbehandlingssystemet. Jo større motoren er (i forhold til køretøjets størrelse), desto større synes problemet at være, men de to vigtigste faktorer for, hvor godt SCR-systemet fungerer, er, hvor lange perioder et køretøj holder stille i løbet af en rute, og hvor ofte disse stop forekommer.

En af konklusionerne er, at de tager længere tid at opvarme og nedkøle motoren på et tungt køretøj (og efterbehandlingsystemets udstødningsgas) i forhold til et mindre køretøj. Det betyder for eksempel, at det er vigtigere at slukke for motoren i løbet af stop i et mindre køretøj i forhold til med et tungt køretøj. Det kan være en god idé at benytte forskellige tilladte maksimumstider ved tomgang for lette og tunge køretøjer. Tiden kunne for eksempel være 2 minutter for lette varebiler og 10 minutter for tunge lastbiler.

Partikelantallet i emissionerne i løbet af alle test var lavt, medmindre dieselpartikelfiltret (DPF) regenererede, hvilket det jo skal gøre af og til. Alle testede køretøjer synes at være af faktor 100 under grænseværdierne, og udstødningsgassen indholdte færre partikler pr. cm^3 end den omgivende byluft.

4. Definitions

Emission Index

By measuring in “wet” condition and vol-% in the exhaust, it is possible to calculate an emissions index (EI). For NOx emissions, a convenient unit is mg NOx/gCO_2 for the EI. The index is calculated from the sensor values for CO_2 and NO_X measured under “wet condition”, i.e., with no drying of the exhaust for either emission component.

Emission factor

This means absolute values, for example, mg NOx per km or per kWh.

Limit values for NOx based on Emission Index

From previous work (Reference 1 and 4) a limit of 1.0 mg NOx per gram of CO_2 have been suggested for both light- and heavy duty (Euro 6 and EURO VI) vehicles during short tests on road. This limit is based on a conformity factor (CF) of 2. The assessment is that this level is high enough to not reject fully functional vehicles and low enough to find defect vehicles. The limit value is based on current knowledge and experience. Important to note is that index will not give values in g/km or g/kWh, but it gives a good picture of the emission level. Read more about this in reference 4.

5. Concept and preparation

Prior to the test campaign in Copenhagen, tests for the delivery VAN were carried out in Gothenburg. The first test was a "full-PEMS" route drive, initially developed for light-duty vehicles. This route is an official test route (registered by the German authority KBA) and it is in accordance with the EC Regulation 692/2008 (and EU-directive No 582/2011).

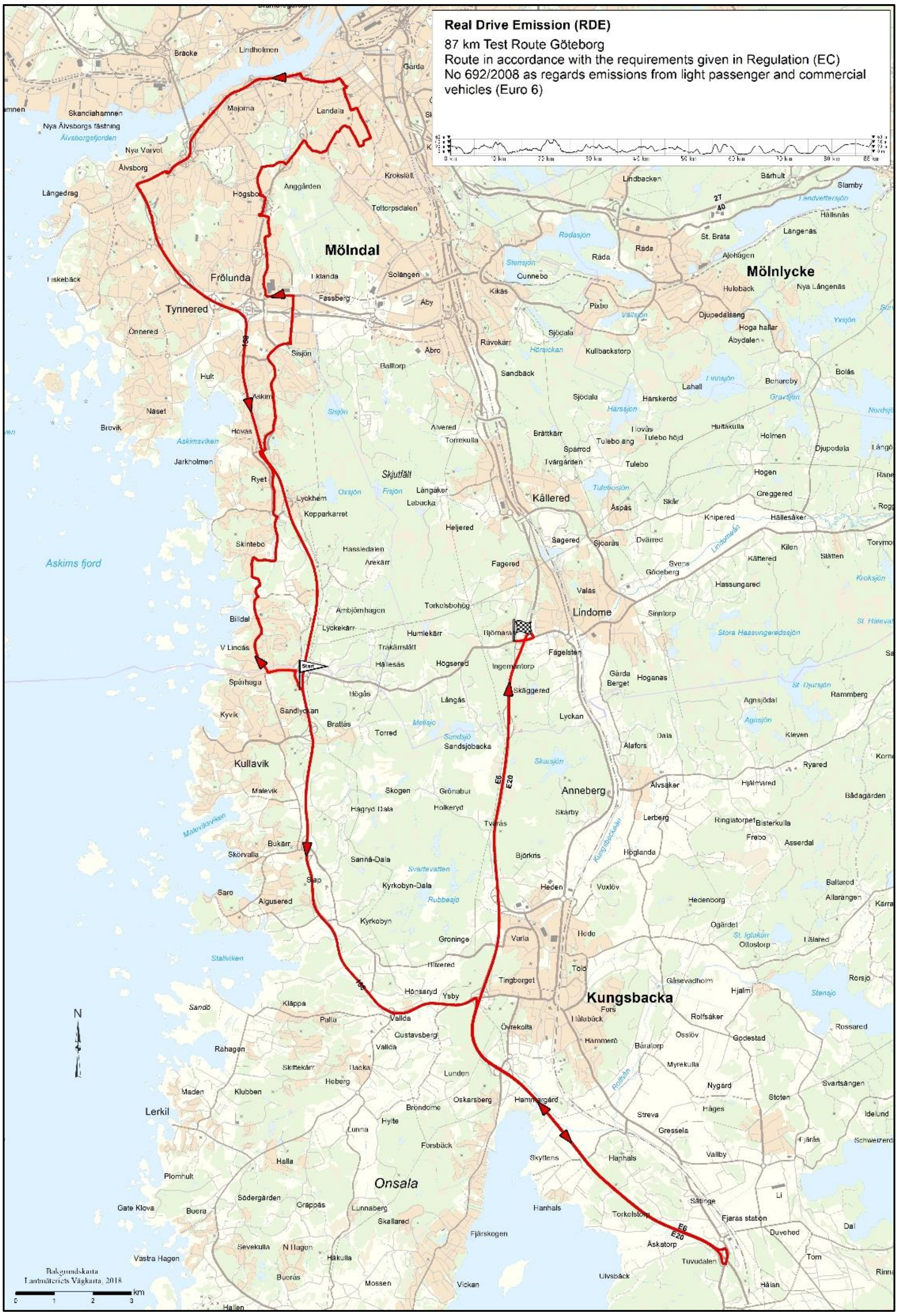

Figure 1. 87 km PEMS-Route, Gothenburg, See the route on [*https://www.youtube.com/watch?v=4bya4eEA444&t=15s*](https://www.youtube.com/watch?v=4bya4eEA444&t=15s)

The distribution across driving in the city (1/3) on highway (1/3) and motorway (1/3) and the route has a duration between 90 and 120 minutes.

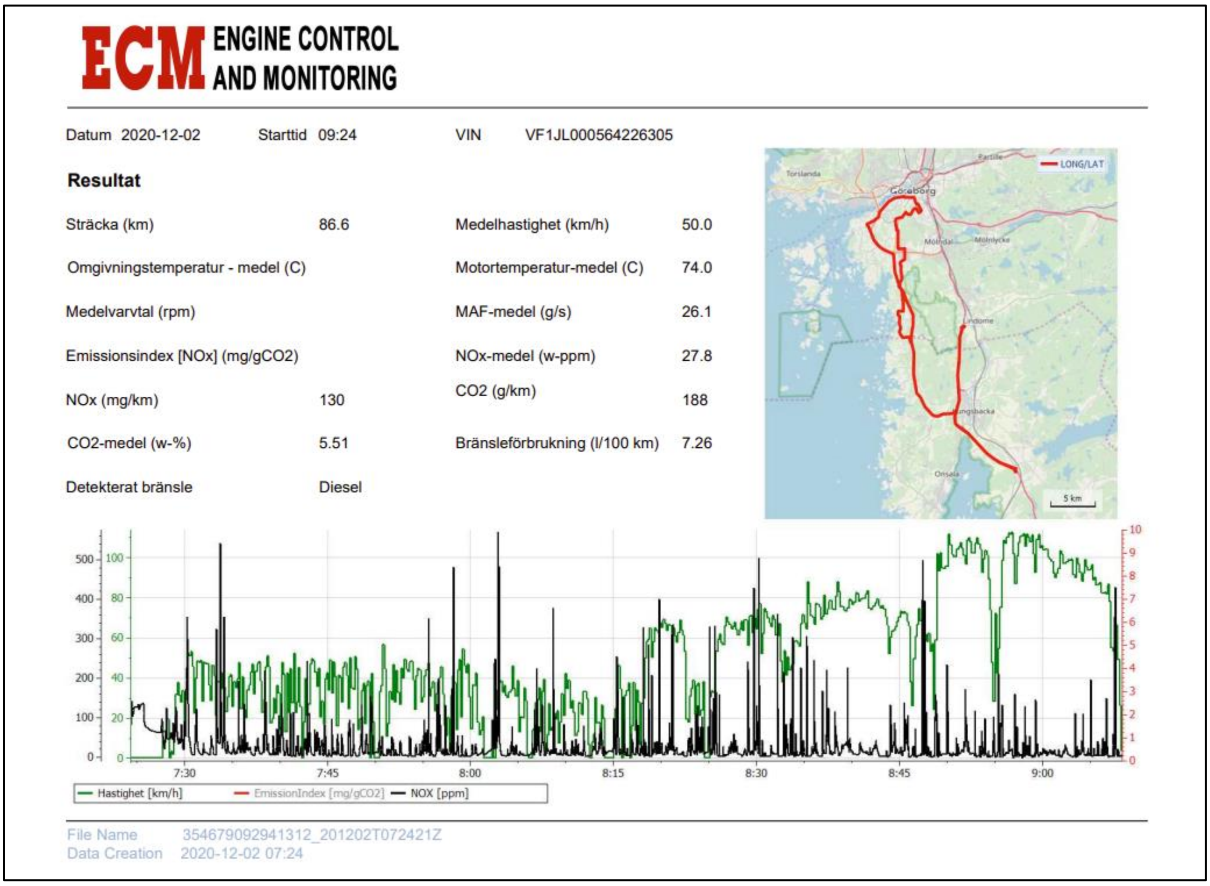

Figure 2. Main results from the PEMS-route test on the delivery VAN

During this test, the Emission Index was measured to 0,52 mg NOx per g CO_2. This I well below the suggested limit of 1,0. The NOx in absolute term was 130 mg/km and this value is also under the limit of 168 mg NOx per km for tests on the roads (RDE). The vehicle was unloaded during the drive.

The particle emissions during this test were very low and close to the detection limit. It was measured to about 1,1xE+9 which is under the limit value of 6 E+11 with high margin.

