THE DANISH AIR QUALITY MONITORING PROGRAMME

Annual Summary for 2016

Scientific Report from DCE – Danish Centre for Environment and Energy No. 234 2017

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Data sheet

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Abstract: The air quality in Danish cities has been monitored continuously since 1981 within the Danish Air Quality Monitoring network. The aim is to follow the concentration levels of toxic pollutants in the urban atmosphere and to provide the necessary knowledge to assess the trends, to perform source apportionment, and to understand the governing processes that determine the level of air pollution in Denmark. In 2016 the air quality was measured in four Danish cities and at two background sites. In addition model calculations of air quality and the impact of air pollution on human health were carried out. At one street station (H.C. Andersens Boulevard) in Copenhagen NO_2 was found in concentrations above the EU limit value for the annual average, while NO_2 levels in Odense, Aarhus and Aalborg were below the limit value. Model calculations indicate exceedances of the NO_2 limit value at several streets in Copenhagen. Annual averages of PM_{10} and $PM_{2.5}$ were below limit values at all stations and the average exposure indicator ($PM_{2.5}$ in urban background) has decreased with about 20 % since 2010. Ozone exceeded at one occasion the information threshold at180 µg/m^3. The concentrations for most pollutants have been decreasing during the last decades.

Keywords: Atmospheric pollution, urban pollution, nitrogen compounds, ozone, sulphur compounds, heavy metals, volatile organic pollutants, dispersion models and measurements, health effects, external cost.

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Contents

Summary and Conclusion

This report presents the result from the Danish Air Quality Monitoring Programme in 2016. The monitoring programme is carried out by the DCE - Danish Centre for Environment and Energy (DCE) at Aarhus University. The core part of this programme consists of continuous measurements at eleven monitoring stations; nine stations situated in the four largest cities, two stations located in background areas and a station in a suburban area. These measurements are supplemented with model calculations using DCE's air quality models.

The aim of the program is to monitor air pollutants relevant to human health in accordance with the EU air quality directives. The programme includes measurements of sulphur dioxide (SO_2), nitrogen oxides (NO_x/NO_2), particulate mass less than 10 (PM_{10}) and 2.5 micrometers ($PM_{2.5}$), particle number, benzene (C_6H_6), toluene (C_7H_8), carbon monoxide (CO), ozone (O_3), polycyclic aromatic hydrocarbons (PAHs) and a number of heavy metals including lead (Pb), arsenic (As), cadmium (Cd), mercury (Hg), nickel (Ni), and a number of volatile organic compounds (VOCs) that are precursors for formation of ozone (O_3). The measurements and model calculations are used to evaluate the Danish air quality in relation to limit values as well as to follow trends. Further, the obtained data are used for determination of sources of the air pollutants, basis for evaluation of the impact of regulations of emissions and as basis for various research projects related to air quality.

The permitted number of exceedances in a year of the diurnal limit value of 50 µg/m^3 for PM_{10} was not exceeded at any station in the measuring network. Likewise, there were no exceedances of the annual limit values for PM_{10} (40 µg/m^3) and $PM_{2.5}$ (25 µg/m^3). The average exposure indicator (AEI) has decreased with about 20 % since 2010 and hence the target (15 % reduction) has been reached.

The number of particles in ambient air was about 13,000 particles per cm^3 as annual average at the street station H.C. Andersens Boulevard. This is roughly a factor of 3.5 higher than in suburban and 4.5 higher than in urban and rural background, respectively. A significant reduction in particle number has been observed since 2002. This reduction has mainly been reached by recution of traffic emissions (cleaner fuel, particle filters etc.).

The annual limit value for NO_2 (40 µg/m^3) was exceeded at one street station in Copenhagen (H.C. Andersens Boulevard), whereas no exceedances were observed in Odense, Aalborg and Aarhus. At H.C. Andersens Boulevard (HCAB/1103) there were still elevated concentrations of NO_2 compared to the situation before 2010 due to a permanent change in the traffic lanes at the street segment in front of the measurement station. Additionally, there has been a gradually decrease in the concentrations during the last years in parallel to the decrease observed at Jagtvej. Jagtvej. In October 2016, the position of the measurement station was adjusted to the previous distance to the road lanes and a subsequent drop in concentrations were observed.

Model calculations at selected streets in Copenhagen and Aalborg indicate that the limit value was exceeded at 6 out of 98 calculated streets in Copenhagen but not at any streets in Aalborg in 2016. The number of street segments

with model calculated exceedances in Copenhagen has now decreased to about one third compared to 2010.

The O_3 levels in 2016 were at the same level as in the previous years. No clear trend is observed for the average O_3 concentration. The information threshold of 180 $\mu g/m^3$ was exceeded in 2016 at the Risø station and the public was informed through the Danish Environmental Protection Agent. The target value for the maximum daily 8-hours mean O_3 concentration of 120 $\mu g/m^3$ was not exceeded, but the long-term objective for this parameter was exceeded at all Danish stations.

Measurements of VOCs at the urban background in Copenhagen showed concentration levels between 0.01 $\mu g/m^3$ and 0.82 $\mu g/m^3$ for the selected 17 different compounds. VOCs can act as O_3 precursors, and the aim of these measurements is to improve the general understanding of the O_3 formation at a European level. The formation of O_3 in Denmark is in general small due to moderate solar radiation. O_3 pollution in Denmark is to a large extent the result of long distance transport of pollutants from other European countries south of Denmark.

The levels of SO_2 and heavy metals have decreased for more than two decades and are now far below the limit values. The limit values for benzene and CO are not exceeded and the levels have decreased for the last decades.

Measurements of concentrations of particle bound PAH were performed at H.C. Andersens Boulevard, Copenhagen and at the suburban measurement station at Hvidovre. The average concentration of benzo[a]pyrene was 0.21 ng/m^3 and 0.23 ng/m^3 at H.C. Andersens Boulevard and Hvidovre, respectively. The target value for benzo[a]pyrene (1 ng/m^3) was not exceeded in 2015.

Measurements of the chemical content in $PM_{2.5}$ showed that the annual average concentrations of ammonium (NH_4^+), sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}), chloride (Cl^-), nitrate (NO_3^-) and sulfate (SO_4^{2-}) are very similar at the street station at H.C. Andersens Boulevard and at the rural station at Risø. The main difference between the two stations is found for elemental carbon (EC), organic matter (OM) and calcium (Ca^{2+}) where the concentrations are higher at the street station compared to the rural background station. This is mainly due to emissions of these compounds from the traffic in Copenhagen.

Model calculations shows that air pollution causes about 3,600 premature deaths in Denmark as average for 2014-2016 and a large number of other negative health effects. About 850 (24 %) of the premature deaths are due to Danish emission sources while the remaining premature deaths are caused mostly by European sources outside Denmark. The total health related external costs for Denmark have been calculated to 3.9 billion EUR (~29 billion DKK) as an average over the three years 2014-2016. The negative health effects and external costs have declined with about 40% since 1988-1990.

Actual data, annual and multi-annual summaries are available at the website of DCE (http://dce.au.dk/en/authorities/air/), in Danish (http://dce.au.dk/myndigheder/luft/).

Danish summary - Dansk resumé

Rapporten præsenterer resultater for 2016 fra Overvågningsprogrammet for luftkvalitet i danske byer. Programmet, som udføres af DCE - Nationalt Center for Miljø og Energi (DCE) ved Aarhus Universitet, er baseret på målinger ved ni målestationer placeret i de fire største danske byer samt ved to baggrundsmålestationer udenfor byerne og en station i et forstadsområde. Disse måleresultater suppleres med resultater fra modelberegninger udført med DCE's luftkvalitetsmodeller.

Formålet med programmet er at overvåge luftforurening af betydning for sundhed. Målingerne udføres i overensstemmelse med EU's luftkvalitetsdirektiver. I henhold til disse og øvrige danske behov måles koncentrationer af svovldioxid (SO_2), nitrogenoxider (NO_x/NO_2), partikelmasse mindre end 10 (PM_{10}) og 2,5 mikrometer ($PM_{2,5}$), partikel antal, benzen (C_6H_6), toluen (C_7H_8), carbonmonoxid (CO), ozon (O_3), udvalgte tungmetaller (fx bly (Pb), arsen (As), cadmium (Cd), kviksølv (Hg), nikkel (Ni)) og polyaromatiske kulbrinter (PAH'er) samt udvalgte flygtige kulbrinter (VOC'er), der kan føre til dannelse af O_3. Målingerne og modelberegningerne anvendes til at vurdere om EU's grænseværdier for luftkvalitet er overholdt. Rapporten beskriver endvidere udviklingen i koncentrationerne. Samtidigt tjener resultaterne fra måleprogrammet som grundlag for vurdering af kilderne til luftforureningen i Danmark, vurdering af effekt af reduktionstiltag og som grundlag for en række videnskabelige undersøgelser, fx vurdering af små partiklers effekt på sundheden.

Der er fastsat grænse- og målværdier for flere af de målte stoffer. Grænseværdierne skal være overholdt fra 2005, 2010 eller 2015 alt efter, hvilke stoffer det drejer sig om. En detaljeret beskrivelse af gældende mål- og grænseværdier og deres gennemførelse findes i en bekendtgørelse fra Miljøministeriet (Miljøministeriet 2016). Bekendtgørelsen er baseret på det 4. datterdirektiv om tungmetaller og PAH'er (EC 2005) samt EU's luftkvalitetsdirektiv fra 2008 (EC 2008). En af de væsentligste ændringer i direktivet fra 2008 i forhold til de tre første datterdirektiver (1999, 2000 og 2002) er, at der stilles krav om målinger af de fine partikler ($PM_{2,5}$), og at der er indført en grænseværdi for $PM_{2,5}$, som skal være overholdt i 2015.

I 2016 blev grænseværdien for NO_2 som årsmiddelværdi overskredet på én (H.C. Andersens Boulevard) af de to gademålestationer i København. I Odense, Aarhus og Aalborg var der ingen overskridelser. Koncentrationerne af NO_2 i 2016 var for hovedparten af målestationerne stort set på niveau med koncentrationerne målt i 2015. På H. C. Andersens Boulevard blev der i 2010 indført en permanent ændring af vejbanerne ud for målestationen, hvilket førte til en forøgelse i koncentrationerne på omkring 8 $\mu g/m^3$ set i forhold til tidligere. Denne forøgelse i koncentrationerne ses fortsat om end koncentrationerne på H.C. Andersens Boulevard i gennem de seneste år er faldet parallelt med det generelle fald i koncentrationerne f.eks. som observeret på Jagtvej. I november 2016 blev placeringen af målestationen justeret i forhold til den tidligere afstand til vejbanerne. Dette medførte et fald i de målte koncentrationer af NO_2.

Modelberegninger indikerer, at grænseværdien i 2016 var overskredet på 6 ud af 98 beregnede gadestrækninger i København, men ikke på udvalgte gadestrækninger i Aalborg. Siden 2010 er antallet af gadestrækninger med beregnede overskridelser af grænseværdien i København blevet reduceret med omkring to tredjedele.

PM_{10} overholdt grænseværdien på 40 µg/m^3 som årsmiddelværdi på alle målestationer. Ligeledes var der ingen målestationer i måleprogrammet, hvor det tilladte antal overskridelser af den daglige middelværdi for PM_{10} (50 µg/m^3 må ikke overskrides mere end 35 gange årligt) blev overskredet.

$PM_{2,5}$ overholdt grænseværdien på 25 µg/m^3 som årsmiddelværdi på alle målestationer. AEI-værdien (average exposure indikator, som er defineret som middel af $PM_{2,5}$ i bybaggrund) er faldet med omkring 20% siden 2010. Dermed er målværdien (15 % reduktion) allerede nået.

Antallet af partikler mellem 6 og 700 nm var omkring 13.000 partikler per cm^3 på gademålestationen H.C. Andersens Boulevard, hvilket er en faktor 3,5 højere end ved forstadsstationen Hvidovre samt en faktor 4,5 højere end både by- og land-baggrundsstationen h.h.v. HCØ og Risø. Siden 2002 har der været et fald på ca. 50% i antal partikler. Faldet er blandt andet sket som følge af indførelse af svovlfrie brændstoffer og krav om partikelfilter på alle nye dieselkøretøjer.

Ozonkoncentrationerne i 2016 var på niveau med 2014. Der er ikke fastsat egentlige grænseværdier for O_3, men kun "målværdier" og "langsigtede mål" (hensigtsværdier). Der var i 2015 ingen overskridelser af målværdierne for beskyttelse af sundhed, mens de langsigtede mål (120 µg/m^3) blev overskredet på alle bybaggrunds- og landstationerne. Tærsklen for information af befolkningen om høje ozonniveauer (timemiddel 180 µg/m^3) blev overskredet i 2016 på Risø stationen. Miljøstyrelsen informerede offentligheden om dette.

De øvrige målte stoffer findes i koncentrationer under grænseværdierne, og for flere stoffer (fx benzen, svovldioxid og bly) er koncentrationerne faldet meget markant siden 1990.

Målinger af partikelbundet PAH blev fortaget på H.C. Andersens Boulevard i København. Middelværdien for benz[a]pyren var 0,21 ng/m^3 og 0,23 ng/m^3 på henholdsvis H.C. Andersens Boulevard og ved målestationen i Hvidovre. Målværdien på 1 ng/m^3 var således ikke overskredet i 2015.

Målinger af 17 udvalgte VOC'er i bybaggrund i København viser koncentrationsniveauer, som spænder fra 0,01 µg/m^3 til 0,82 µg/m^3 i 2015. Disse VOC'er bidrager til den kemiske dannelse af O_3 på europæisk plan, og målingerne skal først og fremmest understøtte den generelle forståelse af ozondannelsen i Europa. I Danmark skyldes størstedelen af O_3 langtransport af luftforurening fra centrale og sydlige dele af Europa.

Målinger af det kemiske indhold i $PM_{2,5}$ ved gademålestationen ved H. C. Andersens Boulevard og ved landbaggrundsmålestationen på Risø viser ligesom i 2011-2015, at de årlige gennemsnitskoncentrationer for ammonium (NH_4^+), natrium (Na^+), kalium (K^+), magnesium (Mg^{2+}), chlorid (Cl^-), nitrat (NO_3^-) og sulfat (SO_4^{2-}) stort set er ens på de to stationer. Dette skyldes, at stofferne for en stor del stammer fra partikler transporteret til målestationer langvejs fra.

De væsentligste forskelle mellem de to målestationer ses for elementært carbon (EC), organiske forbindelser (OM) og calcium (Ca^{2+}), hvor koncentrationerne er højere på gadestationen som følge af trafikken i København.

Modelberegningerne af helbredseffekterne viser, at luftforureningen som gennemsnit for 2014-2016 er skyld i omkring 3.600 for tidlige dødsfald og en lang række andre negative helbredseffekter. Omkring 850 (24 %) af de for tidlige dødsfald skyldes danske kilder, mens resten hovedsageligt stammer fra det øvrige Europa. De eksterne omkostninger som følge af luftforureningen beløber sig til omkring 29 milliarder kr. (omkring 3,9 milliarder euro). De negative helbredseffekter og de eksterne omkostninger er faldet med omkring 40% siden 1988-1990.

1 Introduction

The Danish Air Quality Monitoring Program (LMP) originates back to 1981. Today the programme is part of the National Monitoring Programme for the aquatic and terrestrial environment (NOVANA). The program consists of an urban monitoring network with stations in the four largest Danish cities and two background stations in rural areas (figure 2.1) which is supplemented by model calculations. The results are used for assessment of the air pollution in Denmark with special focus on Danish urban areas. The programme is carried out in co-operation between the DCE - Danish Centre for Environment and Energy (DCE), the Danish Environmental Protection Agency, and the Municipalities of Copenhagen, Aarhus, Aalborg and Odense. DCE is responsible for operating and maintaining the programme. Statistical parameters and actual data are accessible at the website: http://dce.au.dk/-en/authorities/air/, (in Danish http://dce.au.dk/myndigheder/luft/). Selected near real-time data are also available at tele-text, Danish National Television. In addition, this report presents results from model calculations of air quality in Denmark carried out as supplement to the measurements.

The monitoring programme is carried out in accordance with the Danish Statutory Order No. 851 of 30 June 2010 from the Ministry of Environment and food (Miljø- og Fødeministeriet, 2016) that implements the EU directives on air quality in Denmark (EC, 2005; EC, 2008).

One of the main objectives for the monitoring programme is to assess the air quality in relation to various air quality criteria (i.e. limit values, margin of tolerance, target values, long term objectives and alert thresholds) of which the limit values are the legally most important. The Danish air quality criteria are identical to those laid down in the EU directives described above.

The program was revised in 2016. The majority of these revisions will be implemented from January 2017 except for the modelling part of the programme that has been extended, so that they now also include model calculations of the health impacts and the external costs of air pollution. Results from these calculations are presented for the first time in this report.

Since 2012 there have been some important changes for the measurements stations and methods. These are:

- Starting in August 2012 low volume samplers (LVS) for gravimetric determination of particle mass based on the reference method were introduced into the regular measuring programme and gradually installed at the PM-stations in the network to replace some of the older SM200 instruments that needed to be renewed. See introduction to Chapter 7 for an overview.
- A new measurement station at a suburban area in Hvidovre was startet-up in the beginning of 2013 with measurements of PAHs in relation to use of wood burning as household warming. In June 2015, the measurement program in Hvidovre was supplemented with measurements of $PM_{2.5}$ by LVS, elementary (EC) and organic carbon (OC), particle number and nitrogenoxides (NO and NO_2).
- The urban background measurement station in Aarhus was in January 2015 moved to another position (Chapter 2.1).

- The street station in Aalborg had to be temporarily closed down from September 2014 and onwards due to nearby construction work (Chapter 2.1).
- At the street station in Albanigade in Odense there was a large decrease in daily traffic intensity starting from late June 2014 and the street was closed down for traffic in spring 2015. This change was due to major changes in the traffic patterns in Odense (section 2.1). A new street station was opened in 2016 in Odense. The station is situated at Grønnelykkevej (section 2.1).
- October 2016 the measurement station at H.C. Andersens Boulevard was moved 2.7 m (corresponds approximately to the width of a traffic lane) further away from the inner traffic lane. The aim of this replacement is to compensate for the changes in traffic lanes in 2010 that moved the traffic closer to the measurement station. The data presented for 2016 covers data from both the old and the new position. The reporting in 2018 of the data from 2017 will show the full impact of the replacement of the measurement station.

In the following chapters, the results from measurements and model calculations for 2016 are presented and compared to limit and threshold values. Please refer to the EU Directives (EC, 2005; EC, 2008) for a detailed description of the exact definitions of the limit values, margin of tolerance, target values, information and alert thresholds.

2 Measurements and model calculations

2.1 Measurements

The core of measurement stations in the Danish air quality monitoring network originates back to the 1980s and the stations have therefore been positioned before the development of the EU directives on air quality. Despite this, the network still gives a comprehensive fulfilment of the requirements laid down in the directives.

Originally, the Danish measuring strategy was to place one or more pairs of stations in each of the four largest Danish cities. In each city one of the stations is located close to a street lane with a high traffic density. The other is located within a few hundred meters from the street station, and is placed so that it is representative for the urban background pollution; meaning that its location is not influenced by pollutants from a single or a few streets or other nearby sources. In most cases the background stations are placed on rooftops. The short distance between street station and urban background station makes it possible to directly determine the traffic contribution as the difference between the two stations. In addition, two rural stations measure the pollution outside city areas. Further information about the program and results is found at the website: http://dce.au.dk/en/-authorities/air/ (in Danish http://dce.au.dk/myndigheder/luft/). Although this strategy is still valid, it has been necessary to loosen the criteria regarding the distance between the street station and urban background station, since it has not been possible to fulfil these criteria when new sites had to be found for example in Aarhus and Odense.

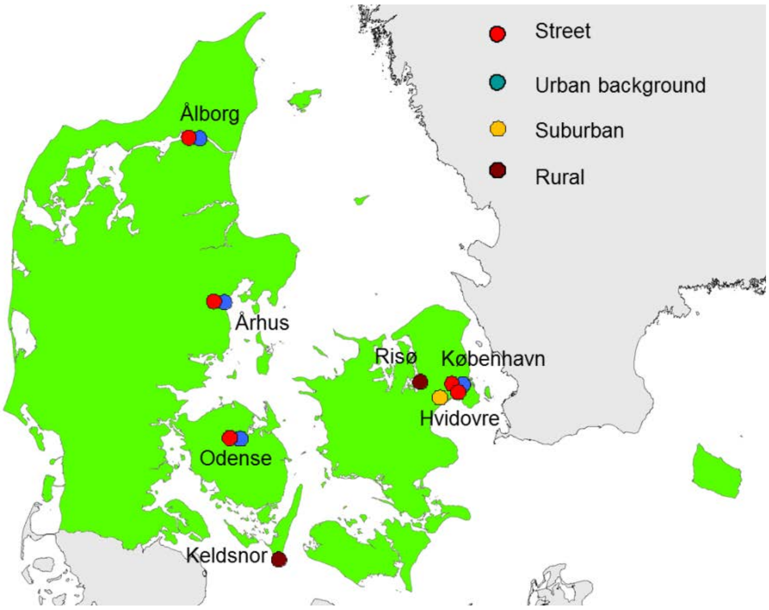


Figure 2.1. Main stations used for monitoring of air quality in relation to health.

Table 2.1. Main stations used for monitoring of air quality in relation to health in 2016

Location	Station type	Station number
Copenhagen		
H.C. Andersens Boulevard (HCAB)	Street	1103
Jagtvej	Street	1257
H.C. Ørsted Institute (HCØ)	Urban background	1259
Hvidovre, Fjeldstedvej 2650	Suburban	2650
Odense		
Grønløkkevej	Street	9156
Town hall in Odense	Urban background	9159
Aarhus		
Banegårdsgade	Street	6153
Botanical Garden	Urban Background	6160
Aalborg		
Vesterbro, Limfjordsbroen	Street	8151
Aalborg/8158	Urban background	8150
Rural		
Lille Valby/Risø*	Rural background	2090
Keldsnor/	Rural background	9055

*The rural station at Lille Valby was in the middle of 2010 moved about 2 km west to Risø and is now situated close to DCE

In 2014-2016 there were four major changes regarding the stations:

- The measurement station on Vesterbro at Limfjordsbroen in Aalborg was closed down temporarily on 8 September 2014 due to a major construction work at the nearby house. Therefore the results for 2014 only represent data for 250 days (70%) and the station was closed down temporarily in 2015.
- In Odense a traffic plan has been adopted by the municipality for the entire city centre and the implementation of this plan began in late June 2014. This resulted in a major decrease in the traffic intensity at Albanigade, where the street station is situated. In spring 2015, Albanigade was closed for traffic. The station was shut down on 16 June 2015 and was moved to a new position at Grønnelykkevej in summer 2016 (figure 2.2).
- In January 2014, the urban background station in Aarhus was moved to a new site since the municipality sold the house that the measurements station was placed upon. The new site is situated in the south easterly part of the Botanical Garden that belongs to Aarhus University.
- On 3 October 2016 the station at H. C. Andersen Boulevard was closed and a new station was placed instead of the old station (figure 2.3). The majority of the measurements were startet-up on 19 October 2016. The new station was located 2.7 m further away from the inner traffic lane in order to compensate for the road change in 2010 (see Appendix 1 for a sketch of the location). Moreover, the station was also mowed about 2 m further away from a tree close to the station in order to comply better with the EU directive (EC, 2008) that specifies that measurements have to be carried out several meters from trees in order to avoid influence of the trees on the measurements.

Figure 2.2. The new street station at Grønløkkevej, Odense (left). The map shows the position of the street station (blue dot).

Figure 2.3. The old measurement station (left) at H.C. Andersen Boulevard closed down 3 October 2016. The new measurement station (right) began measurements 19 October 2016.

The following compounds were measured in 2016:

- Nitrogen oxides (NO, NO_2 and NO_x (= NO + NO_2)) were measured at all stations.
- Particle mass (PM_{10} and/or $PM_{2.5}$) were measured as 24 hour averages at all stations. At the following stations PM was measured throughout the year using low volume samplers (LVS) for gravimetric determination of particle mass based on the reference method EN 12341: 2014: HCAB (PM_{10} and $PM_{2.5}$); HCØ (PM_{10} and $PM_{2.5}$); Jagtvej (PM_{10} and $PM_{2.5}$); Hvidover/suburban ($PM_{2.5}$); Risø (PM_{10} and $PM_{2.5}$); Aarhus/street (PM_{10} and $PM_{2.5}$); Aarhus/urban background ($PM_{2.5}$); Aalborg/urban background ($PM_{2.5}$). At Aalborg/street ($PM_{2.5}$) no data were measured in 2016 due to relocation of the measuring station and problems finding a new site. At Keldsnor/rural (PM_{10}) the measurements for 2016 consist of a combination of SM200 beta-gauge and LVS measurements because the SM200 instrument was closed down and replaced with the LVS reference instrument running from the 18 May 2016. At Odense/street (PM_{10}) the station was due to rearrrangement of the road system closed and the SM200 measurements stopped the 15 June 2015 and PM_{10} measurements were restarted again with LVS at the new street station in Odense 1 July 2016.

