CONTROL OF SCR-SYSTEMS USING ROADSIDE REMOTE SENSING

Results from road experiments 2019

Scientific Report from DCE – Danish Centre for Environment and Energy No. 387 2020

AARHUS UNIVERSITY
DCE – DANISH CENTRE FOR ENVIRONMENT AND ENERGY

[Blank page]

CONTROL OF SCR-SYSTEMS USING ROADSIDE REMOTE SENSING

Results from road experiments 2019

Scientific Report from DCE – Danish Centre for Environment and Energy No. 387 2020

Ole Hertel[1]
Christian Rud Ingvardsen[2]
Thomas Ellermann[1]
Jacob Klenø Nøjgaard[1]

[1] Aarhus Universitet, Institut for Miljøvidenskab
[2] NEQ

AARHUS UNIVERSITY
DCE – DANISH CENTRE FOR ENVIRONMENT AND ENERGY

Data sheet

Series title and no.:	Scientific Report from DCE – Danish Centre for Environment and Energy No. 387
Category:	Scientific advisory report
Title:	Control of SCR-systems using roadside remote sensing
Subtitle:	Results from road experiments 2019
Authors:	Ole Hertel[1], Christian Rud Ingvardsen[2], Thomas Ellermann[1], Jacob Klenø Nøjgaard[1]
Institutions:	[1]Aarhus Universitet, Institut for Miljøvidenskab [2]NEQ
Editors:	Christian Rud Ingvardsen, NEQ
Publisher:	Aarhus University, DCE – Danish Centre for Environment and Energy ©
URL:	http://dce.au.dk/en
Year of publication:	August 2020
Editing completed:	August 2020
Assessor:	Claus Nordstrøm
Quality assurance, DCE:	Vibeke Vestergaard
External comments:	The comments can be found here: http://dce2.au.dk/pub/komm/N2020_387_komm.pdf
Financial support:	Danish Environmental Protection Agency
Please cite as:	Hertel, O, Rud Ingvardsen, C., Ellermann, T., Klenø Nøjgaard, J., 2020. Control of SCR-systems using roadside remote sensing. Results from road experiments 2019. Aarhus University, DCE – Danish Centre for Environment and Energy, 124 pp. Scientific Report No. 387 http://dce2.au.dk/pub/SR387.pdf Reproduction permitted provided the source is explicitly acknowledged

Abstract:	The current project presents results of field campaign studies with roadside remote sensing equipment for online detection of road traffic emissions of nitrogen oxides from individual vehicles. The aim was to test the options for creating a control system for online identification of malfunctioning SCR systems in the on road heavy duty trucks in Danish car park. The measurements demonstrated the importance of selecting measurements sites where the main part of the passing heavy duty trucks will have warm motor, since this is proven to be crucial for actual emissions. Various challenges had to be handled, but the performed campaigns demonstrated that it is possible to develop such a control system based on a road side remote sensing system that may be operated by the Danish traffic police.

Keywords:	Measurements in Denmark, online emissions, on road traffic, remote sensing, detecting malfunctioning SCR systems
Layout:	Majbritt Ulrich
Front page photo:	Ole Hertel
ISBN:	978-87-7156-507-2
ISSN (electronic):	2245-0203
Number of pages:	124
Internet version:	The report is available in electronic format (pdf) at http://dce2.au.dk/pub/SR387.pdf

Content

Preface

This project has only been possible due to cooperation with a series of key participants who has invested substantial time and resources in order to obtain a valuable collection of data and best possible results.

In particular, we would like to acknowledge the crucial contributions from the following key participants and organizations:

Volvo Group Trucks Denmark A/S, Niels Lykkestrøm, Product Quality Engineer, who contributed with extensive knowledge regarding the functionality of the SCR-systems on Volvo trucks in general, but in particular on Euro IV trucks. *Volvo Group Trucks Denmark A/S* supplied us with one Euro VI Volvo truck for the initial testing, and kindly hosted for the project to set up our Remote Sensing Device and perform measurements at the Volvo facility in Taastrup.

Scania Danmark A/S, Johnny Pedersen, Technical Manager and Morten Voss, Service Technician, who contributed with extensive knowledge regarding the functionality of the SCR-systems on Scania trucks in general, but in particular regarding the Euro VI engines. *Scania Danmark A/S* supplied us with several Scania Euro VI and Euro V trucks for initial testing, and they kindly provided the location to set up our Remote Sensing Device and perform measurements at the facility in Ishøj.

CSP Trucks Danmark, Mercedes-Benz Danmark A/S, Morten Østergaard-Hansen, Technical Specialist Trucks. Who contributed with extensive knowledge regarding the functionality of the SCR-system on Mercedes trucks in general, and in particular on Euro VI trucks.*CSP Trucks Danmark* supplied us with several Mercedes Euro VI and Euro V trucks for initial testing and made it possible to set up our Remote Sensing Device and perform measurements at the Mercedes facility in Greve.

Sund & Bælt Holding A/S, Jens Kjær Nielsen, Manager Toll Station at Great Belt who hosted the campaign at the Great Belt Bridge in different lanes at the Toll Station for more than a week. This was of particular value for the project, since the Toll Station is considered one of the most important measuring sites in Denmark. The high activity at the bridge, and the fact that The Great Belt Bridge was implementing a new payment system exactly during the campaign period, which complicated the measurement campaign. The new payment system made it even more critical that the lanes were undisturbed by outside factors such as the RSD.

Rigspolitiet/færdselspolitiet, Freddy Enøe Agerskov and Martin Kristensen. The extraordinary effort from the Danish Police, regarding the understanding of the SCR-systems on modern trucks, and how these can be manipulated using emulators, has been crucial for the project. We are very grateful that the Danish Police contributed with their extensive field knowledge, and supplied us with substantial resources. Their road site control of heavy-duty trucks provided crucial first-hand knowledge about the correlation between the various results from RSD measurements, and malfunctioning of the SCR-system.

Åke Sjødin, IVL Sverige worked with RSD in Europe for the past 25 years. Åke Sjödin has been extremely helpful, and he has advised us with respect to arising matters during the Remote Sensing project.

TJW Fragt contributed with several Euro V trucks and drivers for several days during in the initial testing period.

The current report has been edited by Ole Hertel, Thomas Ellermann and Jacob Klenø Nøjgaard DCE and Christian Rud Ingvardsen NEQ Aps. This group of editors have also written the extended summaries and conclusions in Danish and English, as well as the preface.

The following authors have contributed to various chapters in the report. For each of the chapters the specific contributing authors have been listed. Christian Rud Ingvardsen, NEQ ApS, Professor Ole Hertel, DCE, Senior researcher Thomas Ellermann, DCE, Senior researcher Jacob Klenø Nøjgaard, DCE, Senior advisor Morten Winther, DCE, Professor Jørgen Brandt, DCE, Senior scientist Lise Marie Frohn, DCE, Journalist Michael Strangholt, DCE.

In a few cases NEQ ApS have expressed specific opions / recommendations of their own. In these cases this has been explicitly stated in the text.

The report has received comments from the Danish Environmental Protections Agency and the Danish Road Traffic Authority. These comments have been taken into account by the four editors in the editing for the final version of the report.

1 Summary and conclusion

The company NEQ ApS and Danish Centre for Environment and Energy (DCE) have conducted a project on control of Selective Catalytic Reduction Systems (in the following referred as SCR-systems) and diesel particle filters (DPF), which was initiated in September 2019 and finalized in January 2020. The project was proposed by The Danish Environmental Protection Agency, Ministry of Environment and Food, the Danish Road Traffic Authority, and the Danish National Police. The project focuses on control of SCR cleaning systems for removal of nitrogen oxides (NO_x) in the exhaust from heavy-duty trucks and methods for identification of manipulated and defect SCR-systems (in the following we will use the term malfunctioning as covering both manipulated and defect SCR-systems). The project furthermore focuses on assessing the additional effects on environment and health related to the extra emissions from malfunctioning SCR-systems. The project is a follow up on a previous project which NEQ and DCE likewise conducted for the Danish Environmental Protection Agency, Ministry of Environment and Food, and in cooperation with the Danish Road Traffic Authority, and the Danish National Police (Ellermann et al., 2018, and http://www.ft.dk/samling/20171/-almdel/MOF/bilag/565/index.htm).

In the following, the main conclusions from the project are presented, and subsequently we present the many activities and results that form the basis for these conclusions.

1.1 Main conclusions

Manipulated and defect SCR-systems on Euro V and VI heavy-duty trucks lead to enhanced emissions of nitrogen oxides from the road traffic. The enhanced emissions from road traffic in Denmark lead to about 10 premature deaths in Denmark, as well as it enhances a number of other illnesses including cardiovascular and respiratory illnesses, diabetes and lung cancer. The total external costs in Denmark have been estimated to 1.3 billion DKK per year, which are related to enhanced emissions from road traffic in Denmark related to malfunctioning SCR-systems. These results are findings based on the many measurements conducted in the project forming the basis for model calculations with air quality models at DCE.

The project has furthermore demonstrated that using the remote sensing method is an efficient method for identifying heavy-duty trucks for subsequent roadside control by the police. Combining measurements and roadside control makes it possible to focus the police resources towards controlling heavy-duty trucks with the highest likelihood of malfunctioning SCR-systems. Simultaneously, the combination of measurements and roadside control will have a preventive effect, since the measurements will make it possible to identify a much larger number of heavy-duty trucks with malfunctioning SCR-system than the police is able to find by control based on random selection for roadside control.

The police conducted extensive roadside control involving 52 heavy-duty trucks in parallel with the measurement campaigns at Padborg and the Great Belt Bridge. In total, 44 Euro V and Euro VI heavy-duty trucks with emissions exceeding 800 ppm (comparable to 17 g NO_2/kg fuel) were selected. The police identified malfunctioning SCR-systems among 61% of the selected heavy-duty trucks. As described in detail in the report it is assumed that the remaining 39% showing high emissions are due to cold engines leading to inactive SCR-systems (in the main report this assumption is elaborated further). These observations document that remote sensing in combination with roadside control is an efficient way to target control of malfunctioning SCR-systems within the fleet of heavy-duty trucks.

In total 2,942 heavy-duty trucks and 3,306 passenger cars were measured in the campaigns at the Great Belt Bridge and Padborg. Based on these measurements, we have estimated that about 10% of the Euro V and Euro VI heavy-duty trucks are equipped with malfunctioning SCR-systems. This estimate has been applied for the calculations of health effects related to enhanced emissions from malfunctioning SCR-systems. It should be noted that this estimate (10%) is highly uncertain, since the measurements do not demonstrate a major jump in emissions between well-functioning and non-functioning SCR-systems, but also because the results demonstrate that the heavy-duty trucks with cold engine may have similarly high emissions as heavy-duty trucks with malfunctioning SCR-systems.

The measurements on heavy-duty trucks and passenger cars show that the most recent Euro Norms have significantly lowered emissions from road traffic. For heavy-duty trucks, the emissions of nitrogen monoxide and particle mass are reduced by about 85% when going from Euro V to Euro VI. For passenger cars, the reduction from Euro 5 to Euro 6 is 84% and 50% for nitrogen monoxide and particle mass, respectively. The fraction of Euro VI heavy-duty trucks and passenger cars was 76% and 62%, respectively. These figures are in accordance with the general development concerning substitution rate of the Danish vehicle fleet, where an increasing fraction is constituted by the most recent Euro Norms. The Danish inventories show a significant decrease in emissions (DCE, 2020, not yet published), which for a large part is related to a still increasing fraction of Euro VI heavy-duty trucks and Euro 6 passenger cars, and the associated much lower emissions from these most recent Euro Norms.

In the project, a series of tests with deliberately manipulated SCR-system were performed inside a closed area. The most important conclusions from these tests are:

- When the SCR-systems on Euro VI heavy-duty trucks are switched off, the emissions of nitrogen monoxide are increased by about a factor of 20. This assessment is based on tests of Euro VI heavy-duty trucks where measured emissions are compared to SCR-systems turned on and off, respectively.
- Measurements on six Euro V heavy-duty trucks showed that the average emissions from Euro V heavy-duty trucks with malfunctioning SCR-systems were twice as high as Euro VI heavy-duty trucks with SCR-systems switched off.
- Emissions from Euro VI heavy-duty trucks with cold engines were similar to Euro VI heavy-duty trucks with the SCR-systems switched off. SCR-systems can only operate properly at high temperature, and they only gain high temperature when the engine is warm. A similar

behaviour is expected for Euro V heavy-duty trucks equipped with SCR-systems.

- The tests showed that emissions of nitrogen monoxide increased by a factor of ten after only four minutes idling of the tested heavy-duty truck. This demonstrates that four minutes idling is sufficient for the temperature to drop below the needed temperature range for the SCR-systems to operate properly.
- For Euro VI heavy-duty trucks, the tests indicate that emissions beyond 7 g NO_2/kg fuel (equivalent with 330 ppm NO) can be used as a threshold beyond which there is a large likelihood of malfunctioning SCR-systems. The similar threshold for Euro V heavy-duty trucks has been estimated to 14 g NO_2/kg fuel (equivalent with 660 ppm NO). However, we recommend a flexible approach in connection with future routine controls, where a threshold of 1000 ppm is used initially (see section 8.1).
- Emissions of particulate matter in exhaust from heavy-duty diesel trucks decreased from Euro V to Euro VI. For passenger cars, this was even clearer from Euro norms 3 to 6, where particles filters assure that only 0.1 g PM is emitted per kg fuel. While Euro 3 diesel fuelled passenger cars emits 17 times more PM than petrol fuelled cars of identical Euro norm, Euro 5 and 6 passenger cars have similar PM emission irrespectively of fuel.

1.2 Background and purpose

The most recent Euro Norms for heavy-duty trucks form strict legislative demands for emissions of nitrogen oxides. To comply with these demands, Euro VI heavy-duty trucks are required to use so-called SCR-systems (selective catalytic reduction) to reduce the emissions of nitrogen oxides in the exhaust.

SCR-systems are advanced cleaning systems coupled to the exhaust pipe, which are capable of removing more than 90% of the health hazardous nitrogen oxides from the exhaust fumes. For Euro V heavy-duty trucks, it is not required to use SCR-systems, but most of these are using SCR-systems, while a smaller fraction apply other cleaning technologies.

In recent years, a series of police roadside control in Denmark and other European countries have revealed that a non-negligible fraction of the heavy-duty trucks were equipped with manipulated SCR-systems. At the same time, it turned out that technical errors on the SCR-systems are not uncommon. This tendency has previously been documented in a Danish context by NEQ ApS and DCE, who conducted a pilot project with focus on manipulation of SCR-systems in 2018. The pilot project was funded by the Danish EPA, the Road Traffic Authority, and the Danish National Police (http://www.ft.dk/samling/20171/almdel/MOF/bilag/565/index.htm).

Malfunctioning SCR-systems lead to enhanced emissions of nitrogen oxides, which deteriorate air quality and thereby lead to increased health effects in the population. On this basis, the Government, as part of the Climate and Air Quality Strategy from 2018, initiated a series of initiatives for developing and applying a control method. The control method should help ensuring compliance with legislation concerning emissions of air pollutants with particular focus on emissions from heavy-duty trucks.

The project has the following aims:

- To conduct measurements of emissions from the driving car fleet on Danish roads.
- Assess the extent of malfunctioning of SCR-systems on heavy-duty trucks in Denmark on basis of emission measurements.
- To conduct test measurements inside a closed area, where emissions are measured from deliberately manipulated and defect SCR-systems and compared to similar measurements of emissions from well-functioning SCR-systems.
- On the basis of the measurements, assess the enhanced health effects in Denmark, which are ascribed to enhanced emissions from malfunctioning SCR-systems.
- Investigate whether remote sensing devices are suitable for measurements of pollutants and useful for targeted police control of individual vehicles (primarily heavy-duty trucks).
- Investigate which remote sensing device method that is most suited for routine control of SCR-systems.
- Develop a method for performing routine control of SCR-systems on heavy-duty trucks based on remote sensing devices in combination with subsequent targeted roadside control by the police.

Measurements have to be performed using the RSD method (remote sensing devices), which is a method where the content of nitrogen oxides are measured under real-world conditions on a large number of vehicles (this method is described in more detail in later sections).

1.3 Activities

The project is sub-divided into a series of activities:

1. Assessment of which stationary RSD method that will be most suitable for control of SCR-systems on heavy-duty trucks in Denmark, and under which driving conditions the method can be applied.
2. Perform tests in a closed area with the aim of validating measurement methods, and determining emission levels beyond which heavy-duty trucks are most likely equipped with malfunctioning SCR-systems or particle filters. These emission levels are in the following termed emission thresholds. The tests include measuring emissions from heavy-duty trucks with well-functioning SCR-systems and particle filters followed by measurements on the same heavy-duty trucks where the SCR-systems and particle filters are deliberately switched off or removed. The reason for removing particle filters in some of the tests is that for some of the manipulation methods this is a necessity. In these situations, emissions will be enhanced for both nitrogen oxides and particles.
3. Selection of 1-3 field sites suitable for carrying out measurements with the RSD method in combination with subsequent police control of heavy-duty trucks suspected to be equipped with malfunctioning SCR-systems. The focus of the campaigns is to measure a large number of heavy-duty trucks, and subsequently to perform police roadside control of heavy-duty trucks with emissions exceeding the emission threshold. In addition,

emissions from all passenger cars that pass the measurement site are measured, which allows a large number of samples to be obtained from the Danish car fleet.

4. On basis of the above mentioned, the enhanced emissions of nitrogen oxides related to malfunctioning SCR-systems are estimated. This estimate is used for calculations of the increase in health effects related to enhanced emissions of nitrogen oxides.

5. Develop an outline for a method for routine control of SCR-systems based on measurements of the RSD method in combination with police roadside control of heavy-duty trucks for which the measurements show emissions exceeding the emission threshold indicative of malfunctioning SCR-systems.

In the following we summarize results of these activities, but first we provide a short description of the RSD method.

1.4 The RSD method

The measurement device itself (Figure 1.1) consists of a detector part and an advanced mirror system placed across the road where the measurements are taking place. The detector part sends harmless laser beams across the road to a mirror system, which returns the beam to the detector. The detector subsequently measures the intensity of the laser beam. The intensity in the emitted beam is known, and based on this knowledge and the measurements, the system calculates how much light has been absorbed during the path forth and back across the road. The wave length of the laser beam is selected in a range where it is known that light will be absorbed by air pollution from the exhaust of the passing vehicles. From determining the reduction in light intensity and based on knowledge about the physical characteristics of the pollutants, it is possible to calculate the concentrations of the air pollutant components in the exhaust fumes behind the vehicles. Such calculations are carried out automatic by the RSD system.

In this way, the equipment can measure instant concentrations of the most important air pollutants in the exhaust fumes from passing vehicles. This project has focus on measurements of nitrogen monoxide (NO) and the mass of particles in the air (termed PM for particulate matter). In order to convert the instant concentration measurements to values for the emissions of nitrogen monoxide and PM, the instrument is also measuring carbon dioxide, carbon monoxide and unburned fuel. These are the most important products from the combustion of fuel in engines. Nitrogen monoxide and carbon dioxide as well as all the other parameters are diluted by the same rate when they leave the exhaust pipe. From the instant measurement of the fume behind the exhaust pipe, it is possible to calculate the relationship between the measured parameters, and thereby to determine how many grams of nitrogen monoxide there has been emitted per kg fuel burned in the engine.

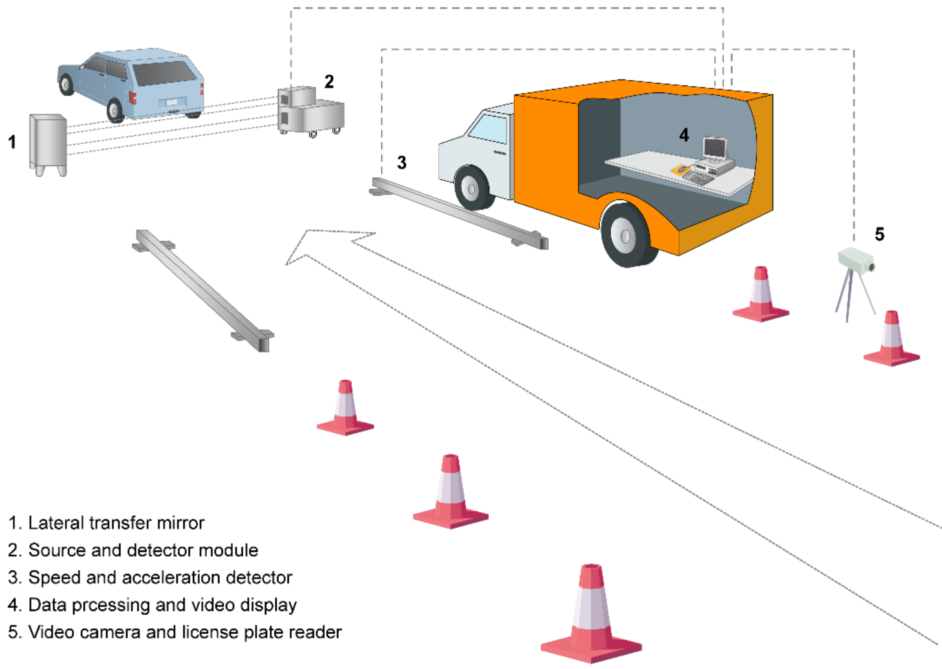


Figure 1.1. Photo top: Measurement of emissions of air pollution components (mainly nitrogen oxides and particles) on the heavy-duty truck with the red trailer. The measurement device is seen on both sides of the roadway immediately after the heavy-duty truck; Sketch bottom: Schematic representation of the RSD set-up (NEQ ApS).

In order to account for air pollution contributions from other sources than the targeted vehicle, two identical sets of measurements are carried out. One measurement is performed immediately before the vehicle is passing and another measurement is performed just after the vehicle has passed. The difference between the two measurements is taken as the contribution from the vehicle passing the instrument. There may, however, be situations where the first measurement is contaminated by emissions from e.g. an old heavy-duty vehicle that has just passed the measurement site immediately before the targeted vehicle. In case the targeted vehicle is a Euro VI heavy-duty truck, there is a risk that the measured concentration before passage is higher than the concentration just after passage of the investigated vehicle. This is the explanation why it is not possible to avoid totally to have some situations where negative concentrations are found in connection with measurements in densely trafficked areas.

The measurements take only few seconds to carry out, and the results are available immediately after these are completed. The equipment can therefore be used to determine emissions from a large number of heavy-duty trucks in short time at roadsides when measured in accordance with certain technical guidelines. Measurements are thus ideal as basis for a fast selection of heavy-duty trucks with potentially manipulated or defect SCR-systems.

The equipment is furthermore supplemented with measurements of the driving speed and acceleration of the vehicle, since the driving speed need to be in the range of 30 to 60 km/h and furthermore include a slight acceleration to obtain optimal measurements. However, experience from this project has shown that the method is relatively robust to these parameters, and that sufficiently good measurements may also be obtained for other driving pattern.

Measurements with the RSD method are automatic and controlled by software that perform the necessary calculations and store the results on the fly. The software ensures coupling of measurements from individual vehicles to photos from a camera included in the equipment that is automatically taking these photos for subsequent identification of the vehicles. Identification is made from digital recognition of the number plate and performing automatic lookup in the Danish Motor Registry. This identification in the motor registry also means identification of the Euro Norm of the vehicle, and also this information is therefore stored on the computer. The described procedure was applied in connection with measurements on passenger cars that therefore only include Danish vehicles. Whenever the quality of the images allowed it, the licence plates were looked up in the Danish Motor Registry for identification of the Euro norm. If not possible, visual identification was applied. Based on guidance from the police, it was possible to identify Euro V and Euro VI purely from the look of the vehicles. Therefore, the project includes results from both Danish and foreign heavy-duty trucks, where identification of the Euro norm of foreign heavy-duty trucks were made solely based on visual identification. The identification of the heavy-duty trucks is of course associated with some uncertainty. However, during subsequent double checks only few deviations from the assignments of Euro norms have been identified.

1.5 Evaluation of the most suitable RSD method

This assessment has been carried out by NEQ.

There are two types of RSD systems available on the market of today. Both systems are developed in USA, and both systems are currently applied on routinely for operational measurements in both USA and Europe. The producers of the two systems are respectively OPUS and EDAR. There are advantages and disadvantages about both systems, but overall, we find that the RSD system from OPUS have some advantages related to the flexibility. The OPUS system can relatively easily be installed (takes less than an hour), and it can therefore be applied at several sites with a time frame of one week or if necessary even within one day. In difference from this system, the RSD system from EDAR need a part of the equipment either to be fixed on top of or to be submerged into the road surface at the measurement site. This means that the equipment in praxis only can be used at relatively permanent measurement sites.

1.6 Test experiments in closed areas

An important part of the project was to conduct a series of test measurements with the RSD system under controlled conditions to compare emissions measured on heavy-duty trucks with well-functioning SCR-systems and particle filters with emissions measured on the same heavy-duty trucks when the SCR-system and the particle filters were switched off. Controlled conditions makes it possible to test the performance of the measurement device and thereby collect data that can be used to assess how external factors affect the emission measurements.

The following situations and conditions were tested in the experiments in the closed areas:

- Measurements of the increased emission of nitrogen monoxide from SCR-systems that are switched off. For this purpose, various equipment for manipulation was purchased, but it turned out to be sufficient to turn off the SCR-systems in a more simple way.
- Measurements of the increased emission of PM from heavy-duty trucks with dismantled particle filters. The background for this is that certain types of manipulation of the SCR-system requires that the particle filter is removed. In such cases, manipulation of the SCR-systems will therefore affect emissions of both nitrogen oxides and PM.
- Studies of how the engine temperature affects emissions from heavy-duty trucks.
- Studies of how weather conditions affect the measurements on heavy-duty trucks.
- Studies of how varying velocity and acceleration affect the measurements on heavy-duty trucks.
- Studies of how the presence of a trailer affect the measurements and measured emissions from heavy-duty trucks.

Measurements with well-functioning and decoupled SCR-system has two important purposes:

- First of all, the emission threshold should be based on the measurements of nitrogen monoxide emissions. The application of this emission threshold is to identify heavy-duty trucks, which are likely to be equipped with malfunctioning SCR-system. The emission threshold is thus intended to be used as a criterion for manual control of heavy-duty trucks in a subsequent roadside control by the Danish Police.
- Secondly, the increase in nitrogen monoxide emissions from the malfunctioning SCR-systems is estimated from these measurements. The enhanced health effects in the population, which can be ascribed to increased emissions from malfunctioning SCR-systems are based on the increase in nitrogen monoxide emissions.

Furthermore, the practical experience obtained in the tests will benefit the establishment of a routine control method for identification of heavy-duty trucks equipped with malfunctioning SCR-systems.

During the two weeks starting with 16th and 23rd September (weeks 38 and 39) in September 2019, we performed 216 tests on Euro VI heavy-duty trucks equipped with active, inactive and decoupled SCR-systems. The tests were performed on four different heavy-duty trucks provided by Mercedes, Scania and Volvo.

For the Euro V heavy-duty trucks, only 26 tests were carried out. Consequently, only a small part of the test program was completed for this Euro Norm. Unfortunately, all tested Euro V heavy-duty trucks turned out to feature malfunctioning SCR-systems. While the original plans scheduled tests for two Euro V heavy-duty trucks, four additional Euro V heavy-duty trucks were provided due to malfunctioning SCR-systems. Implication are, that a total of six Euro V heavy-duty trucks were tested. Despite the extra effort, all six heavy-duty trucks turned out to have malfunctioning SCR-systems contrary to the owners believe.

1.7 NO and PM test results from experiments in closed areas

Figure 1.2, and Tables 1.1 and 1.2 summarise the results from the tests performed in the closed area. The results are subdivided into three categories:

- **Active SCR-system**. This is characterized by active supply of AdBlue to the SCR-system. This requires that the engine is hot, and that the SCR-system has reached a sufficient temperature.
- **Inactive SCR-system**. This is characterized by no supply of AdBlue to the SCR-system. In connection with the tests, the SCR-system is inactive because the SCR-system is too cold.
- **SCR-system switched off**. Heavy-duty trucks were deliberately manipulated to prevent the SCR-systems from working.

Resulting average emissions of nitrogen monoxide for EURO VI equate 0.8 g NO_2/kg fuel for active SCR-systems, 24 g NO_2/kg fuel for inactive SCR-systems and 8 g NO_2/kg fuel, when the SCR-systems were switched off. Thus, a non-functioning SCR-system emits about 20 times more NO than a well-functioning SCR-system. The somewhat higher emission from an inactive SCR-system compared with a switched off SCR-system is within the uncertainty of the measurements.

The average emission of nitrogen monoxide from the tested Euro V heavy-duty trucks with inactive SCR-system was 32 g NO_2/kg fuel (Table 2.2). This is 35% higher than for Euro VI heavy-duty trucks measured under the same conditions, and about a factor of two higher than for a Euro VI heavy-duty truck with the SCR-system switched off. Unfortunately, in this project it was not possible to perform tests af Euro V heavy-duty truck with well-functioning SCR-system, and it is therefore not possible on the basis of these studies to make a direct comparison between Euro V and Euro VI with the SCR-system switched off. However, a recent study of the fleet of heavy-duty trucks measured in the Gothenburg area, Sweden, shows that the ratio of NO_X (derived from measurements of nitrogen monoxide (NO)) from Euro V to that from Euro VI is about 5 (Sjödin et al., 2017).

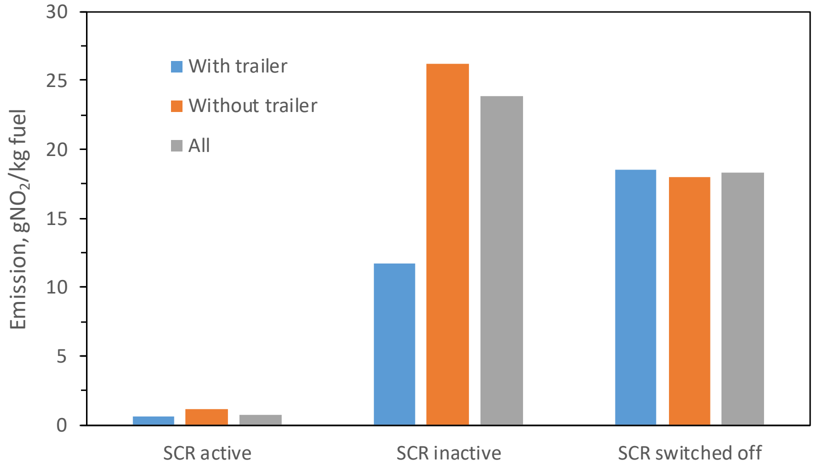


Figure 1.2. Average emission of nitrogen monoxide (NO) from Euro VI heavy-duty trucks with SCR-systems that are respectively active, inactive and switched off. The results are furthermore divided into results for heavy-duty trucks with and without trailer. Emissions are in this and the following figures and tables given in equivalents of nitrogen dioxide (g NO2/kg fuel), which is standard in connection with emission inventories.

Table 1.1. Average emissions of nitrogen monoxide (NO) and particles (PM) for the various tests of Euro VI heavy-duty trucks. The variation is calculated as the standard deviation on the results within a category. This indicates the span of the results within each category.

Status of SCR	Trailer	Particle filter	Number of tests	NO gNO_2/kg fuel		PM gPM/kg fuel	
				Average	Variation	Average	Variation
Active	YES	Yes	37	0.59	0.82	1.0	1.6
Active	No	Yes	15	1.2	1.0	1.1	1.2
Active	Yes/No	Yes	52	0.76	1.4	1.1	1.5
Inactive	Yes	Yes	9	11.8	2.1	1.0	1.2
Inactive	No	Yes	45	26.3	7.1	1.4	1.5
Inactive	Yes/No	Yes	54	23.8	7.5	1.3	1.5
Switched off	Yes	Yes/No	59	18.5	7.1	1.1	1.4
Switched off	No	Yes/No	44	18.0	4.3	0.63	0.43
Switched off	Yes/No	Yes/No	103	18.3	6.1	0.91	1.1
Switched off	Yes/No	Yes	69	15.9	4.6	0.87	1.2
Switched off	Yes/No	No	34	24.2	7.8	0.97	0.77

Table 1.2. Average emissions of nitrogen monoxide (NO) and particles (PM) for tests of Euro V heavy-duty trucks. The variation has been calculated as the standard deviation on the results within a category indicating the span of the results within each category

Status of SCR	Trailer	Particle filter	Number of tests	NO gNO_2/kg fuel		PM gPM/kg fuel	
				Average	Variation	Average	Variation
Inactive	Yes	No	18	36	8.5	1.2	1.1
Inactive	No	No	7	23	4.1	0.67	0.12
Inactive	Yes/No	No	25	32	9.6	1.1	0.98

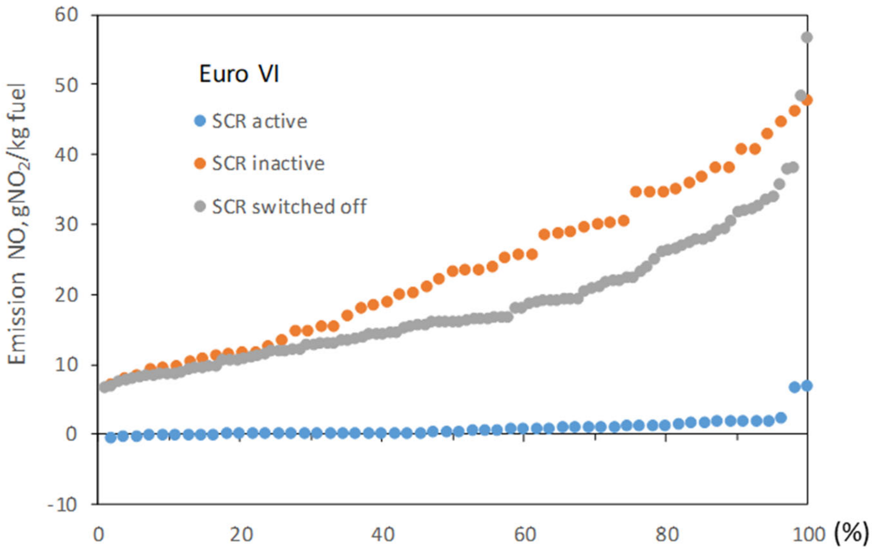


Figure 1.3. Distribution nitrogen monoxide (NO) emissions from Euro VI heavy-duty trucks with the SCR-systems active, inactive (cold engine) and switched off. Results have been sorted according to increasing emissions within the three categories. X-axis shows the percentage of results with an emission below y-value at a given point.

Figure 1.3 shows the distribution of measured emissions from Euro VI heavy-duty trucks subdivided into three different categories. All emissions measured for heavy-duty trucks with the SCR-system switched off are above the similar measurements of emissions from heavy-duty trucks with an active SCR-system. Based on the tests, a threshold of about 7 gNO_2 / kg fuel (330 ppm NO) is proposed. This threshold is equivalent to the lowest measured emission when the SCR-system is switched off. Another important conclusion from the tests is that emissions from a heavy-duty truck with an inactive SCR-system is on the same level as emissions from a heavy-duty truck with the SCR-system switched off. In connection with the test, an inactive SCR-system was a result of a too cold engine. Therefore, measured emissions exceeding the threshold concentration may just as well be due to cold engines as it can be the result of malfunctioning SCR-systems.

The tests on Euro V heavy-duty trucks suggest a higher thresholds concentration than the one for Euro VI heavy-duty trucks. This is based on the fact that average emissions from Euro V heavy-duty trucks with inactive SCR-system are about two times higher than for Euro VI heavy-duty trucks with SCR-systems switched off. These tests thus point at a threshold concentration of about 14 g NO_2 / kg fuel (660 ppm NO).

1.8 Investigating impact of brand

The three brands of heavy-duty trucks indicated relatively large differences in emissions of both nitrogen monoxide and particles. Likewise, the effect of removing the particle filter indicated large differences between the different brands of heavy-duty trucks (Figures 1.4 and 1.5). It is not known whether this is due to differences between the brands, or if it is just related to the specific heavy-duty trucks that were tested. It is thus not known whether the proposed threshold values are representative for all brands of heavy-duty trucks. This furthermore means that the threshold values must be seen as a starting point for control actions, and subsequently an adjustment should be applied when more knowledge has been collected from control actions.

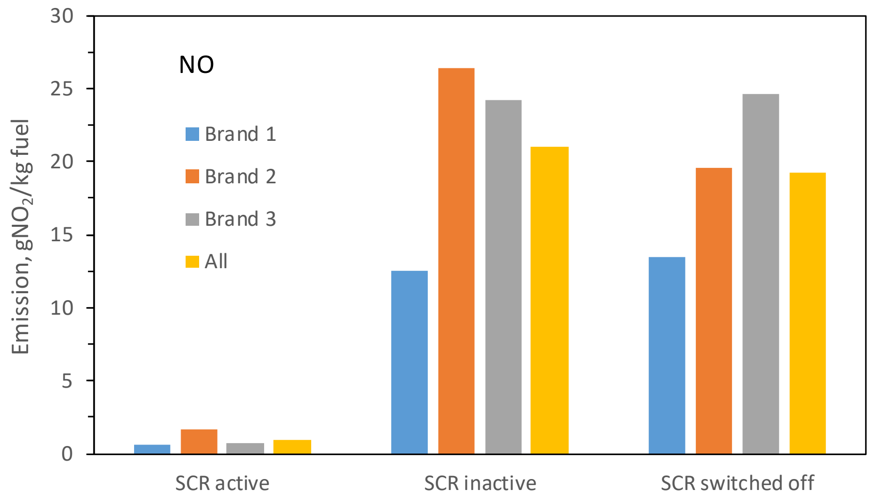


Figure 1.4. Average emission of nitrogen monoxide (NO) from Euro VI heavy-duty trucks with SCR-systems that are respectively active, inactive and switched off. The results are distributed on three different brands of heavy-duty trucks.

For two of the three brands of Euro VI heavy-duty trucks, a doubling in PM emission is observed when the SCR-system is switched off at the same time as the particle filter is removed (Figure 1.5). The reason for this difference between brands is not known, and it is furthermore not known whether the differences are due to differences between brands or if they are just related to the specific heavy-duty trucks that were tested.

h

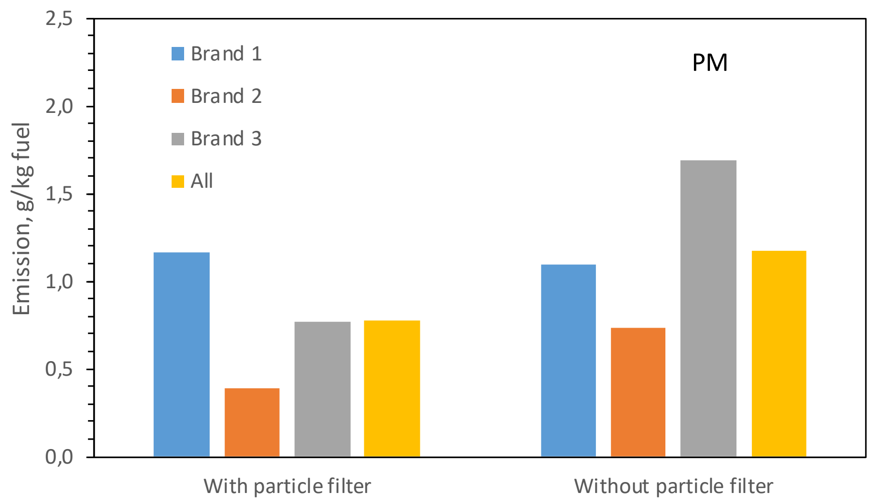


Figure 1.5. Average emissions of particles from Euro VI heavy-duty trucks with SCR-system switched off, as well as with and without particle filter. The averages are distributed according to the three brands of heavy-duty trucks.

In conclusion, we observed different levels of NO and PM emissions from different brands or vehicles which indicates the variation among the fleet of heavy-duty trucks. Moreover, the PM emission from one of the brands was the same with particle filter mounted or dismounted whereas the PM emission from the two other brands was doubled. The variation in the measurements with different brands are relatively high and this has to be taken into account and more test are therefore suggested.

1.9 Tests of other parameters

The measured emissions of nitrogen monoxide have shown to be relatively robust towards variations in driving speed and acceleration during the measurements. This means higher flexibility in relation to choices of measurement site and makes it possible to use shorter roadways than expected.