The average speed during the whole route was 50 km/h and the maximum speed was 113 km/h. After the engine was warmed up, i.e., after 3-4 minutes (and the catalyst reached working temperatures), the exhaust gas aftertreatment system worked without any problem and showed relatively low NOx-values (in average 28 ppm during the whole route but with peaks during accelerations etc), see **Figure 3** below

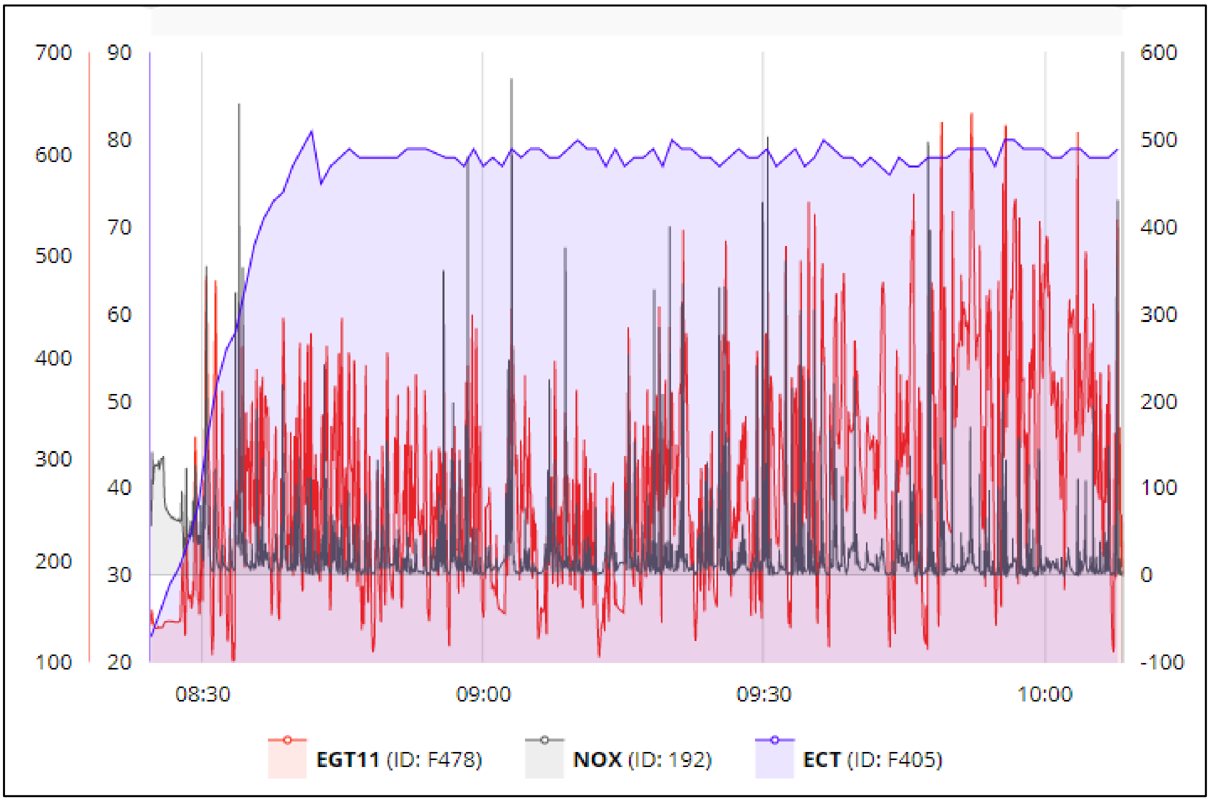

Figure 3. Exhaust gas temperature – red (°C), NOx – black (ppm) and Engine temperature – blue (°C) during the 87 km long PEMS route. The ambient outdoor temperature was 4 °C.

Beside these tests, one test during idle was carried out. See **Figure 4**. The reason for this test was to find out how long it takes from stop until the NOx level starts to increase by cool-down of the emission aftertreatment system. After about 1,5 minutes the NOx emissions start to increase and after another 10 minutes the tail-pipe value reached a plateau at a level of about 80 ppm.

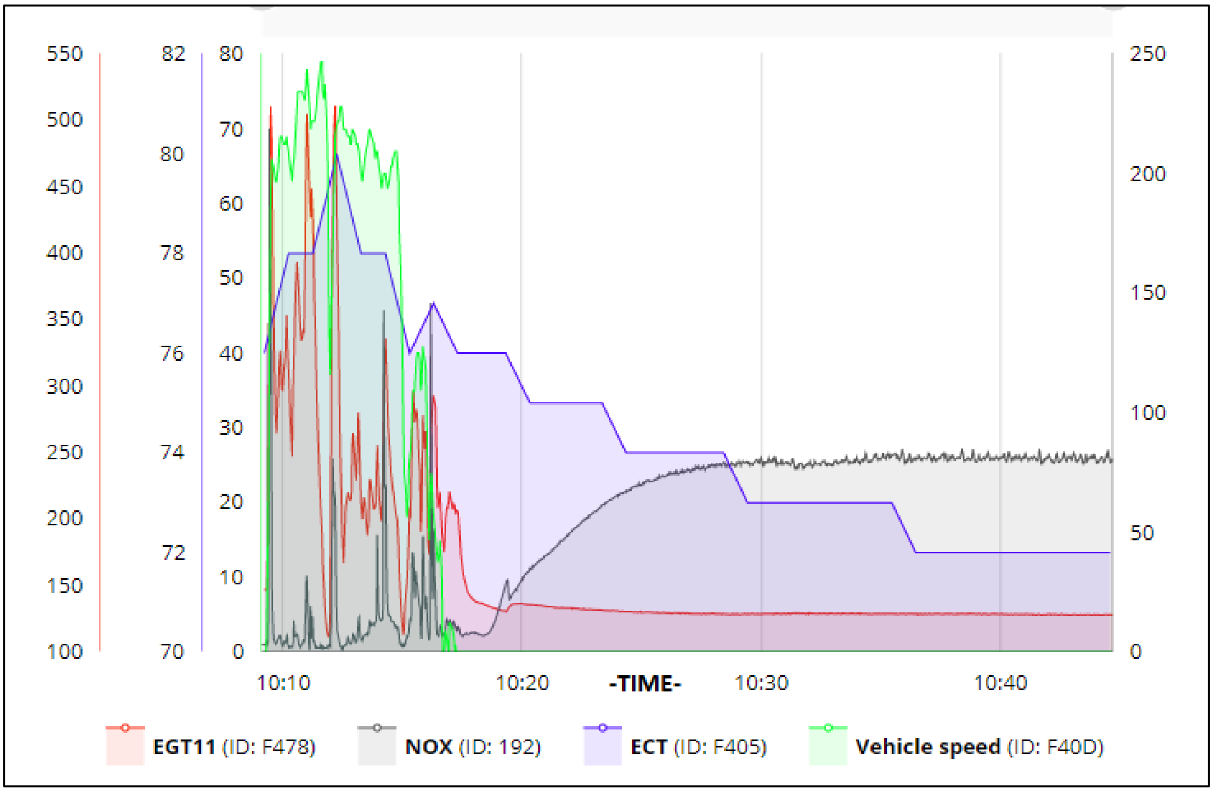

Figure 4. Delivery VAN. Idling after the test drive. The exhaust gas after treatment system worked about 1,5 minutes after stop driving and after that the NOx start to increase. Exhaust gas temperature – red (°C), NOx – black (ppm), Engine temperature – blue (°C) and driving speed – green (km/h). The ambient outdoor temperature was 4 deg °C

The NOx peaks are often correlated to the engine loads (in this case accelerations), but not always. However, this shows that the NOx emission may be affected by the driving behaviour.

As mention above, the PN-emissions from this vehicle was exceptionally low and there is no correlation between load, speed, and particle emission. The reason for this is likely due to an effective DPF (Diesel Particle Filter). If the filter works, the emission of particle is exceptionally low, and if it does not (broken or removed) the number of particles increase by several orders of magnitude (e.g., either it is exceptionally low or remarkably high). The figure below illustrates how effective these filters are. There are less particles inside the exhaust pipe compared with the ambient Gothenburg air. This might be considered as remarkable, but we have experienced this in the past also on other vehicles and it has also been documented in literature. However, any further discussion about this finding is beyond the scope of this report.

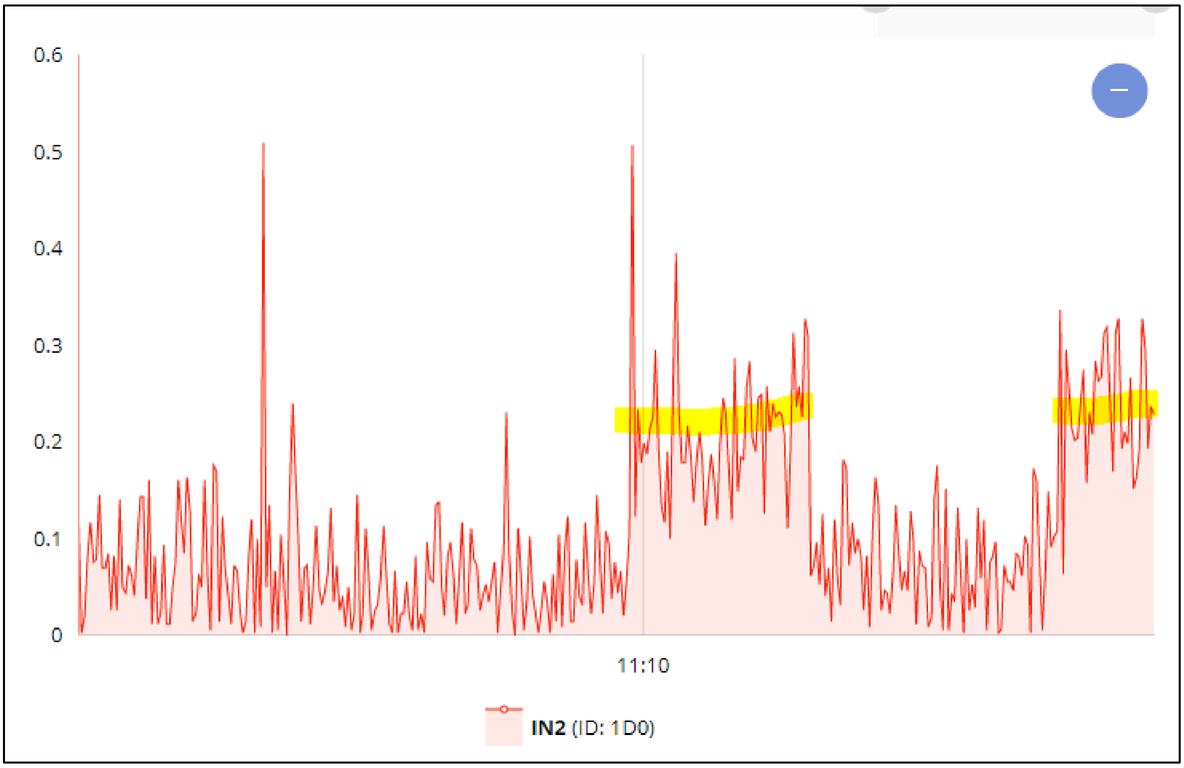

Figure 5. Vehicle no 1. Idling after the test drive. Particle number (raw signal). The yellow marked period illustrates measuring in the exhaust pipe and the rest in the ambient air (about twice as many particles in the ambient air as in the exhaust gas)

6. Test in Copenhagen

Test equipment

During all tests, a SEMS-system named EZ-PEMS from ECM was used. A specific type of sampling probe was used in order to easily switch between different vehicles. In these test sensors for CO, CO_2 temperatures, and particle number (PN) were added to the EZ-PEMS-system. For particle measurement a PPS-M sensor from Pegasor was used. This sensor was during the test fully integrated with the EZ-PEMS system and 23 nm lower cut-off was set for PN sensor. 23 nm is in accordance with current regulations for engine and vehicle testing of particle numbers. The sensor measure particle number in the interval from 300 #/cm³ to 1.3 * 10^9 #/cm³

In a legislative RDE system (a full PEMS system), the exhaust flow is measured by using an exhaust flow meter installed at the tailpipe of the vehicle. In the SEMS system the exhaust flow is often calculated from data taken from the vehicles. The difference in mounting time and maintenance is often very large. In the full PEMS system emission parameters such as NOx is also often calculated in mg/km or mg/kwh which also can be done in a SEMS system, but for these tests and the evaluation, the main focus is on using a NOx Emission Index.