- Elements (heavy metals) in PM_{10} were measured at Copenhagen/street (HCAB), Copenhagen/urban background, Aarhus/street, Odense/street and the rural site Risø.
- Additionally, PM_{10} and $PM_{2.5}$ were measured at both Copenhagen/street (HCAB) and Risø by means of TEOM that measures on a half hourly basis making it possible to resolve the diurnal variation. Part of these measurements was carried out in a research project funded separately by the Danish EPA.
- Particle number was measured at Copenhagen/street (HCAB), Copenhagen/urban background and Risø in cooperation with a particle research project funded separately by the Danish EPA. Additionally, measurements were started at a suburban site in Hvidovre in autumn 2015.
- Ozone (O_3) was measured at all urban background and rural stations, and at the street stations Copenhagen/street (HCAB).
- Carbon monoxide (CO) was measured at all street stations except Jagtvej as well as at the urban background station, Copenhagen/urban background and the rural site Risø.
- Benzene and toluene were measured at Copenhagen/street (HCAB) and Copenhagen/urban background using passive sampling on a weekly basis.
- PAHs were measured at Copenhagen/street (HCAB) and at the suburban site in Hvidovre.
- SO_2 was measured at Copenhagen/street (HCAB). The main purpose was to monitor episodic high concentrations.
- Elemental carbon (EC) and organic carbon (OC) were measured at Copenhagen/street (HCAB) and the rural site Risø. EC was measured at the suburban station in Hvidovre.
- The meteorological parameters – air temperature, wind speed and direction, relative humidity and global radiation - were measured in Copenhagen, Odense, Aarhus and Aalborg at the urban background stations or at a location, which is representative for the meteorology at the urban background station.

The pollutants are described in more detail in Appendix 2.

Measurements of gasses (NO, NO_x, NO_2, O_3, CO, SO_2) and particle number were recorded as ½-hour averages. Particle mass (PM_{10} and $PM_{2.5}$) were measured both as 24 hour averages primarily using LVS (gravimetric method) but also to a lesser extend beta measurements and as ½-hour averages using TEOM (Tapered-Element Oscillating Microbalance). Elements in the particles as well as PAH were measured as 24 hour averages. EC and OC were measured as 24 hour averages. Benzene and toluene were measured weekly by passive sampling. Furthermore, volatile organic compounds were sampled as 24 hour averages.

2.2 Model calculations

In the monitoring programme, the measurements at the permanent measuring stations are supplemented with model calculations using the THOR modelling system. In the present report, model results are presented for NO_2 in streets and for O_3 at a national level.

The THOR system is an integrated model system, capable of performing model calculations at regional scale to urban background scale and further down to individual street canyons in cities – on both sides of the streets. The system is driven by global meteorological analysed data from National Centres for Environmental Prediction, United States, which is used as input to the meteorological model MM5v7 (Grell et al., 1995).

The meteorological data for 2016 from MM5v7 is subsequently used to drive the air pollution models, including the Danish Eulerian Hemispheric Model, DEHM (Christensen, 1997; Brandt et al., 2012), the Urban Background Model, UBM (Berkowicz, 2000b; Brandt et al., 2001) and the Operational Street Pollution Model, OSPM® (Berkowicz 2000a; Ketzel et al., 2012). DEHM is providing air pollution input data for UBM which again is providing air pollution input data to OSPM. Further details about the integrated THOR system can be found in Brandt et al. (2000; 2001 and 2003 or at http://www.au.dk/thor). The same model setup is also used for a new air pollution map that shows modelled urban background and street concentrations at all 2.4 million addresses in Denmark presented at a publicly available website (luftenpaadinvej.au.dk; Jensen et al., 2017).

Model calculations of air quality on national scale is carried out using DEHM (version 5.0), which is an Eulerian model where emissions, atmospheric transport, chemical reactions, and dry and wet depositions of air pollutants are calculated in a 3D grid covering the northern hemisphere with a resolution of 150 km x 150 km. The model includes a two-way nesting capability, which makes it possible to obtain higher resolution over limited areas. Three nested domains are used in the model runs under NOVANA, where the first domain is covering Europe with a resolution of 50 km x 50 km. The second domain is covering Northern Europe with a resolution of 16.7 km x 16.7 km. The calculations of air quality in Denmark are carried out in a third domain with a horizontal resolution of 5.6 km x 5.6 km. In the vertical direction the model is divided into 29 layers covering the lowest 15 km of the atmosphere. Of these, the lowest layers are relatively thin (20 m) while the upper layers are relatively thick (2000 m). The model includes a comprehensive chemical scheme designed for calculation of the chemical reactions in the lower part of the atmosphere. The emission inventories used in DEHM have a geographical resolution of 1 km x 1 km for Denmark transformed into the 5.6 km x 5.6 km resolution domain and 16.7 km x 16.7 km for the remaining part of Europe. The emissions are based on Danish national emission inventories for the year 2015 compiled by DCE (http://envs.au.dk/-en/knowledge/air/emissions/) and international emission inventories for the year 2014 collected and distributed by EMEP (www.emep.int).

The Urban Background Model, UBM (version 9.4), calculates the urban background air pollution based on emission inventories with a spatial resolution of 1 km x 1 km and based on input data from DEHM concerning the regional background. UBM is suitable for calculations of urban or rural background concentrations on high resolution (1 km x 1 km). The model includes a Gaussian plume approximation for calculation of the dispersion and transport of the air pollutants to every receptor point and a simple chemical model accounting for the photochemical reactions of NO_x and O_3. The basic principles of the model are described in Berkowicz (2000b). In the recent years UBM has undergone many improvements in the formulation of physical processes and now treats both area and point sources in a more physically correct manner compared to earlier versions of the model. This has improved the overall performance of the model in comparison with measurements, and provides a more realistic spatial distribution of concentrations around large point sources. The emissions used in the UBM model are based on the SPREAD model that spatially distributes national emissions from 2015 from all sectors on a 1 km x 1 km grid for Denmark (Plejdrup & Gyldenkærne, 2011). In previous years, UBM has been calibrated against measurements at all four urban background stations in order to ensure good correspondence between measured and modelled NO_2. UBM was applied with the same calibration as in the previous years and no additional corrections were necessary in 2016. No calibration was made since the agreement with measurements at the urban background locations of Copenhagen and Aalborg - where calculations are made for selected streets - was good.

Finally, the street canyon model OSPM® (www.au.dk/ospm) is used to calculate the air pollution at 2 m height at the sidewalks of selected streets. Meteorological data from the meteorological model MM5v7 and air pollution concentrations from UBM are used as input to the model. The model includes emissions from traffic, simple chemical reactions describing the reactions of air pollutants in the street canyons and the dispersion of the air pollution in the street canyon (due to meteorological conditions, turbulence induced by traffic and influence of the street geometry).

The input data for the OSPM on traffic data and street configurations for the selected urban streets are generated using the AirGIS system based on a GIS road network with traffic data, GIS foot-prints of buildings with building heights and GIS calculation points (Jensen et al., 2001; 2009 http://envs.au.dk/videnudveksling/luft/model/airgis/).

The traffic data used as input for the calculations with OSPM is updated annually for average daily traffic and vehicle distribution for the selected streets based on information obtained from the municipalities of Copenhagen and Aalborg. Traffic data are estimated at the location of the calculation points. For Copenhagen traffic data is based on manual counts performed annually or in 5-year intervals. Aalborg does not have a systematic traffic counting program similar to Copenhagen, and traffic data is based on available traffic data from manual and automatic counts together with data from a traffic model. Based on information from Copenhagen and Aalborg municipalities the Average Daily Traffic (ADT) and vehicle distribution on all streets have been updated with the most recent available traffic data. The vehicle distribution includes passenger cars, vans, trucks<32t, trucks>32t, and buses. In Copenhagen, 30 out of the 98 calculation points had updated traffic data for 2016. For Aalborg 17 out of 31 streets had updated traffic data.

Manual traffic counts are carried out annually for the street segments in front of the measuring stations of H.C. Andersens Boulevard and Jagtvej in Copenhagen. Manual counts for the 2016 assessment originate from September 2016 in Copenhagen. In Aarhus, automatic traffic recording was carried out to estimate traffic volume and vehicle classification during three seperate weeks in April, June and November 2016. This method provides good estimate of traffic volume but only rough estimate of vehicle classification. One of the shortcomings is that the method can't differentiate between passenger cars and vans as they have the same distance between axles. Hence, a manual count from 2015 was used for vehicle distribution.

In Odense the street (Albanigade) with the measuring station was closed in May 2015 due to construction work and traffic has in recent years decreased considerably due to major changes in the overall traffic plan for Odense City. The station has been moved to a new location in Odense (Grønløkkevej). Automatic traffic recording was carried out during one week in November 2015. Traffic volume and vehicle distribution were established based on this information assuming the same share for vans as average of 98 streets in Copenhagen. In Aalborg (Vesterbro) the measuring station was not in operation during 2016 due to nearby building construction work.

The model calculations for 2016 for Copenhagen and Aalborg have been carried out using the full model calculation system based on the THOR system, including MM5v7, DEHM, UBM, and OSPM. The calculations were carried out in order to determine the NO_2 concentration in 98 streets in Copenhagen and 31 streets in Aalborg.

2.2.1 Model calibration and validation

In the assessment for 2013 the model calculations with OSPM were improved through major revisions. These included changes related to the general building height, revision of NO_x emission factors for Euro 5 and 6 for passenger cars, and use of new travel speeds for the traffic based on GPS data (SpeedMap, speedmap.dk/portal/) and subsequent recalibration. Appendix 3 in Ellermann et al. (2014) describes the changes and presents documentation for the impact of the improved input data for the model calculations. The model setup for the assessment for 2016 is similar to that of 2013, 2014, and 2015.

In previous years, OSPM was calibrated against measurements at the street stations for a single year in order to ensure good correspondence between measured and modelled NO_2. For the assessment of 2016 we have used available data from the last three years to avoid potential fluctuations that a single year approach may introduce. The correlation between modelled and observed NO_2 concentrations for 2016 shows an overall good agreement with zero bias based on the same calibration as in previous years. The street station of H.C. Andersens Boulevard has not been used in the calibration due to the about 8 $\mu g/m^3$ jump in concentrations since a change in street layout moved traffic closer to the station in 2010. The station was moved during October 2016 to compensate for the change in street layout. The correlation between modelled and observed NO_2 concentrations for 2016 are shown in table 2.2. For further details on the calibration see Appendix 3.

Table 2.2. Comparison of modelled and measured annual means of NO_2 concentrations in 2016

Unit: µg/m³	Measurements	Model results	Difference	Models used
Street:				
Copenhagen/HCAB/1103	47/41*	46	-1%/14%	DEHM/UBM/OSPM
Copenhagen/Jagtvej/1257	33	33	1%	DEHM/UBM/OSPM
Aarhus/6153	31	29	-5%	DEHM/UBM/OSPM
Odense/9156	20	25	27%	DEHM/UBM/OSPM
Urban Background:				
Copenhagen/1259	15	14	-5%	DEHM/UBM
Aarhus/6160	14	14	-2%	DEHM/UBM
Odense/9159	11	12	12%	DEHM/UBM
Aalborg/8159	13	13	0%	DEHM/UBM
Hvidovre/2650	13	13	-6%	DEHM/UBM
Rural:				
Risø/2090	8	12	61%	DEHM/UBM
Keldsnor/9055	8	9	9%	DEHM/UBM
Anholt/6001	5	6	29%	DEHM/UBM

* 47 µg/m³ is measured at the measuring station at HCAB. The station was moved about 3.5 m further away from the street in November 2016 to re-establish the distance to the street after a change in street layout that had moved traffic closer to the measuring station. Based on parallel measurements this change was estimated to have led to a jump of about 6 µg/m³ in 2016. This value has been reduced in 2016 compared to previous years in order to take account of the replacement of the station in October 2016. Without the change in street layout, about 41 µg/m³ is expected. OSPM calculations are more representative of the measurements without the jump as OSPM calculations reflect concentration levels in front of the building facade.

2.2.2 Further development of OSPM

The detailed investigation on the impact of the changes in road lanes layout on H.C. Andersens Boulevard (HCAB) (Ellermann et al., 2014) showed that the current OSPM version has some shortcomings in reproducing measurements at the location/re-location of the measuring station. The setting at HCAB is complex with multiple road lanes, inhomogeneous distribution of emissions and a measurement point right next to the nearest road lane, and at the same time a relatively long distance to the façade of the buildings. There is a need for further development of OSPM in order to describe the complex distribution of emissions in streets, definition of location of calculation point etc. A recently finished PhD study (Ottosen et al., 2015) has implemented the capability to handle inhomogeneous distribution of emissions in OSPM describing emissions according to each lane of the street layout. Development of the possiblity to specify the location of the calculation point is also ongoing as the current calculation point is representative of the facade of buildings. These improvements together with future supporting developments are expected to improve model calculations for complex street layouts, e.g. for HCAB, and will result in a new version of the model in years to come.

2.2.3 Health impact and external cost of air pollution

Model calculations of the health impact and external cost of air pollution has been included in the air quality monitoring programme as a consequence of the revision of NOVANA in 2016. High-resolution assessment of health impacts from air pollution and related external cost has therefore been carried out for Denmark for the years 2014-2016 using the integrated EVA (Economic Valuation of Air Pollution) model system, version 2.5 (Brandt et al., 2015; 2016). A three-year average is used in order to smooth out variations in the meteorological conditions between years. EVA is based on the impact-pathway methodology, where the site-specific emissions will result, via atmospheric transport and chemistry, in a concentration distribution, which together with detailed population data, is used to estimate the population-level exposure. Using exposure-response functions and economic valuations, the exposure is transformed into impacts on human health and related external costs (see figure 2.4).

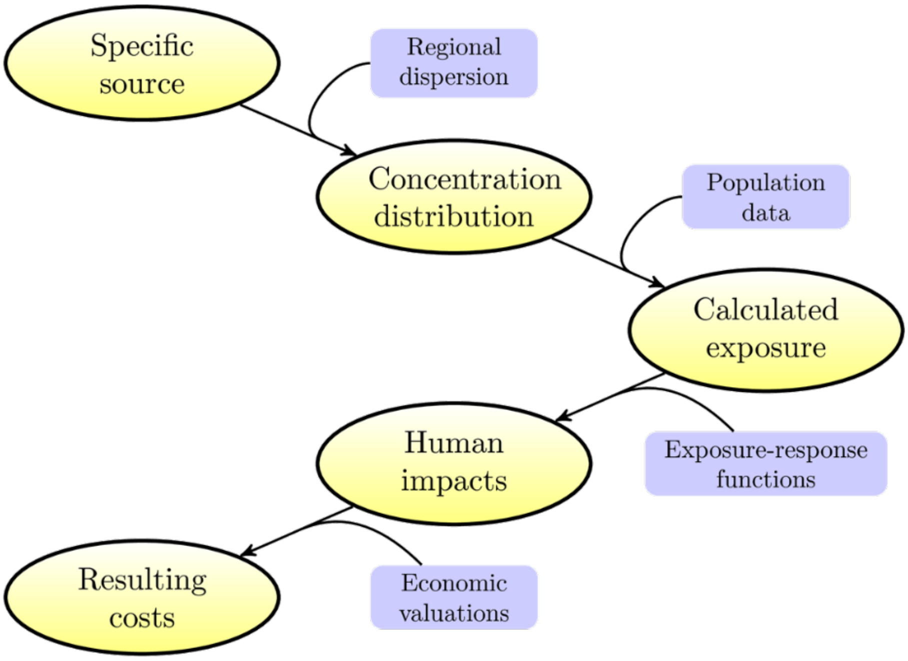


Figure 2.4. An illustration of the EVA model system, based on the impact pathway chain.

The air quality data used in the EVA system is based on a coupling of the two chemistry transport models (DEHM and UBM) described above. table 2.3 shows a comparison between the measured and model calculated annual concentrations of $PM_{2.5}$ at the Danish measurements stations. $PM_{2.5}$ is responsible for the majority of the health impact from air pollution in Denmark. The model calculations give annual concentrations of $PM_{2.5}$ that are slightly lower (18%) than the measured concentrations. This is considered to be in good agreement considering the uncertainties in both measurements and models.

Table 2.3. Comparison of modelled and measured concentraions of $PM_{2.5}$ at all the Danish measurement sites where $PM_{2.5}$ is measured except the street stations. Concentrations are given as three years average of annual averages from 2014 to 2016 except Hvidovre where there are only measurements for the last two years.

	Measurements µg/m³	Model calculations µg/m³
Urban back ground stations		
Copenhagen (HCØ)	11.9	9.0
Aarhus	10.9	8.8
Aalborg	9.8	7.1
Suburban		
Hvidovre	11.1	8.7
Rural background		
Risø	10.9	9.5
Average	10.9	8.6
Average difference		-21%

The population density for Denmark is based on the geographical distribution of the Civil Registration System (CPR data) from 2008, however, the total population is extrapolated to 2016. The individual health impacts in the EVA system is documented in Brandt et al. (2013a) and reviewed in Bønløkke et al. (2011). The economic valuation of the individual health impacts is from Andersen and Brandt (2014) and the methodology for the economic valuation is documented in Andersen et al. (2004) and Bach et al. (2006). The EVA model system has previously been used for assessment of future scenarios (Geels et al., 2015) and has been compared with other health impact assessment systems (Anenberg et al., 2015).

3 Nitrogen oxides

The nitrogen oxides (NO, NO_2, NO_x) are measured at eleven monitoring sites using gas monitors based on chemiluminescence. The concentrations are measured continuously throughout the year with a time resolution of minutes that is aggregated to hourly averages for this report.

3.1 Annual statistics

The annual statistics for 2016 for nitrogen dioxide (NO_2) and nitrogen oxides are shown in table 3.1 and 3.2. There was only exceedance of the annual limit value for NO_2 of 40 µg/m^3 (EC, 2008) at H.C. Andersens Boulevard (Copenhagen/1103). There were no exceedances of the hourly limit value for NO_2 of 200 µg/m^3. This value must not be exceeded more than 18 times in a calendar year (see 19th highest hourly concentration in table 3.1). In 2016 there was no information to the public triggered by exceedance of the information threshold for NO_2 (three hours average must not exceed 400 µg/m^3).

Table 3.1. Nitrogen dioxide (NO_2) in 2016. All parameters are based on hourly averages.

Unit: µg/m^3	Number	Average	Median	98-percentile	19-highest
Street:					
Copenhagen/1257	8075	33	29	87	108
Copenhagen/1103*	7720	47**	44	107	129
Aarhus/6153	8314	31	27	77	101
Odense/9156 §§	4188	20	16	58	71
Aalborg/8151 §	0	-	-	-	-
Urban Background:					
Copenhagen/1259	8262	15	11	47	66
Aarhus/6160	7973	14	10	50	71
Odense/9159	8142	11	8	35	48
Aalborg/8158	8209	13	9	49	75
Suburban:					
Hvidovre/2650	8248	13	10	46	65
Rural:					
Risø	8056	7	5	33	50
Keldsnor/9055	7473	8	6	33	47
Limit value 2010	>7446***	40			200

*) Average for both the old and new position. Position was adjusted in October 2016.

**) Limit value exceeded.

**) 90% data capture of number of hourly measurements in relation to total number of hourly measurements in 2016 excluding hours used for calibration.

§) For Aalborg/8151 (street) there is no data since the station has been shut down due to construction work at the site. It has not yet been possible to reinitiate the measurements in Aalborg (traffic).

§§) The site in Odense/9155 (Albanigade) was affected by a major permanent rearrangement of the roads in Odense. The station changed from a traffic site with relatively high traffic intensity to a site with much reduced traffic intensity. This change took place on 28 June 2014. The station was shut down on 16 June 2015 and has been moved to a new position in summer 2016 and renamed Odense/9156.

Table 3.2. Nitrogen oxides (NO_x=NO+NO_2) in 2016. All parameters are based on hourly averages.

Unit: µg/m^3 (as NO_2)	Number	Average	Median	98-percentile	19-highest
Street:					
Copenhagen/1257	8075	69	50	254	426
Copenhagen/1103 *	7720	116	93	370	556
Aarhus/6153	8314	66	50	227	425
Odense/9156 §§	4188	39	26	171	292
Aalborg/8151 §	0	-	-	-	-
Urban Background:					
Copenhagen/1259	8262	18	13	66	136
Aarhus/6160	7973	19	12	79	213
Odense/9159	8142	14	9	53	116
Aalborg/8158	8209	18	11	77	256
Suburban:					
Hvidovre/2650	8248	18	11	80	281
Rural:					
Risø	8056	9	5	41	93
Keldsnor/9055	7473	9	6	39	71

*) Average for both the old and new position. Position was adjusted in October 2016.

§) Aalborg/8151 (street) there is no data since the station has been shut down due to construction work at the site. It has not yet been possible to reinitiate the measurements in Aalborg (traffic).

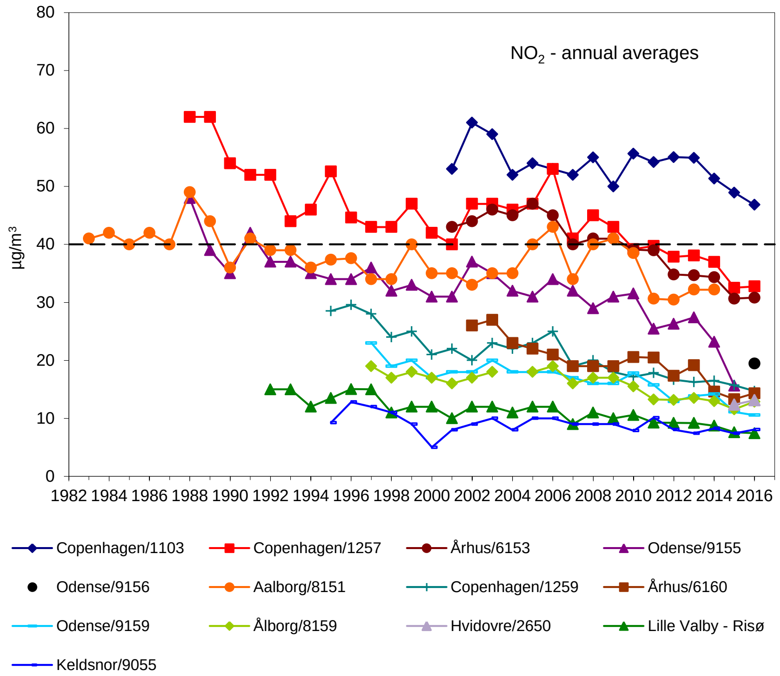
§§) The site in Odense/9155 (Albanigade) was affected by a major permanent rearrangement of the roads in Odense. The station changed from a traffic site with relatively high traffic intensity to a site with much reduced traffic intensity. This change took place on 28 June 2014. The station was shut down on 16 June 2015 and has been moved to a new position in summer 2016 and renamed Odense/9156.

3.2 Trends

The long-term trends for NO_2 and NO_x are shown in figure 3.1. For NO_x there are clear downward trends at all stations. The decreases in the concentrations of nitrogen oxides are due to the national and international regulations of the emissions. The large emission reductions in the cities are achieved by improvement of the vehicles, for example mandatory use of catalytic converters.

For many years the long.term trend for nitrogen dioxide has decreased much slower than observed for NO_x. However, since around 2006 NO_2 has decreased with about the same rate as NO_x. The slow decrease before 2006 was mainly due to an increase in the share of diesel cars and increase in the share of diesel cars with oxidative catalysts where up to about half of the emissions of NO_x consist of NO_2 (called direct NO_2). This increase in the direct emissions of NO_2 counteracted the decrease in the traffic emissions from vehicles. The amount of directly emitted NO_2 reached a maximum in 2009-2011 and has slightly decreased since then. This change in the amount of directly emitted NO_2 is believed to be one of the main reasons why NO_2 now decreases at a similar pace as NO_x.

At Odense street station and Aarhus urban background station there have been large decreases since 2013. In Odense there was a major permanent rearrangement of the roads in Odense Centre that changed the traffic at the street station in Albanigade in two steps from a street with relatively high traffic intensity to a street with much reduced traffic intensity. Finally, the street was closed for traffic in 2015. These changes began on 28 June 2014. This is the reason for the large decrease of the NO_2 and NO_x values for Odense/9155 in 2014 and 2015. The station was shut down on 16 June 2015 and was relocated to Grønnelykkevej and was renamed Odense/9156 in June 2016. The large change at Aarhus/background from 2013 to 2014 is due to the relocation of the measurement site in January 2014 (Chapter 2.1).



