Air View Data on the spatial distribution of air pollution in Copenhagen

Scientific note from DCE – Danish Centre for Environment and Energy

Date: 26. May 2021 | **40**

AARHUS
UNIVERSITY
DCE – DANISH CENTRE FOR ENVIRONMENT AND ENERGY

Data sheet

Scientific note from DCE – Danish Centre for Environment and Energy

Category:	Scientific Advisory Report
Title:	Air View Data on the spatial variability of air pollution in Copenhagen
Authors:	Thomas Ellermann, Jibran Khan, Matthias Ketzel, Steen Solvang Jensen, and Ole Hertel
Institution:	Department of Environmental Science
Referee(s):	Andreas Massling
Quality assurance, DCE:	Vibeke Vestergaard Nielsen
Linguistic QA:	Vibeke Vestergaard Nielsen
Please cite as:	Ellermann, T., Khan, J., Ketzel, M., Jensen, S.S. & Hertel, O. 2021. Air View Data on the spatial distribution of air pollution in Copenhagen. Aarhus University, DCE - Danish Centre for Environment and Energy, 27s. – Scientific note no. 2021|40 https://dce.au.dk/fileadmin/dce.au.dk/Udgivelser/Notater_2021/N2021_40.pdf
	Reproduction permitted provided the source is explicitly acknowledged
Front page photo:	Thomas Hansen
Number of pages:	27

Contents

Key Messages

Since 2018 DCE – Danish Center for Environment and Energy has cooperated with Utrecht University, Copenhagen Municipality and Google on preparation of new data on the spatial distribution of the concentrations of nitrogen dioxide, black carbon and ultrafine particles in Copenhagen, Frederiksberg and Tårnby municipalities. This data, called Copenhagen Air View Data (CAV), provides a valuable additional contribution to existing knowledge on the spatial distribution of air pollution in the Copenhagen area. The Copenhagen Air View Data was produced using a combination of short term measurements with the Google Street View Car and model calculations using Utrecht University's Land-Use Regression air pollution model. The data is available at: https://insights.sustainability.google/labs/airquality

The key messages from this work are as follows:

- The main value of the Copenhagen Air View Data is the new information provided regarding the high-resolution spatial distribution of the health hazardous nitrogen dioxide, black carbon and ultrafine particles. All these pollutants have been associated with negative health effects.
- The results of the project show the highest concentrations of nitrogen dioxide, black carbon and ultrafine particles at the major roads while the lowest concentrations are in residential areas with relatively low traffic intensity. This pattern is expected since traffic is one of the most important emission sources for these air pollution components in cities.
- The Copenhagen Air View Data provide average concentrations for the period from October 2018 to March 2020. For nitrogen dioxide, data represents the annual average. For ultrafine particles and black carbon, data represents working day daytime averages that are estimated to be about 20% higher than the annual average.
- The Copenhagen Air View Data are based on measurements carried out on the traffic lanes and data are therefore estimated to be 20-30% higher than the results from the DCE monitoring stations in the Danish Air Quality Monitoring Program under NOVANA where the street monitoring stations are placed on the roadside. However, this correction factor is uncertain and will depend on local conditions like street configuration, building facades etc.
- The Copenhagen Air View data cannot be used to assess compliance with the limit value of nitrogen dioxide. The EU directive specifies that traffic lanes are not covered by the limit values and therefore measurements to assess compliance cannot be carried out on the traffic lanes. There are no limit values for black carbon and ultrafine particles.
- The Copenhagen Air View data on concentration levels of nitrogen dioxide are in good agreement with the results from the DCE monitoring stations when the difference between meaurements on the traffice lanes and at the roadside is taken into account.
- The Copenhagen Air View Data on ultrafine particles cannot be directly compared to the results from the DCE monitoring stations. Primarily, there is systematic difference between measurements on the traffic lanes and at roadside and systematic difference between the calculations of averages.

Copenhagen Air View Data represents working day daytime averages while the results from the DCE monitoring stations represents annual averages. Additionally, the concentrations of ultrafine particles are higher than the measurements from the DCE monitoring stations by approximately a factor of two. The Copenhagen Air View Data are higher than both the results from the Danish Air Quality Monitoring Program and from the Copenhagen airport project. This indicate that the Copenhagen Air View Data might overestimate the concentrations. However, the observed difference probably also reflects that it is very difficult to carry out accurate measurements of the small particles in the range below 20 nm.

- The Copenhagen Air View Data on black carbon (BC) cannot be directly compared to the results from the monitoring stations of elemental carbon (EC). As for ultrafine particles there is systematic difference due to difference in measurement location (traffic lanes versus road side) and in calculation of average concentrations (working day daytime versus annual average). Additionly, Copenhagen Air View Data provides data for the concentrations of black carbon while the measurements at the monitoring stations determine the amount of particulate elemental carbon. Black carbon (BC) and elemental carbon (EC) are both a measure of soot particles produced in combustion processes (i.e. road traffic) but due to different measurement principles, they cannot be directly compared. The difference (factor of two to three) between the Copenhagen Air View Data for black carbon and the monitoring results for elemental carbon is most likely due to the use of two different parameters. However, more measurements are needed to clarify the reasons for the difference observed between the Copenhagen Air View Data and results from the monitoring stations.
- The elevated concentrations of ultrafine particles seen on the eastern part of Amager are most likely due to emissions from Copenhagen Airport. However, the model calculations of the contribution from Copenhagen Airport have been carried out using a simplified method compared the the more advanced physical-chemical dispersion models. More measurements arround the airport and use of detailed dispersion models are therefore needed in order to verify to what distances the emissions from the airport significantly contribute to the concentrations of ultrafine particles.
- A comparison between Copenhagen Air View Data and DCE's air pollution data for 2019 on address level in Copenhagen (Air Quality at Your Street; http://luftenpaadinvej.au.dk) show fairly good agreement for nitrogen dioxide both with respect to the concentration levels and the spatial variation. The comparison shows furthermore that there is fairly good agreement on the spatial variation for black carbon but here the concentration levels shown by the Copenhagen Air View Data are considerably higher than the results from Air Quality at Your Street. For ultrafine particles there is no correlation between Copenhagen Air View Data and data from Air Quality at Your Street. One reason for this is that Air Quality at Your Street overestimates ultrafine particles at urban background and rural areas, although there is good agreement at street level af H.C. Andersens Boulevard. Other reasons for the missing correlation are that ultrafine particles is a very complex parameter that it is very difficult to accurately measure and model espeacially for particles under 20 nm. More research is needed to improve both measurements and modelling of ultrafine particles.

Dansk sammenfatning

DCE - Nationalt Center for Miljø og Energi ved Aarhus Universitet har siden 2018 samarbejdet med Utrecht Universitet, Københavns Kommune og Google om udarbejdelse af nye data for den geografiske fordeling af luftkoncentrationerne af kvælstofdioxid, black carbon og ultrafine partikler i Københavns Kommune, Frederiksberg Kommune og Tårnby Kommune. Disse data, kaldet Copenhagen Air View Data (CAV), giver værdifuld ny viden, som supplerer den eksisterende viden om den geografiske fordeling af luftforurening i Københavnsområdet.

De nye data offentliggøres den 26. maj 2021 i form af tre interaktive kort, som viser den geografiske fordeling af kvælstofdioxid, black carbon og ultrafine partikler (https://insights.sustainability.google/labs/airquality). Parallelt hermed offentliggør DCE opdaterede data for 2019 for "Luften På Din Vej" med modelberegning af luftkvaliteten på adresseniveau i hele Danmark (http://luftenpaadinvej.au.dk).

DCE har deltaget i flere aspekter af arbejdet, herunder selve arbejdet med målingerne med servicering af instrumenter og deltagelse i en arbejdsgruppe sammen med Utrecht Universitet, Københavns Kommune og Google. DCE har endvidere medvirket til arbejdet omkring modelberegningerne samt tolkning og formidling af resultaterne. Utrecht Universitet har haft hovedansvaret for de omfattende målinger og modelberegninger ligesom de har haft ansvaret for kvalitetssikring af resultaterne.