The same heavy-duty truck was tested twice in order to investigate how the weather conditions affect the measurements. Weather conditions changed only moderately between the two measurement days, however, and this means that only limited information was collected regarding influence of weather on measurements. As a starting point, it is expected that weather conditions affect measurements only moderately. A significant result was, however, that it is not possible to measure during rain, since the rain drops disperse the light beam from the RSD instrument and makes it impossible to conduct the measurements.

The Euro VI heavy-duty trucks were furthermore tested with and without trailer (Figure 1.2). This lead to some changes for the emissions measured with inactive SCR-system but did not change the results when the SCR-system was active or switched off. An explanation for the higher emissions found for trucks without trailer with inactive SCR compared to trucks with trailer could be that the engine are more likely to be cold for a truck without trailer since the load on the engine is lower without trailer. However, this finding has limited impact for the traffic on the Danish road systems were only a minor fraction of heavy-duty trucks drives without trailers. Finally, in connection with the tests on closed area, a series of more practical tests were conducted (one example was a test of how often it is necessary to calibrate the RSD instrument). These practical tests will show useful in connection with the design of the routine control of malfunctioning SCR-systems.

1.10 Measurements at Padborg and the Great Belt Bridge

In September and October 2019, two measurement campaigns were carried out at Padborg and at the Great Belt Bridge. In total measurements were performed on 2,942 heavy-duty trucks and 3,306 passenger cars. 12% of the measured heavy-duty trucks were Danish, and 88% were of foreign origin, whereas all the measured passenger cars were Danish. Euro 5 and Euro 6 passenger cars added up to 87% of the measured passenger cars (Table 1.4). The large share of vehicles with the most recent norm (Euro 5 and Euro 6) are in compliance with the general development for the vehicle fleet on the Danish road network. The foreign heavy-duty trucks constitute the by far largest fraction of the measured heavy-duty trucks, and this is related to the selection of measurement sites at Padborg and the Great Belt Bridge (for a significant part of the time, measurements were performed in the payment roadway where the main fraction of foreign heavy-duty trucks pass). Furthermore, diesel passenger cars constitute 61% of all passenger cars.

Table 1.3. The absolute and relative distribution with respect to Euro Norms of heavy-duty trucks measured at Padborg and the Great Belt Bridge. The total number of measured heavy-duty trucks was 2,942.

	IV		V		VI		Total	
	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage
Danish	0	0	44	1	303	10	347	11
Foreign	3	0.1	654	22	1938	66	2595	88
Total	3	0.1	698	24	2241	76	2942	100

Table 1.4. The distribution with respect to Euro Norms of passenger cars measured at Padborg and the Great Belt Bridge. The total number of measured passenger cars was 3,306.

	2		3		4		5		6		Total	
	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage	Number	Percentage
Gasoline	1	0.002	23	0.7	197	6	318	10	724	22	1263	38
Diesel	0	0	32	1	167	5	511	15	1334	40	2044	61
Total	1	0.02	55	1.7	364	11	829	25	2058	62	3307	100

1.11 Results from heavy-duty trucks

Figure 1.6 shows the average emissions of nitrogen monoxide and particles measured on heavy-duty trucks distributed according to Euro Norm. The results show that the emissions of nitrogen monoxide in average are 88% lower for Euro VI heavy-duty trucks compared with Euro V heavy-duty trucks. The similar decrease for particles is 84%. The emissions of PM from Euro V and Euro VI Heavy-duty trucks were two times higher and similar to, respectively, emissions from comparable trucks reported by Sjödin et al., 2017. The relatively large emission of PM from Danish heavy-duty trucks is due to a small number of heavy-duty trucks with large emissions, and the results is therefore considered to have large uncertainty. In fact, a sensitivity analysis shows that only 7 Euro VI heavy-duty trucks cause the PM emission from Danish trucks (0.60 g / kg) to exceed that of foreign trucks (0.05 g / kg). Upon removal of these trucks, the emission from Danish Euro VI is comparable to foreign Euro VI (0.04 g / kg). A similarly large decrease in emissions of nitrogen monoxide from Euro V to VI was observed in a previous project with Danish measurements with the RSD method in 2017 (Ellermann et al., 2018) although the difference between the two Euro Norms is smaller in the measurements in 2019 compared with the 2017 measurements. The results are not generally representative for Euro IV heavy-duty trucks, since measurements were only performed on three heavy-duty trucks under this Euro Norm.

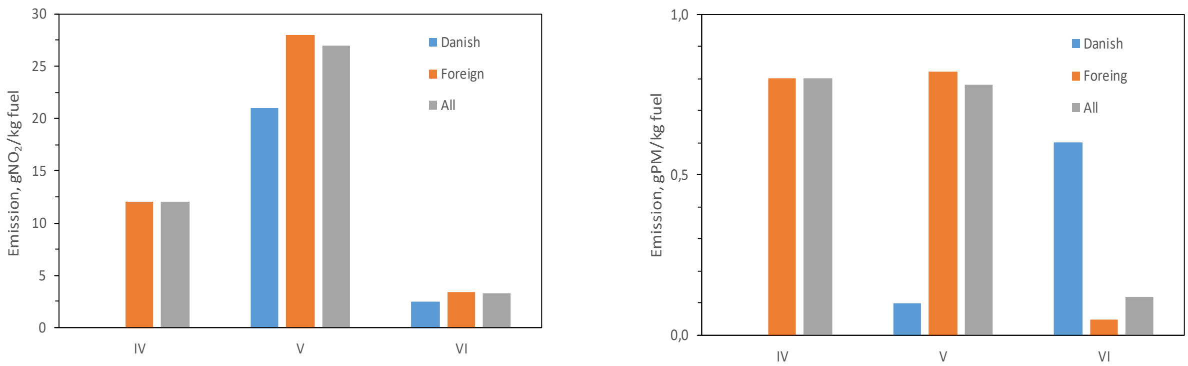


Figure 1.6. Average emission of nitrogen monoxide (left) and particles (right) for Danish and foreign Euro IV, V and VI heavy-duty trucks.

1.12 Results from passenger cars

Figure 1.7 shows the similar results for the average emissions from Danish passenger cars distributed on respectively diesel and petrol fuelled vehicles. For all passenger cars, a significant decrease in emissions are observed between the oldest Euro Norms and the most recent Euro 6 Norm. In general, considerably lower emissions are seen from petrol driven vehicles compared with diesel vehicles. The differences are, however, considerably smaller for Euro 6 passenger cars. This is due to the use of SCR-systems on diesel vehicles, which have given a considerable improvement for emissions of nitrogen monoxide. Diesel fuelled passenger cars account for 76% of emitted PM, while the remaining 24% is emitted by petrol fuelled passenger cars. For Euro 5 and 6 there is almost no difference between emissions of particles from diesel vehicles and petrol driven vehicles, which is caused by the use of particle filters on diesel vehicles. Emissions of PM from passenger cars were somewhat higher than recent results previously published by a Swedish project (Sjödin et al., 2017). Emissions of nitrogen monoxide are in compliance with results from similar measurements in a Swedish investigation (Sjødin, 2017).

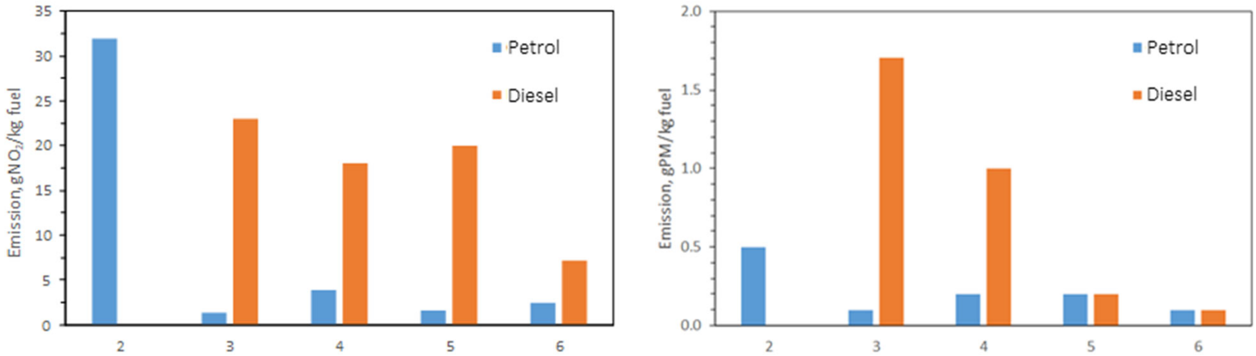


Figure 1.7. Average emissions of nitrogen monoxide (left) and particles (right) for Danish passenger cars distributed in petrol and diesel fueled vehicles and Euro Norm.

1.13 Distribution of emissions

Figures 1.8 and 1.9 show the distribution of emissions of nitrogen monoxide measured for Euro V and Euro VI heavy-duty trucks, respectively. For both Euro Norms, an S shaped curve is seen, where the negative values for the lowest emissions are mainly due to unavoidable artefacts in the measurement method (contamination from other vehicles in the measurement area). The significant increase in the high end of the scale is due to heavy-duty trucks where the SCR-systems are not operating as intended due to malfunctioning SCR-systems. Another fraction of the high emissions may, however, be due to too cold SCR-systems at the time of the measurements. This fraction is not possible to estimate due to the nature of the measurement setup, and it has not been an objective to determine this fraction. Since the results were measured while driving on highway, the share of vehicles with cold SCR-system is assumed to be small, although those at the Great Belt Bridge may be idling, while waiting in line for the payment system. Furthermore, results show a somewhat equal distribution between Danish and foreign heavy-duty trucks. Emissions of NO from Danish Euro V and Euro VI heavy-duty trucks are, however, somewhat lower than those from foreign vehicles (figure 1.6).

It is furthermore noticed, that no real jump is observed in emissions, which would have indicated a marked difference between emissions from heavy-duty trucks with active SCR-systems and SCR-systems that are not working properly. It is thus not possible to determine the exact share of heavy-duty trucks that do not have well-functioning SCR-systems. Data show, however, that for the about 10% highest emissions, there is a significant increase in emissions. For Euro V the 90% percentile is about 20 µg / m^3 which is somewhat higher than the lowest emission measured for a heavy-duty trucks with a defect SCR-system (14 µg / NO_2 / kg fuel) during the tests at the closed area. For Euro VI the 90% percentile is at the same level as measured during the tests (7 µg / NO_2 / kg fuel)

Due to the large uncertainties, we have taken a simple approach and have therefore estimated that about 10% of Euro V and Euro VI heavy-duty trucks have malfunctioning SCR-systems. This estimate has been used in connection with the calculations of health effects related to malfunctioning SCR-systems. It should be noted that this estimate is constrained by high uncertainties.

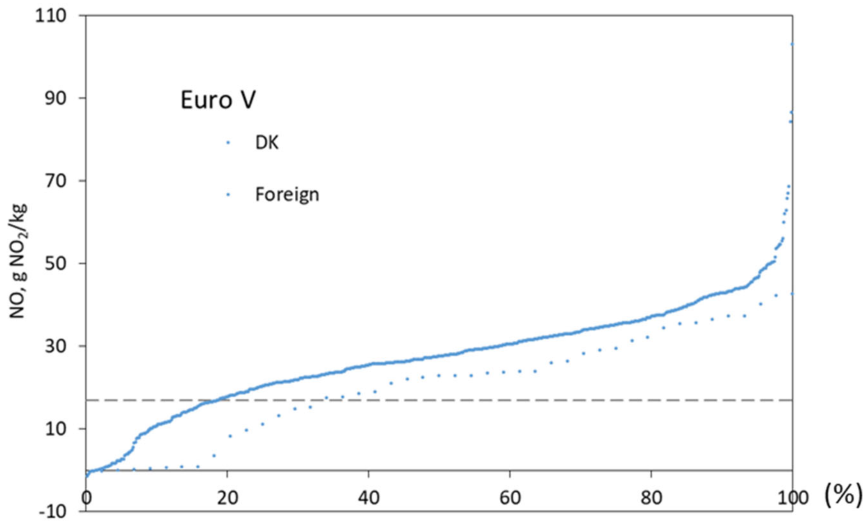


Figure 1.8. The distribution of nitrogen monoxide (NO) emissions. Emissions have been sorted according to increasing emissions for Danish and foreign Euro V heavy-duty trucks, respectively.

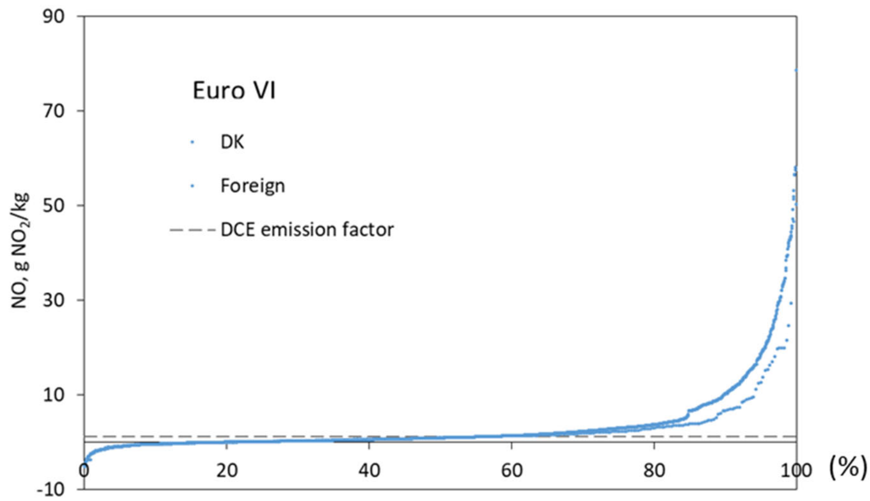


Figure 1.9. The distribution of nitrogen monoxide (NO) emissions. Emissions have been sorted according to increasing emissions for Danish and foreign Euro VI heavy-duty trucks, respectively.

1.14 The police's roadside control

The Danish Police participated in the measurement campaigns at Padborg and the Great Belt Bridge. The police contributed with roadside controls of a number of heavy-duty trucks, where the measurements showed emissions of nitrogen monoxide at a level indicating malfunctioning SCR-systems.

During the seven days where the Danish Police participated, the measurements were focussed on measuring as many heavy-duty trucks as possible. It was furthermore crucial that a relatively large fraction of foreign heavy-duty trucks was included, since experience showed that the extent of manipulation is higher among foreign that among Danish heavy-duty trucks. Many measurements were therefore conducted in the manual payment laines at the Great Belt connection, since this is where most foreign heavy-duty trucks pass.

In total 52 heavy-duty trucks were manually inspected. Only one vehicle was selected based on a too high PM emissions, while the remaining 51 vehicles exceeded the nitrogen monoxide threshold concentrations. A threshold concentration of 1,000 ppm nitrogen monoxide was applied for the main part of the seven days of roadside control. Since the tests at the closed areas were not analysed at that time, this threshold concentration was selected on the basis of tests in Spain. On the first day, a threshold of 800 ppm was applied partly.

Tables 2.5 and 2.6 show an overview of the results from the police roadside control. A total of 36 inspected heavy-duty trucks were Euro V, eight were Euro VI, while two of the Euro Norms could not be assigned. Still, they were either Euro V or Euro VI. Furthermore, it turned out that six of the 52 heavy-duty trucks were Euro IV without SCR-system, and one of the Euro V heavy-duty trucks had another cleaning system. Heavy-duty trucks without SCR-systems are not included in the further presentation of the results.

Four of the 52 heavy-duty trucks were Danish. Two vehicles were Euro V and another two were Euro VI. The main part of the investigated heavy-duty trucks was of foreign origin.

Table 1.5. Results from the police roadside control at the Great Belt Bridge and Padborg. Euro IV and Euro V heavy-duty trucks without SCR-system are not included in columns for well-functioning SCR, malfunctioning SCR-systems.

Euro	Inspected heavy-duty trucks			Well- functioning SCR			Manipulated			Defects		
norm	Total	Danish	Foreign	Total[¤]	Danish	Foreign	Total	Danish	Foreign	Total	Danish	Foreign
IV	6*	0	6*	-	-	-	-	-	-	-	-	-
V	36	2	34§	12	0	12	5[#]	0	5[#]	20[#]	2	18[#]
VI	8	2	6	4	1	3	0	0	0	4	1	3
Unknown	2	0	2	1	0	1	0	-	0	1	-	1
Total	52	4	48	17	1	16	5[#]	0	5[#]	25[#]	3	22[#]

* Euro IV heavy-duty vehicles without SCR
§ En Euro V havde ingen SCR
¤ Euro IV and Euro V without SCR is excluded
Two Euro V had both manipulation and defects

In total, 62% of all investigated heavy-duty trucks with SCR have either manipulated or defect SCR-systems (two heavy-duty trucks had both). It turned out, that among the 83% heavy-duty trucks with malfunctioning SCR-systems, only 17% were manipulated. Malfunction included e.g. errors on the AdBlue, vehicle in error mode, shortcuts, and errors on NO_X sensors. Only for Euro V, manipulated SCR-systems was identified, while no manipulated vehicles were identified among the other Euro norms.

Table 1.6. The percentage distribution of Euro Norms and the percentage distribution of heavy-duty trucks with well-functioning SCR and with manipulated or defect SCR-systems. Furthermore, the share (%) of the heavy-duty trucks with manipulated and with defect SCR-systems of the sum of either manipulated or defect SCR-systems.

Euro norm	Inspected heavy-duty trucs	Well-functioning SCR	Manipulation + defects	Share manipulation, %	Share defects, %
V	78	27	51	20	80
VI	18	9	9	0	100
Unknown	4	2	2	0	100
Total	100	38	62	17	83

Furthermore, 38% of the inspected heavy-duty trucks were equipped with apparently well-functioning SCR-systems despite the emissions exceeded 800 ppm. The reason for this is assumed to be due to too cold engines and therefore not malfunctioning SCR-systems. The relatively high share of vehicles with cold engines is assumed to be related to the measurement conditions. It is e.g. unavoidable that the heavy-duty trucks stop for a while at the tollbooth at the Great Belt Bridge, and this can be sufficient to lower the temperature of the engine. Tests in the closed areas document that four minutes of idling is sufficient for the engine to cool below temperatures where the SCR-systems operate properly. There was a delay between the measurements and the roadside inspection, between which the temperature of the SCR-system may have increased, and hence it is not possible to determine the fraction of vehicles with cold SCR-systems.

The applied NO threshold concentrations of 800 ppm and 1,000 ppm is beyond the threshold suggested from the tests. From the tests, NO threshold concentrations of 660 ppm and 330 ppm were suggested for respectively Euro V and Euro VI heavy-duty trucks.

Looking solely at the results from the police roadside control based on a threshold concentration of 800 ppm, only nine were performed. Of these, none of the five Euro V and four Euro VI heavy-duty trucks were identified with malfunctioning SCR-systems. A total of 42 heavy-duty trucks were selected for police roadside control, because they exceeded a threshold concentration of 1,000 ppm. Of these, 35 were Euro V and Euro VI heavy-duty trucks fitted with SCR-systems of which 77% were identified with malfunctioning SCR-systems.

It is therefore concluded that the low thresholds applied in the performed tests will be too low, since the share of selected heavy-duty trucks with malfunctioning SCR-systems will be relatively low for heavy-duty trucks with emissions below 1,000 ppm. This would be an inefficient use of the resources of the police. Furthermore, the present data material is still relatively limited, and the above conclusion is therefore relatively uncertain.

We thus recommend a flexible approach in connection with future routine controls, where the threshold is adjusted to the practical situation. This means that a threshold of 1,000 ppm is used initially, but in case of vacant capacity in the police, heavy-duty trucks with emissions beyond 660 ppm are selected. Finally, it is important to gather experience from performed routine controls and evaluate the threshold concentrations on basis of this.

1.15 Consequences for the health of the population

An important goal of the project was to assess health consequences of the enhanced emissions resulting from malfunctioning of SCR-systems. This assessment was carried out in the following way:

- Based on the tests in the closed areas, heavy-duty trucks equipped with malfunctioning SCR-systems emitted 20 times more nitrogen monoxide than vehicles with well-functioning SCR-systems. For Euro V heavy-duty trucks, it is estimated that emissions from malfunctioning SCR-systems are twice as high as for Euro VI heavy-duty trucks.
- From the measurements at Padborg and the Great Belt Bridge it has been estimated that 10% of the Euro V and Euro VI heavy-duty trucks on the Danish road network are equipped with malfunctioning SCR-systems. It should be noted that this estimate is highly uncertain. There are no SCR-systems on heavy-duty trucks with Euro Norms below V.
- On basis of the findings above, we have calculated the emissions of nitrogen oxides from all heavy-duty trucks on the Danish road network. These calculations are consistent with the approach that DCE uses for the national emission inventories from road traffic.
- DCE's model systems have been applied to calculate health effects in Denmark that are related to enhanced emissions from malfunctioning SCR-systems. Two sets of calculations have been performed. The first set of calculations are performed for the situation of no malfunctioning SCR-systems. In the second set of calculations there is accounted for malfunctioning SCR-systems. From comparing the two sets of calculations, it is possible to estimate the enhanced health effects related to malfunctioning SCR-systems. Calculations are performed with the UBM (Urban Background Model) and the EVA-model (Economic Valuation of Air pollution).

Malfunctioning SCR-systems on heavy-duty trucks are estimated to increase the number of premature deaths by about 10 (Table 1.7). This is equivalent to about 0.2% of the total number of premature deaths related to air pollution in Denmark. In addition to premature deaths, a series of other health effects are related to air pollution and thus also enhanced emissions that were related to malfunctioning SCR-systems on heavy-duty trucks (see Chapter 9).

Assuming that the extent of malfunctioning SCR-systems in the rest of Europe is similar to those in Denmark, the total number of premature deaths will increase to 33 in Denmark, due to long range transport of air pollution from the rest of Europe to Denmark. This is equivalent to 1% of the total number of premature deaths related to air pollution in Denmark.

The extra external costs related to malfunctioning SCR-systems on heavy-duty trucks in Denmark and the rest of Europe is on the order of 1,000 million DKK, of which about 100 million DKK are related to malfunctioning SCR-systems of heavy-duty trucks in Denmark.

The enhanced emissions of nitrogen oxides from heavy-duty trucks in Denmark will also lead to external costs in the rest of Europe, as a result of long-range transport of air pollution from Denmark to the rest of Europe. These extra external costs amount to about 260 million DKK.

Table 1.7. Number of premature deaths and associated externalities in Denmark resulting from enhanced emissions of nitrogen oxides from heavy-duty trucks with malfunctioning SCR-systems in Denmark and the rest of Europe. *) sum does not fit due to rounding of figures.

	Premature deaths*)	External costs Million DKK
Heavy-duty trucks in Denmark	10	102
Heavy-duty trucks in other European countries	24	898
Total costs in Denmark	33	1000

The estimated health effects and external costs are associated with substantial uncertainties, which is related to the estimate of the extent of malfunctioning SCR-systems, but also to the uncertainties on the calculations of pollutant levels and external costs. The total uncertainty is estimated to be a little more than ±50%.

1.16 Description of a method for routine control for malfunctioning of SCR-systems.

The method for routine control needs to be mobile and fast to both setup and take down. Currently, the OPUS remote sensing system is the most flexible on the market. After an initial phase, the team behind this investigation has obtained good experience with the previous version of the OPUS remote sensing system. Colleagues abroad have furthermore positive experience with the most recent generation of OPUS remote sensing system RSD 5000. It is therefore recommended to base the control system on this equipment.

It is crucial to choose a suitable threshold value for selecting heavy-duty trucks for roadside control. A too low threshold would lead to waste of police resources for controlling well-functioning heavy-duty trucks, and too many chauffeurs will waste time while the heavy-duty truck is controlled. One the other hand, a too high threshold would make the control inefficient with respect to capturing heavy-duty trucks with malfunctioning SCR-systems. The experience from this project shows that a threshold of 1,000 ppm nitrogen monoxide for Euro V lead to identification of 77% heavy-duty trucks with malfunctioning SCR-systems. A threshold of 1,000 ppm is therefore suggested for Euro V heavy-duty trucks. For a threshold value of 800 ppm nitrogen monoxide for Euro VI heavy-duty trucks no malfunctioning was identified on the SCR-systems. It should be noted, that only four Euro VI heavy-duty trucks were observed at a threshold of 800 ppm. With such few observations, it is not possible to judge whether or not the threshold value of 800 ppm is too low. Tests in closed area showed that the lowest emission from malfunctioning SCR-system from a Euro VI heavy-duty trucks was 330 ppm nitrogen monoxide. We recommend the threshold is adjusted during the future routine controls. This means that they should initially be set to 1,000 ppm for Euro VI, but in case of excess capacity from the police, heavy-duty trucks should be selected already at a threshold of 660 ppm. It is important that experience is collected from the performed routine controls and the threshold is routinely evaluated on this basis.

It is suggested to perform control actions distributed over all seasons and at randomly selected time of day. Such a procedure should ensure that there are no safe periods where it is possible to drive on the Danish road network with malfunctioning SCR-systems. Experience from the current study shows, however, that it is not possible to measure during fog or rain, but except for this condition, measurement campaigns should be distributed over any time of year. It is furthermore suggested that between four and eight campaigns of one to two days duration are performed, but the final extent of the program should of course be determined by the deciding authorities. The present project has demonstrated that it is possible to perform measurements for selecting both heavy-duty trucks and passenger cars for control. Experience from the project shows, however, that it is challenging to measure on both heavy-duty trucks and passenger cars with the same setup. The latter is due to e.g. challenges with respect to camera angel in relation to number plate recognition. Effort should be dedicated to solve these challenges or alternatively, the control action should alter between the two groups of vehicles.

It is crucial for the efficiency of the control actions that the selection of campaign sites is made with care. Experience from this project show that it is crucial that the engine of the heavy-duty trucks is sufficiently warm that the SCR-systems work properly. This means that sites should mainly be selected among places where the traffic on the road have been driving for a while. Alternatively, too many resources will be dedicated to control of heavy-duty trucks that show high nitrogen monoxide emissions due to cold engines. Experience from this project shows furthermore that the measurements should be carried out over a single lane to avoid influence from traffic on neighbouring lanes. Sites should therefore be selected so that these are close to highways and where lanes are fairly isolated from other lanes and roads. The project has furthermore shown that it takes time to established experience with a field site, and therefore also to determine the optimal setup for the site. It is recommended that conditions for the selected site is taken into account such as upstream sources like neighbouring lanes and road in prevailing wind directions that might affect measurements. Another experience from the project is that drivers are highly observing with respect to activities around the road and that camera and equipment should be placed in such a way that they are not visible before the measurements are taken. This has to be organised individually for the single sites but might e.g. include the use of a smaller tent. It is suggested that measurements are performed at twenty sites distributed over the country, and that campaigns are altering between these sites in changing order. It is furthermore suggested that experience from these sites is documented with respect to optimisation of future campaigns. In this connection it is furthermore recommended based on experience from campaigns in the current project that Padborg and the Great Belt Bridge are included as sites in the future.

Handling of the remote sensing equipment demands at least one person, but in praxis it will likely demand at least two persons, and similarly there will be a need for at least one and in praxis two persons to perform the road site controls. It is recommended that intensive training courses are performed every four years and shorter follow up courses every second year to train the team that has to handle the remote sensing equipment and perform road site controls. It is recommended that at least six persons are trained for each of these functions. It should be expected that new technology and new devices will be available in the coming years. It is therefore recommended to carry out workshops with participation of researchers as well as people with practical experience with new devices and techniques within this area.

Every year DCE at Aarhus University is compiling the Danish emissions from road traffic within the Danish national emission inventories. The inventories for road traffic are based on emission factors for the individual vehicle categories and accounting for aging. Emission factors are determined by laboratory studies performed on driving stand where the individual vehicle is conducting a driving cycles – this means drive at varying velocity and including acceleration and deceleration to simulate real world driving conditions. These emission factors are used together with information about sale of petrol and diesel, various traffic data from routine counting and traffic models etc. In relation to these national emission inventories, data from remote sensing would be a valuable supplement. It is therefore recommended to investigate the possibilities for establishing a database with measurement data from remote sensing campaigns for this purpose. In this connection, it is of course crucial that data security is in compliance with rules to ensure anonymization and protection of personal data etc.

The routine controls will be resource demanding and it is recommended that evaluation of the entire control system is performed on routine basis to ensure both quality and efficiency. This includes also routine analyses of whether the control system has a positive effect on the number of vehicles with malfunctioning SCR-systems.

Expenses related to the routine control program for emissions from road traffic with focus on heavy-duty trucks will depend totally on the selected setup. As previously stated, it can be necessary with a separate setup for passenger cars. As previously mentioned, for the measurement campaigns there will be a need for at least two persons to handle the remote sensing system and similarly at least two persons for the road site control on the selected vehicles. The latter is of course for the police to decide and will be adjusted when more experience is obtained. To ensure routine operation over longer time periods, it may be meaningful to have training on the site during the campaigns.

Data treatment will include analyses to determine emissions, coupling to central motor registers, selection of vehicles for control in combination with the result of the police's roadside controls.

It is recommended to establish a database for the measurements of nitrogen monoxide emissions from the driving car park on the Danish road network. This will demand resources but also deliver valuable data.

A routine control program will include expenses for rent of equipment, logistics at the campaigns as well as a site for the team to stay and the equipment to be stored. Alternatively, a measurement van may be used for this purpose.

The total expenses for an efficient control program are difficult to determine. NEQ has crudely estimated these expenses to between five and ten million DKK per year for a continuous measurement program over the entire year. For a more limited program with four to sixteen measurement days per year, the expenses will of course be less.

1.17 Acknowledgement

CSP Trucks Danmark, Mercedes-Benz Danmark A/S, Scania Danmark A/S, TJW Fragt, Volvo Group Trucks Denmark A/S, Sund & Bælt Holding A/S, and Danish Police are all thanked for valuable contribution to the project.

2 Udvidet dansk sammenfatning og konklusion

NEQ ApS og DCE – Nationalt center for miljø og energi har i efteråret 2019 og januar 2020 gennemført et projekt for Miljøstyrelsen. Projektet er udbudt med baggrund i den dedikerede indsats mod snyd med NOx-begrænsende udstyr på lastbiler. Arbejdsgruppen der er nedsat i forbindelse med den dedikerede indsats mod snyd med NOx-begrænsende udstyr på lastbiler er et samarbejde mellem Rigspolitiet, Miljø- og Fødevareministeriet samt Miljøstyrelsen og Færdselsstyrelsen. Projektet har fokus på manipulation og fejl på de rensesystemer, Selective Catalytic Reduction (SCR-systemerne), som fjerner kvælstofoxider (NO_x) fra de nyeste store lastbilers udstødning. Det skal bemærkes, at der i denne undersøgelse fokuseres på kategorierne 'Stor lastbil' (større end 3500 kg) og 'Personbil' (på engelsk hhv. 'Heavy-duty truck' and 'Passenger car'). Projektet har endvidere fokus på den ekstra belastning af miljø og folkesundhed fra de ekstra udledninger, som skabes i forbindelse med manipulationen og fejlene på SCR-systemerne. Projektet er en opfølgning på et tidligere projekt, som NEQ og DCE har gennemført for Miljøstyrelsen, og i samarbejde med Færdselsstyrelsen og Rigspolitiet (http://www.ft.dk/samling/20171/almdel/MOF/bilag/565/index.htm).

I det følgende præsenteres først hovedkonklusionerne fra projektet, hvorefter vi beskriver de mange aktiviteter og resultater, som ligger til grund for disse hovedkonklusioner.

2.1 Hovedkonklusioner

Manipulation og fejl på SCR-systemerne på lastbiler med Euro V og VI norm store lastbiler, som giver anledning til forøgede udledninger af kvælstofoxider fra vejtrafikken. De forøgede udledninger fra vejtrafik i Danmark medfører omkring 10 for tidlige dødsfald i Danmark samtidig med en forøgelse af en langt række sygdomme og sygdomsudfald blandt andet hjerte-kar- og luftvejssygdomme, sukkersyge og lungekræft. De samlede eksterne omkostninger i Danmark er vurderet til omkring 1,3 milliarder kr. årligt, som følge af luftforurening relateret til de forøgede udledninger fra vejtrafik i Danmark. Disse resultater er fremkommet på basis af resultater fra de mange målinger i projektet, som har dannet baggrund for modelberegninger med DCE's luftkvalitetsmodeller.

Projektet har endvidere vist, at målinger af udledninger fra store lastbiler ved hjælp af remote sensing-metoden er et effektivt værktøj til udvælgelse af store lastbiler til en efterfølgende vejsidekontrol gennemført af politiet. Ved at kombinere målinger og vejsidekontrol er det muligt at fokusere politiets ressourcer mod undersøgelser af netop de store lastbiler, hvor der er størst sandsynlighed for manipulation af eller fejl på SCR-systemerne. Samtidigt vil kombinationen af målinger og vejsidekontrol potentielt have stor præventiv effekt, da der via målingerne kan foretages en screening til fokuseret kontrol af store lastbiler, som vil gøre det muligt for politiet at finde langt flere store lastbiler med SCR-systemer, som er enten manipulerede eller fejlbehæftede, end det vil være muligt gennem tilfældig udvælgelse til kontrol.

Politiet gennemførte omfattende vejsidekontroller af 52 lastbiler parallelt med projektets målekampagner ved Padborg og Storebælt. Der blev udvalgt 44

Euro V og Euro VI store lastbiler, som havde udledninger over 800 ppm NO (svarende til 17 g NO_2/kg brændstof). På 61% af de udvalgte store lastbiler fandt politiet, at der var tale om enten manipulation eller fejl på SCR-systemerne. Det formodes, at de sidste 39% havde høje udledninger som følge af kold motor og dermed inaktivt SCR-system. Disse observationer dokumenterede, at målinger med remote sensing i kombination med vejsidekontrol vil være en effektiv måde at føre kontrol med manipulation og fejl på SCR-systemer i store lastbiler i den kørende vognpark.

I forbindelse med målekampagnerne ved Storebælt og Padborg blev der samlet gennemført succesfulde målinger af udledninger fra 2,942 store lastbiler og 3,306 personbiler. Ud fra disse målinger har vi estimeret, at der for omkring 10% af Euro V og Euro VI lastvognene, er der tale om store lastbiler med SCR-systemer, som er manipulerede eller har tekniske fejl. Dette estimat er anvendt til beregninger af helbredseffekter relateret til de øgede udledninger fra store lastbiler med manipulerede eller fejlbehæftede SCR-systemer. Der er stor usikkerhed på dette estimat, da målingerne ikke viser et spring i udledninger mellem velfungerende og ikke fungerende SCR-systemer i store lastbiler. Det sidste skyldes, at store lastbiler med kold motor kan have samme høje udledning, som en lastvogn, der har manipuleret eller fejlbehæftet SCR-system.

Målingerne på såvel store lastbiler som personbiler viste, at de nyeste euronormer har givet en markant sænkning af udledningerne. For store lastbiler er udledningerne af kvælstofmonooxid (NO) og partikler (PM) faldet med omkring 85% fra Euro V til Euro VI. For personbiler er faldet fra Euro 5 til Euro 6 på omkring 84 % for kvælstofmonooxid og 50% for partikler. Euro VI store lastbiler og Euro VI personbiler udgjorde henholdsvis 76% og 62% af de målte store lastbiler og personbiler, hvilket er i overensstemmelse med forventningen i forhold til den generelle udskiftning af køretøjsparken i Danmark, hvor en stadig større andel udgøres af de nyeste euronormer. De danske opgørelser over udledninger fra vejtrafik viser et stort fald (DCE, 2020), hvilket for en stor del kan forklares med den stadig større andel af Euro VI store lastbiler og Euro VI personbiler.

I projektet blev der gennemført en lang række test på et lukket område med bevidst manipulation af SCR-systemerne på store lastbiler. De væsentligste konklusioner fra disse tests er:

- Når SCR-systemerne på Euro VI store lastbiler slås fra, så forøges udledningerne af kvælstofmonooxid med omkring en faktor 20. Denne vurdering baseres på testmålinger på Euro VI store lastbiler på lukket område, hvor SCR-systemerne var henholdsvis slået til og fra under målingerne.
- Målingerne på seks Euro V store lastbiler viste, at udledningerne fra Euro V store lastbiler med fejlbehæftede SCR-systemer i gennemsnit lå omkring en faktor 2 højere end gennemsnit for de testede Euro VI store lastbiler med SCR-systemer slået fra.
- Euro VI store lastbiler med kold motor gav udledninger på stort set samme niveau, som for Euro VI store lastbiler med SCR-systemerne slået fra. Årsagen til dette er, at SCR-systemerne kun fungerer, som de skal, ved en relativt høj temperatur, og at denne temperatur kun opnås ved varm katalysator i SCR-systemet som fordrer en varm motor. Tilsvarende forventes for Euro V store lastbiler med SCR-systemer.

- Testene viste, at udledningerne af kvælstofmonooxid steg med en faktor 10 på kun fire minutter, når den testede lastvogn stod i tomgang. I løbet af de fire minutter faldt temperaturen i katalysatoren i SCR-systemerne så meget, at disse ikke længere havde tilstrækkelig høj temperatur til at fungere.
- Testene indikerer, at udledninger over 7 gNO_2/kg brændstof (svarende til 330 ppm NO) medfører stor sandsynlighed for, at der er tale enten manipulation eller fejl på SCR-systemerne for Euro VI store lastbiler. Den tilsvarende grænse er vurderet til 14 gNO_2/kg fuel (660 ppm NO) for Euro V store lastbiler. Dog anbefaler vi en fleksibel tilgang ifm. politiets vejsidekontroller, hvor udgangspunktet er en grænse på 1,000 ppm NO (se afsnit 8.1).
- Emission af PM fra diesel lastbiler aftog fra Euro V til Euro VI. For personbiler var dette billede endnu tydeligere gennem Euro 3 til Euro 6, hvor tilstedeværelsen af partikelfilter for sidstnævnte euronorm gjorde, at udledningen var kun 0.1 g PM/kg brændstof. Hvor emissionen af PM fra Euro 3 dieselbiler var 17 gange højere end fra benzinbiler med samme euronorm, udviste Euro 5 og Euro 6 personbiler samme PM-emission uanset brændstoftype.

2.2 Baggrund og formål

De seneste Euro-normer for store lastbiler stiller store lovgivningskrav til lastvognes udledninger af kvælstofoxider. For at overholde disse krav, er der for Euro-VI-store lastbiler krav om anvendelse af såkaldte SCR-systemer (selektiv katalytisk reduktion). SCR-systemer er avancerede rensesystemer koblet til udstødningen, som sørger for at fjerne mere end 90% af de sundhedsskadelige kvælstofoxider fra udstødningsgassen. For størstedelen af Euro-V-lastvognene anvendes ligeledes SCR-systemer, mens en mindre del af lastvognene anvender anden renseteknologi.

Igennem de seneste år har der været gennemført en række kontrolaktioner i Danmark og andre europæiske lande, som har vist, at der sker en ikke ubetydelig manipulation med SCR-systemerne på store lastbiler, der kører i Danmark. Samtidigt har det vist sig, at der er en del store lastbiler, som har tekniske fejl på SCR-systemerne. Denne tendens blev også tidligere dokumenteret af NEQ APS og DCE – Nationalt Center for Miljø og Energi, da man i 2018 gennemførte et pilotprojekt for Miljøstyrelsen, Færdselsstyrelsen og Rigspolitiet med fokus på manipulation af SCR-systemerne i Danmark (http://www.ft.dk/samling/20171/almdel/MOF/bilag/565/index.htm).

Manipulation og fejl på SCR-systemer fører til ekstra udledning af kvælstofoxider, hvilket forringer luftkvaliteten og dermed medfører øgede helbredseffekter i befolkningen. Derfor har regeringen, som led i Klima- og luftkvalitetsstrategien fra 2018, vedtaget at iværksætte en række initiativer for at udvikle og implementere en kontrolmetode, som kan sikre overholdelse af reglerne for køretøjers udledning af luftforurening med særlig fokus på udledninger fra store lastbiler.

Projektet har følgende formål:

- Der skal foretages målinger af udledninger fra flåden af køretøjer, som kører på det danske vejnet.

- Omfanget af manipulation og fejl på SCR-systemer på store lastbiler i Danmark skal vurderes på basis af målinger af udledningerne.
- Der skal gennemføres testmålinger på lukkede områder, hvor blandt andet udledninger fra manipulerede og fejlbehæftede SCR-systemer sammenlignes med udledninger fra velfungerende SCR-systemer.
- På basis af målingerne vurderes de forøgede helbredseffekter, som manipulation og fejl på SCR-systemerne giver i Danmark.
- Det skal undersøges, om målinger kan anvendes som mistankegrundlag for en efterfølgende målrettet politikontrol af udvalgte køretøjer (primært store lastbiler).
- Det skal vurderes hvilken RSD-metode (Remote Sensing Devices), der er bedst egnet til rutinekontrol af SCR-systemer.
- Der skal udarbejdes en metode til gennemførelse af rutinekontrol af SCR-systemer på store lastbiler baseret på RSD-målinger i kombination med efterfølgende vejsidekontrol gennemført af politiet.