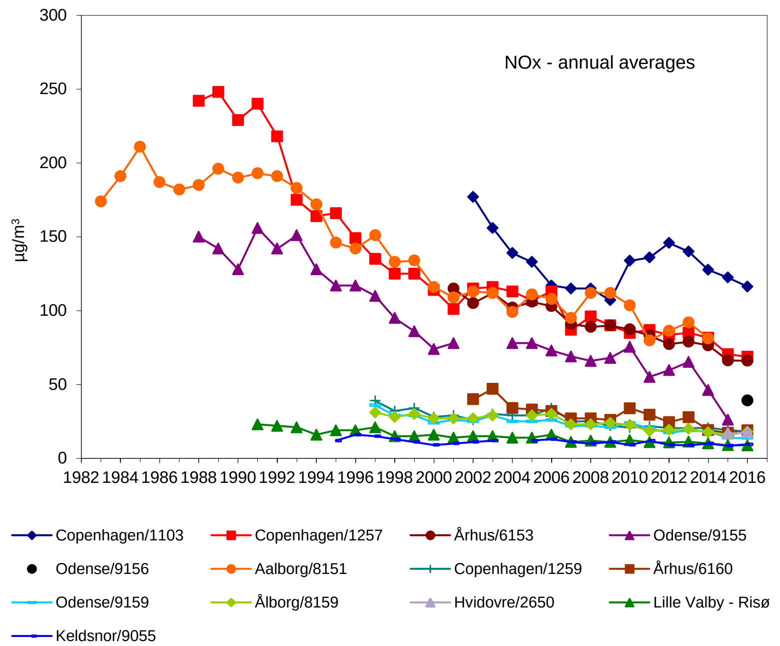


Figure 3.1. The graphs show the time series for the annual average values of NO_2 and NO_x. The dashed line on the upper graph shows the limit value that entered into force in 2010. Results from the previous (6159) and the new background station (6160) in Aarhus are shown on the same curve.

During October 2016 the measurement station at H.C. Andersens Boulevard was moved 2.7 m (corresponds approximately to the width of a traffic lane) further away from the inner traffic lane. The aim of this replacement was to return to the same distance from the traffic lane as it was before 2010 (see Chapter 2.1 for further details). In 2010 the driving lanes were changed at the section of H.C. Andersens Boulevard where the measurement station (Copenhagen/1103) is located. This change moved the traffic closer to the measurement station and resulted in an increase in the annual average concentrations of NO_2 of about 8 µg/m^3 in comparison to the levels measured before the introduction of the new driving lanes. This increase in the concentrations of NO_2 is still observed, although there has been a general reduction of concentrations in line with the observations at other stations e.g. at Jagtvej. Moreover, in 2016 the annual average covers data from both the old and the new position. The data from 2017 will show the full impact of the replacement of the station on the annual average.

3.3 Results from model calculations

Model calculations of NO_2 have been performed for selected streets in Copenhagen (capital) and Aalborg (fourth largest city). The selected streets represent busy streets and are mainly so-called street canyons. Concentrations are elevated in this type of streets due to the high emissions and restricted dispersion conditions. 98 streets were selected in Copenhagen and 31 in Aalborg. ADT (Average Daily Traffic) was between 5,700 and 67,600 vehicles/day in Copenhagen and between 2,700 and 29,800 vehicles/day in Aalborg.

Model calculations have been carried out in order to determine the annual concentrations of NO_2 for comparison with the limit values. The air quality limit value for the annual mean is 40 µg/m^3. The number of streets with exceedances is one of the parameters discussed in the next section. An exceedance is registered if the calculated concentration is higher than 40.5 µg/m^3 since the limit value is given as an integer.

3.3.1 NO_2 model calculations for Copenhagen

The annual mean concentrations of NO_2 for streets in Copenhagen in 2016 are shown in figure 3.2 (bar chart) and figure 3.3 (map). The average of NO_2 street concentrations at all 98 streets decreased slightly from 2015 to 2016 (-1.2 µg/m^3) and the same is true for the average urban background concentrations (-1.7 µg/m^3). However, the regional background contribution slightly increased from 2015 to 2016 (0.4 µg/m^3). The small decrease in street concentrations is a result of a combination of changes in traffic, emission factors, urban background and meteorology. There has been no average change in traffic as the ADT and heavy-duty share remained the same as in 2015 and travel speeds are assumed to be the same as in 2015. However, there have been some changes in ADT and heavy-duty share in between streets. Vehicle emission factors show a decrease due to the general replacement of the car fleet and would lead to a decrease in modelled concentrations, if other paramers were kept equal. However, due to lower wind speed and lower mixing height in 2016 compared to 2015 predicted concentrations become higher than they would otherwise be. In 2016 the limit value for the annual mean concentration was exceeded in 6 out of the 98 selected streets in Copenhagen according to the model results (figure 3.2). This is less exceedances compared to 2015 (9 exceedances). The number of streets exceeding the limit value is very sensitive to small changes in concentrations and uncertainties in the assumptions as can be seen from figure 3.2 where a number of streets are close to the limit value.

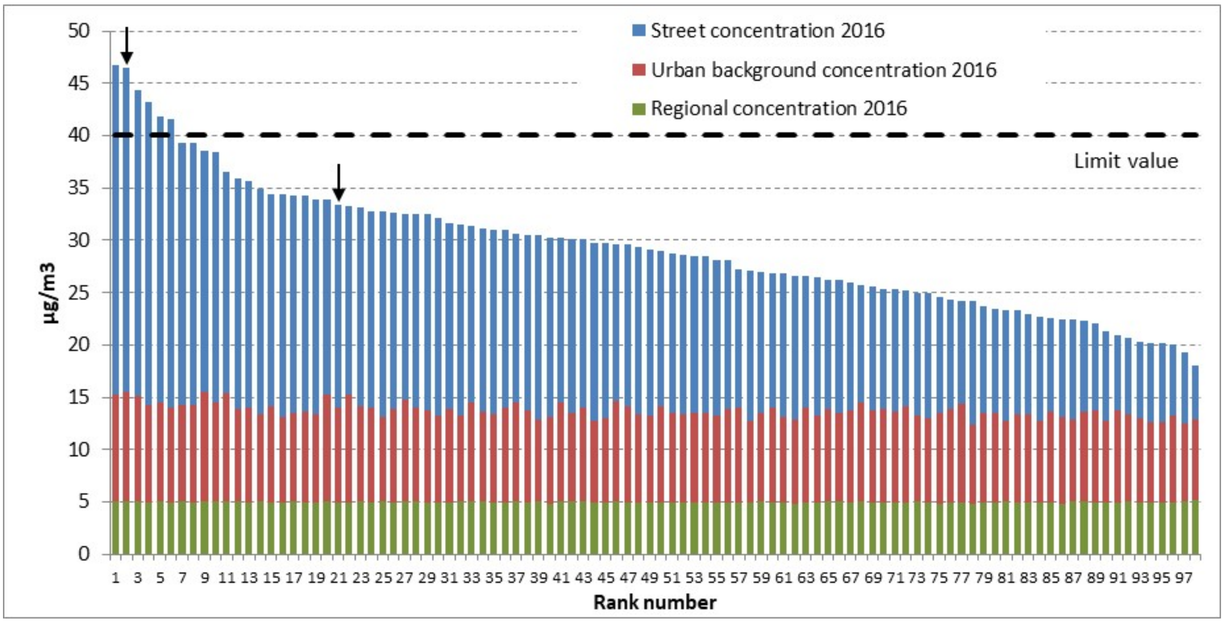


Figure 3.2. Annual mean concentrations of NO_2 in 2016 for 98 streets in Copenhagen according to model calculations. The contribution from traffic in the street canyons is based on the street canyon model OSPM® (blue colour). The urban background (reddish colour) is obtained from calculations with the urban background model UBM with input from the regional scale model DEHM (green colour). The value for a street segment is for the side of the street with the highest annual mean concentration of the two sides. However, for streets with a measuring station it is the side where the station is located. The names of the streets can be seen in table 3.3. Arrows indicate street segments with a measuring station.

The streets where the limit value were exceeded have average daily traffic in the range of 12,800 to 67,600 vehicles per day. However, it is not only the traffic intensity which determines the concentration of NO_2. Also the travel speed, vehicle distribution, and street geometry like the width of the streets, the height of the surrounding buildings, openings in the building facade, orientation of the street and background concentrations and meteorology have impacts on the concentration of NO_2 in a street.

The names of the 98 streets are given in table 3.3 and the locations of the streets together with the annual NO_2 concentration levels are shown in figure 3.3. It is seen that the exceedances are concentrated in the central part of the city and at the main arterial roads from H.C. Andersens Boulevard to Ågade, and also Stormgade and Øster Søgade.

There have been minor changes in the ranking of streets according to NO_2 concentrations from 2015 to 2016 due to mainly small changes in traffic inputs. The highest modelled NO_2 concentration in 2016 is at H.C. Andersens Boulevard (2) (46.7 µg/m^3). The second highest (46.5 µg/m^3) is where the measuring station is located (H.C. Andersens Boulevard (1)). Observed concentrations are 47/41 µg/m^3 (see explanation in table 2.2).

Table 3.3. Rank number and names for the street segments that are shown in figure 3.2 and 3.3. The streets are numbered (1-98) according to NO_2 levels in 2016 (1 = highest, 98 = lowest). The numbers in parentheses refer to different segments of the same street that has more than one model calculation. An asterisk (*) indicates a street segment with a measurement station.

No.	Street name	No.	Street name	No.	Street name
1	H C Andersens Boulevard(2)	34	Torvegade	67	Rebildvej
2	H C Andersens Boulevard(1)*	35	Gammel Kongevej(1)	68	Ingerslevsgade
3	H C Andersens Boulevard(3)	36	Tagensvej(3)	69	Tagensvej(4)
4	Øster Søgade	37	Gothersgade(1)	70	Godthåbsvej(2)
5	Gyldenløvesgade	38	Jagtvej(3)	71	Bülowsvej(2)
6	Ågade	39	Amagerbrogade(1)	72	Jagtvej(2)
7	Åboulevard(1)	40	Frederikssundsvej(8)	73	Røde Mellemvej(1)
8	Åboulevard(3)	41	Nørre Farimagsgade	74	Ålholmvej(2)
9	Stormgade	42	Amagerfælledvej	75	Frederikssundsvej(2)
10	Nørre Søgade	43	Toldbodgade	76	Tuborgvej(1)
11	Bernstorffsgade(1)	44	Søndre Fasanvej(2)	77	Øster Voldgade(2)
12	Vesterbrogade(1)	45	Strandvejen(1)	78	Frederiksborgvej(1)
13	Fredensgade	46	Nørre Voldgade(2)	79	Slotsherrensvej(2)
14	Amagerbrogade(2)	47	Nordre Fasanvej(3)	80	Peter Bangs Vej(1)
15	Frederikssundsvej(3)	48	Godthåbsvej(3)	81	Englandsvej(1)
16	Toftegårds Allé(1)	49	Folehaven(1)	82	Folke Bernadottes Allé
17	Enghavevej	50	Frederikssundsvej(1)	83	Blegdamsvej
18	Tagensvej(2)	51	Ålholmvej(1)	84	Peter Bangs Vej(2)
19	Østerbrogade(4)	52	Tagensvej(1)	85	Dag Hammarskjølds Allé
20	Bernstorffsgade(2)	53	Roskildevej(1)	86	Slotsherrensvej(1)
21	Jagtvej(1)*	54	Jyllingevej(1)	87	Amagerbrogade(3)
22	Lyngbyvej(2)	55	Tuborgvej(2)	88	Vesterfælledvej
23	Bredgade	56	Nørrebrogade	89	Bellahøjvej
24	Nordre Fasanvej(1)	57	Hillerødgade(1)	90	Gammel Køge Landevej(2)
25	P Knudsens Gade(2)	58	Gammel Køge Landevej(1)	91	Halmetgade
26	Tomsgårdsvej(2)	59	Kalvebod Brygge	92	Artillerivej
27	Hammerichsgade	60	Hillerødgade(3)	93	Frederiksborgvej(2)
28	H.C. Ørsteds Vej(2)	61	Grøndals Parkvej	94	Strandvænget(2)
29	Falkoner Alle(2)	62	Frederikssundsvej(5)	95	Vigerslevvej(2)
30	Vesterbrogade(3)	63	Hulgårdsvej(2)	96	Strandvejen(2)
31	Øster Voldgade(1)	64	Østerbrogade(1)	97	Røde Mellemvej(2)
32	Scandiagade	65	Istedgade	98	Englandsvej(2)
33	Vester Farimagsgade	66	Amager Boulevard		

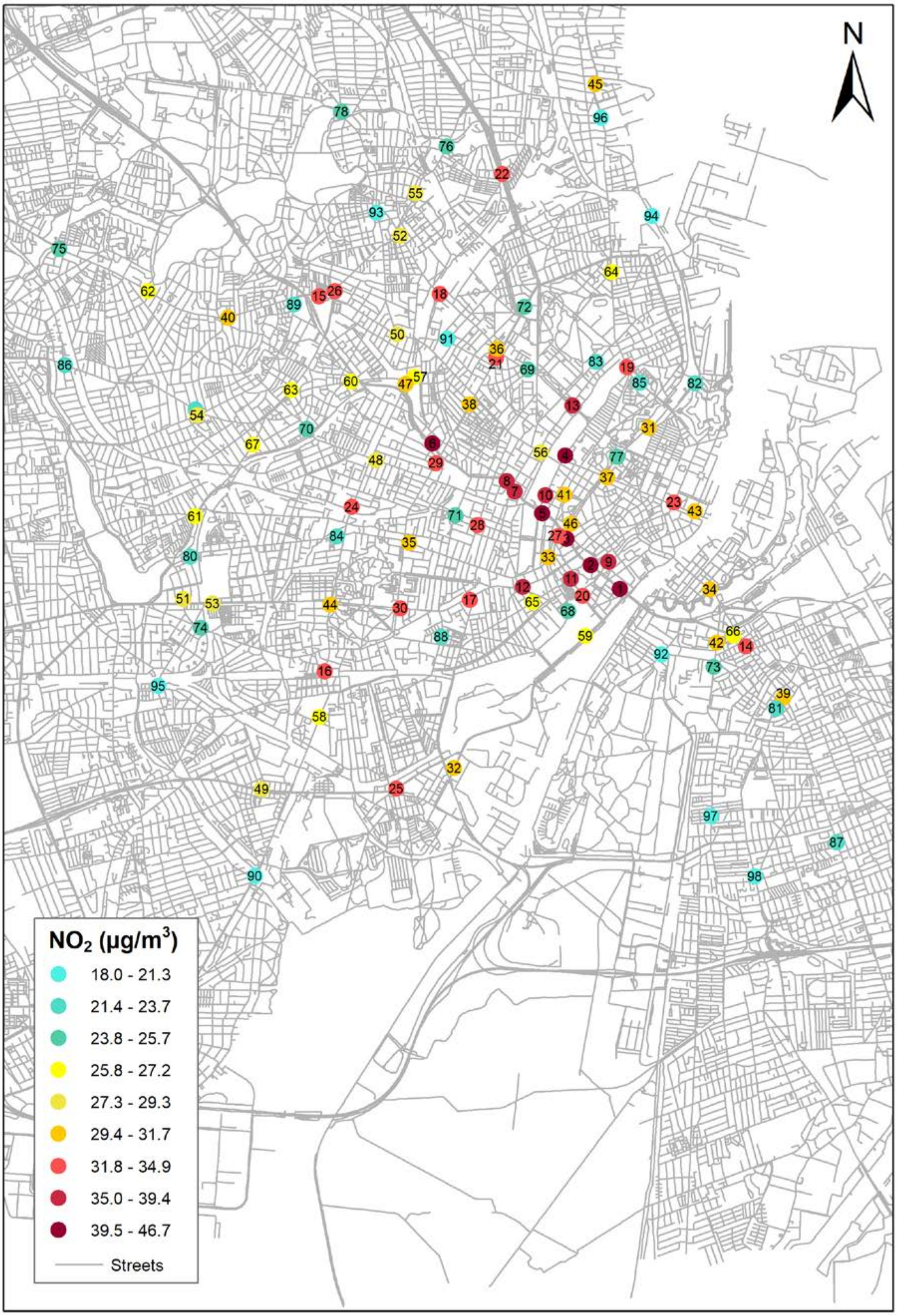


Figure 3.3. Map showing the locations of the selected streets in Copenhagen and the annual mean concentrations of NO_2 for 2016 together with the rank number visualised on top of the calculation point. The contribution from traffic in the street canyons is based on the street canyon model OSPM®. The urban background is obtained from calculations with the urban background model UBM with input from the regional scale model DEHM. The value for a street segment is for the side of the street with the highest annual mean concentration of the two sides. However, for streets with a measurement station it is the side where the station is located. The names and numbers for the streets are shown in table 3.3. The map can be viewed at a webGIS service, see https://arcg.is/1Hv5vz0

3.3.2 NO_2 model calculations for Aalborg

For Aalborg the modelled street concentrations show an average increase of about 10% for NO_2 compared to 2015 when considering all 31 street segments, corresponding to an average increase of about 2 µg/m³. The general increase is a result of a combination of several factors. The contribution from regional and urban background is almost entirely responsible for the modelled increase as urban background concentrations on average increase by about 2 µg/m³. On average ADT increased about 3.1% whereas the heavy-duty share of vehicles was unchanged, and travel speeds were assumed to be unchanged. This would - all other parameters equal - slightly increase concentrations due to these changes in traffic inputs. However, reduced emissions due to replacement of the car fleet should lead to lower concentrations. Overall the street contribution (difference between street and urban background concentrations) is unchanged (0%).

According to the model calculations the limit value for the annual mean concentration in 2016 was not exceeded at any of the 31 selected streets which was also the case in 2015 (figure 3.4 and figure 3.5). The order of some of the streets has changed slightly due to changes in traffic data.

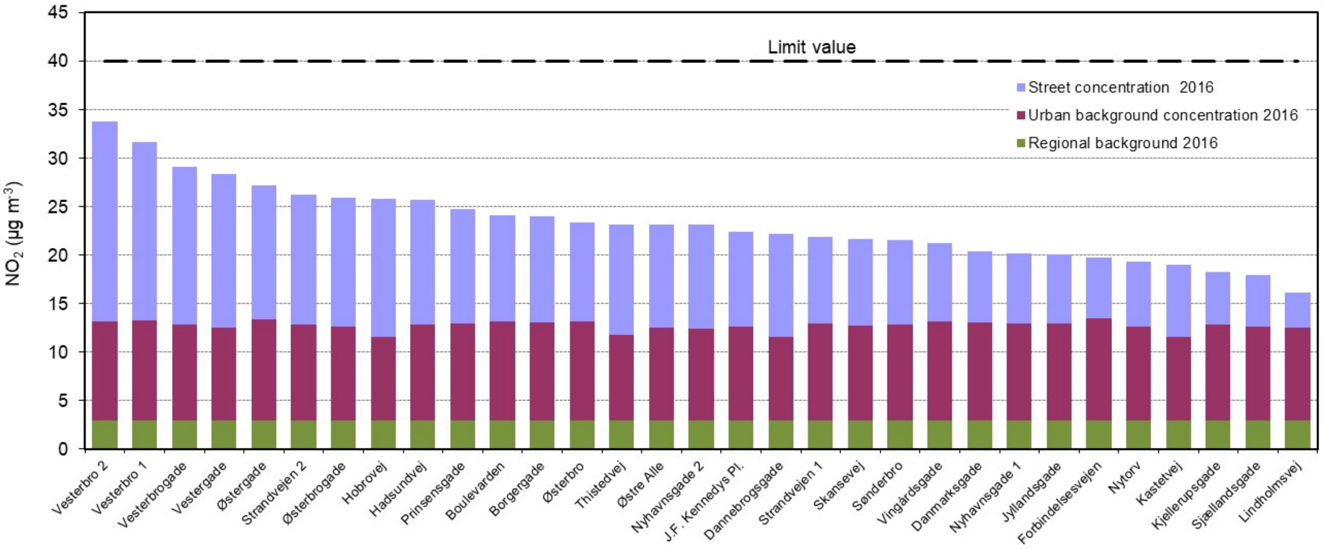


Figure 3.4. Modelled annual mean concentrations of NO_2 in 2016 for 31 streets in Aalborg. The contribution from traffic in the street canyons is based on the street canyon model OSPM® (blue colour). The urban background (dark red colour) is obtained from calculations with the urban background model UBM (reddish colour) with input from the regional scale model DEHM (green colour). The value for a street segment is for the side of the street with the highest annual mean concentration of the two sides. However, for streets with a measurement station it is the side where the station is located. Vesterbro 1 is the street segment where the measurement station is located. However, the station was not operational during 2016 due to nearby building construction works.

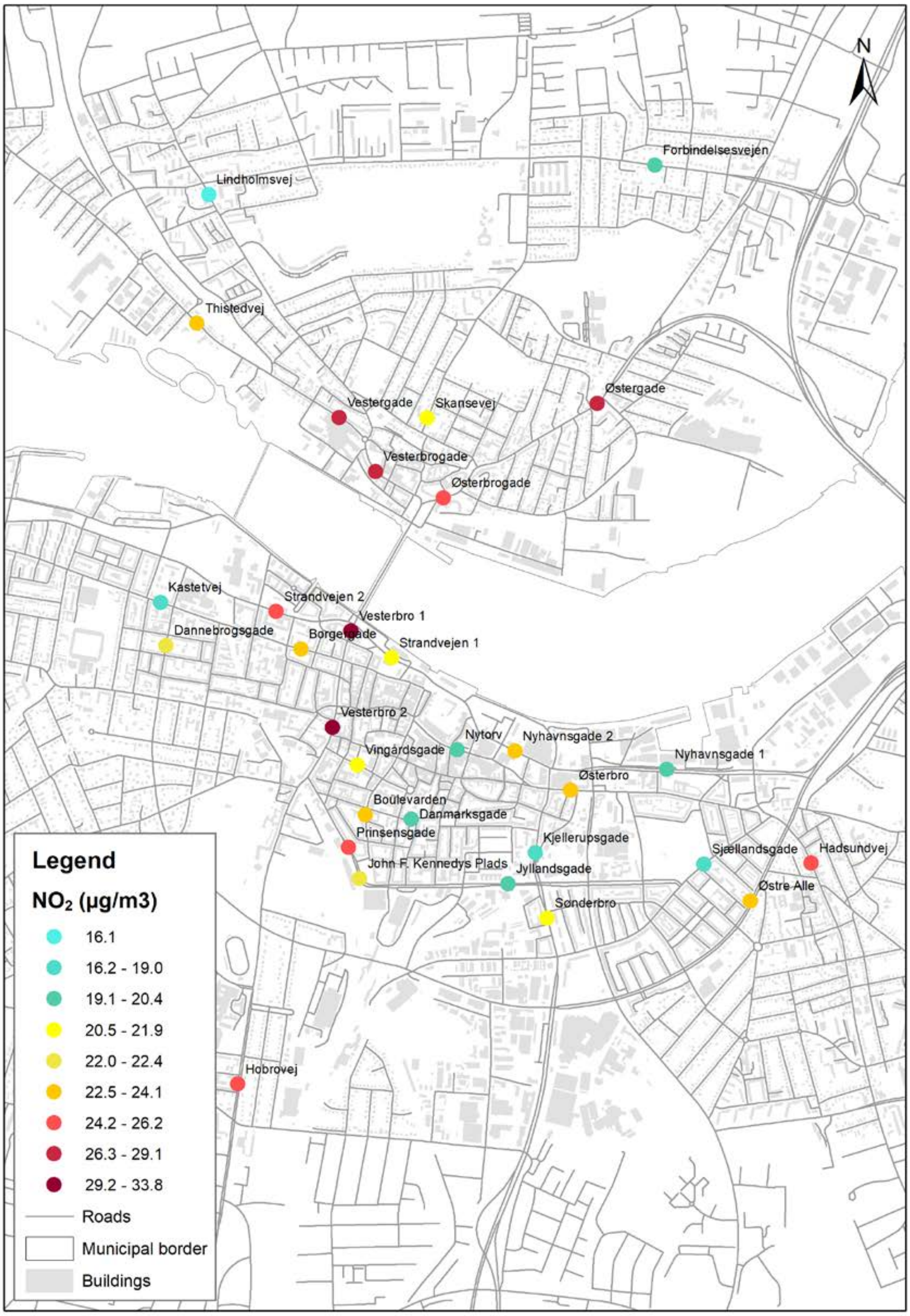


Figure 3.5. Map showing the location of the selected streets in Aalborg and the annual mean concentrations of NO_2 for 2016. The contribution from traffic in the street canyons is based on the street canyon model OSPM®. The urban background is obtained from calculations with the urban background model UBM with input from the regional scale model DEHM. The value for a street segment is for the side of the street with the highest annual mean concentration of the two sides. However, for streets with a measurement station it is the side where the station is located. Vesterbro 1 is the street segment with the measurement station, however, not operating in 2016 due to nearby building construction work. Map can be viewed at a webGIS service, see https://arcg.is/0qnDj9.