EZ-PEMS is a small and rugged device specifically designed with rapid real-time PTI and vehicle screening tests in mind. EZ-PEMS takes just a few minutes to install and it´s sensor technology is very robust and accurate. It incorporates the unique NOx Index method, but also continuously measures NOx and O_2 and subsequently CO_2. With add-ons for OBDII communication it will also give data from the vehicle. The user interface can be through a RED/GREEN light or a more comprehensive display unit. With a connection to a data acquisition server, various reports and statistics of all tests conducted can be generated.

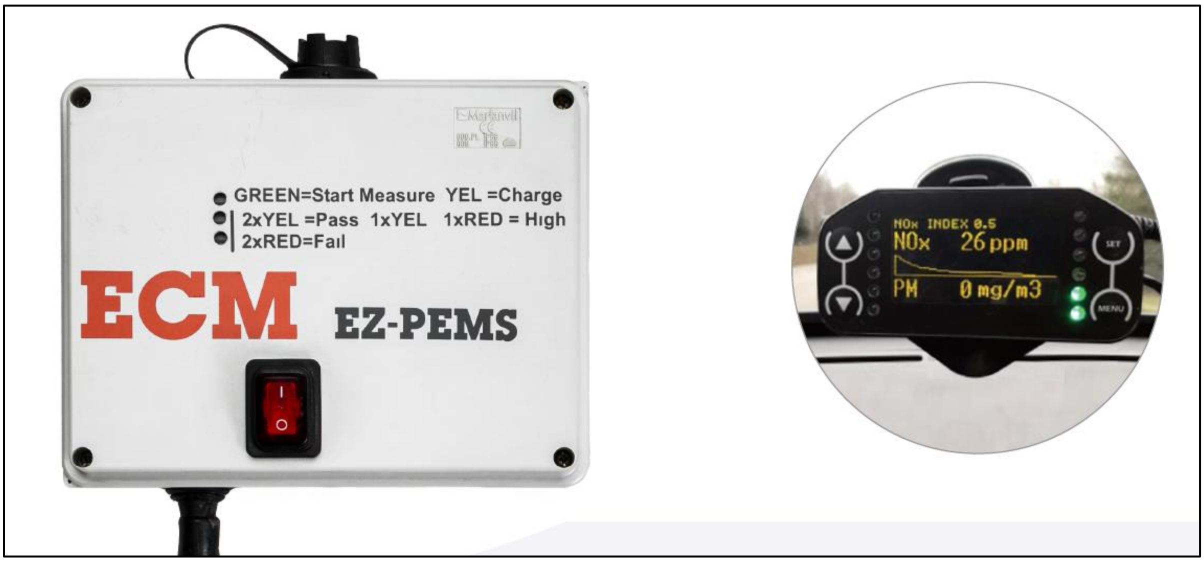

Figure 6. The EZ-PEMS system. To the left the main unit to which the senor is connected. To the right is the display where real time data can be viewed and buttons to control start and stop of the tests. After stop of a test the data is uploaded to the cloud and reports are automatic generated.

Data such as engine load, engine and exhaust temperatures, engine speeds, DPF delta pressures were taken from the vehicles via the OBD connector. As the technology differs between different vehicles, vehicle-specific programming was done to find the right signals.

Figure 7. After the test are stopped the data can be downloaded from the cloud server. It is also possible to follow in real-time.

Figure 8. Different type of report can be generated and exported.

Vehicles

A total number of 4 vehicles have been tested within the framework of this project, 1 delivery van and 3 heavy-duty trucks. Below, a short summary of the test fleet is provided.

The VAN vehicle represents a commercial vehicle / delivery van of the latest emission class.

Truck no 1 was chosen in order to represent a truck delivering goods or food etc. Some vehicles for tasks like this can be 2 axle or 3 axles but the overall size is similar. The engine capacity is 11 litres and may be considered a midsize engine. This truck was also chosen since it was straightforward to test it loaded or unloaded.

Truck no 2 was chosen in order to represent a second truck in the same class as the truck no 1, but with a smaller 8-liter engine.

Truck no 3 was chosen in order to represent a vehicle with a large engine. The engine is one of the biggest on the market (16L). It was considered to investigate how a truck with a large engine would behave when driven in city traffic and doing deliveries with relatively low load in contrast to a long-distance lorry, which is the main application for such a large engine.

VAN	Renault
Type	Delivery VAN
Power	107 kW
Engine size	1 997 cm3
Odometer	18 000 km
Fuel	Diesel
Euro Class	Euro 6 d TEMP-ISC
Truck no 1	Volvo
Type	3-axle HD-truck
Power	260 kW
Engine size	11 L
Odometer	51 500 km
Fuel	Diesel
Euro Class	EURO VI d
Truck no 2	Mercedes
Type	3-axle HD-Truck
Power	250 kW
Engine size	8 L
Odometer	7 700 km
Fuel	Diesel
Euro Class	EURO VI d
Truck no 3	Volvo
Type	4-axle HD-Truck
Power	550 kW
Engine size	16 L
Odometer	102 000 km
Fuel	Diesel
Euro Class	EURO VI c

Table 1. Vehicles overview used in the tests. Truck 1 were tested twice, first with about 6-ton load and second with no load.

Test Procedure

All tests were performed in Copenhagen and the outdoor temperature varied between 4 and 8 °C. The same test route was used for all four vehicles. Prior to the test the exhaust gas probe was connected to the vehicles exhaust tailpipe, the OBD-connector was connected. The display for control of the system was placed on the windscreen inside the vehicle.

- All relevant data about the vehicle such as year model, emission class, odometer reading, win No. etc was recorded on a protocol.
- After start of the engine, the data acquisition system was started.
- Then driving the test route was initiated and simultaneous the NOx ppm, NOx Index, CO, CO_2, Engine speed and Particle numbers could be followed on the display.
- The test drive started at Applus' facility in Hvidovre. After about five minutes' drive they reach the highway and followed it until you turned off and reached the first stop. (for all vehicles except Truck no 3, this was enough to warm up the vehicle and aftertreatment (Read more about this under results).
- During all stops the engine was turned off.
- After completion of driving (when reaching the end point), separate idle tests were performed on all vehicles.

Test Route

In the Figure 9 below the test route is showed. The route is 48.6 km long included 6 stops and started and ended by motorway driving.

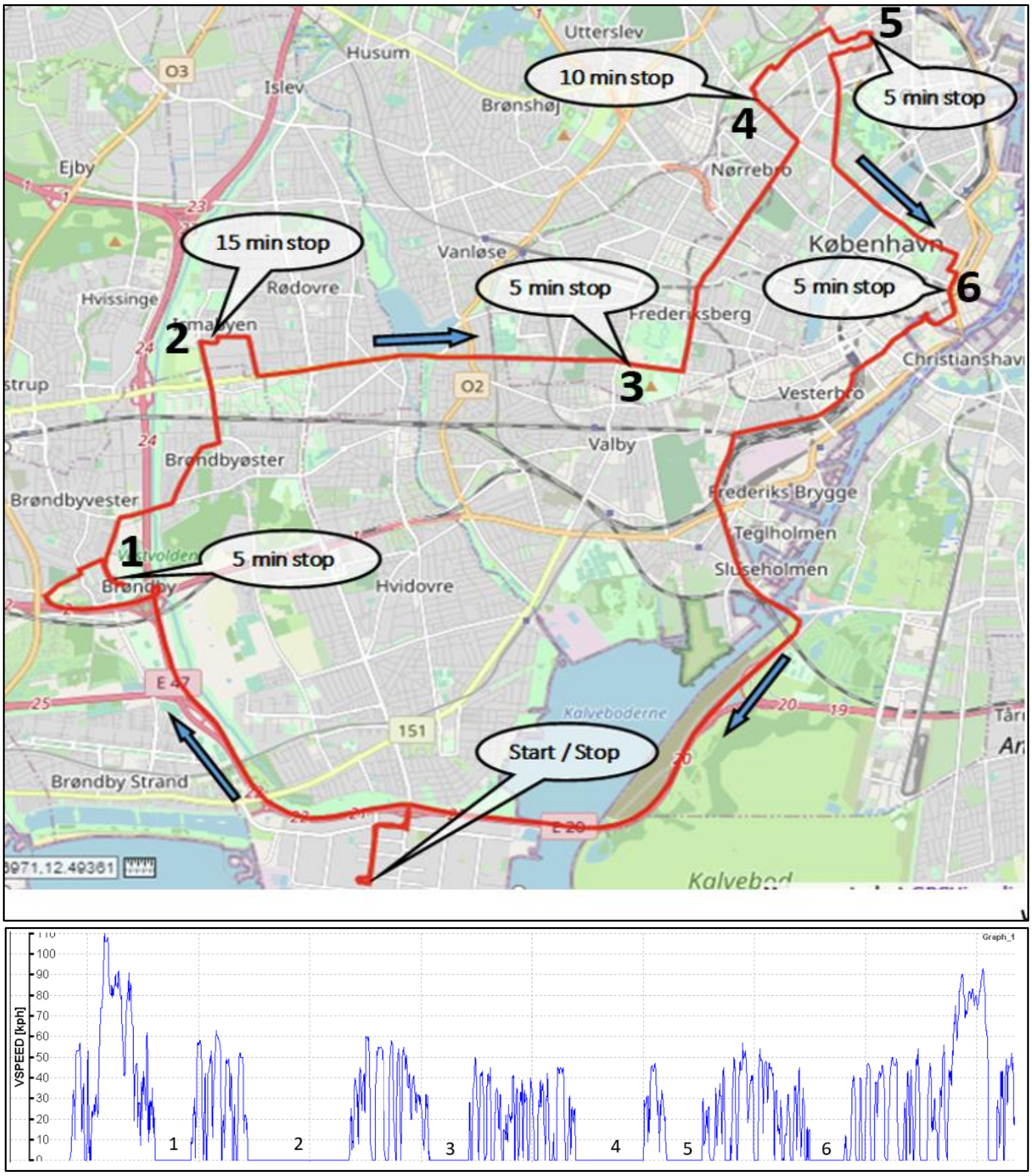

Figure 9. Test route Copenhagen and an example of speed profile (delivery VAN), 48,6 km and include 6 stops (stop 1 at Brøndby). Start and stop at Applus Hvidovre. After starting it is city driving to the highway (E20) and after that highway almost the whole way to stop 1. Between stop 1 and stop 6 it is city driving. After leaving the city and passing the "Sluseholmen" it is highway back to the point of leaving the highway and driving back to the start/stop.

7. Results

When the vehicles were driven on highway the NOx emissions were low and after entering the city area it can be seen that the aftertreatment system is subject to a decrease in temperature and efficiency. This does not always, or automatically, mean that the emissions are high, and the vehicles may be able to do the full test route without significant increase in NOx emissions. The main parameter is how high the temperature of the aftertreatment system is and how well it can preserve heat during stops. In heavy traffic and several unplanned stops a big increase in NOx can sometimes be seen and it corresponds to a loss of temperature in the after-treatment system. This can be seen in Figure 17 where the temperature curve is getting lower and lower throughout the city driving. The larger the engine is (in relation to the vehicle size), the bigger the problem seems to be. Figure 26 shows this where the exhaust temperature is relatively low and dropping throughout the city driving and the NOx ppm is very often showing high numbers.

Just as a reference the emissions of NOx in mg/km (delivery VAN) and mg/kWh (Heavy Duty Trucks) have roughly been measured and estimated to the values in the Table 2 below for the whole test route, see Figure 9. It is important to note that the values for this route and these driving conditions may not be compared to other routes and driving conditions.

Delivery VAN	122 mg/km
Truck 1 - unloaded, heavy traffic	3 059 – 3 198 mg/kWh
Truck 1 - loaded	298 – 313 mg/kWh
Truck 2	348 – 363 mg/kWh
Truck 3	3 406 – 3 561 mg/kWh

Table 2. Measured and estimated NOx-emissions for the whole test route

CO (carbon monoxide) was exceptionally low during all tests and after a short drive close to zero. CO is easy to oxidate in the oxygen rich atmosphere of diesel exhaust.

