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Deliverable D14 (D2.6)

Added value of mobile and citizens' observations for urban mapping and health

RI URBANS

RI-URBANS

Research Infrastructures Services Reinforcing Air Quality Monitoring Capacities in European Urban & Industrial AreaS (GA n. 101036245)

By

vito

UNIVERSITY OF BIRMINGHAM

DCMR milieudienst Rijnmond

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Deliverable D14 (D2.6): Added value of mobile and citizens' observations for urban mapping and health

Authors: Jules Kerckhoffs (UU), Martine van Poppel (VITO), Jelle Hofman (VITO), Jan Theunis (VITO), Jan Peters (VITO), Dimitrios Bousiotis (UoB), Francis Pope (UoB), Roy Harrison (UoB), Sef van den Elshout (DCMR), Emre Özdemir (DCMR) & Gerard Hoek (UU)

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Comments	This report summarises experiences in RI-urbans pilot studies with complementary approaches to traditional AQMS in order to derive high-resolution air pollution exposure maps for epidemiological studies, source evaluation and to assess policy actions at urban scale. Generally positive experiences were obtained with the proposed methodology, which included citizens and mechanisms to enroll citizens that can be readily upscaled at European level.

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1. ABOUT THIS DOCUMENT

As outlined in the RI-URBANS Deliverable D13 (D2.5), improved spatiotemporal resolution of multi-component air quality (AQ) data is critical for improved understanding of the connection between AQ parameters, human exposure and consequent health effects. In practice, to assess the impact of AQ on health it is important to have fine-scale data on AQ exposure (Baxter et al., 2013; Kumar et al., 2015; Shen, 2022). Advances in sensor technologies and the availability of portable and sensing devices give rise to new opportunities for mobile monitoring and denser fixed sensor networks. Different approaches can be used to assess exposure to pollutant concentrations including Ultra Fine Particles (UFP), Black Carbon (BC), nitrogen dioxide (NO_2), particle mass concentrations (PM) smaller than 2.5 µm (PM2.5) at high spatial resolution for epidemiological analyses and for better informing urban policy actions. Mobile sensing platforms and fixed sensor networks can be used as complementary tools to data from fixed regulatory Air Quality Monitoring Networks (AQMNs). The collected high-spatial resolution data from mobile monitoring is often sparse in terms of temporal coverage and, therefore, needs processing in order to obtain high spatial resolution exposure maps (i.e., long-term averaged concentration maps) for epidemiological studies and informing policy.

More specifically, D13 (D2.5) summarised complementary approaches to traditional AQMS in order to derive high-resolution exposure maps for health and epidemiological studies, to inform policy actions at urban scale and other applications. Monitoring approaches were classified into four approaches, based upon involvement of citizens (yes/no) and whether monitoring was fixed or mobile (Figure 1). These monitoring approaches were subsequently tested in three RI-URBANS pilot cities as part of WP4. Specifically, pilots were conducted in the cities Birmingham (UK), Rotterdam (The Netherlands) and Bucharest (Romania). The approaches included mobile monitoring with and without involvement of citizens and with and without fixed site measurements or low-cost sensors. The lessons learned from these pilot city initiatives are compiled in this Deliverable D14 (D2.6).

This document is delivered to the European Commission as RI-URBANS deliverable D14 (D2.6) and shared with all RI-URBANS partners for their use. It will also be made available in the public domain, https://riurbans.eu/work-package-2/#deliverables-wp2.

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2. AIMS OF THE DELIVERABLE

The aim of this Deliverable D14 (D2.6) is to present:

- Lessons learnt from the application of monitoring methods outlined in Deliverable D13 (D2.5) to map outdoor air pollution in three RI-URBANS pilot cities;
- New methodological insights from the pilots;
- Added value of mobile monitoring and citizen science to monitoring outdoor air pollution;
- Reflections on methodological choices; more specifically for each pilot:
    - **Monitoring strategy**: Considerations for study design and impact design choices;
    - **Data processing**: Reflection on method choices;
    - **Modelling strategy**: Reflection on modelling choices;
    - **Results:** New insights based on pilot.

This deliverable D14 (D2.6) focuses on methods based on monitoring, including direct use of the monitoring results and (land use regression) models based upon monitoring. Deterministic modelling is not part of this deliverable. WP3 has evaluated deterministic modelling in detail. The deliverable focuses on the methodological issues, detailed results have been reported as part of WP4 reports. Detailed results of the pilots are being combined for a peer-reviewed publication.