Målinger skal gennemføres med RSD-metoden, som er en målemetode, hvor udstødningens indhold af blandt andet kvælstofoxider kan måles under virkelighedstro forhold på et stort antal køretøjer (Måleteknikken uddybes yderligere i senere afsnit).

2.3 Aktiviteter

Projektet er opdelt i en række aktiviteter:

1. Vurdering af hvilken stationær RSD-metode der vil være bedst egnet til kontrol af SCR-systemer i Danmark, og under hvilke kørselsforhold metoden kan anvendes.

2. Gennemførelse af test på lukkede områder med henblik på at validere målemetoden, og fastsætte udledningsniveauer, over hvilke lastbiler med stor sandsynlighed er manipulerede eller har fejl på SCR-system eller partikelfilter. Disse udledningsniveauer omtales i det følgende som udpegningsgrænser. Testene involverer målinger af udledninger fra store lastbiler med velfungerende SCR-systemer og partikelfiltre efterfulgt af målinger på de selvsamme store lastbiler, hvor SCR-systemerne og partikelfilter bevidst er sat ud af funktion / fjernet. At partikelfiltret bliver fjernet i nogle test skyldes, at en del af manipulationsmetoderne netop kræver, at partikelfiltret decideret fjernes. I sådanne tilfælde vil der således være forøgede udledninger af såvel kvælstofoxider som partikler.

3. Udvælgelse af 1-3 målesteder, som er egnet til gennemførelse af målinger med RSD-metoden i kombination med efterfølgende politikontrol af store lastbiler mistænkt for manipulation eller fejl i SCR-systemerne. Målingerne har fokus på måling af udledninger fra et stort antal store lastbiler, og i tilknytning til disse målinger gennemføres efterfølgende politikontrol for udvalgte store lastbiler med målte udledninger over den valgte udpegningsgrænse. Endvidere måles på alle personbiler, der passerer målestedet, så der opnås et stort antal stikprøver af udledninger fra køretøjsflåden på det danske vejnet.

4. På basis af ovenstående udarbejdes et estimat over de forøgede udledninger af kvælstofoxider, der skyldes manipulation eller fejl på SCR-systemer. Ud fra

dette estimat beregnes de forøgede helbredseffekter, som er en følge af de ekstra udledninger af kvælstofoxider.

5. Udarbejdelse af forslag til metode til rutinekontrol af SCR-systemer baseret på målinger med RSD-metoden i kombination med politikontrol af store lastbiler, hvor målingerne har vist udledninger over udpegningsgrænsen, og derved giver grundlag for mistanke om manipulation eller fejl på SCR-systemet.

I det følgende giver vi en sammenfatning af resultaterne af disse aktiviteter, men forinden gives en kort beskrivelse af, hvordan RSD-metoden fungerer.

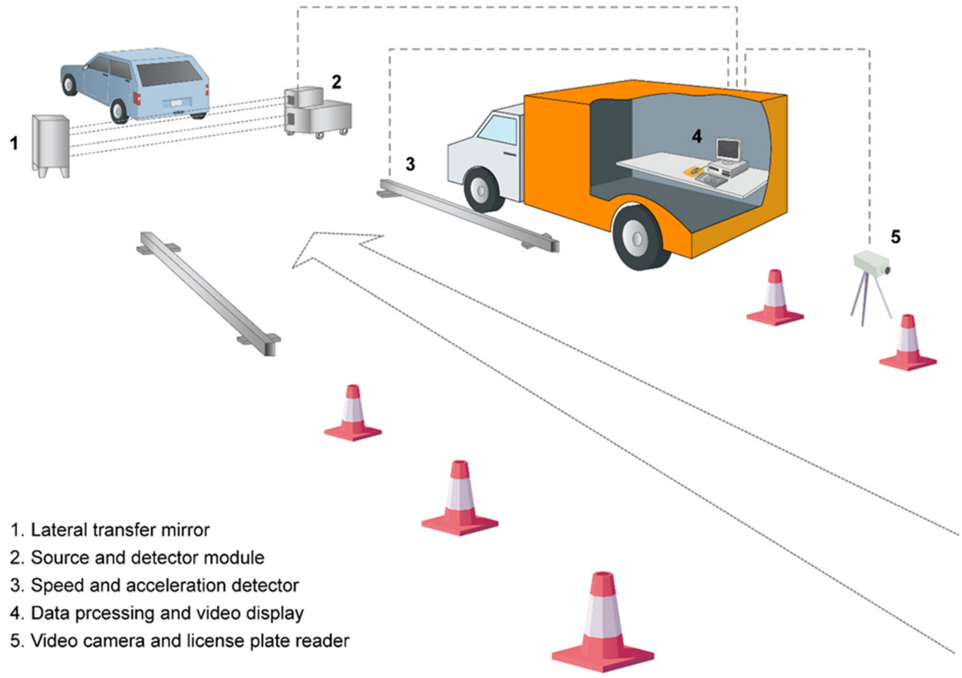
2.4 RSD-metoden

Selve måleudstyret (Figur 2.1) består af en detektordel og et avanceret spejlsystem, som placeres på hver side af vejbanen, hvor målingerne foretages. Detektordelen sender uskadelige stråler af laserlys tværs over vejen til spejlsystemet, som returnerer laserstrålerne til detektoren. Detektoren måler herefter lysstyrken i de reflekterede laserstråler. Lysstyrken i den udsendte laserstråle kendes og ud fra målingerne bestemmes det, hvor meget lys, der er absorberet (tabt) på vejen frem og tilbage over vejbanen. Laserstrålens bølgelængder er udvalgt i et område, hvor man ved, at lys vil bliver absorberet af luftforurening stammende fra vejtrafikkens udstødning. Ved at måle, hvor meget laserstrålens styrke formindskes på rejsen frem og tilbage over vejbanen, og på baggrund af kendskab til luftforureningskomponenternes fysiske egenskaber, beregnes koncentrationerne af de enkelte luftforureningskomponenter i udstødningsskyen bag køretøjerne.

På denne måde kan udstyret måle øjeblikskoncentrationer af de vigtigste luftforureningskomponenter i udstødning fra passerende køretøjer. Dette projekt har fokus på måling af kvælstofmonooxid (NO) og massen af partikler i luften (kaldet PM = particulate matter). For at omsætte de målte øjeblikskoncentrationer til en værdi for udledningen af kvælstofmonooxid og PM, så måles også koncentrationen af kuldioxid (CO_2), kulstofmonooxid og uforbrændt brændstof. Disse forbindelser er i denne sammenhæng de vigtigste produkter, som dannes ved forbrændingen af brændstof i motorer. Kvælstofmonooxid og kuldioxid samt de øvrige parametre fortyndes lige hurtigt, når de forlader udstødningsrøret. Ud fra øjebliksmålingen i skyen bag udstødningsrøret kan man beregne forholdet mellem de målte parametre og ud fra dette bestemme, hvor mange gram kvælstofmonooxid, der er udledt per kg forbrændt brændstof.

Da luftforureningen kan komme fra andre kilder end det målte køretøj, så foretages der i realiteten to sæt af målinger. Et sæt målinger foretages lige inden køretøjet passerer udstyret, og et ny sæt målinger foretages umiddelbart efter køretøjet har passeret. Forskellen mellem de to sæt af målinger giver det bidrag, som stammer fra køretøjet, der har passeret instrumentet. Der kan imidlertid være situationer, hvor den første måling er ”kontamineret” af udledninger fra for eksempel en gammel lastvogn, der lige har passeret målestedet. Hvis det målte køretøj for eksempel er en Euro VI lastvogn, så vil man kunne risikere, at målingen før passage viser større koncentrationer end målingen efter. Dette er forklaringen på, at det ikke er muligt helt at undgå situationer, hvor der måles negative koncentrationer ved fx målinger i tæt befærdede områder.

Målingerne tager få sekunder at gennemføre, og resultaterne er tilgængelige umiddelbart herefter. Udstyret kan derfor bruges til at bestemme udledninger fra et meget stort antal store lastbiler på kort tid og under aktuelle forhold i trafikken (dog er der en begrænsning for hvor hurtigt køretøjerne må passere instrumenterne i forbindelse med målingerne). Målingerne er tiltænkt som grundlag for en hurtig udvælgelse af store lastbiler, hvor der potentielt er tale om manipulation med eller fejl på SCR-systemerne.



Figur 2.1. Øverst: Foto af en måleopstilling. Udledning af luftforureningskomponenterne (navnlig kvælstofoxider og partikler) er lige netop blevet målt på lastvognen med den røde container. Måleudstyret ses på begge sider af vejbanen umiddelbart efter lastvognen. Nederst: Principskitse (kilde: NEQ ApS)

Udstyret suppleres endvidere med måling af køretøjernes hastighed og acceleration, da kørselshastigheden i henhold til udstyrets guidelines skal ligge mellem 30 og 60 km/t med en let acceleration for at få de mest optimale målinger. Erfaringerne fra projektet har dog vist, at metoden er relativt robust, og at gode målinger også kan opnås under andre kørselsforhold.

Målingerne med RSD-metoden er automatiserede og styres af software, som løbende foretager de nødvendige beregninger, og ligeledes automatisk gemmer resultaterne. Softwaret sørger endvidere for at koble målingerne fra de enkelte køretøjer med tilhørende fotos, der automatisk tages af et kamera knyttet til instrumentet med henblik på efterfølgende identifikation køretøjerne. Identifikationen foretages ud fra manuel eller automatisk aflæsning af nummerplader og efterfølgende opkobling til Det Danske Motorregister. Gennem identifikationen bestemmes samtidig hvilken euronorm køretøjet tilhører. Denne fremgangmetode blev anvendt i forbindelse med målinger på personbiler, som derfor alene omfatter danske personbiler. For lastvognene er fastlæggelsen af euronormer foretaget ud fra lastvognenes udseende. Hvor billedkvaliteten tillod det, blev nummerpladerne slået op i Motorregistret med henblik på at identificere euronormen. I modsat fald blev euronormen fastlagt ud fra visuel genkendelse. På baggrund politiets erfaring er det muligt at identificere Euro V og VI store lastbiler alene ud fra udseendet. Derfor omfatter projektet resultater fra både danske og udenlandske store lastbiler. Fastlæggelse af euronorm er formodentlig behæftet med en lille fejl. I forbindelse med dobbeltcheckene, er der dog kun registreret få afvigelser.

2.5 Vurdering af bedst anvendelige RSD-metode

Den følgende vurdering er udarbejdet af NEQ.

Der er to forskellige typer RSD på markedet i dag. Begge systemer er udviklet i USA, og begge systemer anvendes i dag operationelt til målinger i både USA og Europa. Producenterne af de to forskellige typer RSD er henholdsvis OPUS og EDAR. Der er fordele og ulemper ved begge systemer, men overordnet set vurderer vi, at systemet fra OPUS har en væsentlig fordel, som er knyttet til systemets fleksibilitet og håndterbarhed. Systemet fra OPUS kan opsættes relativt hurtigt (mindre end en time), og det kan derfor anvendes på forskellige målesteder inden for et tidsrum af en uge, eller endda inden for en enkelt dag. Samtidig er OPUS-system relativt let at skjule for trafikanterne i trafikken. Til forskel fra dette system, så kræver systemet fra EDAR, at en del af udstyret fræses ned i eller på anden vis fastgøres på overfladen af asfalten på målestedet, så udstyret i praksis kun kan anvendes på faste målesteder.

2.6 Test på lukkede områder

En vigtig del af projektet var gennemførelsen af en række test med RSD-målinger på et lukket område, fordi det giver mulighed for at sammenligne målinger på store lastbiler med velfungerende SCR-systemer og partikelfiltre med målinger foretaget på de samme store lastbiler, hvor SCR-systemet og partikelfilter er frakoblet. De kontrollerede forhold gør det muligt at teste målesystemet og indsamle data, som kan bruges til at vurdere, hvordan diverse ydre forhold påvirker målingerne af udledninger.

De situationer og forhold, der blev testet, var følgende:

- Måling af forøgelsen af udledning af kvælstofmonooxid, når SCR-systemet frakobles. Der blev til dette indkøbt en række forskellige manipulationsudstyr, men det viste sig tilstrækkeligt af afkoble SCR-systemerne på mere simpel vis.
- Måling af forøgelsen af udledning af PM ved fjernelse af partikelfilter. Baggrunden er, at visse former for manipulation af SCR-systemerne kræver fjernelse af partikelfiltret. Manipulation af SCR-systemerne kan dermed have konsekvenser for udledningerne af både kvælstofoxider og PM.
- Studier af betydningen af temperaturen af katalysatoren for SCR-systemets indflydelse på udledningerne.
- Studier af vejrets indflydelse på målinger og udledninger.
- Studier af effekt af varierende hastighed og acceleration under målingerne.
- Studier af effekten af trailer på målinger og udledning.

Målinger med både velfungerende og frakoblet SCR-system har to vigtige mål.

- For det første skal resultaterne bruges til at fastlægge en udpegningsgrænse for udledning af kvælstofmonooxid. Denne udpegningsgrænse skal anvendes til at udvælge store lastbiler, som potentielt set kan være manipulerede eller have fejl på SCR-systemet. Udpegningsgrænsen tænkes benyttet som udgangspunkt, når Dansk Politi skal udvælge store lastbiler til efterfølgende vejsidekontrol.
- For det andet skal målingerne anvendes til at estimere, hvor meget udledningerne af kvælstofmonooxid øges ved manipulation eller fejl på SCR-systemerne. Denne information bruges i forbindelse med beregninger af, hvor meget helbredseffekter i den danske befolkning øges som følge af forøgede udledninger relateret til manipulation og fejl på SCR-systemer.

Endvidere skal de mange praktiske erfaringer, som erhverves ved testene, anvendes som baggrund for udarbejdelse af en plan for metode til rutinekontrol for manipulation og fejl på SCR-systemer.

I ugerne 38 og 39 i september 2019 blev der udført 216 test på Euro VI store lastbiler med aktive, inaktive og helt frakoblede SCR-systemer. Testene blev udført med fire forskellige store lastbiler stillet til rådighed af Mercedes, Scania og Volvo.

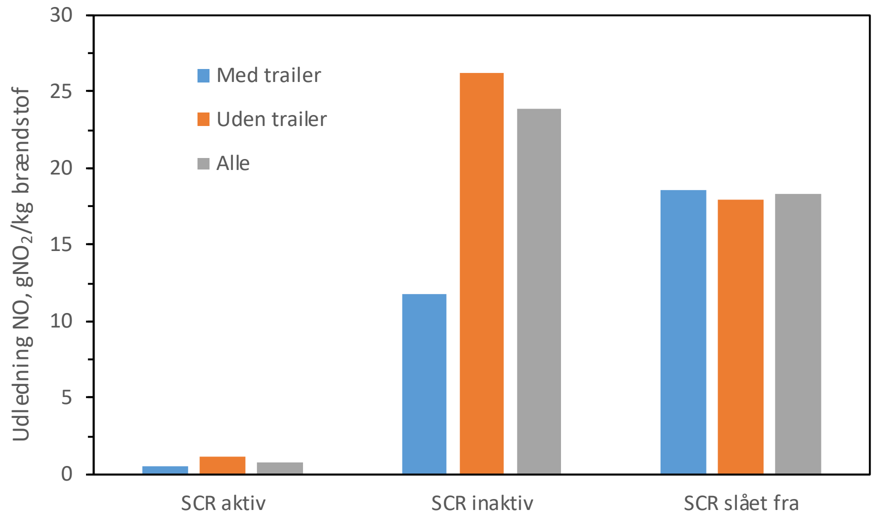
For Euro V store lastbiler blev der kun udført 26 test. Derfor blev kun en lille del af testprogrammet gennemført for Euro V store lastbiler. Årsagen til dette var, at alle de testede Euro V store lastbiler viste sig at have fejl på SCR-systemerne. Som udgangspunkt skulle der testes to store lastbiler, men grundet fejlene blev der skaffet yderligere store lastbiler, så der i alt blev testet seks forskellige Euro V store lastbiler. Alle de testede store lastbiler havde fejl på SCR-systemerne, selv om ejerne troede, at de var velfungerende.

2.7 NO og PM testresultater fra lukkede områder

Figur 2.2, og Tabellerne 2.1 og 2.2 sammenfatter resultaterne fra testene. Resultaterne er opdelt i tre kategorier:

- **Aktivt SCR-system**. Dette er kendetegnet ved aktiv tilførsel af AdBlue til SCR-systemet. Det kræver, at motoren er varm, og at SCR-katalysatoren har nået en tilstrækkelig høj temperatur.
- **Inaktivt SCR-system**. Dette er kendetegnet ved, at der ikke sker aktiv tilførsel af AdBlue til SCR-systemet. I forbindelse med testene, skyldes det inaktive SCR-system, at SCR-katalysatoren er for kold.
- **SCR-system slået fra**. I dette tilfælde var lastvognene bevidst manipulerede, så SCR-systemet ikke virkede.

Resultaterne for Euro VI store lastbiler viste en gennemsnitlige udledning af kvælstofmonooxid ækvivalent med 0,8 g NO_2/kg brændstof for aktive SCR-systemer, 24 g NO_2/kg brændstof for inaktive SCR-systemer og 18 g NO_2/kg brændstof, når SCR-systemet var slået fra (Tabel 2.1). Der var derfor omkring en faktor 20 mellem udledningerne fra et velfungerende SCR-system og fra et ikke fungerende SCR-system. Årsagen til den lidt højere udledning fra et inaktivt SCR-system i forhold til et SCR-system, som er slået fra, kan formodentlig tilskrives måleusikkerhed.



Figur 2.2. Gennemsnitlig udledning af kvælstofmonooxid (NO) fra Euro VI store lastbiler med SCR-systemer, som er henholdsvis aktive, inaktive og slået fra. Resultaterne er endvidere opdelt efter om lastvognene kørte med eller uden trailer. Udledningerne er i denne, og i de følgende figurer og tabeller angivet i ækvivalenter af kvælstofdioxid (gNO_2/kg brændstof), hvilket er standard i forbindelse med udledningsopgørelser.

Den gennemsnitlige udledning af kvælstofmonooxid fra de testede Euro V lastbiler med inaktivt SCR-system var ækvivalent med 32 g NO2/kg brændstof (Tabel 2.2). Dette er 35% højere end for Euro VI lastbiler målt under de samme betingelser, og omkring en faktor to højere end for en Euro VI lastvogn med SCR-systemet slået fra. Desværre var det i forbindelse med dette projekt ikke muligt at teste en Euro V lastvogn med velfungerende SCR, og det er derfor ikke muligt på baggrund af disse undersøgelser at lave en direkte sammenligning mellem Euro V og Euro VI med SCR-systemet slået fra. Dog viser et nyligt studie af lastbilemissioner i Göteborg, Sverige, at forholdet mellem udledningerne af NO fra Euro V og Euro VI er omkring 5 (Sjödin et al., 2017).

Tabel 2.1. Gennemsnitlige udledninger af kvælstofmonooxid (NO) og partikler (PM) for de forskellige test af Euro VI store lastbiler. Variationen er beregnet som standardafvigelsen på resultaterne inden for en kategori. Dermed angiver den, hvor stor spredningen er på resultaterne inden for den enkelte kategori.

Status for SCR	Trailer	Partikelfilter	Antal test	NO gNO2/kg brændstof		PM gPM/kg brændstof	
				Middel	Variation	Middel	Variation
Aktiv	Ja	Ja	37	0,59	0,82	1,0	1,6
Aktiv	Nej	Ja	15	1,2	1,0	1,1	1,2
Aktiv	Ja/Nej	Ja	52	0,76	1,4	1,1	1,5
		Ja					
Inaktive	Yes	Ja	9	11,8	2,1	1,0	1,2
Inaktive	No	Ja	45	26,3	7,1	1,4	1,5
Inaktive	Yes/No	Ja	54	23,8	7,5	1,3	1,5
Slået fra	Yes	Ja/Nej	59	18,5	7,1	1,1	1,4
Slået fra	Nej	Ja/Nej	44	18,0	4,3	0,63	0,43
Slået fra	Ja/Nej	Ja/Nej	103	18,3	6,1	0,91	1,1
Slået fra							
Slået fra	Ja/Nej	Ja	69	15,9	4,6	0,87	1,2
Slået fra	Ja/Nej	Nej	34	24,2	7,8	0,97	0,77

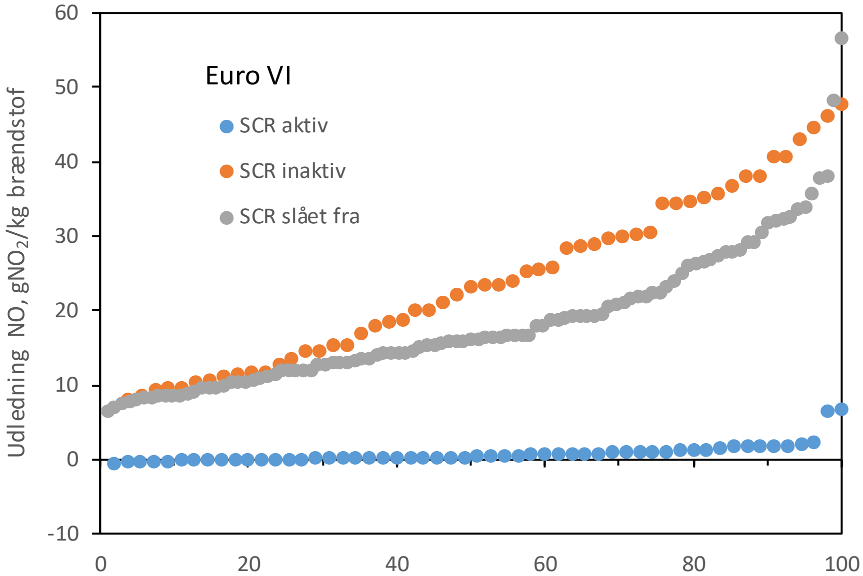
Tabel 2.2. Gennemsnitlige udledninger af kvælstofmonooxid (NO) og partikler (PM) for test af Euro V store lastbiler. Variationen er beregnet som standardafvigelsen på resultaterne inden for en kategori. Dermed angiver den, hvor stor spredningen er på resultaterne inden for den enkelte kategori.

Status for SCR	Trailer	Partikelfilter	Antal test	NO gNO2/kg brændstof		PM gPM/kg brændstof	
				Middel	Variation	Middel	Variation
Inaktiv	ja	Nej	18	36	8,5	1,2	1,1
Inaktiv	Nej	Nej	7	23	4,1	0,67	0,12
Inaktiv	Ja/nej	Nej	25	32	9,6	1,1	0,98

PM og NO emissionerne fra Euro VI lastbiler var dermed ikke påvirket af tilstedeværelsen af trailer med SCR slået fra eller partikelfilter for lastbilerne med inaktiv SCR. Faktisk gav ingen af modifikationerne anledning til ændrede PM- og NO-emissioner. Derimod var NO-emissionen, som forventet, særdeles påvirket af, om SCR-systemet var aktivt eller ej.

De samme konklusioner kunne ikke drages for Euro V lastbiler, da det ikke var muligt at fremskaffe et aktivt SCR-system hertil. Tilstedeværelsen af trailer ændrede hverken PM- og NO-emissionerne. NO-emissioner var omtrent dobbelt så høje fra Euro V med inaktiv SCR (32 g NO_2/kg, n= 25) sammenlignet med Euro VI med inaktiv SCR (18 g NO_2/kg, n = 103).

Figur 2.3 viser fordelingen af de målte udledninger fra Euro VI store lastbiler opdelt i de tre forskellige kategorier. Alle udledninger målt for store lastbiler med SCR-systemet slået fra ligger over de tilsvarende målinger af udledningerne for store lastbiler med et aktivt SCR-system. På basis af testene foreslås derfor en udpegningsgrænse på omkring 7 g NO_2/kg brændstof (330 ppm NO), hvilket svarer til den laveste målte udledning, når SCR-systemet er slået fra. En anden vigtig konklusion fra testene er, at udledningerne fra et inaktivt SCR-system ligger på niveau med udledningerne fra et SCR-system, som er slået fra. I forbindelse med testene, så skyldes det inaktive SCR-system, at motoren er for kold. Årsagen til en målt udledning over udpegningskriteriet kan derfor lige så godt være en kold motor, som det kan skyldes manipulation eller fejl på SCR-systemerne.

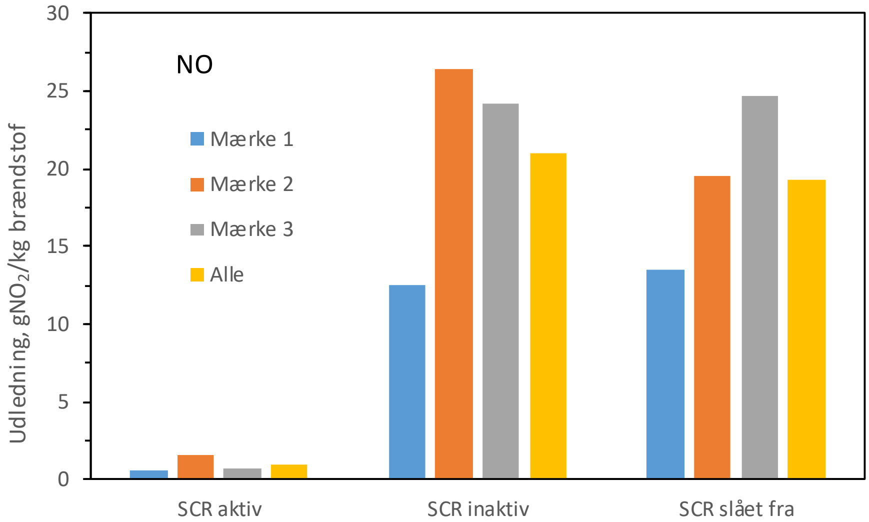


Figur 2.3. Fordeling af udledningerne af kvælstofmonooxid (NO) fra Euro VI store lastbiler med SCR-systemer, som er aktive, inaktive og helt slået fra. Resultaterne er sorteret efter stigene udledning inden for de tre kategorier. X-aksen angiver procentdelen af resultater med en udledning lavere end y-værdien for et givet punkt.

Testene med Euro V store lastbiler peger på, at udpegningsgrænsen skal ligge højere end for Euro VI. Dette er begrundet i, at Euro V store lastbiler med inaktivt SCR-system i gennemsnit har en udledning, som ligger to gange højere end gennemsnittet for Euro VI store lastbiler med SCR-systemerne slået fra. Testene peger derfor på en udpegningsgrænse på omkring 14 gNO_2/kg brændstof (660 ppm NO).

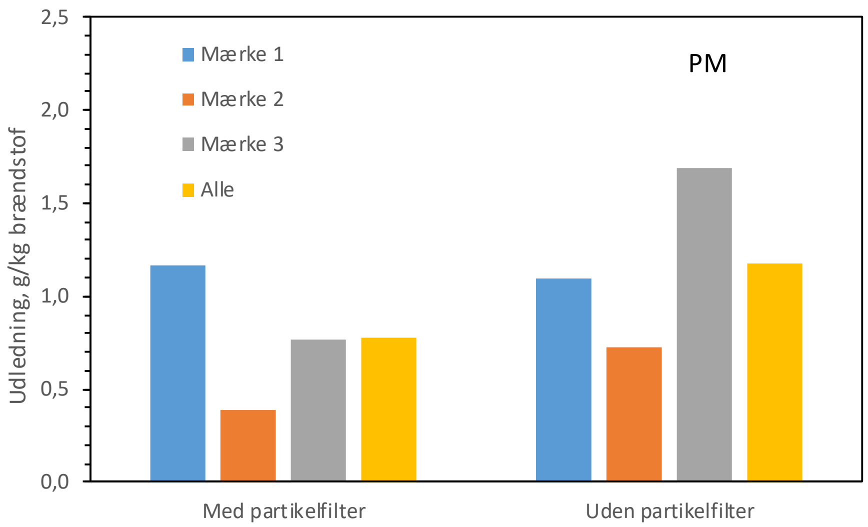
2.8 Betydning af lastbilmærke

De tre forskellige lastvognsmærker viste relativt store forskelle i udledningerne af både kvælstofmonooxid og partikelmasse. Tilsvarende viste de forskellige lastvognsmærker store forskelle i effekten af at fjerne partikelfilteret (Figurerne 2.4 og 2.5). Det vides ikke om årsagen skal findes i forskelle mellem de tre forskellige lastvognsmærker, eller om det er relateret til de specifikke store lastbiler, der er blevet testet. Det vides således ikke, om de foreslåede udpegningsgrænser er repræsentative for alle lastvognsmærker. Derfor skal udpegningsgrænser ses som udgangspunkt for kontrolaktioner, og der bør efterfølgende ske en tilpasning af udpegningsgrænserne i takt med, at der indsamles erfaringer fra kontrolaktionerne.



Figur 2.4. Gennemsnitlig udledning af kvælstofmonooxid (NO) fra Euro VI store lastbiler med SCR-system, som er henholdsvis aktivt, inaktivt og slået fra. Resultaterne er fordelt på de tre forskellige lastbilmærker.

For to af de tre lastvognsmærker ses en fordobling i udledningerne af PM, når SCR-systemet er slået fra samtidig med at partikelfiltret er fjernet (Figur 2.5). Årsagen til denne forskel mellem lastvognsmærkerne kendes ikke, og det vides heller ikke, om forskellen skyldes forskelle mellem lastvognsmærkerne, eller er relateret til de specifikke store lastbiler, som er blevet testet.



Figur 2.5. Gennemsnitlig udledning af partikler (PM) fra Euro VI store lastbiler med SCR-systemet slået fra, og med og uden partikelfilter. Gennemsnittene er opdelt for de tre forskellige lastbilsmærker.

Vi observerede dermed forskellige niveauer af PM- og NO-emissioner fra forskellige lastbilmærker eller individuelle køretøjer, hvilket formodentligt vil give anledning til en vis variation i emissionerne blandt flåden af lastbiler. Desuden fandt vi, at PM-emissionen fra ét mærke var uændret med og uden monteret partikelfilter. For de to andre mærker blev emissionen af PM omtrent fordoblet, når partikelfiltret blev afmonteret. Variationen i målingerne for forskellige bilmærker er relativt stor, og det må tages i betragtning fremadrettet, hvor det anbefales, at flere tests bliver gennemført.

2.9 Supplerende tests

Målingerne af udledningerne af kvælstofmonooxid viste sig relativt robuste over for variationer i hastighed og acceleration under målingerne. Dette giver en højere fleksibilitet i forhold til valg af måleområder, og det gør det muligt at anvende kortere kørebaner end forventet.

Den samme lastvogn blev testet to gange for at undersøge, hvordan vejrforholdene påvirkede målingerne. Vejrforholdene ændrede sig dog kun svagt mellem de to dage, og derfor blev der kun indsamlet meget begrænset information om vejrforholdenes indflydelse på resultaterne. Som udgangspunkt forventes vejforholdene dog kun at have begrænset indflydelse på målingerne. Et tydeligt resultat var dog, at det ikke er muligt at måle i forbindelse med kraftig regn, da regndråberne spreder RSD-instrumentets lysstråle og gør det umuligt at gennemføre målinger.

Euro VI lastbilerne blev endvidere testet med og uden trailer (Figur 2.1). Dette førte til nogen ændringer i udledningerne målt for inaktive SCR-systemer, men gav ingen ændringer, når SCR-systemet var aktivt eller slukket. En mulig forklaring på forskellen for inaktiv SCR-system kunne være at en motoren i lastvogn uden trailer hurtigere bliver kold, da motoren udsættes for mindre belastning. Imidlertid skal det bemærkes, at dette resultatet har begrænset indflydelse på trafikken på det danske vejnet, hvor kun en mindre andel af tunge lastbiler kører uden trailer. I forbindelse med testene på lukket område blev en serie tests af mere praktisk karakter gennemført (et eksempel var test af, hvor ofte det var nødvendigt at kalibrere RSD-instrumentet). Disse praktiske tests kan vise sig nyttige i forbindelse med design af system til rutinemæssigt kontrol af manipulerede eller fejlbehæftet SCR-systemer.

2.10 Målinger ved Padborg og Storebælt

I september og oktober 2019 blev der gennemført målekampagner ved Padborg og Storebæltsbroen, hvor der samlet blev gennemført valide målinger på 2,942 store lastbiler og 3,306 personbiler. 12% af de målte store lastbiler stammende fra Danmark, og 88% var udenlandske, mens alle personbiler var danske. Euro 5 personbiler og Euro 6 personbiler udgjorde samlet 87% af de køretøjer, der blev målt på (Tabellerne 2.3 og 2.4). Den store andel af køretøjer med den nyeste norm (Euro 5 og Euro 6) er i overensstemmelse med det generelle billede for udvikling af køretøjsparken på de danske vejnet. De udenlandske store lastbiler udgør langt hovedparten af de målte store lastbiler, hvilket hænger sammen med, at målingerne er foretaget i Padborg og på Storebæltsbroen (der blev i en stor del af tiden målt i den betalingsbane, som har det største antal udenlandske store lastbiler). Endvidere udgør dieselpersonbiler omkring 60% af de målte personbiler.

Tabel 2.3. Den relative og absolutte fordelingen af store lastbiler målt ved Padborg og Storebæltsbroen. Det samlede antal målte personbiler var 2,942.

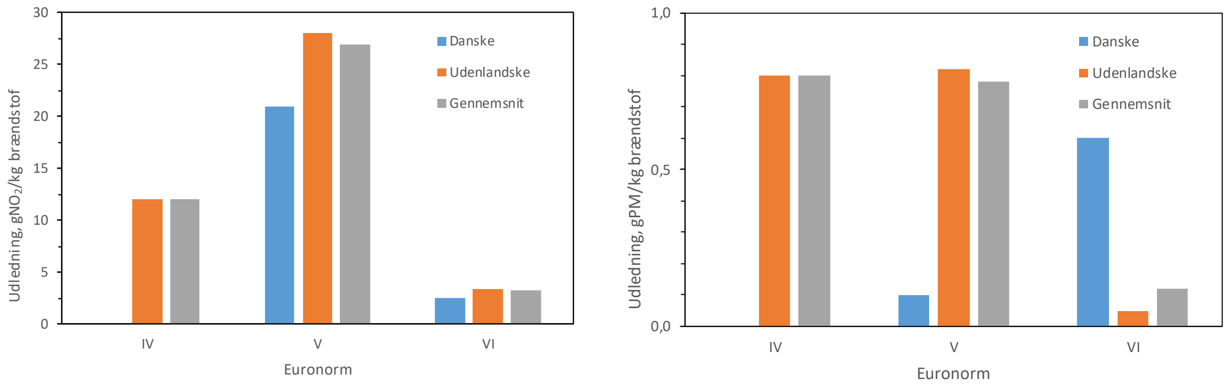
	IV		V		Vi		Total	
	Antal	Procent	Antal	Procent	Antal	Procent	Antal	Procent
Danske	0	0	44	1	303	10	347	11
Udenlandske	3	0,1	654	22	1938	66	2595	88
Samlet	3	0,1	698	24	2241	76	2942	100

Tabel 2.4. Fordelingen af personbiler målt ved Padborg og Storebæltsbroen. Det samlede antal målte personbiler var 3306.

	2		3		4		5		6		Total	
Benzin	1	0,02	23	0,7	197	6	318	10	724	22	1263	38
Diesel	0	0	32	1	167	5	511	15	1334	40	2044	61
Samlet	1	0,02	55	1,7	364	11	829	25	2058	62	3307	100

2.11 Resultater fra lastbiler

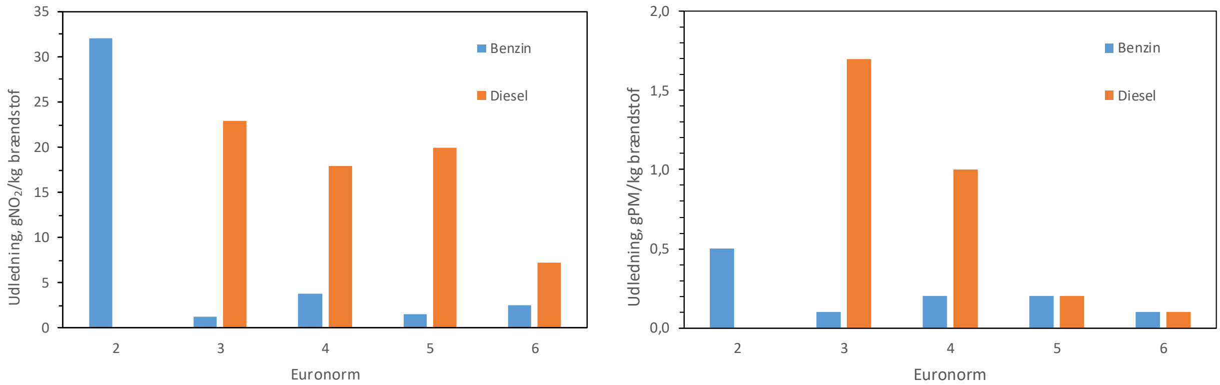
Figur 2.6 viser de gennemsnitlige udledninger af kvælstofmonooxid og partikler på de målte store lastbiler fordelt efter euronorm. Da der kun er målt på tre Euro IV store lastbiler, så er resultaterne ikke repræsentative for udledningerne fra denne type store lastbiler. Resultaterne viser, at udledningerne af kvælstofmonooxid i gennemsnit er 88% lavere for Euro VI store lastbiler sammenlignet med Euro V store lastbiler. Tilsvarende ses et gennemsnitligt fald på 84% for udledningerne af partikler. PM-emissionen fra Euro V og Euro VI lastbiler var hhv. dobbelt så høj og ens med emissionerne rapporteret fra sammenlignelige lastbiler i et nyligt svensk studie (Sjödin et al., 2017). Den relativt høje udledning af PM fra danske store lastbiler skyldes et lille antal store lastbiler med store udledninger, og det vurderes derfor, at resultatet er behæftet med stor usikkerhed. En sensitivitetsanalyse viser, at de 7 Euro VI lastbiler med højest NO-emission afgør, om PM-emissionen fra danske store lastbiler (0.60 g/kg) overstiger den fra de udenlandske (0.05 g/kg). Fjernes de 7 omtalte lastbiler fra datasættet, bliver emissionen fra de danske lastbiler sammenlignelig med de udenlandske (0.04 g/kg). Derfor kan resultatet ikke konkluderes at være repræsentativt for udledningerne af partikler fra danske Euro VI store lastbiler. Et tilsvarende stort fald i udledningerne af kvælstofmonooxid fra Euro V til VI blev observeret i det tidligere projekt med danske målinger med RSD-metoden i 2017 (Ellermann et al., 2018) om end forskellen mellem de to euro-normer ikke er helt så stor ved målingerne i 2019, som observeret i 2017. Målingerne for Euro IV lastbiler vurderes til ikke at være repræsentative for euronormen, da kun tre lastbiler blev målt.



Figur 2.6. Gennemsnitlig udledning af kvælstofmonooxid (venstre) og partikler (højre) for danske og udenlandske Euro IV, V og VI store lastbiler.