3.3.3 Trends in modelled exceedances of NO_2

In figure 3.6 modelled trends in exceedances of annual mean of NO_2 are shown for Copenhagen and Aalborg. The limit value of 40 µg/m³ for annual mean of NO_2 had to be met in 2010 and in previous years the limit value plus a margin of tolerance depending on the year in question had to be met.

For Copenhagen the number of exceedances has decreased from 58 in 2008 to 6 in 2016. The main reason for the increase in number of exceedances in Copenhagen from 32 in 2007 to 58 in 2008 is the following: The limit value plus margin of tolerance for the annual mean concentration of NO_2 decreased from 46 µg/m³ in 2007 to 44 µg/m³ in 2008 (EC, 2008). This decrease naturally leads to a higher number of streets exceeding the limit value plus margin of tolerance in 2008 compared to 2007. If the limit value plus margin of tolerance had been 44 µg/m³ in 2007, then the number of streets exceeding the limit value plus margin of tolerance would have been 53. Roughly the same level as in 2008. In Copenhagen the analysis includes 138 streets during 2007 to 2010 and 98-99 the following years. The reduction of included streets from 2011 and onwards was implemented to better match locations of selected streets with locations with manual traffic counts.

For Aalborg 3-4 exceedances were modelled in 2007-2009 and none since 2010. Here the analysis includes 32 streets from 2007 to 2010, and 31 streets from 2011 onwards.

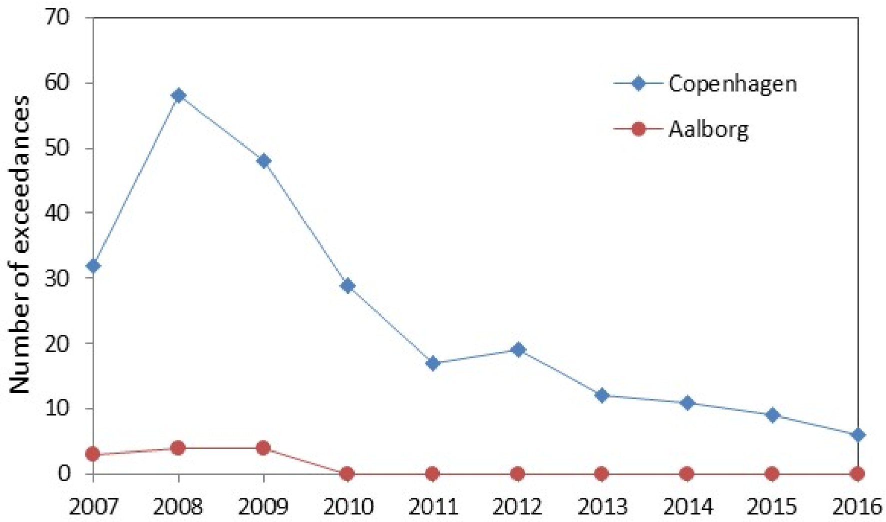


Figure 3.6. Trends in modelled exceedances of annual mean of NO_2 in Copenhagen and Aalborg.

4 Ozone

O_3 is measured at seven monitoring sites using gas monitors based on ultraviolet photometry. The concentrations are measured continuously throughout the year with a time resolution of minutes that is aggregated to hourly averages for the present report.

4.1 Annual statistics

The annual statistics for 2016 for O_3 are shown in table 4.1. The maximum 8-hour daily mean value must not exceed 120 µg/m^3 more than 25 days per calendar year averaged over three years (EC, 2008). This target value was not exceeded for 2014-2016 at any of the stations. The long-term objective (maximum 8-hour daily mean value must not exceed 120 µg/m^3; table 4.1 column 5) was exceeded at six of the stations. However, the long-term objective has not entered into force.

In 2016 there was one exceedance of the information threshold at the Risø station (hourly average 180 µg/m^3). There was no exceedance of the alert threshold (hourly average 240 µg/m^3) for O_3.

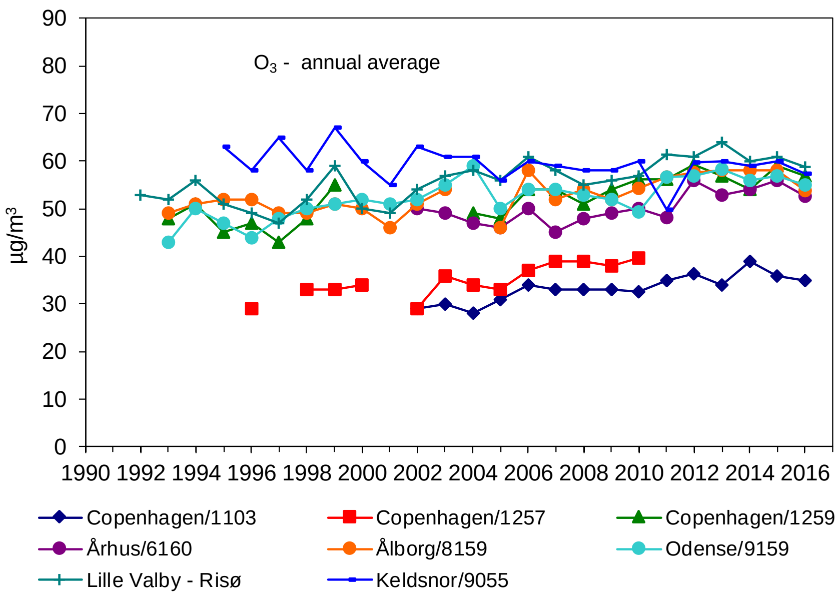
Table 4.1. O_3 in 2016. All parameters are based on one-hour average values. The 8-hour values are calculated as a moving average based on hourly measurements. Days above target value is the number of days that the maximum running 8-hour average exceeds 120 µg/m^3 averaged over 2014-2016.

Unit: µg/m^3	Number of results	Average	Median	Max 8-hours	Days above target value 8-hours	Max 1 hour
Urban Background:						
Copenhagen/1259	7783	57	58	136	3	172
Aarhus/6160	7691	53	54	122	1	158
Odense/9159	7895	55	55	134	7	166
Aalborg/8158	7921	54	55	125	1	143
Rural						
Risø/2090	7809	59	60	152	2	191
Keldsnor/9055	7935	57	59	128	6	169
Traffic						
Copenhagen/1103 §	7430	35	34	93	0	107
Target value*	-	-	-	-	25	-
Long term objective	-	-	-	120	-	-
Information threshold	-	-	-	-	-	180
Data capture**	>7446	-	-	-	-	-

*) As average over 3 years.
**) 90% data capture of number of hourly measurements in relation to total number of hourly measurements in 2016 excluding hours used for calibration.
§) Average for both old and new position.

4.2 Trends

The long-term trends of O_3 are shown in figure 4.1. The annual averages of O_3 have been nearly constant since 1992. The Danish and European reductions of the precursors to O_3 formation (NO_x, volatile organic compounds) have therefore not been sufficient to reduce the concentration. However, the reductions of the precursors have decreased the maximum concentrations of O_3. This is illustrated by the decrease in the maximum eight hour average concentrations.



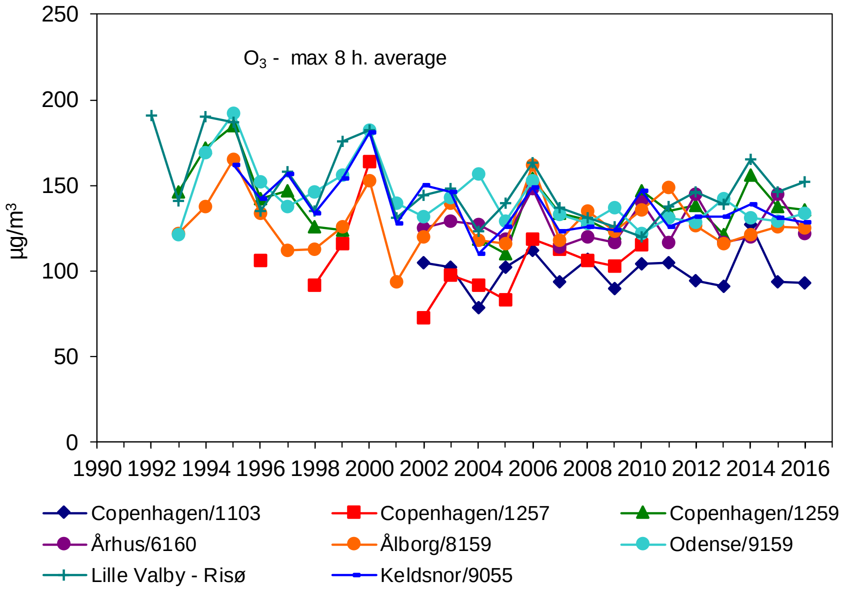


Figure 4.1. Annual average values and the max. 8-hour average value of O_3. The latter is calculated as 8-hourly running averages according to the provisions in the EU Directive (EC, 2008). Results from the previous (6159) and the new background station (6160) in Aarhus are shown on the same curve.

4.3 Results from model calculations

The annual mean concentration of O_3 is fairly constant throughout Denmark (figure 4.2). This is because the main production of O_3 takes place in the southern part of Europe and is subsequently long-range transported to Denmark. At the coasts the concentrations are slightly higher than over the remaining land areas, because O_3 is deposited faster over land than over sea. In the cities the concentrations are lower than the average, because O_3 is degraded by nitrogen oxide emitted from mainly traffic in the cities. This is clearly seen for Copenhagen. Both model results and measurements show O_3 concentrations in 2016 of approximately the same level as in 2015.

The target value for protection of human health is that the running 8-hour mean concentration of O_3 must not exceed 120 $\mu g/m^3$ more than 25 times during a calendar year calculated as an average over three years. The long-term objectives are that the running 8-hour mean concentration of O_3 must not exceed 120 $\mu g/m^3$. The target value and long-term objective are given in the EU Directive (EC, 2008). Results from the model calculations for 2016 show that the number of days with maximum daily 8-hour mean value above 120 $\mu g/m^3$ was well below the target value for the entire country. Highest number of days was seen at coastal areas where the maximum number of days reached 13 days above 120 $\mu g/m^3$ (figure 4.3). The target value that is determined as an average over three years (2014-2016), was not exceeded. However, the long-term objective was exceeded all over Denmark (figure 4.4). The highest 8-hour mean concentrations were observed at coastal areas due to slow deposition over sea and long-range transport of O_3.

According to the directive (EC, 2008) the public has to be informed if the one-hour average concentration exceeds the information threshold at 180 $\mu g/m^3$. Measurements showed that there were one exceedance of the threshold while model calculations gave no excedance in 2016 (figure 4.5). This differnce is beceause model calculations underestimate the maximum one-hour mean concentration with about 10-20%. One of the reasons for this discrepancy is most likely that the model does not include emissions of O_3 precursors from wild fires that are known to increase episodic O_3 concentrations.

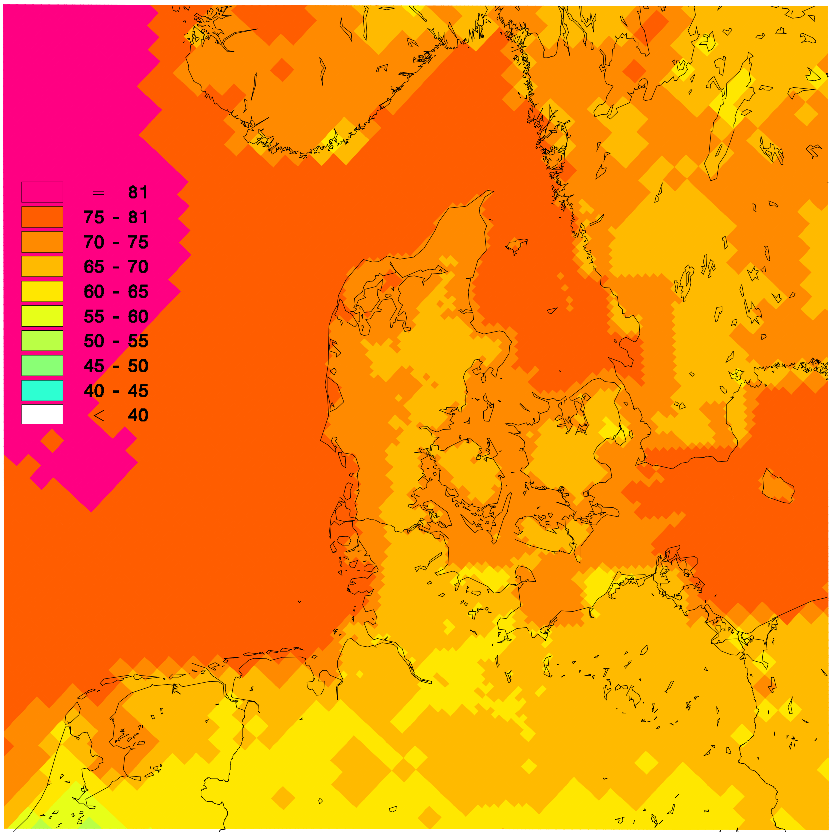


Figure 4.2. Annual mean concentrations of O_3 (µg/m^3) for 2016 calculated using DEHM. The figure shows the average concentrations for the 6 km x 6 km grid cells used in the model.

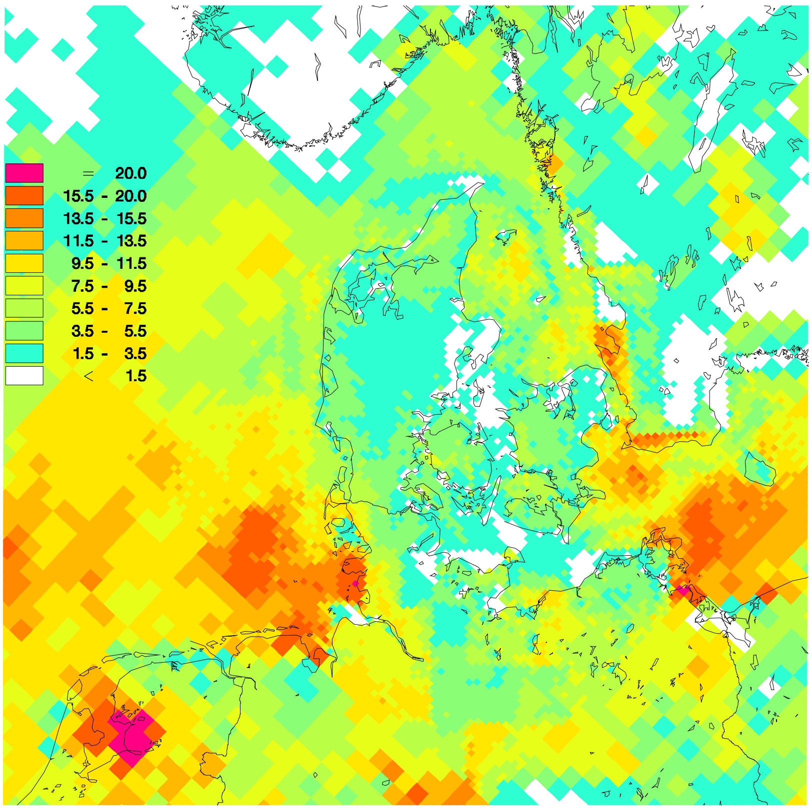


Figure 4.3. Number of exceedances of 120 µg/m^3 for 8-hour running mean concentrations of O_3 in 2016. The calculations were carried out using DEHM.

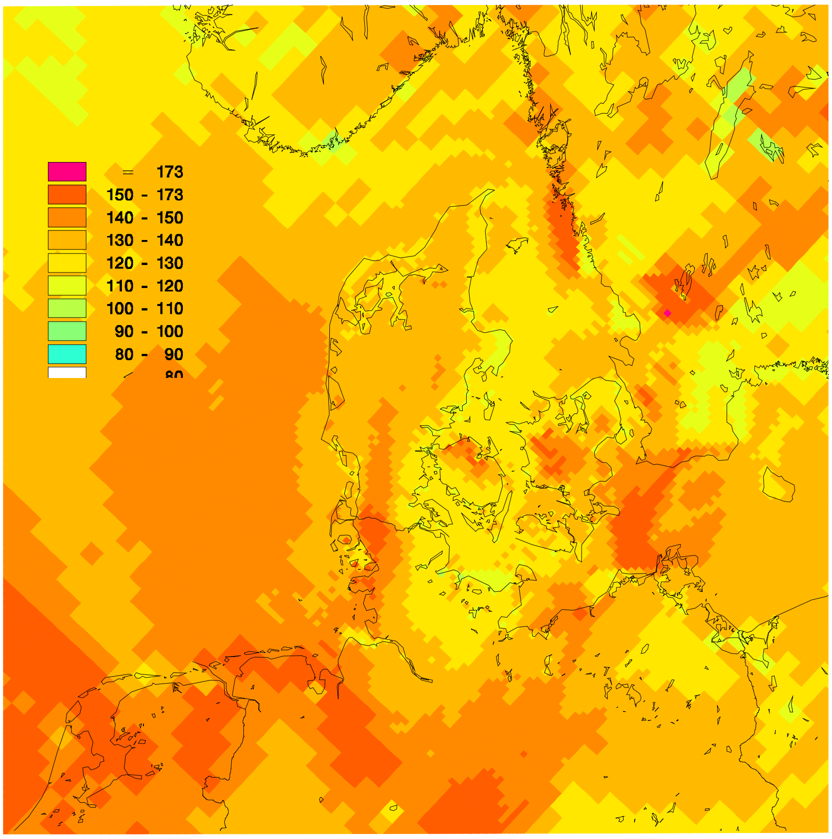


Figure 4.4. Maximum 8-hour running mean concentration (µg/m³) of O_3 in 2016 calculated using DEHM.

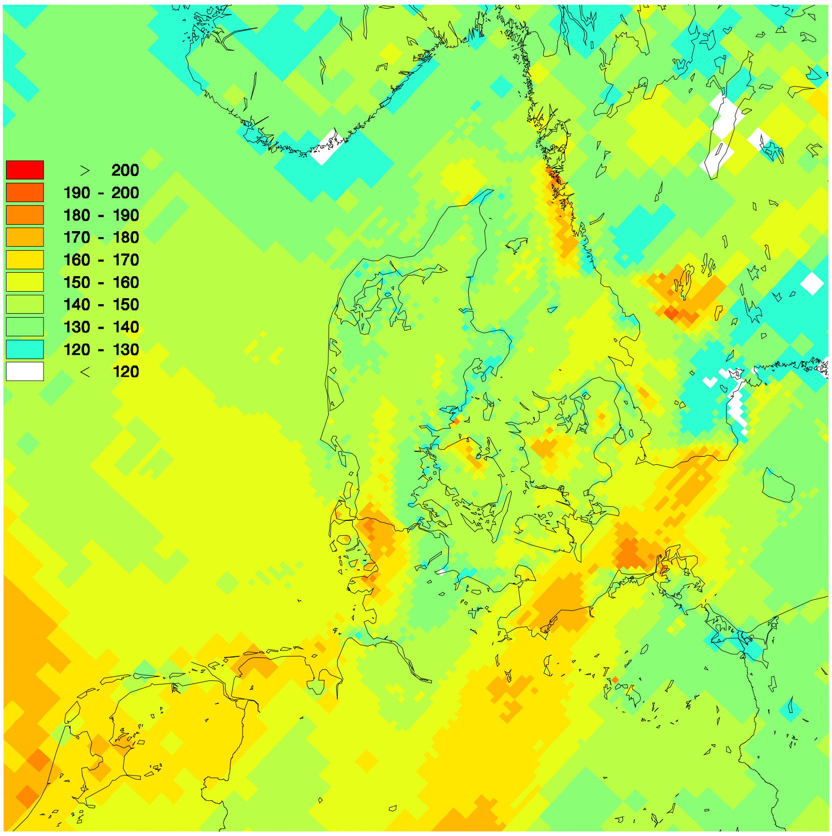


Figure 4.5. Maximum one-hour mean concentration of O_3 (µg/m³) in 2016 calculated using DEHM.

5 Carbon monoxide

CO is at present measured at three traffic oriented monitoring sites (Aalborg street is temporarily closed down), at the urban background site in Copenhagen and at the rural site at Risø using gas monitors based on non-dispersive infrared spectroscopy. The concentrations are measured continuously throughout the year with a time resolution of minutes that is aggregated to hourly averages for this report.

5.1 Annual statistics

The annual statistics for 2016 for CO are shown in table 5.1. The limit value for CO is based on the maximum daily 8-hour average concentration that must not exceed 10,000 µg/m³ (EC, 2008). This limit value was not exceeded at any of the stations.

Table 5.1. Annual statistics for CO in 2016. All parameters are based on hourly average. The 8-hour values are calculated as a moving average based on hourly results.

Unit: µg/m³	Number	Average	Median	98-percentile	99.9-percentile	Max. 8-hours	Max. hour
Traffic:							
Copenhagen/1103*	7493	357	324	755	1268	1240	1925
Århus/6153	8238	246	226	539	877	1112	1382
Odense/9156 §	3954	282	260	604	1423	1413	1808
Aalborg/8151 §§	0	-	-	-	-	-	-
Urban Background:							
Copenhagen/1259	8231	194	184	361	640	645	774
Rural:							
Risø	7938	181	160	419	1096	1246	1356
Data capture**	>7446	-	-	-	-	-	-
EU Limit value	-	-	-	-	-	10 000	-
WHO Guideline values (WHO, 2000)	-	-	-	-	-	10 000	30 000

*) Average of both old and new position.

**) 90% data capture of number of hourly measurements in relation to total number of hourly measurements in 2016 excluding hours used for calibration.

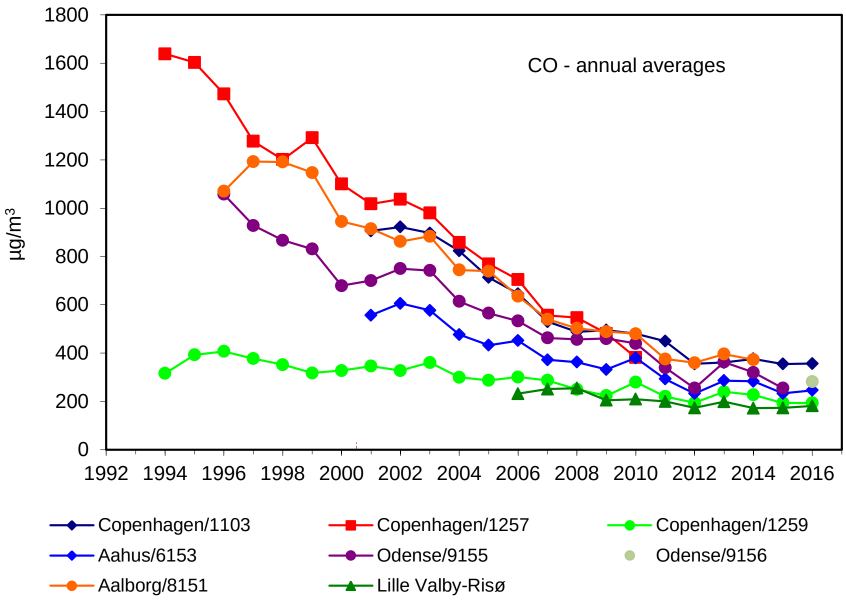
§) The site in Odense/9155 (Albanigade) was affected by a major permanent rearrangement of the roads in Odense. It changed from a traffic site with relatively high traffic intensity to a site with much reduced traffic intensity. This change took place on 28 June 2014. The station was shut down on 16 June 2015 and has been moved to a new position during summer 2016 and was renamed to Odense/9156.

§§) For Aalborg/8151 (traffic) there is no data since the station has been shut down due to construction work at the site. It has not yet been possible to reinitiate the measurements at the street station in Aalborg.

5.2 Trends

The long-term trends for CO are shown in figure 5.1. During the last two decades there has been a large decrease of both the annual concentrations and of the maximum daily 8-hour average concentrations. The reductions are due to national and international regulation of the emissions, among others by requirement of catalytic converters on all vehicles.

At the street stations in Odense/9155 (Albanigade) there was a larger reduction in CO from 2013 to 2015 than at the other stations. This is due to a major permanent rearrangement of the roads in Odense that resulted in a large reduction in the traffic intensity in Albanigade. The street station in Odense was therefore relocated to Grønløkkevej (Odense/9156) where measurements started in June 2016.