Type approval limit for Particles Numbers (PN) from Heavy duty Trucks is 6E+11 per kWh and this correspond to a concentration of about 50 000 #/cm^3. For upcoming PTI (Periodical Technical Inspection) methodology it has been suggested to start checking the particle number emission and the suggested limit will be 250 000 #/cm^3, providing a margin by a factor of 5. A removed, tampered, or broken diesel particle filter (DPF) will result in particle number concentration of up to 5 000 000 #/cm^3. Typical values during idle for all tested vehicles in this study is often below 2 000 #/cm^3 (and the ambient air about 4 000 #/cm^3). The particle number is also low during driving. This means that all tested vehicle seems to be a factor of 100 below the limit values and the exhaust gas has lower concentration (i.e., contains fewer particles per cm^3) than the typical ambient air in a city.

One question prior to this study was how long after start of idling the exhaust gas aftertreatment system will be active. Figure 10 below shows the NOx emissions during idling. It is obvious that the NOx emissions from the VAN starts to increase earlier than the case with the heavy-duty vehicles. Truck 1 and 2 shows almost a similar behaviour and the NOx starts to increase after about 10 minutes idling.

Truck 3 shows a little different behaviour for a truck in terms of time before NOx starts to increase which happens already after about 3-4 minutes idling. This may be due to the fact that the engine on this vehicle is relatively big (16 litre) and the vehicle was carrying lower load in relation to the maximum load capacity in comparison to the other vehicles, and consequently the cool-down period is there for reduced. Truck no 2 does not show the same type of “jump” or “hook” in the curve and this may be due to a different method being used to control the NOx emissions and strategy to keep the aftertreatment system warm.

To sum up the idle tests, it has been shown that it is more important to turn off the engine on a VAN than on a truck during a stop.

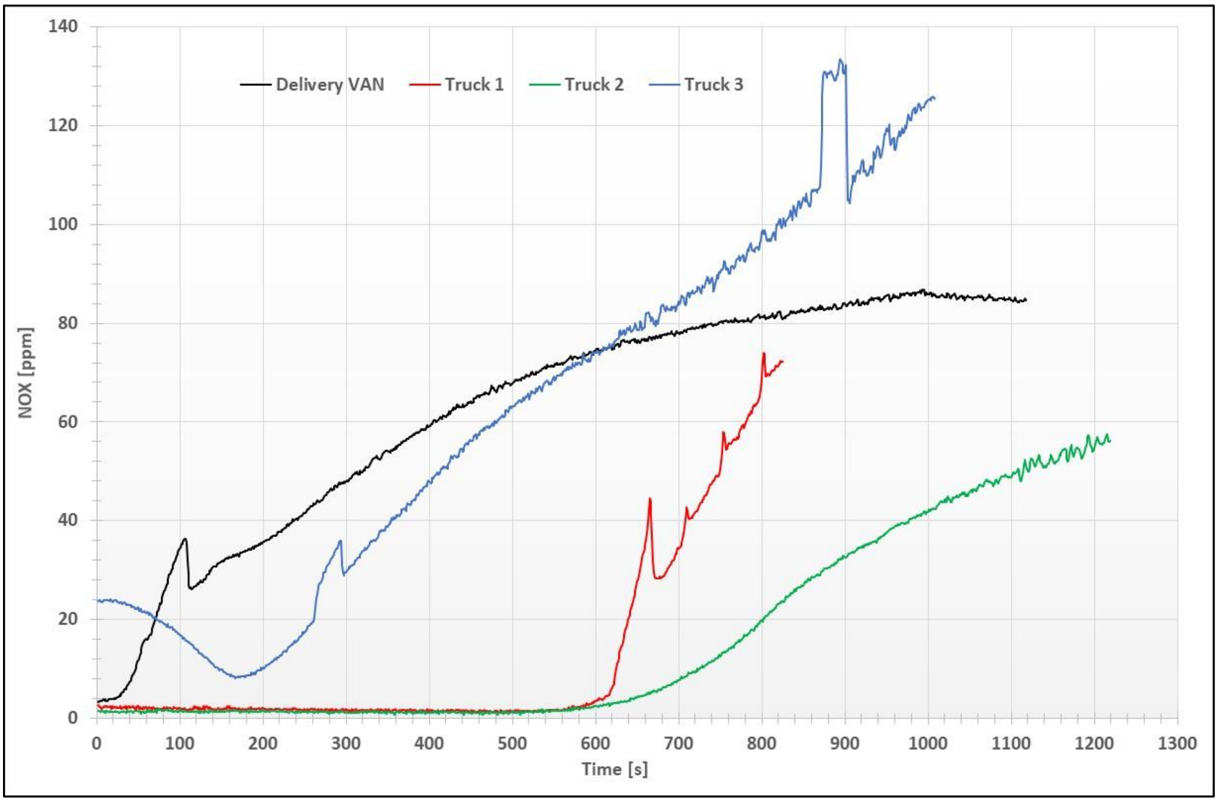

Figure 10. Idling after test route. The engine and exhaust gas aftertreatment system are fully warm prior to the idle tests.

VAN, Engine Euro 6d temp.

This vehicle was functioning well throughout the complete test. No real issues with high emissions even if there is a tendency to slightly higher NOx emissions directly after stand still. Figure 11 below shows the complete test route and trace for NOx ppm and NOx Index. The NOx index curve is easy to look at in this case and it does not stand out during any part of the test route other than during standstill when it is not valid.

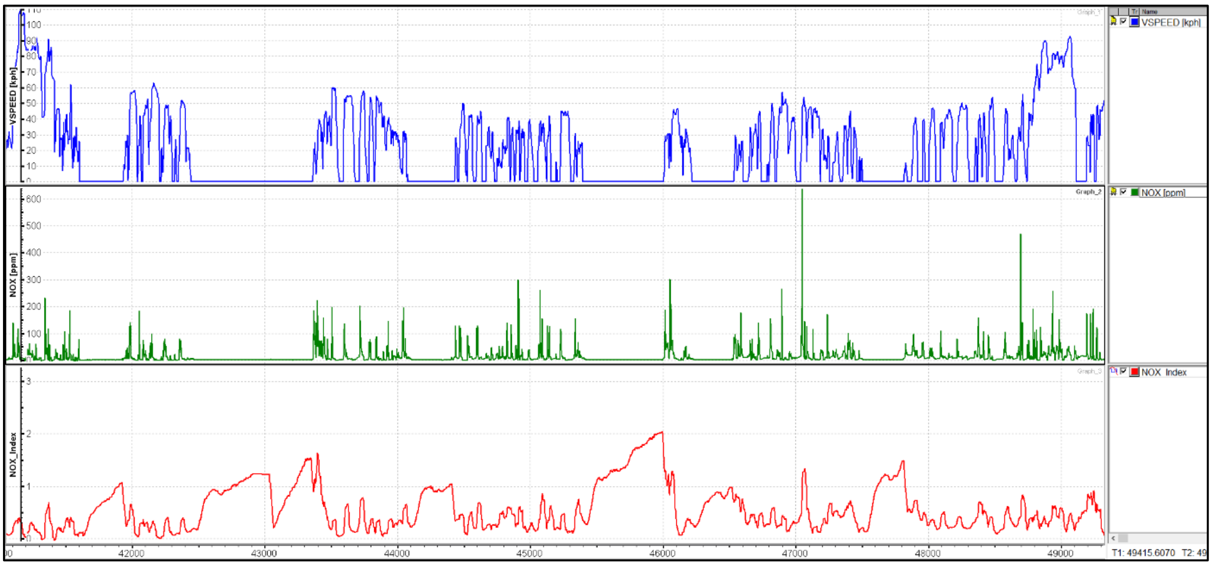

Figure 11. Speed-blue(km/h), NOx – green(ppm), NOx Index – red

Figure 12 below shows the speed trace in blue and the PN trace in orange. The profile of the PN curve is very typical for all the vehicles in the test and it clearly shows that a vehicle equipped with a DPF has lower PN number coming from the exhaust than what is in the surrounding air. There are well defined sections on the orange curve where the PN number goes up and that is when the vehicle is standing still with the engine turned off. The PN instrument then draws in air from the ambient air at the location it was stopped.

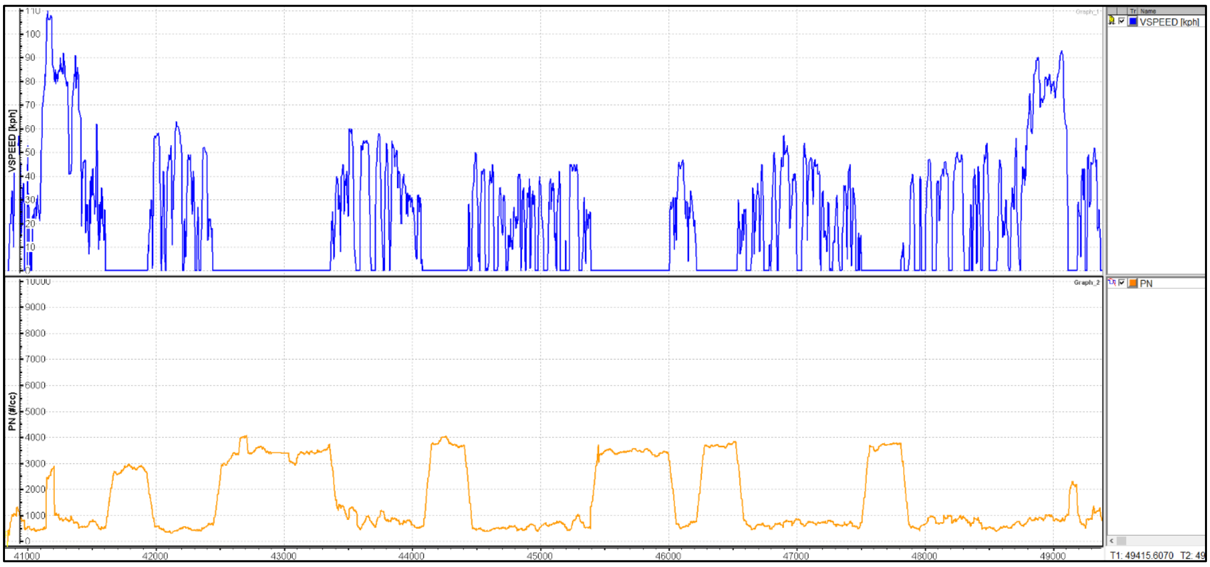

Figure 12. Speed – Blue(km/h), PN – Orange(#/cc). PN goes up when engine is turned off and the instrument measures surrounding air outside the tailpipe.

An Idle test shows that already after 30 seconds SCR aftertreatment system shows signs of cooling down so much that it loses efficiency, and the NOx levels start rising. Se Figure 13 below. This means it´s likely better to turn the engine off when doing a stop instead of keeping it at idle. During the test route, the engine was always turned off during a stop for delivery which corresponds to the law that says that a maximum of 1 min idle is allowed in Copenhagen. What happens at idle is that a lot of air is pushed through the exhaust system and the low exhaust temperature at idle cools the SCR system. If you instead turn the engine off the heat may be better stored in the system and the system can work better when the engine is started again. Looking at the temperature at three different locations in the exhaust system gives some further insight to what is happening. In Figure 13 below the red curve is the temperature going into the aftertreatment system and then the purple and the blue curves are positions further downstream in the after-treatment system. At the beginning of the idle test the exhaust gas temperature out of the engine and into the aftertreatment system is lower than the temperature and heat that is stored in the aftertreatment system. Typically, it´s the other way around during driving and with the engine under load, but this situation occurs as soon as the vehicle starts idling. After about 6,5 min there is crossover point where the aftertreatment system has cooled off so much that the temperatures in the aftertreatment system is cooler than the temperature out of the engine.