2.12 Resultater fra passagerbiler

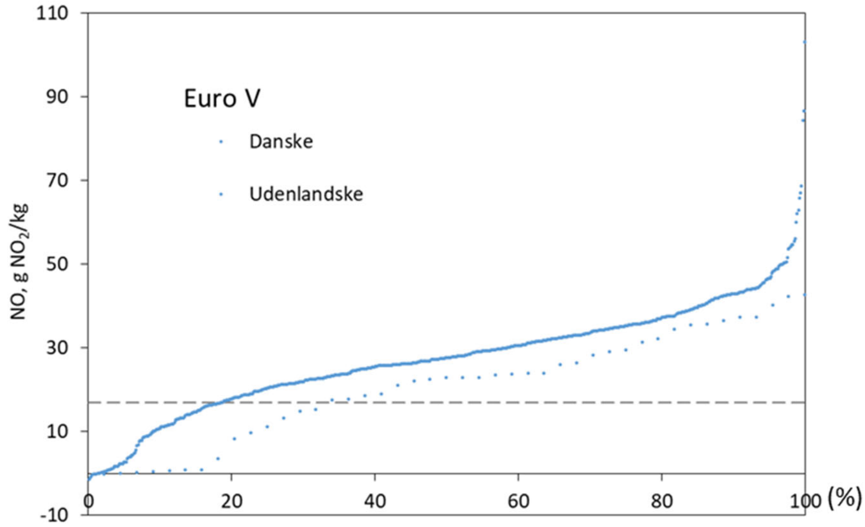
Figur 2.7 viser de tilsvarende resultater for de gennemsnitlige udledninger fra danske personbiler fordelt på henholdsvis diesel- og benzindrevne køretøjer. For alle personbiler ses et væsentligt fald i udledningerne fra de ældste euronormer og frem til de nyeste Euro 6 normer. Generelt ses væsentligt lavere udledninger fra benzinbiler end dieselbiler. Forskellen er dog betydeligt mindre for Euro 6 personbiler. Det skyldes anvendelsen af SCR-katalysatorer på dieselkøretøjer, som har givet en væsentlig forbedring i forhold til udledningerne af kvælstofmonooxid. PM-emissionen fra dieselbiler udgjorde 76%, mens benzinbilerne stod for de resterende 24%. For Euro 5 og 6 er der ingen forskel på udledningerne af partikler for dieselbiler og benzinbiler, hvilket hænger sammen med brug af partikelfiltre på dieselbilerne. Udledningerne af kvælstofmonooxid er i god overensstemmelse med resultaterne fra tilsvarende målinger fra en svensk undersøgelse (Sjødin, 2017). PM-emissionerne fra personbiler var noget højere end rapporteret i et nyere svenske studie (Sjödin et al., 2017).



Figur 2.7. Gennemsnitlig udledning af kvælstofmonooxid (venstre) og partikler (højre) for danske personbiler opdelt i benzin- og dieselpersonbiler og efter euronorm.

2.13 Fordeling af emissioner

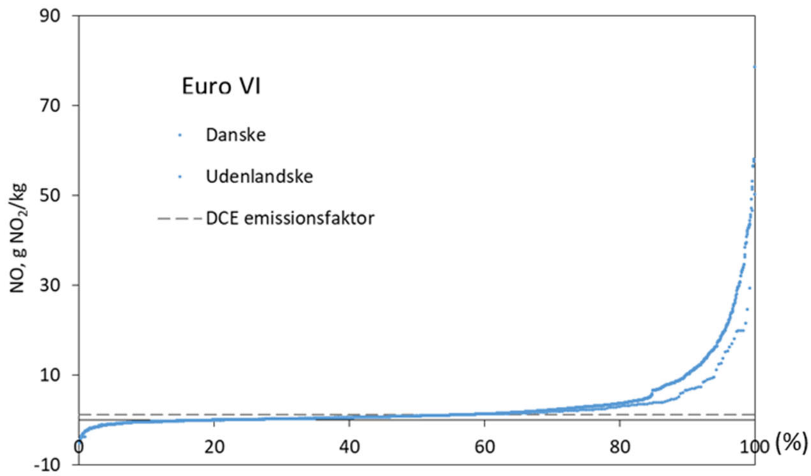
Figurerne 2.8 og 2.9 viser fordelingen af udledningerne af kvælstofmonooxid målt for henholdsvis Euro V og Euro VI store lastbiler. For begge euronormer ses en S-formet kurve, hvor de negative værdier målt for de laveste udledninger hovedsageligt skyldes et uundgåeligt artefakt ved selve målemetoden (kontaminering fra andre køretøjer i måleområdet). Den kraftige stigning i den høje ende af skalaen skyldes store lastbiler, hvor SCR-systemerne ikke fungerer efter hensigten grundet enten manipulation eller fejl på SCR-systemerne. En ukendt andel af de høje udledninger kan imidlertid skyldes, at SCR-systemerne har været for kolde på det tidspunkt, hvor målingerne bliver foretaget. Denne andel kan ikke bestemmes med den pågældende opsætning, ligesom det har ikke været intensionen at bestemme denne. Da målingerne er foretaget i forbindelse med kørsel på motorvej forventes andelen af køretøjer med koldt SCR-system dog at være lille, selv om de ved Storebæltsbroen kan komme til at holde stille i forbindelse med betalingsanlægget. Endvidere ses nogenlunde den samme fordeling af NO-emissioner for danske og udenlandske Euro V og Euro VI store lastbiler, hvor de danske store lastbiler dog generelt ligger noget under de udenlandske (Se figur 2.6).



Figur 2.8. Fordeling af udledningerne af kvælstofmonooxid (NO). Udledningerne er sorteret efter stigende udledninger for henholdsvis danske og udenlandske Euro V store lastbiler

Resultaterne viser ikke er et egentligt "hop" i udledningerne svarende til den markante forskel, der er mellem udledningerne fra aktive SCR-systemer og SCR-systemer, som ikke fungerer. Det er derfor ikke muligt præcist at fastlægge andelen af lastvognene, som kører med ikke-fungerende SCR-systemer. Data viser dog, at der for de 10%, som omfatter de højeste udledninger, er en markant stigning i udledningerne. For Euro V er 90%-fraktilen omkring 20 µg / m^3, hvilket er noget højere end de laveste udledninger målt for tunge køretøjer med defekt SCR-system (14 µg / NO_2 / kg brændstof) under tests på lukket område. For Euro VI er 90 %-fraktilen på samme niveau som målt under tests (7 µg / NO_2 / kg brændstof).

Som følge af de store usikkerheder har vi anvendt en simpel tilgang og har derfor skønsmæssigt vurderet, at omkring 10% af Euro V og Euro VI lastvognene har manipulerede eller fejlbehæftede SCR-systemer. Dette skøn er anvendt i forbindelse med beregningerne af de helbredsmæssige konsekvenser af manipulation og fejl på SCR-systemerne. Det skal bemærkes, at der stor usikkerhed på dette skøn.



Figur 2.9. Fordeling af udledningerne af kvælstofmonooxid (NO). Udledningerne er sorteret efter stigende udledninger for henholdsvis danske og udenlandske Euro VI store lastbiler.

2.14 Politiets vejsidekontrol

Dansk Politi deltog i målekampagnerne ved Padborg og Storebælt. Politiet bidrog med vejsidekontrol af en række af de store lastbiler, hvor målingerne viste udledninger af kvælstofmonooxid på et niveau, som gav anledning til mistanke om manipulation eller fejl på lastvognenes SCR-systemer.

I de syv dage hvor politiet deltog, var målingerne fokuseret på at måle udledningerne på så mange store lastbiler som muligt. Det var endvidere vigtigt, at en relativt stor andel udenlandske store lastbiler indgik i målingerne, da erfaringer har vist, at omfanget af manipulation ofte er større på udenlandske store lastbiler end danske. Derfor blev mange af målingerne ved Storebæltsbroen foretaget i en af de manuelle betalingsbaner, da det er i denne bane, at langt hovedparten af de udenlandske store lastbiler kører.

Der blev i alt kontrolleret 52 store lastbiler. En enkelt blev udvalgt ud fra en måling af en høj PM-udledning, mens resten blev udvalgt, fordi målingerne af udledningerne af kvælstofmonooxid overskred udpegningsgrænserne. Der blev anvendt en udpegningsgrænse på 1,000 ppm kvælstofmonooxid for langt hovedparten af de syv dage med vejsidekontrol. Da evalueringen af resultaterne fra testene endnu ikke var færdigbehandlet, så blev udpegningsgrænsen sat til 1,000 ppm, hvilket var et valg på baggrund af tests i Spanien. Den første dag blev der dog for en del af dagen anvendt en udpegningsgrænse på 800 ppm.

Tabel 2.5 viser en oversigt over resultaterne fra politiets vejsidekontrol. 36 ud af de kontrollerede store lastbiler var Euro V store lastbiler, otte var Euro VI store lastbiler og der var to, hvor euronormen ikke blev fastlagt, men hvor de var enten Euro V eller Euro VI. Endvidere viste det sig, at seks ud af de 52 store lastbiler var Euro IV lasvogne, som ikke har SCR-system, og en af Euro V lastvognene havde en anden type rensesystem. Lastvogne uden SCR-system er ikke inkluderet i den videre omtale af resultaterne.

Fire ud af de 52 store lastbiler var danske, heraf to Euro V og to Euro VI. Langt hovedparten af de undersøgte store lastbiler var således udenlandske.

Tabel 2.5. Resultater fra politiets vejsidekontrol ved Storebælt og Padborg. Euro IV og Euro V store lastbiler uden SCR er ikke medtaget i kolonnerne for velfungerende SCR, og for manipulerede eller fejlbehæftede SCR-systemer.

Euronorm	Kontrollerede lastvogne			Velfungerende SCR			Manipulation			Fejl		
	Samlet	Dansk	Udenlandsk	Samlet#	Dansk	Udenlandsk	Samlet	Dansk	Udenlandsk	Samlet	Dansk	Udenlandsk
IV	6*	0	6*	-	-	-	-	-	-	-	-	-
V	36	2	34§	12	0	12	5#	0	5#	20#	2	18#
VI	8	2	6	4	1	3	0	0	0	4	1	3
Ukendt	2	0	2	1	0	1	0	-	0	1	-	1
Samlet	52	4	48	17	1	16	5#	0	5#	25#	3	22#

* Euro IV lastvogne uden SCR

§ En Euro V havde ingen SCR

¤ Euro IV og Euro mV uden SCR er ikke inkluderet

To Euro V have både manipulation og fejl

Samlet set havde 62 % af alle de undersøgte store lastbiler SCR-systemer, som var enten manipulerede eller fejlbehæftede (to store lastbiler havde begge dele). Det viste sig, at for store lastbiler med manipulerede eller fejlbehæftede SCR-systemer, så udgjorde fejlene hovedparten (83%), mens manipulation kun udgjorde en relativt lille andel (17%). Fejlene omfattede bla. fejl på AdBlue, køretøj i fejltilstand, kortsluttet elektronik samt fejl på NO_X-sensorer. Det var kun for Euro V, at der blev fundet manipulation, mens der for Euro VI og de to store lastbiler med ukendt euronorm, ikke blev fundet manipulerede store lastbiler.

Endvidere havde 38% af de kontrollerede store lastbiler velfungerende SCR-systemer på trods af, at udledningerne i alle tilfælde lå over 800 ppm. Årsagen til dette formodes at være kolde motorer, og dermed ikke fungerende SCR-systemer. Den relativt høje andel med kolde motorer formodes at hænge sammen med selve målesituationen. For eksempel kan det ikke undgås, at lastvognene holder i kø ved betalingsanlægget ved Storebælt, og dette kan i visse tilfælde være nok til at sænke motorens temperatur under grænsen for, hvor SCR-systemerne fungerer. Testene på lukket bane dokumenterede, at fire minutters tomgang kan være nok til, at motoren bliver så kold, at SCR-systemerne ikke fungerer, som de skal. Eftersom der var en forsinkelse mellem selve målingerne og vejsidekontrollen, kunne SCR-systemets temperatur være øget på kontroltidspunktet, hvorfor det ikke er muligt at bestemme andelen af køretøjer med kolde SCR-systemer.

Tabel 2.6. Den procentvise fordeling af euronormer, og den procentvise fordeling af store lastbiler med velfungerende SCR og SCR som er manipulerede eller fejlbehæftede. Endvidere vises andelen (%) af store lastbiler med manipulerede og andelen med fejlbehæftede SCR-systemer set i forhold til det samlede antal store lastbiler med enten manipulerede eller fejlbehæftede SCR-systemer.

Euronorm	Kontrollerede lastvogne	Velfungerende SCR	Manipulation + fejl	Anden manipulation	Andel fejl
V	78	27	51	20	80
VI	18	9	9	0	100
Ukendt	4	2	2	0	100
Samlet	100	38	62	17	83

De anvendte udpegningsgrænser på 800 ppm og 1000 ppm ligger over de udpegningsgrænser, som blev foreslået på basis af testene. Ud fra testene blev grænser på 660 ppm og 330 ppm foreslået for henholdsvis Euro V og Euro VI store lastbiler.

Hvis man alene ser på resultaterne af kontrollerne, der blev udført med udpegningsgrænse over 800 ppm, så blev der kun udført ni af disse. Heraf havde ingen af de 4 Euro VI og 5 Euro V store lastbiler manipulerede eller fejlbehæftede SCR-systemer. 42 store lastbiler blev udvalgt med en udpegningsgrænse på 1000 ppm, hvoraf 35 var Euro V og Euro VI med SCR-system, og heraf udgjorde 77% store lastbiler med manipulerede eller fejlbehæftede SCR-systemer.

Det konkluderes derfor, at de lave udpegningsgrænser fra testene i praksis vil være for lave, idet andelen af udvalgte store lastbiler med manipulerede eller fejlbehæftede SCR-systemer vil være relativt lille for store lastbiler med udledninger under 1,000 ppm. En så lav udpegningsgrænse ville således føre til ineffektiv anvendelse af politiets ressourcer. Dog er det nuværende datamateriale stadig relativt lille, så derfor er der relativt stor usikkerhed på ovenstående konklusion.

Vi anbefaler derfor, at man i forbindelse med kommende rutinekontroller anvender en fleksibel tilgang, hvor man tilpasser udpegningsgrænserne i forhold til den praktiske situation. Dette skal forstås på den måde, at udpegningsgrænsen som udgangspunkt sættes til 1,000 ppm, men at der i tilfælde med ledig kapacitet hos politiet udvælges store lastbiler i forhold til en udledningsgrænse på 660 ppm. Endeligt er det vigtigt med indsamling af erfaringer fra udførte rutinekontroller og løbende evaluering af udpegningsgrænserne på basis af disse.

2.15 Konsekvenser for befolkningens helbred

Et vigtigt mål for projektet var at vurdere, hvilken konsekvens manipulation og fejl på SCR-systemerne har for befolkningens helbred. Denne vurdering er blevet udarbejdet på følgende måde:

- Ud fra testene på lukket område er det vist, at manipulation eller fejl på SCR-systemerne på Euro VI store lastbiler giver en 20 gange højere udledning af kvælstofmonooxid. For Euro V store lastbiler er det vurderet, at udledningerne fra manipulerede eller fejlbehæftede store lastbiler ligger dobbelt så højt, som for Euro VI store lastbiler.
- Ud fra målingerne ved Padborg og Storebæltsbroen er det estimeret, at 10% af Euro V og Euro VI lastvognene på det danske vejnet kører med manipuleret eller fejlbehæftede SCR-systemer. Der er ikke SCR-systemer på store lastbiler med ældre euronormer. Der er stor usikkerhed på dette estimat.
- På basis af ovenstående har vi genberegnet udledningerne af kvælstofoxider fra alle store lastbiler, som kører på det danske vejnet. Disse beregninger af udledningerne følger den samme metode, som anvendes af DCE til de nationale opgørelser af udledningerne fra trafik.
- Ved hjælp af DCE’s modelsystemer er det beregnet, hvor meget manipulation og fejl på SCR-systemerne på store lastbiler øger helbredseffekterne fra luftforureningen i Danmark. Der er gennemført to sæt beregninger. Først er der lavet beregner uden antagelser om manipulation og fejl, og derefter er der lavet beregninger, hvor manipulation og fejl er inddraget. Ved at se på forskellen mellem de to sæt beregninger kan vi vurdere helbredseffekterne fra manipulation og fejl på SCR-systemerne. Beregninger er gennemført med UBM-modellen (Urban Background Model) og EVA-modellen (Economic Valuation of Air pollution).

Manipulation og fejl på SCR-systemer på store lastbiler på det danske vejnet er estimeret til at forøge antallet af for tidlige dødsfald med omkring 10 (Tabel 3.7), hvilket svarer til omkring 0,2% af det samlede antal for tidlige dødsfald fra luftforureningen i Danmark. Udover for tidlig død, så er der også en lang række andre helbredseffekter, hvilket er angivet i kapitel 9.

Hvis vi antager, at omfanget af manipulation og fejl på SCR-systemerne har samme omfang i de øvrige EU-lande, så vil det samlede antal for tidligt døde i Danmark stige til 33, som følge af langtransport af luftforurening til Danmark fra de øvrige EU-lande. Dette svarer til lidt under 1% af det samlede antal for tidlige dødsfald fra luftforureningen i Danmark.

De ekstra omkostninger fra manipulation og fejl på SCR-systemerne på lastvognstrafikken i Danmark og det øvrige EU ligger på omkring 1 milliard kroner, hvoraf de omkring 100 millioner kr. stammer fra manipulation og fejl på lastvognstrafikken i Danmark.

Den forøgede udledning af kvælstofoxider fra lastvognstrafikken vil også give helbredsomkostninger i de øvrige EU, som følge af transport af luftforurening fra Danmark til de øvrige EU-lande. Denne omkostning beløber sig til omkring 260 millioner kroner.

Tabel 2.7. Antallet af for tidlig død og de eksterne omkostninger i Danmark, som følge af manipulation og fejl på SCR-systemerne på store lastbiler i Danmark og store lastbiler i de øvrige EU-lande. *) summen stemmer ikke på grund afrunding af tallene.

	For tidlig død*)	Eksterne omkostninger millioner kroner
Lastvogne i Danmark	10	102
Lastvogne i øvrige Eu-lande	24	898
Samlet omkostninger i Danmark	33	1000

Der er særdeles stor usikkerhed på estimaterne af helbredseffekterne og de eksterne omkostninger forbundet med manipulation og fejl på SCR-systemerne, hvilket skyldes usikkerhederne forbundet til estimering af omfanget af manipulation og fejl samt usikkerheder på selve beregningerne af helbredseffekterne og de dertil knyttede eksterne omkostninger. Det skønnes, at den samlede usikkerhed er på lidt over ±50%.

2.16 Metode til rutinemæssig kontrol af SCR på store lastbiler i Danmark

Kontrolsystemet skal være mobilt og hurtigt både at opsætte og nedtage. I øjeblikket er OPUS remote sensing-system det mest fleksible på markedet. Efter en indkøringsfase har teamet bag denne undersøgelse høstet gode erfaringer med den tidligere version af OPUS remote sensing-systemet. Kolleger i udlandet har endvidere gode erfaringer med seneste generation af OPUS remote sensing-system RSD 5000. Det anbefales derfor at basere kontrolsystemet på dette udstyr.

Det er afgørende, at der vælges en passende udpegningsgrænse for at udtage store lastbiler til vejsidekontrol. Vælges en for lav udpegningsgrænse, så vil politiet spilde for mange ressourcer på at kontrollere velfungerende store lastbiler, og unødigt mange chauffører vil tabe tid mens lastvognen kontrolleres. På den anden side vil en for høj udpegningsgrænse betyde, at der kontrolleres for få store lastbiler, og at kontrollen bliver ineffektiv i forhold til at fange store lastbiler med manipulerede eller fejlbehæftede SCR-systemer. Erfaringerne fra dette projekt viste, at en udpegningsgrænse på 1,000 ppm kvælstofmonooxid for Euro V resulterede i identifikation af 77% store lastbiler med manipulerede eller fejlbehæftede SCR-systemer. Derfor foreslås en udpegningsgrænse på 1,000 ppm kvælstofmonooxid for Euro V store lastbiler. Med en udpegningsgrænse på 800 ppm kvælstofmonooxid for Euro VI lastvognene blev der ikke identificeret fejl på eller manipulation med SCR-systemer. Det skal bemærkes, at der kun blev observeret 4 Euro VI lastbiler med en udpegningsgrænse på 800 ppm. Med så få observationer er det ikke muligt at vurdere, om en udpegningsgrænse på 800 ppm er for lav eller ikke. Tests på lukket bane viste, at den laveste udledning med manipulerede eller fejlbehæftede SCR-systemer fra en Euro VI lastvogn lå på 330 ppm kvælstofmonooxid. Vi anbefaler til kommende rutinekontroller, at udpegningsgrænserne tilpasses. Således skal de i udgangspunktet sættes til 1,000 ppm for Euro VI, men i tilfælde med ledig kapacitet hos politiet udvælges store lastbiler i forhold til en udledningsgrænse på 660 ppm. Det er vigtigt at indsamle af erfaringer fra de udførte rutinekontroller og løbende evaluere udpegningsgrænserne på baggrund heraf.

Det foreslås, at der gennemføres kontrolaktioner spredt i alle sæsoner og på vilkårlige tidspunkter af dagen. Denne fremgangsmåde skal sikre, at der ikke er sikre perioder, hvor man kan køre på det danske vejnet med manipulerede eller fejlbehæftede SCR-systemer. Erfaringerne fra dette studie viser dog, at det ikke er muligt at måle i regnvejr, men derudover bør målekampagner fordeles på vilkårlige tidspunkter af året. Det foreslås således, at der gennemføres mellem fire og otte årlige målekampagner af en til to dages varighed, men det endelige omfang må naturligvis fastlægges af de besluttende myndigheder. Det foreliggende projekt har vist, at det er muligt at foretage målinger til udvælgelse for kontrol af både store lastbiler og personbiler. Det foreslås derfor, at der udføres kontrolaktioner rettet mod både store lastbiler og personbiler. Erfaringerne fra dette projekt viser dog, at det giver udfordringer at gennemføre målinger for store lastbiler og personbiler i samme setup. Det skyldes bl.a. udfordringer i forhold kameravinkel i forbindelse med identifikation af nummerplade. Der bør arbejdes med at løse disse udfordringer eller alternativt skiftes mellem kontrol for de to grupper af køretøjer.

Det er afgørende for kontrolaktionernes effektivitet, at udvælgelsen af lokaliteter for kampagnemålingerne foretages med velovervejet omhu. Erfaringerne fra dette projekt viser, at det er helt afgørende, at lastvognenes motorer er tilstrækkeligt varme til, at SCR-systemerne fungerer. Det betyder, at der primært skal sigtes mod lokaliteter, hvor en overvejende del af trafikken har kørt nogen tid inden køretøjer udtages til kontrol. Alternativt vil der spildes mange ressourcer med kontrol af store lastbiler, som viser høje udledninger af kvælstofmonooxid pga. kold motor. Erfaringerne fra projektet viser ligeledes, at målingerne skal udføres over en enkelt vejbane for at undgå påvirkning fra trafik på tilstødende vejbaner. Lokaliteterne bør derfor udvælges således, at de er tæt ved motorvej, og på vejbaner som er rimeligt isolerede fra andre vejbaner og veje. Projektet har endvidere vist, at det tager nogen tid at opbygge erfaringer med en målelokalitet, og derfor også med at finde det optimale setup for lokaliteten. Det anbefales, at der ved valget af lokalitet tages højde for fremherskende vindretning, og hvorledes det kan influere på målingerne i forhold til påvirkning fra andre vejbaner og veje. En anden erfaring fra projektet er, at chaufførerne er meget opmærksomme på aktiviteter omkring vejen, og at kamera og måleinstrumenter gerne skal placeres således, at udstyret ikke er synligt før målingen foretages. Dette må tilrettelægges for den enkelte lokalitet, men kan fx omfatte brug af et mindre telt. Det foreslås, at der udpeges tyve lokaliteter ud over landet, og at der skiftes mellem disse lokaliteter fra kampagne til kampagne i skiftende rækkefølge. Det foreslås endvidere, at erfaringer fra disse lokaliteter dokumenteres med henblik på at optimere kommende kampagner. I denne forbindelse anbefales det ligeledes at trække på dette projekts erfaringer fra kampagnerne ved Padborg og Storebæltsbroen, målelokaliteter som det anbefales også at benytte fremover, når flere målelokaliteter udvælges.

Betjening af remote sensing udstyret fordrer mindst en person, men i praksis vil det nok fordre to personer, og tilsvarende vil der være behov for mindst en og i praksis to personer til at gennemføre vejsidekontrollerne. Det anbefales, at der gennemføres intensive træningskurser hvert fjerde år og korterevarende opfølgningskurser hver andet år til at uddanne det mandskab, som skal betjene remote sensing-udstyret samt gennemføre vejsidekontroller. Det anbefales, at mindst seks personer uddannes til hver af disse funktioner. Det må forventes, at ny teknologi og nye instrumenter vil blive tilgængelige på markedet i de kommende år. Det anbefales derfor at gennemføre workshops med deltagelse af forskere og folk med praktisk erfaring med nyt udstyr og nye teknikker inden for området med henblik på udveksling af erfaringer og viden.

Hvert år opgør DCE ved Aarhus Universitet de danske udledninger af luftforureningskomponenter fra vejtrafik i forbindelse med de nationale udledningsopgørelser for luftforurening. Opgørelserne for vejtrafik baseres på udledningsfaktorer for de enkelte køretøjskategorier og under hensyntagen til forældelsesfaktorer. Udledningsfaktorerne er bestemt ved laboratoriestudier foretaget på en såkaldt kørestand, hvor det enkelte køretøj gennemfører en såkaldt kørecyklus – kørsel ved forskellige hastigheder og inklusive acceleration og deceleration for at simulere kørsel på vejnettet. Disse udledningsfaktorer anvendes sammen med diverse andre informationer så som salg af benzin og diesel, diverse trafikdata bl.a. fra rutinemæssige tællinger og trafikmodeller etc. I relation til disse nationale udledningsopgørelser ville data fra remote sensing potentielt være et værdifuldt supplement. Det anbefales derfor, at man undersøger mulighederne for at udarbejde en database med måledata fra remote sensing-kampagnerne til dette formål. I denne forbindelse vil det naturligvis være afgørende, at der sikres en håndtering af data, således at alle regler håndhæves i forhold til anonymisering og beskyttelse af persondata etc.

De rutinemæssige kontroller vil være omkostningstunge, og det anbefales at foretage regelmæssige evalueringer af hele kontrolsystemet i forhold til både kvalitet og effektivitet. Det omfatter ligeledes regelmæssige analyser af, om kontrolsystemet har en positiv effekt i forhold til at reducere omfanget af store lastbiler med manipulerede eller fejlbehæftede SCR-systemer.

Udgifterne forbundet med et rutinemæssigt kontrolprogram for udledninger fra vejtrafik med fokus på store lastbiler vil afhænge fuldstændig af det setup, som vælges. Det kan som tidligere nævnt være nødvendig med et separat setup for personbiler. Til målekampagnerne, som tidligere nævnt, vil der være behov for minimum to personer til at betjene remote sensing udstyret, og tilsvarende minimum to personer til den efterfølgende vejsidekontrol på udvalgte køretøjer. Det sidste må politiet naturligvis beslutte og justeres i takt med nye erfaringer. For at sikre kontinuerlig drift af denne aktivitet over en længere tidshorisont kan det være aktuelt med sidemandsoplæring under kampagnerne.

Databehandling omfatter analysen til bestemmelse af udledninger, koblingen til det centrale motorregister, udvælgelse af køretøjer til kontrol, samt resultatet af politiets vejsidekontroller.

Det anbefales, at der etableres en database til målingerne af kvælstofmonooxidudledningerne fra den kørende vognpark på de danske veje. Det vil i givet fald have nogle omkostninger men også levere værdifulde data.

Et rutinemæssigt kontrolprogram vil omfatte udgifter til leje af instrumenter, logistik ved kampagnerne samt et sted, hvor mandskabet kan opholde sig og udstyr opbevares. Alternativt kan der anvendes en målevogn til dette formål.

De samlede udgifter til et effektivt løbende kontrolprogram er vanskelige at fastsætte. NEQ har løseligt estimeret disse udgifter til mellem fem og ti millioner DKK per år for et program, som kører kontinuerligt over hele året. For et program med 4 til 16 måledage årligt vil denne udgift naturligvis være mindre.

2.17 Taksigelser

CSP Trucks Danmark, Mercedes-Benz Danmark A/S, Scania Danmark A/S, TJW Fragt, Volvo Group Trucks Denmark A/S, Sund & Bælt Holding A/S, og det danske Politi er alle takket for deres værdifulde bidrag til dette projekt.

3 Introduction

This report presents results from a project that has focussed on the problems related to malfunctioning of SCR-systems on heavy-duty trucks in Denmark, and furthermore on the effects this has on air pollution and related health effects. The project has been carried out in 2019 and 2020 by NEQ ApS and the Danish Center for Environment and Energi (DCE) for the Danish Environmental Protection Agency (EPA), and in cooperation for the Danish Road Safety and Transport Agency, and the Danish Police.

3.1 Background and aim of project

In recent years SCR-systems (Selective Catalytic Reduction) on modern vehicles have led to substantial reductions in emissions from road traffic. This has e.g. been one of the major reasons for the substantial decrease measured in nitrogen dioxide in busy streets in Denmark. However, recent Danish and other European control actions have revealed an extensive frequency of cheating with the SCR-system (manipulation with the functioning of the NO_x after treatment system). This tendency has also been documented in a previous project carried out by NEQ and DCE in 2017 and 2018 for the Danish EPA (http://www.ft.dk/samling/20171/almdel/MOF/bilag/565/index.htm).

The current project is part of the follow up on the Danish Governments strategy on Climate and Air Quality from 2018. In this strategy, it was decided to initiate activities to develop and implement control methods for enforcing the rules concerning vehicles emissions of air pollutants with specific focus on emissions from heavy-duty trucks.

The main aim of the project is to investigate to what extent measurements with remote sensing techniques can be used as basis for selecting mainly heavy-duty trucks suspected for manipulation of the SCR-systems. The selected heavy-duty trucks shall subsequently be subject to road site control by the Danish Police. Another intension with the project is to obtain more detailed knowledge on the status of the emissions from the fleet of vehicles driving on Danish roads, and a more consolidated knowledge about the impact of malfunctioning SCR-systems on air pollution levels and associated health effect in Denmark.

The focus on the problems related to the SCR-systems on heavy-duty trucks was initiated by the findings of deliberate manipulation of the SCR-systems on heavy-duty trucks. It has later been clear, that in addition to those manipulated, a large number of heavy-duty trucks has technical problems with the SCR. This project has focus on both these types of problems with the SCR-systems and throughout this report, we will refer to malfunctioning and deliberate manipulation collectively as malfunctioning of the SCR-systems.

3.2 Activities

The project is divided in the following activities:

- Assessment of the most suitable remote sensing technique for control of emissions, and furthermore evaluating the conditions under which the technique can be applied.

- Testing and characterizing vehicle emissions in a closed area with the aim of validating the measurement method. The objective is to determine thresholds of NO above which there is a high probability that the SCR-system of the vehicle is malfunctioning.
- Selection of one to three locations for measurement campaigns of mainly NO and PM at close to normal driving conditions.
- Evaluation of the impact of malfunctioning SCR-systems on air pollution levels and associated health effects in Denmark.
- Description of a method for routine control of malfunctioning SCR-system. This method has to be based on measurements with the remote sensing technique and be suitable for selecting heavy-duty trucks with high probability of malfunctioning of the SCR-systems.

3.3 Organization

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

Christian Rud Ingvardsen, NEQ ApS, Overall project leader

Professor Ole Hertel, DCE, Project leader for DCE's activities

Senior researcher Thomas Ellermann, DCE

Senior researcher Jacob Klenø Nøjgaard, DCE

Senior advisor Morten Winther, DCE

Professor Jørgen Brandt, DCE

Senior scientist Lise Marie Frohn, DCE

Journalist Michael Strangholt, DCE

In addition, a number of other experts from NEQ ApS and DCE has been involved in the project.

Finally, NEQ ApS has the following subcontractors for their part of the activities:

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.

NEQ ApS was responsible for organizing the measurement campaigns and for carrying out both the measurements and the quality control of the results. In addition, NEQ has the responsibility for assessing the two remote sensing techniques. Finally, NEQ has the responsibility for the suggested method for routine control of malfunctioning of SCR-systems.

DCE has the responsibility for the further evaluation of the data and for the assessment of the impact that malfunctioning of SCR-system has on air pollution levels and associated health effects in Denmark.

4 Evaluation of different methods for performing remote sensing measurements

Christian Rud Ingvardsen and Jesper Risager Nielsen

Remote sensing is a method designed for measuring emissions from a driving vehicle without interfering with the vehicle itself. Thus, Remote Sensing measures Real Driving Emissions (RDE) from individual vehicles at selected locations during real-life driving. Thereby, this type of measurements differ substantially from measurements carried out on vehicles during a driving cycle on a stand in a test laboratory or a workshop. Among the benefits of using Remote Sensing Devices (RSD) is that the measurements are made under work load of the vehicle engine, which is a prerequisite for being able to determine, among other things, the emission of nitrogen monoxide. It should be emphasized, that the RSD only measures the emission at the exact moment when the vehicle passes the equipment / device, and not over a longer distance of travelling. Thus, it represents a snapshot where many factors can affect the individual measurement. This applies, among other things to the temperature of the engine / catalytic converter, the acceleration of the vehicle, the weather conditions, the type of engine, etc. On the other hand, with the RSD, it is possible to measure a very large number of vehicles within a short period of time. In the summer of 2019, a field experiment was carried out in Krakow, Poland. In this field experiment, the project team managed to measure emissions from more than 10,000 vehicles within a single day. This demonstrates that with the right setup and during optimal conditions, it is possible to conduct vast number of measurements with RSDs.

RSD is thus not directly comparable to measuring equipment mounted directly on a vehicle. The latter is called PEMS (Portable Emissions Measurement System). However, RSD is considered to be an important supplement to PEMS, as the two measurement techniques complement each other, and the combination can offset some of the weaknesses of each other.

4.1 Types of measuring equipment

There are currently two types of RSD systems for measuring emissions available on the market. Both systems have been developed in the United States, and both systems are currently used both in the United States and in Europe. The manufacturers of these systems are respectively OPUS and EDAR.

Over the past 30 years, OPUS has developed a mobile emissions measurement system that can easily be set up without physical interference at the selected measurement site. The measuring equipment from OPUS measures horizontally, which means that it measures across the road when a vehicle passes the measuring equipment. The equipment itself consists of a speedometer, a measuring box that transmits light across the distance, a mirror that reflects the light back to the measuring box, a weather station that measures temperature, pressure and humidity, and a camera that takes a picture of the vehicle passing by.

The equipment developed by OPUS is very well documented and has been used both by various authorities and researchers for mange years. It takes approx. 20 - 30 minutes to set up and calibrate the equipment. The fact that it can quickly be brought into operation is a great advantage. The equipment can be operated via a battery, which greatly increases the mobility of the equipment. This means that it is easy both to adjust and reposition the equipment.

Figure 4.1. Photo showing the OPUS Remote Sensing Device.

A relatively new remote sensing product on the market has been developed by Hager Environmental and Atmospheric Technologies. Unlike the OPUS device, the EDAR device measures vertically. This means that measurements are carried out as the vehicle passes under the measuring device. Just like the OPUS device, the EDAR device sends out a light beam, but in this case the light is reflected by reflector placed on the surface of the road. The intension from the manufacturer is that the reflector is recessed into the top asphalt layer of the road, but it also possible to operate the system with the reflector placed on top of the road surface. The EDAR RSD is equipped with a weather station and a camera for taking pictures of the measured vehicles.

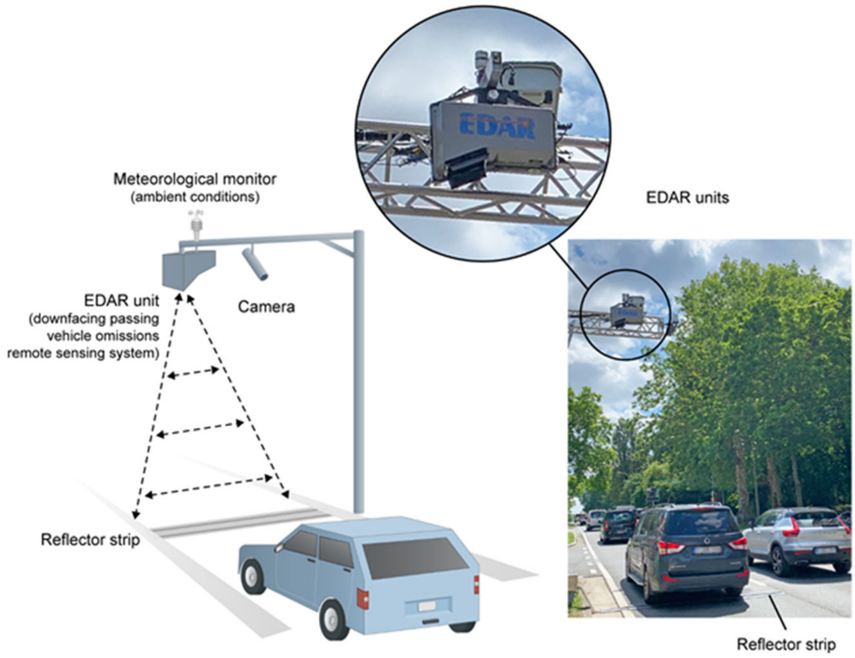


Figure 4.2. Sketch and photo showing the EDAR Remote Sensing Device. The sketch and the photo of EDAR in operation have been made available by the producer Hager Environmental and Atmospheric Technologies.

The EDAR equipment is not as mobile as the OPUS RSD, and the preparation of operation for this device thus demands a more permanent character of the measurement site. It is not possible to directly move the EDAR equipment to another site or at the site in case this would be appropriate. So far, the equipment requires 230V power connection via cable. However, a solution where a battery can be used as a power supply is in preparation.

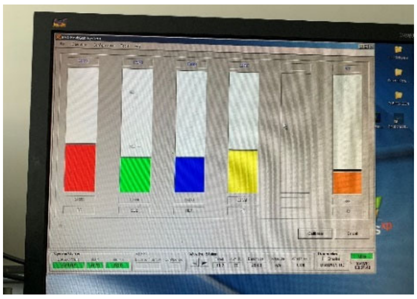
4.2 Conditions for optimal measurements

For both types of RSDs, there are various conditions that need to be met in order to yield optimum results. Firstly, the RSDs must be set up in a road lane where the vehicles can be under acceleration and have reached a certain speed when passing the RSD. When measuring emissions from a vehicle at RDE (Real Driving Emissions), it is important that the engine is under a certain work load. The ideal setting is therefore to perform the measurements where the road has a positive slope causing a strain on the engine and at the same time making it unlikely that the driver will disengage or even slow down the vehicle.

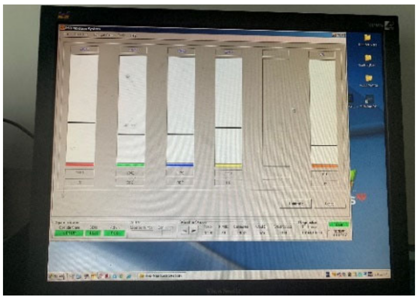
Furthermore, it is important to ensure that both engine and catalyst is hot when the emission measurements are carried out. Cold engines have a significantly higher emission of gasses compared with hot engines. Euro V and Euro VI engines are equipped with SCR-system that supply AdBlue to the exhaust gases. However, this system is not active before the catalyst achieves a suitably high temperature. For most vehicles, it is our experience that the supply of AdBlue is initiated only when the catalysts reach temperatures above 200 ^{0}C.

The third condition is that the weather does not prevent the measurements from being carried out. Both systems use light rays to detect the various gases in the exhaust, so it is important that the light has unobstructed passage through the exhaust. This means that if the air is full of precipitation, it will be very difficult to perform the measurements, and thereby also to obtain a satisfactory number of valid measurements. Raindrops and snowflakes will act as prisms in the air, and therefore, the light rays will be reflected away from the device. Thus, it is not possible to obtain the desired strength of light rays reflected back from the mirror or reflector.

Fourth condition, it should be noted that both types of RSDs achieve the best results by measuring on a road with a single lane. For both types of devices, it is in principle possible to measure on roads with several lanes side by side. However, as far as we know, no method has yet been found a good way to compensate for pollution contributions from the adjacent roads. Measurements taken on roads with several lanes will therefore be associated with considerable uncertainty.



Strength of UV light beam in dry conditions (orange column, value 1007)



Strength of UV light beam in heavy rain (orange column, value 101)

Measuring at Padborg in heavy rain

Figure 4.3. Photo's illustrating the RSD measurements during dry and wet conditions.

4.3 Remote Sensing for Use in Control Measurements

Control measurements can both aim at creating a broad data base for all types of vehicles or be more specifically targeted at specific vehicles and specific violations of applicable law. In this project, we develop control methods to counter manipulation of SCR-systems on Heavy-duty trucks.

The project takes outset in the similar project from 2017 / 2018 in Denmark, as well as in a project from Spain, where the local authorities used RSDs to reveal manipulation with the SCR-systems on Heavy-duty trucks. The experience gained from these projects will therefore form a basis for our assessment of the suitability of the RSDs for use in such control measurements.