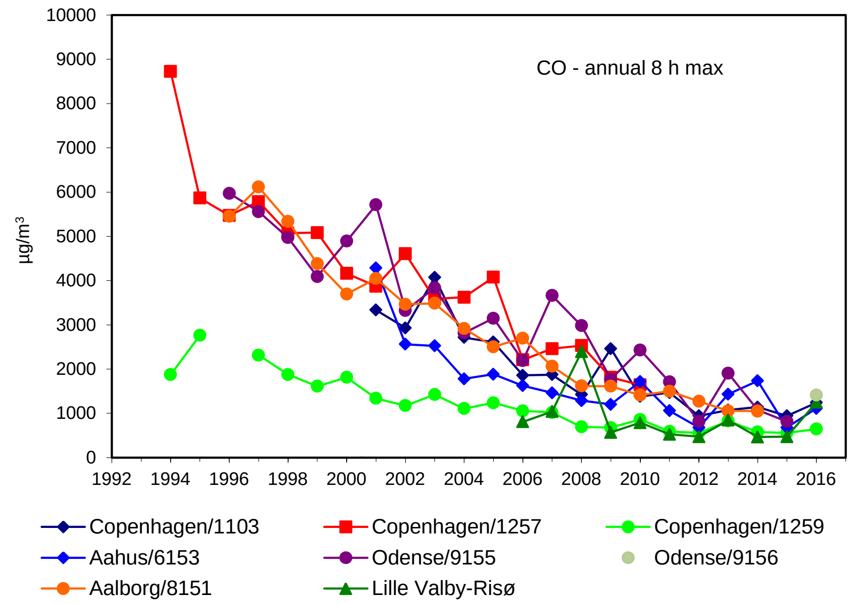


Figure 5.1. Annual average values and highest 8-hour values calculated based on an hourly moving average of CO. The site in Odense/9155 (Albanigade) was due to a major permanent rearrangement of the roads in Odense. It changed from a traffic site with relatively high traffic intensity to a site with much reduced traffic intensity. This change took place on 28 June 2014. A new street station was opened in Odense at Grønnelykkevej in June 2016.

6 Benzene and other Volatile Organic Compounds

This section merges previous years sections on *Ozone Precursors* and *Benzene and Toluene*, all of which are Volatile Organic Compounds (VOC).

Benzene, toluene, ethylbenzene and xylenes are monitored on two kerbside stations in Copenhagen in weekly resolution, i.e. Jagtvej/1257 and H.C. Andersen's Boulevard/1103. These VOCs are collected using passive sampling, and subsequently extracted and analysed by Gas Chomatography MS (GC-MS).

Benzene and toluene are additionally measured in urban background (Copenhagen/1259) with 16 other potential O_3 precursor VOCs in diurnal time resolution. The focus is VOCs of anthropogenic origin, though isoprene which is typically emitted from deciduous trees is included. Air samples are sampled and preconcentrated on Carbopack and analysed using Thermal Desorption Gas Chromatography Mass Spectrometry (TD-GC-MS).

6.1 Annual statistics and trends

Annual averages of benzene and toluene are listed in table 6.1 and 6.2 for 2016. Benzene is well below the EU-limit value of 5 µg/m^3 (EC, 2008), averaging 0.74 and 0.75 µg/m^3 at the kerbside stations, and 0.45 µg/m^3 in urban background. Thus the local input of benzene from traffic amounts to 39% at the kerbside concentration. For toluene, the local input is as high as 58%. Other than traffic exhaust, residential wood combustion is an important source of benzene, and for this reason the summer concentrations of benzene are lower even at kerbside stations. Both kerbside stations in Copenhagen show similar concentrations of anthropogenic aromatic compounds, including toluene and benzene (table 6.1), in spite of their differences with respect to traffic load and buildings close to the street. These VOCs decreased dramatically at the kerbside stations during 2004-2008 (figure 6.1) and has continued to do so, though at a slower yet comparable rate in the urban environment. In fact, benzene has decreased by 44% and 41% at the kerbside station and urban background, respectively, from 2010 to 2016. With respect to toluene, the corresponding decrease is 40%. Of the monitored VOCs at kerbside, toluene is by far the most abundant. Other aromatic compounds are comparable in abundance to benzene (table 6.1).

Table 6.1. Annual statistics for benzene, toluene, ethylbenzene and xylenes in 2016 based on weekly average concentrations (µg/m³) at kerbside stations Jagtvej (1257) and H.C. Andersens Boulevard (1103) at 1 atm., 293 K. The limit value for benzene is 5 µg/m³ (EU Directive 2008/50/EC).

Concentration µg/m³	Copenhagen/1103	Copenhagen/1257	Number of results
Benzene	0.75	0.74	48, 52
Toluene	1.87	1.95	48, 52
Ethylbenzene	0.47	0.38	48, 52
m/p-Xylene	1.21	1.27	48, 52
o-Xylene	0.49	0.48	48, 52

Benzene is not measured directly in Aarhus and Odense. However, an objective estimate of the concentrations can be used to determine the concentration levels, since the concentrations are below the lower assessment threshold limit.

The objective estimate for benzene is based on the correlations between the average concentrations of benzene and CO. Ellermann et al. (2011) documented that the benzene concentrations can be estimated based on the simple empirical model:

$$\text{Benzene} = 0.0044 \cdot \text{CO} - 0.37$$

where benzene and CO are in units of µg/m³. Based on this and the concentrations of CO (table 5.1) the annual average concentrations of benzene is estimated to about 0.7 µg/m³ for all the three street stations in Aarhus, Odense and Aalborg in 2016.

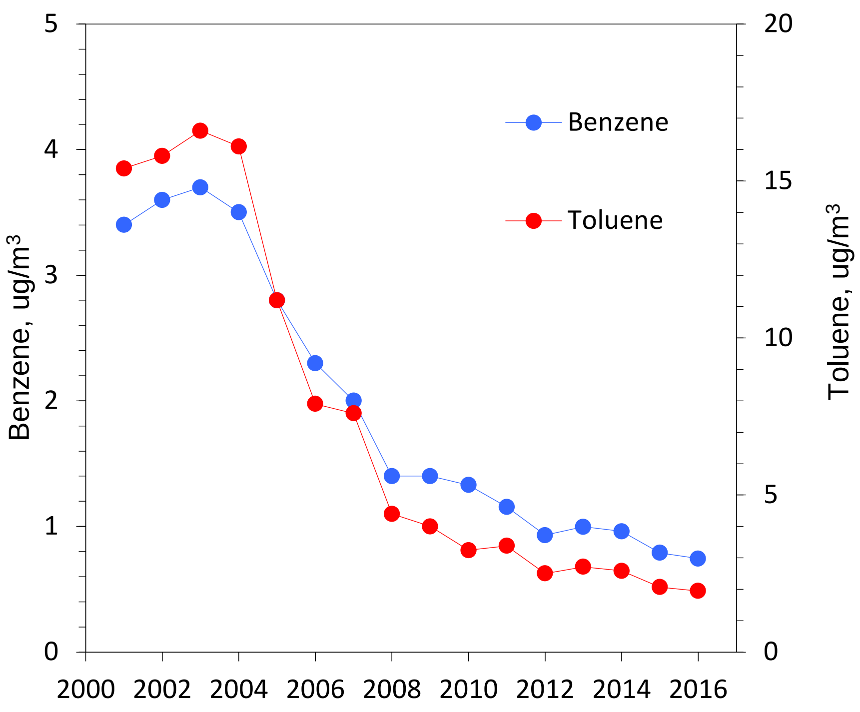


Figure 6.1. Trend in benzene and toluene (annual averages) on the kerbside station Jagtvej, Copenhagen/1257.

The main reasons for the significant decrease of benzene and toluene up to 2008 are reductions of the emissions from gasoline-fueled traffic due to increased use of catalysts and higher ratio of diesel cars.

Table 6.2. Annual statistics for VOCs in urban background in Copenhagen (1259) based on daily average concentrations (1 atm., 293 K).

Concentration (µg/m³)	**Annual average 2010**	**Annual average 2016**	**Data coverage**
1-Pentene	0.04	0.03	83%
n-Pentane	0.53	0.57	89%
Trans-2-pentene	0.02	0.01	82%
Isoprene	0.03	0.05	86%
2-Methylpentane	0.31	0.22	78%
n-Hexane	0.19	0.14	69%
Benzene	**0.75**	**0.45**	**86%**
n-Heptane	0.28	0.15	89%
2,2,2-Trimethylpentane	0.10	0.05	76%
Toluene	**1.36**	**0.82**	**83%**
n-Octane	0.08	0.04	89%
Ethylbenzene	0.28	0.14	89%
m,p-Xylene	0.78	0.42	89%
o-Xylene	0.41	0.16	89%
1,3,5-Trimethylbenzene	0.10	0.01	84%
1,2,4-Trimethylbenzene	0.34	0.11	89%
1,2,3-Trimethylbenzene	0.09	0.03	89%
Sum of VOCs	5.68	3.39	

Measurements of mainly anthropogenic volatile organic compounds in urban background, which may act as O_3 precursors, were initiated in 2010 in the urban background. The major O_3 precursors are the aromatic compounds: benzene, toluene, ethylbenzene, xylenes and trimethylbenzenes (TMB), which are also measured at the kerbside stations in Copenhagen (1103 and 1257), and the C_5-C_7 alkanes: pentane, 2-methylpentane hexane and heptane. The more reactive unsaturated compounds are less abundant (table 6.2).

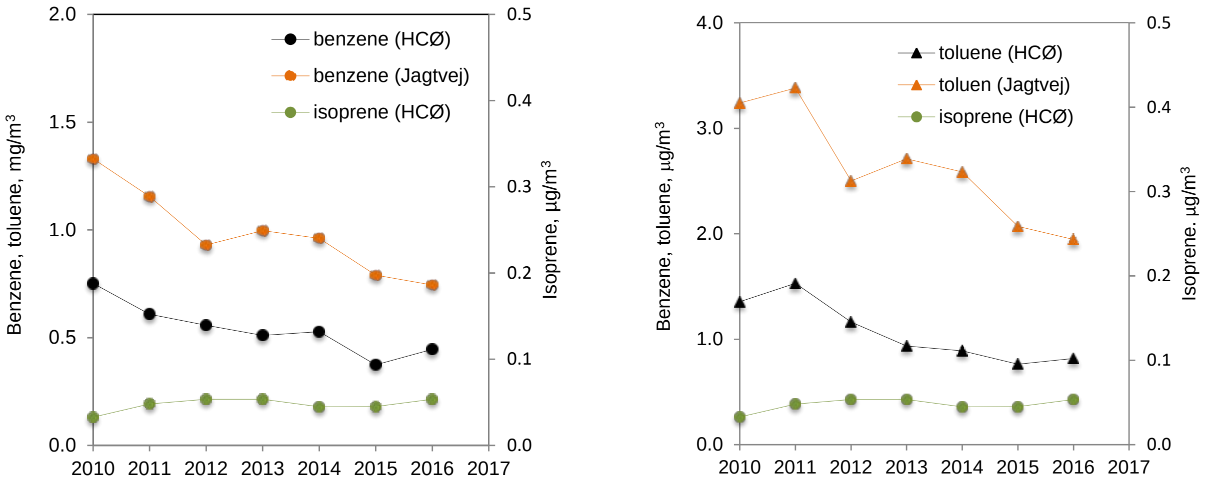


Figure 6.2. Annual average concentrations of benzene (left) and toluene (right) at the kerbside station, Copenhagen/1257, and at urban background, Copenhagen 1259. Ispoprene that is predominantly naturally emitted, is also shown for comparison.

The annual isoprene concentration has remained fairly constant from 2010-2016. Isoprene origins mainly from natural sources, e.g. terrestrial vegetation and peaks in the warmer summer months June, July and August with low concentrations in the winter months. One the contrary, the mainly anthropogenic compounds benzene and toluene has decreased in concentrations at comparable rates in both urban background and kerbside within this period (figure 6.2), thoug not as pronounced as from 2001-2008 (figure 6.1). Except for n-pentane, all anthropogenic VOCs either stayed constant during 2010-2016 or decreased.

The urban background ratio between toluene and benzene is somewhat smaller than both kerbside stations, i.e. 2.0 versus 2.6 reflecting the higher toluene/benzene ratio in traffic exhaust compared to e.g. the toluene/benzene ratio from biomass combustion in ambient air.

7 Particles (TSP, PM_{10}, $PM_{2.5}$ and particle number)

The measurements of particles (PM_{10} and $PM_{2.5}$) are today primarily carried out using EU's reference method (EN 12341: 2014, into which the previous standards for PM_{10}, EN 12341: 1998, and for $PM_{2.5}$, EN 14907:2005, have been merged). The basic measuring principle of the reference method uses LVS i.e. a flow of 2.3 m^3/hour on a diurnal basis with subsequent gravimetric determination of the sampled mass in the laboratory. Finally the particle samples were analysed in the laboratory.

The LVS-sampling method has during the period from 2012 to 2016 gradually replaced the old SM200 beta (β) samplers (manufactured by OPSIS, Sweden) that collect particles on filters on a diurnal basis with subsequent determination of the sampled mass using β-absorption technique. This method is equivalent with the reference method. Comparison of the two methods have not documented any systematic deviation between the two measuring methods except for an improved reproducibility and data capture using the LVS instruments.

Additionally, PM is measured using a TEOM (Tapered-Element Oscillating Microbalance) instrument at the Copenhagen street station HCAB (PM_{10} and $PM_{2.5}$) and at the rural station at Risø (PM_{10} and $PM_{2.5}$). The TEOM measurements have a time resolution of 30 minutes (table 7.3 and 7.4) and enables near real time reporting of the data to the public. During sampling the collected particles are heated to 50°C. At that temperature some of the VOCs evaporate (mainly secondary aerosols). The loss will depend of the actual composition of the aerosols. The European Commission has accepted that measurements of PM using TEOM could be applied with a default correction factor of 1.3. However, the correction factor depends e.g. on the specific measurement site and seasonality and correction of TEOM measurements of PM using a correction factor of 1.3 do therefore have considerable uncertainty.

Measurements of particle numbers have been carried out since 2002 in cooperation between the monitoring programme and research projects financed by the Danish Environmental Protection Agency. The measurements have been carried out using a Differential Mobility Particle Sizer (DMPS) that counts particles with mobility diameter between 6 and 700 nm. In 2016, additional measurements were started at the measurement station in Hvidovre using a Scanning Mobility Particle Sizer (SMPS) with mobility diameter measured between 11 and 478 nm.

7.1 Annual statistics

In 2016, the permitted number of exceedances in a year of the diurnal limit value of 50 μg/m^3 for PM_{10} was not exceeded at any stations in the measuring network, even at stations where exceedances previously have occurred (the two traffic stations in Copenhagen (HACB/1103 and Jagtvej/1257)). Likewise, there were no exceedances of the annual limit value for PM_{10} (40 μg/m^3) and $PM_{2.5}$ (of 25 μg/m^3) at any measuring station.

The EU-directive on air quality (EC, 2008) prescribes that the national average exposure indicator (AEI) has to be determined based on three years average of the average urban background concentration of $PM_{2.5}$. In Denmark the average exposure indicator is measured in urban background at Copenhagen/1259, Aarhus/6159 and Aalborg/8158. For the years 2014-16 the AEI is determined to 11 µg/m³ which is a decrease of about 20% since 2010.

In 2016, the number of particles in ambient air was about 13,000 particles per cm³ at the street station H.C. Andersens Boulevard (table 7.5). This is a factor of about 3.5 higher than suburban and 4.5 higher than in urban background and rural background, respectively.

Table 7.1. Annual statistics for PM_{10} in 2016. All parameters are given as diurnal averages at ambient temperature and pressure.

Unit µg/m³	Number of results	Average (µg/m³)	Median	Days above 50 µg/m³	90-percentile	Max. day
Street						
Copenhagen/1103[1]	332	28	26	11	43	80
Copenhagen/1257[1]	361	23	21	6	36	70
Aarhus/6153[1]	364	20	18	2	30	56
Odense/9156[1] §	180	19	18	0	30	42
Urban background						
Copenhagen/1259[1]	353	15	14	0	25	46
Rural						
Risø[1]	357	14	12	0	23	46
Keldsnor/9055[2]	334	16	14	1	27	52
Limit value (2005)		40		35**		
90% data capture	>329*					

[1] Measurements based on low volume sampling with gravimetric determination of particle mass.

[2] Combination of low volume sampling and SM200 beta absorption measurements of particle mass.

* 90% data capture of number of diurnal measurements in relation to the total number of days in 2016 (366).

**Permitted number of exceedances in a year of the diurnal limit value of 50 µg/m³.

§ During the course of 2015-16 the traffic station Odense/9155 (Albanigade) was relocated and the PM_{10} measurements with LVS were started at the new site with the name Odense/9156 (Grønlykkevej) from the July 2016.

Table 7.2. Annual statistics for $PM_{2.5}$ in 2016. All parameters are given as diurnal averages at ambient temperature and pressure.

Unit µg/m³	Number of results	Average (µg/m³)	Median	90-percentile	Max. day
Street					
Copenhagen/1103	329	15	13	25	46
Copenhagen/1257	358	13	11	23	51
Aarhus/6153	365	12	10	22	42
Aalborg/8151*					
Suburban					
Hvidovre/2650	346	10	8	19	39
Urban background					
Copenhagen/1259	331	10	8	17	41
Aarhus/6159	365	12	10	22	42
Ålborg/8158	335	9	7	15	40
Rural					
Risø[1]	357	9	7	17	42
Limit value (2015) (parenthesis gives proposed value for 2020)		25(20)			
90% data capture	>329**				

Measurements at all stations in 2016 were based on low volume sampling (LVS) with gravimetric determination of particle mass

* No data from Aalborg/8151 (traffic site) in 2016 because the station is closed temporarily due to construction work.

**90% data capture of number of diurnal measurements in relation to the total number of days in 2016 (366)

Table 7.3. Annual statistics for PM_{10} measured in 2016 using TEOM. The values are based on ½-hourly averages. Total annual number of ½-hours is 17,568.

Unit: µg/m³	Number of results	Average	Average x 1.3
Street			
Copenhagen/1103	16147	31	40
Rural			
Risø	15778	12	15
Limit value			40

Table 7.4. Annual statistics for $PM_{2.5}$ measured in 2016 using TEOM. The values are based on ½-hourly averages. Total annual number of ½-hours is 17,568.

Unit: µg/m³	Number of results	Average	Average x 1.3
Street			
Copenhagen/1103	15448	11	14
Rural			
Risø	16039	7	9
Limit value (2015) (parenthesis gives proposed value for 2020)			25 (20)

Table 7.5. Annual statistics for particle number measured in 2016. All values are based on ½-hourly averages. Total annual number of ½-hours is 17.568.

Unit: particles per cm^3	Number of results	Average
Street		
Copenhagen/1103*	7554	13028
Urban Background		
Copenhagen/1259*	7027	2925
Suburban		
Hvidovre/2650**	14405	3737
Rural		
Risø*	13527	2966

* Measured with DMPS (6nm – 700 nm)

** Measured with SMPS (11nm – 478 nm)

DMPS and SMPS measure slightly different size ranges of particles. It is estimated that less than 10% of the particles are in the size range from 6nm – 10nm plus 479nm – 700nm. The underestimation of the SMPS measurements due to the slightly narrower size range compared to the DMPS measurements is therefore estimated to be less than 10%.

7.2 Trends

Up to the year 2000 PM was measured as Total Suspended Particulate matter (TSP) corresponding to particles with a diameter up to around 25 µm (figure 7.1). The exact cut-off depends strongly on the wind velocity. From 2001 most of the measurements of particulate matter were changed from TSP to PM_{10} according to the EU directive adopted in 1999 (EC, 1999) and PM_{10} measurements were started at all stations except Copenhagen/1103 where the TSP measurements were continued to the end of 2005. The TSP is on the average 30-80% higher than PM_{10} at the street stations, while the difference is less at urban background and rural sites.

The measurements show a tendency for a decrease in PM_{10} at all the measurement stations since 2001, where the measurements began (figure 7.2). Although the measurements at HCAB (Copenhagen/1103) began later, there is also a decrease in PM_{10} at this station. However, this is mainly due to a major reduction (7 µg/m^3) in PM_{10} from 2008 to 2009. Detailed examination of all the measurements at HCAB showed that the main reason for this decrease from 2008 to 2009 was new asphalt surface on the road laid out during August and September 2008 (Ellermann et al., 2010) that significantly reduced dust generation from road abrasion.

The site in Odense/9155 (Albanigade) was affected by a major permanent rearrangement of the roads in Odense. It changed from a traffic site with relatively high traffic intensity to a site with much reduced traffic intensity. This change took place on 28 June 2014. This has affected the measured PM_{10} levels in the second half of 2014 and this is the reason why there is unchanged PM_{10} value for Odense/9155 in 2014 while all the other traffic stations display an increase in 2014 compared to 2013. In 2015, the road next to the measuring station was closed for traffic. PM_{10} measurements from Odense/9155 (Albanigade) for 2015 do not represent a traffic site but rather have character of an urban background site. In the process of relocating the station the PM_{10} measurements were closed down the 15 June 2015. The PM_{10} measurements at the new traffic station in Odense/9156 (Grønløkkevej) were initiated 1 July 2016.

The measurements of $PM_{2.5}$ started in 2007 at Copenhagen/1103 and at the other stations in 2008. Figure 7.3 presents all the results from diurnal measurements of $PM_{2.5}$ until now. There seems to be a tendency towards a small reduction in $PM_{2.5}$, although this tendency is uncertain due to the relatively short period with measurements.

The AEI for $PM_{2.5}$ is determined as the average $PM_{2.5}$ measured at urban background in Copenhagen, Aarhus and Aalborg over a three-year period. Thus e.g. the 2010 AEI value represents the average of the years 2008-10. The trend for AEI is shown in figure 7.4 and as seen for $PM_{2.5}$ itself, there is a small reduction in the AEI, although this tendency is uncertain due to the relatively short period with measurements and the large interannually variation in $PM_{2.5}$ due to the natural variations in the meteorological conditions. Over the period 2010 to 2016 the AEI has been reduced with about 20%.

The measurements show a significant reduction of particle number concentration in ambient air over the entire measuring period (figure 7.5). On HCAB the number of particles has decreased about 50% during the period 2002-2016. At the urban background station (HCØ) particle numbers show a similar decrease of about 50% for the same period. At the rural background station (LVBY/Risø) over the period 2005-2016 a reduction in particle numbers was also observed, though the decrease is only about 30%.

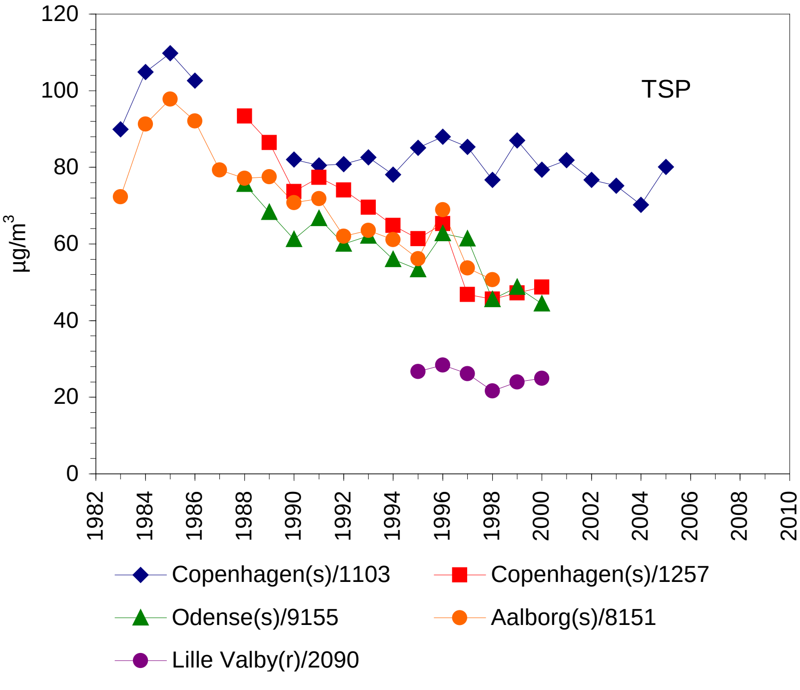


Figure 7.1. Annual averages for TSP measured at street stations (s) and at rural background station (r).