It´s also interesting to see that there is significant “jump” in the NOx ppm curve with a corresponding change of the rate of increase in NOx ppm. This can be related to how the engine is controlled. This has been seen on several different engines and is most likely due to a control strategy that aims to decrease the emissions. When this occurs, there is also a change in rpm (red curve), a drop in DPF backpressure, an increase in load (light green curve), and an increase of CO_2. The increase in CO_2 means the engine is less efficient, but it also gives less NOx.

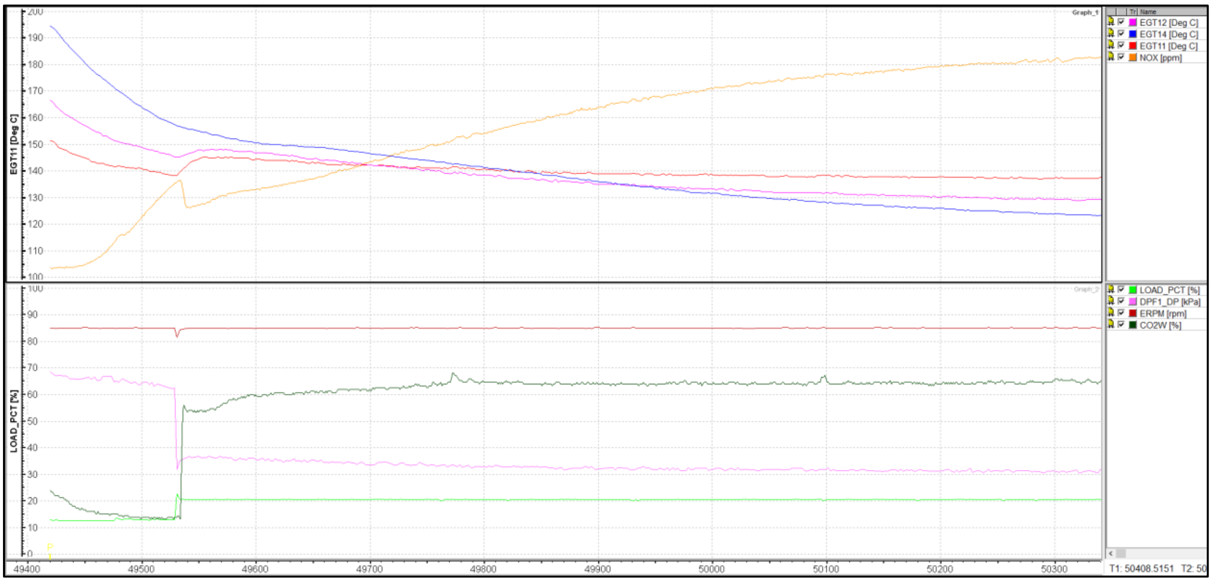

Figure 13 NOx – orange(ppm), Exhaust temperature – red, blue, purple (°C), green – Engine load, pink – DPF delta pressure (kPa), red – Engine speed (rpm), CO_2 – dark green (%).

Truck no 1, 260 kW, 11L, Euro VI d, 3 axles.

From a perspective of the efficiency of the aftertreatment system, this vehicle is ok over the complete route, but about halfway through the route the aftertreatment system starts showing decreasing efficiency. This correlates to lower exhaust temperatures and an increase in NOx directly after the stand still/stops which remains during driving as long as there isn´t long enough sections of constant driving or highway driving. The shorter driving between the stops the worse it gets. When entering the highway, the emissions goes down again.

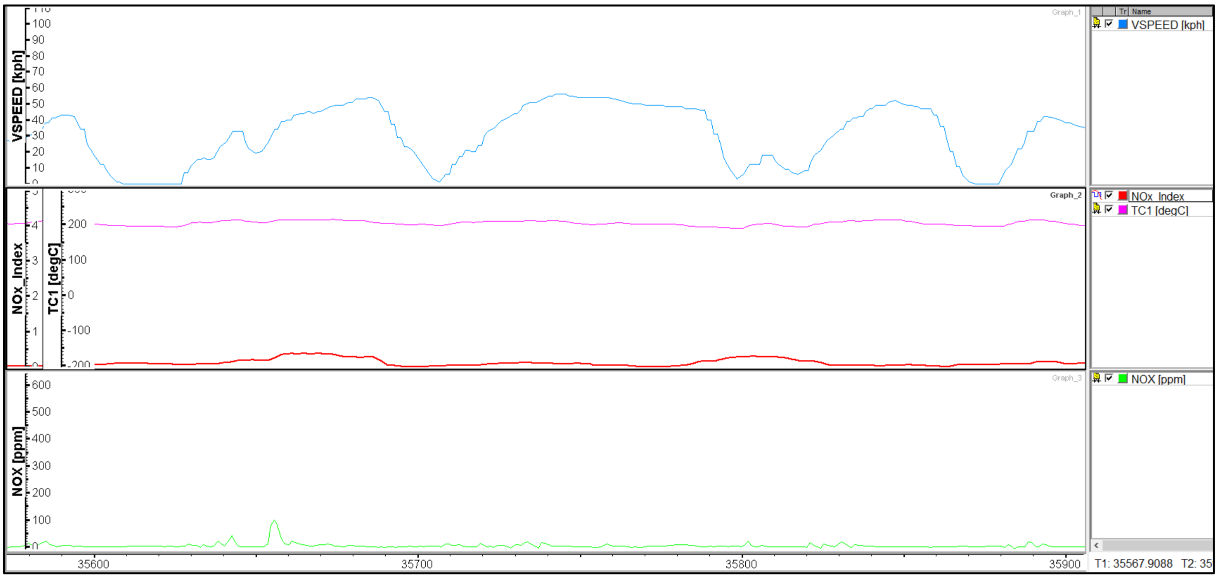

Figure 14. After the first stop and during driving the NOx ppm and NOx index are low, exhaust temperature at the tailpipe is about 200 deg C. Speed-blue(km/h), NOx – green(ppm), NOx Index – red, Temperature at tailpipe – pink (°C).

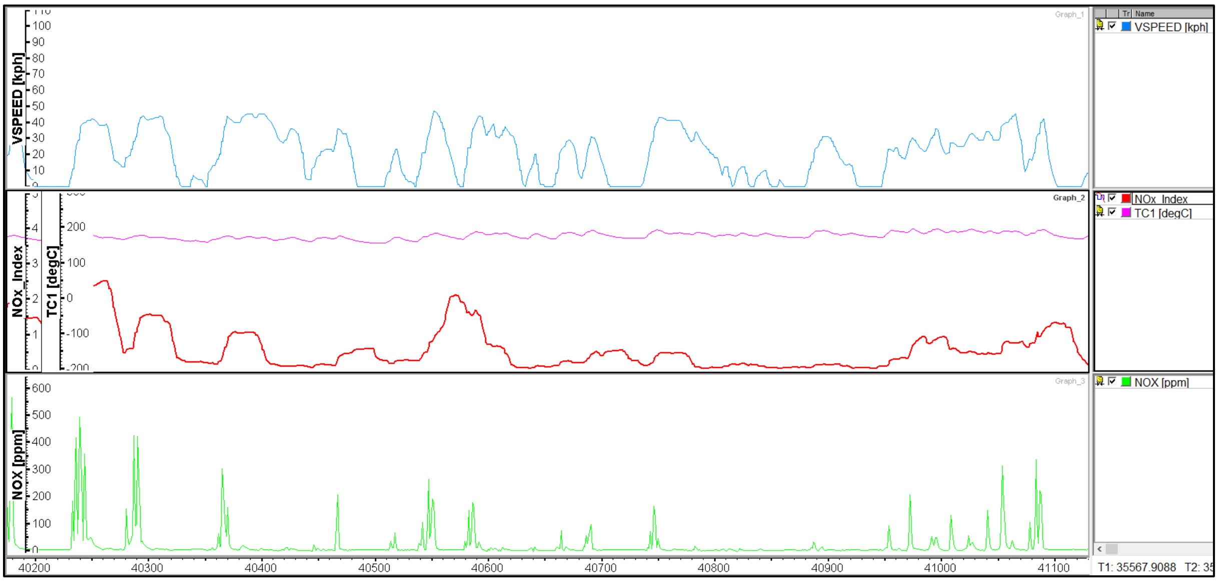

Figure 15. After 5 stops and during driving it´s a clear increase in NOx ppm and the NOx index is varying a lot, exhaust temperature at the tailpipe has gone down to about 170 °C. Speed-blue(km/h), NOx – green(ppm), NOx Index – red, Temperature at tailpipe – pink (°C).

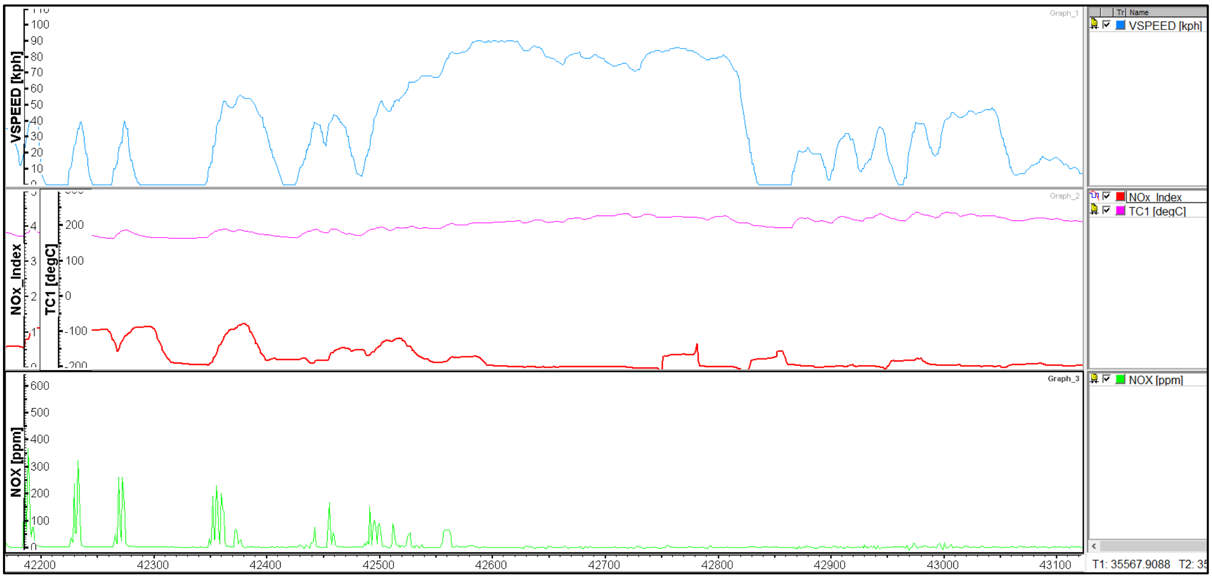

Figure 16. As the vehicle enters highway (see speed) the NOx emissions drop to near zero and the exhaust temperature at tailpipe is increasing to 220 °C. Speed-blue(km/h), NOx – green(ppm), NOx Index – red, Temperature at tailpipe – pink (°C).