Data bag kortene er udarbejdet ved hjælp af en kombination af målinger og modelberegninger. Målingerne er udført med en Google Street View Car udstyret med instrumenter til måling af de tre luftforureningskomponenter. Bilen har i et fastlagt mønster gennemtravlet gaderne i de tre kommuner. Målingerne er foretaget fra oktober 2018 til marts 2020. Målingerne er opdelt i 50 meters gadesegmenter, hvor der for hvert gadesegment typisk er foretaget målinger i omkring 30 sekunder til nogle få minutter ad typisk fire til seks omgange fordelt ud over måleperioden. Målingerne giver derfor en form for snapshot af luftkoncentrationerne for de tre luftforureningskomponenter. Resultaterne fra de mange målinger kombineres herefter med modelberegninger udført med Utrecht Universitets luftkvalitetsmodel (Land-use Regression model, såkaldt LUR model), og det er disse data som betegnes Copenhagen Air View Data. Data angiver middelværdier for måleperioden, hvilket til en god tilnærmelse kan sammenlignes med årsmiddelværdierne for 2019.

For kvælstofdioxid viser kortet middelværdier baseret på målingerne med bilen i selve trafikken. Af denne årsag er resultaterne for kvælstofdioxid fra Copenhagen Air View Data omkring 20-30% højere end resultaterne fra DCE's gademålestationer i det danske luftkvalitetsovervågningsprogram under NOVANA. Denne systematiske forskel skyldes, at koncentrationerne er højere på vejbanen, hvor målebilen er tæt på udledningerne fra andre biler, mens DCE's målestationer ved vejsiden er længere væk, hvor fortynding giver lavere koncentrationer.

For black carbon og ultrafine partikler viser kortene middelværdier, som ligeledes er omkring 20-30% højere end resultaterne fra DCE's gademålestationer, som følge af den systematiske forskel mellem målinger i trafikken og ved vejsiden. Middelværdierne fra Copenhagen Air View Data repræsenterer endvidere ikke selve årsmiddelværdien, men middelværdien for hverdage i dagtimerne. Dette giver også en systematisk forskel mellem årsmiddelværdierne fra DCE's målestationer og Copenhagen Air View Data. Ud fra målingerne ved DCE's målestationer vurderes at dette giver en yderligere forskel på omkring 20% mellem Copenhagen Air View data og data fra DCE's gademålestationer. Samlet set vil der derfor være omkring 45% til 55% forskel mellem kortenes værdier og resultaterne fra DCE's målestationer. Der er stor usikkerhed på vurderingen af den systematiske forskel mellem kortenes værdier og DCE´s måleresultater.

DCE's hovedbudskaber fra arbejdet er følgende:

- Copenhagen Air View Data er et værdifuldt supplement til den eksisterende viden om den geografiske variation af luftforureningen med kvælstofdioxid, black carbon og ultrafine partikler i Københavnsområdet. De tre luftforureningskomponenter er alle koblet til de negative helbredseffekter af luftforureningen.
- De højeste koncentrationer af kvælstofdioxid, black carbon og ultrafine partikler ses ved de største veje, mens de laveste koncentrationer ses i boligområder. Dette mønster er forventeligt, da trafik er en af de vigtigste kilder til udledninger af disse tre luftforureningskomponenter i danske byer.
- Copenhagen Air View Data er et gennemsnit for perioden fra oktober 2018 til marts 2020. For kvælstofdioxid repræsenterer data årsmiddelværdien.
- For black carbon og ultrafine partikler repræsenterer resultaterne middelværdi for hverdage i dagtimerne. Det er skønnet ud fra analyse af målingerne på DCE's målestationer, at dette betyder, at resultaterne for black carbon og ultrafine partikler fra Copenhagen Air View vil være omkring 20% højere end årsmiddelværdierne fra DCE's målestationer.
- Copenhagen Air View Data er baseret på målinger udført i selve trafikken. Resultaterne skønnes derfor at være 20-30% højere end resultaterne fra DCE's gademålestationer i det danske luftkvalitetsmåleprogram, hvor målestationerne er placeret mellem vejbanerne og husfacaderne.
- Resultaterne kan ikke anvendes til at vurdere overholdelse af EU's grænseværdier for kvælstofdioxid. EU-direktivet (2008/50/EF) angiver, at vejbanerne ikke er omfattet af grænseværdierne og at målingerne, som anvendes til vurdering af overholdelse af grænseværdierne, ikke må foretages på vejbanerne. Der er ingen grænseværdier for koncentrationerne af black carbon og ultrafine partikler i udeluft.
- Koncentrationsniveauerne for kvælstofdioxid er i god overensstemmelse med resultaterne fra målestationerne, når der tages hensyn til forskellen mellem målingerne i trafikken på vejbanerne og målingerne ved siden af selve vejen.
- Copenhagen Air View Data for ultrafine partikler kan ikke sammenlignes direkte med resultaterne fra målestationerne. Dels er der ovennævnte systematiske forskelle i målested og beregning af gennemsnit. Dels giver Copenhagen Air View Data koncentrationsniveauer som er omkring en faktor to højere end resultaterne fra målestationerne. Copenhagen Air View data er højere end både resultaterne fra det danske luftkvalitetsmåleprogram og målingerne i lufthavnen, hvilket indikerer at Copenhagen Air

View Data kan være for høje. Den observerede forskel skyldes formentligt også, at det er meget svært at udføre nøjagtige målinger af antallet af partikler i området under 20 nm.

- Copenhagen Air View Data for black carbon kan ikke sammenlignes direkte med resultaterne fra målestationerne. Som for ultrafine partikler er der de systematiske forskelle mellem målested og beregning af gennemsnit. Men derudover er der forskel i målemetode, da der ved DCE's målestationer måles elementært kulstof, mens Copenhagen Air View Data er baseret på målinger af black carbon. Både elementært kulstof og black carbon er et udtryk for sodpartikler, som stammer fra udledninger fra forbrændingsprocesser (fx vejtrafik), men grundet forskellige målemetoder, så kan de to parametre ikke sammenlignes direkte. Den relativt store forskel som observeres mellem resultaterne fra Copenhagen Air View Data og målestationerne kan skyldes forskellen mellem de to forskellige parametre. Der er derfor behov for yderligere målinger for at få mere viden om forholdet mellem elementært kulstof og black carbon.
- På den østlige del af Amager observeres forhøjede koncentrationer af ultrafine partikler. Dette skyldes mest sandsynligt udledninger fra Københavns Lufthavn. Modelberegningerne bag Copenhagen Air View Data er imidlertid udført med en simplificeret metode. Derfor er der behov for at dokumentere bidraget fra lufthavnen yderligere via målinger i området omkring lufthavnen og modelberegninger med mere detaljerede modeller, som kan give bedre beregninger af selve spredningen af luftforureningen fra lufthavnen.
- Sammenligning mellem Copenhagen Air View Data og data fra DCE's modelberegninger på adresseniveau (Luften på din vej, http://luftenpaadinvej.au.dk) viser, at der er relativt god overensstemmelse mellem de observerede koncentrationsniveauer og den geografiske variation for kvælstofdioxid. Sammenligningen viser ydermere, at der er relativt god overensstemmelse mellem den geografiske variation i luftkoncentrationerne for black carbon. For black carbon ses dog en forskel i koncentrationsniveauerne, hvor Copenhagen Air View Data er væsentligt højere end "Luften på din vej". For de ultrafine partikler er der ingen korrelation mellem resultaterne fra Copenhagen Air View Data og "Luften på din vej". En årsag til dette er, at modelberegningerne bag "Luften på din vej" giver for høje koncentrationer i bybaggrund og landområder, og at modelberegningerne undervurdere bidraget fra vejtrafikken. Sammenlignet med målingerne giver "Luften på din vej" dog fin overensstemmelse for gademålestationen på H.C. Andersens Boulevard. Andre grunde for den manglende korrelation er at koncentrationen af ultrafine partikler er en meget kompleks parameter, som det er meget svært at måle eller modellere nøjagtigt specielt for partikeler under 20 nm. Mere forskning er nødvendig til at forbedre målinger og modellering af partikel antal.

1 Introduction

During the last three years (2018-2021), Utrecht University, Copenhagen Municipality, Google and DCE – Danish Center for Environment and Energy have cooperated on a project that has resulted in new data on the spatial distribution of air pollution in Copenhagen, Frederiksberg and Tårnby municipalities. The results from the project, Copenhagen Air View Data (CAV) are available on May 26, 2021 on a public internet platform in the form of digital maps presenting the spatial distribution of nitrogen dioxide, black carbon and ultrafine particles in the three municipalities (https://insights.sustainability.google/labs/airquality).