For the selection of measurement sites in Denmark, it was important to find measurement sites that meet the criteria described above. Based on a scanning of various options, it was decided to select the border crossing at Padborg, and the toll station on the Great Belt Bridge as the two measurement sites. In both cases, it was necessary to choose a RSD system that was flexible and mobile, as we could not expect to perform the measurements in the same way day after day. This was due to several factors:

- In Padborg, a large number of trucks crosses the border every day. In general, drivers are highly aware of interferences on the roadway, and any interference may cause changes in driving pattern. During the practical measurements, it became evident that the presence of many employees near the roadway, and clearly erected cameras etc., made the drivers slow down and avoid accelerations. As described above, this is inappropriate in relation to obtaining the desired measurement results, and it was therefore important with mobile equipment and ability to experiment with different setups.

- In addition to the fact that the drivers are paying attention to the roadway, the police are aware that many truck drivers communicate in various ways about police controls. In the Spanish project, there was a correlation between the number of measured vehicles with elevated NO values and the number of hours the measurements were going on. The longer the time with measurements, the fewer violations were found. It is thus desirable that you can change your RSD measuring strategy relatively quickly. In Padborg, it was evident that the truck drivers became aware of the camera taking pictures of the license plates. The driving pattern changed, and only when the camera was hidden behind a car, the drivers returned to the original driving pattern.
- At the Great Belt Bridge, there are 10 different lanes through the payment facility, and different types of vehicles are passing in the various lanes. Furthermore, not all lanes are available continuously, as lanes are opened and closed depending on the traffic activity on the bridge. During weeks when we performed measurements, there was furthermore an ongoing renovation of lanes. This meant that we had to move the equipment continuously, in order to measure the desired trucks. Often the changes were advised at 10 minutes notice, and it was crucial that we were able to take down equipment quickly and quickly setup in a new lane.

In relation to performing control measurements on trucks, it is our assessment that mobility is the most important parameter for the choice of equipment. In this regard, there is no doubt that OPUS RSD has a clear advantage over the EDAR RSD. Of course, we make the reservation that control measurements can have many different purposes, and it cannot be excluded that the EDAR RSD will be more appropriate in other contexts.

4.4 Physical requirements for the system setup

As described above, it is crucial to select an optimal measurement sites to obtain the optimal results. The criteria for selecting locations provide a limited number of possible geographical locations. The physical requirements for the measuring equipment thus play an important role in the execution of the measurements themselves.

Based on previous experience with vehicle measurements in Denmark and abroad, there will often be a limited space to operate when performing the desired measurements. Whether measured by approach roads in the cities, at traffic hubs within the cities themselves, or at traffic junctions at highways such as the border crossing in Padborg or at the toll station at the Great Belt Bridge, the opportunity to place the equipment is limited by the physical conditions of the metrics such as general access conditions, the consideration of other drivers, or the consideration of other operators in the area such as, for example, the customs authorities at the border crossing or the staff at the payment facility on the Great Belt Bridge.

Therefore, it is important for the selection of equipment to make sure that it fits the purpose. In relation to the performance of control measurements throughout Denmark, it is not immediately possible to accurately describe the measurement locations in advance, and therefore, it is not possible to set specific requirements for the physical equipment of the measuring equipment. However, one can optimize the selection of sites by having an equipment that fits into most purposes and sites, and with the current setup this currently applies to the OPUS RSD.

Measuring site with Danish customs authorities working at the same time

Narrow access conditions at Great Belt bridge

Figure 4.4. Photo's from the measurement sites at the Danish – German boarder and at the Great Belt Bridge.

Regarding measurements at fixed measurement sites, the EDAR RSD may serve most useful, as it has less requirements with respect to calibration and control of devices during the actual measurement period. However, we have until now not found impartial descriptions of how valid the measurements are when using such a setup. In this context, it will be interesting to examine ongoing experiments in Belgium, where the Belgian authorities are using such a system to control emissions from heavy-duty trucks.

Both manufacturers are, of course, aware of the above limitations in their devices and therefore, according to their presentations of the devices at a conference in Brussels in November 2019 on the use of remote sensing, both are currently improving the devices to make them more useful for authorities that wish to use remote sensing as a method to measure vehicle emissions.

5 Experimental set-up using road-side remote sensing

Thomas Ellermann, Ole Hertel and Jacob Klenø Nøjgaard

Remote Sensing Devices (RSD) are in this context 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 5.1). 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 close to normal driving conditions.

5.1 Introduction

The remote sensing devise (AccuScan™ RSD 4600) was delivered from the Spanish company OPUS RSE. It is the same type of instrument that were used during the previous project on malfunctioning of SCR on heavy-duty trucks in Denmark. 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 trucks 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 (see next chapter). The RSD 4600 can be used to determine the emissions of carbon monoxide (CO), hydrocarbons (HC), nitrogen monoxide (NO) and Particulate Matter (PM). In this study, where the focus is on determining malfunctioning of the SCR, focus is on measurements of NO and PM.

Speed bars were applied alongside the remote sensing devices in order to measure the velocity and acceleration of the heavy-duty trucks simultaneously with the emission measurements. The local meteorology (temperature, wind speed, wind direction, pressure and humidity) was 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 vapour 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.

A camera (one for each remote sensing device) was used to take pictures of the heavy-duty trucks simultaneously with passage of the remote sensing devices. The cameras are placed in front of the remote sensing devices in order to take pictures from the front of the heavy-duty trucks.

A sophisticated software ensures correct connection of all measurements (emissions, sped, meteorology) with the picture and number plate information for the heavy-duty trucks. The software presents near real time results together with the pictures of heavy-duty trucks (Figure 5.1).

In the beginning of the campaigns the Spanish team operated the remote sensing devises, speed measurements and meteorology while NEQ operated the equipment during the late stages of the measurement campaigns. The remote sensing devises were calibrated regularly with certified calibration gasses in order to ensure accurate measurements (Figure 5.3). 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 trucks and carried out the final quality control and evaluation of the results from the many measurements.

Figure 5.1. The setup for the remote sensing measurements with parallel measurements using RSD 4600 and RSD 5000 operated in the 2017 and 2018 campaigns. The measured heavy-duty trucks 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 truck. Two cameras, one for each instrument, are placed about 10 m further up the road in order to take pictures of the heavy-duty trucks from the front. There are also two set of speed bars, one for each instrument, that measures velocity and acceleration as close as possible to the emission measurements. The computers controlling and storing the measurement results are placed in the white van. Note that this picture was taken under the previous campaigns in Køge where two instruments were used in parallel and only the RSD 4600 was used during the measurement campaigns carried out during this project.

Figure 5.2. 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 concentrations, the ratios between the compounds and CO_2, speed - and meteorological data.

Figure 5.3. Calibration of the remote sensing devices using reference gasses.

5.2 Measurements principle

Two automatic measurements are carried out with the instrument. The first is a measurement of the background concentrations. This measurement is carried out just before the vehicle passes the measurement instrument. The second measurement is carried out immediately after the passage of the measurements instruments and measures a “snap shot” of the concentrations in the exhaust plume. The difference between the two measurements give the concentration of the compounds inside the exhaust plume.

In some cases the calculated results are negative. There are two reasons for this:

- At very low emissions the uncertainty of the measurements might be so high that the subtraction of the two measurement ends up with a negative result simply due to the random uncertainty of the measurements.
- In the situation where there is short distance between the measured vehicle and other vehicles there might be “contamination” of the background measurements from the other vehicles. If the emissions from the other vehicles are high (for example an old heavy-duty truck) then the background concentration erroneously become higher than the exhaust emissions and the final results can be negative emissions from the measured vehicle. During the measurement campaigns a number of negative emissions were measured that clearly can be explained in this way. To an example, at the Great Belt Bridge the traffic can be quite dense and a number of vehicles can que up for the payment making it difficult to avoid contamination in such situations.

The basic measurements are absorption measurements for NO, CO_2, CO and HC (hydrocarbons) and opacity measurements for PM. These measurements give the instant concentrations of the compound in the more or less diluted exhaust plume. The dilution occurs due to the wind in the area and due to the turbulence in the wake behind the moving vehicle. In order to get information on the actual emissions it is necessary to take this dilution in to account i.e. to calculate back from the diluted concentrations to the actual concentrations in the undiluted exhaust.

The method for correction for the dilution of the exhaust plume is based on the ratios between the compounds. The basic idea is that all compounds in the exhaust are diluted in the same way and to the same extend. The ratio between NO and the carbon containing products from the combustion of the fuel can therefore be used to calculate back from the concentration of NO in the plume to the amount of emitted NO per unit fuel combusted.

If we for a moment assume that a perfect combustion has taken place, then all the fuel has been converted to CO_2. The ratio of NO and CO_2 can therefore easily be used to calculate back to the amount of emitted NO per kg fuel:

$$NO\ (ppm) / CO_2\ (\%) = x$$

$$NO\ (g / kg\ fuel) = x \cdot (0.0001 \cdot 30) / (14 / 1000)$$

Where 30 is the molar weight of NO and 14 is the molar weight of CH_2. The assumption of a ratio of one C to two H atoms is commonly used for standard fuel (diesel and petrol). This assumption is widely used by scientist working with remote sensing measurements.

In praxis, the combustion of fuel is not complete and therefore minor fractions of CO and unburnt hydrocarbons (HC) are emitted together with CO_2. The ratios of CO/CO_2 and HC/CO_2 are also determined by the remote sensing instrument. The software used for the subsequent handling of the data has equations implemented that automatically carries out the conversion of the ratio of NO/CO_2 to the emissions of NO in g/kg fuel used. These equations take also the formation of CO and hydrocarbons into account by used of the above mentioned ratios.

The calculation of PM follows the same principles.

Throughout the report we have mainly given the emissions of NO in equivalents of NO_2. This is because all emission inventories by convention report emissions of nitrogen oxides in equivalents of NO_2. The conversion from NO (g/kg fuel) to equivalents of NO_2 is carried out by multiplication with 1.53 (46 g NO_2/mole divided by 30 g NO/mole).

6 Controlled tests of malfunctions of SCR-systems and particle filters

Thomas Ellermann, Ole Hertel, Jacob Klenø Nøjgaard, Christian Rud Ingvardsen and Jesper Risager Nielsen

6.1 Aim of tests

One of the major tasks in the project was to carry out a series of tests of RSD measurements within a closed area. Emission measurements from at least four heavy-duty trucks should be measured under controlled conditions. The overall aims of this part were to:

- Characterize NO emissions from vehicles with SCR-systems deliberately switched off using manipulation devices.
- Characterize PM emissions from vehicles with dismantled particle filter.
- Characterize other parameters and their effects on emissions.

The reason for testing PM emission with dismantled particle filter is that the particle filter normally needs to be removed when the SCR-system is manipulated.

Other parameters that should be tested included:

- engine temperature
- weather
- speed
- acceleration
- the presence of a trailer

The main outcome of the investigations in the closed areas was to establish threshold concentrations of pollutants. The intension was to apply these at a later stage to discriminate between normal functioning SCR-systems and malfunctioning SCR-systems for roadside inspections.

Moreover, characterization of nitrogen monoxide (NO) from malfunctioning SCR-systems is applied to evaluate emissions and how these affect pollution levels and associated health effects in Denmark (chapter 9).

In addition, a number of minor practical trials and tests are conducted in the closed areas and serve as input to establish a method for routine control of manipulations with SCR-systems (chapter 10).

6.2 Description of the test

Euro V (n=3) and Euro VI (n=3) heavy-duty trucks were tested in close cooperation with Mercedes, Scania and Volvo from 17.09.2019 – 23.09.2019. Closed areas including vehicles, technical experts and drivers were kindly provided by the companies. Moreover, they allowed us to switch off the SCR-systems and remove the particle filters whenever needed. In addition, TJW Freight provided a heavy-duty truck and a trailer at their facility in Karlslunde.

6.2.1 Selection of test areas

Choices of closed areas for testing were based on practical considerations. Originally, the plan was to use the facilities at TJW Freight in Karlslunde since this area had a sufficiently long road with a slight slope that would fulfill requirements for the measurements. Furthermore, warming up of the engines could be achieved after 15 minutes' drive on a highway nearby. The only drawback was that the manipulated and hence illegal heavy-duty trucks should drive on public road, and it was not possible to get a dispensation for this.

The solution was therefore to use the facilities at Mercedes, Scania and Volvo, which were quite large, and it was feasible to make a sufficiently long route to ensure sufficient speed and acceleration at the measurement point. Moreover, particle filters could be dismantled in workshops within the facilities.

6.2.2 Speed and acceleration

The RSD is recommended to measure at speeds between 30 and 60 km/hr while accelerating, which may be difficult to achieve in some closed areas. Therefore, tests were performed to evaluate how sensitive the measurements are to speed and acceleration. Different choices of speed, acceleration and lengths of test route were investigated. This information is also needed for the quality control of the measurements.

6.2.3 Influence of weather conditions

The weather conditions may impact the measurements, for which reason tests were performed on different weekdays during the weeks starting with 16th and 23rd September 2019 (weeks 38 and 39). However, it is important to emphasize that this particular parameter is inherently difficult to control, and therefore measurements over longer periods of time are needed to characterize the influence of weather conditions.

Rain has been found to disturb the measurements, which relies on the transmission of different wave lengths through the exhaust plumes of the vehicles being measured. That is, the intensity of the light at particular wave lengths determined by absorption from pollutants in ambient air is used to calculate concentrations of e.g. NO. Liquid water droplets in the air may reflect light at these wave lengths and thus disturb the measurements. During the actual testing phase, we did not experience rain. On the contrary, conditions of unstable weather and rain influenced the measurements campaigns at Padborg and Great Belt Bridge resulting in invalid data.

6.2.4 Active or inactive SCR, warm and cold engine

A well-functioning SCR-system on a heavy-duty truck adds the agent AdBlue to the exhaust, which removes most of the NO_X gas in a chemical process in the catalyst. A sufficiently high temperature of the SCR-system is required (over 200 °C). No AdBlue is added below working temperature and thus the SCR-system does not work properly, according to the technicians at Scania, Volvo and Mercedes who assisted us during the tests. This state is termed inactive SCR throughout this report.

We could not verify when the individual truck's control systems activated this supply during the tests and therefore it was necessary to monitor the vehicles own data to ensure that the SCR was active and injected AdBlue. In practice, this was achieved by manually driving the vehicle during the various tests with a passenger next to the driver. The passenger monitored the diagnostic output to assure whether the SCR-system was active or inactive and whether AdBlue was supplied.

To achieve a temperature at which AdBlue was supplied, it was necessary to warm up the engine by driving for 15 minutes outside the closed area. Tests showed that it was possible to achieve a SCR-system temperature at which AdBlue was injected with and without a trailer attached to the vehicle. However, it was difficult to maintain a high SCR-system temperature for a long time when driving inside the closed area. This is an important observation also regarding the roadside inspections (Chapter 8). Furthermore, Åke Sjödin (IVL Swedish Environmental Research Institute, Gothenburg) made a similar observation for busses that went from a driving pattern on authentic road to a closed area (Åke Sjödin, personal communication).

6.2.5 Manipulation of SCR and particle filter

Various types of equipment were purchased to manipulate the SCR-system on the tested heavy-duty trucks. A number of websites within EU and outside the European marked sell so-called emulators. In several cases, the websites actually point out that tampering with SCR-systems could be illegal in individual countries. Apparently, this did not prevent customers from purchasing the equipment. The websites put emphasis on the applicability of the emulators: whether a particular emulator fits Euro V and Euro VI engines, or if it can be mounted on any given Euro norm. In this project, Scania, Volvo and Mercedes provided heavy-duty trucks for testing. We purchased different types of equipment, from the simplest versions to more advanced products previously applied by the Danish Technological Institute. Emulator prices ranged from about 100 Euro to 800 Euro – all came with mounting instructions.

In the beginning of the test process, only the simple versions were available, and they only fitted Euro V engines contrary to the information at the websites. At the same time, the staff at Scania, Volvo and Mercedes were concerned whether the emulators could irreversibly affect the control systems making it difficult to revert to factory settings.

After having consulted the technicians at Scania, Volvo and Mercedes, Martin Kristensen from the Danish Police and Sune Elkjær from Christonik, who is an expert in engine management control and diagnostics on vehicles, we decided not to install the emulators, but rather uninstall a fuse in the SCR-system. Removing the fuse should produce the same result as an installed emulator, which is to prevent addition of AdBlue. Inspections of trucks in collaboration with the police partly confirmed this theory, though it is not possible on the basis of the tests performed to exclude the possibility that other changes may have occurred. There is a very rapid development in this field and a mapping of the manipulation equipment itself would require a more thorough examination, which is beyond the scope of this project.

It has been assumed that manipulating the SCR-system on Euro VI heavy-duty trucks required dismantling of the particle filter. Since all Euro VI engines are equipped with a particle filter, there is also a need for regeneration to ensure that the filter does not clog. By installing emulators that prevent addition of AdBlue, the regeneration of the filter is thus cancelled for which reason it will be necessary to remove the entire particle filter to avoid clogging. However, during the course of the project, we became aware that there are now methods, which manipulates the truck's software itself. This method is not well described and neither the Danish experts, which we consulted, nor the Danish Police have in-depth knowledge in the area. It is therefore important to emphasize that more knowledge is needed in this area before we can comment on the need to remove the particle filter. However, there will always be a higher emission of NOx gases when the supply of AdBlue stops.

We tested Euro VI heavy-duty trucks with dismantled particle filter to verify if remote sensing could detect this. Removal of a particle filter is not trivial, and was performed by the staff at the workshops within the closed areas.

The final tests concerned vehicles with emulators installed and dismantled particulate filters. In practice, it is not possible to have a functioning SCR-system and a disassembled particle filter at the same time, since the disassembly itself requires deactivation of the SCR-system. Otherwise the system will send an error message to the control system, and consequently the truck will not be able to run in normal mode. Measurements with dismantled particulate filter / active SCR-system, and dismantled particle filter / inactive SCR-system were therefore merged in the test.

6.2.6 With or without trailer

In order to validate the measurement equipment, it was tested whether the presence of a trailer influenced the results.

A trailer may impact the measurements in two ways. First, the presence of a trailer may physically disturb the light beam from the instrument to pass through the exhaust plume. Some trailer designs allow the light beam to return immediately after the exhaust pipe, while other trailers are designed in a way, that the measurements take place at some distance to the exhaust pipe. Second, the presence of a trailer may simply increase the engine load and consequently increase the engine temperature faster than without a trailer attached. In order to evaluate this, measurements with active SCR-system versus inactive and SCR-system switched off were performed with and without trailer.

Figure 6.1. Photo and results from test of Euro VI heavy-duty trucks with and without trailer. Emissions of NO were low in both measurements, but about twice as high with trailer than without trailer.

6.2.7 Recording test conditions

All information from the tests were recorded in a scheme, which could be accessed by the NEQ's technicians on their smartphones. The scheme included information about VDF number (a unique identification code of an observation), Euro norm, measured NO_X concentration corresponding to the one displayed on the instrument display, time of measurement etc. After completing the scheduled tests, all data was reviewed to check for consistency between images, measurements etc.

6.3 Results of the tests in closed areas

During a period from 18.09.2019 – 24.09.2019, 242 test measurements were performed in the closed areas of Mercedes, Scania and Volvo. The majority of the tests involved Euro VI heavy-duty trucks (n= 216), while only 26 tests involved Euro V. A number of initiatives were taken to provide measurements on Euro V heavy-duty trucks with correctly functioning SCR-systems. Despite all efforts, the measurements revealed that none of the Euro V heavy-duty trucks featured correctly functioning SCR-systems. This explains the few tests involving Euro V and consequently differences between active and manipulated SCR-system on Euro V heavy-duty trucks.

Tables 6.1 and 6.2 summarize the test results divided into three categories:

- **SCR active**. AdBlue is supplied to the exhaust, which requires that the temperature of the SCR-system has reached working conditions.
- **SCR inactive**. AdBlue is not supplied to the SCR-system, which implies that the temperature of the inactive catalyst is insufficient.
- **SCR switched off**. The heavy-duty truck is deliberately manipulated and consequently the SCR-system is not working.

Table 6.1. Average emissions of NO and PM for different test of Euro VI heavy-duty trucks. The variation is calculated as the standard deviation of replicate measurements, which indicate the span of the results.

Status of SCR	Trailer	Particle filter	Number of tests	NO gNO_2/kg fuel		PM gPM/kg fuel	
Active	**Yes**	**Yes**	**37**	**0.59**	**0.82**	**1.0**	**1.6**
Active	No	Yes	15	1.2	1.0	1.1	1.6
Active	Yes/No	Yes	52	0.76	1.4	1.1	1.5
Inactive	Yes	Yes	9	11.8	2.1	1.0	1.2
Inactive	No	Yes	45	26.3	7.1	1.4	1.5
Inactive	Yes/No	Yes	54	23.8	7.5	1.3	1.5
Switched of	Yes	Yes/No	59	18.5	7.1	1.1	1.4
Switched of	No	Yes/No	44	18.0	4.3	0.63	0.43
Switched of	Yes/No	Yes/No	103	18.3	6.1	0.91	1.1
Switched of	Yes/No	Yes	69	15.9	4.6	0.87	1.2
Switched of	Yes/No	No	34	24.2	7.8	0.97	0.77

Table 6.2. Average emissions of NO and PM for different tests of Euro V heavy-duty trucks. The variation is calculated as the standard deviation of replicate measurements, which indicate the span of the results.

Status of SCR	Trailer	Particle filter	Number of tests	NO gNO_2/kg fuel		PM gPM/kg fuel	
Inactive	Yes	No	18	36	8.5	1.2	1.1
Inactive	No	No	7	23	4.1	0.67	0.12
Inactive	Yes/No	NO	25	32	9.6	1.1	0.98

In the following, the parameters which influence the test results are discussed.

6.3.1 Speed, acceleration and length of test road in the closed areas

Varying speed and acceleration of the heavy-duty trucks were tested in the closed areas. Figure 6.2 shows measured NO emission for three different categories of the SCR-system as function of speed. No correlation is observed between emissions of NO and speed in the range 5 - 45 km / hr for any state of the SCR-system. Similarly, Figure 6.3 shows measured NO emission as function of acceleration. Again, there is no significant correlation between emissions of NO and acceleration.

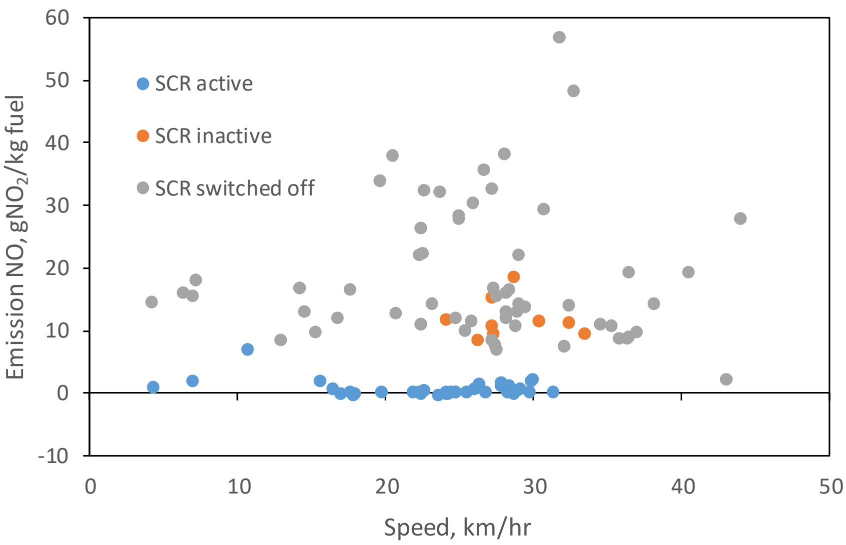


Figure 6.2. Emissions of NO from heavy-duty Euro VI trucks with active SCR, inactive SCR and SCR-system switched off as function of speed. Emissions are calculated as NO_2 equivalents (g NO_2/kg fuel).

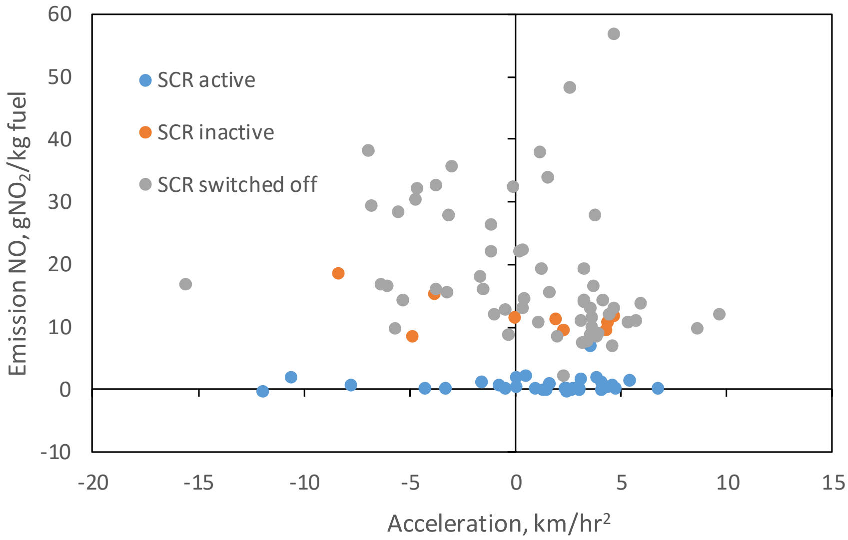


Figure 6.3. Emissions of NO from heavy-duty Euro VI trucks with active SCR, inactive SCR and SCR-system switched off as function of acceleration. Emissions are calculated as NO_2 equivalents (gNO_2/kg fuel).

The tests show that measurements of NO are quite robust and apparently independent of speed and acceleration for the studied velocity and acceleration ranges. Other test parameters (i.e. supply of AdBlue or engine temperature) are probably more important and the variation in these determine the plots in Figures 6.2 and 6.3. However, the findings obtained in the closed areas are not necessarily identical to the observations on authentic roads, where parameters cannot be controlled as in closed areas.

During the tests, different lengths of test roads were evaluated (appendix for chapter 6). Findings showed that only relatively short lengths of test road were needed to achieve acceptable results, and furthermore speeds down to 20 km/hr were sufficient. These findings are supported by the results presented in Figure 6.2. Moreover, at the preliminary tests in Karlslunde (17.09.2019), it was determined that the test road had to be sufficiently long to ensure that a heavy-duty truck including trailer is able to pass the measurements equipment at a minimum velocity of 20 km/hr prior to braking or turning.

6.3.2 Impact from alternating weather conditions

It is generally believed that weather conditions do not significant impact measurements, except for rainy conditions which makes measurements impossible due to scattering of the light beams from the instrument.

Part of the objective was to verify whether or not weather conditions impact the measurement results. Due to practical issues, it was necessary to perform the tests at the Mercedes, Scania and Volvo facilities, where each brand should be tested separately. Due to these constraints, it was only possible to test the Scania truck on two different days (18.09.2019 and 23.09.2019). The weather was very similar on the two days showing differences in temperature and wind speed of only 2˚C and 1 m/s, respectively (https://www.dmi.dk/vejrarkiv/). These small differences made it impossible to test the influence of weather conditions on the results.

6.3.3 Impact of status of the SCR-system

Figure 6.4 shows the average results of measured emissions of NO from Euro VI heavy-duty trucks divided into three different categories of SCR-systems (Active, inactive, switched off). In addition, the results are subdivided according to trailer on / trailer off. This might be important since a heavy-duty truck with a trailer is more likely to have a warm engine and SCR-system.

Average NO emissions equaled 0.8 g NO_2/kg fuel for active SCR, 24 g NO_2/kg fuel for inactive SCR and 18 g NO_2/kg fuel for active when SCR is switched off (Table 7.1). Thus, NO concentrations differ by a factor of 20 between a wellfunctioning SCR and an SCR that does not work. The difference between an inactive SCR and an active, but switched of SCR is not systematic apparent from the variation in Table 6.1.

For active and inactive SCR-systems, lower emissions are observed with trailer than without trailer. This might simply be because the engines has to work harder with load than without load. As a consequence the engines are warmer with trailer than without trailer and the warmer the engines the higher chance for a an active SCR. In the case where the SCR deliberately has been switched off, there is no difference between the results with and without trailer. In this case, the temperature of the engine has no influence on the activity of the SCR and therefore the results do not depend on trailer or no trailer.

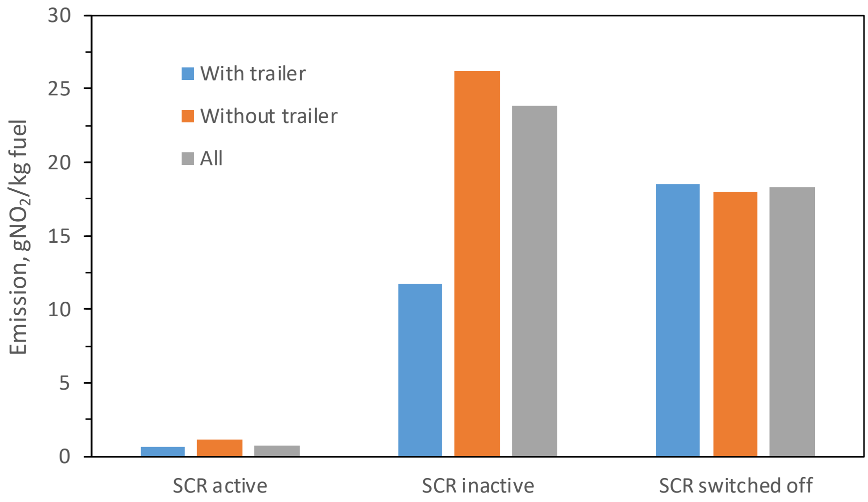


Figure 6.4. Average emissions of NO from heavy-duty Euro VI trucks with active SCR, inactive SCR and SCR-system switched off. The results are subdivided into measurements with and without trailer. The emissions are calculated as NO_2 equivalents (g NO_2/kg fuel).

Figure 6.5 shows the distribution of measured NO emissions ranked according to increasing emissions. All emissions from active SCR-systems are much lower than emissions from inactive SCR and SCR-systems switched off. The lowest emissions with inactive SCR and SCR switched off are around 7 g NO_2/kg fuel, which corresponds to around 460 ppm NO, which is clearly higher than the highest emissions measured with active SCR. These findings suggest a threshold concentration, at which the SCR-system is probably malfunctioning, at around 7 g NO_2/kg fuel (330 ppm NO). However, the results clearly show that high NO emissions could just as well be ascribed to an inactive SCR, e.g. arising from a cold engine.

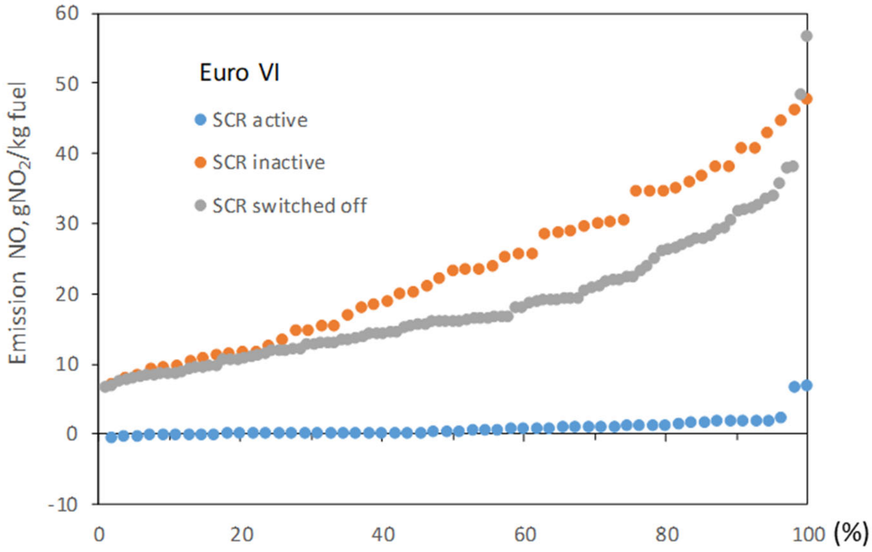


Figure 6.5. Distribution of NO emissions from heavy-duty Euro VI trucks with active SCR, inactive SCR and SCR-system switched off. Results are ranked according to increasing emissions. The x-axis represents the percentage of results with an emission lower than the NO emission at a given point. The emissions are calculated as NO_2 equivalents (g NO_2/kg fuel).

Average NO emissions from tested Euro V heavy-duty trucks with inactive SCR are 32 g NO_2/kg fuel (Table 6.2). This is 35% higher than for Euro VI measured under similar conditions and about a factor of two higher than for Euro VI with SCR switched off. Unfortunately it was not possible to test a Euro V with wellfunctioning SCR and it has therefore not been possible to make a comparison between Euro V and Euro VI with SCR-system switched off.

The distribution of NO emissions for Euro V heavy-duty trucks with inactive SCR are shown in Figure 6.6. The highest emissions are only slightly higher than the emissions from the Euro VI with inactive SCR but the lowest emissions are about at factor 3 higher than for the Euro VI. This may be explained by the fact that Euro VI are generally better than Euro V engines.

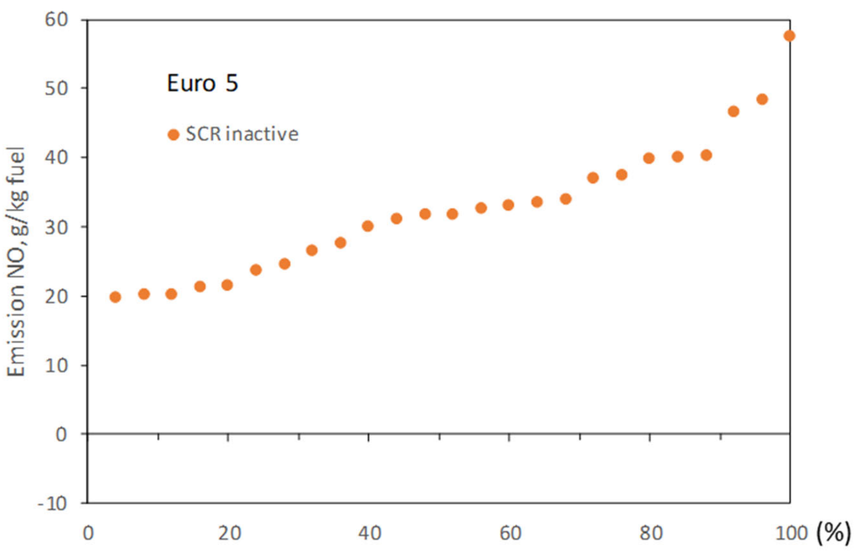


Figure 6.6. Distribution of NO emissions from heavy-duty Euro V trucks with inactive SCR-system. Results are ranked according to increasing NO emissions. The x-axis represents the percentage of results with an emission lower than the NO emission at a given point. The emissions are calculated as NO_2 equivalents (g NO_2/kg fuel).

6.3.4 Impact of brand

The results indicate difference between the brands of Euro VI heavy-duty trucks from Mercedes, Scania and Volvo. Figure 6.7 shows average NO emissions for each brand for active SCR, inactive SCR and SCR-system switched off. Clearly, brand 1 performs better than the other brands. Since we have only tested one or two heavy-duty trucks from each brand it is not possible to conclude whether the difference is due to actual differences between the heavy-duty trucks tested or whether one brand generally performs better than the other.

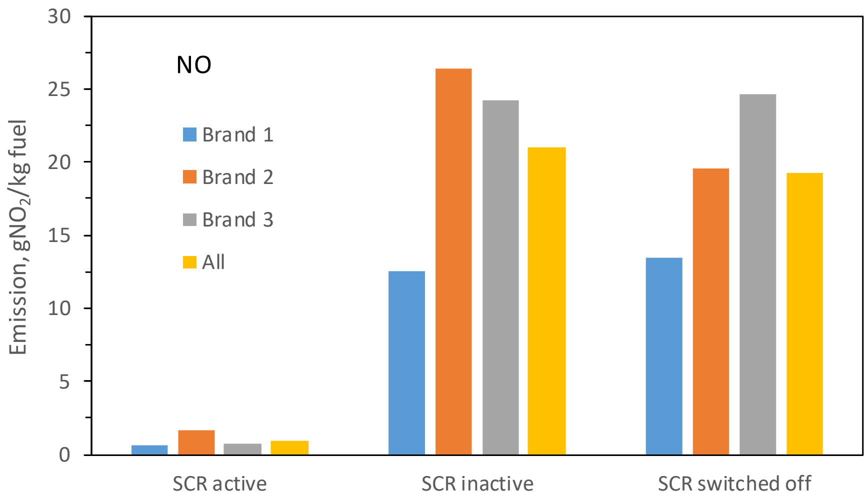


Figure 6.7. Average NO emissions from heavy-duty Euro VI trucks with active SCR, inactive SCR and SCR-system switched off for three different brands. The emissions are calculated as NO_2 equivalents (g NO_2/kg fuel).

6.3.5 Impact of particle emissions

PM emissions were measured with remote sensing equipment simultaneously with NO. Figure 6.8 and 6.9 show the results from the exact same tests as those used for NO measurements (Figure 6.5 and 6.6). Results are ranked in the same order as for NO. The plots for PM show no clear trend. Evidently, there is no correlation between high emissions of NO and PM. Moreover, PM emissions are apparently not related to the functioning of the SCR-system, except for cases where the particle filter has been removed (see paragraph below). High PM emissions do therefore not indicate manipulation with the SCR-system, though manipulation of the SCR-system could be one of the reasons.

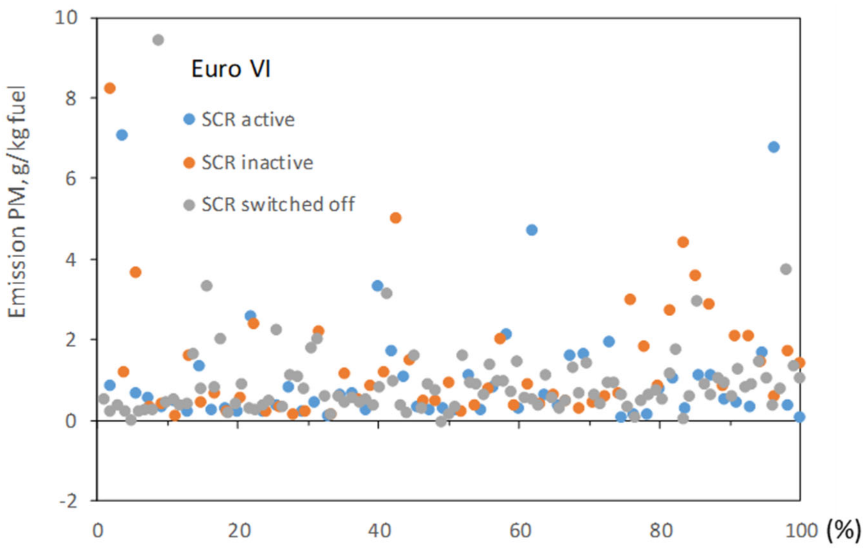


Figure 6.8. Distribution of PM emissions from heavy-duty Euro VI trucks with active SCR, inactive SCR and SCR-system switched off. Results are ranked according to increasing NO emissions (Figure 6.5). The x-axis represents the percentage of results with emissions lower than the PM emission at a given point.

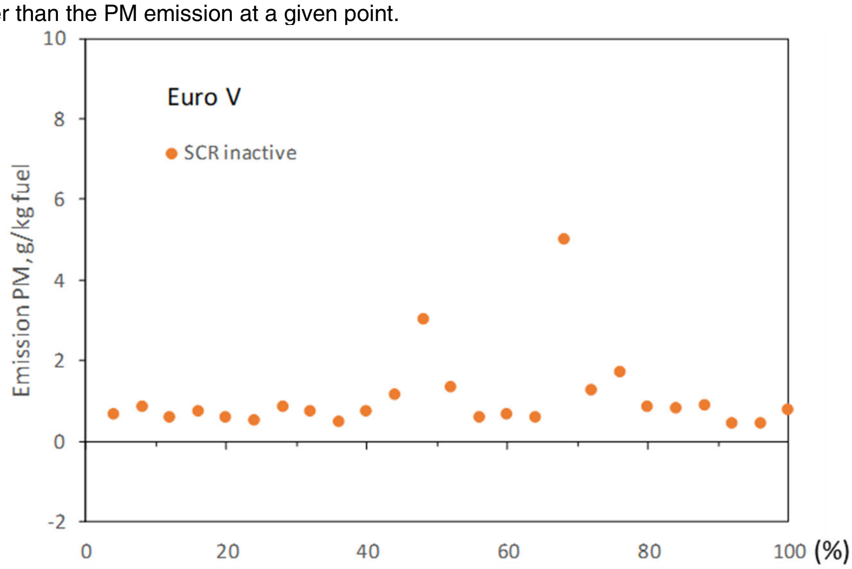


Figure 6.9. Distribution of PM emissions from heavy-duty Euro V trucks with inactive SCR-system. Results are ranked according to increasing emissions of NO (Figure 6.6). The x-axis represents the percentage of results with an emission lower than the PM emission at a given point.