When the vehicle was tested without load it was also driven in more heavy traffic. The emissions got much worse over the complete route, and a clear distinction can be made when the traffic increased. Figure 17 below shows how the exhaust temperature at tailpipe starts out at around 190 °C, then decreases in steps after each stop to reach a minimum of 120 °C and then it increases up to 200 °C when entering the highway. When making a plot of the mean NOx Index over the complete route it shows a very clear increase in the curve after about 15 km and 62 min (including 3 stops of totally 25 min) after exiting the highway and then a drop after entering the highway again. The same observation can be made by just looking at the increased NOx ppm levels. The sharp increase of the curve is due to the temperatures of the aftertreatment reached too low temperatures and this is confirmed by that the emissions dropping directly as soon as the vehicle drives on highway and tailpipe exhaust temperature reaching to 200 °C.

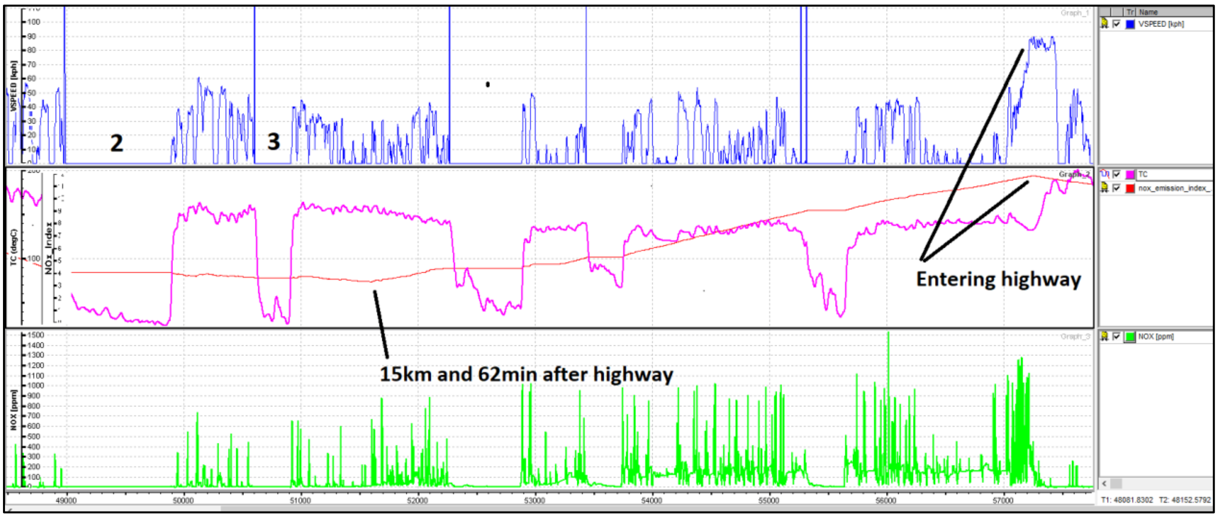

Figure 17. When the vehicle hits traffic and make repeatedly short stops out of the normal stop for delivery one can clearly see how the emissions are going up and the NOx levels are high. Speed-blue(km/h), NOx – green(ppm), NOx Index – red, Temperature at tail-pipe – pink (°C).

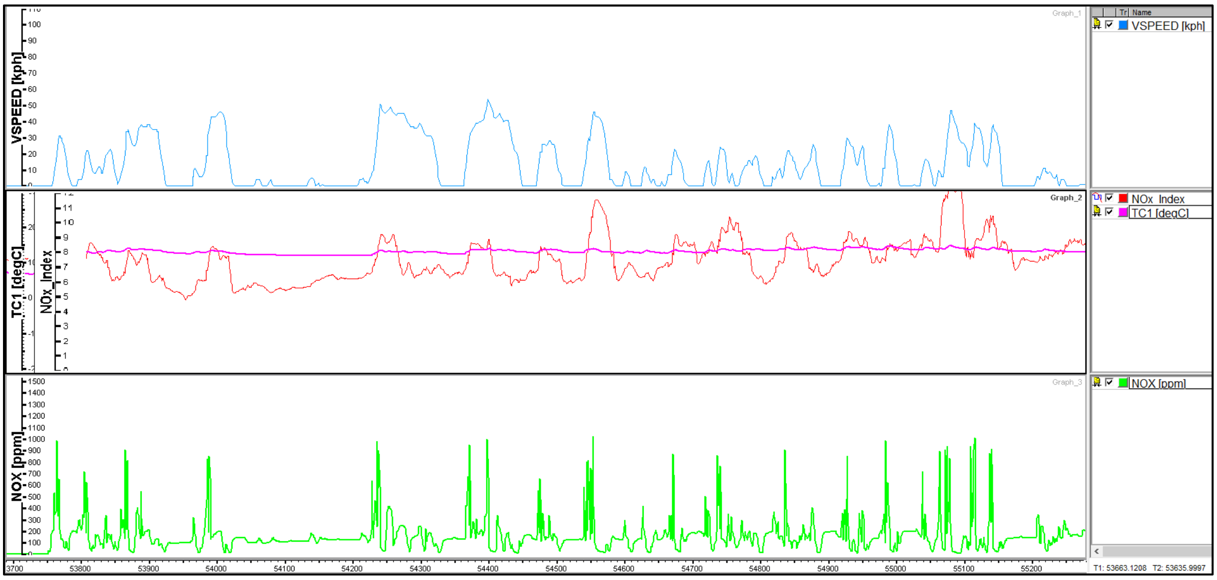

Figure 18. Showing the section of the route in city traffic for the unloaded truck after stop/delivery no 5. Increased number of stops in traffic and high NOx ppm and NOx Index. Speed-blue(km/h), NOx – green(ppm), NOx Index – red, Temperature at tailpipe – pink (°C).

If one compares the tests with load and no load at the beginning of the route, no major differences can be seen in terms of emissions, but one can see that the temperature generated from the engine is slightly lower and therefor it will take a bit longer for a vehicle with less load to heat up the after-treatment system. There is a smaller difference in utilization of engine power, which corresponds to a minor impact on the SCR systems functionality.

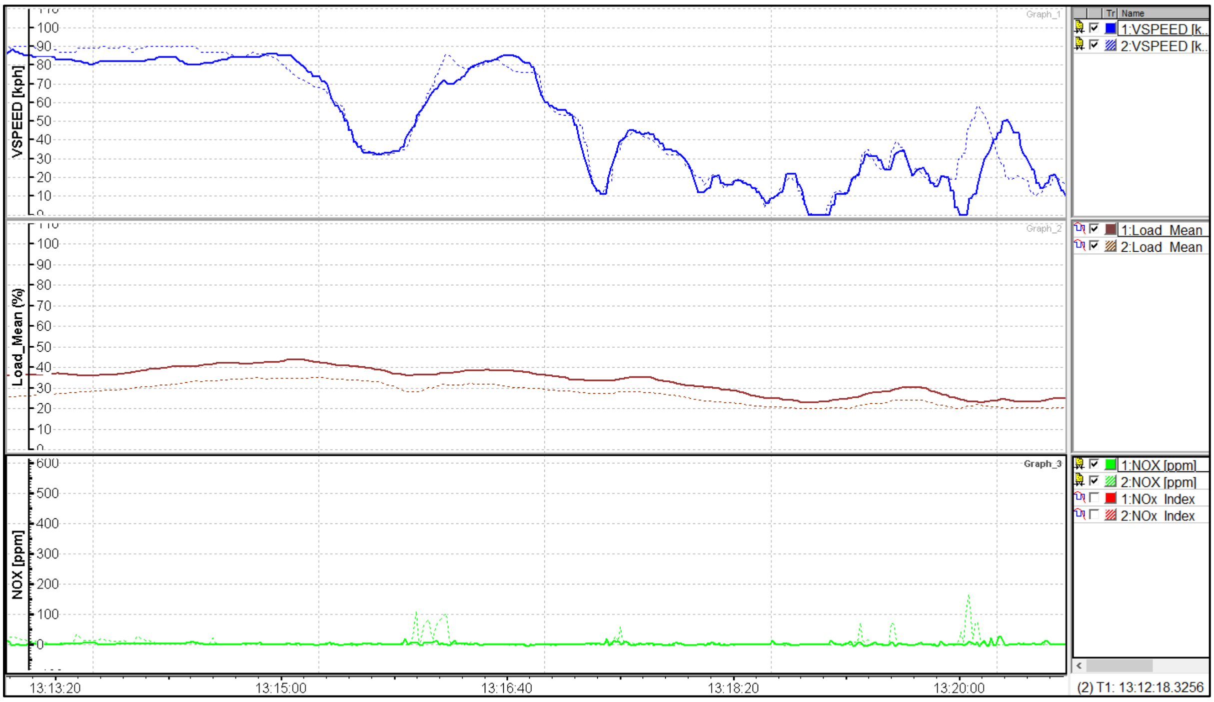

Figure 19. Comparing loaded and unloaded Truck at initial highway section. Dotted lines are unloaded. Speed-blue(km/h), NOx – green(ppm), Engine Load – Brown. A slightly lower engine load for the unloaded vehicle can be seen, but the green curve shows very similar and low NOx emissions.

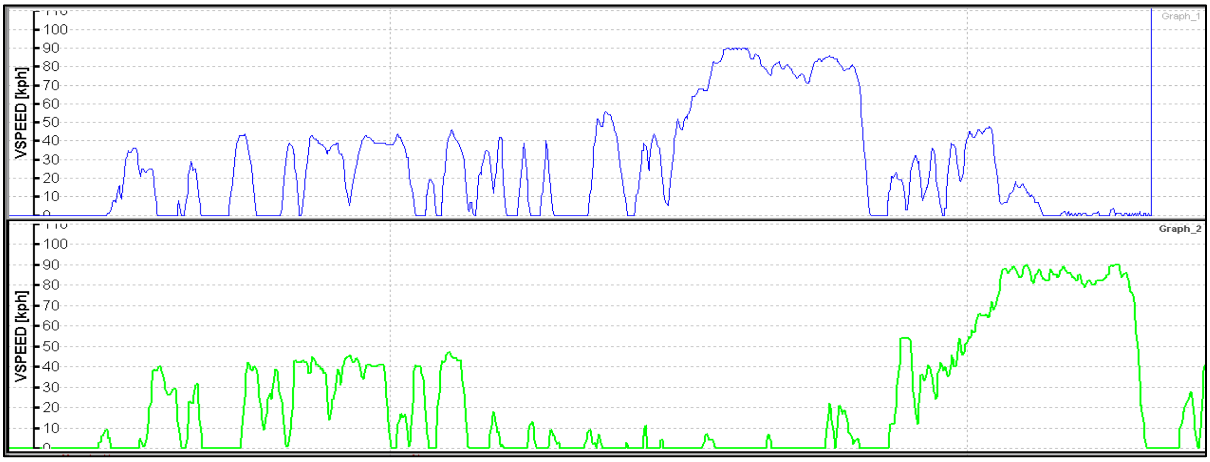

Figure 20. Truck 1 Showing the difference in speed and increased number of standstills. Blue is normal and green is heavy traffic. Speed with normal traffic-blue (km/h), Speed with heavy traffic-green (km/h). Both curves represent the last 13 km of the route.

As soon as the vehicle enters the highway the temperatures goes up and the emissions goes down to normal levels.

Truck 2, 250 kW, 8L, Euro VI d, 3 axles.

This truck showed good emission levels in general throughout the route and even if it, like the other tested truck no 1, with similar engine power also showed an increase in emissions in the city driving it was still within its limits and it did not show such a significant drop in exhaust temperatures. As the truck enters the highway after the city driving the NOx emissions are really low. This vehicle happened to enter active regeneration mode of the DPF at the beginning of the route, which largely affected the PN values. See Figure 21. After the regeneration was completed the PN numbers went back to normal low levels. It should be noted that heavy-duty vehicles rely on continuous regeneration of the DPF to a great extent, in contrast to light-duty vehicles, and therefore, active regenerations will happen rarely on heavy-duty trucks. It was kind of a co-incidence that it happened during this test.