The main sources of nitrogen dioxide, black carbon and ultrafine particles are combustion processes and in cities traffic is the most important of such sources. Other sources like wood burning, power plants, industries and airports are also important. All three air pollution components have been linked to the health impacts of air pollution exposure.

This scientific note describes DCE's involvement in the project, and briefly describes the methods that have been used to prepare the data. The results generated in the project are compared to measurement data from the national air quality monitoring station in Copenhagen, as well as to the updated data from the model calculations for the "Air Quality at Your Street" project representing 2019 (see further explanation below). Finally, the scientific note presents DCE's view on the quality of the new data, and DCE's interpretation of these.

In connection to the Danish Air Quality Monitoring Program, DCE has most recently carried out new and updated model calculations for the same three air pollution components as discussed in this scientific note. This data covers calculations for 2.5 million addresses in Denmark for the year 2019. The data are also public available by May 26, 2021 on the homepage for the project "Air Quality at Your Street" (http://luftenpaadinvej.au.dk). The data is described in a separate DCE report (Jensen et al., 2021, http://dce2.au.dk/pub/-SR445.pdf).

2 DCE's involvement in production of CAV

DCE has been involved in the preparation of the CAV data on several levels.

During the campaign measurement period using the Google Street View Car, DCE undertook the task to perform daily service of the instruments in the car, as well as the handling of data storage. Utrecht University designed and build the instruments etc. into the Google Street View Car and carried out the calibration and repair of the instruments. The subsequent data preparation and analyses has carried out in a cooperation between the two research groups under the lead of Utrecht University, since they have designed the project and have experience from a prior project carried out in the US.

Since the beginning of the project, DCE has participated in a working group connected to the project. The working group included participants from Google (Natalie Smailou, Karin Tuxen-Bettman), Municipality of Copenhagen (Rasmus Reeh, Christian Gaarde Nielsen), Utrecht University (Roel Vermeulen, Jules Kerckhoffs) and DCE (Thomas Ellermann, Ole Hertel, Matthias Ketzel and Jibran Khan). This working group has followed the progress of the work, as well as it has discussed practical and scientific issues of relevance for the project. Within the framework of the working group, DCE has participated in the discussions of the quality of the results, the methods developed for modelling, and the presentation of the data, etc. The final quality assurance and the model calculations are carried out by Utrecht University.

In addition, DCE has delivered a series of data sets that have been central for the analyses carried out in the project and the corresponding generated results. These data sets include:

- Air quality data from the Danish air quality monitoring stations in Copenhagen (Ellermann et al., 2021) covering the entire measurement campaign period for the Google Air View Car study. The data was used in connection with the validation of the measurements themselves, but also for the subsequent corrections of the data (However, only for nitrogen dioxide, since the necessary data for black carbon and ultrafine particles were not available).
- High-resolution data on building footprints and building height in Copenhagen.
- Traffic information for all streets in Copenhagen from DCE's Road and Traffic Database (Jensen et al., 2019).

3 Short description of method

The new data on the spatial distribution of air pollution in Copenhagen are generated in three steps. The first step consists of measurements using the Google Air View car, and the second step consists of Land Use Regression (LUR) model calculations by the Utrecht University. In the third step, the results from the measurements and model calculation were combined into a so-called "mixed" model, using measurements and LUR model calculations. It is these final data that are called CAV data. This combination of measurements and LUR model estimates have been increasingly used during the latest decades and is termed as a "mixed" or linear mixed-effects model.

3.1 Measurements

The measurements were carried out in the time period from October 2018 to March 2020. The measurements were carried out from the Google Air View Car, which is a Google Street View Car equipped with scientific grade instruments for measurements of nitrogen dioxide, black carbon and ultrafine particles.

Ultrafine particles is defined as the particles with diameter below 100 nm. The instrument for measurement of ultrafine particles measures the total number of particles above 7 nm, and include particles with diameter well above 100 nm. Strictly speaking, the measured particle number does therefore not entirely follow the definitions for the ultrafine particles. Typically, the particle number is slightly larger than the number of ultrafine particles. However, in popular context, ultrafine particles is the most commonly used term for this group of particles. We will therefore use this term in this DCE scientific note.

The measurements were carried out with high time resolution (1 Hz). In addition, the car has an intake of air to the instruments on the roof, a GPS system for exact spatial location of the measurements and an advanced data sampling and handling system.

During the entire measurement period, the car made daily drives in Copenhagen. The drives followed a laid-out pattern ensuring that the car measurements would cover all streets several times during the whole campaign period. The performed number of drives on each street are from four to six times with more frequent drives on the major roads and fewer drives on smaller less trafficked/important roads. Each street is subdivided into 50 meters street segments, in order to obtain a high spatial resolution of the obtained measurement data. The typical measurement time for each street segment ranges from 30 seconds to a few minutes in total for all the passages.

Therefore, the measurements have to be regarded as a kind of a snapshot of the concentration levels in 2018-2020 based on the average concentrations measured during the typical four to six passages of the specific street segment. Prior to the averaging, the concentrations of nitrogen dioxide were corrected temporarily using the measured concentrations of the urban background monitoring station at Copenhagen University (H.C. Ørsted Institut). The aim of this correction was to compensate for the seasonal and daily variations in the concentrations of nitrogen dioxide. For black carbon and ultrafine particles, it has not been possible to make this correction, and the averages for these air pollution components represents solely the daytime conditions corresponding to the period where the car has been driving.

The measurements were carried out with a car driving inside the traffic in the streets. The measurement results obtained from the car will therefore be higher than the results from the monitoring stations that are placed between the traffic lanes and the facades of the houses along the street. Utrecht University has measured this difference in Amsterdam and they found that on average the concentrations was about 20-30% higher in the traffic compared to the monitoring stations (Kerchhoffs el at., 2021a, 2021b). However, this correction factor is uncertain and will depend on local conditions like street configuration, building facades etc.

3.2 Model calculations

The modelled concentrations of the three air pollution components have been carried out using Utrecht University's Land Use Regression (LUR) model that has been set up for the Copenhagen Area. The Land-use Regression Model is set up for 50-m street segments and utilizes several geographical variables in buffer distances in the range 100 m – 5000 m. The variables, among others, include traffic intensity (number of vehicles/day), total road length (in 50 m – 1000 m buffer distances), estimated building heights in meters (in 25 m, 50 m and 100 m buffer distances), and land use data, including port, industry, urban greenery, airports and population/household density (in 100 m – 5000 m buffer distances).

As stated above, the LUR model includes calculations of the contributions from Copenhagen airport based on a buffer distance approach. The buffer extends up to 5 km around the airport.

3.3 Mixed model calculations

In the last step, the results from the measurements and LUR model calculations are combined via a statistical approach. The statistical approach, the so-called "mixed" model, is also known as the linear mixed-effects model (Pinheiro and Bates, 2006). Here, variables from the LUR model are used as the "fixed-effect" in the mixed model, whereas measurements are used as the "random-effect". The aim of this step was to change the results from the measurements, where uncertain (due to high variability, low number of measurements), hereby low or high values are "smoothed out" towards the LUR model estimates.

The final result from this step is called the mixed model estimates. The results represent the average concentrations for the measurement period from October 2018 to March 2020. To a good approximation, this will correspond to the annual average for 2019. For nitrogen dioxide, the results represent the annual average, whereas for black carbon and ultrafine particles, the mixed model estimates are limited to the annual daytime average.

The measurements and model calculations are described in two scientific papers by Kerckhoffs et al. (2021a) and Kerckhoffs and Khan et al. (2021b).

4 Results

The primary direct output from the project are three generated maps showing the spatial distribution of average concentrations of nitrogen dioxide, black carbon and ultrafine particles for the time period October 2018 to March 2020. The results are available via the internet (https://insights.sustainability.google/-labs/airquality), where it is possible to obtain and assess the mapping of the spatial distribution of the concentrations and to zoom in on the individual street segments to study the local spatial distribution down to single street level. Figure 4.1, 4.2 and 4.3 show overviews of the spatial distribution for the three air pollution components.