In some tests, the objective was to measure the impact on PM emissions following a removal of the particle filter. This is because some manipulations of the SCR-system involve the removal of the particle filter. In fact, detailed evaluations revealed an expected increase in PM emissions in cases where the particle filter was removed.

Figure 6.10 shows average PM emissions from Euro VI heavy-duty trucks with SCR-system switched of, either with or without particle filter. For practical reasons, the tests were only performed with SCR-system switched off, since it is the combined manipulation of the SCR-system and particle filter, which is investigated. No change in particle emissions with or without particle filter was observed for brand 1. On the contrary, brand 2 and 3 nearly doubled the PM emissions, when the particle filter was removed. In average for all three brands, an increase in PM emissions was observed after removal of the particle filter. Again, it is not possible to assign these differences to specific heavy-duty trucks or general differences between the brands.

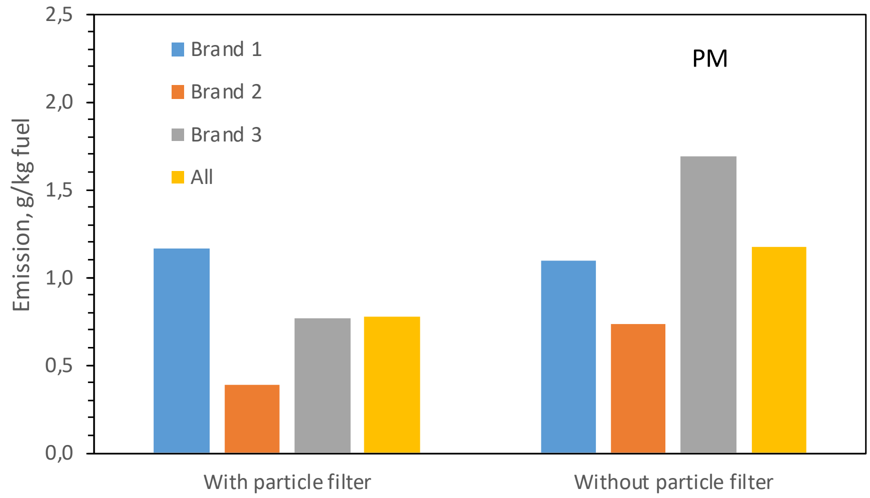


Figure 6.10. Average PM emissions from heavy-duty Euro VI trucks with active SCR, inactive SCR and SCR-system switched off for brands 1, 2 and 3.

6.4 Conclusion

During weeks 38 and 39 in September 2019, a large number of test measurements were performed in closed areas. Heavy-duty trucks that were deliberately manipulated with respect to SCR-system function and particle filter were tested against fully functional heavy-duty trucks.

A total of 216 tests were performed on Euro VI heavy-duty trucks with active SCR, inactive SCR and SCR-system switched off, with and without particle filter as well as with and without trailer. The tests were conducted under a number of different conditions to test the impact of speed and acceleration. In total, 4 Euro VI heavy-duty trucks from Mercedes, Scania and Volvo were tested.

A total of 26 tests were performed on Euro V heavy-duty trucks, and as a consequence only a small part of the test program could be realized. It turned out that the tested Euro V heavy-duty trucks all experienced errors on the SCR-system. Originally the plan was to test two Euro V heavy-duty trucks, but due to the faulty SCR-systems, we managed to test six different Euro V heavy-duty trucks. Unfortunately, all of them experienced errors on the SCR-system. This was contrary to the owners believe that the vehicles functioned properly.

In the following, the main conclusions from the test are summarized:

- Average NO emissions equaled 0.8 g NO_2/kg fuel for active SCR, 24 g NO_2/kg fuel for inactive SCR and 18 g NO_2/kg fuel for active SCR-system with the SCR switched off. Thus, NO emissions differ by a factor of 20 between wellfunctioning SCR and malfunctioning SCR-systems. The difference between the malfunctioning SCR-systems is within the uncertainty of the measurements.
- NO emissions from Euro V heavy-duty trucks featuring an inactive SCR-system averaged 32 g NO_2/kg fuel (Table 7.2). This is 35% higher than for Euro VI measured under similar conditions and about a factor of 2 higher

than for Euro VI with the SCR-system switched off. Unfortunately it was not possible to test Euro V with wellfunctioning SCR-system for which reason it has not been possible to make a comparison between Euro V and Euro VI with SCR switched off.

- For Euro VI heavy-duty trucks, the present findings suggest a threshold concentration, at which the SCR-system is probably malfunctioning, at around 7 gNO_2/kg fuel (330 ppm NO). However, the results clearly show that a high NO emission could just as well be ascribed to an inactive SCR, e.g arising from a cold engine.
- For Euro V heavy-duty trucks, the tests results suggest a threshold concentration, at which the SCR-system is probably malfunctioning, which is higher than for Euro VI. This is based on the fact, that Euro V heavy-duty trucks with inactive SCR in average has 2 times higher NO emissions compared to the average for Euro VI heavy-duty trucks with SCR switched off. The test themselves therefor point at a threshold of about 14 g NO_2/kg fuel (660 ppm NO).
- The three different brands showed relatively large differences with respect to emissions of NO and impact of NO following removal of the particle filters. It is not known whether these differences can be ascribed to general differences between the brands or whether it is due to differences between the specific heavy-duty trucks under test.
- Removal of the particle filter in connection with switching off the SCR-system increased the PM emissions about a factor of 2 for two of the tested brands, while the third brand was unaffected. The reason for this is not known at the moment, and it may be ascribed to problems with a specific heavy-duty truck under test.
- A supplementary test of a Euro V heavy-duty trucks based on the onboard diagnostic equipment showed low emissions of NO in the exhaust. Moreover, these tests showed that onboard diagnostic equipment may provide interesting information that could be used for further projects on malfunctioning SCR-systems on heavy-duty trucks.
- The measurements of NO during the tests were very robust towards variations in speed and acceleration. This means higher flexibility with respect to testing at closed areas and makes it possible to use shorter testing roads as previously thought.
- The weather conditions did not change significantly between the two days of testing the same heavy-duty trucks for which reason it was not possible to test to what extend weather conditions influenced the measurements. However, it is clearly not possible to measure during rain since the droplets scatter the light beam and thus influence the measurements.
- A number of other practical test were carried out (for example test of the requirements for calibrations) that enables us to make a more consolidated suggestion for a routine control method to identify malfunctioning SCR-system in heavy-duty trucks.

7 Measurements at Padborg and at the Great Belt

Jacob Klenø Nøjgaard, Ole Hertel, Thomas Ellermann, Christian Rud Ingvardsen and Jesper Risager Nielsen

7.1 Objective of the measurement campaigns

The main purpose of the measurements at the test facilities was to develop a procedure by which heavy-duty trucks with malfunctioning SCR-systems can be identified in collaboration with the police. In this context, a malfunctioning SCR-system can be manipulated deliberately or having technical errors. Different heavy-duty trucks brands, Euro norms, engine load etc. were measured with well-functioning and malfunctioning SCR-systems as well as particle filters. The resulting data provided valuable insight about the range of NO emissions from well-functioning and malfunctioning SCR-systems, particle filters as well as other parameters that affect emissions. The Danish Police were represented during the initial tests (section 8.2) of the equipment and demonstrated good understanding of the setup and measurement procedures on location.

During the measurement campaigns at Padborg and the Great Belt Bridge, the experience learned at the test facilities was applied to real locations at realistic conditions, which provided measurements of sufficient quality from a total of 2,942 heavy-duty trucks and 3,306 passenger cars. The objective of these campaigns was to estimate the fraction of heavy-duty trucks with a malfunctioning SCR-system. This estimate is subsequently extrapolated to the entire country in order to estimate the additional emission of NO from malfunctioning SCR-systems on a national level and estimate the impact of this extra emission on air pollution levels and associated health effects (Chapter 9).

PM and NO were measured simultaneously from heavy-duty trucks and passenger cars. These measurements provided important new knowledge on the present status of the Danish vehicle.

Figure 7.1. Example of the measurement setup in collaboration with Danish Police. The camera is hidden in a tent behind the dark car.

7.2 Police inspection at Padborg and the Great Belt Bridges

Appendix for chapter 7 presents a detailed description of the measurement campaigns including the applied activities and test. In the following, a brief overview is extracted.

Padborg at the Danish-German border and the Easterly located toll-booth at the Great Belt Bridge served as locations for vehicle measurements during the weeks 39 - 43 2019. At these sites, up to 3,000 vehicles were registered daily from 9.00 – 17.00. Either passenger cars or heavy-duty trucks were measured, since it was not possible to measure both types of vehicles at the same time.

On campaign days were the police was present for manual inspection of heavy-duty trucks based on NO_X measurements, the objective was to select vehicles based on exceedance of a threshold NO_X concentration and identification of the cause. The focus was to establish a method for detecting heavy-duty trucks with malfunctioning SCR-systems in close cooperation with the police. Except for two days, the focus was on heavy-duty trucks, only, based on the instrument setup applied during the measurements at the test facilities (see Chapter 7). The instrument operator and the police, who identified the Euro norm of the vehicle in question, communicated by radio or telephone, since automatic identification of vehicles turned out to be inefficient. Based on experiences from a previous project, we expected a majority of foreign vehicles among vehicles with abnormal NO emissions, which indicates a malfunctioning SCR-system. This was confirmed in the present project. By far, the majority of vehicles passing were Euro V and VI, for which a general threshold concentration of 1,000 ppm NO was applied. A threshold of 800 ppm was applied for a limited period of time, only, since no malfunctioning SCR-systems were detected using this threshold.

Heavy-duty trucks were inspected from 24.09.2019 - 26.09.2019 and 09.10.2019 - 10.10.2019 at Padborg. The procedure was changed from visible inspection by the police from 24.09.2019 - 26.09.2019 to non-visible inspection from 26.09.2019. The motivation was that visible inspection could induce anxiety among the chauffeurs, which consequently could change their driving pattern.

Malfunctioning equipment affected the number of registered vehicles, which resulted in missing data records, and exchange of equipment at Padborg 24.09.2019 - 25.09.2019. Different camera setups were tested to see if one setup could be applied to both passenger cars and heavy-duty trucks. However, this was not possible for which reason the two types of vehicles were tested on different days. On 26.09.19 the camera was hidden behind a passenger car, which caused the heavy-duty trucks to accelerate faster with a more natural driving pattern. Another test at the facilities in Ishøj was performed on the equipment hereafter, involving the police, NEQ and RSE. Calibrations were improved and the equipment worked as expected. Measurements and inspections continued from 09.10.2019, only with the modification that the camera was hidden in a tent, and vehicles selected for inspection were confronted somewhat after the measurement site.

Heavy-duty trucks were inspected from 01.10.2019 - 03.10.2019 at the Great Belt Bridge using a threshold of 1,000 ppm NO. The first day, instruments were setup in Brobizz lanes 2 and 3, while the police was located at the other side of the bridge to handle vehicles selected for manual inspection. Instrumentation was moved to lanes 6-9 on 01.10.2019, where foreign heavy-duty trucks were primarily passing through. However, the time spend waiting in line for the payment facility in these lanes could have cooled the SCR-systems resulting in high emissions of NO while the SCR-system is intact.

Figure 7.2. Measurement site at Padborg 26.09.2019

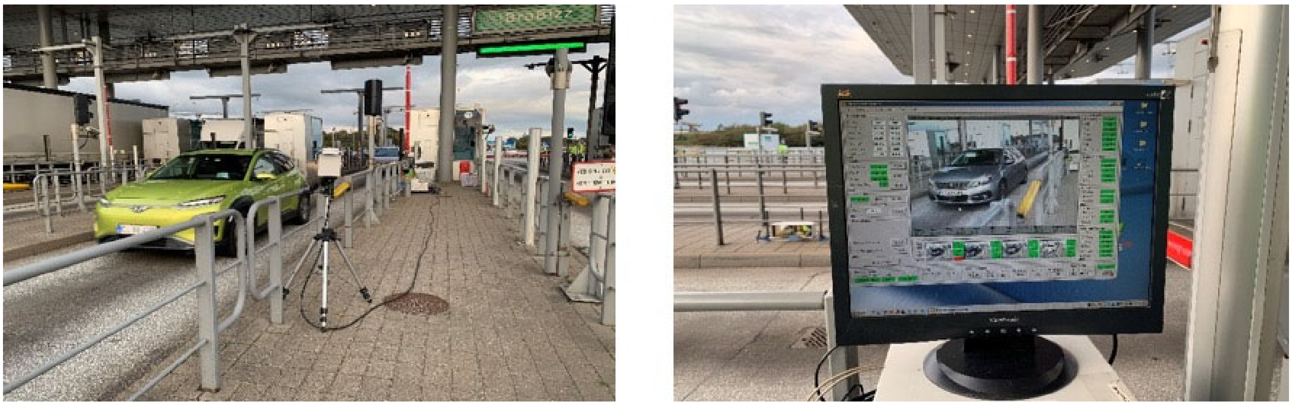


Figure 7.3. Great Belt Bridge, lane 2. Camera position (left) and data acquisition on-site (right)

7.3 Measurement campaigns at Padborg and the Great Belt Bridge

On the remaining campaign days without police inspection, the objective was to measure as many vehicles as possible. The setup of instrumentation was modified from the one with police inspection, but still visible to the vehicles. Two days were spent in Padborg with focus on heavy-duty trucks from 22.10.2019 – 23.10.2019. The setup was modified from the previous setup by the fact that the camera was hidden in a tent.

At the Great Belt Bridge, measurements on passenger cars were conducted on 04.10.2019 and 07.10.2019. License plates were manually identified and vehicle specifications subsequently obtained from registries. Description of activities and results from police roadside inspections.

Part of the heavy-duty trucks measured at Padborg and the Great Belt Bridge on 24.09.2019 - 26.09.2019, 02.10.2019 - 03.10.2019 and 10.10.2019 were visually inspected by the police. A total of 46 Euro V and Euro VI trucks were inspected. Heavy-duty trucks of foreign nationality with ambient NO measurements exceeding 800 ppm were mainly selected for inspection. Most measurements from 24.09.2019 – 26.09.2019 were not properly recorded, implying that the actual NO emission is not known. However, it is known that the concentration equalled or exceeded 800 ppm part of 24.09.2019), while being equal to or higher than 1,000 ppm during the remaining period.

Based on the measurement campaigns and testing at the test facilities, a relationship between NO emissions in NO_2 equivalents (g NO_2/kg fuel consumed) could be derived. From the DCE emission factors of NO in the same unit (Table 8.2), threshold ambient concentration in ppm were calculated for Euro IV (19 g NO_2/kg, 855 ppm), Euro V (17 g NO_2/kg, 765 ppm) and Euro VI (1.2g NO_2/kg, 54 ppm).

On the remaining days, two Euro IV heavy-duty trucks exceeding the emission factor used by DCE in official reporting up to 1.5 times, were found to have a well-functioning SCR-system. For Euro V, 3 heavy-duty trucks exceeded the DCE emissions factor 1.6 – 2.0 times, yet the SCR-systems were ok. Ten Euro V heavy-duty trucks exceeding the DCE emission factor 1.3 – 2.5 times, were found to have malfunctioning SCR. Finally, 4 Euro VI heavy-duty trucks exceeding the DCE emission factor 2.3 – 35.1 times did all have a well-functioning SCR-system. One parameter which is crucial for the operation of the SCR-system is the temperature. Thus, one possible explanation for latter finding could be cold SCR-systems due to insufficient warm-up time, e.g. from resting or fuelling the vehicle immediately prior to the measurements.

The difference in NO emission factors for Euro V and Euro VI heavy-duty trucks, and different NO emissions for malfunctioning SCR-systems for the two Euro norms, suggest that different criteria for police control of heavy-duty trucks should be applied. Based on the inspection reports from the police, a relationship between ambient NO concentration in ppm and fraction of well-functioning and malfunctioning SCR-system can be derived for Euro V. Use of 1,000 ppm NO as a criterion for police control of Euro V, resulted in 23 malfunctioning SCR-systems out of 30 vehicles. That is, malfunctioning SCR-systems were identified in 77% of the police controls by application of a threshold concentration of 1,000 ppm. In the same way, 23% of the inspected SCR-systems were neither manipulated nor showed sign of technical errors. By use of a threshold concentration of 800 ppm, 4 Euro VI heavy-duty trucks were selected for police control, though no malfunctioning SCR-systems were identified. Conversely, 3 Euro VI heavy-duty trucks showed malfunctioning SCR-system by use of a threshold concentration of 1,000 ppm. Moreover, one Euro VI was inspected by the police with an emission of NO on 147 ppm. This Euro VI was selected based on a high PM emission - not from exceeding a NO threshold concentration - and it turned out that the SCR was malfunctioning. Please notice that given the number of Euro VI heavy-duty trucks is very low, the statistical uncertainty is high. Thus, a threshold concentration of 800 ppm is not necessarily a too low criterion even though no malfunctioning SCR-system were detected.

A vehicle may exceed the NO threshold concentration, even though its SCR-system shows no indication of malfunctioning, in cases where the SCR–system operates under insufficient temperature or has undetected malfunctions. Whereas 1,000 ppm NO appears to be a reasonable criterion for police control of Euro V, a lower criterion can probably be justified for Euro VI (see Chapter 6), though this was not justified during the campaigns.

7.4 Measurements on heavy-duty trucks in Denmark

NO and PM were measured during the measurement campaigns at the Great Belt bridge (30.09.2019 - 03.10.2019) and at the Danish-German border in Padborg (24.09.2019 – 26.09.2019, 09.10.2019 – 10.10.2019 and 22.10.2019 – 23.10 2019). NO and PM emissions from 2,942 heavy-duty trucks and 3,306 passenger cars were measured using the remote sensing equipment. Passenger cars and heavy-duty trucks were measured on different days, since the two types of vehicles required different instrumental setups (section 8.2). The vast majority of heavy-duty trucks were registered in other countries than Denmark, i.e. 1% of all vehicles were Danish Euro V and 10% of all vehicles were Danish Euro VI (Table 7.1).

Euro IV accounted for only 0.1% of the heavy-duty trucks, whereas foreign Euro VI accounted for 66% of the heavy-duty trucks. Part of the Euro V and all Euro VI use SCR-systems. It was not possible to distinguish Euro V with and without SCR in this project. As apparent from Table 8.1, Euro VI dominates the investigated Euro norms (76%). Euro V accounts for the remaining 24%. Only 11% of all heavy-duty trucks were registered in Denmark.

Euro IV showed negligible contributions to both measured pollutants (Table 7.1). Furthermore, only 3 Euro IV trucks equal to 0.1 % of the total number were measured, and therefore the results are highly uncertain for this Euro norm.

In this project we measured NO emission factors for Euro IV, V and VI to be 12, 27 and 3.3 g NO_2/kg fuel consumed (Table 8.2). In Ellermann et al. (2018), we measured NO emissions from Euro IV, V and VI heavy-duty trucks to be 41, 18 and 1.5 g NO_2/kg. The corresponding DCE emissions factors are 19, 17 and 1.2 g NO_2/kg.

The ratio of NO from Euro VI to Euro V in this project is 8, which is lower than expected from the DCE emission factors (ratio = 14), which are based on the European COPERT 5 road transport emissions model documented by the EMEP/EEA air pollutant emission inventory guide book and used by Danish Centre for Environment and Energy. A ratio = 12 for NO emissions from Euro V/Euro VI was obtained from our precious work presented in Ellermann et al. (2018).

In order to calculate the contribution from the combination of a given Euro norm and nationality (e.g. Euro V DK) to the total emission of a pollutant in this project, the following approach was applied: for every combination of Euro norm and nationality, the average pollutant emission was multiplied by the number of trucks to find the emission from this combination of Euro norm and nationality. Emissions for all combinations of Euro norm and nationality were then added to yield a total emission, from which the relative contributions from combinations of Euro norm and nationality could be calculated (Table 7.1). As an example, the abundance of Danish Euro VI trucks accounted for 10% of all measured heavy-duty trucks, but contributed only to 3% of emitted NO. In the same way, although the abundance of Euro V was only 24% of all heavy-duty trucks, they accounted for 72% of emitted NO and 66% of emitted PM. Euro VI accounted for the remaining 28% of NO and 34% of PM.

Table 7.1. Emitted NO and PM from heavy-duty truck according to Euro norm and nationality. Emitted nitrogen oxide (NO) as parts per million (ppm) in air and gram per kilo consumed fuel (as equivalent nitrogen dioxide (NO_2)), and emitted particulate matter (PM) as gram per kilo consumed fuel based on 2,942 heavy-duty trucks (heavy-duty trucks) measured at the German-Danish border in Padborg and the Great Belt Bridge. Shares denote the fraction of heavy-duty trucks of a particular Euro norm and nationality relative to the total number of heavy-duty trucks measured. NO and PM are averages of pollutants measured for heavy-duty trucks differentiated by Euro norm and nationality. The percentage of NO and PM in brackets is calculated as the product of number of vehicles and average NO or PM from a particular Euro norm and nationality relative to the total emission.

Nationality	**Number**	**Share**	**NO (ppm)**	**NO (g NO2/kg fuel)**	**PM (g/kg fuel)**
Euro IV DK					
Euro IV Foreign	3	**0.1%**	566 (0.1%)	12 (0.1%)	0.80 (0.3%)
Euro IV Total	3	**0.1%**	566 **(0.1%)**	12 **(0.1%)**	0.80 **(0.3%)**
Euro V DK	44	1%	964 (3%)	21 (3%)	0.10 (1%)
Euro V Foreign	654	22%	1267 (68%)	28 (68%)	0.82 (66%)
Euro V Total	698	**24%**	1248 **(72%)**	27 **(72%)**	0.78 **(66%)**
Euro VI DK	303	10%	114 (3%)	2.5 (3%)	0.60 (22%)
Euro VI Foreign	1938	66%	158 (25%)	3.4 (25%)	0.05 (11%)
Euro VI Total	2241	**76%**	152 **(28%)**	3.3 **(28%)**	0.12 **(34%)**

The very low emissions of PM from Danish Euro V compared to foreign Euro V heavy-duty trucks may be because the number of Danish Euro V is low and therefore not representative. For Euro VI the PM emissions of Danish heavy-duty trucks are much higher than the foreign Euro VI. This high average emission of PM from Danish Euro VI is because of very high emissions from the 5% highest emitting Danish Euro VI heavy-duty trucks. In fact, from the data set it is apparent that only 7 Euro VI heavy-duty trucks causes the PM emission from Danish vehicles (0.60 g/kg) to exceed that of foreign vehicles (0.05 g/kg). Upon removal of these vehicles, the emission from Danish Euro VI heavy-duty trucks is comparable to foreign Euro VI (0.04 g/kg). The apparently inconsistent differences between Danish and foreign Euro V and Euro VI heavy-duty trucks may therefore be due to the sample size and PM being more sensitive than NO to high emitting vehicles.

PM emissions in Table 8.1 can be compared to a recently published report from the Swedish Environmental Research Institute (Sjödin et al., 2017). For example, PM emitted from Euro V heavy-duty trucks (0.78 g/kg) is two times higher than those obtained from Sjödin et al. (0.4 g/kg). For Euro VI heavy-duty trucks (0.12 g/kg) the results from this project match those of Sjödin et al. (0.1 g/kg).

Table 7.2. Danish Centre for Environment and Energy (DCE) emission factors and measured emissions of NO from heavy-duty trucks. DCE emission factors for NO based on the European COPERT 5 road transport emissions model and emissions measured in the Environmental project 2021 (Ministry of Environment and Food of Denmark, 2018) based on 874 heavy-duty trucks are compared to the findings in this project.

	DCE emission factor NO ($g\ NO_2/kg$ fuel)	Environmental project 2021 ($g\ NO_2/kg$ fuel)	This project ($g\ NO_2/kg$ fuel)
Euro IV	19	41	12
Euro V	17	18	27
Euro VI	1.2	1.5	3.3

The distribution of NO emissions ranked according to increasing emissions for Danish and foreign Euro V heavy-duty trucks are shown along with the DCE emission factor in Figure 7.7. The two curves are not coinciding, rather the emissions from foreign vehicles are elevated relative to the emissions from Danish vehicles. However, there are 15 times more foreign vehicles in the data set for which this curve is also smoother for foreign vehicles. A minor jump on this curve appears at 88% corresponding to emissions 50-60% higher than the DCE emissions factor, implying that there could be two populations of foreign Euro V heavy-duty trucks. However, the jump is subtle and could possibly be ascribed to other factors than malfunctioning SCR-systems.

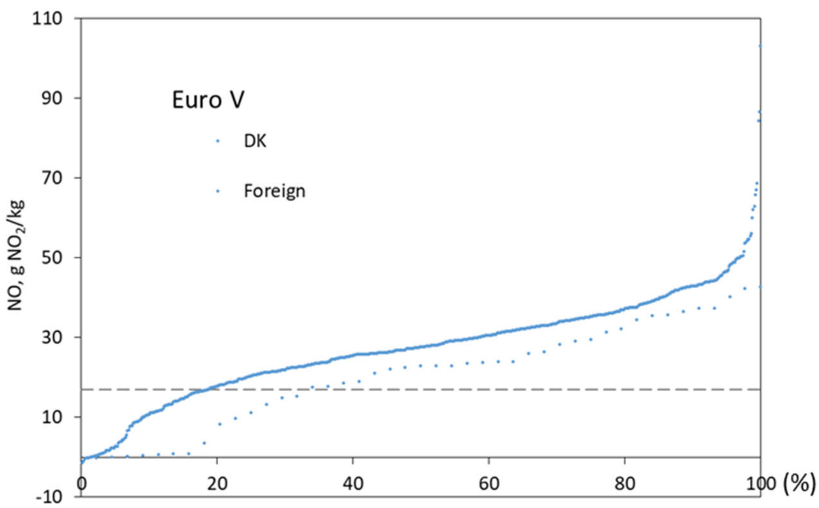


Figure 7.4. Distribution of NO emissions ranked according to increasing emissions for Danish and foreign Euro V heavy-duty trucks. The emissions are calculated as NO_2 equivalents. Also shown is the DCE emission factor.

Figure 7.8 illustrates the same relationship for Euro VI heavy-duty trucks. In contrast to the Euro V standard, the subtle jump appears at 85% corresponding to a NO emission from foreign Euro VI heavy-duty trucks about 3 times higher than the DCE emission factor. Again, the jump is subtle and could be ascribed to other factors than malfunctioning SCR-systems. There are more Danish Euro VI heavy-duty trucks than Euro V heavy-duty trucks. However, a jump in the curve illustrating Danish Euro VI heavy-duty trucks cannot be identified.

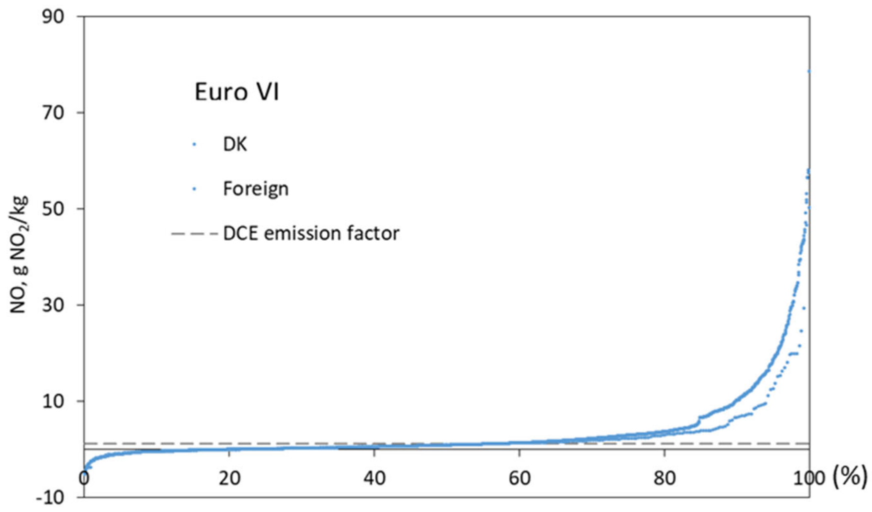


Figure 7.5. Distribution of NO emissions ranked according to increasing emissions for Danish and foreign Euro VI heavy-duty trucks. Emissions are calculated as NO_2 equivalents. Also shown is the DCE emission factor.

Figures 7.7 and 7.8 show weak indications of a jump in the distribution of emissions of NO but it is also apparent from the data, that there is no clear way to separate those heavy-duty trucks with well-functioning SCR from those with malfunctioning SCR-systems. However, based on the "small jumps" and the tendency for a steeper increase in emission from about 90% of the heavy-duty trucks and onwards, we have estimated that about 10% of the vehicles are likely to have malfunctioning SCR-systems. It is clear that this estimate is very uncertain.

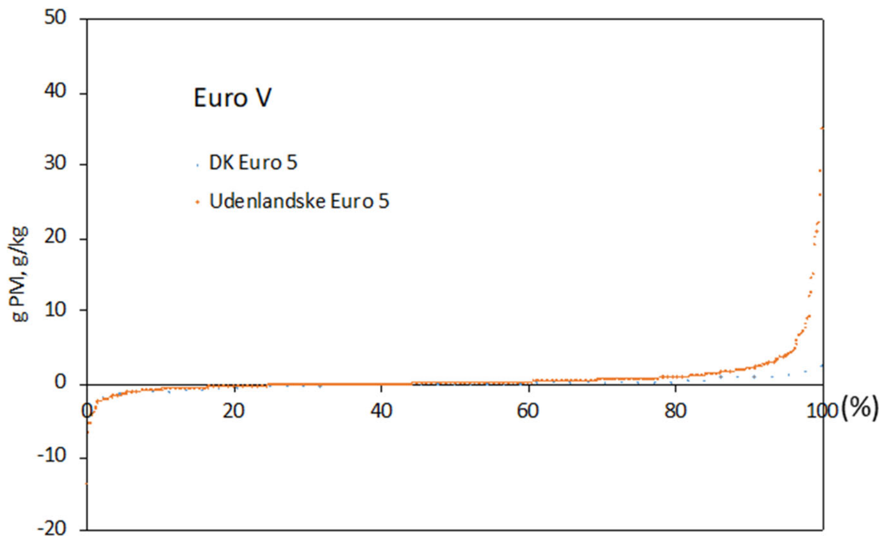


Figure 7.6. Distribution of PM emissions ranked according to increasing emissions for Danish and foreign Euro VI heavy-duty trucks.

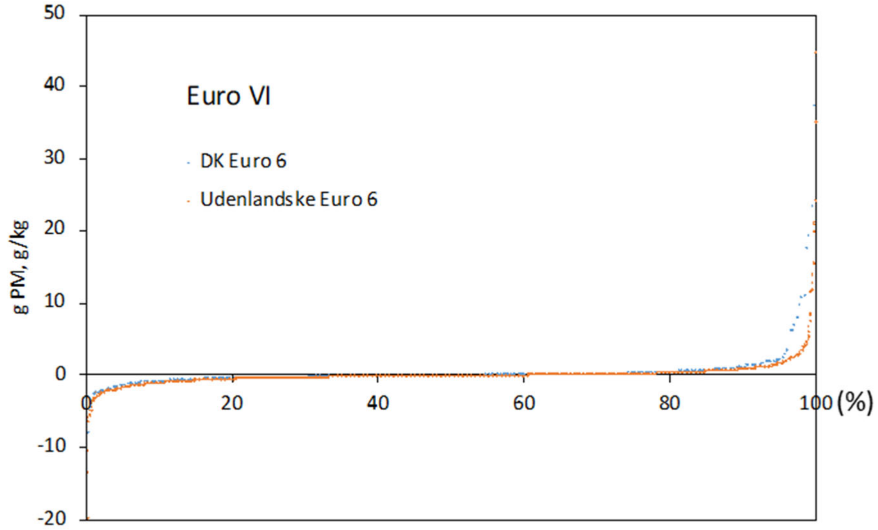


Figure 7.7. Distribution of PM emissions ranked according to increasing emissions for Danish and foreign Euro VI heavy-duty trucks.

The distribution of PM emissions ranked according to increasing emissions are comparable to those for NO and are shown in Figures 7.9 and Figure 7.10.

8.1.5 Measurements on passenger cars in Denmark

Only passenger cars with Danish registration numbers were selected for measurements at the Great Belt Bridge (04.10 and 07.10 2019), which provided information about Euro norm fuel type etc. Emission standards spanned Euro norms 2 to 6, though the former included only one petrol fuelled vehicle (Table 8.3). Euro norm 6 accounted for 62% of all vehicles followed by Euro 5 (25%), Euro 4 (11%) and Euro 3 (1.7%). Except for Euro 4 with 54% petrol vehicles, a majority of diesel vehicles was observed for Euro norms 3 to 6, most pronounced for Euro 6 (65%). Vans of total weight less than 3500 kg were included in this category, but accounted for less than 3% of the vehicles.

Measured NO emissions from diesel vehicles were comparable for Euro 3 (23 g NO_2/kg), Euro 4 (18 g NO_2/kg) and Euro 5 (20 g NO_2/kg). However, emissions from Euro 6 were only 7 g NO_2/kg. The effect of Euro norm appears to be more pronounced for PM (Table 8.3). NO emissions from petrol cars showed a less consistent trend, i.e. from Euro 3 (1.3 g NO_2/kg) to Euro 4 (3.9 g NO_2/kg) and Euro 5 (1.6 g NO_2/kg) to Euro 6 (2.5 g NO_2/kg). Emitted PM from diesel vehicles decreases from Euro 3 (1.7 g/kg) to Euro 4 (1.0 g/kg). Euro 5 and Euro 6 emissions were only 0.2 and 0.1 g/kg, respectively, which equals a factor of 17 from Euro 3 to Euro 6. PM emissions from petrol vehicles were 0.1 - 0.2 g/kg for Euro norms 3 to 6.

As for heavy-duty trucks, the contribution to a pollutant's emission can be calculated from the average emission by a Euro norm and fuel type multiplied by the number of vehicles in that category relative to the total emission of a particular pollutant. Using this approach, it becomes evident that Euro 5 diesel vehicles, which accounted for 16% of the measured vehicles, emit 39% of all NO (Table 8.3). This is slightly more than Euro 6 diesel vehicles, which account for 40% of all measured vehicles and emitting 36% of all NO. With respect to PM, 26% of all PM is emitted by Euro 4 diesel vehicles though they make up only 5% of all measured vehicles. This PM emission is slightly larger than that from Euro 6 diesel vehicles, which make up 40% of all measured vehicles and emitting 23% of all PM.

Table 7.3. Emitted NO and PM from passenger cars according to Euro norm and fuel. Emitted nitrogen oxide (NO) as parts per million (ppm) in air and gram per kilo consumed fuel calculated as nitrogen dioxide (NO_2), and emitted particulate matter (PM) as gram per kilo consumed fuel based on 3,306 passenger cars measured at the German/Danish border in Padborg and at the Great Belt Bridge. Shares denote fraction of passenger cars in a particular Euro norm and fuel type relative to total number of passenger cars measured. NO and PM are averages of pollutants measured for passenger cars differentiated by Euro norm and fuel type. The percentage of NO and PM in brackets has been calculated as the product of number of vehicles and average NO and PM for a particular Euro norm and fuel type relative to the total emission.

Nationality	Number	Share	Ratio diesel /petrol	NO ppm	NO g/kg fuel	PM g/kg fuel
Euro 2 petrol	1	0.02%		1463 (0.1%)	32 (0.1%)	0.5 (0.1%)
Euro 2 diesel						
Euro 2 total	1	**0.02%**		1463 **(0.1%)**	32 **(0.1%)**	0.5 **(0.1%)**
Euro 3 petrol	23	0.7%		62 (0.1%)	1.3 (0.1%)	0.1 (0.4%)
Euro 3 diesel	32	1.0%		1035 (2.7%)	23 (2.7%)	1.7 (8.4%)
Euro 3 total	55	**1.7%**	58%	628 **(2.8%)**	9 **(2.8%)**	1.0 **(8.8%)**
Euro 4 petrol	197	6.0%		179 (2.9%)	3.9 (2.8%)	0.2 (5.6%)
Euro 4 diesel	167	5.1%		846 (11%)	18 (11%)	1.0 (26%)
Euro 4 total	364	**11%**	46%	486 **(14%)**	6.9 **(14%)**	0.6 **(31%)**
Euro 5 petrol	318	9.6%		74 (1.9%)	1.6 (1.9%)	0.2 (10%)
Euro 5 diesel	511	16%		932 (39%)	20 (39%)	0.2 (19%)
Euro 5 total	829	**25%**	62%	603 **(41%)**	8.6 **(41%)**	0.2 **(29%)**
Euro VI petrol	724	22%		113 (6.6%)	2.5 (6.6%)	0.1 (8.8%)
Euro VI die-sel	1334	40%		331 (36%)	7.2 (36%)	0.1 (23%)
Euro VI total	2058	**62%**	65%	254 **(42%)**	3.6 **(42%)**	0.1 **(31%)**

Measured NO emissions from passenger cars in Gothenburg differentiated by Euro norm and fuel type have recently been published in a report from the Swedish Environmental Research institute (Sjödin et al., 2017). The majority of the reported NO emissions agree with those in Table 8.3 within 27%. However, PM emissions in this project (Table 8.3) exceed those obtained by Sjödin et al. For example, PM emitted from Euro 4 (1.0 g / kg), Euro 5 (0.2 g / kg) and Euro 6 (0.1 g / kg) exceed those reported by Sjödin et al., i.e. about 0.15 g / kg, 0.05 g / kg and 0.05 g / kg. The reason for this is not known, but could be related to differences in the vehicles fleet, including composition of brands, type of particle filters and their age and condition.

The distribution of NO and PM emissions ranked according to increasing emissions for petrol and diesel passenger vehicles according to Euro norm are different from those of heavy-duty trucks in Figures 7.4 to 7.7. Contrary to heavy-duty trucks, NO emissions from diesel vehicles do not show a steep increase in emissions, but increases more steadily (Figure 7.8). However, NO emissions from Euro 6 petrol passenger cars show a closer resemblance with that of heavy-duty trucks. Euro 3 and 4 passenger cars show differences in PM emission with diesel vehicles having much higher PM emissions. On the contrary, PM emissions from Euro 5 and Euro 6 passenger cars are highly comparable showing almost coinciding PM emission curves. Examples of Euro 6 passenger cars are shown in Figures 7.8 and 7.9.

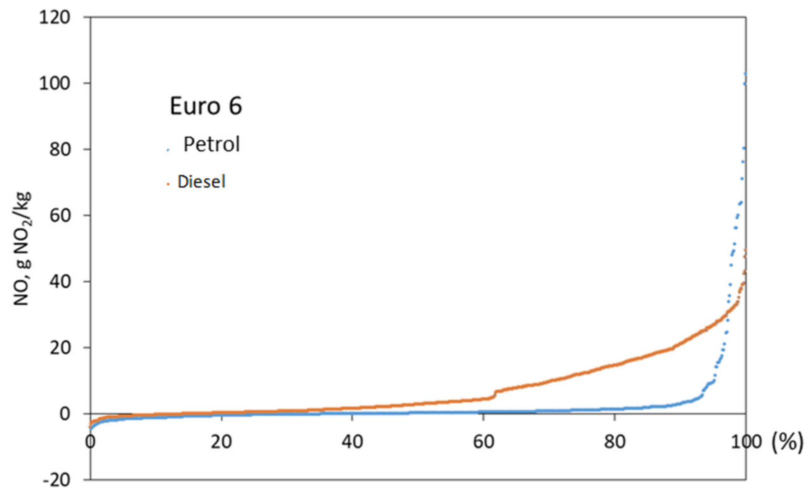


Figure 7.8. Distribution of NO emissions as NO_2 equivalents ranked according to increasing emissions for Euro 6 petrol and diesel passenger vehicles.

