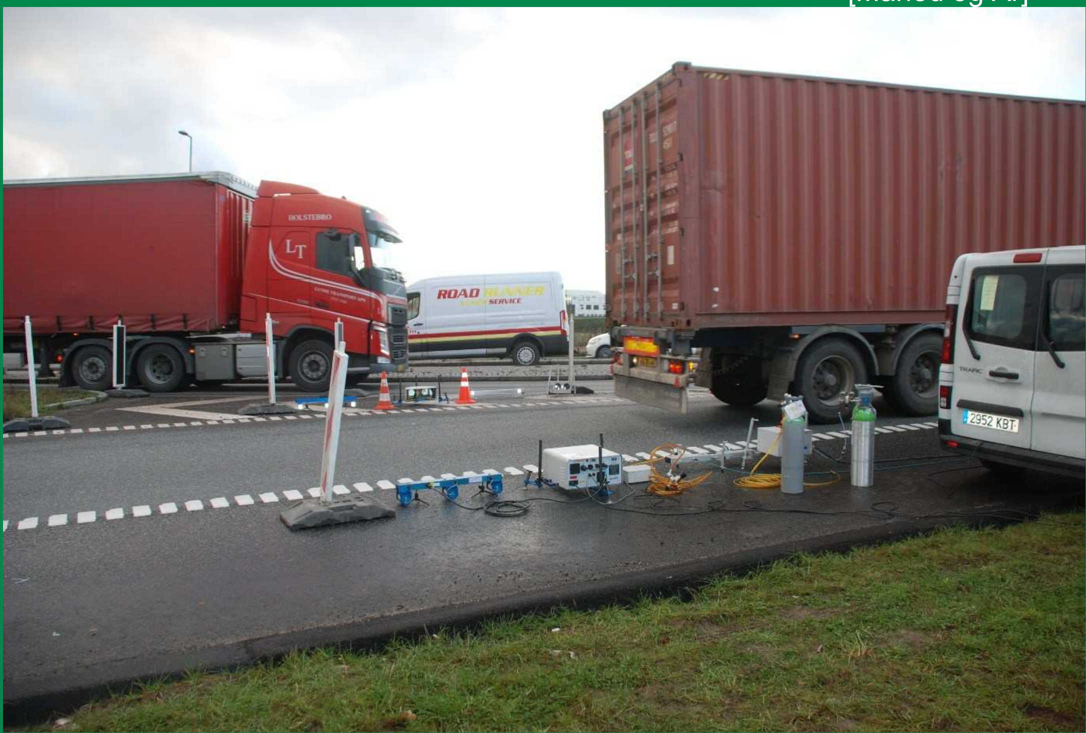
Miljø- og Fødevareudvalget 2017-18
MOF Alm.del Bilag 565
Offentligt

Ministry of Environment
and Food of Denmark
Environmental
Protection Agency

Measurements of cheating with SCR catalysts on heavy duty vehicles

[Serietype og nummer]

[Måned og År]



Publisher: The Danish Environmental Protection Agency

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Background and aim of project

This report presents the results from an experimental project carried out in 2017 and 2018 by NEQ Aps and the DCE - Danish Center for Environment and Energi, Aarhus University (DCE) for the Danish Environmental Protection Agency (EPA). It is the aim of the project to improve the knowledge on the extend of cheating with SCR catalysts in Denmark (manipulation with the functioning of the NO_x after treatment system). This is done by carrying out measurements on a large number of heavy-duty vehicles using devices that can detect emissions at levels that indicate cheating with SCR catalysts. Moreover, it is the aim of the project to consolidate the estimate of the health impact related to cheating with catalysts by use of data gathered from the measurements. In addition, the project is a practical test on the feasibility of use of remote sensing measurements as basis for picking out heavy-duty vehicles for police roadside inspection of cheat with the SCR catalyst. This test combining remote sensing measurements with police roadside inspections is carried out for the first time in Denmark and probably also in Europe.

Measurement campaigns

During two weekly measurement campaigns in November and December 2017, remote sensing measurements were used to determine the emissions of nitrogen monoxide from heavy-duty vehicles. Remote sensing measurements are based on absorption of light from a laser beam that traverses the exhaust from the tail pipe. The amount of absorbed light is proportional to the concentration of NO in the exhaust. The measurements take few seconds and the measurement technique is therefore ideal for measurements of emissions from heavy-duty vehicles driving under real world conditions although relatively high variability of the results are unavoidable due to the measuremt conditions.

The measurements took place at Padborg close to the Danish-German border and at Køge on exit 32 from highway E20 close to the Scandinavian Transport Center. During the measurement campaigns, the emissions from 874 heavy-duty vehicles were successfully measured (Table 1). About half of the heavy-duty vehicles were Danish and half were foreign. 35% and 58% of the heavy-duty vehicles were Euro Standard V and VI, respectively. It is heavy-duty vehicles with these Euro Standards that use SCR catalysts to decrease the emissions of NO, though other reduction techniques are used for part of the Euro Standard V heavy-duty vehicles.

TABLE 1. The number of heavy duty vehicles measured during this project divided in Euro Standards and Danish and foreign heavy-duty vehicles.

	Danish	Foreign	Total	Percentage
Euro I	1	0	1	0,1
Euro II	2	0	2	0,2
Euro III	18	0	18	2,1
Euro IV	30	0	30	3,4
Euro V	132	171	303	35
EEV	17	0	17	2
Euro VI	249	254	503	58
Total	449	425	874	100

Police roadside inspection

During the first campaign in Padborg the measurements were combined with roadside inspection of heavy-duty vehicles carried out by the Danish police. Nine heavy-duty vehicles with high emissions (at the beginning 400 ppm and later 600 ppm) were picked out for inspection. Two foreing Euro V heavy-duty vehicles with cheating devices were found. In addition four heavy duty vehicles with malfunctioning of the SCR catalyst (No adblue on the tank, defect sensor, engine problems) were found. It is the first time that remote sensing measurements have been applied in this way to pick out heavy-duty vehicles that can be suspected to cheat with the SCR catalysts. The concept proved to be feasibly, and it is believed that it can be an effective tool that can be used as part of the enforcement of the Euro Standard regulation in Denmark.

Results

The remote sensing measurements showed a large variation in the actual emissions from the heavy-duty vehicles. For Euro V there is a substantial difference between the emissions from Danish and foreign heavy-duty vehicles. The lowest and worst emitters looks approximately similar, but for the middle range (about 10 to 85 percentiles of the Euro Standard V heavy-duty vehicles), the foreign heavy-duty trucks have significantly higher emissions than the Danish heavy-duty vehicles. For Euro VI the distribution looks similar for Danish and foreign heavy-duty vehicles with relative low emissions for more than 90% of the heavy-duty vehicles.

The distributions for the NO emissions are relatively smooth and there are no large jumps in the distributions that could indicate a threshold above which there are malfunctioning or cheat with the SCR catalysts. The distribution for the Danish Euro V heavy-duty vehicles show a small jump at around 25 gNO_2/kg that might indicate such a threshold; however, this is not seen for the foreign heavy-duty vehicles. For Euro VI there is a steep increase in emissions above 3 gNO_2/kg, indicating a kind of threshold for the onset of malfunctioning or cheat with SCR catalysts. Thresholds of 25 and 3 gNO_2/kg for Euro V and VI, respectively, is therefore suggested as thresholds for future use of remote sensing measurements as guide for picking out heavy-duty vehicles for the roadside inspections carried out by the Danish police (this corresponds to a ratio between NO and CO_2 of 0,0052 and 0,0006 mole/mole).

The measurements can point out potential heavy-duty vehicles that cheat or has malfunction of the SCR catalyst. However, the measurements do not give confirmation whether or not these heavy-duty vehicles are cheating or have malfunction. Despite this, the present study indicate, that the number of heavy-duty vehicles that are cheating, is less than 25%. This indicates that the effect of cheating on the health effects in Denmark is less than the previous crude estimate.

In this study the composition of heavy-duty vehicles monitored at the Padborg and Køge measurement sites are more modern than the overall Danish fleet composition for 2015 used in the previous assessments of health effects related to cheating with SCR catalysts in Denmark. The fleet composition found in this study indicates that today Euro VI heavy-duty vehicles accounts for about half of the Danish heavy-duty vehicle fleet. It has to be noted that this estimate Is based on results from only two measurement sites in connection to the Danish highways.-

The results also show that the NO_x emission factors measured for Euro V and VI heavy-duty vehicles are significantly lower than for the previous Euro standards, which is also the case for the emission factors used in the previous health assessment calculations made by DCE. The Euro V and VI emission factors are about 50% and less than 10% of the emisson factors of Euro IV, respectively.

Health effetcs

Predominantly due to the updated heavy-duty fleet composition, the emissions from heavy duty vehicles in this study are lower than the emissions in the previous health effect calculations presented by DCE. This also means that the health effects in Denmark was somewhat overestimated in previous assessments building on the Danish 2015 fleet composition and that health effect figures will decrease further when model results using based on the actual vehicle fleet in Denmark for 2017 are available.

In 2017, DCE (Brandt et al, 2017) presented a crude estimate of the health effects related to cheating with SCR catalysts in Denmark. This estimate pointed at 3-4 premature deaths in Denmark due to cheat with use of SCR catalysts in Denmark. The results from the present work indicate that this estimate is somewhat to the high end. Due to lack of updated traffic and emission data for 2017 it has not been possible to quantify this better by specific model calculations with DCE models.

Practical lessons learnt

Moreover, a number of practical lessons were learnt from the campaigns:

- The site in Padborg was ideal for carrying remote sensing measurements in combination with Police road site inspections.
- The site in Køge was less ideal due to the curve of the road.
- It is necessary to pick out two or more sites in order to ensure both a large number of Danish and foreign heavy-duty vehicles.
- November-December is not an ideal time of year for such studies, since weather conditions are unfavorable. It is better to carry out the measurements during the summer half year.
- The planning period up to the measurement campaigns were too short, since it takes relatively long time to obtain the necessary permissions for carrying out the measurements.
- The ratio of NO to CO_2 shall be used for picking out heavy-duty vehicles that are under suspicion for cheat with the SCR catalysts.

Udvidet dansk sammenfatning

Baggrund og formål

Politiets vejsidekontrol af lastbiler i Danmark i 2017 viste, at hver fjerde af de undersøgte last- vogne anvendte ulovligt udstyr, som kan snyde lastvognenes SCR-katalysatorer (selektiv katalytisk reduktion), der under normal funktion reducerer indholdet af nitrogenoxideer (NO_x) i lastvognes udstødning. Snyd skal i denne sammenhæng forstås som manipulation med last- vognes SCR-katalysatorer. Herved kan vognmændene spare omkring 20.000 kr. årligt per lastvogn. Det ulovlige udstyr gør det muligt for vognmændene at undlade at bruge tilsætnings- stoffet, som er nødvendigt for, at SCR-katalysatorer kan fjerne omkring 90% af udledningerne af nitrogenmonooxid (NO) og nitrogendioxid (NO_2) fra lastbilernes udstødning.

På den baggrund har Miljøstyrelsen fået udført dette projekt, som NeQ og DCE – Nationalt Center for Miljø og Energi står bag.

Formålet med projektet var at få yderligere informationer om omfanget af snyd med SCR- katalysatorer i Danmark og på den baggrund vurdere betydningen for luftkvalitet og de hel- bredsskadelige effekter af luftforureningen i Danmark. Desuden var projektet en praktisk test af, hvordan målingerne af udledningerne fra lastvogne kan benyttes i sammenhæng med politiets vejsidekontrol med snyd med SCR-katalysatorer. Ideen er, at udledningen af nitro- genoxiderne fra alle lastvogne, som passerer kontrolstedet, vil blive målt. Målingerne kan benyttes som mistankegrundlag for at stoppe og undersøge de lastvogne, som har uforholds- vis store udledninger, og hvor der derfor er mistanke om snyd med SCR-katalysatorerne.