The results of the project show the highest concentrations at the major roads for all three air pollutants, while the lowest concentrations are in residential areas with relative low traffic intensity. Especially the main traffic corridors and highways are standing out with the highest concentrations. This pattern is expected since traffic is one of the most important sources of emissions for these three air pollutant components in Danish cities.

The concentrations of nitrogen dioxide (Figure 4.1) reach in some of the most heavily trafficked streets above 40 $\mu g/m^3$. The EU annual average limit value for nitrogen dioxide is 40 $\mu g/m^3$ (2008/50/EC). However, the CAV data cannot be used to assess compliance with this limit value since the EU directive specifies that traffic lanes are not covered by the limit values and that the measurements used to assess compliance must not be carried out on the traffic lanes.

For black carbon (Figure 4.2), slightly higher concentrations are observed for Vesterbro compared to other parts of the inner city. At present, the reason for this is not known, and more work has to be carried out to determine wheter this is due to higher emissions in that particular area of Copenhagen, or this due to the uncertainties in the data originating from the measurements or the model approach.

For ultrafine particles (Figure 4.3), elevated concentrations are observed in the eastern part of Amager in the area around the airport. In a previous study from DCE (Ellermann et al., 2011), it was documented that the emissions of ultrafine particles are high, and that the concentrations of ultrafine particles at the western border of the airport are comparable to the concentrations measured at the monitoring station at H.C. Andersens Boulevard. It is therefore expected that the area around the airport will have elevated concentrations compared with similar areas in other parts of the city. However, the modelling of the dispersion of ultrafine particles from the airport to the surrounding areas has been carried out using a simplified method compared to more advanced physcal-chemical dispersion models, and the extent and spatial distribution of a significant contribution from the airport is therefore uncertain. Thus, it is necessary to supplement the CAV data with measurements of ultrafine particles in the area around the airport, and to carry out calculations using more detailed models that can estimate the actual dispersion of the emissions from the airport.

Figure 4.1. Overview of the spatial distribution of nitrogen dioxide based on CAV. This map has been provided by Utrecht University and Google, 2021.

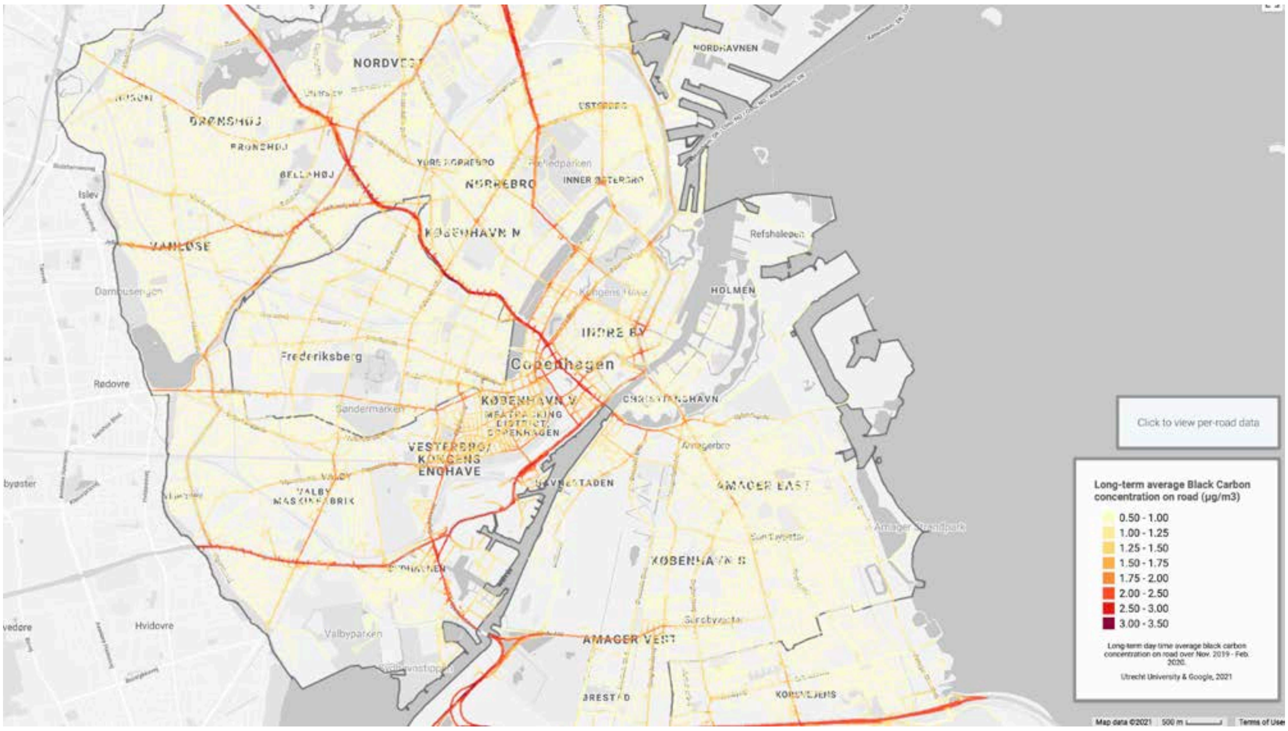

Figure 4.2. Overview of the spatial distribution of black carbon based on CAV. This map has been provided by Utrecht University and Google, 2021.

Figure 4.3. Overview of the spatial distribution of ultrafine particles based on CAV. This map has been provided by Utrecht University and Google, 2021.

Figure 4.4 shows an example of the spatial variation of the concentration of ultrafine particles on local scale.

It is unavoidable that there can be identified sites for which the results will have particular high uncertainties. CAV data rely on data sets on traffic information, street geometry, building data etc. and uncertainties in this data will result in uncertainties in the results. It is beyond the scope of this project to carry out a detailed quality control on all the input data, and it is however evident that large uncertainties can occur on local scale.