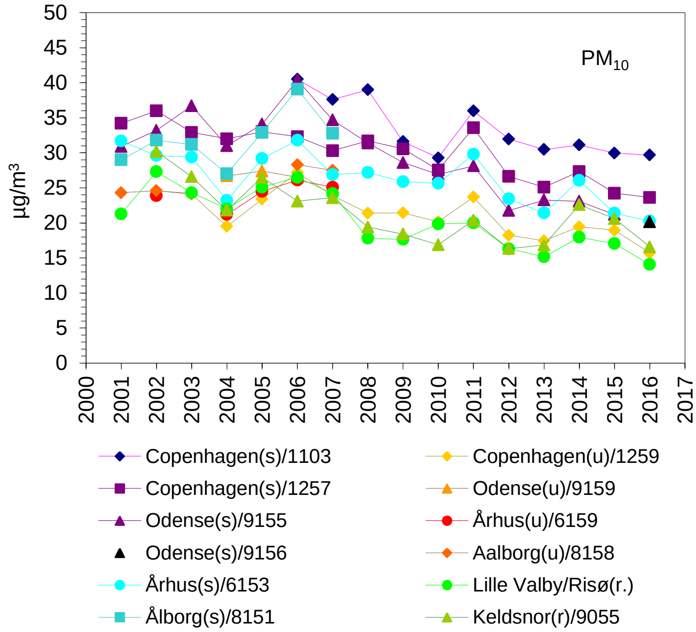


Figure 7.2. Annual averages for PM_{10} measured at street stations (s), urban background stations (u) and at rural background stations (r). The change from gravimetric determination using the SM200 as a filter sampler to the use of the same instrument as a β-gauge from 2006 gives rise to a 5-10% increase due to the shift in method. The value for PM_{10} at Copenhagen/1103 in 2008 and 2009 is based on the measurements with SM200 in combination with an estimated value. Data are given at standard temperature- and pressure conditions (0ºC and 1 atm.). PM given at ambient temperature and pressure conditions is on an annual average approximately 3-4% lower than PM-results given at standard conditions. The measurements in Odense/9155 (Albanigade) were stopped the 15 June 2015 whereafter the station was relocated to a new street site where the PM_{10} measurements with LVS were started from 1 July 2016 with the name Odense/9156 (Grønlykkevej).

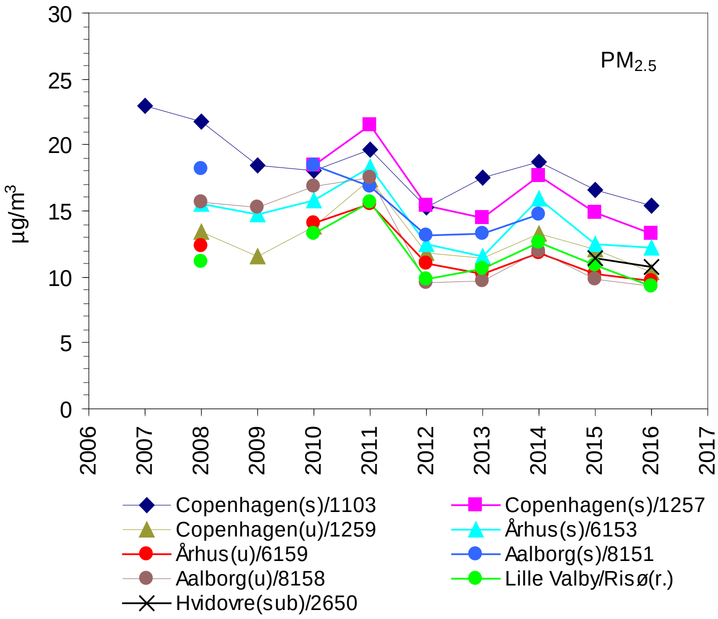


Figure 7.3. Annual averages for $PM_{2.5}$ measured at street (s), suburban (sub), urban background (u) and at rural background station (r). Only annual averages covering more than 2/3 of the years are shown except for the newly established suburban station at Hvidovre (began in 17 June 2015) and Aalborg(s) for 2014 (data covering the period 1/1 - 7/9). Data are given at standard temperature- and pressure conditions (0ºC and 1 atm.). PM given at ambient temperature and pressure conditions is on an annual average approximately 3-4% lower than PM results given at standard conditions.

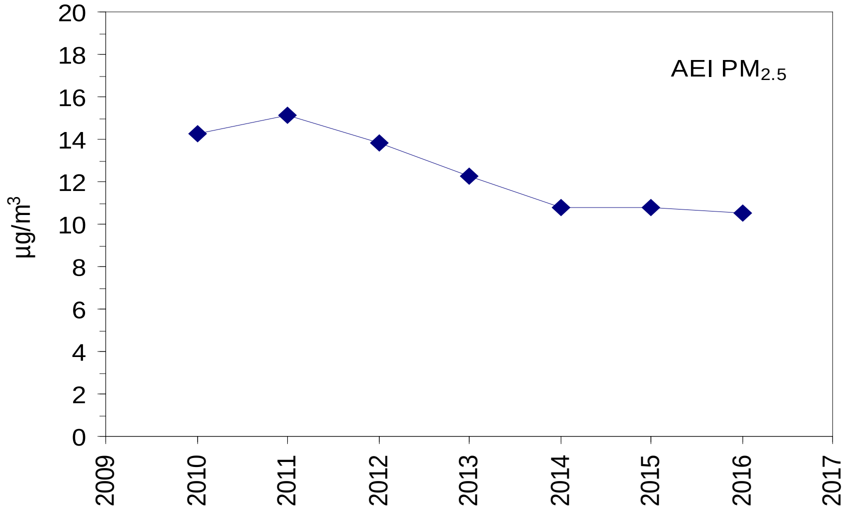


Figure 7.4. The trend for AEI for $PM_{2.5}$. AEI is determined as the average $PM_{2.5}$ measured at urban background in Copenhagen, Aarhus and Aalborg averaged over a three year period. The value shown for 2010 corresponds to the average of the concentrations for 2008 to 2010 and likewise for the other years.

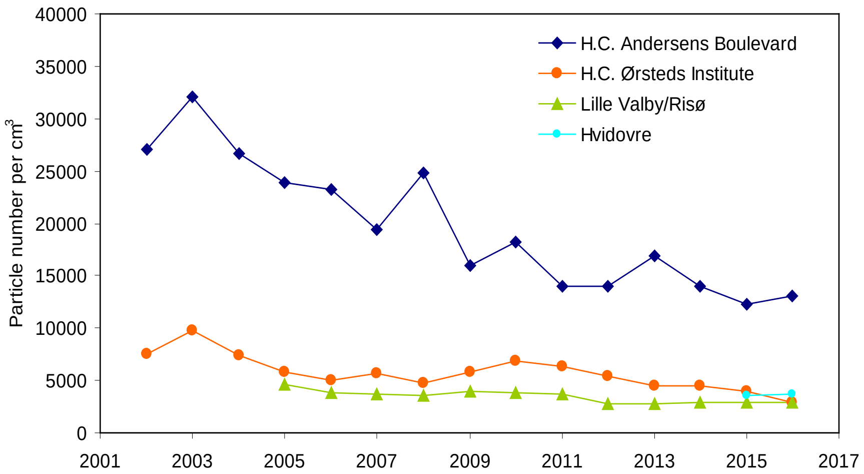


Figure 7.5. Annual averages for particle number at street level (H. C. Andersens Boulevard), suburban (Hvidovre), urban background (H.C. Ørsted Institute) and rural background (Lille Valby/Risø). For Hvidovre the measurements started 1 October 2015 and data for that year thus only covers the period from 1 October – 31 December.

7.3 Impact of salt from winter salting and sea

The EU air quality directive (EC, 2008) gives the member states the possibility to compensate for the impact of salt from sea salt and winter salting on PM_{10} (Article 20 and 21). Salt from sea salt can be subtracted from PM_{10} prior to comparison with the limit values. If the limit values are exceeded due to winter salting then the member states do not have to prepare an air quality plan in order to reduce the levels of PM_{10}. These rules account for both the annual limit value and the daily limit value that states that the daily PM_{10} concentration must not exceed 50 µg/m³ more than 35 days in a calendar year.

On the basis of this the monitoring program was expanded in 2010 with daily sampling and analysis of sodium at the street stations H.C. Andersens Boulevard, Copenhagen (1103), Odense (9155/9156) and Aarhus (6153) and at the urban background station in Copenhagen (H.C. Ørsted Institute/1259). table 7.6 gives the annual average concentrations for sodium and estimate for total salt (NaCl) in 2016 (calculated from the measured sodium concentration).

Table 7.6. Annual statistics for sodium and estimate of total salt (NaCl) in 2016.

	Na µg/m³	**NaCl µg/m³**
Street:		
Copenhagen/1103	1.5	3.8
Aarhus/6153	1.3	3.2
Urban Background:		
Copenhagen/1259	1.0	2.5

*) The site in Odense/9155 (Albanigade) was from 28 June 2014 affected by a major permanent rearrangement of the roads in Odense, and the site changed from a traffic site with relatively high traffic intensity to a site with much reduced traffic. On 15 June 2015 the measurements had to be stopped.

Figure 7.6 shows the results from measurements of sodium at the street station H.C. Andersen's Boulevard, Copenhagen (1103) and at urban background in Copenhagen (H.C. Ørsted Institute/1259). The high concentrations at the street station during the winter months are due to winter salting of the roads. The high correlation between the sodium concentrations for the main part of the remaining year is due to long-range transport of sea salt that have equal impact on the two stations.

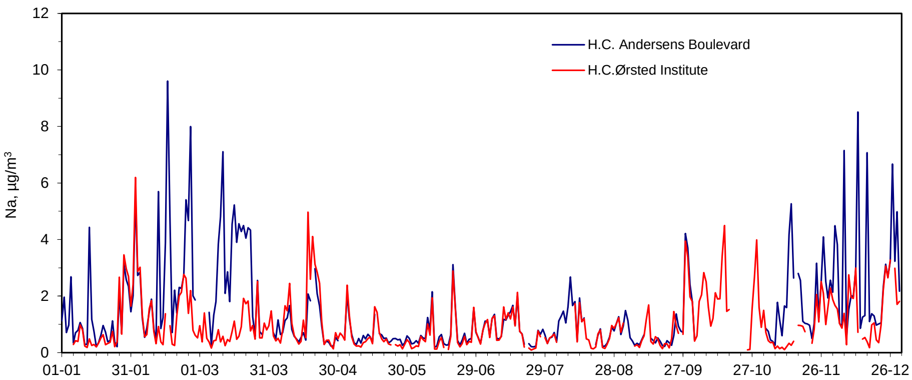


Figure 7.6. Diurnal concentrations in 2016 of sodium at H.C. Andersens Boulevard, Copenhagen (1103) and at the urban background in Copenhagen (H.C. Ørsted Institute/1259).

In 2016 the permitted number of exceedances in a year of the diurnal limit value of 50 µg/m³ for PM_{10} was not passed at any stations in the measuring network and therefore it has not been necessary to correct PM_{10} for the content of NaCl due to sea salt and winter salting of the roads.

8 Heavy Metals

Heavy metals in PM_{10} are measured by collection of PM_{10} on filters that are analysed by ICP-MS (Inductively Coupled Plasma Mass Spectrometry) for their content of elements. Results for 10 heavy metals are presented in table 8.1. Comparison between results from ICP-MS and the previously used PIXE-method (Proton Induced X-ray Emission) showed only minor changes in the annual averages, when the low concentration levels are taken in to account. The table also presents results for analysis of heavy metals in TSP at the measurement station Risø. The content of these heavy metals in PM_{10} and TSP are approximately equal since these metals are mainly found in the fine particle fraction.

The ICP-MS analysis provides the measurements of Arsenic (As), Chromium (Cr) and Nickel (Ni) included in the EU Directive 2004/107/EC (EC, 2005) and Lead (Pb) included in EU Directive 2008/50/EC (EC, 2008). According to the directive (EC, 2005) also Mercury (Hg) has to be measured, however, these measurements can be carried out in cooperation with neighboring countries. As part of a bilateral agreement "Development of the mutual partnership on air pollution" between Denmark and Sweden, it has been agreed that the Swedish measurements at Röå (table 8.2) can fulfil the Danish obligations on measurements of Hg. This agreement is based on the fact that the spatial variation of background Hg concentrations is small.

8.1 Annual statistics

The annual statistics for the selected heavy metals are shown in table 8.1 and 8.2. The concentrations are low for all of the heavy metals and there were no exceedances of the target/limit values for the four metals (As, Cd, Ni, and Pb) that are regulated by use of target/limit values (EC, 2005, 2008).

Table 8.1. Annual statistics for Vanadium (V), Chromium (Cr), Manganese (Mn), Nickel (Ni), Cupper (Cu), Zink (Zn), Arsenic (As), Selenium (Se), Cadmium (Cd) and Lead (Pb) measured in PM_{10} during 2016. For comparison the table also includes results for these heavy metals measured in TSP at the rural background station Risø.

Unit ng/m^3	V	Cr	Mn	Ni	Cu	Zn	As	Se	Cd	Pb
***PM$_{10}$*, Street**										
Copenhagen/1103	2.0	8.1	22	3.2	94	44	0.6	0.5	0.07	3.6
Aarhus/6153	1.1	3.3	7.1	2.0	30	20	0.4	0.4	0.05	2.3
***PM$_{10}$*, Urban background:**										
Copenhagen/1259	1.5	1.3	5.9	1.3	14	17	0.5	0.5	0.07	3.1
TSP, Rural Background										
Risø	0.9	0.9	3.0	0.9	3.0	8.4	0.4	0.4	0.05	1.9
EU Target (Limit) Values *				20			6		5	500
Guideline value (WHO)**	1000		150						5	
Life time risk level at 1:10^5				25			6.6			

*) Target values for Ni, As and Cd are implemented through EU Council Directive 2004/107/EC (EC, 2005). The limit value for Pb is found in EU Directive 2008/50/EC (EC, 2008).

**) The guidelines and life time risk for the carcinogenic metals are established by WHO (WHO, 2000). The lifetime risk level is defined as the concentration that through a lifelong exposure is estimated to give an excess risk of 1:105 for developing cancer.

Table 8.2. Annual statistics for Hg 2016 measured at Råö in southern Sweden by the Swedish Environmental Research Institute.

Unit: ng/m^3	Total Gas Hg (ng/m^3)	Total Particles Hg (ng/m^3)
Råö (SE00014)	1.3	0.003

8.2 Trends

The long-term trends for six of the heavy metals are shown in figure 8.1. For Pb, As, Ni and Manganese (Mn) there are clear reductions in the concentrations due to national and international regulations of the emissions. The reduction is most pronounced for Pb where removal of Pb from gasoline has resulted in large reductions of the concentrations. For Cu there has not been any clear long-term change in concentration. Emssions in Denmark show a slight increase during the period from 1990 to 2013 (DCE, 2017).

For Mn the long term trend at H.C. Andersens Boulevard deviates from the other stations. This is believed to be due to high Mn concentrations in the asphalt used at H.C. Andersens Boulevard during the period from 1991 to 2008 (in 2008 new asphalt was laid on HCAB). The sharp decrase in concentration in 2006 is due to the change in sampling method from TSP to PM_{10}.

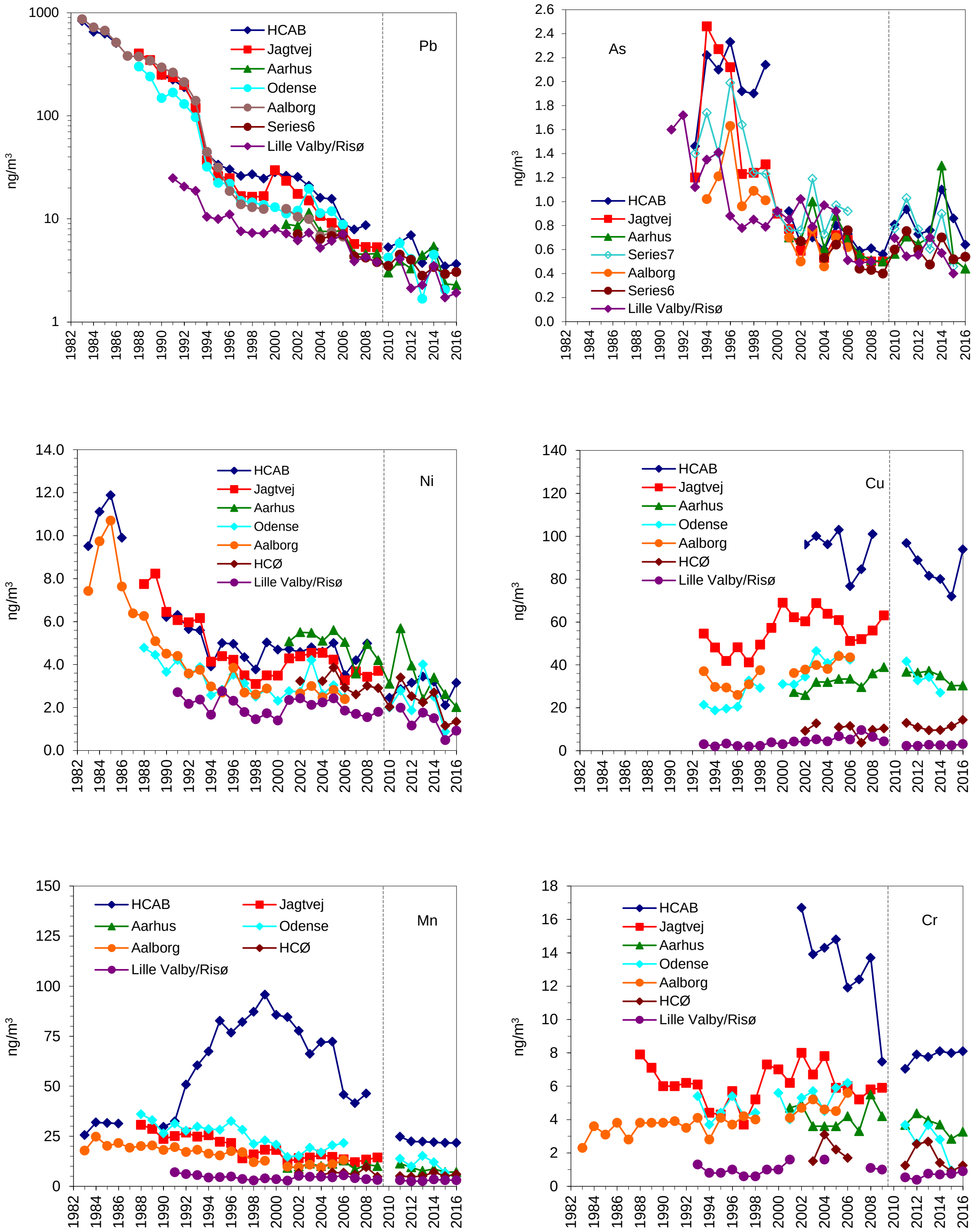


Figure 8.1. Annual averages from selected stations for some heavy metals in particulate matter. Until 2000 in TSP and later in PM_{10} – except for Copenhagen/1103 where PM_{10} replaced TSP from the beginning of 2006. The heavy metals are usually found in fine particles, which make the TSP and the PM_{10} values comparable. Note that the scale for Pb is logarithmic. The dashed line indicates that the analysis method has been changed from 2009 to 2010.

9 Sulphur dioxide

The concentration of sulphur dioxide (SO_2) has reached very low levels in Denmark and it is therefore only necessary with a limited monitoring of the concentrations; both with respect to the number of stations and the quality of the measurements. Hence it is only measured at two traffic stations (Copenhagen and Aalborg) with focus on episodes with high concentrations of SO_2. It is measured using gas monitors based on ultraviolet fluorescence. The concentrations of SO_2 are often below the detection limit of the instruments and hence the uncertainties of the measurements are large. The concentrations are measured continuously throughout the year with a time resolution of minutes that is aggregated to hourly averages for this report.

9.1 Annual statistics

The annual statistics for 2016 for SO_2 are shown in table 9.1. None of the limit values (EU, 2008) were exceeded in 2016. In 2016, there was no information to the public due to exceedance of the alert threshold for SO_2 (one hour average 500 µg/m^3).

Table 9.1. Annual statistics for SO_2 in 2016. All parameters are calculated based on hourly average. The detection limit for the monitors is a few µg/m^3, which makes the average and median values encumbered with high relative uncertainties.

Unit: µg/m^3	Number of results	Average year	Average winter	Median	98-percentile	Max. Hour	4th highest diurnal mean
Traffic:							
Copenhagen/1103*	7762	1.8	2.0	1.32	6.7	16.9	6.9
Aalborg/8151 §	0	-	-	-	-	-	-
Limit values	>7446**	20	20			350	125

*) Data from both old and new position.

**) 90% data capture of number of hourly measurements in relation to total number of hourly measurements in 2016 excluding hours used for calibration.

§) Aalborg/8151 (traffic) there is no data since the station has been shut down due to construction work at the site. It has not yet been possible to reinitiate the measurements at the street station in Aalborg.

9.2 Trends

The long-term trends for SO_2 are shown in figure 9.1. Since the beginning of the 1980s the annual concentrations have decreased by more than a factor of five due to effective national and international regulations of the emissions. The emission reductions are due to use of effective cleaning technologies in combination with decrease of the sulphur content in fuel.

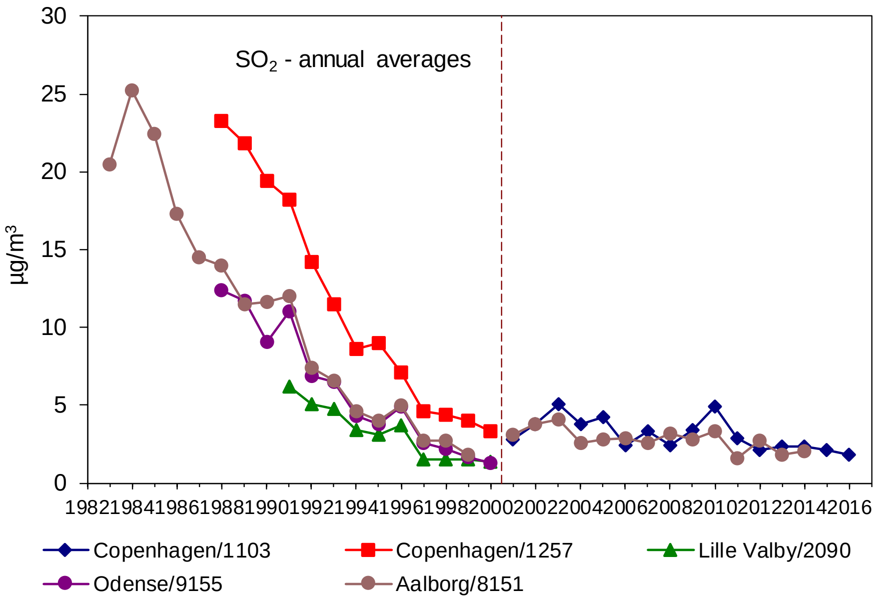


Figure 9.1. Annual averages for SO_2. Until 2001 the results were obtained using KOH impregnated filters for collection of SO_2. These measurements ceased in 2000 and after 2000 the SO_2 measurements have been carried out using SO_2 monitors in order to monitor episodic results. The detection limit for the monitors is a few µg/m^3, which makes the average and median values encumbered with high relative uncertainties. The shift in level from 2000 to 2001 is due to shift of the methods. The station in Aalborg (traffic) has temporarily been shut down due to construction work at the site. There is therefore no data from Aalborg from 2015 and on.

10 Polyaromatic Hydrocarbons (PAHs)

Following the EU Directive 2004/107/EC (EC, 2005), measurements of atmospheric concentrations of benzo[a]pyrene and other particle bound polyaromatic hydrocarbons (PAH) have been introduced in the air quality monitoring programme starting from June 2007. The target value for benzo[a]pyrene in ambient air is set to 1 ng/m^3 averaged over a calendar year (EC, 2005). Benzo[a]pyrene is used as a marker for the carcinogenicity of PAHs.

Particulate matter (PM_{10} fraction) is collected at the urban station of H.C. Andersens Boulevard (Copenhagen/1103) in Copenhagen and at a temporary station in a suburban area in Hvidovre. PM is collected by high volume sampling (HVS) at a flow rate of 0.5 m^3 min^{-1} over a period of 24 hours for an average total volume of 700 m^3. The filters are kept frozen until analysis. Weekly based PAH concentrations are obtained by analysis of pooled fractions of daily collected samples. For each day 4 x 1.5 cm^2 are taken from the filter and the fractions from the whole week are pooled and extracted. The pooled filters are extracted with dichloromethane and cleaned up on silica. Before extraction, the filters are spiked with deuterium-labeled PAH. Analysis of the extracts is carried out by GC-MS. Concentrations of individual PAHs in samples are corrected for recovery of a deuterium-labelled PAH standard with the closest molecular weight. A total of 18 PAHs are analysed with the method.

10.1 Annual Statistics

The average concentration of benzo[a]pyrene in 2016 was 0.21 ng/m^3 and 0.23 ng/m^3 at the street station on HCAB and the suburban station in Hvidovre, respectively. The monitoring hut was moved (and thus no measurements were performed) in weeks 40-43 at the HCAB station and in weeks 42-45 at the Hvidovre station. The missing concentrations from these weeks might be the cause of the lower annual average concentration of benzo[a]pyrene measured in 2016 compared to 2015. Overall, it can be concluded that the target value for benzo[a]pyrene of 1 ng/m^3 was not exceeded in 2016. In 2016, the concentrations are quite similar at the two stations.