Målekampagner

I november og december 2017 blev der i projektet gennemført to målekampagner af en uges varighed med målinger af udledninger af nitrogenmonooxid fra lastvogne (figur 1).

Måleudstyret sender en uskadelig laserstråle på tværs af vejen gennem lastvognenes udstød- ningsgas. En del af lyset blev absorberet af nitrogenoxiderne i udstødningsgassen og på basis af absorptionens størrelse

bestemmes udledningen af nitrogenoxider fra den enkelte lastvogn. Målingerne tager få se- kunder at gennemføre, og giver et øjebliksbillede af indholdet i udstødningsgassen. Måleresul- taterne er tilgængelige umiddelbart herefter. Udstyret kan derfor bruges til at måle udledninger fra et meget stort antal lastvogne på kort tid og under de aktuelle forhold i trafikken.

FIGUR 1. Udledning af nitrogenmonooxid er lige netop blevet målt på lastvognen med den røde container. Måleudstyret ses umiddelbart til venstre for den hvide teknikervarevogn

De målte lastbiler blev i projektet ikke alle standset, men identificeret via nummerpladerne. For danske lastbiler blev data on Euro-normer hentet via det danske motorregister, mens informationerne om Euro-normer for udenlandske lastvogne blev vurderet ud fra udseendet af lastvognen.

Målingerne blev foretaget på motorvej E45 i Padborg tæt på den dansk-tyske grænse og ved Køge på afkørsel 32 fra motorvej E20 tæt ved Skandinavisk transportcenter. I løbet af målekampagnerne blev udledningerne fra 874 lastvogne registreret med god kvalitet i målingen (Tabel 1). Omkring halvdelen af lastvognene var danske og den anden halvdel var udenlandske. 35 % og 58 % af lastvognene var henholdsvis Euro-norm V og VI. Det er lastvogne med disse to Euro-normer, som benytter SCR-katalysatorer til reduktion af udledningerne af nitrogenoxiderne. Dog er det kun en del af lastvognene med Euro V, som anvender denne teknik.

TABEL 1. Antallet af målinger af udledninger fra lastvogne fordelt efter Euro-norm samt dansk og udenlandsk nationalitet.

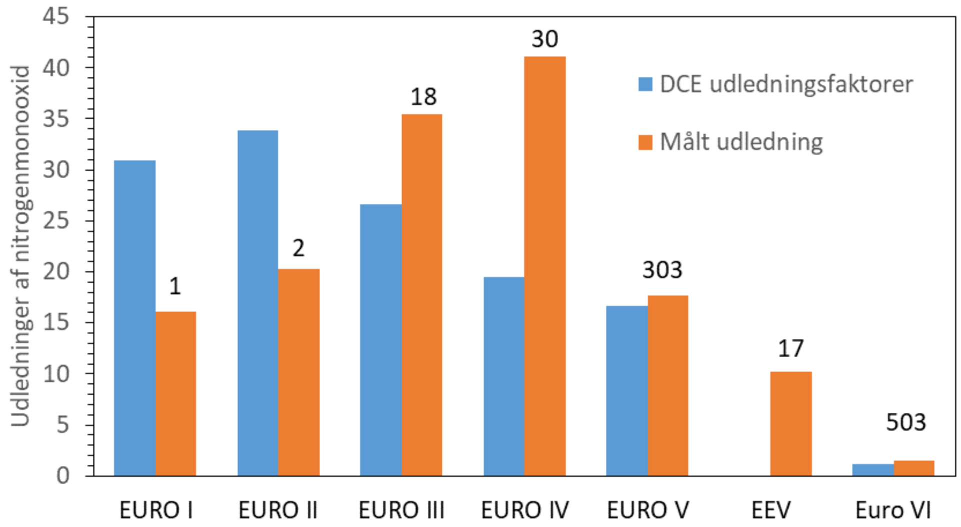
	Danish	Foreign	Total	Percentage
Euro I	1	0	1	0,1
Euro II	2	0	2	0,2
Euro III	18	0	18	2,1
Euro IV	30	0	30	3,4
Euro V	132	171	303	35
EEV	17	0	17	2
Euro VI	249	254	503	58
Total	449	425	874	100

Politiets vejsidekontrol

I den første målekampagne i Padborg blev målingerne kombineret med vejsidekontrol af lastvogne udført af Dansk Politi. Målingerne blev anvendt til at udvælge ni lastvogne med høj udledning af nitrogenmonooxid (i begyndelsen mere end 400 ppm = 400 milliontedele, hvilket senere blev øget til 600 ppm). Politiet gennemførte vejsidekontrol af de udvalgte lastvogne og fandt udstyr som benyttes til snyd med SCR-katalysatorerne på to udenlandske Euro V lastvogne. Endvidere fandt politiet tre lastvogne, hvor SCR-katalysatorene ikke virkede som den skulle grundet manglende Adblue i tanken, defekt sensor og motorproblemer. Det er første gang i Danmark og formentligt i Europa, at denne type målinger er blevet anvendt som mistankegrundlag for udvælgelse af lastvogne til politiets vejsidekontrol for snyd med SCR-katalysatorer. Målekampagnen viste sig at være en succes, og kombineret med vejsidekontrol er lasermålingerne et effektivt værktøj som kan indgå som en del af håndhævelsen af Euronormerne i Danmark.

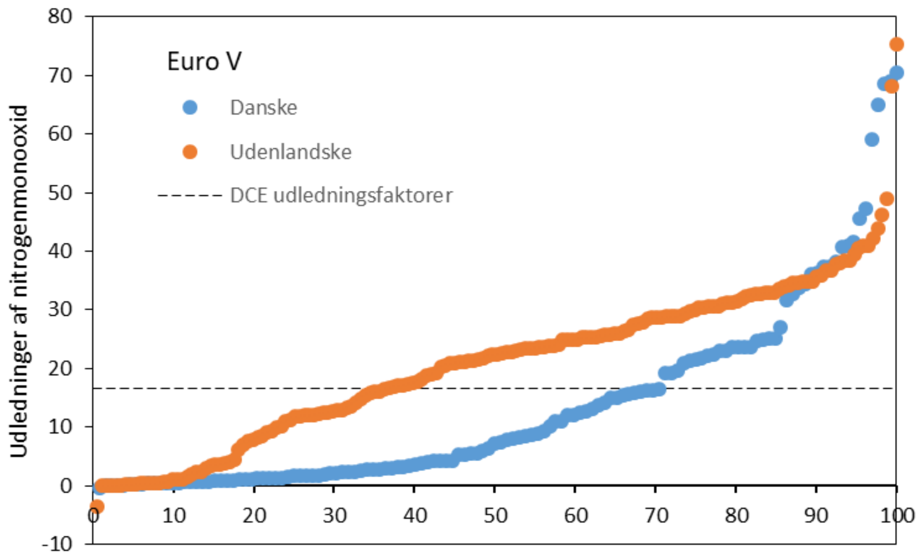
Resultater

Figur 2 viser de gennemsnitlige udledninger målt på de 874 lastvogne. Der er stor forskel på Euro-normerne med de højeste gennemsnitlige udledninger målt for Euro III og IV. Euro V og VI har væsentligt lavere udledninger, hvor Euro V ligger på lidt under halvdelen af Euro IV, mens Euro VI ligger på under en tiendedel af Euro-norm IV. Figuren viser også de udledningsfaktorer, som DCE anvender i forbindelse med de nationale udledningsopgørelser, som årligt indberettes til EU. For Euro III og IV er de målte udledninger væsentligt højere end DCE's udledningsfaktorer, mens der er væsentligt bedre overensstemmelse for Euro-norm V og VI. Der er en række tekniske forskelle mellem måleresultaterne og den måde udledningsfaktorerne er opgjort på. Derfor skal sammenligning kun ses som et fingerpeg på, hvor måleresultaterne ligger niveaumæssigt set i forhold til de udledningsfaktorer, som anvendes til de nationale udledningsopgørelser.

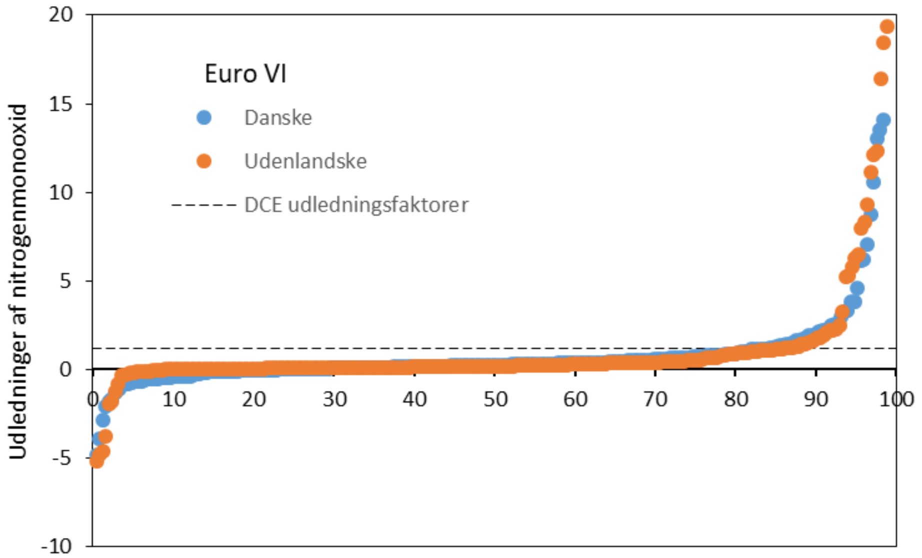


FIGUR 2. Gennemsnitlige udledninger af nitrogenmonooxid i udstødningsgasserne fra 874 lastvogne fordelt efter Eurostandard. Til sammenligning vises også de udledningsfaktorer, som DCE anvender i forbindelse med DCE's nationale opgørelser af udledningerne af nitrogenoxider fra lastvogne. De viste udledningsfaktorer gælder for bykørsel, hvilket svarer nogenlunde til måleforholdende. Udledningerne er angivet i ækvivalenter af nitrogendioxid (gNO_2/kg). Tallene over de orange kolonner angiver antallet af lastvogne målt med den pågældende Euronormer.

For Euro V er der stor forskel mellem udledningerne fra danske og udenlandske lastbiler. De højest og de laveste udledninger ser relativ ens ud, men for mellemområdet (over de 10 laveste % og op til 85 % af lastvognene) har de udenlandske lastvogne væsentligt højere udledninger end de danske lastvogne. For Euro VI er fordelingen stort set ens for danske og udenlandske lastvogne med relativt lave udledninger for mere en 90% af lastvognene.
Figur 3 og 4 viser fordelingen af udledningerne af nitrogenmonooxid opdelt på danske og udenlandske lastvogne for henholdsvis Euro V og VI.



FIGUR 3. Fordeling af udledning af nitrogenmonooxid sorteret efter stigende udledning fordelt på danske og udenlandske lastvogne med Euro V. x-aksen angiver den procentdel af de målte lastvogne, som ligger under en given udledning. Udledningerne af nitrogenmonooxid er angivet i ækvivalenter af nitrogendioxid (gNO_2/kg).



FIGUR 4. Fordeling af udledning af nitrogenmonooxid sorteret efter stigende udledning fordelt på danske og udenlandske lastvogne med Euro VI. x-aksen angiver den procentdel af de målte lastvogne, som ligger under en given udledning. Udledningerne af nitrogenmonooxid er angivet i ækvivalenter af nitrogendioxid (gNO_2/kg).