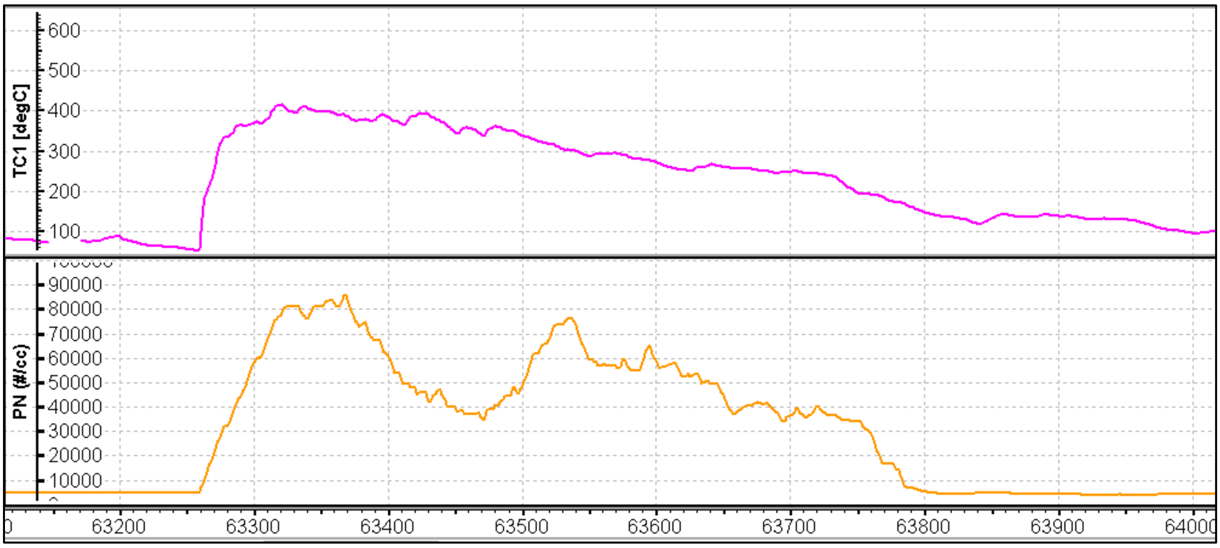

Figure 21. Truck no 2. High Exhaust temperature and PN numbers during regeneration. Exhaust tailpipe temperature-purple (°C), PN – orange (#/cc).

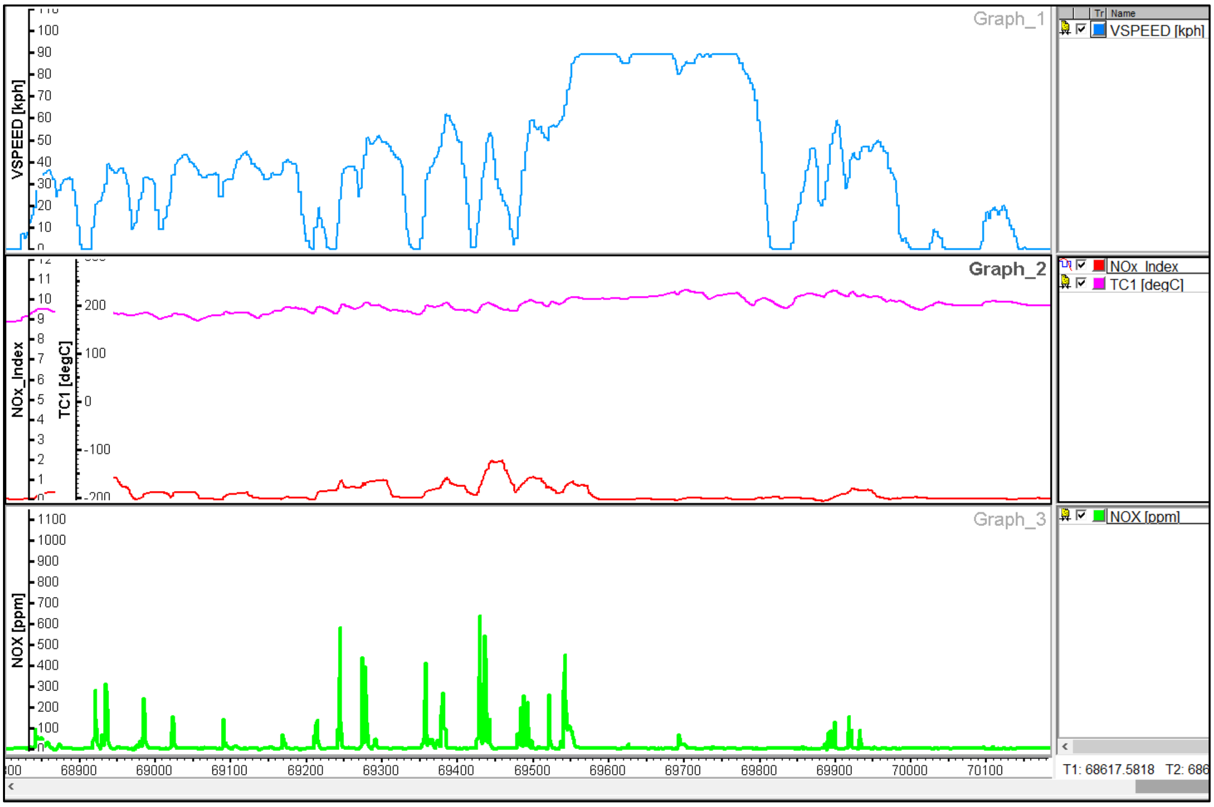

Figure 22. Truck no 2. Slightly higher emissions during city driving, but still very low. Exhaust temperatures at tailpipe remain 180 °C throughout city driving and goes up to 220 °C on highway. Speed-blue (km/h), NOx – green (ppm), NOx Index – red, Temperature at tailpipe – pink (°C).

Truck 3, 550 kW, 16L, Euro VIc, 4 axles

This truck had a large 16L engine and compared to the other trucks it became apparent that it required a much longer driving on the highway in order to heat it up properly before the test. Initially, a first test was started, but after the first two stops it was aborted and returned for driving / heating up on the highway. See **Figure 23** and **Figure 24**. Then a new test was started. In this way we can compare the initial phase of both tests and see what happens with this type of vehicle if it´s not heated up sufficiently before carrying out slower driving with many stops. During the complete route, this vehicle clearly shows how it´s NOx emissions gets worse and worse as it enters the city and traffic. The exhaust temperatures go down and subsequently the emissions go up. Already after the first 5 min stop/delivery at 2 km and 10 min after the highway this trend can be seen but after the third stop and at 15 km and 57 min (including 3 stops of totally 25min) while still into a sector of driving it can be seen very clearly. As the Truck enters highway again the emissions go down to normal level. See **Figure 25**. Note that this type of truck is intended for long-distance lorries and the normal load factor is much higher than during this testing. Higher engine load increase temperature and aftertreatment efficiency, indicating that this test was kind of "worst-case" scenario for this type of vehicle.

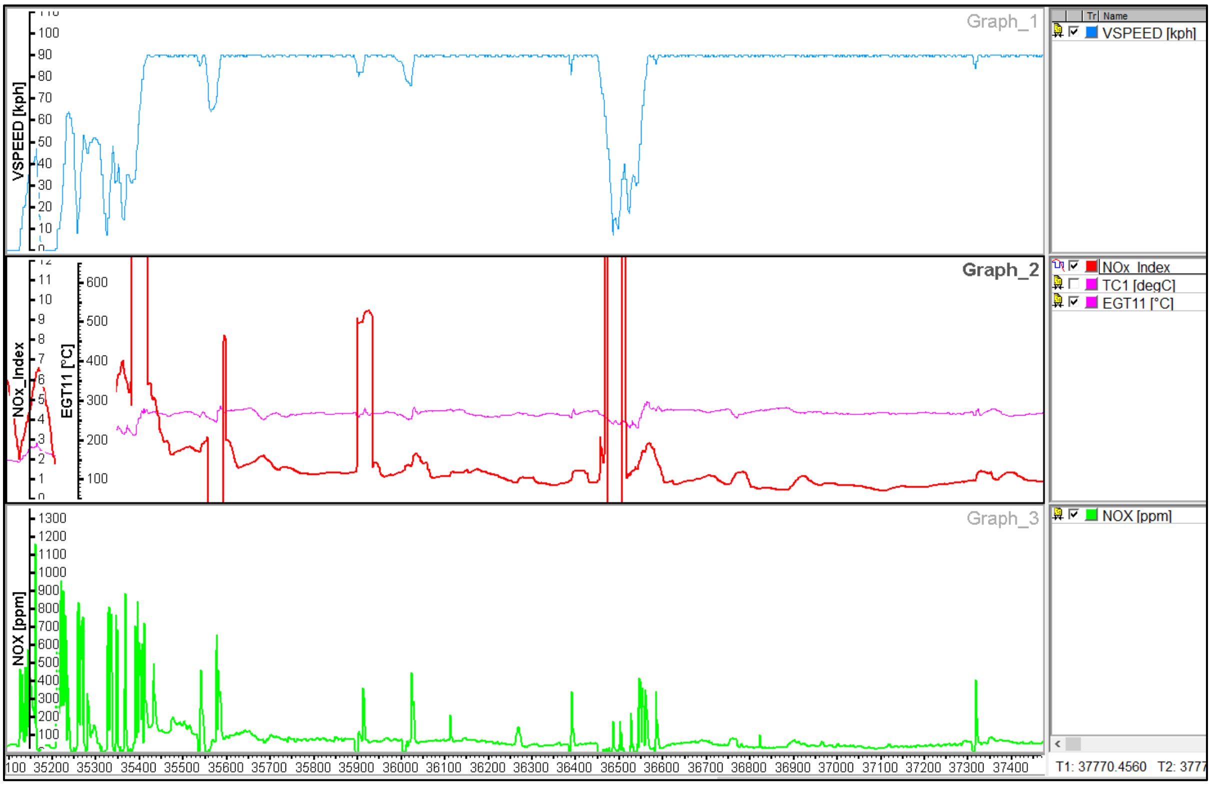

Figure 23.Truck no 3. About 25 min at highway needed in order to reach a NOx index below 1. Exhaust gas temperature into the aftertreatment system 260 °C during the Highway driving. Speed-blue (km/h), NOx – green(ppm), NOx Index – red, Temperature at tailpipe – pink (°C).

Figure 24. Map showing the extra drive on the highway for heating up the engine and aftertreatment system.