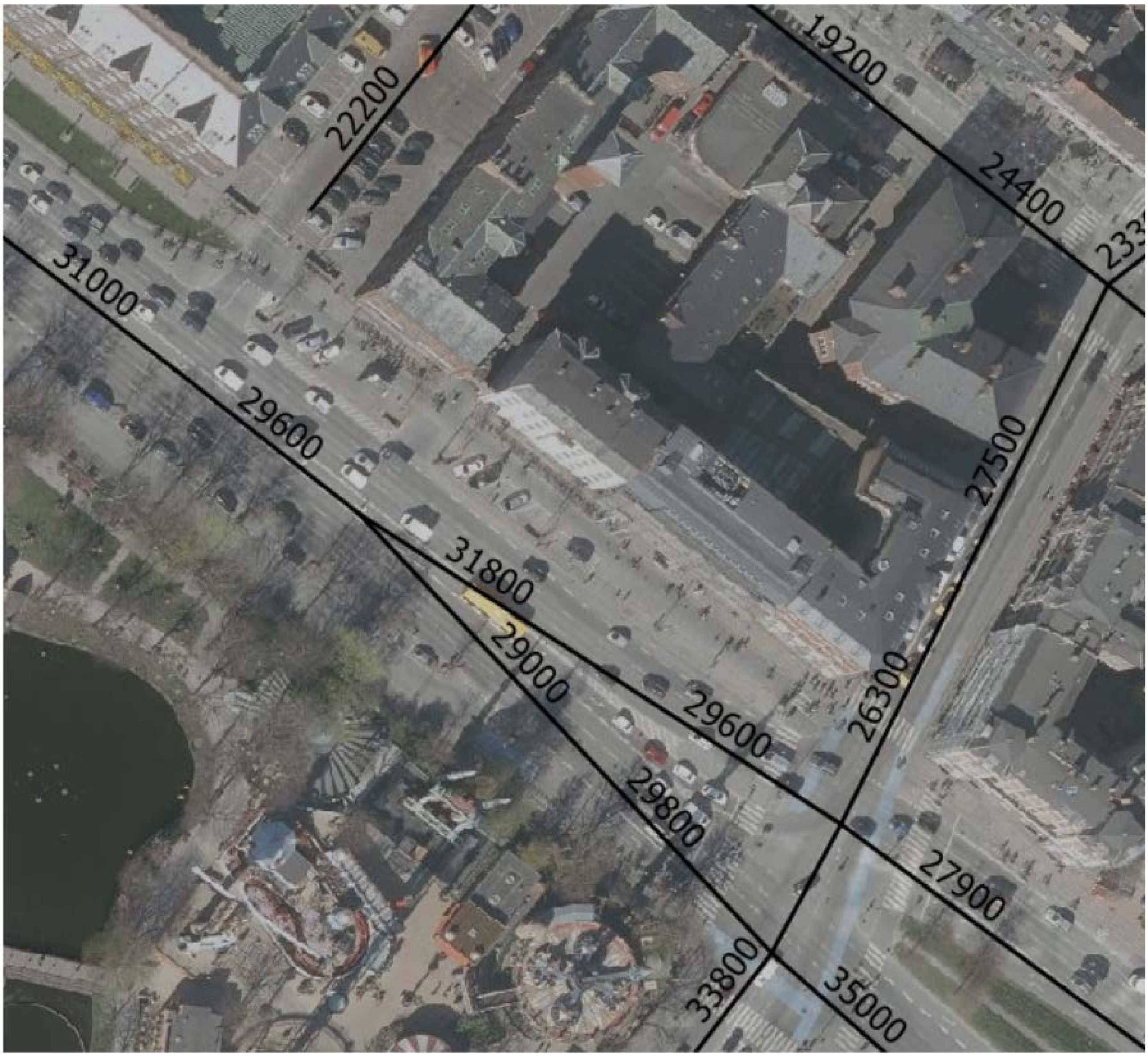

Figure 4.4. Example on data at local scale. The map shows the variation in the concentrations of ultrafine particles (units: particle numbers per cm^3) at the traffic light between H.C. Andersens Boulevard and Stormgade. Background map: Danish Agency for Data Supply and Efficiency, https://sdfe.dk.

5 Comparison with measurements at monitoring stations

Comparison of CAV data with measurements from the DCE monitoring stations will provide useful information about the quality of the new data. In the following paragraphs, CAV data is compared to annual average values from the monitoring stations in the Danish Air Quality Monitoring Program (Ellermann et al., 2020):

- The street station at H.C. Andersens Boulevard (nitrogen dioxide, ultrafine particles and black carbon).
- The street station at Jagtvej (nitrogen dioxide).
- The urban background station at the rooftop of H.C. Ørsted Institute at the Copenhagen University (nitrogen dioxide, ultrafine particles and black carbon).

In addition, data is compared to results for nitrogen dioxide and ultrafine particles from the Copenhagen Airport monitoring station, which is located about 100 meters from the western border of the airport (Jensen et al., 2020). The measurements at this monitoring station are carried out by Force Technology. Figure 5.1 shows the locations of the four monitoring stations.

The CAV project covers data from the period from October 2018 to March 2020. To a good approximation, this corresponds to the annual average for 2019 and hence annual averages from 2019 are used from the monitoring stations for comparison.

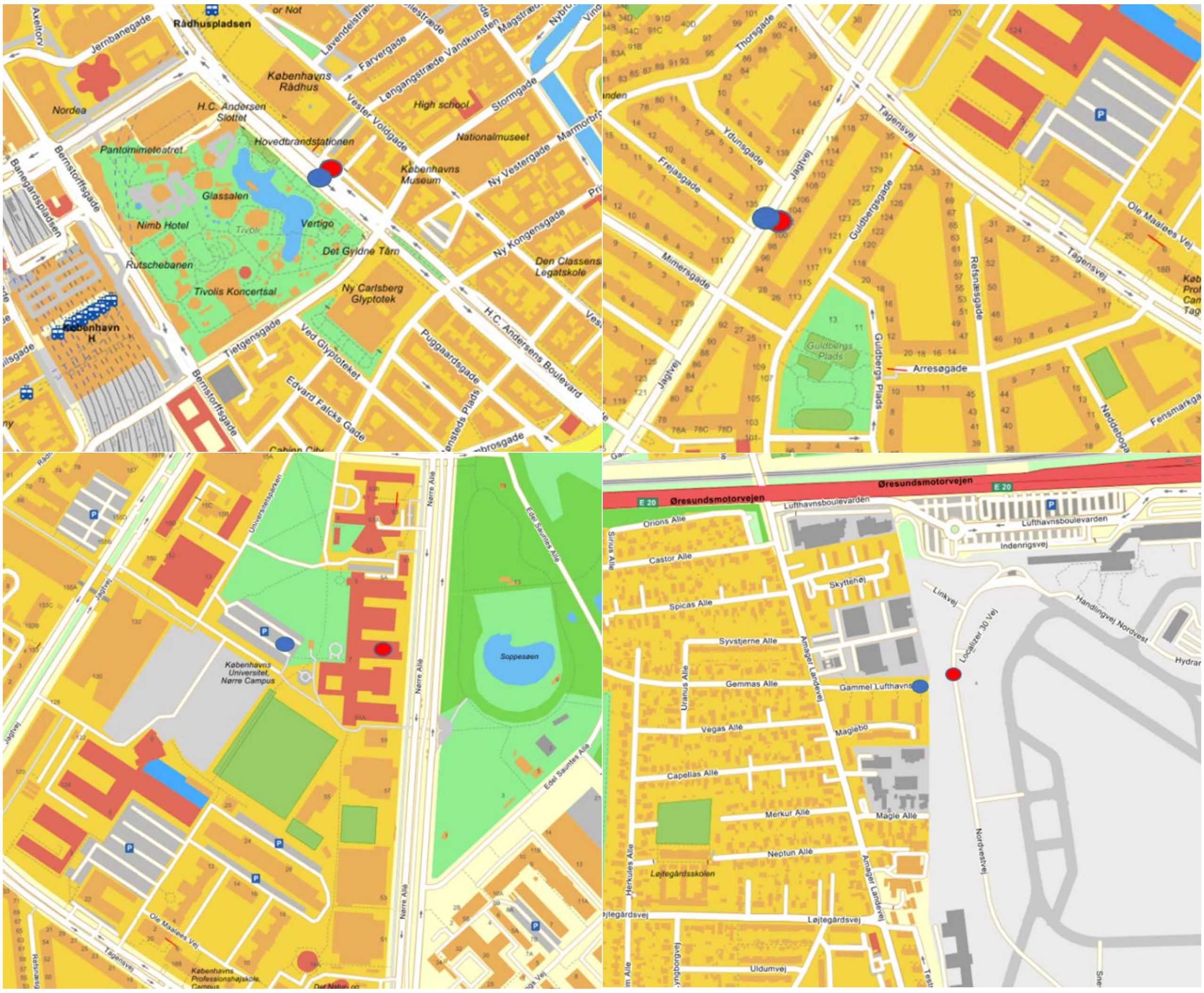

Figure 5.1. Maps showing the locations of the monitoring stations (red dot) and the street segment for CAV used for the comparisons. Upper left: H.C. Andersens Boulevard, upper right: Jagtvej, lower left: urban background at H.C. Ørsted Institute, Copenhagen University and lower right: Airport West. Background maps; Krak.dk.

Figure 5.2 and Table 5.1 show a comparison for nitrogen dioxide between the CAV data, the annual average values from the monitoring stations, and the annual averages for the two street monitoring stations (here, also corrected values are presented additionally). The correction of the measured values is due to the fact that CAV is based on measurements carried out in the traffic lanes, while the street measurement stations are placed at the roadside about 1-4 meters from the outer traffic lane. Kerckhoffs et al. (2021a) observed in Amsterdam, that nitrogen dioxide concentrations in the traffic lanes are approximately 20-30% higher than what is observed at the roadside. Based on this, the corrected annual averages are estimated by increasing the measured annual averages by 25% for the DCE street monitoring stations. The CAV results are in good agreement with the measured annual averages when taking into account the difference between measurements on the traffic lanes and at the roadside. It shall also be kept in mind that this correction factor is uncertain and most likely this correction factor will depend on local conditions like street configuration, building facades etc.