Fordelingen af udledningerne af nitrogenmonooxid er relativt jævn og der er ikke store spring i fordelingen, som kan indikere en grænse, hvorover der formentligt vil være tale om snyd eller fejl på SCR-katalysatoren. Fordelingen for danske Euro V er der et mindre spring omkring 25 gNO_2/kg, som kan indikere en sådan grænse, men tilsvarende spring er ikke set for udenlandske lastbiler. Fordelingen for Euro VI viser en stor stigning i udledningerne over 3 gNO_2/kg, hvilket peger på at grænsen for snyd eller fejl i SCR-katalysatoren skal ligge heromkring.

Målingerne kan benyttes som mistankegrundlag for udpegning af mulige lastvogne med snyd eller fejl med SCR-katalysatoren, men målingerne af udledningerne giver i sig selv ikke information om hvorvidt det er tilfældet eller ikke. DCE’s forskere vurderer, at målingerne på de 874 lastbiler viser at snyd med SCR-katalysatorerne formentligt er mindre end de 25 %, som politiet fandt ved den første vejsidekontrol i 2017.

Resultaterne fra denne undersøgelse peger på, at der i den sidste årrække er sket en stor ændring i sammensætning af Euro-normer for de lastvogne, som kører i Danmark. Dette ses navnlig for Euro VI, som i denne undersøgelse udgjorde mere end 50% af de lastvogne, der blev målt udledninger på. Endvidere viser målingerne at udledningerne fra Euro V og VI er faldet væsentligt set i forhold til Euro III og IV. Dette tyder på, at lastvognenes bidrag til udledningerne af nitrogenoxider er faldet markant siden 2015.

Helbredsskadelige effekter

De seneste opgørelser af de helbredsskadelige effekter af luftforureningen har benyttet opgørelser over udledningerne fra 2015. Der er derfor grund til at antage, at disse opgørelser ligger for højt, og at man vil få lavere helbredsskadelige effekter af luftforureningen ved anvendelse af udledningsopgørelser, som repræsenterer den aktuelle flåde af lastvogne, som kører i Danmark i dag.

DCE offentliggjorde i 2017 (Brandt et al, 2017) et skøn over de helbredsskadelige effekter, som kan forbindes med snyd med SCR-katalysatorer i Danmark. Dette skøn pegede på at snyd med SCR-katalysatorer var skyld i 3-4 for tidlige dødsfald, som kunne være undgået, hvis der ikke havde været snyd med SCR-katalysatorerne. Målingerne i dette projekt peger alt i alt på, at omfanget af snyd er mindre end det, som politiet fandt ved deres vejsidekontrol og at konsekvenserne for udledningerne er mindre end antaget i DCE’s skøn fra 2017. Undersøgelserne viser derfor at det oprindelig skøn er for højt. Da vi endnu ikke har de nødvendige udledningsopgørelser for 2017 har det ikke været muligt at komme med et mere præcist bud på de helbredsskadelige effekter af snyd med SCR-katalysatorer.

Praktiske erfaringer

Projektet har givet en række værdifulde praktiske erfaringer i forbindelse med udførelse af målinger af udledninger fra lastvogne:

- Målestedet i Padborg viste sig at være ideelt for målinger af udledninger med laserundersøgelse i kombination med vejsidekontrol udført af politiet.
- Målestedet i Køge var mindre ideelt navnlig grundet vejens kurve ved målestedet.
- Det er nødvendigt med to forskellige målesteder, hvis man ønsker at måle på et stort antal af både danske og udenlandske lastvogne.
- November-december er ikke et ideelt tidspunkt, da vejrforholdene ikke er favorable for denne type målinger. Sommerhalvåret er et langt bedre tidspunkt.
- Perioden afsat til forberedelse af målekampagnerne var for kort, da det kan tage relativt lang tid at få de nødvendige tilladelser til gennemførelse af målingerne.
- Forholdet mellem nitrogenmonooxid og carbondioxid (CO_2) skal benyttes til at udpege de lastbiler, hvor der potentielt kan være tale om snyd med SCR-katalysatorerne. Årsagen til dette er, at man ved at benytte dette forhold kan tage højde for hvor meget udstødningsgasserne er blevet fortyndet inden selve målingerne finder sted. Dette kan ikke vurderes ved blot at anvende selv koncentrationen af nitrogenmonooxid.

1. Introduction

This report presents the results from a project on determination of the extend as well as the impact on human health of cheating with use of SCR catalysts in heavy duty vehicles in Denmark. The project have been carried out in 2017 and 2018 by NEQ Aps and the Danish Center for Environment and Energi (DCE) for the Danish Environmental Protection Agency (EPA).

1.1 Background and aim of project

Through the latest ten years, SCR-catalysts (Selective Catalytic Reduction) have been applied on the majority of the modern heavy-duty vehicles in Denmark. SCR-catalysts remove typically 90 % of the nitrogen oxides (NO_x: sum of nitrogen monoxide (NO) and nitrogen dioxide (NO_2)) in the exhaust from heavy-duty vehicles. However, Danish, Norwegian and German control actions carried out during the latest years have revealed an extensive cheating with the SCR-catalysts (manipulation with the functioning of the NO_x after treatment system).

Normally heavy-duty vehicles can only drive very slowly without filling up the additives that are needed for the functioning of the SCR-catalyst. However, this can be avoided by use of software/hardware that overrules the normal systems that ensures the proper functioning of the SCR-catalyst. Hauliers save the cost to the additives (estimated to about 20,000 kr. annually), however, with a significant increase in the emissions from the heavy-duty vehicles as a result. In April 2017, Danish Police carried out a control action in Southern Jutland close by the Danish - German border. This control showed that the SCR-catalyst were switched off in 25% of the tested heavy-duty vehicles.

On a European level, about 20% of the health effects related to air pollution originates from road traffic (Brandt el al., 2017), and hence increased emissions due to cheating with SCR-catalysts will have significant impact on health. If it is assumed that all SCR-catalysts in heavy-duty vehicles in Denmark have been switched off then the emissions of NO_x from heavy-duty traffic in Denmark will increase with 130% and the total emissions from road traffic will increase with 34%. If just 25% of the heavy-duty vehicles have the SCR-catalyst switched off (corresponding to the result from the Danish Police control action), then the emissions of NO_x from road traffic are increased by 9%. On a European level about 500,000 people dies prematurely due to air pollution, and the similar figure for Denmark about 4000 (Brandt et al., 2017). Danish Center from Environment and Energy (DCE) has made an estimate of the impact on health due to cheating with SCR-catalyst in relation to an inquiry from the Danish Parliaments Transport, Building and Housing Committee (DCE memorandum, 2017). The estimate showed that about 7,500 people would die prematurely in Europe if 25% of all heavy-duty vehicles in Europe cheats with the SCR-catalyst, and that there would be about 70 premature deaths in Denmark alone. These premature deaths can be avoided if all SCR-catalysts are operating as intended.

These estimates take outset in only one control action and a crude and simple estimate of the impact on health. It is therefore the aim of this project to improve the knowledge on the extend of cheating with SCR catalysts in Denmark by carrying out measurements on several thousand heavy-duty vehicles that can detect cheating with SCR catalysts. Moreover, it is the aim of the present project to consolidate the estimate of the health impact related to cheating with catalysts by using data gathered from measurements.

1.2 Activities

The project is divided in the following activities:

1. Two measurement campaigns with direct measurement of the emissions of exhaust from individual heavy-duty vehicles during “real world” driving. These measurements are carried out with remote sensing and make it possible to determine whether or not cheating devices are been used in the heavy duty vehicles in order avoid use of the additive for the SCR catalyst. The measurement campaigns lasted one week each and were carried out at Padborg (20/11 – 25/11 2017) at the border to Germany and in Køge (27/11 – 1/12 2017) close to the Scandinavian Transport Center.
2. Determination of the Euro Class of the heavy-duty vehicles that has been measured with the remote sensing instruments. This is based on pictures of the number plate of the heavy-duty vehicles that are taken of each heavy-duty vehicles when it passes the instruments. Information of the Euro Class is obtained using the public available information from the motor registries.
3. Assessment of the impact of the cheating with the SCR catalysts on heavy duty vehicles on air quality and human health in Denmark. The assessment is based on the results from the measurements campaigns. This data is generalized to give an estimate of the cheating on a national level, and subsequently an estimate of the impact on air quality and human health is determined.

1.3 Organization

The project is carried out in a cooperation by NEQ ApS and DCE by the following key employees:

Jesper Risager Nielsen, NEQ ApS, Projektleader and responsible for activity 1, 2, and 4.
Christian Rud Ingvardsen, NEQ ApS
Senior researcher Thomas Ellermann, DCE. Responsible for activity 3.
Professor Ole Hertel, DCE
Senior advisor Morten Winther, DCE
Journalist Michael Strangholt, DCE
A number of other experts from NEQ ApS and DCE has been involved in the project as well.

NEQ ApS has the following subcontractors:

Åke Sjödin, Senior Project Manager, IVL Swedish Environmental Research Institute
Josefina de la Fuente, Managing Director OPUS RSE
Javier Buhigas, Director of Technical Consultancy, OPUS RSE
David A. Lizarazo Fernández, RSD Head of Operation, OPUS RSE

1.4 Guidance to the report

The report begins with a chapter describing the measurement campaigns with a short description of the method (further details can be found in appendix) and detailed description of the two campaigns and the measurement sites. This chapter describes also the work carried out in order to obtain the Euro Classes of the measured heavy-duty vehicles. The second chapter presents the results from the two measurement campaigns and relates the results from thus project with international findings. The third chapter describes the method for upscaling of the measured extend of cheating during the two campaigns to an estimate of the cheating on a national level and estimates of the impact of cheating on air quality and human health in Denmark. In the fourth chapter the results from this project is discussed in context of the other project carried out for the Danish Environmental Protection Agency as described above.

2. Methods

Two weekly measurement campaigns were carried out at Padborg (20/11 – 24/11 2017) at the border to Germany and in Køge (27/11 – 1/12 2017) close to the Scandinavian Transport Center, respectively. The aim of these measurement campaigns was to demonstrate the applicability of remote sensing measurements as an instrument for picking out heavy-duty vehicles suspected of cheating with SCR catalysts for subsequent police roadside inspection.

2.1 Remote Sensing measurements

Remote Sensing Devices (RSD) are specially designed emission analyzers that are placed along the roadside and that are capable of measuring individual vehicle exhaust emissions as the vehicles are passing the remote sensing devices (Figure 2.1). The remote sensing devises take a “snap shot” of the emissions from the exhaust tailpipe during less than a second. They can therefore be used to carry out measurements of emissions during normal driving conditions.

Two different remote sensing devises (AccuScan^{TM} RSD 4600 and AccuScan^{TM} RSD 5000) from the Spanish company OPUS RSE were used in parallel during the two measurement campaigns. The remote sensing devises consist of a Source and detector module and a mirror (Lateral Transfer Mirror). The Source and detector module sends two parallel light beams of infrared (IR) and ultra violet (UV) light across to the other side of the road where the light beams hit the mirror and is send back to the detector in the Source and detector module. The light beams are adjusted in such a way that they approximately are in the height of the tailpipes. This is done to ensure that the light beams traverses the center of the vehicles exhaust plume (for heavy-duty vehicles with exhaust tailpipe above the roof of the drivers cap this will of course not be the case). The IR and UV light is absorbed by the gasses in the exhaust plume and by detection of the magnitude of the absorbance it is possible to determine the ratio between various gasses and carbon dioxide (CO_2). From these ratios, the emissions of the gasses per kg fuel can be determined.