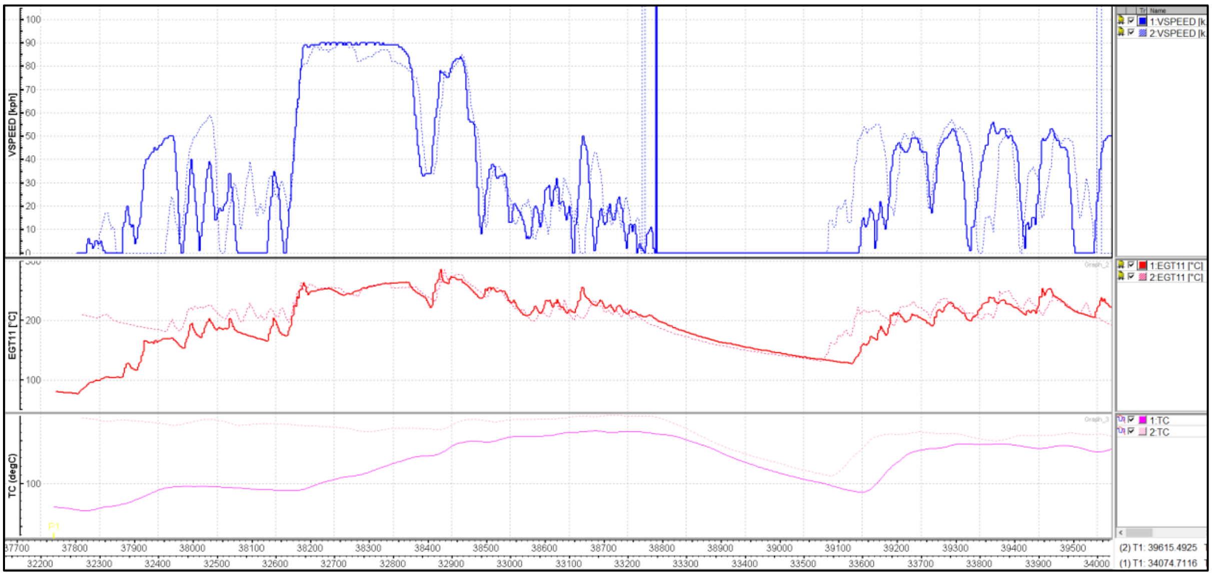

Figure 25. Truck no 3, comparing initial phase of the route with respect to heat of engine and after treatment system. Solid line is warmup route and dotted line is from second route with longer heat up period. Temperature out of engine is similar between the two tests, but tailpipe temperature is quite different due to the time it takes to heat up all the components in the aftertreatment system. Speed-blue(km/h), Temperature at tailpipe – pink (°C), Temperature out of engine – red (°C).

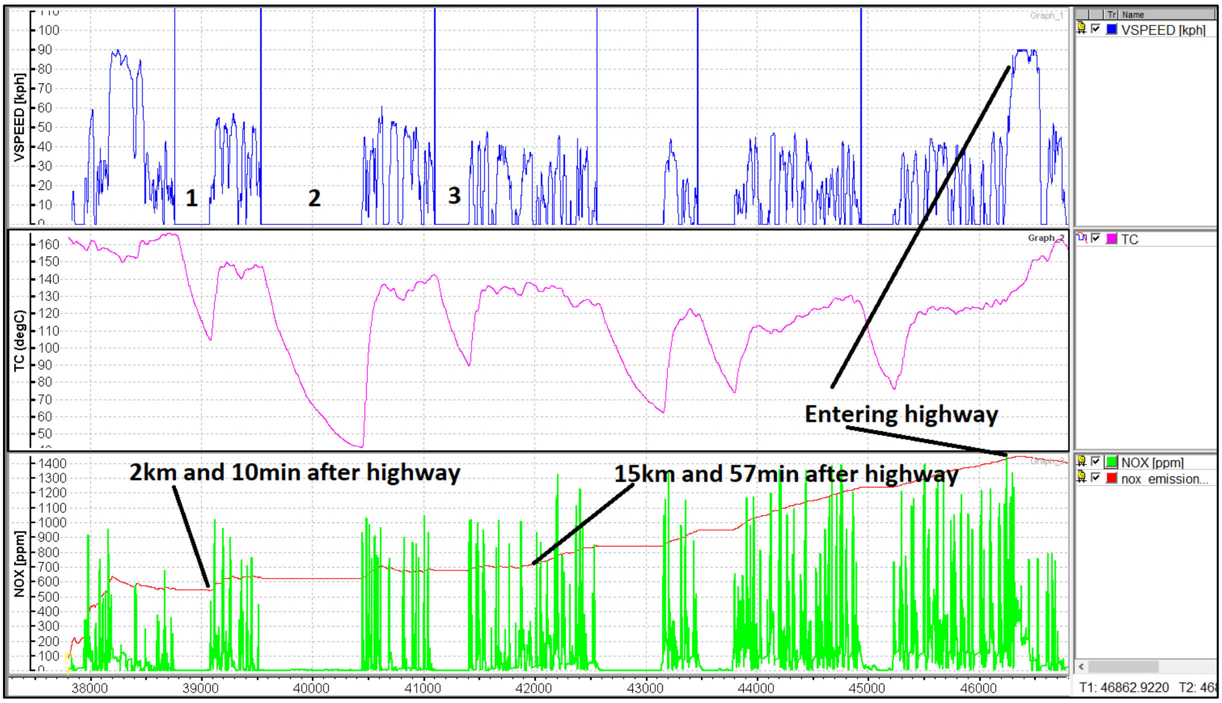

Figure 26. Truck no 3, Exhaust temperatures dropping after each stop/delivery and NOx emissions going up. Red curve with NOx Index shows the trend. Improving when entering highway again. Speed-blue (km/h), NOx – green(ppm), NOx Index – red, Temperature at tailpipe – pink (°C).

8. Conclusions and discussion

All vehicles in this study were diesel-fuelled vehicles. Diesel powered vehicles are often used for goods transport because they are powerful in combination with a relatively low fuel consumption. The disadvantage of this type of engine has mainly been particles and NOx emission. Other exhaust emissions such as HC and CO are not a problem when catalysts are being used as they are easily oxidized in the oxygen-rich environment in the exhaust gas. Particles are also not a problem when diesel particle filters are used (DPF´s).

Modern vehicles use a reducing agent (urea, AdBlue) that is added to the exhaust gases and react with NOx in the SCR-system (Selective Catalytic Reduction). This is a highly effective way to reduce NOx emissions. For this concept to work with highest efficiency, it is required that the exhaust aftertreatment system have a certain minimum temperature. If, above it, NOx is reduced very effectively, but below, the flow of reducing agents must be shut off (e.g., to avoid excessive emissions of urea and creating deposits in the exhaust system) and this results in increased NOx emissions. This study shows this behaviour of the aftertreatment system. The SCR-system worked well as long as the temperature of the exhaust gas going into the system was high enough. Two major factors for how well the SCR system works is how long periods a vehicle is standing still during a route and how often those stand stills occur.

With regards to under which conditions the aftertreatment system is functioning and not functioning on the vehicles tested in this report one can say the following:

- The SCR-system seems to work well during highway driving and NOx levels are down to zero or a few ppm´s.
- Driving in heavy traffic results in lower temperatures in the aftertreatment system with higher NOx emissions as a consequence and vice versa.
- All type of driving that gives low exhaust temperatures effects the NOx-reduction in a negative direction, example low speed (city driving) and low load.
- The delivery van seems to be insensitive to it´s load with regards to it´s emissions during these limited tests. During the test in Copenhagen and the preparations in Gothenburg It has been tested with zero and 240 kg load and it worked well during both conditions. It´s suspected that driving behaviour, number of stops and length of stops will have more significant impact on a vehicle like this.
- A truck with a large engine in combination with relatively low load results in long heat up time and fast cool off during city driving and idling. This may be a common issue for trucks with large engines.
- In order for a SCR system to function an exhaust gas temperature into the SCR system of at least around 180 °C during a certain amount of time seems to be required.
- The tests in this report shows a sensitivity to decreasing temperature of the aftertreatment system and increasing NOx emissions after about 15 km and 60 min (including 3 stops of totally 25 min) from leaving the highway. This distance and time for when the aftertreatment system loses its efficiency will be dependent on the driving speed and the number and duration of stops, but it shows that there is a relationship and it´s valid for more than one vehicle.
- After leaving the city driving (slow driving and standstill) and entering the highway all the trucks shows an improvement in the NOx emissions. It only takes about 1,5-2 min and 1,5-2 km before the SCR-system is performing optimally again for Truck no 1 (loaded) and Truck no 2, while it takes about 4,5 min and 4,5 - 5,5 km for Truck no 1 (unloaded) and Truck no 3 which both suffered from relatively low exhaust temperature during the city driving.
- Measuring the temperature at the tailpipe is a useful tool to show and correlate exhaust gas temperatures to SCR-System functionality and NOx emissions, but the absolute values should not be used to compare between different vehicles etc since it is very dependent on the design (mainly length) of the exhaust pipe.

- For the function of the temperature dependent SCR-system it´s an advantage having a vehicle with an engine that is relatively small compared to the vehicle weight so the engine needs to perform a decent amount of work. Engine size versus vehicle weight naturally also has an effect on other things such as fuel consumption and soot levels going into the DPF.
- It takes longer time to warm-up and cool-down a heavy-duty vehicle compared to a smaller vehicle. This means that for example that it is more important to turn off the engine during stops on a small vehicle compared to a heavy-duty truck. It may be a good idea to use different maximum allowed idling time on light and heavy-duty vehicles. As an example, it could be 2 minutes for light duty vehicles and 10 minutes for heavy duty trucks.
- CO emission were close to zero during all tests.
- Particulate number emissions (PN) were extremely low (fewer particles in the exhaust gases than in the Copenhagen air) for all tested vehicles. There is no clear correlation of PN numbers due to how the vehicle is driven.
- Vehicles with a functional DPF does not show any high particle number emissions during driving other than when regeneration occur. This is quite typical for a DPF system where it either works or it doesn´t work. As an example, if there is a small damage (hole) on a DPF filter it will instantly result in very high particle emissions.

9. Suggestion for further studies

To collect more data, a proposal is to mount measuring equipment on a few different vehicles at a distribution company (and follow the vehicles for a long time, half year). In this way, it is possible to collect data on how the vehicles are driven in daily operation. At the same time, data about different outdoor temperatures, different queue situations, different stop times, etc. will also be obtained.

Another proposal is to perform multiple tests on a single vehicle, such as a EURO VI e Truck which is the very latest standard and therefor representative of how the coming trucks performs and where the manufacturers stand with their technology. Euro VI e trucks has not yet really reached the market and hence they were not possible to get hold of for this study. It would also be an idea to drive the same route several times with full load, empty, different drivers, different times, with the engine on and off during stops, etc. In this way it may be possible to draw more firm conclusions about which factors that have the biggest impact on emissions.

In Denmark it may be a case where Semi Trucks are used in combination with a small single axle trailer for transportation in the city area. The results. In this report indicated that this may be a vehicle combination that is not optimal with regards to how a NOx reduction after treatment system works. Since these trucks often have a relatively large engine. It may be that they are not loaded enough to reach optimal temperatures when using these small trailers.

This study shows that CO is close to zero from modern Euro 6 and EURO VI vehicles. Also, the particulate emissions are extremely low (often fewer particles in the exhaust gases than in the ambient air). This means that there may be less interest to measure these parameters to a large extent as long as it is modern vehicles and the diesel particle filter isn´t removed or broken. Of course, there may still be a case for doing smaller number of measurements in order to understand how the modern DPF systems performs in general. This means that the most interesting emission component to measure in general on heavy-duty vehicles is NOx. By just focusing on NOx the test procedure will be significantly easier to perform. The mounting and dismounting times will be shorter, etc. In total this means that it will be possible to do more tests per day by just focusing of the most important emission component. In addition, the simplified NOx measurement instrumentation is better suited for long-term measurements than the currently available instruments for measuring particle number emissions.

10. References

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3. Measuring real emissions with simplified PEMS, 23rd Transport and Air Pollution Conference, Thessaloniki 2019, P Per Öhlund, Swedish Transport Agency and Lars Eriksson, Ecotraffic
4. SEMS equipment in connection with periodic technical inspections (PTI) of lorries, Færdselsstyrelsen, Lars Eriksson EXIS, Martin Sventen ECM, 2020

11. Appendix

Photos from the tests

Figure 27. Test set-up inside the cabin. From this screen the logging were start and stopped. It is also possible for the driver do follow the trends etc. There are 5 different pages on the screen

Figure 28. Test probe mounted in exhaust pipe. The heated line is for particle measurement and the sensors for NOx, CO, CO_2, O_2, lambda.

Figure 29. 3 axle Truck.

Figure 30. Delivery VAN