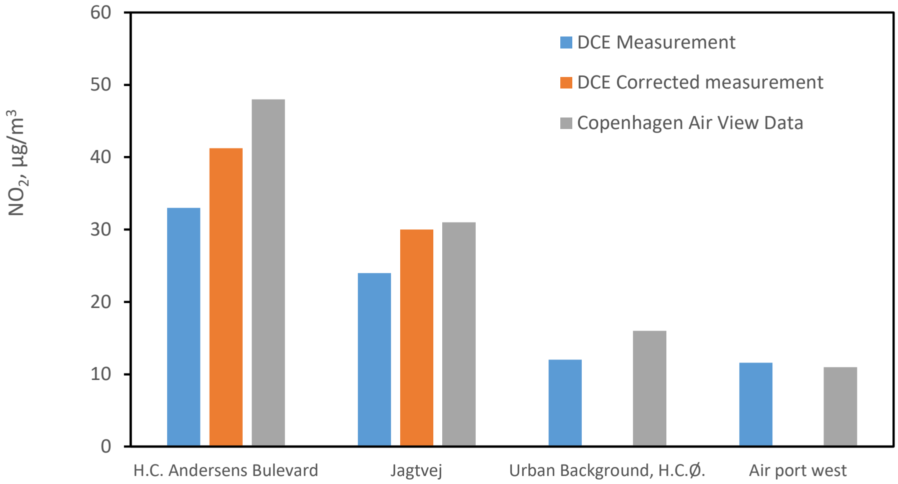

Figure 5.2. CAV results and the annual averages for nitrogen dioxide for 2019 from the street stations at H.C. Andersens Boulevard and Jagtvej, the urban background station at H.C.Ø. and the station close to the western border of Copenhagen Airport. The annual averages from the street stations are corrected for estimated difference between measurements in the traffic lanes and at the roadside.

Table 5.1. CAV results and the annual averages for nitrogen dioxide for 2019 from the street stations at H.C. Andersens Boulevard and Jagtvej, the urban background station at H.C.Ø. and the station close to the western border of Copenhagen Airport. The annual averages from the street stations are corrected for estimated relative differences between measurements in the traffic lanes and at the roadside.

	DCE Measurement µg/m³	DCE Corrected Measurement µg/m³	Copenhagen Air View Data µg/m³	Relative Difference %
H.C. Andersen Boulevard	33	41	48	16
Jagtvej	24	30	31	3
Urban Background, H.C.Ø.	12		16	33
Airport west	12		11	-5

Figure 5.3 and Table 5.2 show a comparison for ultrafine particles between CAV data, annual average values from the DCE monitoring stations and corrected annual averages. In 2019 the results from the DCE monitoring stations covered only the range of particles from 41 nm to 480 nm (Ellermann et al. 2020). The numbers presented in Figure 5.3 and Table 5.2 are therefore interpolated values for 2019 based on the results from 2016 and 2020, where the measured data covered the full range above 10 nm and upwards (Ellermann et al., 2021).

The measured values for H.C. Andersens Boulevard are corrected both for the difference due to the measurement location (traffic lane versus roadside) and for the difference in the averaging period, while the measured value at Airport west has only been corrected for the difference in averaging period. The correction to reflect measurement location is assumed to be approximately 20-30% (Kerckhoffs and Khan et al., 2021b). The measured data from the monitoring stations represent annual averages while CAV data represents the annual working day daytime average. The measurements at H.C. Andersens Boulevard and urban background is carried out as hourly averages and hence it is possible to calculate a correction factor between daytime working day average and annual average. Based on data from 2020 (Ellermann et al., 2021) it is found that the correction factor is +20% for H.C. Andersens Boulevard, and that no correction is needed for the urban background.

There is also a difference between the annual average and annual working day daytime average at the Airport west. However, since we have no available data that can be used to determine the correction factor, it has been assumed that the correction is at the same level as for H.C. Andersens Boulevard.

CAV data results are 82-117% higher for ultrafine particles compared to the results from the DCE monitoring stations, even after the correction of the data from the DCE monitoring stations. CAV results are about a factor of two higher than the original data from the Danish Monitoring Program and the airport. This indicates that CAV results might overestimate the concentrations. However, it is difficult to carry out accurate measurements of the number of ultrafine particles below 20 nm. In addition, different instruments have been used for CAV data, the DCE monitoring stations and at the airport. This may result in differences in the cut-off for the lower end of the measured particle range leading to significant differences in the measured values.

CAV results can therefore not be compared directly with the results from the DCE monitoring stations. On the other hand, there is good agreement between the relative difference between the street, urban background and airport monitoring stations and hence the relative spatial variation is plausible.

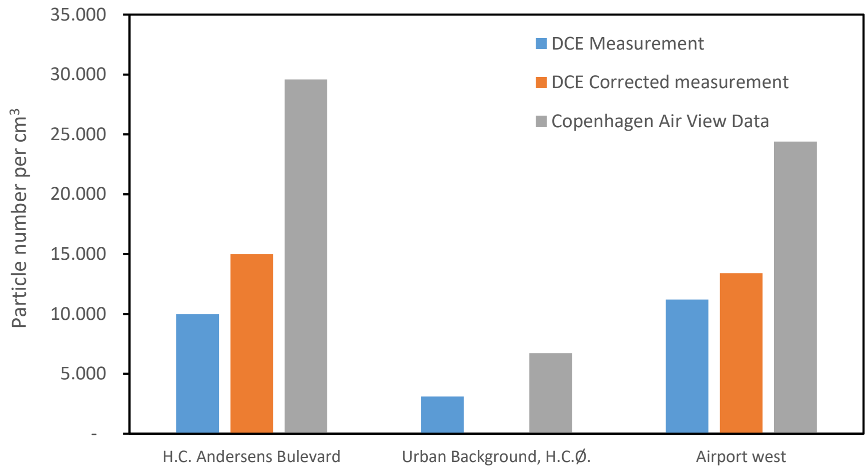

Figure 5.3. CAV results and annual averages for ultrafine particles for 2019 from the street station at H.C. Andersens Boulevard, the urban background station at H.C.Ø. and the station close to the western border of Copenhagen Airport. The annual averages from H.C. Andersens Boulevard and Airport west are corrected for estimated differences between measurements on the traffic lanes and at the roadside (only street station) and differences between the annual average and working day daytime average.

Table 5.2. CAV results and annual averages for ultrafine particles for 2019 from the street stations at H.C. Andersens Boulevard, the urban background station at H.C.Ø. and the station close to the western border of Copenhagen Airport. The annual averages from H.C. Andersens Boulevard and Airport west are corrected for estimated differences between measurements on the traffic lanes and at the roadside (only street station), and the differences between annual average and working day daytime average.

	DCE Measurement particles/cm^3	DCE Corrected Measurement particles/cm^3	Copenhagen Air View Data particles/cm^3	Relative Difference %
H.C. Andersen Boulevard	10.000	15.000	29.600	97
Urban Background, H.C.Ø.	3.100		6.740	117
Airport west	11.200	13.400	24.400	82

Figure 5.4 and Table 5.3 show a comparison between CAV for black carbon and the annual average values for elemental carbon from the monitoring stations and corrected annual averages for the street monitoring stations. Black carbon and elemental carbon are two different parameters used to describe soot particles. The measurement principles are very different, and the results can therefore not be directly compared.

The measured values for H.C. Andersens Boulevard have been corrected both for the difference due to the measurement location (traffic lane versus roadside), and for the difference due to averaging period, while no correction has been applied for the urban background monitoring station. The correction of the measurements reflecting the location (roadside versus street lane) is estimated to be 20-30% (Kerckhoffs and Khan et al., 2021b). The measurements of elementary carbon are based on diurnal averages, and it is therefore not possible to determine a correction factor on basis of the measurements. It has therefore been assumed, that the correction factor (+20%) for ultrafine particles is applicable for elementary carbon as well.

CAV results are nearly two to three times higher compared to the results from the measurements, even after correction of the data from the monitoring roadside station. The main reason for this is believed to be the different parameters measured (black carbon versus elementary carbon). However, the difference between the CAV results for black carbon and monitoring data for elemental carbon is high, and this indicate that CAV results might overestimate the amount of black carbon. In order to establish a conversion factor between black carbon and elemental carbon at the monitoring stations, it would therefore be necessary to carry out additional measurements.