RSD 4600 measures the ratios of carbon monoxide (CO), hydrocarbons (HC), nitrogenmonoxide (NO) and Particulate Matter (PM). In addition to this, RSD 5000 measures nitrogen dioxide (NO_2). However, the measurements of NO_2 is a recent addition to the remote sensing devices and these measurements are not as robust as for the other compounds. In this study, where the focus is on determining cheat with SCR catalysts, focus is on measurements of nitrogen monoxide and nitrogen dioxide.

Two speed bars were applied alongside the remote sensing devices in order to measure the velocity and acceleration of the heavy-duty vehicles simultaneously with the emission measurements. The local meteorology (temperature, wind speed, wind direction, pressure and humidity) were measured on site with a weather station. All this data is used in connection with the interpretation and validation of the results. Especially humidity is important since the water vapor interfere with the concentration measurements. The remote sensing devices can therefore not be used during rain and snow. Moreover, the remote sensing devices cannot be operated at too low temperatures.

Two cameras (one for each remote sensing device) were used to take pictures of the heavy-duty vehicles simultaneously with passage of the remote sensing devices. The cameras are placed after the remote sensing devices in order to take pictures from the front of the heavy-duty vehicles (except the first two days in Padborg where the cameras by a mistake were placed so that they took pictures from the rear of the heavy-duty vehicles).

A sophisticated software ensures correct connection of all measurements (emissions, sped, meteorology) with the picture and number plate information for the heavy-duty vehicles. The software presets near real time results together with the pictures of heavy-duty vehicles (Figure 2.2).

The Spanish team operated the remote sensing devises, speed measurements and meteorology during the entire measurement campaigns. The remote sensing devises were calibrated regularly with certified calibration gasses in order to ensure accurate measurements (Figure 2.3). The Spanish team took care of the data handling and was responsible for the subsequent validation and quality control of the results. Subsequently NEQ and DCE received data for all validated measurements of exhaust from heavy-duty vehicles.

FIGURE 2.1. The setup for the remote sensing measurements with parallel measurements using RSD 4600 and RSD 5000. The measured heavy-duty vehicles passes between the Source and detector units and the mirror units. As can been seen there are about 1.5 m between the two instruments and the instruments are therefore not measuring on the exact same exhaust from the heavy-duty vehicle. Two cameras, one for each instrument, are placed about 10 m further up the road in order to take pictures of the heavy-duty vehicles from the front. There are also two set of speed bars, one for each instrument, that measures velocity and acceler-ation as close as possible to the emission measurements. The computers controlling and storing the measurement results are placed in the white van. The photo is taken at the measurement site in Køge.

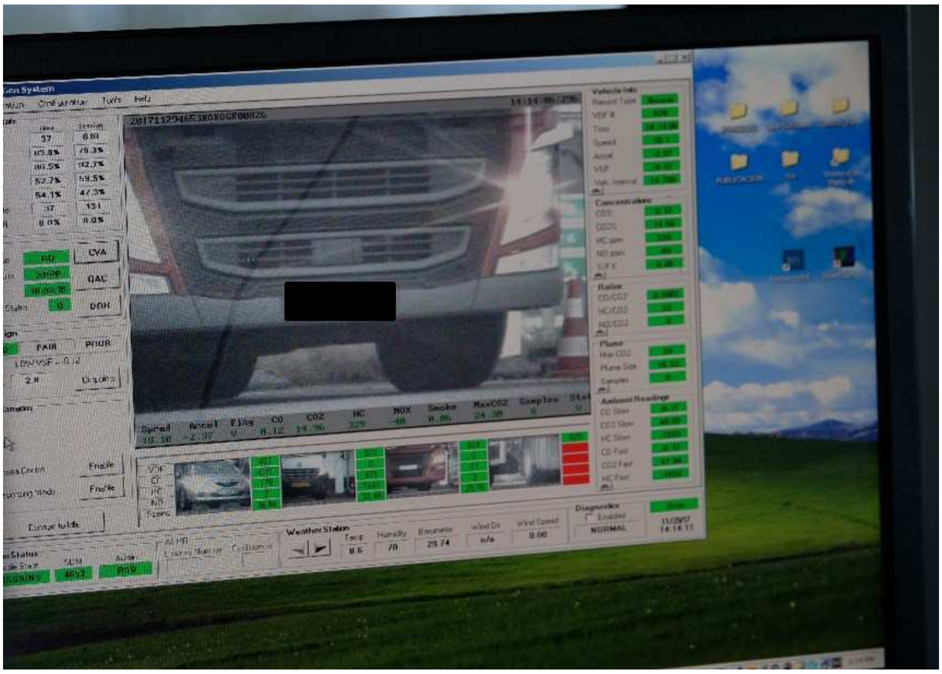


FIGURE 2.2. An example of the PC screen that shows the near real time results from the measurements. The large picture shows the vehicle that just has been measured while the smaller picture shows the four previous measured vehicles. The screen shows the measured concentra-tions, the ratios between the compounds and CO_2, speed - and meteorological data

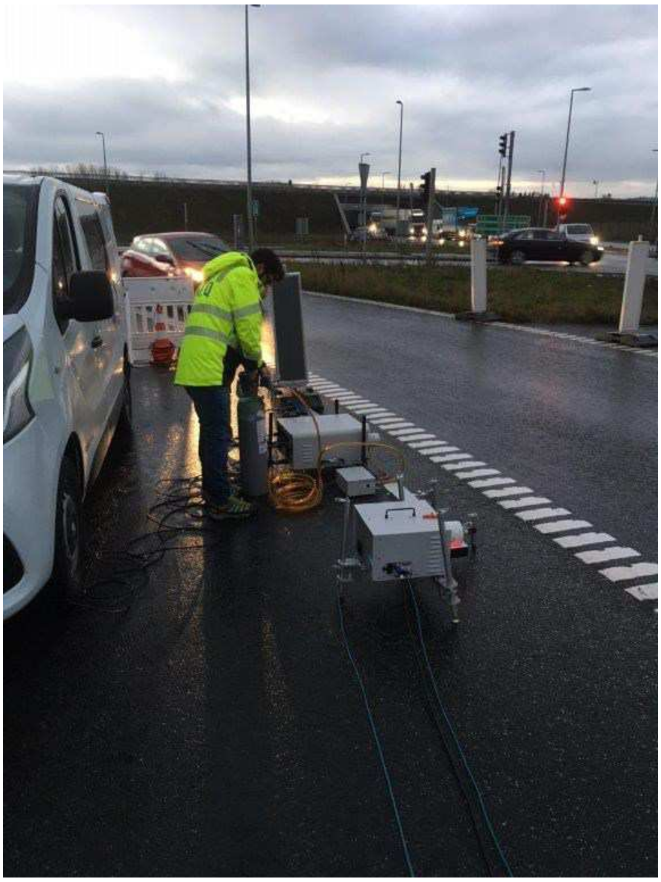


FIGURE 2.3. The remote sensing devices were calibrated several times during a day by use of certified calibration gasses.

2.2 Number plate information

The number plates were used to obtain information on the Danish heavy-duty vehicles. NEQ has access to a database that subtracts information directly from the Danish Register of Motor Vehicles operated by the Danish Tax Authorities. NEQ were able to make a query to the database and thereby collect information on thousands of vehicles in short time. At first hand, it is the Euro Standards that are most important for the analyses in this project, but information on brand and age was also collected.

Unfortunately, it was not possible to obtain access to databases containing information on the foreign heavy-duty vehicles during this project. The Euro Standard of the foreign heavy-duty vehicles was therefore obtained manually by visible inspection of the photos taken of all the heavy-duty vehicles. This manual inspection was based on information from the Danish Police that most often are able to determine the Euro Standard simply judged by the appearance of the heavy-duty vehicles. There is therefore a risk for misclassification of the Euro Standard for some of the heavy-duty vehicles.

2.3 Measurement sites

A number of requirements have to be fulfilled in order to obtain useful measurements of emissions using remote sensing devices. The requirements are as follows:

- The speed of the heavy duty vehicles is between 30 and 50 km/h.
- The heavy-duty vehicles are accelerating.
- It is a single lane because the distance between Source and detector unit and the mirror unit must not exceed 6 m.
- The road is slightly ascending in order to assure a proper load of the engine.
- The site has to be placed so that the engine of the heavy-duty vehicles is warmed up (about 20 min) in order to ensure proper functioning of the SCR catalyst.
- There has to be sufficiently space on both sides of the road for placement of equipment and the technicians van. The instruments have to be calibrated and adjusted so it is necessary for the technicians to be able to pass the road safely and legally.
- The number of heavy-duty vehicles passing the site has to be sufficiently large to ensure a large number of measurements.
- The site has to be safe for both traffic, technicians, and equipment.
- The measurements must not give to much disturbance of the daily traffic.

Four possible sites usable for the measurements campaigns were originally identified during a meeting between the Environmental Protection Agency, Danish Road Safty Agency , Danish Police and NEQ and DCE. However, two off these sites were subsequently disregarded since more detailed inspection of the sites showed that there were practical hindrances for carrying out the measurements at these sites. Finally, Padborg close to the Danish-German border and Køge at the Scandinavian Transport Centre were picked as the two sites for the measurements. Padborg could ensure measurements of a large number of foreign heavy-duty vehicles while Køge could ensure a large number of Danish and more local heavy-duty vehicles.

2.4 Measurements in Padborg

The measurement campaign campaign took place between Monday the 20th and Friday the 24th of November 2017 at the border control area in Padborg on E45 in the southern part of Jutland (Figure 2.4). The measurements were organized in cooperation with the Danish Police that helped with the permissions and enabled use of the Danish Polices normal setup for control of vehicles passing the border. The heavy-duty vehicles will be slowed down to 20-30 km/h at the control area and then hereafter they will accelerate to approximately 40-50 km/h while they pass the remote sensing equipment.

During Monday the 20th and Wednesday the 22nd the Danish Police carried out road site inspection of heavy duty vehicles that were picked out on the basis of the near real-time results from the remote sensing measurements. The heavy-duty vehicles were inspected for cheat or malfunctioning of the SCR catalysts. Further detail about this is given in Chapter 3.5.

FIGURE 2.4. The measurement site at E45 a few hundred meters north of the Danish-German border. The yellow pin marks the position of the measurements

FIGURE 2.5. Measurements at the Danish Polices control area at the Danish-German Border in Padborg on road E45 north bound. The source and detector unit is placed close to the white van at the left site of the road. The mirror is placed opposite at the right site of the road. The setup with the warning vehicle and warning signs is part of the Danish Polices normal arrangements for control of the vehicles passing the border

Padborg was an ideal measuring site for the following reasons:

- A high number of heavy-duty vehicles passing the border daily of which many are foreign export heavy-duty vehicles.
- It was possible to combine remote sensing measurements with Police roadside inspections.
- The heavy-duty vehicles are forced down to a slow speed and will have to accelerate when they pass the measurement site
- The heavy-duty vehicle drivers are used to controls at the site and they will therefore not change their driving pattern.
- The Danish Police has long experience with the setup.
- It is safe and it is easy to access the instruments for calibration and adjustments.

The only setback was the weather conditions. The weather was relatively cold and it rained two out of the five measurement days. This had negative impact on the quality of the results and the measurements had to be cancelled on two of the days. Moreover, the short daylight period in November reduced the time that the measurements could be carried out. The difficult weather conditions reduced the number of valid measurements to 393 heavy-duty vehicles, which is much less than expected but still quite high compared to similar studies (see Chapter 3.4).