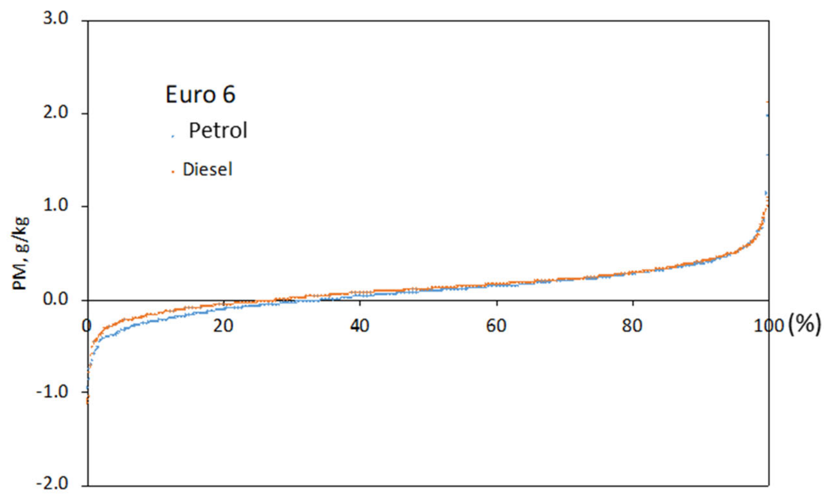


Figure 7.9. Distribution of PM emissions ranked according to increasing emissions for Euro 6 petrol and diesel passenger vehicles.

7.5 Conclusions

Emissions from 2,942 heavy-duty trucks and 3,306 passenger cars were measured during two measurement campaigns at Padborg and at the Great Belt Bridge in September – October 2019. Among the heavy-duty trucks, 11% were registered in Denmark and 89% were of foreign origin. Euro norm 5 accounted for 24%, while the remaining heavy-duty trucks were Euro 6 (76%). The fleet of passenger cars were composed of Euro 3 (2%), Euro 4 (11%), Euro 5 (25%), and Euro 6 (62%). The fraction of diesel cars spanned 46 (Euro 4) - 65% (Euro 6) of all measured vehicles.

The Danish Police was present on location in parts of the campaign, where measurements focused on heavy-duty trucks. On these occasions, heavy-duty trucks were selected for police control of SCR-systems, where NO emissions exceeded a particular threshold concentration. With a threshold concentration of 1,000 ppm NO, 77% of the inspected Euro V heavy-duty trucks showed evidence of a malfunctioning SCR-systems. Whereas 1,000 ppm NO appears to be a reasonable criterion for police control of Euro V heavy-duty trucks, a lower criterion can probably be justified for Euro VI heavy-duty trucks though this could not be verified experimentally during the measurement campaigns.

Emissions of NO and PM were obtained for Euro norm V and VI diesel heavy-duty trucks differentiated by nationality, and Danish Euro 2, 3, 4, 5 and 6 passenger cars differentiated by fuel type. By comparison with NO and PM emissions obtained using similar equipment in Environmental Project 2021 (Ministry of Environment and Food of Denmark, 2018) as well as DCE emission factors, the emissions in this project was found to be higher for both NO and PM. Furthermore, the ratio of NO emissions from Euro V to Euro VI heavy-duty trucks were lower in this project (ratio=8) compared to those derived from Environmental Project 2021 as well as DCE emission factors (ratio=14 and 12, respectively). The emissions of PM from Euro V and Euro VI Heavy-duty trucks were two times higher and similar to, respectively, emissions from comparable vehicles reported by Sjödin et al., 2017. An inconsistency in PM emissions from Danish and foreign heavy-duty trucks of same Euro norm may be due to the sample size and PM being more sensitive than NO to high emitting vehicles. Diesel fuelled passenger cars account for 76% of emitted PM, while the remaining 24% is emitted by petrol fuelled passenger cars. Of all PM, 26% is emitted by Euro 4 diesel passenger cars though they make up only 5% of all measured vehicles. This PM emission is slightly larger than that from Euro 6 diesel vehicles, which make up 40% of all measured vehicles. Emissions of PM from passenger cars were somewhat higher than recent results previously published by a Swedish project (Sjödin et al., 2017). We observed a consistent decrease in PM from Euro 3 to Euro 6 with a decreasing ratio of PM emitted by diesel vehicles relatively to petrol vehicles. For Euro norms 5 and 6, the PM emissions from petrol vehicles and diesel vehicles were similar.

Emissions of NO from passenger cars generally agreed with results previously published by a Swedish project. Euro V made up only 24% of the heavy-duty trucks, but accounted for 72% of the total NO emission. On the contrary, Euro VI made up 76% of all heavy-duty trucks, but accounted for only 28% of NO. Of the passenger cars, Euro 5 diesel made up only 25% of the vehicles, but accounted for 39% of the total NO emission. On the contrary, Euro 6 diesel made up 40% of all vehicles and accounted for 39% of NO.

Emission data for NO for 2,942 heavy-duty trucks did not show clear separation between Euro V and VI heavy-duty trucks with well-functioning and malfunctioning SCR. However, based on the available data is was estimated that about 10% of the Euro V heavy-duty trucks and 10% of the Euro VI heavy-duty trucks had malfunctioning SCR-systems. This result is used for the further evaluation of the health effects from the extra emissions that is made by the malfunctioning SCR-systems. The estimate of the percentage of heavy-duty trucks with malfunctioning of the SCR is very uncertain and this has to be kept in mind in connection with further interpretation of the data.

The data clearly showed that Euro norms IV and lower for heavy-duty trucks, as well as Euro norms 2 and lower for passenger cars were scare. For this reason, the measurement uncertainty is very high for heavy-duty truck Euro IV (0.1% abundance), and passenger cars of Euro norm 3 (1.7% abundance) and Euro 2 (0.02% abundance).

8 Impact of malfunction of SCR-systems and particle filters on air quality and human health

Jørgen Brandt, Lise Marie Frohn, Morten Winther, and Ole Hertel

8.1 Methods

In this chapter we present calculations of the impact on air quality in Denmark and the associated health impact in the Danish population. Based on the measurements, we have estimated the extent of malfunctioning SCR-systems, and the impact that the malfunctioning has on emissions from malfunctioning heavy-duty trucks. In the performed calculations, it is thus assumed that 10% of the heavy-duty trucks have malfunctioning SCR-systems. Furthermore, it is assumed that a malfunctioning Euro VI heavy-duty truck emits six times as much as a truck with well-functioning SCR-system. For the Euro V heavy-duty trucks, it is assumed that a malfunctioning heavy-duty truck emits twice as much as a truck with well-functioning SCR-system. A new emission inventory has been derived on basis of these assumptions.

Impact on air quality and associated health effects is assessed by carrying out calculations for the year 2017 with the original (baseline) emission inventory and the new emission inventory accounting for malfunctioning SCR-systems. The contribution from malfunctioning is then determined by subtracting the results from the two calculations from each other.

The calculations are performed with two models: The Urban Background Model (UBM v11.0, in the following just referred to as UBM) is applied for mapping air pollution concentrations, and the Economic Valuation of Air pollution (EVA v5.2, in the following just referred to as EVA). The same versions of UBM and EVA are applied in the NOVANA report for 2018 (Ellermann et al., 2020). This version of the EVA model system is furthermore documented in Andersen et al. (2019). UBM is a local scale model operating on a 1km x 1km grid for the entire Danish domain. Concentrations on the boundaries for the UBM are provided by the long-range transport model DEHM (Danish Eulerian Hemispheric Model). All the applied models and model systems are developed and applied by Department of Environmental Science, Aarhus University.

As already stated, two model runs are performed with the UBM for Denmark for the year 2017. The first is a basis model run with all emissions included, and the second is a scenario run where the NOx emission from SNAP0703 (heavy-duty vehicles including both trucks and buses) is multiplied with 1.1345 to simulate the increased emission of NOx as a consequence of malfunctioning SCR-systems. The factor 1.1345 is obtained from the earlier mentioned assumptions of 10% heavy-duty trucks with malfunctioning SCR-systems with six times higher emissions for Euro VI heavy-duty trucks and two times higher emissions for Euro V heavy-duty trucks.

Following the calculations with UBM, the EVA model system has been applied to calculate the health effects and related external costs in Denmark, which can be attributed to the additional NOx emissions from heavy-duty trucks in the scenario run.

The estimates of health effects and related external costs for Europe are loosely based on emissions for the whole of EU28 on basis of total NOx emissions for SNAP07 and SNAP0703. In these calculations, it has crudely been assumed that the same fraction of heavy-duty trucks have malfunctioning SCR-systems and that the impact on the emissions is also the same as found in the current study.

8.2 Results

In the following we present the calculated health effects in Denmark as a consequence of the estimated increased NOx emissions related to heavy-duty trucks having malfunctioning SCR-systems. It is assumed that the emissions related to the heavy-duty trucks with malfunctioning SCR-systems correspond to an increase of 13.45% (which is the reason for the previous presented factor 1.1345 to be multiplied to the total emission) of the total emission of the transport sector SNAP0703, including both heavy-duty trucks and busses (20.71% for the heavy-duty trucks alone). These figures are again generated on basis of the previously mentioned figures for the fraction with malfunctioning SCR-systems.

Table 8.1 shows the calculated number of cases of different health effects on the regional scale, which is based on calculations with the DEHM and EVA performed in a previous project (Andersen et al., 2019). On the regional scale, changes in nitrate, nitrogen-dioxide and ozone are accounted for in the calculations. Furthermore, the table presents number of cases of different health effects on the local scale, which is based on calculations with UBM and EVA performed within the present project. On the local scale, changes in nitrogen-dioxide and ozone are accounted for in the calculations.

Table 8.1. Additional health effects in Denmark related to increased NOx emissions due to heavy-duty trucks with malfunctioning SCR-systems.

Health impact	Regional (DEHM)	Local (UBM)	Sum DK sources	Contribution from EU28	Sum Denmark + EU28
Premature deaths from short term exposure	3.0	3.2	6.2	15.1	21.2
Premature deaths from long term exposure	3.5	0	3.5	8.6	12.2
Total number of premature deaths	6.5	3.2	9.7	23.7	33.4
Respiratory hospital admissions	11.4	12.9	24	59.5	83.7
Cerebro-vascular hospital admissions	0.0	-0.4	-0.4	-1.0	-1.4
Episodes with asthma among children	0.5	0	0.5	1.1	1.6
Episodes with bronchitis	3.5	0	3.5	8.6	12.2
Episodes with bronchitis among children	12.1	0	12.1	29.5	41.6
Work loss days	1.5	0	1.5	3.6	5.1
Restricted activity days	4343	0	4343	10633	14976
Minor restricted activity days	-2.7	-1.1	-3.8	-9.4	-13.2
Lung cancer	0.1	0	0.1	0.3	0.4
Infant mortality	0.0	0	0.0	0.0	0.0

For comparison, the table presents also the contribution from foreign countries (EU28 minus Denmark), and these results have been estimated from the most recent results that have previously been published in Ellermann et al. (2020). These results show that 29% of the health effects in Denmark can be attributed to Danish sources, whereas 71% of the health effects in Denmark arises from sources abroad. Finally, the overall health effects, calculated as a sum of the contribution from Danish and EU28 (minus Denmark) sources, is presented for the assumed scenario with heavy-duty trucks with malfunctioning SCR-systems.

Table 8.2 shows the total health related external costs arising from heavy-duty trucks with malfunctioning SCR-systems in Denmark and EU28 (minus Denmark). The local contribution from Danish sources is calculated within the present project with UBM and EVA. The regional contribution in Denmark from Danish sources is calculated based on a unit cost of 205 DKK / kg-NO_2, which has been calculated for SNAP07 in a previous project (Andersen et al., 2019). It has furthermore been assumed that the total emission of NOx related to heavy-duty trucks with malfunctioning SCR-systems is 1,290 tonnes per year in Denmark. The regional contribution from foreign sources to the external costs has been estimated from the share of the contribution from foreign sources to health effects relative to the total health effects in Denmark (Ellermann et al., 2020).

Table 8.2. Total external costs (million DKK) in Denmark from Danish and foreign sources related to heavy-duty trucks with malfunctioning SCR-systems.

External costs from heavy-duty trucks with malfunctioning SCR-catalysts (million DKK)	Nitrogen dioxide (NO_2)	Ozone (O_3)	Nitrate, ozone and nitrogen dioxide ($NO_3/O_3/NO_2$)	Sum
Regional contribution from foreign sources	-	-	898	898
Regional contribution from Danish sources	-	-	264	264
Local contribution from Danish sources	105	-3	-	102
Total (million DKK) per year				**1,265**

The total health effects from heavy-duty trucks with malfunctioning SCR-systems in Europe are estimated using the following approach. The total NOx emission in EU28 from SNAP7 is 2832.9 ktonnes-NO_2 for 2017. Out of this total, 954.6 ktonnes-NO_2 originate from heavy-duty trucks and busses (together for Europe labelled SNAP0703). We assume that 65% of the emission from the European SNAP0703 is related to heavy-duty trucks. We then assume that the SNAP0703 emission is 13.45% higher due to heavy-duty trucks with malfunctioning SCR-systems. The resulting emission from heavy-duty trucks with malfunctioning SCR-systems on a European scale is then 83.5 ktonnes-NO_2, which corresponds to approximately 3% of the total SNAP7 emissions in Europe.

In Brandt et al. (2013), the contribution from SNAP7 in Europe to the total health impacts in Europe has been calculated to 18%. The total number of premature deaths related to air pollution in EU28 is approximately 400,000 per year. From this, we can estimate that approximately 72,000 premature deaths in EU28 are related to SNAP7 emissions, and approximately 2,100 premature deaths (2.9%) are related to emissions from heavy-duty trucks with malfunctioning SCR-systems.

8.3 Conclusions concerning health impact related to malfunctioning SCR-system on heavy-duty trucks

Based on the results from the field campaigns, it was concluded that about 10% of the heavy-duty trucks have malfunctioning SCR-systems with six times higher emissions for Euro VI and two times higher emissions for Euro

V. These figures were then used to produce an updated emission inventory that account for the extra emission related to heavy-duty trucks with malfunctioning SCR-systems. As a crude assumption, the same figures were used for correcting emission from heavy-duty trucks in other European countries. The resulting emission from heavy-duty trucks with malfunctioning SCR-systems on a European scale is estimated to 83.5 ktonnes-NO_2, which corresponds to approximately 3% of the total SNAP7 emissions in Europe.

For determining impact on air pollution levels and associated health effects (and costs related to the latter), two sets of calculations were performed with the Urban Background Model (UBM) and the Economic Valuation of Air pollution (EVA) system both developed and applied by Department of Environmental Science, Aarhus University.

The calculations show that about 10 premature deaths in Denmark are related to emissions from heavy-duty trucks with malfunctioning SCR-systems. The total number of premature deaths related to air pollution in EU28 has previously been estimated to approximately 400,000 per year. From this, we have estimated that approximately 72,000 premature deaths in EU28 are related to road traffic emissions, and approximately 2,100 premature deaths (2.9%) are related to emissions from heavy-duty trucks with malfunctioning SCR-systems. Total external costs (million DKK) in Denmark from Danish and foreign sources related to heavy-duty trucks with malfunctioning SCR-systems have been estimated to 1,265 million DKK per year.

9 Method for routine control of SCR-systems on heavy-duty trucks using remote sensing

Ole Hertel, Christian Ingvardsen, Jacob Klenø Nøjgaard, Thomas Ellermann and Jesper Risager Nielsen

9.1 Choice of remote sensing device

The remote sensing device for a control system needs to be mobile and fast to setup and take down. The OPUS systems are more flexible compared to the alternative systems from EDAR that have a fixed setup and hence are more demanding to move around at the site and between sites. On basis of the analyses in this project *it is recommended to base the control method on remote sensing equipment from OPUS RSD*. Preferably the latest version (OPUS RSD 5000) that is next generation of the OPUS remote sensing device from the one used in the present project.

9.2 Threshold for selection of heavy-duty trucks

The choice of threshold concentration as criterion for selection of heavy-duty trucks for police roadside control makes a tremendous difference with respect to how many vehicles that potentially need to be inspected. A too low threshold will most likely be inefficient, since it is labour demanding to make roadside control for the police and the risk will be that too many well-functioning heavy-duty trucks is inspected thereby disturbing many drivers unnecessarily and wasting police resources. On the other hand, a too high threshold might have the consequence that too few heavy-duty trucks are inspected, and that the police control becomes inefficient with respect to catching the heavy-duty trucks with malfunctioning SCR-systems. Using 1,000 ppm NO as a criterion for control of Euro V heavy-duty trucks resulted in identification of 77% malfunctioning SCR-systems. *It is therefore suggested to use 1,000 ppm as criterion for Euro V heavy-duty trucks.* By use of 800 ppm NO as a criterion for control of Euro VI heavy-duty trucks resulted in no malfunctioning SCR-systems. The tests at the closed area showed that looking at the population of malfunctioning SCR-systems, the minimum emission was 330 ppm NO, which exceeds the highest emission of NO from well-functioning SCR-systems. Furthermore, the emission of NO from the 10% highest emitting Euro VI heavy-duty trucks during the campaigns at Padborg and the Great Belt Bridge actually corresponded to 330-2,408 ppm. *It is therefore* recommended to apply a flexible approach in connection with future routine controls, where the threshold is adjusted to the practical situation. A threshold of 1,000 ppm should be applied initially, but in case of vacant capacity in the police, heavy-duty trucks with emissions beyond 660 ppm are selected. Finally, it is important to gather experience from performed routine controls and evaluate the threshold concentrations on basis of this.

9.3 Number and extent of campaigns

It is suggested to perform control randomly throughout the year in all seasons and at any time of day. It is important that there is no periods where it is commonly known never to be controls on the Danish road network with malfunctioning SCR-systems. Experience show, however, that it is not possible to carry out controls during rain, snow and fog. *It is suggested to carry out four to* *eight campaigns per year of one to two days duration, however the final extent of the controls has to be decided by the authorities.* The experience from the field campaigns show that care has to be taken in order to perform measurements on both heavy-duty trucks and passenger car in the same measuring setup due to issues concerning camera angles etc. Furthermore, combining measurements of emissions with roadside control of heavy-duty trucks involve an additional location, where the actual inspections could take place. It is a requirement that there is a certain distance between the measurement location and the site of inspection in order to be able to take the heavy-duty trucks in for a roadside control by the police.

9.4 Selection of sites

The experience from the current project shows that it is crucial that the engines and the catalysts of the heavy-duty trucks are sufficiently warm for the SCR-systems to work properly. The measurements need to be carried out on single lane road to avoid influence from emissions from traffic in neighbouring lanes. Moreover, the instruments do not allow more than one traffic lane between the detector module and mirrors. The sites need therefore to be placed close to highways to ensure warm engines and catalysts on the heavy-duty trucks and on road segments that are somewhat separated from other lanes and roads. The field campaigns revealed furthermore that it takes time to establish experience about the site and find the optimal setup and that the setup often need to be modified several times during a campaign. In the selection of sites, it is recommended to take into account prevailing wind directions when evaluating potential influence from traffic emissions on other lanes and roads surrounding the site. Another experience from the field campaigns in this project is that drivers are highly aware of activities nearby the road, and cameras, equipment and personnel shall preferable not be visible before the measurements have been taken. This can be achieved in different ways, and have in the field campaigns in this project included use of tents. *It is suggested to select eight to ten sites distributed over Denmark to ensure that all parts of the main road network is included.* However, it is recommended to alter between sites and time for campaigns and to consider adding new sites over the years, in order to avoid predictability of where and when campaigns will take place. *It is furthermore recommended to document experience from these sites to ensure that future campaigns take advantage of experience from previous campaigns at these sites. Finally, it is suggested to initiate the control at Padborg and the Great Belt Bridge where experience already have been gained on the best suitable set-up.*

9.5 Resources and qualifications to operate the system

Operating the system demands as a minimum two persons at the remote sensing device and two persons for the manual control. It is recommended to run intensive training courses every four years, and short upgrade courses every second year, to educate the necessary staff in operating the remote sensing devices and the roadside control. It is recommended that as a minimum six persons are educated to operate the remote sensing device and six people to handle the manual control. It is assumed that new techniques and devices to alter SCR-systems may enter the market over the years. It is therefore recommended to organise workshops including researchers and people with practical experience concerning new devices and techniques in this area to exchange knowledge.

9.6 Data handling

Emissions from traffic on the Danish road network are derived every year by DCE at Aarhus University on basis of emission factors. These emission inventories are based on emission factors from national and especially international laboratory tests of vehicles on a stand running through driving cycles. Information from these tests are combined with information about the vehicle fleet, petrol sales, and traffic data on road network etc. Data from the remote sensing campaigns could serve as a valuable supplement to the work with these inventories, and *it is recommended to investigate the possibilities for creating a database* with measurement data for this purpose. In this context, it is naturally necessary to handle issues around anonymization and necessary protection of personal data etc.

9.7 Regular evaluations

It will be costly to carry out effective routine controls combined with roadside control. It is therefore suggested to make regular evaluations of the results from the controls. This includes also exploiting the many data collected in order to examine whether the controls lead to a reduction on the number of malfunctioning heavy-duty trucks driving in Denmark.

9.8 Costs

The costs of a program dedicated for quantification of NO emissions from vehicles in Denmark is highly dependent on the actual setup. Different setups might be required for passenger cars and heavy-duty trucks and an additional site is required for roadside control of the latter, when these are relevant.

For field campaigns involving both the police and measurement staff, there will be a need for a team of two operators of the measurement equipment. The resources needed from the police have to be decided by the police but a guesstimate will be that two to four police officers is needed for the manual road site control. In addition comes education of staff in four days for a basic and two days for an upgrade course. In order to make the campaigns work smoothly over a longer time horizon, additional staff should be educated using on-site training.

Data evaluation is divided into preliminary data evaluation, and a merge of this data with information in the Central Motor Data Registry and police inspections.

The establishment of a database containing data from the coming project with the measurements of NO emissions from driving vehicle fleet should be considered, and in this case, associated running costs need to be included.

Costs related to purchase or leasing of instrumentation, logistics related to campaigns and housing for equipment and staff need also be included. Alternative to a housing, equipment might be stored in a van dedicated to the purpose.

Currently it is hard to estimate actual total costs for an effective control system running over the years. NEQ has crudely estimated the total costs to between five and ten million DKK per year.

10 References

Andersen, M. S., L. M. Frohn Rasmussen og J. Brandt, 2019. Miljøøkonomiske beregningspriser for emissioner 3.0. Notat fra DCE - Nationalt Center for Miljø og Energi. Dato: 14. marts 2019. pp. 22. Institut for Miljøvidenskab, Aarhus Universitet. http://dce.au.dk/fileadmin/dce.au.dk/Udgivelser/Notater_2019/Miljoeoekonomiske_beregningspriser_for_emissioner.pdf

Brandt, J., J. D. Silver, J. H. Christensen, M. S. Andersen, J. Bønløkke, T. Sigsgaard, C. Geels, A. Gross, A. B. Hansen, K. M. Hansen, G. B. Hedegaard, E. Kaas and L. M. Frohn, 2013: "Contribution from the ten major emission sectors in Europe to the Health-Cost Externalities of Air Pollution using the EVA Model System – an integrated modelling approach". *Atmospheric Chemistry and Physics*, Vol. 13, pp. 7725-7746, 2013. www.atmos-chem-phys.net/13/7725/2013/, doi:10.5194/acp-13-7725-2013.

Ellermann, T., Nygaard, J., Nøjgaard, J.K., Nordstrøm, C., Brandt, J., Christensen, J., Ketzel, M., Massling, A., Bossi, R., Frohn, L.M., Geels, C. & Jensen, S.S. 2020. The Danish Air Quality Monitoring Programme. Annual Summary for 2018. Aarhus University, DCE – Danish Centre for Environment and Energy, 83 pp. Scientific Report from DCE – Danish Centre for Environment and Energy No. 218. http://dce2.au.dk/pub/SR360.pdf

Ellermann, T., Hertel, O., Winther, M., Nielsen, J.R., and Ingvardsen, C.R., 2018. Measurements of cheating with SCR-systems on heavy-duty trucks. Report No 2021 in the Series Environmental Reports from the Danish Environmental Protection Agency, June 2018. https://www2.mst.dk/Udgiv/publications/2018/06/978-87-93710-42-9.pdf

Sjödin, Åke, Martin Jerksjö, Henrik Fallgren, Håkan Salberg, Rasmus Parsmo, Cecilia Hult, Mohammad-Reza Yahya, Tomas Wisell, Jenny Lindén, 2017. On-Road Emission Performance of Late Model Diesel and Petrol Vehicles as Measured by Remote Sensing Report number B2281 SBN 978-91-88319-70-8. IVL Swedish Environmental Research Institute 2017

11 Appendix for Chapter 7

Christian Rud Ingvardsen and Jesper Risager Nielsen

11.1 Description of tests and test sites in closed areas

In this chapter the test sites are described in more detail. In addition, detailed information is provided about activities on specific test days.

The first four test sites were all closed areas connected with TJW Freight, Scania Denmark A/S, Volvo Trucks and Mercedes Trucks workshops, respectively. These parties provided heavy-duty trucks, mechanics and facilities to carry out the required tests.

11.1.1 Pre-test of Euro V heavy-duty truck in Karlslunde on 17.09.2019

We performed the first pre-test at TJW Freight on Silovej in Karlslunde. The test was carried out on a Volvo heavy-duty truck with Euro V engine and it took place in the parking lot of the shipping company area. There were no optimal conditions as the heavy-duty truck had to turn sharply to the right immediately after the measuring equipment and thus the driver had to slow down immediately after the measurement, which is not optimal. The conclusion was that in the upcoming tests there should be a lane where the heavy-duty trucks could continue their acceleration through the measuring range. Partly to get usable data, and partly to replicate a measurement setup on the roads. Unfortunately, data from the test could not be validated according to the applicable standards as the calibration gas could not be connected to the equipment.

Figure 11.1. Test of Euro V at TJW Freight in Karslunde.

However, it was possible to see the variations in the emission of NOx and the test was therefore still interesting for the project as we tested different setups in relation to different driving patterns.

We started by measuring on a heavy-duty truck with cold engine and catalytic converter to later send the truck out on the highway to obtain a hot engine and catalytic converter. When the truck subsequently returned, we found that the SCR-systems did not add AdBlue to the exhaust. The system was malfunctioning without this causing any problems for the heavy-duty truck itself.

It would later prove to be a general problem to find a Euro V heavy-duty truck with a working SCR-system despite several tests with this type of engine.

11.1.2 Testing at Scania in Ishøj on 18.09.2019

The test performed at Scania in Ishøj took place at the back of their workshop. There is a roadway of over 100 meters where the heavy-duty trucks could pass the measuring equipment at varying speeds and with varying acceleration. During the day we achieved speeds in excess of 50 km / h. Furthermore, the proximity to the workshop meant that it was easy to make the desired adjustments on the heavy-duty truck. The truck was driven by Morten Voss, service technician at Scania Trucks.

Figure 11.2. Test site at Scania in Ishøj and Scania Euro V heavy-duty trucks with high exhaust pipe.

Scania made both a heavy-duty truck with Euro V and Euro VI engine available. We were informed in advance that the Euro V truck had an error on the SCR-system but that Scania would try to rectify this error during the measurements. Unfortunately, it was found that the truck with Euro V engine was equipped with high exhaust exit, which means that the exhaust exits above the cab. This meant that it was not possible to measure the emissions from this truck regardless of the state of the SCR-system and we then concentrated on the heavy-duty truck with Euro VI engine.

We started with measurements of the heavy-duty truck with cold engine. The truck made several runs through the measuring equipment and these showed a discharge of NOx that was clearly above what was expected for a heavy-duty truck with an active SCR-system. After that, the truck was driven to operating temperature with a trailer behind it. It took approx. 15 minutes to drive the truck hot enough that the catalyst reached a temperature of 250 degrees Celsius. This is necessary if the truck's management system is to activate the SCR-system and thus add AdBlue to the exhaust and thus reduce the emission of NOx.

During runs of the measuring equipment with hot engine and catalytic converter, there was a slight reduction of NOx, but not a reduction that met our expectations of the NOx values of a well-functioning SCR-system with the supply of AdBlue for the exhaust. The truck's management system reported an active SCR-system, but it is doubtful whether AdBlue was added to the system. With the help of Scania, we were able to get a print of the data produced by the management system of the truck. However, the quality of these data is not adequate to explain the differences we were seeing at the measurements.

Another explanation might be that, despite driving the truck for over 15 minutes, the catalyst had not reached a sufficiently high temperature for the system to supply AdBlue. This is an important insight into the operation of the SCR, and especially in relation to police control heavy-duty trucks It is not yet sufficiently clear how long a truck should have driven and under what circumstances (speeds, cargo, obstacles in the form of traffic lights or other traffic etc.) the truck has driven before the SCR-system starts and stops the supply of AdBlue to exhaust. This insight later became valuable through the checks carried out with the police on the roads. We made further measurements on the same truck five days later and here there was a clear reduction of the NO gases in the measurements.

Runs with different speeds and accelerations were performed and this did not affect emissions. Also, Scania made a fully loaded trailer available to increase the load on the truck. However, this did not affect the measured data.

As previously described, the purchased emulators turned out not to fit a Euro VI engine, so we, in collaboration with Scania's technicians, chose to do another form of manipulation of the SCR-system. We removed the fuse on the truck that checks the signal for the SCR-system. Thus, by removing this fuse, the SCR-system was deactivated regardless of the catalyst temperature. The subsequent measurements gave the same result as when running with cold catalyst, which was a clear indication of the effect of AdBlue in relation to NOx emissions.

In the last tests with the dismantled particle filter, no significant changes in the emission of particles from the truck were measured. On the other hand, we noticed an interesting difference in the emission of NO at respectively full load of the engine and partial load of the engine. Contrary to what was immediately expected, NOx emissions decreased at full load compared to partial load engine operation. Several different possible explanations for these results were discussed but no conclusion could be drawn based on the tests performed.

It became clear already after this test that the general knowledge about how the SCR-system works and about the relationship between different driving patterns as well as temperatures of respectively engine and catalyst are very limited. Although we performed measurements in collaboration with workshops that should have the most comprehensive knowledge in the field, it is clear that this area remains fairly undescribed. Throughout the entire project, new theories and conjectures have been constantly emerging, which we have subsequently tried to prove through measurements on primarily heavy-duty trucks. However, there is a basis for far more in-depth studies in this area, which would likely give a clearer understanding of how these systems work on trucks, especially the advanced Euro VI engines.

In relation to the need for a calibration of the equipment during the day, this test day showed that one calibration is possible. A calibration was performed during the day, but this was to train NEQ's technicians to perform the calibration and not because there was a technical need.

11.1.3 Testing at Volvo in Taastrup on 19.09.2019

The test at Volvo in Taastrup took place at the back of their workshop, where there is a distance of over 100 meters, where the heavy-duty trucks could reach acceptable speeds of up to 35 km/hr and continue the acceleration through the measuring range. Volvo made a truck with Euro VI engine available which was driven by Niels Lykkestrøm, Product Quality Engineer at Volvo trucks. TJW Freight later came with a Volvo heavy-duty truck with Euro V engine. TJW also brought a trailer that was filled with concrete blocks to put a greater load on the truck.

Figure 11.3. Test site at Volvo in Taastrup and exhaust pipe on a Volvo Euro VI heavy-duty trucks.

The actual installation of the measuring equipment was done this time by NEQ and this resulted in a few recalibrations, as the equipment was not completely level. The preliminary tests showed that the set-up and calibration of the equipment requires careful consideration of the selection of the measurement location and that the operator is constantly critical towards the equipment and measurements that is made.

The calibration of the equipment was further postponed due to the fact that an older truck was standing in the area and was idling. This was because some necessary tests had to be carried out on the truck so that it would run at idle for at least 10 minutes. As the exhaust from this truck drove over the measuring equipment, it was not possible to make a calibration as the test gas used was disturbed by these exhaust gases. This showed that the equipment is quite sensitive to the influence of other vehicles if they operate in the immediate vicinity of the measuring equipment. Compared to vehicle measurements on the roads, this is a minor problem, but it should be taken into account in the selection of measurement areas. In relation to the calibration of the equipment, this became important in both Padborg and the Great Belt

Bridge. Having obtained this experience from the test days, we were able to handle this as the measurements took place elsewhere.

The Volvo heavy-duty truck with Euro VI engine had an exhaust pipe sitting opposite the Scania heavy-duty truck tested the day before. As the truck was started to travel the route at different speeds and different acceleration, we could see that this did not affect the results. This was fully in line with expectations as the equipment transmits light rays across the roadway and returns via a mirror. Therefore, it should not matter if the exhaust pipe points one way or the other. The truck was initially tested with cold engine and cold catalyst. It was estimated that we could achieve satisfactory results with even short runs and at speeds above 20 km / hr. When the next truck with Euro V engine arrived from TJW Freight, after an inspection of the truck's operating system, we found that it was a heavy-duty truck that was upgraded to run with Euro VI software. In relation to the test, we therefore chose not to use this truck but to procure another Euro V heavy-duty truck. This was made available by Volvo but upon closer inspection it appeared that the SCR-system did not work on this truck. However, we chose to include this truck in the test as we wanted to see how high the emissions were from a Euro V heavy-duty truck when the SCR-system was not active. This corresponds to a manipulation of the SCR-system.

As with Scania the day before, in collaboration with Niels Lykkestrøm from Volvo and Martin Kristensen from the Traffic Police, we decided not to mount the purchased emulators but instead manipulate the SCR-system by removing the fuse that controls the system. Again, it was agreed that this would give the same result as the emulator assembly, though of course with the same reservations as at Scania.

Another significant observation can be seen in Table 12.1. The table shows measurements of NO values in ppm for a period of approx. half an hour. On the first four measurements, the SCR-system is active in relation to adding AdBlue to the exhaust, which gives a significant reduction in NO values compared to the subsequent measurements. If you look at the time of the measurements you can see that the change will happen very shortly. At the first measurement at 10:48:14 the engine and catalytic converter have just run warm and therefore AdBlue is supplied. In the actual test at Volvo the heavy-duty truck drove around the test area and therefore it was not possible to maintain the required temperature of the catalyst. This is clearly seen in the three measurements, where the values suddenly increase by a factor of ten. We could see from the diagnostic parameters from the truck that the supply of AdBlue had stopped at this point.

As seen from the last measurement from 11:16:33 the truck has a trailer mounted and has now been driven warm again. And now the NO value has dropped to an even lower level than before. This observation is crucial in relation to police control of heavy-duty trucks. If the trucks are allowed to stand for too long or drive around an area where it will not be possible to maintain the required temperatures, it will be difficult to assess whether the truck's SCR-system supplies AdBlue as expected. It has not been possible to obtain useful information on how fast the catalyst is losing temperature, but it will be interesting to investigate further if you want to make the police's efforts more effective in this area.

Table 11.1. Data from a series of test that illustrated how quickly the emission of NO can change due to changes in the temperature of the SCR.

Euronorm	Regn.no.	Load	SCR active	Trailer	Emulator	Particalfilter	VdfTime	ppmNO
6	CA93593		Yes	No	No	Yes	10:48:14	43,0439
6	CA93593		Yes	No	No	Yes	10:49:13	-4,1985998
6	CA93593		Yes	No	No	Yes	10:51:16	30,5781
6	CA93593		Yes	No	No	Yes	10:52:10	40,3853
6	CA93593		No	No	No	Yes	10:53:10	477,25049
6	CA93593		No	No	No	Yes	10:54:08	368,9938
6	CA93593		No	No	No	Yes	10:54:55	537,7757
6	CA93593		Yes	Yes	No	Yes	11:16:33	7,4654999

In conclusion, it was found that both test area and equipment worked as intended. After the initial challenges with the calibration, it was not necessary to calibrate the equipment and it can therefore be found once again that there is no need for more than one daily calibration if the conditions are otherwise optimal for carrying out the measurements.

11.1.4 Testing at Mercedes in Greve on 20.09.2019

The third test of trucks took place at Mercedes trucks in Greve. The area was, as in previous days, in connection with Mercedes' truck workshop and as we had learned from the experience of Volvo, a shorter distance was selected than the previous days, as this had proved sufficient.

Figure 11.4. Two photos from the test site at Mercedes Trucks in Greve.

Mercedes made two heavy-duty trucks available with Euro VI engine, which was a good opportunity to have two identical trucks tested against each other. Mercedes also provided two fully loaded trailers as well as two drivers, one of which was Morten Østergaard-Hansen, technical specialist on Mercedes trucks. The other driver was an experienced Mercedes technician.

At Mercedes, we started by driving both trucks warm by mounting a trailer and then letting the trucks run for 15 - 20 minutes out on the nearby highway. Thus the engine was warmed up when the measuring equipment was set up and calibrated and the measurements then also showed a very low emission of NOx gases. Inside the test area, the trucks drove around the workshop and back to the measuring area. This meant that just like the previous day, there was a cooling of the engine and catalyst. Similar to the measurements the day before at Volvo, we could observe that the values of NOx gases suddenly increased and after consulting the drivers we were able to find that the supply of AdBlue had been shut off for the exhaust. Figure 11.5 shows the development over four measurements on the same Mercedes truck.

In approx. four minutes, the emission of NOx increases from 6 to 496 ppm; an increase of a factor of 83 in such a short time. The immediate explanation is that the catalyst drops in temperature and thus shuts off the supply of AdBlue supply, but it is important to emphasize that there may be other strategies for the SCR-system that may have an effect on the injection.

Figure 11.5. For pictures documenting the sharp increase in emissions of NO as a consequence of a drop in the temperature of the SCR and hence stop of the AdBlue supply. The emission of NO increased from 6 ppm (upper left corner) to 496 ppm (lower right) corner within four minutes.

The Euro VI heavy-duty trucks underwent all the described scenarios with the same modification regarding the emulators as in previous days. Since the replacement of particle filters on the tested trucks was a very difficult process, a third truck was chosen for the scenario of driving without a particle filter. The truck was tested both with and without particle filter and immediately there was a significant difference between the two measurements. However, whether this can be used as a parameter for police in selecting vehicles for control is questionable as during the test runs, significantly higher values for

PM were not measured on the trucks without particle filter compared to trucks driven with particle filter.

Finally, an opportunity arose to measure on a heavy-duty truck with Euro V engine. Prior to the test, the mechanic who drove one of the trucks expressed scepticism about the possibility of measuring on a well-functioning SCR-system as his experience was that many Euro V trucks had defects in this system and that maintenance of the system did not necessarily have a high priority at the owners.

Unfortunately, it turned out that the mechanic was right in his scepticism. Despite a longer trip on the road with the truck which provided a catalyst that should be sufficiently warm to activate the SCR-system, this was not the case. This was thus the 5th truck with Euro V engine which did not have a functioning SCR-system or which had a different control system.

During our measurements at Mercedes, we also measured other trucks to investigate variability between different types of trucks. As can be seen clearly in Figure 11.6, with the same set of measuring equipment we could take pictures of both trucks, vans and passenger cars with a clear view of the license plate. This proved that the equipment can handle several different types of vehicles. In the measurements that were later carried out in collaboration with the police and to collect larger amounts of data this was not an option and the consequences of course became a much smaller number of measurements than we first thought possible. A more detailed description of this problem will appear in the description of the measurements made on the Great Belt Bridge and in Padborg.