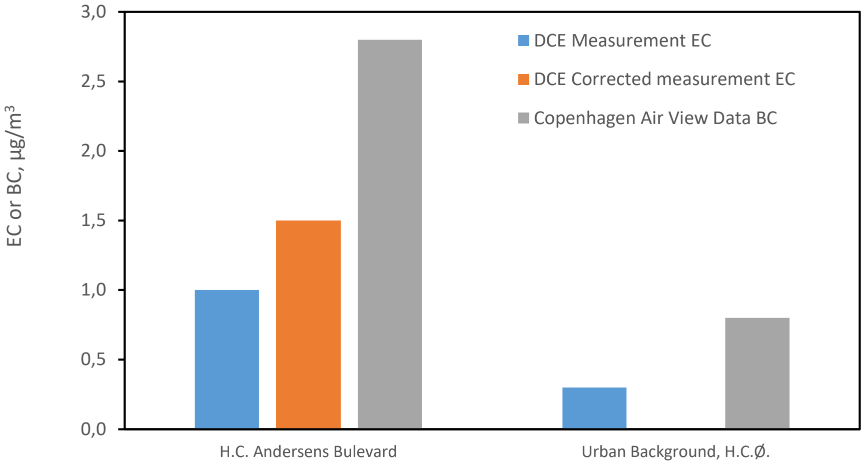

Figure 5.4. CAV results for black carbon (BC) and annual averages for elemental carbon (EC) for 2019 from the street station at H.C. Andersens Boulevard and the urban background station at H.C.Ø. The annual averages from H.C. Andersens Boulevard are corrected for estimated differences between measurements on the traffic lanes and at the roadside and the differences between annual average and working day daytime average.

Table 5.3. CAV results for black carbon (BC) and annual averages for elemental carbon (EC) for 2019 from the street station at H.C. Andersens Boulevard and the urban background station at H.C.Ø. The annual averages from H.C. Andersens Boulevard are corrected for estimated differences between measurements on the traffic lanes and at the roadside and differences between the annual average and working day daytime average.

	DCE Measurement EC µg/m³	DCE Corrected Measurement EC µg/m³	Copenhagen Air View Data BC µg/m³	Relative Difference %
H.C. Andersen Boulevard	1,0	1,5	2,8	87
Urban Background, H.C.Ø.	0,3		0,8	167

6 Comparison between CAV and DCE's Air quality on your street

In the following, we will present the results from a first comparison between CAV data and DCE's data presented on the portal Air Quality at Your Street (LPDV based on the Danish name). Both data sets provide high-resolution data for the annual average of nitrogen dioxide, black carbon and ultrafine particles. Additionally, Air Quality at Your Street also presents data for concentrations of $PM_{2.5}$ and PM_{10} (particles with diameters below 2.5 and 10 micrometer, respectively).

The LPDV data is computed using DCE's air quality models that are based on physical-chemical modelling of the processes determining the air concentrations of nitrogen dioxide, black carbon and ultrafine particles. These models are described in a Scientific Report from DCE (Jensen et al., 2021).

Since both data sets have been finalized recently, the conclusions presented here of comparisons shall be regarded as preliminary, and more work has to be done to get a more detailed knowledge on the difference between the results from the two data sets.

Figure 6.1 shows a scatter plot between CAV and LPDV for nitrogen dioxide. The coefficient of determination (also called R-squared) R^2 is 0.36 meaning that 36% of the variation in one variable can be explained by the other variable. The correlation between the two data sets are therefore not excellent but on the other hand, this level of correlation is not uncommon when two very different methods for determining high-resolution data on the spatial variability are compared. A perfect correlation would have a R^2 of 1 and a strong correlation between the two variables would be in the order of 0.7-1.

Moreover, the statistical analysis of the data shows that on average the concentrations of nitrogen dioxide are about 20% higher in CAV data compared to LPDV data. There is therefore good agreement between the average concentration levels determined by the two different methods when it is taken into account that CAV data is determined from measurements on the traffic lanes while LPDV represents the concentrations at the facade.

One distinct group of data seems to differ more than the remaining group of data. This is the data in the ellipsoid in Figure 6.1, where the LPDV model shows concentrations in the range between 12 and 17 $\mu g/m^3$ and CAV data are between 15 and 45 $\mu g/m^3$. Three explanations for the very low correlation for this group of data can be:

- LPDV describes the emissions from traffic and the impact of meteorology in a very detailed way based on traffic intensity, composition of fleet of vehicles, travel speed, detailed meteorological date etc. CAV rely on a less detailed modelling approach in combination with short-term measurements using the Google Street View Car.
- Data from some of the street segments are based on only one or two passages of the street, and this makes data from these street segments uncertain.

- CAV results include the contribution of nitrogen dioxide from the traffic emissions on the highways while LPDV does not take these emissions into account on local scale.

All these differences in methods and input data might lead to distinct differences for a group of street segments. However, there can also be various other explanations for the differences, and a more detailed comparison of the two data sets is necessary in order to explain the observed differences for this particular group of data.

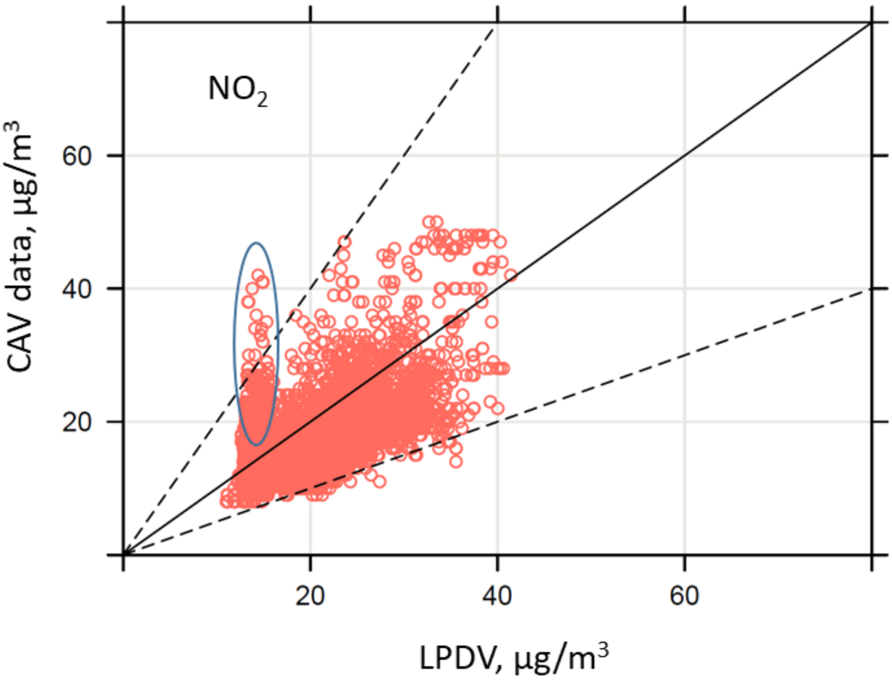

Figure 6.1 Comparison of concentrations of nitrogen dioxide from CAV data and annual averages from LPDV. The black line is the 1:1 line and the dashed lines are the 2:1 and 1:2 lines. The ellipsoid indicates the group of data specially mentioned in the text above. The comparison is based on the 14776 street segments from CAV that are within 10 meters distance to LPDV address points.

Figure 6.2 shows a scatter plot between CAV and LPDV for black carbon. The coefficient of determination R^2 is 0.36 meaning that 36% of the variation in one variable can be explained by the other variable which is about the same as for nitrogen dioxide.

The absolute values differ significantly between the two data sets. Data from CAV is about a factor of three higher compared to data from the LPDV model. The same difference was observed when the CAV data was compared to the measurements from the DCE monitoring stations (Chapter 5).

Part of the reason for this difference is that CAV represents results for the traffic lanes while LPDV represents the concentrations at the facades. Moreover, CAV represents averages for working day daytime while LPDV are annual averages. Both these differences result in higher concentrations for results from CAV compared to LPDV.

The difference between the absolute levels might be due to the very different approaches used for CAV and LPDV. The absolute levels determined by CAV rely on a combination of results from short time measurements of black carbon on the traffic lanes and model calculations. LPDV is based on DCE's air quality models that are based on a physical-chemical modelling of the processes determining the concentration levels and using emission inventories for black carbon as one of the important input data sets. It is well known that the emission inventories for black carbon are very uncertain, and this can hence also be part of the explanation for the large differences. However, more comparisons are necessary in order to further investigate the reasons for the observed differences.