2.5 Measurements in Køge

The second measurement campaign took place in Køge from Monday 27th November to 1st December 2017. The measurement site were located close to the Scandinavian transport Center on exit 32 on highway E20 about 3 km north of Køge (Figure 2.6).

The proximity to the Scandinavian Transport Center ensured that a large number of heavy-duty vehicles passed the measurements site every day. The majority of the heavy-duty vehicles were Danish. The two sites complemented therefore each other with mostly foreign heavy-duty vehicles at Padborg and mostly Danish heavy-duty vehicles at Køge. Moreover, a number of more local heavy-duty vehicles passed the site more than once enables us to obtain information on the reproducibility of the measurements.

The site was placed on a slight curve where the road is slightly ascending (Figure 2.6 and 2.7). The idea behind selection of the site was that the curve would slow down the heavy-duty vehicles to approximately 20-40 km/h and that the slightly ascending road forced them to accelerate at the measurement point. However, it turned out not to work that way. The measuring setup with the needed construction site markings together with the curve forced many of the heavy-duty vehicles to apply the breaks more or less corresponding to the position of the instruments. The initial setup was therefore slightly adjusted so that it worked out better for the majority of the period.

At the same time the Køge site did not have the same flexibility as the Padborg site, which did not give the Spanish operators much room for changes of the setup. The Spanish experts were due to their high experience able to make minor adjustments to the original setup. These changes made a big improvement in the measurements, making the Køge site an acceptable solution even though it was not perfect.

The weather conditions in Køge were quite unstable as in Padborg with temperatures around 5-10 degree Celsius and lot of rainy and misty weather too, which again made it difficult to measure. Despite the difficulties with the physical layout of the site and the weather conditions, 481 heavy-duty vehicles were measured during the five-day campaign.

FIGURE 2.6. The measurement site in Køge on exit 32 of highway E20 towards the Scandinavian Transport Centre. The yellow pin marks the position of the measurements.

FIGURE 2.7. The measurement site at the Scandinavian Transport Centre in Køge. The van and the Spanish crew are seen on the right site of the curved road. The Source and receiver units are placed just behind the warning signs and the mirror units are placed opposite at the left side of the road. The construction site markings were setup especially for this measurement campaign.

3. Results

3.1 Measured heavy-duty vehicles

During the two measurement campaigns in Padborg and Køge exhaust gases from a total number of 874 heavy-duty vehicles were measured successfully with the remote sensing equipment (Table 3.1). Euro V and VI accounted for 92 % of the heavy-duty vehicles and more than half of these were Euro VI. The heavy-duty trucks were roughly half Danish and half foreign.

It is heavy-duty vehicles with Euro Standards V and VI that use SCR catalysts in order to reduce the emissions of NO_x. For Euro Standard V only part of the heavy-duty vehicles use SCR catalysts. However, it has not been possible to distinguish between Euro V with or without SCR catalysts in this study.

EEV (Enhanced environmentally friendly vehicle) is a term used in the European emission standards for the definition of a "clean vehicle" > 3.5 tons. EEV lie between the levels of Euro V and Euro VI. There are only few EEV's measured during the measurement campaigns and they have therefore not been as thoroughly treated as Euro Standards V and VI.

The foreign heavy-duty vehicles were only Euro V and VI while there were also 11% of older Euro Standards among the Danish heavy-duty vehicles and about 4 % EEV. The lack of older Euro Standards among the foreign heavy-duty vehicles is expected since export heavy-duty vehicles normally drive longer per year than domestic heavy-duty vehicles, and they are therefore out-phased more rapidly than domestic heavy-duty vehicles. In addition, the Euro Standards of the foreign heavy-duty vehicles were determined by visible inspection of the pictures of the heavy-duty vehicles and here focus was on the recognition of the heavy-duty vehicles with Euro Standard V and VI.

TABLE 3.1. The number of heavy duty vehicles measured during this project divided in Euro Standards and Danish and foreign heavy-duty vehicles.

	Danish	Foreign	Total	Percentage
Euro I	1	0	1	0,1
Euro II	2	0	2	0,2
Euro III	18	0	18	2,1
Euro IV	30	0	30	3,4
Euro V	132	171	303	35
EEV	17	0	17	2
Euro VI	249	254	503	58
Total	449	425	874	100

There were distinct difference in the distribution of heavy-duty vehicles measured in Padborg and Køge (Table 3.2). About 75% of the foreign heavy-duty vehicles were measured at Padborg at the Danish-German border, and only about 25% were foreign in Køge. For the Danish heavy-duty vehicles, it was the other way around with about 83% measured in Køge and only 17% in Padborg. Moreover, nearly all the heavy-duty vehicles with older Euro Standards were measured in Køge. The latter demonstrates that the older heavy-duty vehicles are used primarily for more local goods transport and not for export.

TABLE 3.2. The number of heavy duty vehicles measured in Padborg and Køge divided in Euro Stand-ards and Danish and foreign heavy-duty vehicles

	Padborg		Køge	
	Danish	Foreign	Danish	Foreign
Euro I	0	0	1	0
Euro II	0	0	2	0
Euro III	0	0	18	0
Euro IV	6	0	24	0
Euro V	15	141	117	30
EEV	1	0	16	0
Euro VI	52	178	197	76
Total	74	319	375	106

3.2 Uncertainty of measurements

During the measurement campaigns two instruments were used in parallel (RSD 4600 and RSD 5000) and 134 of the heavy-vehicles were measured successfully with both instruments. Moreover, a number of trucks passed the measurement site in Køge several times. The results from the parallel and repeated measurements gives information on the quality of the results.

Table 3.3. shows two examples on the repeatability of the measurements. These examples have been selected in order to illustrate how it looks in case of respectively good and bad repeatability. The first case is a new Scania Euro VI, with good repeatability between both the parallel measurements (averages of RSD 4600 and RSD 5000) and the individual measure-ments, and this is despite the concentrations in the emission are quite low. The second is an Iveco Stralis EEV from 2012 where both the parallel and individual measurements disagree. Figure 3.1 shows the difference between the results for the 134 heavy-duty vehicles that have been measured with both of the parallel instruments. In general, there is good agreement between the results from the two different instruments, although there also are cases with large disagreement.

TABLE 3.3. Examples of parallel and repeated measurements of the same heavy-duty vehi-cles in Køge. The first is a Scania Euro VI from 2017 where there is good agreement between the repeat-ed measurements with the same instruments as well as between the two instru-ments. The second is an Iveco Stralis EEV from 2012 where there is large difference between the two different instruments and also between the individual measurements with RSD 5000

Heavy-duty vehicle		Instrument	Average	Standard deviation	Individual measurements						
First	Euro VI	RSD 4600	**0.14**	0.16	0.7	0.00	0.37	0.05	0.32	0.19	-0.03
		RSD 5000	**0.26**	0.25	0.44	0.08					
Second	EEV	RSD 4600	**0.49**	0.65	-0.01	0.27	1.23				
		RSD 5000	**9.82**	10.18	2.62	17.02					

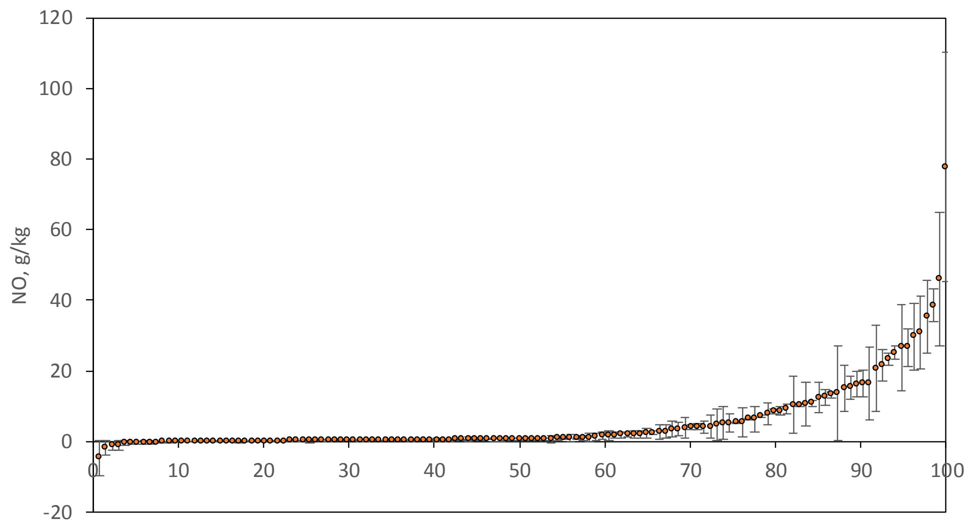


FIGURE 3.1. Results from the parallel measurements with RSD 4600 and RSD 5000 of 134 heavy-duty vehicles ranked with increasing emissions of NO. The x-axis show the percentiles of the heavy-duty vehicles with emissions lower than a given value. The dots show the average of the results from both instruments and the "error bars" shows the individual results from the two instruments. The average is used, if a heavy-duty vehicle has been measured more than one time with each of the instruments.

The reason for the difference between the results is to be found in the uncertainties connected with the actual measurements with the instruments, but also differences between the conditions under which the parallel and repeated measurements are carried out. The instruments take a snap shot during a few seconds of the exhaust from the heavy-duty vehicles. There are therefore a number of factors that can lead to differences in the results from the parallel and repeated measurements:

- RSD 4600 and RSD 5000 can only be placed with a few meters distance. It is therefore not exactly the same air that the instruments are measuring.
- In the cases where the heavy-duty vehicles passed the measurement site in Køge several times, this is most likely due to local traffic in the area around the measurement site. Some of the passages may therefore have taken place where the SCR catalyst did not have sufficient temperature to function properly.
- The measurement site in Køge where placed in a curve. It was clearly visibly on the site that some of the heavy-duty vehicles for example had to apply the brake in level with the instruments. This will most likely lead to larger differences in the measurement conditions than at a more ideal location of the instruments.
- Some heavy-truck drivers may become aware of the measurements and although they may not know what is being measured, they may consciously alter their driving pattern from the first to the next passages of the measurement site.
- The site in Køge is on the way to the Scandinavian Transport Center, and it is therefore likely that the repeated passages of the measurement site takes place after stop at the transport center. They may therefore not carry the same load at each passage.
- The Scandinavian Transport Center includes possibilities for refilling of add-blue. It might in the worst case be that a heavy-duty truck have run out of add-blue, and that it is on its way to refilling. Some passages may therefore take place with and without add-blue.

The RSD 5000 instrument is normally able to measure NO_2 as well as NO while RSD 4600 only measures NO. Figure 3.2 shows a comparison between measured emissions of NO and NO_2. We will expect some form of correlation between NO and NO_2 with a tendency for higher NO_2 emissions together with higher NO emissions. However, the results shows that there is no correlation between NO and NO_2. Moreover, there are several high negative emissions of NO_2. There has therefore been some kind of error in the measurements of NO_2, and these results will therefore not be used in this project.