The average annual concentrations of the other five PAHs listed as relevant in the EU Directive are shown in table 10.1.

Table 10.1. Annual average concentrations for the six PAHs listed in the EU Directive.

	HCAB ng/m^3	Hvidovre ng/m^3
Benzo[a]pyrene	0.21	0.23
Benzo[a]atracene	0.24	0.23
Benzo[b]fluoranthene	0.34	0.34
Benzo[j+k]fluoranthenes	0.32	0.35
Indeno[1,2,3-cd]pyrene	0.26	0.33
Dibenzo[a,h]anthracene	0.07	0.05

The seasonal trends in PAH concentrations are summarized in figure 10.1 and 10.2. As expected, the atmospheric concentrations are low during summer months, while concentrations increase in winter months due to higher emissions and less photochemical degradation of the compounds. The seasonal variation also seems to vary between the two measurements stations (table 10.2). The winter concentrations at Hvidovre are higher than at HCAB in 2013-2016 while the summer concentrations are at the same level in 2013 and 2014 and lower at Hvidovre than at HCAB in 2015 and 2016. This is because the sources of benzon[a]pyrene in Hvidovre is largely wood burning for house hold heating while the sources at HCAB are both wood burning and traffic. The seasonal variation in the emissions from traffic is small compared to that of wood burning.

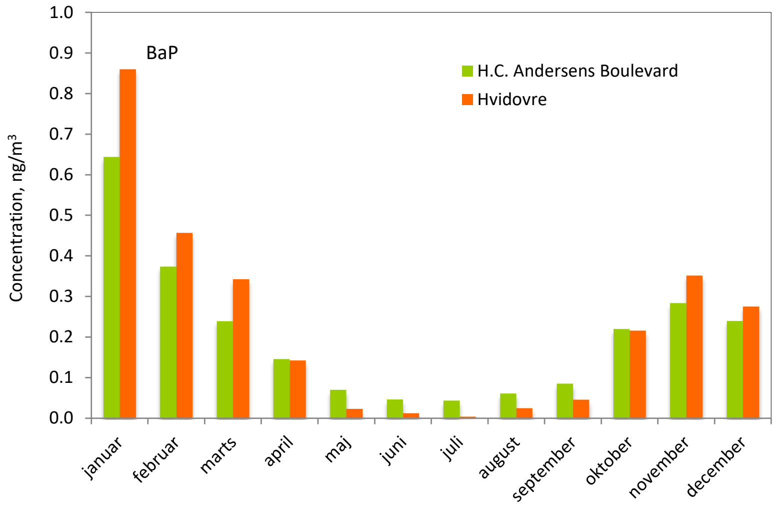


Figure 10.1. Monthly average concentrations of benzo[a]pyrene at H.C. Andersens Boulevard and Hvidovre in 2016.

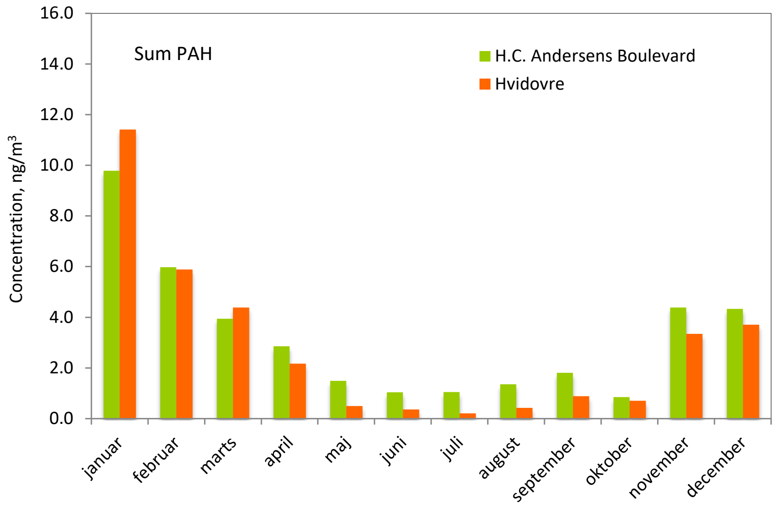


Figure 10.2. Monthly average concentrations of the sum of all analyzed PAH at H.C. Andersens Boulevard and Hvidovre in 2016.

Table 10.2. Winter, summer and annual average concentrations of benzo[a]pyrene for 2013-2016

	Hvidovre				HCAB			
	2013	**2014**	**2015**	**2016**	**2013**	**2014**	**2015**	**2016**
Winter	0.53	0.73	0.42	0.42	0.38	0.50	0.44	0.33
Summer	0.12	0.10	0.06	0.04	0.11	0.10	0.12	0.08
Annual	0.34	0.38	0.25	0.23	0.24	0.29	0.29	0.21

10.2 Trends

The annual averages of benzo[a]pyrene since 2008 at the street station on HCAB are shown in figure 10.3 together with four years of data from the suburban station in Hvidovre. A decrease in the annual averages of benzo[a]pyrene at HCAB is observed since 2008, and there is also a downward trend at Hvidovre since 2013. However, longer time series are needed in order to verify whether or not this tendency is persistent.

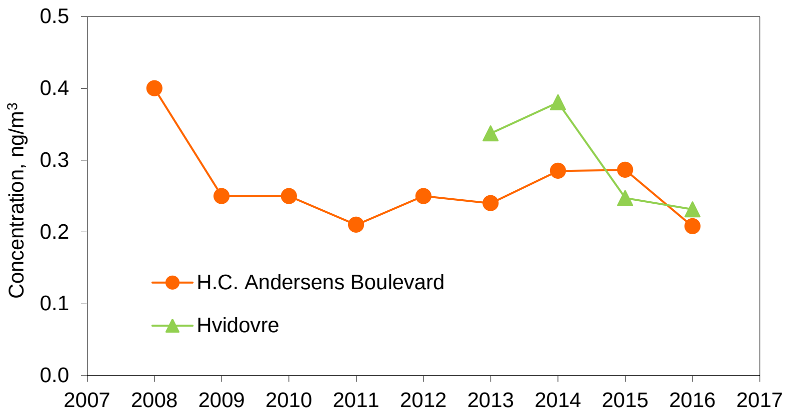


Figure 10.3. Annual average concentrations of benzo[a]pyrene at H.C. Andersens Boulevard and Hvidovre.

11 Organic carbon and elemental carbon

Ambient concentrations of particulate Organic Carbon (OC) and Elemental Carbon (EC) are measured on the kerbside station H.C. Andersens Boulevard/1103 in Copenhagen and the rural background station Risø / 2090 north of Roskilde. Additionally, EC is measured on H.C. Ørsted Instituttet /1259 (Urban background, Copenhagen) and at Fjeldstedvej / 2650 (suburban site, Hvidovre), which is considered to be a hot spot for residential wood burning. $PM_{2.5}$ particulate matter is sampled on two filters in tandem, i.e. quartz-behind-quartz, to correct for positive artifacts from adsorption of volatile and semivolatile organic compounds, which are not particulate material. The filters are analyzed for OC and EC by a thermal/optical method according to the European EUSAAR2 temperature protocol (Cavalli et al., 2010).

11.1 Annual statistics and trends

OC and EC have been measured in $PM_{2.5}$ since 2010. During this relatively short period, the annual averages of OC in rural background have oscillated between 1.2 and 1.8 µg/m^3. Since biogenic sources are expected to account for the majority of the OC in $PM_{2.5}$ a constant trend biased by natural variation is expected. OC covariates at the kerbside station HCAB and the urban background station HCØ with an increment corresponding to the traffic source (figure 11.1). On the contrary, EC in rural background (0.29 µg/m^3) has decreased by 36% relative to its 2010 concentration in 2016. The kerbside station (1.8 µg/m^3), which is largely impacted by local traffic, has experienced a 26% decrease in EC in the same period. In 2016, urban background (0.38 µg/m^3) and the suburban site (0.44 µg/m^3) experienced EC concentrations 32 and 50% higher than semi-rural background. The ratio of EC to total carbon (TC) differs significantly between rural background (0.19) and the kerbside station in Copenhagen (0.43). While the EC/TC ratio has decreased from 2010 to 2015 at HCAB, EC/TC shows a nearly constant trend at RISØ (figure 11.1).

A clear seasonal pattern was observed for EC and OC at the rural and urban background with minimum summer concentrations and higher winter concentrations. EC and OC showed less seasonal variation at the kerbside station.

Table 11.1. Annual statistics for OC in 2016. The values are based on daily averages of Copenhagen curbside and semi-rural background west of Copenhagen.

Concentration µg/m^3	Data capture	OC, average
Copenhagen / 1103	91%	2.4
Risø / 2090	94%	1.3

Table 11.2. Annual statistics for EC in 2016. The values are based on daily averages of Copenhagen curbside and urban background, semi-rural background west of Copenhagen and suburb southwest of Copenhagen.

Concentration µg/m^3	Data capture	EC, average
Copenhagen/1103	91%	1.8
Copenhagen/1259	93%	0.38
Risø / 2090	94%	0.29
Hvidovre	92%	0.44

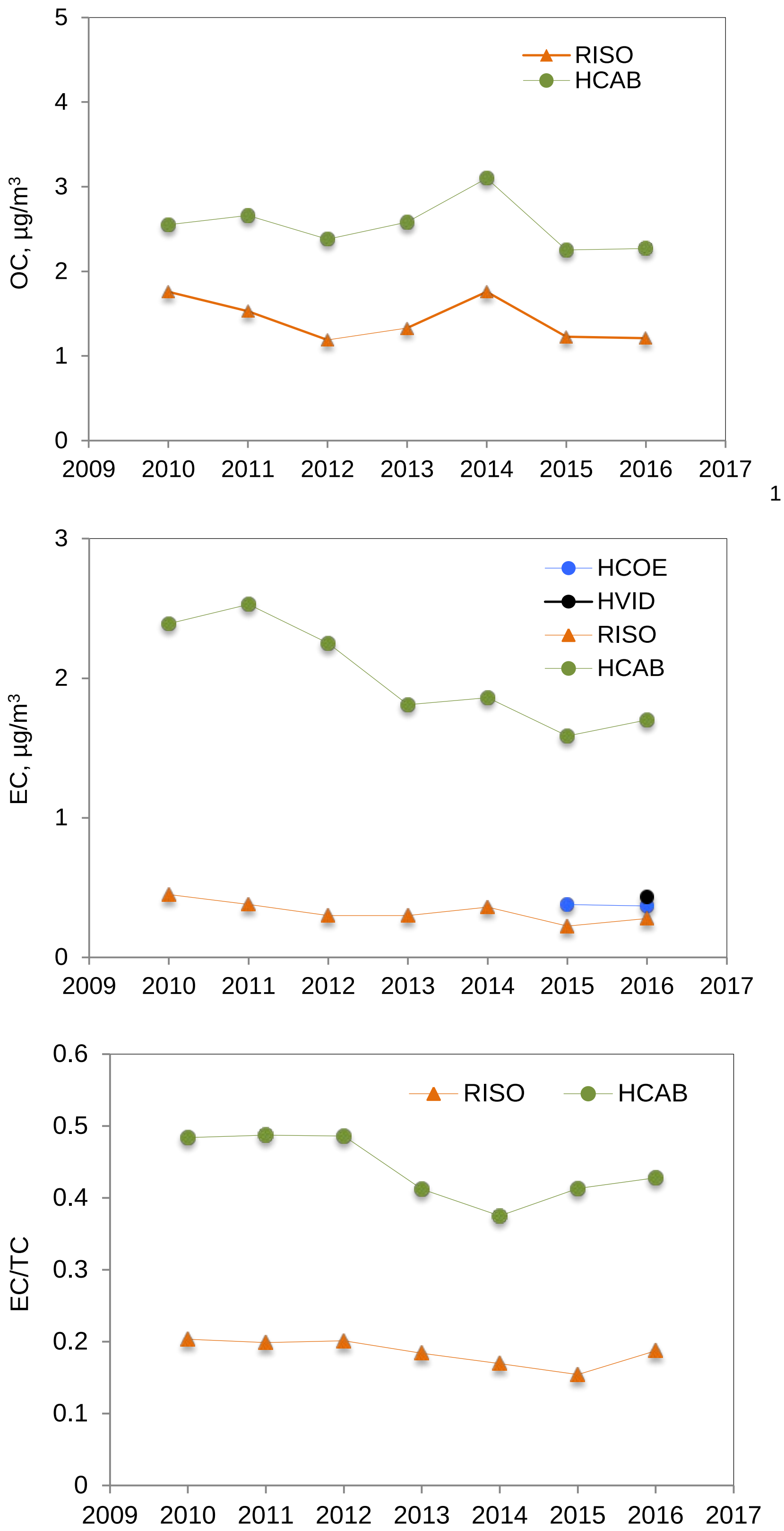


Figure 11.1. OC, EC and the ratio of EC to total carbon (EC/TC) at curbside (HCAB), semi-rural background (RISØ), urban background (HCØ) and sub-urban (HVID).

12 Chemical composition of $PM_{2.5}$

In addition to the measurements of elemental and organic compounds, also measurements of the main inorganic compounds in $PM_{2.5}$ (ammonium (NH_4^+), sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), nitrate (NO_3^-), sulfate (SO_4^{2-})) have been conducted at H.C. Andersen's Boulevard (HCAB, Copenhagen/1103) and Risø. The measurements at HCAB closed down 2 October 2017 due to relocation of the monitoring station and revision of the program. These measurements are carried out on the basis of the air quality directive from 2008 (EC, 2008). The method is chemical analysis of the daily $PM_{2.5}$ particle filters sampled using the SM200 monitors.

Examples of the daily variations of the concentrations are shown in figure 12.1 together with the variation of $PM_{2.5}$. For Na^+ the annual average concentrations are similar at HCAB and Risø due to long-range transport of sea salt. For the winter months Na^+ is higher at HCAB than Risø due to winter salting of the roads in Copenhagen. The variations of Cl^- follow the variations of Na^+ because the main source is sea salt and winter salting. Mg^{2+} originates only from sea salt and there are therefore similar concentrations at the two stations throughout the year. SO_4^{2-} and NH_4^+ originate mainly from long-range transport hence only minor differences between the two stations are observed (figure 12.1). This is also the case for NO_3^- and K^+. Ca^{2+} is in general higher at HCAB than at Risø. This is due to road dust at HCAB since asphalt contains large quantities of calcium.

The annual contributions to $PM_{2.5}$ of the different compounds are shown in figure 12.2. The annual average concentrations of NH_4^+, Na^+, K^+, Mg^{2+}, Cl^-, NO_3^-, SO_4^{2-} are very similar at the two stations, just as the daily variation. The main variations between the two stations are for EC, OM (organic matter) and Ca^{2+} where the concentrations are higher at the street station compared to the rural background station. This is mainly due to emissions of these compounds from the traffic in Copenhagen. As in the previous year, the unknown mass is higher at HCAB than at Risø. The mass of the unknown is very uncertain because it is calculated from the difference between $PM_{2.5}$ and the sum of all the analysed constituents. The unknown mass is water attached to the particles, dust (e.g. SiO_2), heavy metals and other trace constituents.

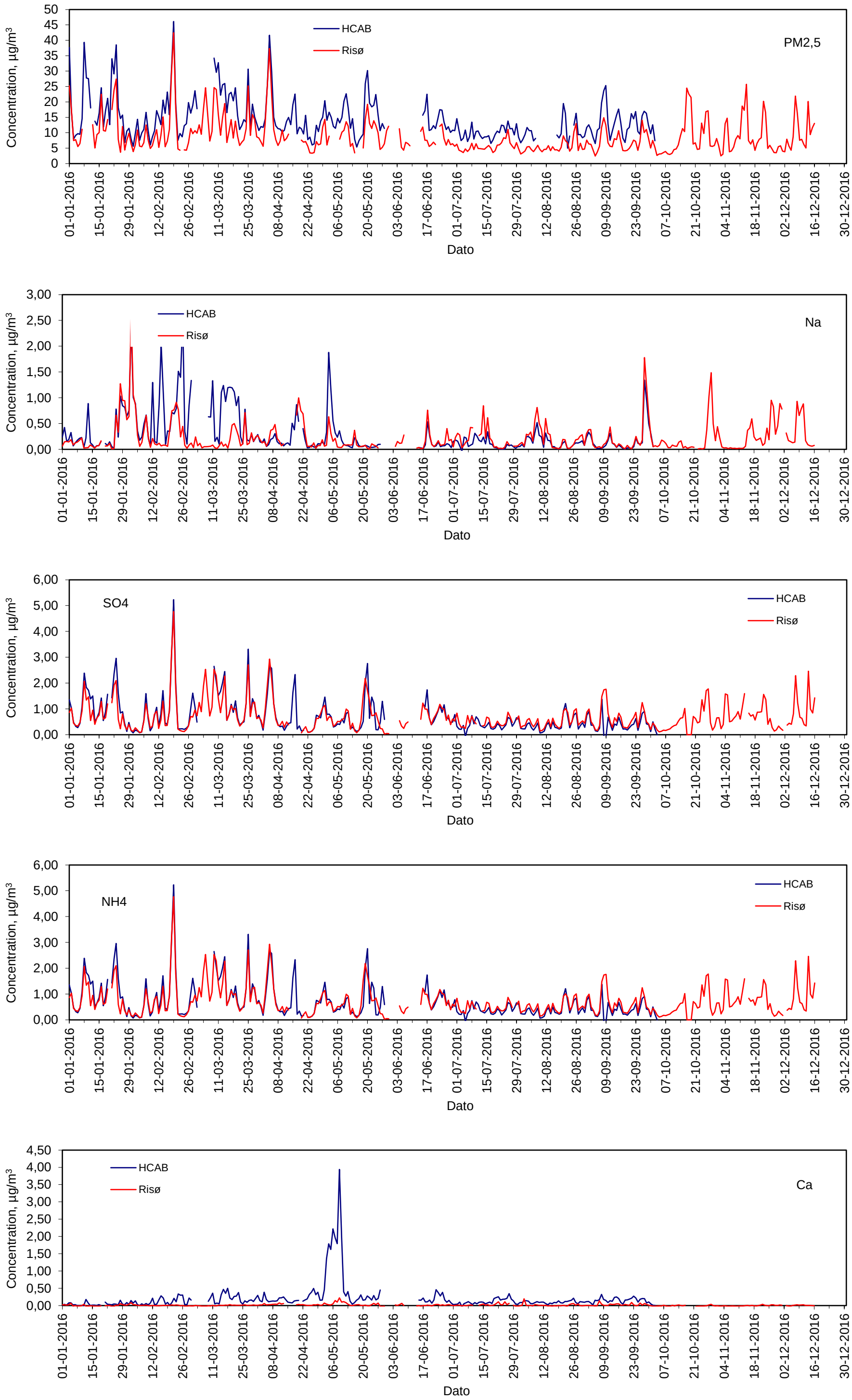


Figure 12.1. Daily variations of the concentrations of $PM_{2.5}$ (Na^+, SO_4^{2-}, NH_4^+ and Ca^{2+}) at H.C. Andersens Boulevard (HCAB, Copenhagen/1103) and Risø in 2016. Data from HCAB only covers the first 9 months, as these measurements were closed down 2 October 2016.

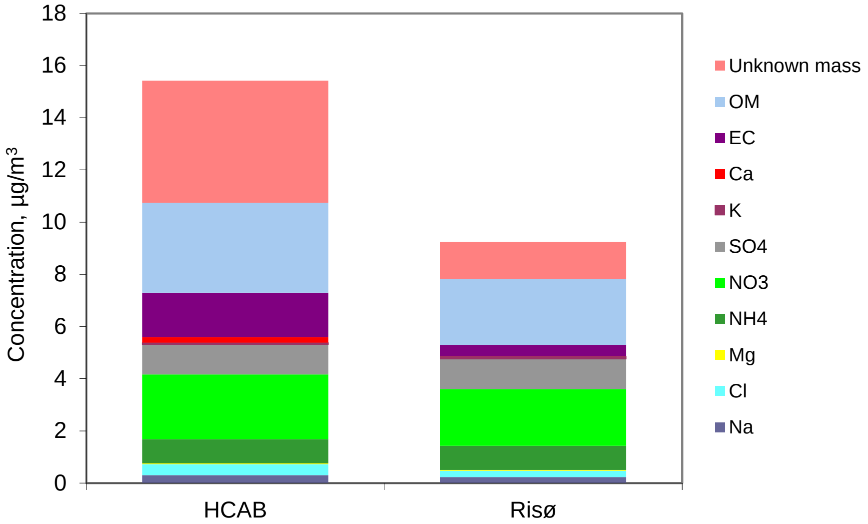


Figure 12.2. Annual average contributions to the chemical composition of $PM_{2.5}$ at H.C. Andersens Boulevard (HCAB, Copenhagen/1103) and Risø in 2016. Data from HCAB only covers the first 9 months, as these measurements were closed down 2 October 2016. Organic matter (OM) has been estimated from the measured concentrations of OC by multiplication of OC with a factor of 1.5 for the fresh OM at HCAB and 2.1 for the aged OM at HCAB and Risø, respectively (Turpin and Lim, 2001). This is in order to account for the contribution of hydrogen, oxygen, nitrogen etc. to the mass of the organic compounds.

13 Health effects of air pollution in Denmark

According to WHO, air pollution is now considered the world's largest single environmental health risk. Around 3.7 million people died prematurely in 2012 as a result of outdoor air pollution exposure (WHO, 2014). This high impact of air pollution on human health is the background for inclusion of model calculations of the health risk and associated external economic cost of air pollution in Denmark in the Air Quality Monitoring Program under NOVANA.

The model calculations are carried out with the model system EVA. EVA is an integrated part of a multi-scale model system that is capable of describing the contribution from intercontinental, regional, national and local sources on air pollution and hence also on the impact of air pollution on human health. For further details of the EVA-system, see chapter 2.3.

The health effects are associated with $PM_{2.5}$, NO_2, CO, SO_2 and O_3. Of these, $PM_{2.5}$ and O_3 are the most extensively used in studies of economic costs, as their effects are dominant compared to the other species. Atmospheric particles are considered responsible for mortality and morbidity, primarily via cardiovascular and respiratory diseases. A review from Hoek et al. (2013) includes the most comprehensive analysis of cardio-respiratory impacts in long-term studies and concludes that the long-term relative risk for total mortality is 6.2% per 10 µg/m^3 increase in $PM_{2.5}$, which is used in EVA.

13.1 Status and trend for health effects

In table 13.1, the number of cases for the different health outcomes due to the total air pollution concentrations calculated using the EVA model system as a mean over the three years 2014-2016 is given. The impact from short-term exposure of SO_2 and O_3 is given as "acute deaths", while the impacts from long-term exposure of $PM_{2.5}$ is given as Years Of Life Lost (YOLL), which is then applied to calculate the number of "chronic" premature deaths using an average number of life years lost (10.6 years, see Brandt et al., 2013a). The total annual number of premature deaths due to the total air pollution levels is calculated to around 3,600 cases in Denmark. Health impacts due to exposure of NO_2 are presently not included in the EVA system. However, in the air quality assessment for Europe for 2016 the European Environmental Agency included premature deaths for NO_2. (European Environmental Agency, 2016). In these calculations, about 2% of all predicted premature deaths for Denmark are due to NO_2.

The main driver for the health impacts is $PM_{2.5}$, which in these calculations consist of the total primary emissions of $PM_{2.5}$, including mineral dust, fresh and aged black carbon (BC), OC, sea salt from sea spray, as well as the secondary inorganic aerosols (SIA) and the secondary organic aerosols (SOA). $PM_{2.5}$ account for about 93% of all premature deaths, O_3 for about 6% and SO_2 for less than 1% (as a mean over the three years 2014-2016).

The risk of premature death resulting from exposure to $PM_{2.5}$, O_3 and SO_2 is rather homogeneously distributed over Denmark. The explanation is that the majority of premature deaths is related to $PM_{2.5}$, and the geographical variation in the concentration of $PM_{2.5}$ is fairly small due to the large contribution to $PM_{2.5}$ originating from long range transport of air pollution mainly from the northern parts of the European continent, giving however a smaller gradient from south to north.

Model calculations with the EVA system have been carried out in order to calculate the development of the health impacts for the period 1990-2016. In figure 13.1, the total number of premature deaths due to $PM_{2.5}$, O_3 and SO_2 in Denmark as annual averages due to the total air pollution, is presented. The total number of premature deaths has decreased from around 5,800 cases/year to around 3,600 cases/year – a reduction of 38% over this period. The variation from year to year are due to natural variations in the meteorological conditions.

Recent results for Europe (Brandt et al., 2013a; 2013b) show that outdoor air pollution caused about 570,000 premature deaths in 2011. For 2016, the number of premature deaths in Europe has decreased to ~500,000, and hence there has also been a significant reduction in health impacts of air pollution on a European level. The decrease in the health impact in Denmark and in Europe as well is due to decrease in the emissions.