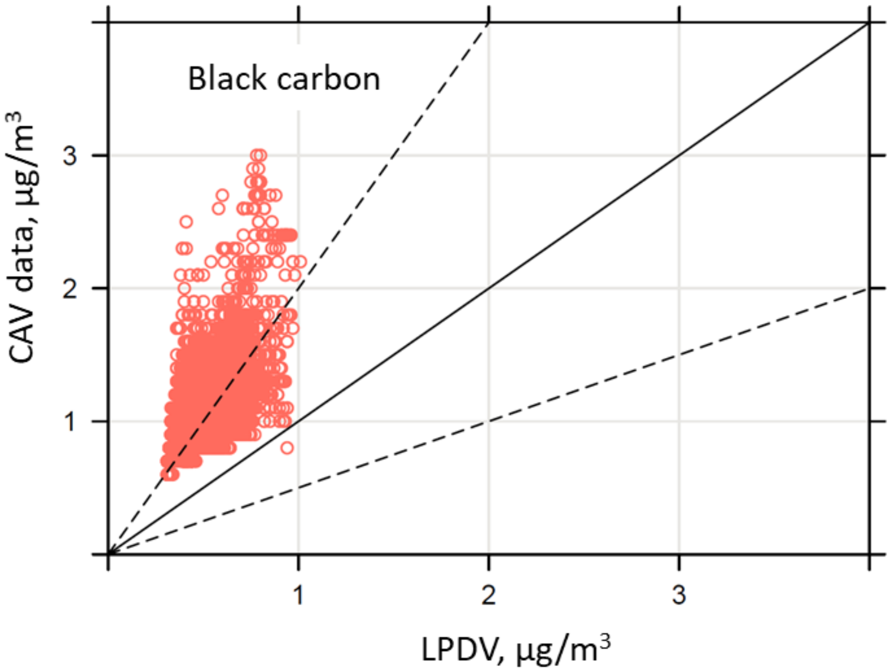

Figure 6.2. Comparison of concentrations of black carbon from CAV data and annual averages from LPDV. The black line is the 1:1 line and the dashed lines are the 2:1 and 1:2 lines. The comparison is based on the 14503 street segments from CAV that are within 10 meters distance to LPDV address points.

The first initial comparison of results from CAV data and LPDV for ultrafine particles shows that the spatial variability is very different in the two data sets, and that the two data sets do not correlate (Figure 6.3). One reason for this is that LPDV overestimates the concentrations of UFP in urban and regional backgrounds. On the other hand, the result from LPDV at the monitoring station at H.C. Andersen Boulevard is in good agreement with the annual average from the measurements (Jensen et al., 2021) while CAV results are approximately a factor of two higher when compared to the results from the DCE monitoring station (Chapter 5). Other reasons for the missing correlation are that ultrafine particles is a very complex parameter that it is very difficult to accurately measure and model espeacially for particles under 20 nm. This complex picture illustrates the need for further development of the model calculations behind LPDV and a more thorough comparison of the results from CAV, measurement data and LPDV.

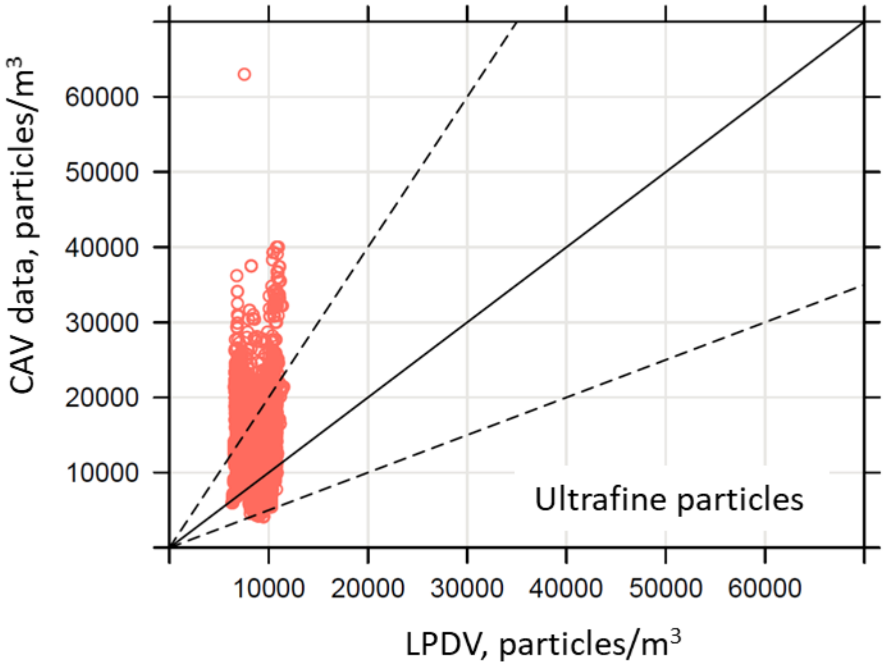

Figure 6.3. Comparison of concentrations of ultrafine particles from CAV data and annual averages from LPDV. The black line is the 1:1 line and the dashed lines are the 2:1 and 1:2 lines. The comparison is based on the 14528 street segments from CAV that are within 10 meters distance to LPDV address points.

7 Reference

Ellermann, T., Massling, A., Løfstrøm, P, Winther, M., Nøjgaard, J. K. & Ketzel, M., 2011. Undersøgelse af luftforureningen på forpladsen i Københavns Lufthavn Kastrup i relation til arbejdsmiljø. DCE - Nationalt Center for Miljø og Energi, Aarhus Universitet. 148 s. - Teknisk rapport fra DCE – Nationalt Center for Miljø og Energi nr. 5. http://www2.dmu.dk/Pub/TR5.pdf

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

Ellermann, T., Nordstrøm, C., Brandt, J., Christensen, J., Ketzel, M., Massling, A., Bossi, R., Frohn, L.M., Geels, C., Jensen, S.S., Nielsen, O.-K., Winther, M., Poulsen, M.B., Nygaard, J. og Nøjgaard. J.K., 2020. Luftkvalitet 2019. Status for den nationale luftkvalitetsovervågning. Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi, 128 s. - Videnskabelig rapport nr. 410 http://dce2.au.dk/pub/SR410.pdf.

Ellermann, T., Nøjgaard, J. K., Massling, A. & Bossi, R., 2021. The Particle Project 2020. Aarhus University, DCE – Danish Centre for Environment and Energy, xx pp. Scientific Report from DCE – Danish Centre for Environment and Energy. In preparation.

Jensen, S.S., Ellermann, T., Hertel, O., 2020. Program for kortlægning af partikler i Tårnby Kommune. Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi, 50 s. - Teknisk rapport nr. 183 http://dce2.au.dk/pub/TR183.pdf

Jensen S.S., Plejdrup M.S. & Hillig, K. 2019: GIS-based national road and traffic database 1960-2020. Technical Report from DCE – Danish Centre for Environment and Energy No. 151:1-31.

Jensen, S.S., Ketzel, M., Khan, J., Valencia, V.H., Brandt, J., Christensen, J.H., Frohn, L.M., Nielsen, O.-K. Plejdrup, M.S., Ellermann, T. (2021): Luften på din vej 2.0. DCE-Nationalt Center for Miljø og Energi, 62 s. - Videnskabelig rapport fra DCE – Nationalt Center for Miljø og Energi nr. 445, http://dce2.au.dk/pub/SR445.pdf

Kerckhoffs, J., Khan, J., G. Hoek, Ellermann, T., Hertel, O., Ketzel, M., Jensen, S.S., Meliefste, K.,Vermeulen, R. (2021a). Development of a NO_2 Mixed-effects Modelling Framework for Amsterdam and Copenhagen using Google Street View Measurements. In preparation.

Kerckhoffs, J., Khan, G. Hoek, J., Ellermann, T., Hertel, O., Ketzel, M., Meliefste, K., Jensen, S.S., Vermeulen, R. (2021b). Exploring hyperlocal variation of nitrogen dioxide, black carbon and ultrafine particles in Amsterdam and Copenhagen using Google Street View measurements. (Kerckhoffs and Khan are both first authors). In preparation.

Pinheiro, J., & Bates, D. 2006: Mixed-effects models in S and S-PLUS. Springer Science & Business Media.