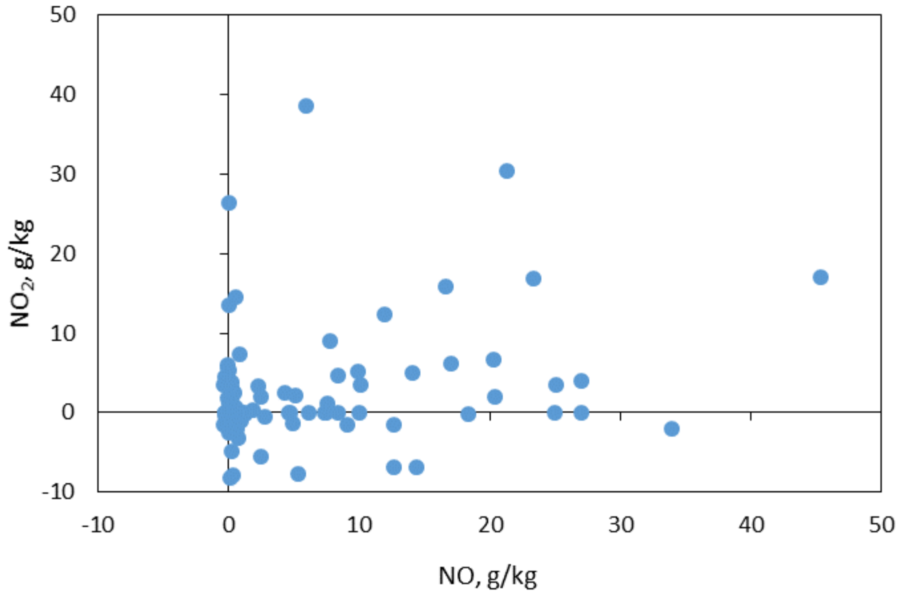


FIGURE 3.2. Emissions of NO_2 as function of NO. The measurements are carried out with RSD 5000.

It is obvious from the parallel and repeated measurements that there are some variability in the results from the remote sensing measurements of the emissions of NO. However, this variability is most likely not due to errors in the measurements themselves, but due to variations in the measurement conditions. On the other hand, there are for the majority of the parallel and repeated measurements reasonably good agreement between the results. It is therefore concluded that the quality of the results are sufficient for the scope of this project i.e. to be able to pick out heavy duty trucks when there is suspicion of malfunction or cheat with the SCR catalyst.

3.3 NO emissions

Figure 3.3 and table 3.4 shows the results for the average emissions of NO for all 874 heavy-duty vehicles given as averages for the different Euro Standards. The averages are compared to emission factors that are used by DCE as input to the Danish national emission inventories for emissions of NO_x from road transport with heavy-duty vehicles in Denmark. Note that the measured emissions are only NO while the emission factor are NO_x that includes both NO and NO_2. For heavy duty vehicles, the directly emitted NO_2 accounts for about 20% of Euro III, 10% for Euro IV and V, and 35% for Euro VI (Sjödin et al, 2017) of the total emission of NO_x. The specific emission factors presented in figure 3.3 and table 3.4 represents urban road transport (set to 30 km/h) with heavy-duty vehicle between 40 and 50 tons and 50% load. These conditions do not apply for all the measured heavy-duty vehicles. There are therefore differences between measured emissions and the DCE emissions factors, and the comparison

shall therefore only to be seen as a rough indication on how our measurements agree with the national emission inventories.
The DCE emission factors are based on the European COPERT 5 road transport emission model documented in the EMEP/EEA air pollutant emission inventory guidebook (formerly called the EMEP CORINAIR emission inventory guidebook), please refer to EMEP/EEA (2016). The COPERT 5 emission factors are based on experiences based on are large number of international studies and are those that are applied as basis for the national emission inventories reported by many EU member states to the EU and the UNECE Convention on Long Range Transboundary Air Pollution (CLRTAP convention). The emission factors used in COPERT are for the older Euro Standards higher than specified in the Euro Standards due to the fact that the majority of the heavy-duty vehicles have higher emissions under actual driving conditions than under test conditions.

The units of the emission factors of NO_x are usually given in g/km as equivalents of NO_2. In order to compare to the results from the remote sensing instruments they are converted to gNO_2/kg using average fuel consumption per km as used in the Operational Street Pollution Model (OSPM; Kakisimos et al., 2010). The numbers are given in table 3.5.

The OSPM is used together with DCEs other air quality models to calculate air concentrations of NO and NO_2 in Denmark (Kakisimos et al., 2010). The emission factors used in the model calculations are also shown in table 3.5. There are good agreements between the input parameters used for the national emission inventory and the model calculations except for Euro VI that lack an update of this parameter in the models (this will be updated in coming model calculations).

For Euro I and II there are only a few measurements and hence these averages are not representative for the average of all Euro I and II in Denmark. For Euro III and IV the number of measurements are higher but still not large enough to be representative for the average emissions from these Euro norms. Both Euro III and IV are significantly higher than the DCE emission factors. For Euro V and VI the numbers of heavy-duty vehicles are considerably higher and the averages are therefore expected to give a good indication of the average emissions from heavy-duty vehicles with these Euro Standards in Denmark. The average measured emissions for Euro V and VI are in relative good agreement with the DCE emission factors. Moreover, Euro V is about a factor of two lower than Euro IV and Euro VI are again more than 10 times lower than Euro V. Similar picture are seen in other European studies (se chapter 3.4).

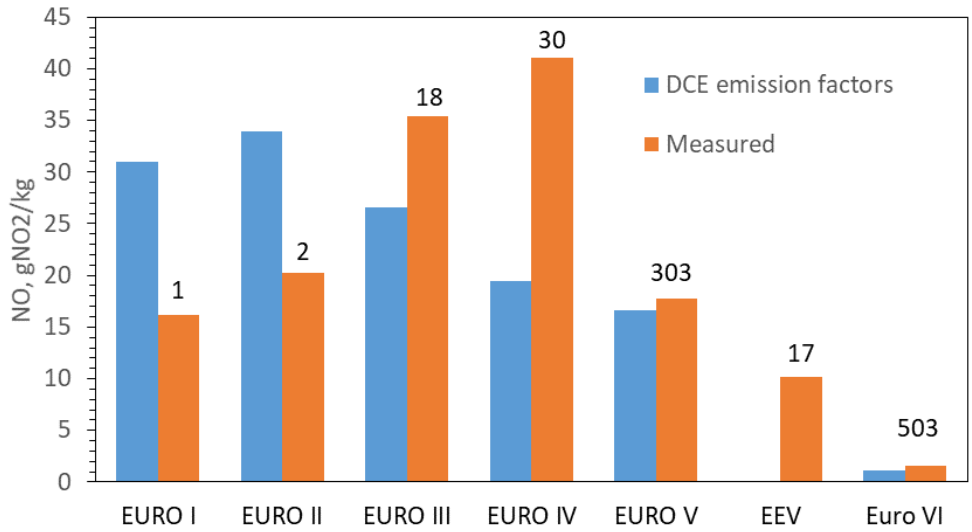


FIGURE 3.3. Average emissions of NO for the different Euro Standards compared to the DCE emission factors. The emissions of NO are given in NO_2 equivalents (gNO_2/kg). The numbers above the orange columns show the number of heavy-duty vehicles in the different categories.

TABLE 3.4. Number of heavy-duty vehicles, DCE emission factors, average, minimum and maximum emissions of NO for the different Euro norms. The emissions are given in NO_2 equivalents (gNO_2/kg).

	Number of vehicles	DCE emission factors gNO_2/kg	Average	Minimum	Maximum
Euro I	1	31	16		
Euro II	2	34	20	17	24
Euro III	18	27	35	12	68
Euro IV	30	19	41	1,6	78
Euro V	303	17	18	-3,6	75
EEV	17		10	0,2	32
Euro VI	503	1,2	1,5	-7,9	79
Total	874		9,4	-7,9	79

TABLE 3.5. Average fuel consumption and emission factors used as input parameters for the model calculations with the operational street pollution model (reference), and for the Danish na-tional emissions inventories prepared annually by DCE (Nielsen et al., 2017). The emission factors have been converted to units of gNO_2/kg fuel by division with the average fuel con-sumption. This enables a direct comparison between the emission factors and the results from the remote sensing measurements.

	Fuel comsumption	OSPM emission factors		DCE emission factors	
	g/km	gNO_2/km	gNO_2/kg	gNO_2/km	gNO_2/kg
Euro I	423	14	33	13	31
Euro II	413	15	35	14	34
Euro III	425	12	28	11	27
Euro IV	395	7	18	8	19
Euro V	403	7	18	7	17
Euro VI	402	0,9	2,1	0,5	1,2

Figure 3.4 shows the distribution of NO emissions for both the Danish and foreign the heavy-duty vehicles. The emissions are primarily ranked with respect to Euro Standard and secondly with increasing emissions. The figure shows also the DCE emission factors. For Euro I to IV less than 50% of the heavy-duty vehicles lie below the DCE emission factors. For Euro V about half of the heavy-duty vehicles lie below the DCE emission factors. The improvements with Euro VI is clearly visible with more than 80% lying below the DCE emission factors. Interestingly, the worst emitters are roughly on the same level independently of the Euro Standard.

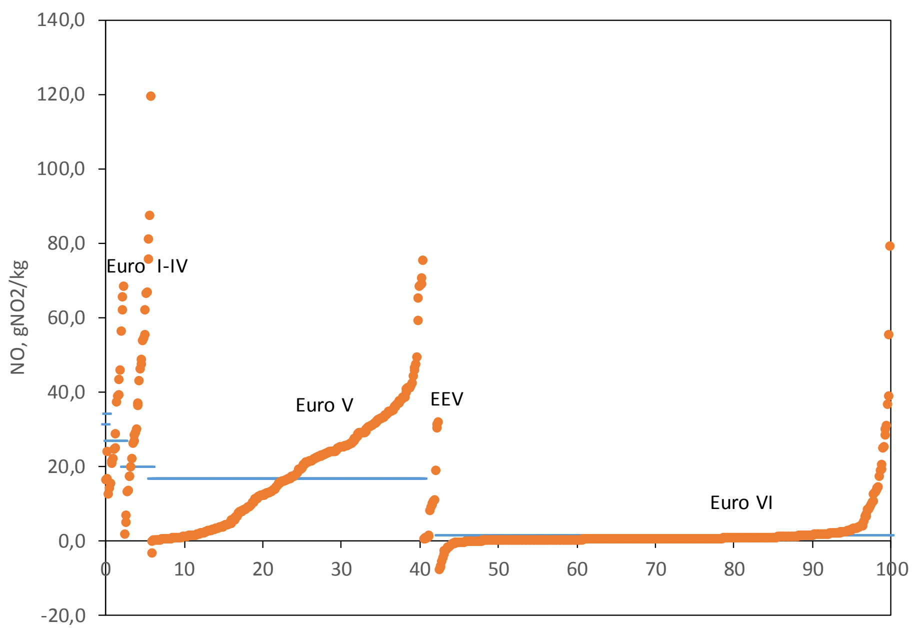


FIGURE 3.4. The distribution of NO emissions ranked primarily after the Euro Standards and secondly after increasing emissions. The emissions are given in NO_2 equivalents. The blue lines show the DCE emission factors for the different Euro Standards.

In table 3.6 and 3.7 the emissions are split in Danish and foreign heavy-duty vehicles. The table for foreign heavy-duty vehicles shows only Euro V and VI since no heavy-duty vehicles were measured for the other Euro Standards. The emissions from the foreign Euro V and VI heavy-duty vehicles are 50 % and 31 % higher than the Danish heavy-duty vehicles, respectively.

TABLE 3.6. Number of Danish heavy-duty vehicles, DCE emission factors, and average, minimum and maximum emissions of NO for the different Euro Standards. The emissions are given in NO_2 equivalents (gNO_2/kg).

	Number of vehicles	DCE emission factors gNO_2/kg	Average gNO_2/kg	Minimum gNO_2/kg	Maximum gNO_2/kg
Euro I	1	31	16		
Euro II	2	34	20	17	24
Euro III	18	27	358	12	68
Euro IV	30	19	41	1,6	78
Euro V	132	17	14	-0,4	71
EEV	17		10	0,2	32
Euro VI	249	1,2	1,3	-4,8	79
Total	449		9,4	-4,8	79

TABLE 3.7. Number of foreign heavy-duty vehicles, DCE emission factors, and average, minimum and maximum emissions of NO for Euro Standard V and VI. The were no foreign heavy duty vehicles for the other Euro Standards. The emissions are given in NO_2 equivalents (gNO_2/kg).