The development of the number of premature deaths in Denmark due to exposure of O_3 and SO_2 is displayed in figure 13.2. The number of premature deaths due to SO_2 has decreased from around 290 cases/year to around 37 cases/year, a decrease of 87%, while the number of premature deaths due to O_3 has increased from around 154 to around 190, an increase of around 23%. The increase is due to general increasing background levels of O_3, partly due to decreased NO_x emissions in Denmark and Europe over this period. Lower emissions of NOx reduce the degradation of O_3 locally and hence lead to higher O_3 concentrations.

An emission reduction scenario with the DEHM model has been conducted in order to estimate the contribution from emissions in foreign countries to Denmark (in this case all emissions in the Northern Hemisphere (both natural and anthropogenic) and the contribution from anthropogenic emissions in Denmark to the number of premature deaths, calculated by the EVA model system, see table 13.2. The contribution from foreign countries to Denmark is estimated to 2,730 (76% of the total number of cases in Denmark), while the contribution from Danish emissions contributes with 850 premature deaths in Denmark (24%). The contribution from Danish emissions to the number of premature deaths in Europe (excl. Denmark) is estimated to about 2,280 cases/year. The "import" of air pollution related health impacts is therefore about 16% greater than the "export". It is also seen that Danish emissions cause nearly a factor of three more premature deaths in foreign countriesas they do in Denmark, due to long-range transport.

Table 13.1 The number of cases for the different health outcomes in the EVA model system due to the total air pollution concentrations as a mean over the three years 2014-2016 for the whole of Denmark.

Health outcome	Number of cases
Chronic Bronchitis	3.390
Restricted Activity Days	3.460.000
Respiratory Hospital Admissions	176
Cerebrovascular Hospital Admissions	422
Congestive Heart Failure	388
Lung Cancer	518
Bronchodilator Use Children	86.800
Bronchodilator Use Adults	662.000
Cough Children	300.000
Cough Adults	682.000
Lower Respiratory Symptoms Children	116.000
Lower Respiratory Symptoms Adults	246.000
Acute premature deaths (SO2)	10
Acute premature deaths (O3)	120
Chronic YOLL (PM2,5)	36.600
Total no. of premature deaths	3.580
Infant mortality (PM2,5)	3

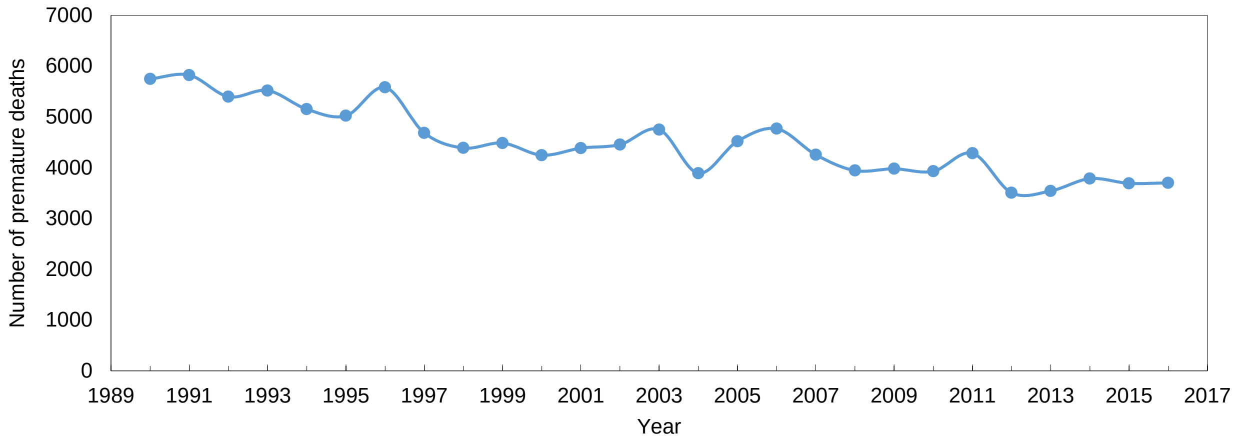


Figure 13.1. Total number of premature deaths due to $PM_{2.5}$, O_3 and SO_2 in Denmark as annual averages, due to the total air pollution, calculated with the EVA model system.

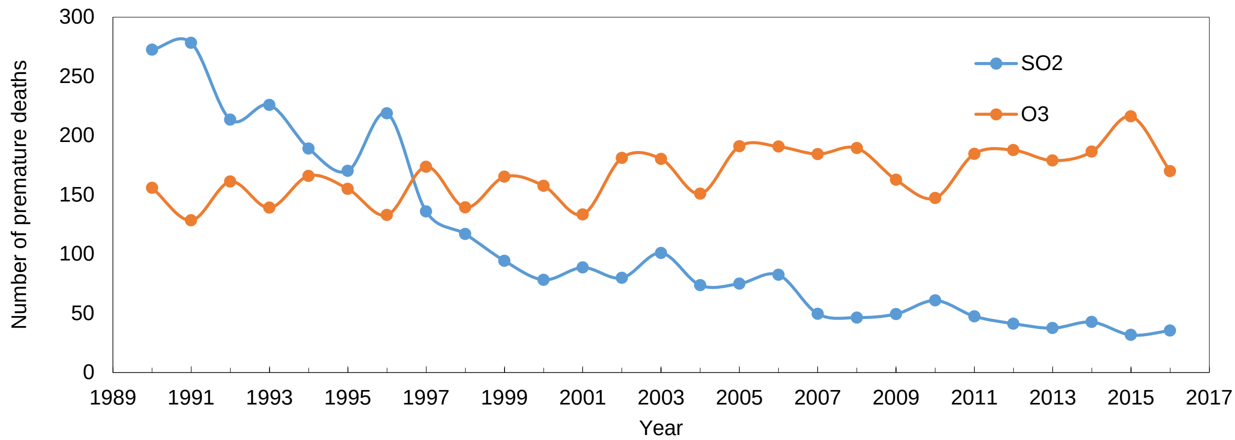


Figure 13.2. Total number of premature deaths due to O_3 and SO_2 in Denmark as annual avarage, calculated with the EVA model system.

Table 13.2. Contribution from emissions in foreign countries to Denmark and the contribution from emissions in Denmark to the number of premature deaths, calculated by the EVA model system for the year 2016.

Contributions 2016	Number of premature deaths	% of total
Total air pollution in Denmark	3.580	100
Foreign contribution to Denmark	2.730	76
Denmark's contribution to Denmark	850	24
Denmark's contribution to Europe incl. Denmark	3.130	100
Denmark's contribution to Europe excl. Denmark	2.280	73

13.2 Status and trend for external costs of health effects

An external cost occurs when producing or consuming a good or service imposes a cost upon a third party, as e.g. activities leading to increased air pollution concentrations, which results in impacts on health, nature or climate. In the EVA system, the external costs related to health impacts from air pollution are calculated.

The total health related external costs for Denmark have been calculated to 3.9 billion euros (~29 billion DKK) as an average over the three years 2014-2016 using the economic valuation of the individual health outcomes in Brandt et al. (2016) in 2013 prices. The similar number for 2016 is 3.6 billion euros (~27 billion DKK). The trend of the total external costs is similar to the development of the total number of premature deaths and is therefore not shown here. The total health related external cost as an average over the years 1988-1990 is 6.5 billion euros (~49 billion DKK) and has therefore decreased by 40% since then.

The contribution from emissions in foreign countries to Denmark and the contribution from emissions in Denmark to the total health related external costs, calculated by the EVA model system, is given in table 13.3. The contribution from foreign countries to Denmark is estimated to 2.9 billion euros or 22 billion DKK (80% of the total health related external costs in Denmark), while the contribution from Danish emissions contributes with 0.72 billion euros (5.4 billion DKK) in Denmark (20%). The contribution from Danish emissions to the total health related external costs in Europe excluding Denmark is 2.6 billion euros (20 billion DKK).

Table 13.3. Contribution from emissions in foreign countries to Denmark and the contribution from emissions in Denmark to the total health related external costs, calculated by the EVA model system for the year 2016.

Contributions 2016	Billion Euro	Billion DKK	% of total
Total air pollution in Denmark	3.6	27	100
Foreign contribution to Denmark	2.9	22	80
Denmark's contribution to Denmark	0.7	5.4	20
Denmark's contribution to Europe incl. Denmark	3.3	25	100
Denmark's contribution to Europe excl. Denmark	2.6	20	79

The Ministry of Finance announced new external costs for a statistical life in August 2017. The updated external cost is 32 million DKK. The external cost of a statistical life in the EVA-system is 15.5 million DKK (2013-prices). The external costs in table 13.3 would be about twice as high if the assumptions of the Ministry of Finance were assumed as premature deaths constitute the majority of the external costs.

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Appendix 1

Relpacement of the station at H.C.Andersens Boulevard

On 3 October 2016 the station at H. C. Andersen Boulevard was closed and a new station was placed instead of the old station (figure 2.3). The majority of the measurements were startet-up on 19 October 2016. The new station was located 2.7 m further away from the inner traffic lane in order to compensate for the road change in 2010 (figure 1 and 2). Moreover, the station was also mowed about 2 m further away from a tree close to the station in order to comply better with the EU directive (EC, 2008) that specifies that measurements have to be carried out several meters from trees in order to avoid influence of the trees on the measurements.

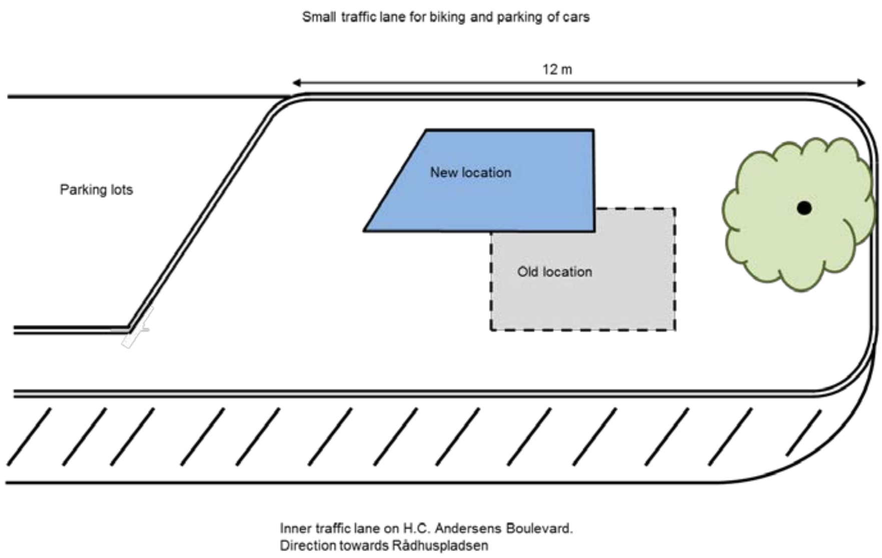

Figure 1. Sketch of the location of the old and new lacation of the measurement station at H.C. Andersens Boulevard.

Figure 2. Aerial photo of the location for the measurement station (red circle) at H.C. Andersens Boulevard.

Appendix 2

Pollutants measured in the network

NO and partly NO_2 are formed by combustion at high temperatures. The main sources are power plants and traffic. At the street stations the traffic is the main source. The application of catalytic converter in the exhaust reduces the emission considerably. NO is relatively harmless, but NO_2 can cause respiratory problems.

Most of the NO_2 in the urban atmosphere is produced by oxidation of nitrogen monoxide (NO) by ozone (O_3). The reaction will take place immediately, if sufficient O_3 is present. O_3 is often the limiting component for a complete oxidation in the street canyons, but practically all NO is oxidised at the urban background and rural stations. Within a few hours the NO_2 is further oxidised to nitrate and/or nitric acid, which may cause acid precipitation and eutrophication. NO_2 is a toxic gas, which may cause respiratory problems. There are limit values for the allowed concentration of NO_2 in the atmosphere.

O_3 is formed by photochemical reactions (i.e. by the influence of sunlight) between nitrogen oxides and volatile organic compounds (VOC's). The VOC's can be of natural and anthropogenic origin. The major part of the O_3 measured in Denmark originates from sources outside the country. Usually the highest concentrations are found at rural and urban background sites. O_3 is removed by NO at street level. O_3 is a toxic gas, which may cause respiratory problems and damage on crops and forests. There are so-called target values for the concentration of O_3 in the atmosphere.

The main source of CO in urban air is petrol-fuelled cars. The CO is formed due to incomplete combustion. The application of catalytic converter in the exhaust reduces the emission considerably. CO is only slowly removed from the atmosphere. CO is a toxic gas that may prevent the uptake of oxygen in the blood. There are limit values for the allowed concentration of CO in the atmosphere.

Benzene is present in petrol. It may also be formed in engines due to incomplete combustion. Since 1994 the benzene content in petrol has been reduced by up to a factor of 5. The concentration in the atmosphere has been reduced correspondingly. Benzene is a carcinogenic gas. There is a limit value for the average content in the atmosphere.

Many different VOC's are present in the air. Several of these are emitted by incomplete combustion in e.g. engines and wood burning stoves. Several of the VOC's are carcinogenic. A "target value" is implemented through an EU Council Directive in 2004 for Benzo[a]-pyrene as indicator for PAH (Polycyclic Aromatic Hydrocarbones).

The main sources for PM_{10} and $PM_{2.5}$ are combustion and resuspended dust. PM are also produced by chemical reactions in the atmosphere e.g. oxidation of nitrogen dioxide, sulphur dioxide and VOC. The submicron particles, which are formed by combustion and chemical reactions in the atmosphere, are suspected to be the most harmful for the health. There are still a lack of knowledge about the connection between health effects and particle size. Limit values for the PM_{10} concentration in the atmosphere are implemented at present.

PM_{10} and $PM_{2.5}$ is measured using three different methods in the monitoriong program:

- The Beta method: The particles are collected on filters for 24 hours intervals. The mass on the filters is automatic determined by measurements in the instrument of β-absorption in the filter with sampled dust. This method is considered to be equivalent to the reference method (EN 12341:1999 and EN14907:2005).
- The LVS method: The particles are collected on filters for 24-hour intervals by a low volume sampler (LVS). The mass on the filters is subsequently determined in the laboratory by gravimetric measurements of the dust. This method is the current reference method for the determination of the PM_{10} or $PM_{2.5}$ mass concentration of suspended particulate matter in ambient air (EN 12341: 2014, into which the previous standards for PM_{10}, EN 12341: 1998, and for $PM_{2.5}$, EN 14907:2005, have been merged).
- The TEOM method: The particles are continuously collected on a "tapered oscillating microbalance" (TEOM) and heated to 50˚C. During heating volatile compounds may evaporate. The loss will be most pronounced for "secondary aerosols" containing ammonium nitrate. PM results are given with a time resolution as ½-hourly averages.

There are a number of different heavy metals (HM) in the atmosphere. They are emitted from e.g. coal and oil fired power plants, waste incinerators and industries. HMs may also be emitted from traffic due to wear on engines, tires and brake pads. Several HMs are toxic even in low concentrations and a few also carcinogenic. A limit value is implemented for lead. Target values are implemented for arsenic, cadmium, nickel and mercury. WHO has proposed guideline values for the toxic non-carcinogenic and estimated life time risks for the carcinogenic HMs.

Sulphur dioxide (SO_2) is formed by burning of fossil fuel and biomass. The SO_2 is oxidised in the atmosphere to particulate sulphuric acid and sulphate. The conversion time depends strongly on the temperature and humidity in the air. It is typically in the order of one day. Sulphuric acid contributes to "acid rain" and the deposition of sulphate causes damage to sensitive ecosystems. Since the beginning of the 1980s the reduction of sulphur in fossil fuel and improved flue gas cleaning has reduced the concentration of SO_2 with one order of magnitude. SO_2 may cause respiratory problems. There are limit values for the allowed concentration of SO_2 in the atmosphere.

Appendix 3

Details on the calibration of OSPM

In previous years OSPM was calibrated against measurements at the street stations for a single year in order to ensure good correspondence between measured and modelled NO_2. For the assessment of 2016 we have used available data from the last three years to avoid potential fluctuations that a single year approach may introduce. The correlation between modelled and observed NO_2 concentrations is shown in figure 3 and shows an overall good agreement with zero bias based on the same calibration as in previous years. The street station of H.C. Andersens Boulevard has not been used in the calibration due to the about 8 µg/m³ jump in concentrations since a change in street layout moved traffic closer to the station in 2010. The station was moved during October 2016 to compensate for the change in street layout.

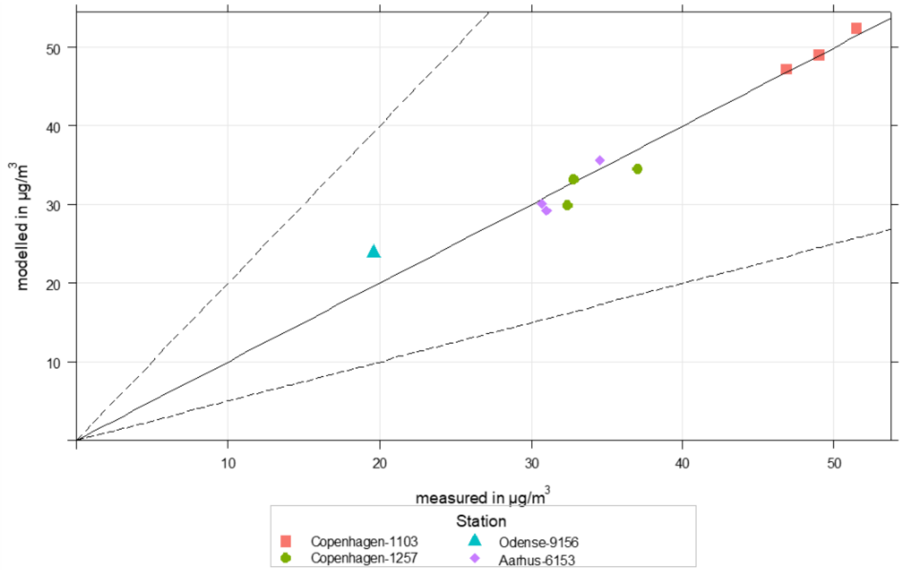

Figure 3. Correlation between modelled and observed annual levels of NO_2 for street stations for 2014, 2015 and 2016. All years are not available for all stations.

In figure 4 model calculations with DEHM-UBM are compared with measured annual means at the fixed urban background and rural stations for available data from 2013 to 2016. It is seen that the model overall has no bias.

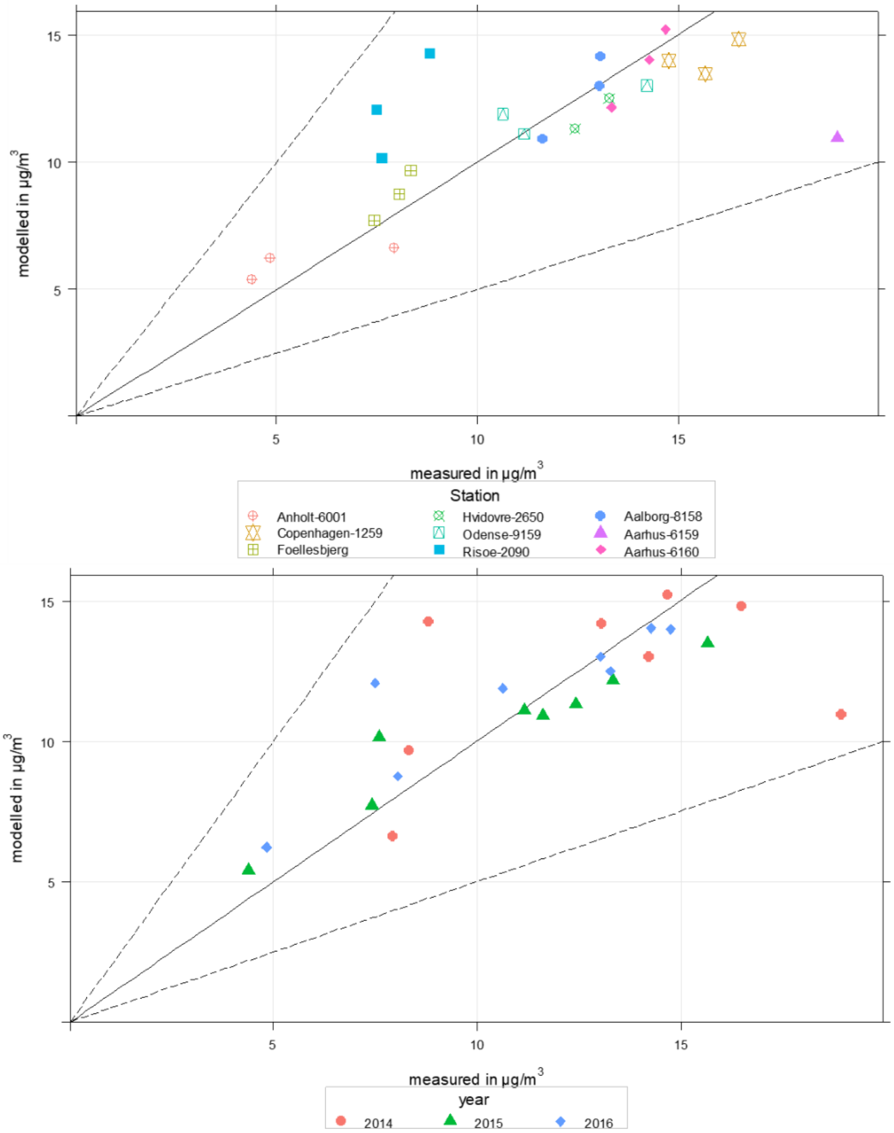

Figure 4. Correlation between modelled and observed annual levels of NO_2 for urban background and rural stations for 2014, 2015 and 2016. All years not available for all stations. Lower figure shows same data as upper figure just by year.

Calculations with the full model chain of DEHM-UBM-OSPM have been compared to measured NO_2 concentrations in 2016 for the fixed street measuring stations in Copenhagen, Aarhus and Odense (table 1). The street station in Odense is new and was established in June 2016 at Grønløkkevej. The measurement station in Aalborg was not operational during 2016 due to construction works and will be moved to a new location. The model system very slightly overestimates annual NO_2 concentrations with 1% for Jagtvej (Copenhagen) and underestimates with 5% for Banegårdsgade (Aarhus) but overestimates with 27% for Odense. The model very slightly overestimates by 1% for H.C. Andersens Boulevard (Copenhagen) when comparing to measurements, and overestimates by 14% when taking into account the jump of about 6 µg/m^3 (this value has been reduced in 2016 compared to previous years in order to account for the replacement of the station in October 2016) due to a change in street layout that has moved traffic closer to the measuring station.

Calculations with the coupled DEHM-UBM models have also been compared to the fixed urban background measuring stations in Copenhagen, Aarhus, Odense, Aalborg and Hvidovre (table 1). The station in Hvidovre is a new urban background station located in a suburban area with little traffic. Here the model system estimates observations at the urban background stations within -6 to 12%. DEHM overestimates observations at rural stations by 9-61%. The overestimation at the measurement stations in coastal areas is well known and most likely due to too low predicted mixing heights leading to overestimation of concentrations (Risø, Anholt, Keldsnor).

Table 1. Comparison of modelled and measured annual means of NO_2 concentrations in 2016

Unit: µg/m^3	Measurements	Model results	Difference	Models used
Street:				
Copenhagen/HCAB/1103	47/41*	46	-1%/14%	DEHM/UBM/OSPM
Copenhagen/Jagtvej/1257	33	33	1%	DEHM/UBM/OSPM
Aarhus/6153	31	29	-5%	DEHM/UBM/OSPM
Odense/9156	20	25	27%	DEHM/UBM/OSPM
Urban Background:				
Copenhagen/1259	15	14	-5%	DEHM/UBM
Aarhus/6160	14	14	-2%	DEHM/UBM
Odense/9159	11	12	12%	DEHM/UBM
Aalborg/8159	13	13	0%	DEHM/UBM
Hvidovre/2650	13	13	-6%	DEHM/UBM
Rural:				
Risø/2090	8	12	61%	DEHM/UBM
Keldsnor/9055	8	9	9%	DEHM/UBM
Anholt/6001	5	6	29%	DEHM/UBM

* 47 µg/m^3 is measured at the measuring station at HCAB. The station was moved about 3.5 m further away from the street in November 2016 to re-establish the distance to the street after a change in street layout that had moved traffic closer to the measuring station. Based on parallel measurements this change was estimated to have led to a jump of about 6 µg/m^3 in 2016. This value has been reduced in 2016 compared to previous years in order to take account of the replacement of the station in October 2016. Without the change in street layout, about 41 µg/m^3 is expected. OSPM calculations are more representative of the measurements without the jump as OSPM calculations reflect concentration levels in front of the building facade.

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