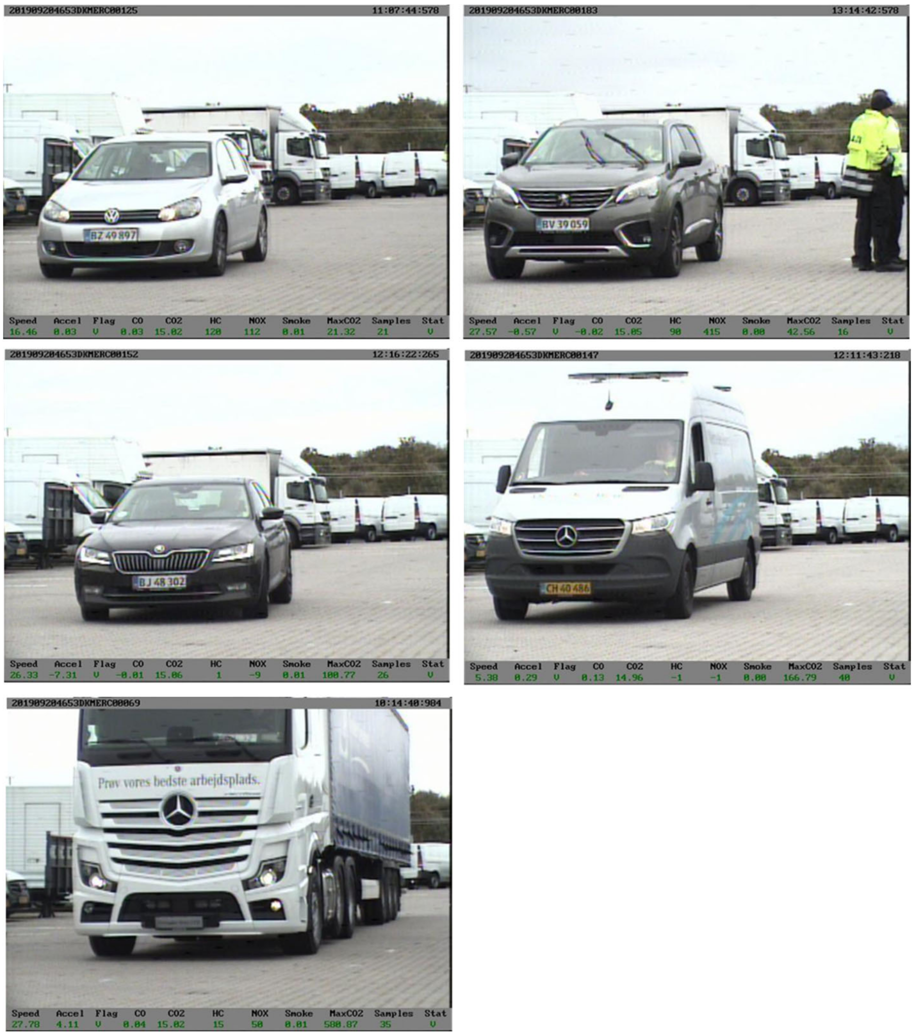


Figure 11.6. Pictures documenting that the camera is capable of taking pictures of the number plates of different vehicles types with sufficient quality in order to make automatic recognition of the number plates. The number plate of the Euro VI heavy-duty trucks was covered but the other test illustrate that it is possible to read the number plate.

11.1.5 Testing at Scania in Ishøj on 23.09.2019

Since on the first day at Scania, we had registered measurements that did not match our expectations in relation to the emission of NO. We therefore chose to take another day with measurements at Scania. On the first day, we furthermore became aware of a possible difference in emissions depending on load on the engine when passing through the measuring range.

We measured on the same heavy-duty truck with Euro VI engine as on the first day at Scania and on exactly the same route. However, for these tests we did not drive with a trailer, as this had proved to be of no significance to the emissions of NO. On this day, we obtained significantly smaller values for NO, when the truck was running warm. As for the measurements on the truck at different loads, the results did not give a clear answer as to whether this affects the emissions in a significant way. However, also this is an area that needs further investigation, if the police aim for optimizing their control efforts.

The measurements at Scania in Ishøj showed that even in the test runs there is a need for an experience that can only be obtained by performing more measurements. There are obviously some variables that are not well described in relation to the SCR-systems and how they handle the injection of AdBlue. There is no doubt that continuous work in this area will enable police to identify heavy-duty trucks that tamper with the SCR-system far more accurately than is currently the case.

11.1.6 Testing at Christonik in Ishøj on 23.09.2019

As described above, it was very difficult to find a Euro V heavy-duty truck with a well-functioning SCR-system. One of the challenges was that our partners did not have these types of vehicles in the workshop very often. And many Danish shipping companies driving long distances have already replaced these vehicles with newer versions with Euro VI engines.

TJW freight could, however, make available a Euro V truck which was measured at Christonik, Industrigrenen 21 in Ishøj. The measurement area was similar to the other areas a stretch behind an industrial building where the truck could reach the desired speeds.

After several measurements and driving on the highway, we once again found that the SCR-system did not work. Unfortunately, this was the last opportunity to test a Euro V engine with a well-functioning SCR-system with Remote Sensing equipped, so we chose to try another Euro V engine test drive, but this time without RSD measurements.

11.1.7 Testing at Volvo Trucks in Aarhus on 19.12.2019

Finally, and as a supplement we drove a Volvo truck with Euro V engine at Volvo in Aarhus. In this last test we did not have RSD equipment available but looked solely at data from the diagnostic equipment that was connected to the truck's engine management system.

At the end of December, Volvo was able to make a heavy-duty truck with Euro V engine available in Aarhus. Sune Elkjær arranged a tour with a Volvo technician who brought original diagnostic equipment. As in the case of Scania, we could see that the data from the diagnostics is very complex and difficult to interpret in relation to the strategy for injecting AdBlue. However, we found that the sensors measured values between 0 and just below 1,000 ppm for the NOx while the SCR-system was active. The emission of NOx on this truck was obviously affected by both driving pattern, engine load, EGR activation, SCR-system strategy etc. Our assessment is that if you want more clarity on how to utilize the vehicle's own diagnostics, you should initiate a separate project for this which includes synchronous measurements of the exhaust with remote sensing and the readings from the vehicles engine management while driving. In relation to this project, it can be noted that NOx values above 1,000 ppm should raise suspicion of a malfunctioning SCR-system.

12 Appendix for Chapter 8

Christian Rud Ingvardsen and Jesper Risager Nielsen

12.1 Objective of the measurement campaigns

The main purpose of the measurements in the closed areas was in collaboration with the Danish Police to develop a procedure by which heavy-duty trucks with malfunctioning SCR-systems can be identified. In this context, a malfunctioning SCR-system can be manipulated deliberately or having technical errors. Replicate emission measurements on different suppliers of heavy-duty trucks, Euro norm, engine load etc. were conducted with well-functioning and malfunctioning SCR-systems as well as particle filters. The resulting data provided valuable insight about the range of NO emissions from well-functioning and malfunctioning SCR-systems, particle filters as well as other parameters influencing emissions. The police were represented during the initial tests (section 7.2) of the equipment and showed a good understanding of the setup procedure and how to carry out the measurements on location.

During the measurement campaigns at Padborg and the Great Belt Bridge, the experience obtained from the test fields was applied at authentic locations under realistic conditions, which provided measurements of sufficient quality from a total of 2,942 heavy-duty trucks and 3,306 passenger cars. The objective of these campaigns was to estimate the fraction of heavy-duty trucks with a malfunctioning SCR-system. This estimate is subsequently extrapolated to the entire country in order to estimate the extra emissions of NO from malfunction of the SCR on a national level and estimate the impact of this extra emission on air pollution levels and associated health effects (Chapter 8).

At the same time, the emissions of PM from heavy-duty trucks were measured and together with NO and PM emissions from a relatively large number of passenger cars. The measurements provided important new knowledge on the present status of the Danish vehicle fleet with respect to NO and PM emissions.

12.2 Description of measurement campaigns and measurement sites

Chapter 7.2 - 7.6 gives a description of the measurement campaigns and describes the activities and test that were carried out during these.

The original plan for the project was to select three to five sites for the measurement campaigns. However, after consultancy with the police, the number of measurement sites was narrowed down to two: at the Danish-German border at Padborg, and at the toll booth at the Great Belt Bridge in a westbound direction. The originally scheduled two weeks of measurement campaigns at these sites, had at the Great Belt Bridge to be reduced to only 6 days due to roadwork. Thus, the remaining days were spent at Padborg where the campaign was extended accordingly. Initially, NEQ was responsible for the measurements, but for technical reasons it became necessary to request assistance from RSE.

The westbound direction at the Great Belt Bridge was chosen, because measurements on heavy-duty trucks traveling eastbound would disrupt traffic unnecessarily. The sites were constructed in a way, which imposed a natural pause in traffic, where the measurements took place. Thus, the police had sufficient time to select vehicles for roadside control without building up a long queue. Following, passing vehicles had to accelerate to continue their journey, and measurements were conducted without bothering the traffic.

It was assumed that the heavy-duty trucks of interest were sufficiently abundant at these two locations. More than 5,000 vehicles were expected to pass the locations daily. However, an upper limit of only 3,000 vehicles were registered from nine am to five pm on campaign days. The campaign days were grouped into two categories: those performed on days when the police was present to manually inspect heavy-duty trucks based on NOx emission measurements, and those which focused on measuring as many vehicles as possible, though with emphasis on heavy-duty trucks. In the former category, the focus was in close cooperation with the police to establish a method for detecting heavy-duty trucks with malfunctioning SCR-systems and without focus on the number of vehicles passing. This is reflected in the measurements at the Great Belt Bridge from 01.10.2019 – 03.10.2019, where we selected a lane with a high proportion of foreign heavy-duty trucks, but measured on only few vehicles passing in terms of total number. Based on test measurements, we expected to be able to measure all types of vehicles, but in practice this was not possible. We therefore focused on heavy-duty trucks and used the same instrument setup during the measurements with the police. The implication was a reduction in the total number of measurements.

As a starting point, we wanted to automate the process of identifying the heavy-duty trucks selected for roadside control. Based on our experience with well-functioning and malfunctioning SCR-systems at the closed areas, and after having reviewed the procedure with the police on location, however, we realized that this procedure was neither possible nor desirable. Communication between the operator of the measurement equipment and the police had to be fast.

Figure 12.1. Example of the measurement setup in collaboration with Danish Police. The camera is hidden in a tent behind the dark car.

Therefore, there was not sufficient time for the systems to identify Euro norm of the measured vehicle, and for this reason it was done manually. In practice, communication by radio or telephone worked fine.

From the experience learned during the previous project on remote sensing and in other projects in Europe, there was expected an overweight of foreign

European heavy-duty trucks with high emissions of NO indicating a malfunctioning SCR-system. Since we do not have access to information about foreign vehicles in our databases, these vehicles had to be manually inspected. However, measurements at the Great Belt Bridge and at Padborg confirmed this assumption. Measurement data revealed that the majority of heavy-duty trucks passing was Euro norm V or VI. We chose the same threshold concentrations of NO as criteria for police roadside control of both Euro norms.

12.2.1 Padborg 24.09.2019

The measurements started at the border crossing in Padborg on Tuesday 24.09.2019 immediately after the completion of the initial tests in the Copenhagen area. Already on the first day of measurement, it was planned for the police to participate with a number of officers who could take heavy-duty trucks in for inspection.

The measuring equipment was set up immediately after the border check on a section of road where the vehicles had to turn briefly to the left and then straighten to continue on the highway. This would lead to a minor acceleration and the speed would not be too fast. As described below, it was not possible to store data from this day, but we estimate that the heavy-duty trucks were driving 10 - 20 km / h on the selected route. We concluded on the basis of the test measurements and driving patterns that the site was suitable for measurements.

The police chose to inspect the selected heavy-duty trucks immediately after the survey was completed. This might have caused some anxiety in the area and may also affected the chauffeurs' driving pattern. As the measurements continued with the police in Padborg on 26.09.2019, this procedure was changed. Accordingly, the police selected heavy-duty trucks for control on the highway and then guided them into the police control area.

Figure 12.2. Measurement site at Padborg 24.09 2019. The measurement van can be seen on the right site of the read heavy-duty truck.

Unlike the test measurements, the measurements on location were hampered this day by technical issues with the instrumentation. There were problems with calibrations and communication with the camera. The measurements started at 10 am and heavy-duty trucks were quickly identified, which seemed suspicious based on an increased emission of NO. Initially a threshold concentration of 1,000 ppm was applied. Tentatively, the threshold concentration was reduced to 800 ppm later on, but only in a short period of time since no malfunctioning SCR-systems were identified at this concentration. During the first part of the day, measurements of NO emissions agreed with findings from the roadside control by the police. On the contrary, the remaining part of the day gave nothing but frustrations due to lack of correlation between measurements and what was observed at roadside control.

However, the police managed to select 14 heavy-duty trucks based on the selection criteria of which five had malfunctioning SCR and nine were ok. The time of control was not noted, for which reason it is not possible check whether the malfunctioning SCR-systems were selected in the morning or in the afternoon. However, according to police they were most likely detected during the morning.

The primary result of these measurements was to establish a contact between the measuring equipment operator and the police. During the day it was decided that the operator should provide information about VDF number (VDF number is the unique number for the measurement in the measuring equipment), colour of the heavy-duty truck, brand, NO emission on the measurement and information about S/F factor (Smoke factor, which is a parameter for the emissions of particles). Subsequently, the VDF number would act as a key to data so that the measurements could be linked to police reports.

Due to the problems with the measuring equipment, it was also not possible to store the measurements for this day, and therefore it was not possible to link the measured data with the police reports. Therefore, it was also not possible either to use this data to determine whether there was any measurable explanation for the good results in the morning and the poor results in the afternoon.

There was some concern that speed and acceleration might not be sufficient at the specific destination. For this reason, it was decided in collaboration with the police to move the equipment for the following days. It was also discussed whether the setup was too visible for the drivers, resulting in changed driving pattern that might affect the results. Finally, a new set of equipment was ordered for delivery the next day, since applied equipment did not work as expected.

12.3 Padborg 25.09.2019

The new measuring equipment arrived at noon and was completely installed at 3 pm. In about two hours, 501 vehicles were measured of which 218 were heavy-duty trucks.

When the police was not present, various arrangements of the equipment were used instead. Instead of standing at the border checkpoint, the equipment was moved further away so that the cars were now measured on a straight line. The measuring equipment and camera were still visible to the drivers of the vehicles but speed and acceleration were increased.

Figure 12.3. The measurement site at Padborg on 25.09.2019

Figure 12.4. Photos from 25.09.2019 of passenger car (left) and heavy-duty trucks (right) prior to adjustment of the camera angel.

Figure 12.5. Photos from 25.09.2019 of passenger car (left) and heavy-duty trucks (right) after adjustment of the camera angel.

At the same time, it was tested how the camera could take the best possible pictures when measuring both heavy-duty trucks and passenger cars. As can be seen from the following, with this setup it was still possible to take usable pictures of both types of vehicles, although there was a challenge with heavy-duty trucks that were too far away from the camera. Consequently, part of the license plate was not visible and therefore a new set up was tested, to make the license plates visible. Implications were wider angles of the camera and this subsequently caused a poorer quality of the images of passenger cars. It was decided to test these setups in the following days, but as will be seen, this was not possible as a visible camera was concluded to have a disruptive effect on the heavy-duty truck's driving pattern.

12.3.1 Padborg 26.09.2019

The police participated from early morning, and a setup identical to the day before was established. However, the camera was now hidden behind a passenger car. As a result, the heavy-duty trucks accelerated faster yielding a more natural driving pattern. Usable images of both heavy-duty trucks and passenger cars also benefitted from this modification. However, since one of the primary priorities of the project was to develop a new method for screening and control of vehicles by the police, we chose to keep the new set-up for the remaining measurement period in Padborg.

The various arrangements of the measurement equipment gave a negative result. Thus, it was impossible to detect a correlation between controls and measurements in the first half of the day while there was good correlation in the latter part of the day. This, of course, caused some frustration on the parties involved, but the explanation was possibly the change in equipment setup.

Despite the above, eight heavy-duty trucks were selected for control, of which seven were selected based on the measurements. Out of the seven, two were ok, whereas one was a model without SCR-system. Another two SCR-systems were malfunctioning and the remaining two featured an engineered SCR-system, including one, which was software manipulated.

Figure 12.6. Measurement site at Padborg 26.09.2019

Despite the above results, NEQ, in collaboration with the police, chose to take the equipment back to the NEQ site in Ishøj to review the equipment again. At the same time, it was decided to get assistance from specialists at RSE (Remote Sensing Europe), who assisted NEQ during the previous tests.

12.4 Conclusion after the first week of measurements with the Danish Police

After the first week of measurements, we found that there were challenges in measuring on authentic locations compared to the test facilities in closed areas under controlled conditions. In addition to the technical problems with the equipment itself, it was clear that cooperation between the operator of the equipment and the police was a challenge that could be improved. In addition, the experience of the operators was still limited and therefore it required an evaluation of this process in order for the future measurements to yield better results.

At the same time, it was clear that despite the tests, there was still some lack of knowledge about the vehicles' control of AdBlue supply and thus the reduction of NO emissions. In addition, in the past week it was not possible to comment on possible limit values for the emission of particles as these figures did not give clear indications of the manipulations of the heavy-duty trucks. The lack of knowledge gave rise to many different theories about the mode of operation and thus also some uncertainty about the connection between the measurements and the reasons for this on the heavy-duty trucks themselves.

In relation to the actual installation of the equipment and the police set-up of officers in the immediate vicinity of the measuring equipment, many improvements had been found. The position of the camera, the position of the measuring equipment, the visibility of the operator as well as the visibility of the police were all factors that seemed to have a negative impact on the driving, because, among other things, speed changes of the heavy-duty trucks. At the same time, there will of course always be some variation in identifying malfunctioning SCR-systems resulting from the fact that different staff members in the police are performing the controls.

12.4.1 Great Belt Bridge 30.09.2019

Prior to the measurements 30.09.2019, NEQ and the RSE specialist tested the equipment 27.09.2019 and 29.09.2019. The conclusion was that the calibration could be somewhat improved, but overall the equipment worked as expected. In order to optimize the efforts with the police, NEQ chose to use the specialist from RSE during the first 3 days of the campaign on the Great Belt. Also, project manager Christian Rud Ingvardsen became a permanent operator of the equipment until all parties had confidence in the measurements again.

From 30.09.2019, NEQ initiated measurements on the Great Belt. Based on the experience of the first week's measurements in Padborg, the police chose not to arrive until the equipment and set-up had been tested by NEQ at the payment facility in a westbound direction on the Great Belt Bridge. The first day was allocated to setup and testing. Basically, we wanted to measure in the lanes, where most heavy-duty trucks were passing. According to the control room on the Great Belt Bridge, this was track 2 and 3 which are equipped with Brobizz.

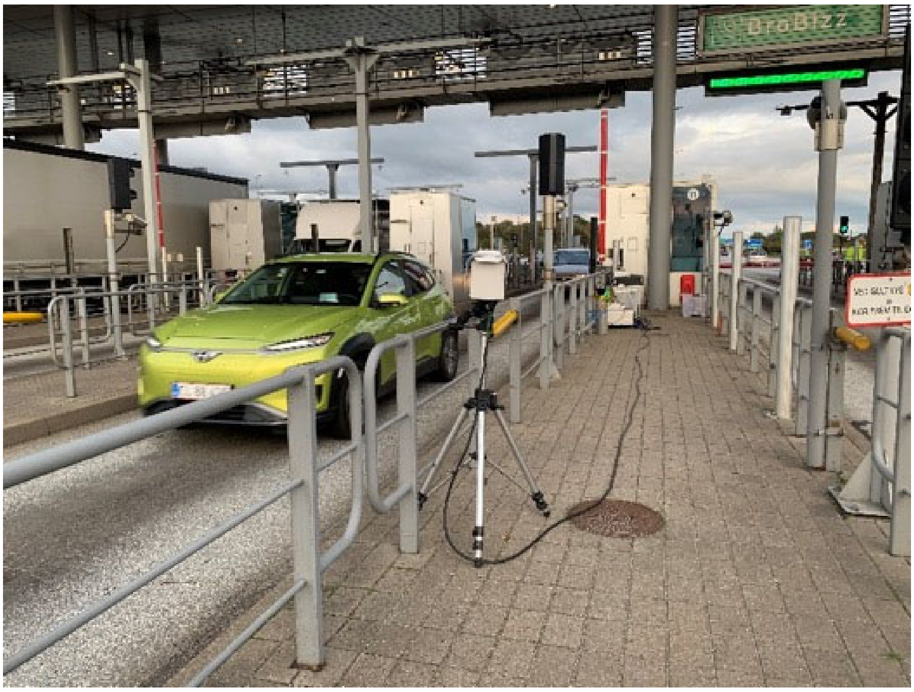


Figure 12.7. Instrument setup at Great Belt Bridge, lane 2 with camera in close position to passing vehicles.

The equipment was setup in track 2 after several tests of the equipment. Due to safety precautions, the equipment could only be placed in restricted areas making it difficult to position the camera optimally. At the same time, the areas between the tracks are restricted to ensure that no staff enters to lanes by mistake. The vehicles passing these tracks can have a speed of up to 60 km / h. At locations where the camera could be placed in the confined areas, it was actually an advantage due to the shelter from the roof. It will enable any future measurements even in rainy weather. However, in case of heavy rain, it will still be doubtful whether a satisfactory result can be obtained, regardless of whether the area is covered, as rain from the roadway in this case can disturb the signals from the measuring equipment.

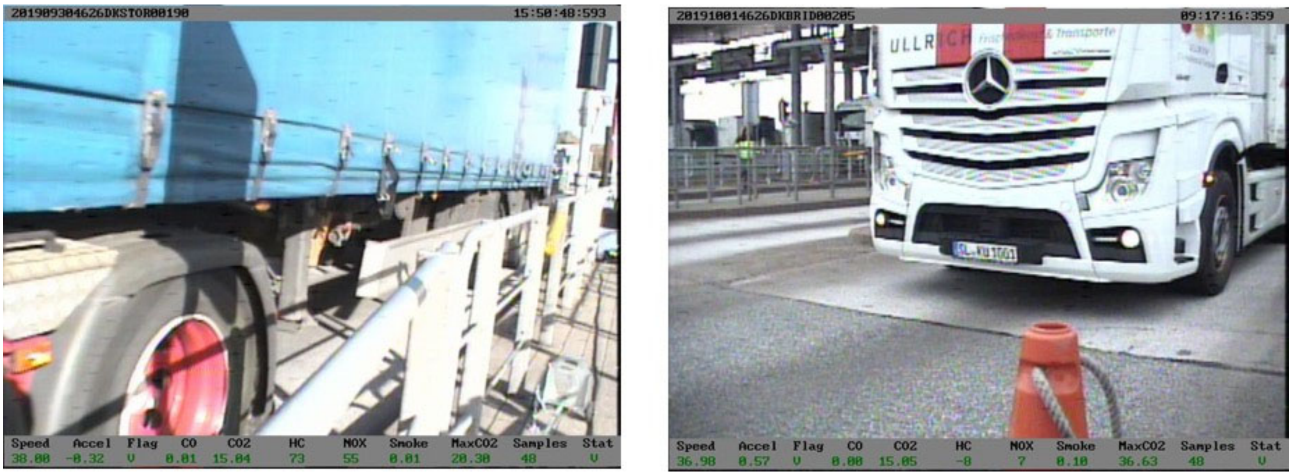


Figure 12.8. Pictures of heavy-duty trucks at the Great Belt Bridge, lane 2 with camera located inside the safety area (left) and outside the safety area (right).

The experience from the different setups indicated a need for placing the camera outside the screened area, in order to obtain actionable photos of heavy-duty trucks. This required a separate permit from the Great Belt. For space reasons, we ended up with a set up that provided photos of heavy-duty trucks but not of cars due to the angle of the camera.

Compared to the measurements in Padborg, the heavy-duty trucks came at a significantly higher speed and therefore the camera had to be positioned further away in relation to the measuring equipment itself.

As can be seen from the pictures above, it was necessary to set up the camera outside the security areas where the staff of the Great Belt normally operates. In order not to bother the traffic, it was necessary to angle the camera in such a way that it could only take pictures of heavy-duty trucks and not of cars.

The police did not attend that day, and we measured 511 vehicles, including 69 heavy-duty trucks. However, due to the various tests of arrangements, these measurements were not useful.

12.4.2 Great Belt Bridge 01.10.2019

We installed the equipment in lane two and the police installed themselves on the other side of the bridge where heavy-duty trucks could be selected for police control. Based on previous tests as well as measurements at Padborg, the criterion for police control was 1,000 ppm NO. Less attention was payed to particles (PM), but it was decided to note particularly high PM concentrations during measurements.

The fact that lane two is intended for Brobizz, discriminates the nationality of the vehicles to primarily Danish ones. It was realized, that actually more heavy-duty trucks were passing lane three, which had access to a payment facility. Only few vehicles met the criterion for police control. In total, we measured 1,245 vehicles, of which 64 were heavy-duty trucks.

During the measurements 01.10.2019, we communicated with the police about this problem, and discussed how this challenge could be solved. The police were pleased with their location, as it was far away from the measuring area, and thus did not lead to unnecessary and unwanted attention from the drivers. At the same time, they had very good opportunities to inspect several heavy-duty trucks at the same pull-up, which provided a unique opportunity to exchange experience between the officers. The challenge was to identify tracks with most foreign heavy-duty trucks.

Upon closer examination, mainly foreign-registered heavy-duty trucks were passing lanes six to nine. This was because these lanes have only manual payment and not Brobizz. We therefore explored the possibility of switching to measuring in these lanes. The staff at Great Belt Bridge was simultaneously testing new equipment for automatic license plate registration. We could therefore only obtain such a permit, if we could guarantee to be able to pack the equipment down within less than 10 minutes. This is possible, and we therefore started measuring in these lanes the following days. On this day, the police selected one heavy-duty truck for control featuring a manipulated SCR-system.

12.4.3 Great Belt Bridge 02.10.2019

In lanes six to nine, we measured significantly more heavy-duty trucks from abroad. The picture was completely different from the previous days. In one hour, four heavy-duty trucks were selected for control. However, the police only identified the cause of the elevated NO emission in one of these vehicles. A possible explanation may be difficulties in identifying the causes of malfunctioning SCR-systems.

Figure 12.9. Instrument setup at the Great Belt Bridge, lanes 6-9.

In relation to the installation of the measuring equipment, a setup was chosen which had previously been used by the Spanish Guardia Civil in a similar campaign in Spain. As the heavy-duty trucks stopped, it was a concern that speed and acceleration would not be sufficient to achieve usable results, but this did not prove to be the case. Due to safety and not to arouse unnecessary suspicion, the camera was set up well away from the measuring equipment. As a consequence, it was not possible to identify the license plates of the vehicles passing. However, it was found that the arrangement of equipment in relation to the vehicles was crucial. In these measurement days, we saw how an arrangement just 50 cm closer to the roadway made the drivers more cautious and thus changing the driving pattern. As a result, the measurements were not usable, and we had to move the equipment again. It is an important conclusion that the layout of the equipment has to be very mobile. The drivers of the vehicles appear to be very cautious, and if they perceive disruptive elements near the roadway both speed and acceleration are reduced. At the same time, it is often necessary to adjust the layout to optimize the results. Finally, we would not have had the opportunity to measure in different lanes on the Great Belt Bridge without the ability to move the setup in a very short time.

During the day, nine heavy-duty trucks were selected for control. Only one SCR functioned properly and another one was too old to be equipped with one. The remaining seven SCR-systems were deliberately malfunctioning. Communication with the police was now in place, and the setup of the inspection area implied that there was enough time to notify the police in advance.

The fact that measurements were now conducted in other lanes implied that much fewer vehicles were now measured. In total, only 353 vehicles were measured on 02.10.2019 and 523 vehicles on 03.10.2019.

12.4.4 Great Belt Bridge 03.10.2019

Measurements continued in lanes six to nine, and the results were very similar to the day before. The communication and cooperation with the police were again impeccable, and the police selected eight heavy-duty trucks for control of which six SCR-systems were malfunctioning and the remaining two worked fine. Based on the ongoing campaign and the experience of the test measurements, the police also checked the km history of the heavy-duty trucks. Both heavy-duty trucks with well-functioning SCR-system were suspected to have been driving too short time, implying that the catalyst was simply not hot enough to activate the injection of AdBlue. At the same time, there was a delay in the transit of the payment system, and this may also have contributed to the cooling of the catalysts.

The above shows once again the need for police and researchers to gain a better understanding of how the SCR-systems actually work. At the same time, it is important to emphasize that a proper measurement location is crucial for obtaining useful results. There will be a longer discussion of the implications of this in the report's section on recommendations for streamlining police control efforts.

Based on the measurements at the Great Belt Bridge, the police was pleased with the efforts, and confidence to the measurement system was restored. This was clearly expressed by one of the controls on a heavy-duty truck which was selected for control on the basis of a high NO emission. After the preliminary investigations, the police was finishing the investigations, but without explanations for the high NO emissions. Because of the confidence in the measurements, the police continued anyway, and finally found some values that were very suspicious. The heavy-duty truck was sent to an original Volvo workshop, and then it was found that a software manipulation of the SCR-system had been performed.

It is important to emphasize that it is a prerequisite for a satisfactory collaboration that mutual experience is gained in the use of the system. Especially the operator of the equipment is critical for securing that the system is used to ensure sufficient quality of measurements in the checking of heavy-duty trucks.

12.4.5 Great Belt Bridge 04.10.2019 and 07.10.2019

As the police were not present these days, measurements were performed in lane 1. The focus was on passenger cars and on obtaining the highest possible number of measurements. The installation of the measuring equipment in this case is kept within the barriers, and during the day, it was only necessary to calibrate the system during the installation. Two different arrangements were tested, respectively pictures of the cars from front and behind. Whether to select one or the other depends highly on the weather conditions such as light, rain, blown etc.

On the two days, respectively 3,070 and 2,747 vehicles were measured. As apparent from these figures, there is a large difference in number of measured vehicles depending on selection of lane. Since the main objective of the project was to develop a method for police roadside control of heavy-duty trucks by the police, it was necessary to prioritize the relevant measurements on heavy-duty trucks over a high quantity of measurements. Initially, we expected to obtain more than 100,000 valid measurements. However, both the total number of vehicles that passed the selected measurement points, and the selected focus on heavy-duty trucks made it impossible to achieve this goal.

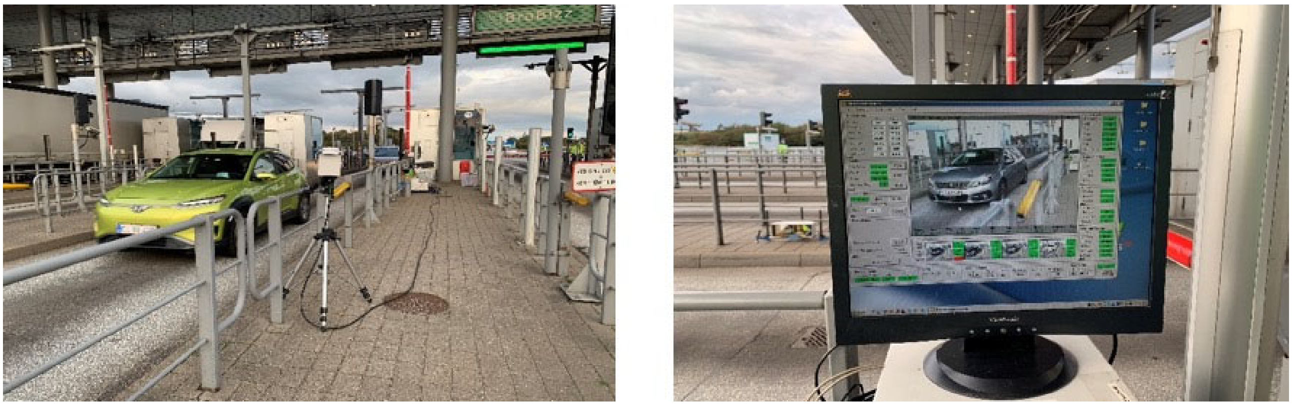


Figure 12.10. Great Belt Bridge, lane 2. Camera position (left) and data acquisition on-site (right)

Unfortunately, the pictures from these days are of impaired quality, so the uncertainty of making an automatic license plate recognition was considered too high. We therefore chose to manually identify vehicles with Danish license plates. The license plates were subsequently held against the Danish motor register to define fuel type, Euro norm etc. Immediately after measurements on 07.10, the Great Belt Bridge announced that they could not now allow us to continue. As their own number plate testing equipment needed to be expanded to include multiple lanes, they could not house our equipment. We continued the measurements in Padborg from the following day.

12.4.6 Conclusion after the second week of measurements together with the police

After learning a great deal about the equipment, and about how it is optimally operated on the location in Padborg, there was a much better collaboration and considerably more benefit was obtained from the measurements in the second week. The cooperation with the police worked impeccably, which is to a large extent attributed to the police's very constructive approach to the project. We have no doubt at any time about the police involvement in this project, and without their advice and guidance, the project would not have had the same chances of success. In terms of measurement, we learned a lot after the first somewhat chaotic week in Padborg. The equipment was flexible, reliable and relatively easy to use as long as the operator was adequately trained in operation of the system, and the operator had a critical approach to both setting up the equipment as well as to the data acquisition. This part depended strongly on good and close cooperation with the police, as their feedback on the control part provided valuable knowledge about recognition of suspicious vehicles. Finally, it was demonstrated that the equipment is capable of measuring many vehicles over a short time period, provided that the setup is correct and fits the purpose.

12.4.7 Padborg 08.10.2019

The weather forecast indicated rain throughout the day. Measurements were postponed to 09.10.

12.4.8 Padborg 09.10.2019 and 10.10.2019

Both days were influenced by rain, but in agreement with the police we initiated the measurements.

Figure 12.11. Measurement site Padborg. Danish Customs Authorities are operating in the lane next to the measurements.

This was a great opportunity to get the equipment tested in various types of weather as the days offered everything from sunshine to rain. We copied the setup of equipment from 26.09 with the modification that the camera was hidden in a tent. This was partly to protect the equipment from rain, but also to further hide the equipment from the drivers. In addition, the boxes that protected the measurement equipment was painted green and black for the purpose of camouflage. The police changed method for selection of vehicles for control. That is, the heavy-duty trucks were allowed to drive for some distance prior to being confronted at the highway. In a single case, this implied that a heavy-duty truck selected for control was not checked in, but otherwise this method worked better, and showed a more natural driving pattern compared with the previous setup.

On 09.10, our measurements were affected by customs inspection, which was conducted in the lane next to the measuring equipment. Obviously, the drivers were paying close attention to people in yellow jackets at the location where we were measuring. This confirmed our observations about the necessity of having a mobile device, which can easily be moved and hidden to obtain the best possible measurement results.

As seen in the photo from the measurements (Figure 7.12), the weather changes considerably. Each time there had been a major rainfall, the equipment had to be recalibrated. This was not a problem in itself, but with heavy traffic in the opposite direction and wind blowing towards the measuring device, this gave problems with interference with emissions from the traffic in the opposite direction. This must be considered, when calibrating the equipment on roads under such conditions.

The police participated to a limited extent these days due to lack of resources. However, several heavy-duty trucks were successfully controlled with good agreement between heavy-duty trucks selected from the measurements and the police subsequent findings (manipulation equipment on the heavy-duty trucks). In total, five heavy-duty trucks were selected for control and all five were either defective or were too old to feature an SCR-system. A total of 2,035 vehicles were measured on these two days, of which 983 were heavy-duty trucks. Based on these measurements, the police called for at a meeting in the steering committee on 11.11.2019, stating that they were fully satisfied with the test in relation to their control efforts. The police stated furthermore that they were convinced of the link between the measurements of NO emissions with RSD, and the errors or deficiencies they could find on the heavy-duty trucks. Freddy Agerskov announced that the police would not participate further in measurement campaigns, since the objective was fulfilled.

Figure 12.12. Measurement site Padborg 09.10 and 10.10 2019.

12.4.9 Conclusion after the third week of measurements in cooperation with the police

After three weeks of measurements in cooperation with the police, it was clear that we had built a well-functioning method in relation to identifying heavy-duty trucks with suspiciously high NO emission. The criterion of 1,000 ppm had proven effective in identifying heavy-duty trucks that could be of interest to the police. Furthermore, the method to provide the police the necessary information about the vehicle to inspect the heavy-duty truck in question also worked without problems. It was clear in the third week that a trust and well-functioning cooperation had now been established between the operator of the system and the officers who were to carry out the checks. This was of great significance in relation to the actual control of heavy-duty trucks, as the officers now knew that a technical explanation for the measured NO values was very likely to be found. With respect to identification of heavy-duty trucks based on high particulate emissions, we never found a pattern in the emissions that was useful for police controls. This was partly because it was not possible for the operator to find a consistent picture of heavy-duty trucks that were suspicious on the basis of the PM values, and partly because the NO emissions were so simple and clear to apply that there was no immediate need for using other parameters.

12.4.10 Padborg 21.10 – 25.10.2019

As there were days left in the scheduled campaign, it was decided to conduct the remaining measurements in week 43 in Padborg. Due to rainy weather and high moisture content in the air influencing the performance of the instruments, these measurements were limited to 22.10 – 23.10 2019. On these days, 1,520 (692 heavy-duty trucks) and 2,656 (1,174 heavy-duty trucks) vehicles were measured, respectively. In the setup, the camera was hidden in a tent behind a passenger car.

12.4.11 Conclusion on measurements campaigns at Padborg and the Great Belt Bridge.

Measurements were performed for 13 days, and 4 measurement days had to be cancelled due to rain and faulty equipment. A total of 25 measurement days were allocated in the project, including test measurements.

A total of 17,826 vehicles were measured during the period, of which 4,155 were heavy-duty trucks. The starting point was to focus on Danish vehicles. However, after the initial measurements, and after consulting with the police, it was decided to change focus towards foreign heavy-duty trucks. Significantly more foreign vehicles exceeded the NOx threshold value of 1,000 ppm. In particular for the Great Belt Bridge, the location of the the measuring equipment proved important.

This campaign demonstrated that the equipment is indeed suitable for measuring vehicle emissions. However, it is important to point out that a successful use of remote sensing is highly depending on several factors to obtain the best possible data.

First of all, it is important to carefully consider which data should be generated, and what the data should be used for. As can be seen from the description of the campaign, there are natural restrictions for the use of the equipment when aiming for control campaigns in collaboration with the police. Here, the focus was on identifying heavy-duty trucks for police control, and both the location of the destination and the presence of police and other people in yellow jackets gave a need for the equipment to be hidden to avoid this from affecting the driving pattern of the heavy-duty trucks. This may be redundant when measuring “background” data, only, as this does not require the presence of the police. Also, the drivers may communicate internally and warn each other about on-road control campaigns. We could not verify this from our, but it is a possibility according to the police. Therefore, it has to be considered when setting up the equipment.

To carry out an optimal measurement campaign experience from the individual measurement sites proves important. For the two selected sites, a great deal of time was spent in finding the best set-up, not only in terms of obtaining the desired data quality, but also in handling practical details such as accessibility at the measurement site, parking opportunities, cooperation with the local authorities, etc. During the project, a confidentiality was established between the operators of the equipment and the staff at the border crossing. This enabled a smooth working procedure where both parties helped establishing the best possible conditions for the measurements.

The measurement campaign emphasized the importance of having a mobile instrument setup. There was continuously a need to be able to adjust the setup of the equipment. This has proven to be the case with the OPUS RSD of the selected setup that can be done within 30 minutes including the calibration of the equipment.

It is also important to emphasize the need for measurements that extend over longer periods of time and ideally take place continuously throughout the year. In our geographical area, there are large seasonal variations in daylight and weather conditions that affect the measurements and need to be accounted for. It will be important to document that successful measurements conducted in collaboration with the police in this project, can be replicated at other times of the year.

Continuous measurements will also have the great advantage of building a circle of experienced operators who can quickly detect changes in driving pattern, values that should arouse wonder, ensure an optimal use of the technical possibilities the system contains etc. In this project it became very clear, that the operator plays a very important role in understanding what is being measured and which areas to pay special attention.

The measurements conducted in collaboration with the police have emphasized the need for more knowledge about how the heavy-duty trucks SCR-systems work. In order to make effective measurements with the lowest possible limit values, and for the police to carry out the most effective checks on the selected heavy-duty trucks, it is crucial that both police and to some extent also the operator have an understanding of when the heavy-duty truck can be expected to add AdBlue to the exhaust. It is therefore recommended that resources be devoted to continuous training of the staff performing the controls.

There is currently insufficient understanding of the importance of slow driving, such as when driving in a queue, impact of many stops in traffic, such as for many light traffic approaches or for many other types of driving with all types of vehicles. This is an area that should be explored further in future RSD studies of emissions from the driving carpark.

A greater understanding of this area will make it possible to differentiate threshold values for NO emission. Clearly, Euro VI engines have significantly lower NO emission than Euro V engines. When taking continuous measurements at many different locations, it will become possible to establish a criterion for selecting Euro VI heavy-duty trucks for police roadside control.

CONTROL OF SCR-SYSTEMS USING ROADSIDE REMOTE SENSING

Results from road experiments 2019

The current project presents results of field campaign studies with roadside remote sensing equipment for online detection of road traffic emissions of nitrogen oxides from individual vehicles. The aim was to test the options for creating a control system for online identification of malfunctioning SCR systems in the on road heavy duty trucks in Danish car park. The measurements demonstrated the importance of selecting measurements sites where the main part of the passing heavy duty trucks will have warm motor, since this is proven to be crucial for actual emissions. Various challenges had to be handled, but the performed campaigns demonstrated that it is possible to develop such a control system based on a road side remote sensing system that may be operated by the Danish traffic police.

ISBN: 978-87-7156-507-2
ISSN: 2245-0203