	Number of vehicles	DCE emission factors gNO_2/kg	Average gNO_2/kg	Minimum gNO_2/kg	Maximum gNO_2/kg
Euro V	171	17	21	-3,6	75
Euro VI	254	1,2	1,7	-7,9	55
Total	425		9,4	-7,9	75

Figure 3.5 and 3.6 shows the distribution of the NO emissions divided in Danish and foreign heavy-duty vehicles for Euro V and VI, respectively. For Euro V there is a large difference between the emissions from Danish and foreign heavy-duty vehicles. The lowest and worst emitters looks approximately similar, but for the middle range (about 10 to 85 percentile), the foreign heavy-duty trucks have significantly higher emissions than the Danish heavy-duty vehicles. For Euro VI the distribution looks similar for Danish and foreign heavy-duty vehicles with relative low emissions for more than 90% of the heavy-duty vehicles.

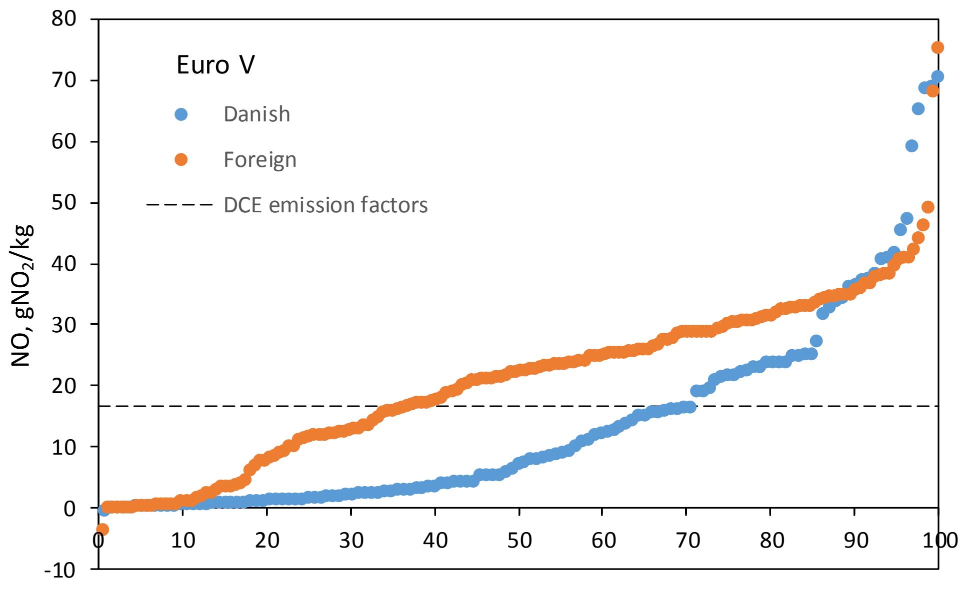


FIGURE 3.5. Distribution of NO emissions ranked after increasing emissions for Danish and foreign Euro V vehicles. The emissions are given in NO_2 equivalents.

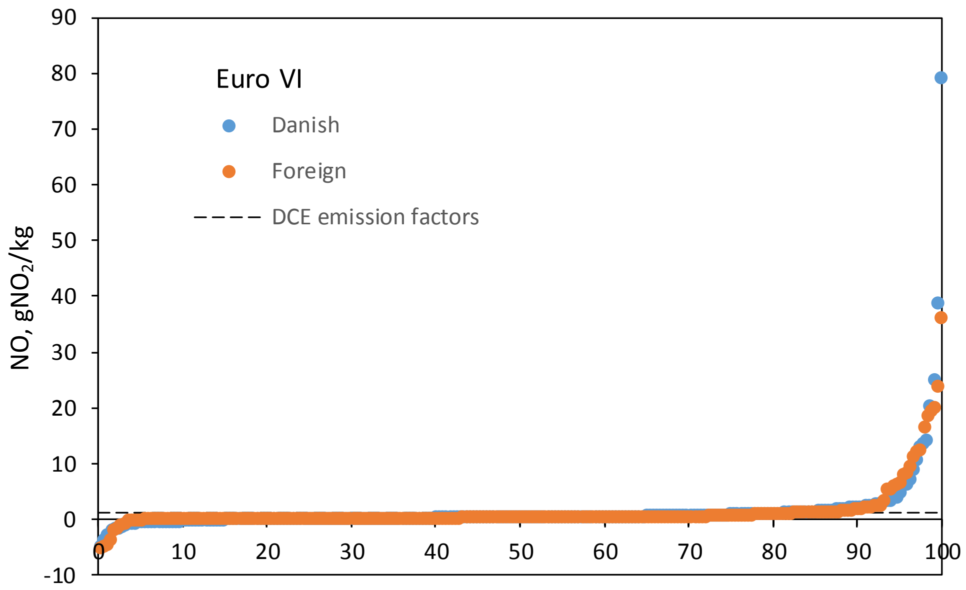


FIGURE 3.6. Distribution of NO emissions ranked after increasing emissions for Danish and foreign Euro VI vehicles. The emissions are given in NO_2 equivalents

The distributions for the NO emissions are relatively smooth and there are no large jumps in the distributions that could indicate a threshold above which there are malfunctioning or cheat with the SCR catalysts. The distribution for the Danish Euro V heavy-duty vehicles show a small jump at around 25 gNO_2/kg that might indicate such a threshold; however, this is not seen for the foreign heavy-duty vehicles. For Euro VI there is a steep increase in emissions above 3 gNO_2/kg indicating a kind of threshold for the onset of malfunctioning or cheat with SCR catalysts.

Thresholds of 25 and 3 gNO_2/kg for Euro V and VI, respectively, is therefore suggested as thresholds for future use of remote sensing measurements as guide for picking out heavy-duty vehicles for the roadside inspections carried out by the Danish police (this corresponds to a ratio between NO and CO_2 of 0,0052 and 0,0006 mole/mole. On the instrument screens, this will be seen as 52 and 6). Hager (2017) suggested a threshold of 20 gNO_2/kg independent on Euro Standard based on a large remote sensing study carried out for the West Lothian Government, Scotland. The Hager threshold value is in reasonably agreement with our suggestion.

It should be emphasized, that these thresholds have to be seen as simple guidelines based on visible inspection of the distribution curves and that they shall be revised during future campaigns with remote sensing measurements combined with roadside inspection. This revision can be based on comparison of the results from the remote sensing measurements with the information that the Police gathers during their roadside inspections.

3.4 Comparison with international remote sensing studies

Two international remote sensing measurement studies has been carried out in Scotland and Sweden in 2016 (Hager, 2017; Sjödin et al., 2017). The results from these studies are compared to the results from this study in figure 3.7. For Euro II to IV there are relatively few heavy duty trucks measured in the Danish and Swedish studies and the averages are therefore not representative for the fleet of heavy-duty vehicles. For Euro V and VI the number of measured heavy-duty vehicles are considerable higher and it is therefore expected that the averages give a reasonable picture of the fleets. The results for this study and Sjödin et al. (2017) are in quite good agreement while the results from Hager is somewhat higher for both Euro V and VI. Part of these differences are due to uncertainties of the measurements and that there most likely are differences in the fleets of heavy-duty vehicles in Denmark, Sweden and Scotland.

All three studies show nearly the same pattern for the changes between the Euro Standards. The highest emissions are for Euro III and IV and then stepwise significant improvements are seen for Euro V and VI.

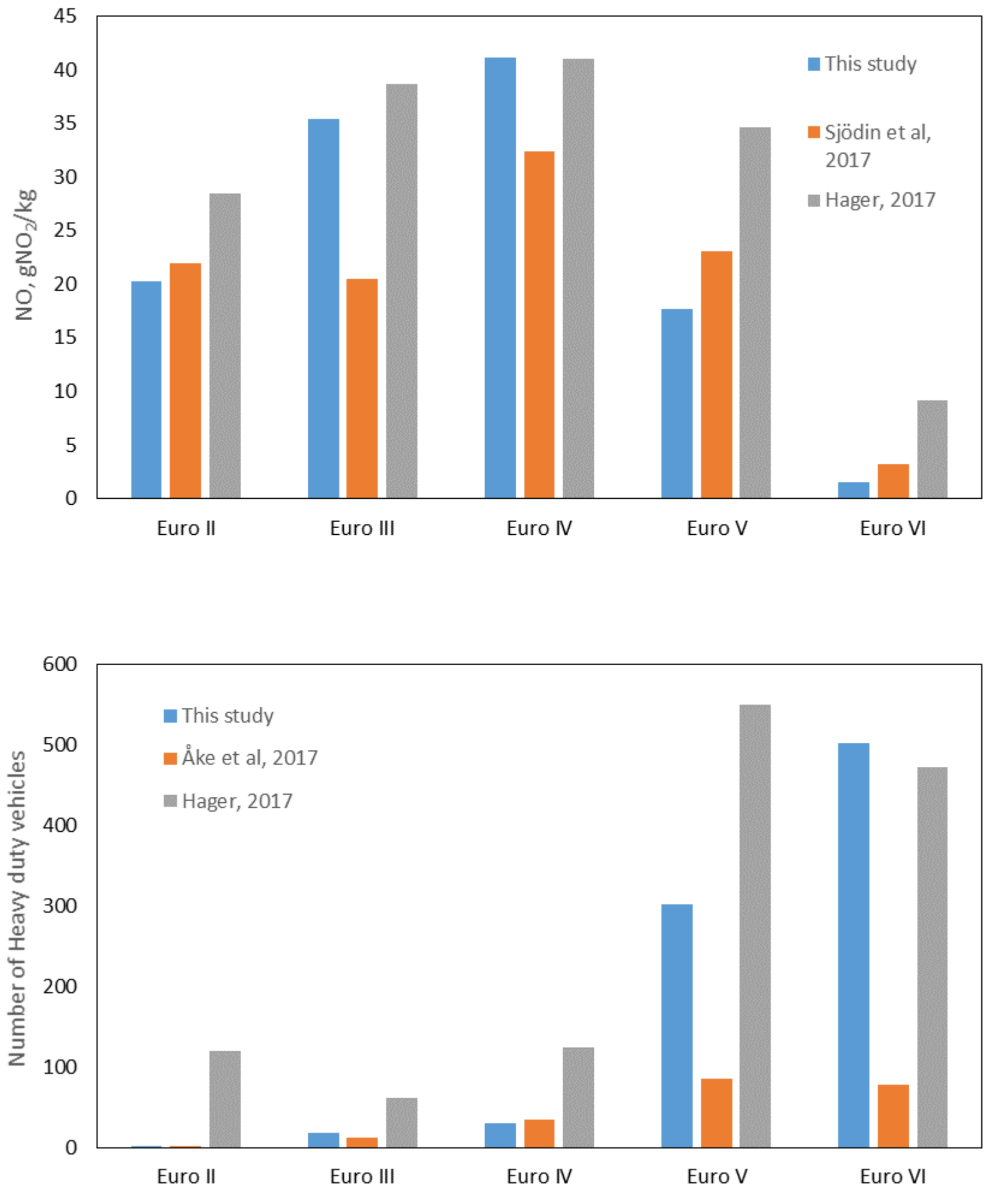


FIGURE 3.7. Average NO emissions (above) for the different Euro Standards determined in this study, Sjödin et al. (2017) and Hager (2017) and number of heavy-duty vehicles measured in the different sturdies (below). The units for emissions are calculated in NO_2 equivalents. The results from Sjödin et al. (2017) has been read from graph showing the total emission of NO_x and subsequently we have subtracted the NO_2 part of the emission based on Sjödin et al.'s (2017) measured ratio between NO_2 and NO_x. The results from Hager (2017) has been read from graph showing the ratio of the emissions of NO and CO_2 and subsequently recalculated to emissions of NO in gNO_2/kg fuel using the amount of CO_2 emitted per kg fuel.

3.5 Police roadside inspection of heavy-duty trucks at Padborg

During the remote sensing measurement campaign at the Danish-German Border in Padborg the Danish Police carried out road side inspection of heavy-duty vehicles (20 and 22 November 2017). The heavy-duty vehicles were selected for inspection based on the real time measurements of the emissions of NO. When the emissions of NO from heavy-duty vehicles were above a certain threshold, it was picked out for inspection immediately after the measurements. The Police inspected nine heavy duty vehicles during the measurement campaign. They found two foreign Euro V heavy-duty vehicles that used cheating devices (Figure 3.8) and three heavy-duty vehicles with malfunctioning SCR catalysts (for example lack of Adblue in the tank or defect sensor). The first attempt to combine remote sensing measurements of emissions with Police road side inspection was therefore successful.

The threshold for picking out heavy-duty vehicles were at the beginning set to 400 ppm NO, but the experience were that the threshold were too low and it was raised to 600 ppm. Unfortunately, the number plates of the inspected heavy-duty vehicles were not recorded. It has therefore not been possible to combine the information from the inspections with the results from the remote sensing measurement in order to select the best possible threshold for picking out heavy-duty vehicles for inspection.

FIGURE 3.8. Picture of cheating device found in one of the heavy duty vehicle that was inspected by the Danish Police in Padborg.

During the first campaign, the threshold used was the NO concentration measured in the exhaust. However, this parameter depends strongly on the distance between the exhaust and the measurement point, the shape of the heavy-duty vehicle, position of exhaust pipe (below truck bed or above drivers cab), wind speed etc. It would therefore have been better to use a threshold for the ratio between the emissions of NO and CO_2.

4. Impacts of cheating wit SCR catalysts on air quality and human health

In this chapter we will elaborate on the impact on health of the cheating with SCR filters on heavy duty-vehicles. In order to extrapolate the results from the two measurement sites to the entire road network, we will initially look at the distribution of heavy-duty vehicles in Denmark. Then we will summarize current knowledge on health effects related to air pollution in Denmark, and finally we will with outset in a previous very crude estimate, combine this information to a best estimate of the health effects related to cheating with CRT filers on heavy-duty vehicles in Denmark.

4.1 Distribution of heavy-duty vehicles in Denmark

When the European Commission adopt a new Euro standard, vehicles bought after the time of implementation need to comply with the standard set by this Euro standard. Since the vehicles have, a certain lifetime that especially for heavy-duty vehicles may be long, vehicles complying with older Euro standard will be present on the road network for a number of years. Figure 4.1 shows the distribution on Euro standard in Danish road traffic for four different vehicle categories (gasoline (petrol) and diesel passenger cars, light duty vehicles and trucks and busses).

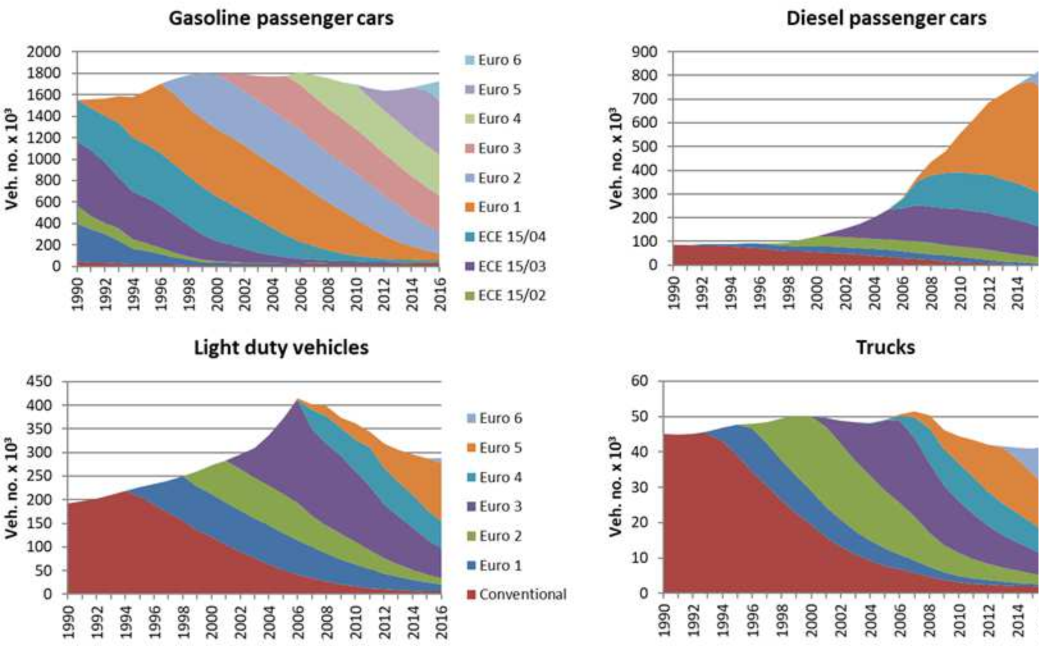


FIGURE 4.1. Distribution in 1990-2016 of vehicle numbers according to Euro standard for gasoline pas-senger cars (upper left), diesel passenger cars (upper right), light duty vehicles (lower left), and trucks and busses (lower right), respectively (Nielsen et al., 2017).

The data in Figure 4.1 concern data up to 2016. Data for 2017 have not yet been available. However, the heavy-duty trucks are substituted relatively fast, since they are driving on the roads almost continuously and fast reach a vast number of kilometers. A crude estimate for the number of Euro VI heavy-duty vehicles in 2017 is thus in the order of 50 to 60%.

4.2 Health effects of air pollution in Denmark

The health effects and the associated externalities (economic burden on the society) related to air pollution in Denmark have been calculated using the EVA system and presented in the annual monitoring report for 2016 (Ellermann et al., 2017). A calculated average health outcome for the years 2014-2016 is shown in Table 4.1. These model calculations were made on basis of emission inventories for year 2015. This applies therefore also for road traffic data and related air pollution emissions. The distribution on Euro standard has changed substantially over the most recent year (see section 4.1), and the fraction of heavy-duty vehicles on Euro VI is therefore substantially underestimated in these inventories. This means that the figures in Table 4.1 will be somewhat overestimated and that figures for 2017 will be further reduced.

TABLE 4.1. The number of cases for the different health outcomes in the EVA model system due to the total air pollution concentrations as a mean over the three years 2014-2016 for the whole of Denmark.

Health outcome	Number of cases
Chronic Bronchitis	3.390
Restricted Activity Days	3.460.000
Respiratory Hospital Admissions	176
Cerebrovascular Hospital Admissions	422
Congestive Heart Failure	388
Lung Cancer	518
Bronchodilator Use Children	86.800
Bronchodilator Use Adults	662.000
Cough Children	300.000
Cough Adults	682.000
Lower Respiratory Symptoms Children	116.000
Lower Respiratory Symptoms Adults	246.000
Acute premature deaths (SO_2)	10
Acute premature deaths (O_3)	120
Chronic YOLL ($PM_{2,5}$)	36.600
Total no. of premature deaths	3.580
Infant mortality ($PM_{2,5}$)	3

Most of these health outcomes are related to pollutant contributions from foreign sources. In fact, the figures for premature deaths related to pollutant contributions from foreign sources have been calculated to 76% or 2,730 cases, whereas the calculations indicate that Danish sources account for about 850 annual premature deaths. However, it should be noted that Danish sources contribute to about 2,280 annual premature deaths in our neighboring countries.

Most of the health effects of air pollution are related to particulate matter, and current assessments are mainly based on fine fraction particles, $PM_{2.5}$. Emissions of nitrogen oxides contribute to the formation of $PM_{2.5}$, but the formation takes time – about one days transport in the atmosphere is typically needed for this conversion to take place. This means that most of the nitrogen oxides emitted from Danish sources will be transported out of the country before being converted into particles. In recent years, there has been a debate in the scientific community concerning a direct effect of NO_2. Such a direct effect of NO_2 is not yet implemented in the EVA system, but the European Environment Agency have included a direct effect of NO_2 in their estimates of premature deaths (EEA, 2016), and find that for Denmark 2% of premature deaths related to air pollution can be associated with exposure to NO_2. This means that the total number of annual premature deaths in Denmark may be 50-70 too small.

4.3 Health effects related to cheating with SCR in Denmark

In a technical note to the Danish EPA, DCE has previously made a crude estimate of the health effects related to cheating with SCR catalysts on heavy-duty vehicles in Denmark (Brandt et al., 2017). In these estimates, it was assumed that 25% of all heavy-duty vehicles were cheating with SCR catalysts-filters, and that such a cheating vehicle would emit 10 times as much as one in compliance with the Euro standard. The selection of the figure 25% as the number cheating was made on basis of the figures obtain in a police campaign at the Danish-German boarder earlier in 2017. This assumption was based on the fact than SCR catalysts normally remove more than 90% of NO_x in the exhaust. Applying these figures for heavy-duty vehicles in Denmark, this would then lead to an increase in emissions from the total road traffic sector of 9%.

In Europe, it has been estimated that annually about 500,000 people die prematurely due to air pollution (Brandt et al., 2017). In case 25% of heavy-duty vehicles in Europe are cheating with SCR catalysts, this would lead to annually additional 7,500 premature deaths in Europe and 70 premature deaths in Denmark. In case 25% of heavy-duty vehicles in Denmark are cheating, and disregarding similar cheating in Europe, this would lead to additional 3-4 premature deaths annually.

In the present study we have carried out remote sensing measurements in order to pick out heavy-duty vehicles where the emission of NO_x is so high that there is suspicion for cheating with the SCR catalysts. However, we have actually not confirmation whether or not these heavy-duty vehicles are cheating or not. Despite this, the present study indicate, that the number of heavy-duty vehicles that are cheating, is less than 25%. The measurements of emissions indicate that many of those vehicles that may be cheating emit less than 10 times what they would have emitted in case the SCR catalysts were operating. This indicates that the effect of cheating on the health effects in Denmark is less than the previous crude estimate.

In this study the composition of heavy-duty vehicles monitored at the Padborg and Køge measurement sites are more modern than the overall Danish fleet composition for 2015 used in the previous assessments of health effects related to cheating with SCR catalysts in Denmark. The fleet composition found in this study indicates that today Euro VI heavy-duty vehicles accounts for about half of the Danish heavy-duty vehicle fleet.

The results also show that the NO_x emission factors measured for Euro V and VI heavy-duty vehicles are significantly lower than for the previous Euro standards, which is also the case for the emission factors used in the previous health assessment calculations made by DCE. The Euro V and VI emission factors are about half and less than one tenth of Euro IV, respectively.

Predominantly due to the updated heavy-duty fleet composition, the emissions from heavy-duty vehicles in this study are lower than the emissions in the previous health effect calculations presented by DCE. This also means that the health effects in Denmark was somewhat overestimated in previous assessments building on the Danish 2015 fleet composition and that health effect figures will decrease further when model results using based on the actual vehicle fleet in Denmark for 2017 are available.

As previously stated, the estimates of health effects related to cheating with SCR catalysts in Denmark that were presented in Brandt et al. (2017) pointed at 3-4 premature deaths in Denmark. The results from the present work indicate that this figure is somewhat to the high end, but currently there is not available traffic and emission data to quantify this better by specific model calculations with DCE models.

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