We first discussed results per pilot (Birmingham, Rotterdam, Bucharest), and then presented an overall assessment. We prepared a common set of questions to the pilot study partners, based upon the aims. In Birmingham, these were answered in a continuous text, covering the questions; in Rotterdam the specific questions were explicitly answered. The text for the Bucharest pilot was taken from WP4 deliverables, as the researcher was not able to participate in preparation of this WP2 text.

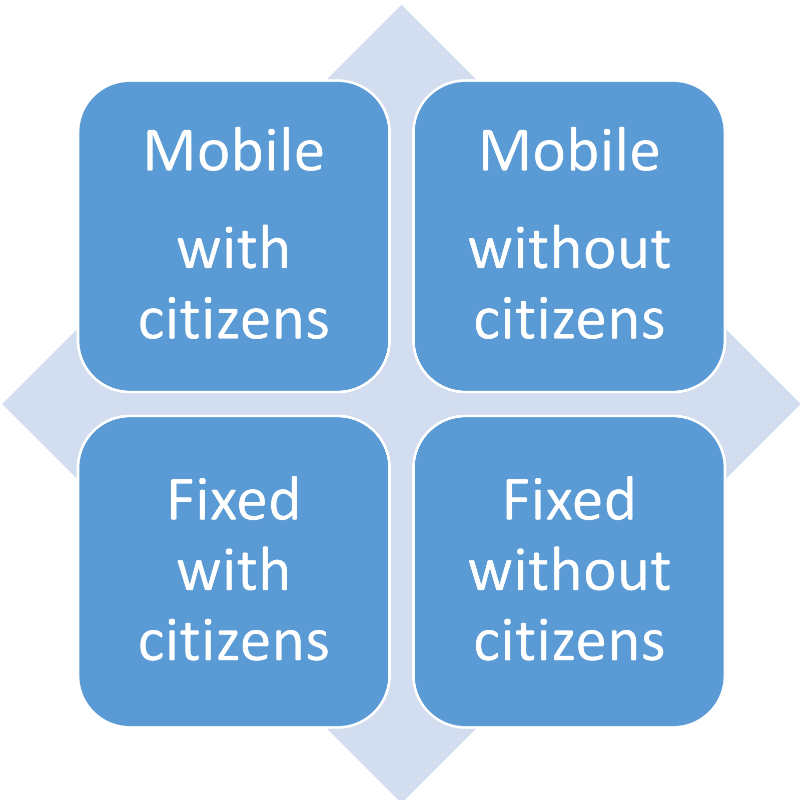

Figure 1: *Schematic overview of different approaches for collecting data for high-resolution exposure mapping.*

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3. BIRMINGHAM PILOTS

3.1 Overview

We tried several approaches using low-cost sensors (LCS) and citizen involvement for monitoring AQ and identifying the sources of pollution in Selly Oak, a residential area near the University of Birmingham (UK) and about 3 km south-west from the city center. The main study area was a residential block of about 1 km^2, though in some monitoring activities additional area was covered. This area is of great interest as it is the home of about 10,000 residents, who are mostly students at the University. The main measuring period was in the spring and summer of 2023, though some additional measurements were also done in the autumn of 2022. The main LCS used was the Alphasense OPC-N3, measuring PM (PM1, PM2.5, and PM10) as well as particle counts in 24 size bins in the range between 0.35-40 µm, with a temporal resolution of 10 seconds. The OPC-N3 is an optical particle counter and can measure particle counts up to 10,000 particles/cm^3. The PM accuracy of the sensor, as reported by the manufacturer, is lower than 1 µg/m^3 and the PM range measured is between 0 and 2000 µg/m^3. The main setup also included a sensor collecting meteorological data (Bosch BME-280), namely relative humidity (RH) (used for the calibration of the sensors), ambient air temperature and atmospheric pressure, a GPS module for geolocation and a GSM module for rapid reporting.

Additionally, for specific monitoring activities we used a medium-cost sensor for BC measurements (MAGEE microAeth AE51) measuring in a varying resolution between 10 seconds to 1 minute (according to the environment and conditions). This sensor measures the rate of absorption of transmitted light (880 nm) due to continuous collection of aerosol deposit on a filter. Using the changes in absorption rate the sensor internally calculates and reports the BC concentrations (hence, it is reported as equivalent BC (eBC) in some studies). The measurement range is 0–1 mg/m^3 of BC and the precision is ±0.1 µg/m^3 of BC. The device comes with its own rechargeable battery which can power the device for about 2 days.

The calibration of the LCS was done by collocating them to the research grade instruments at the Birmingham Air Quality Supersite (BAQS). The OPC-N3, as most PM LCS, suffers in high humidity conditions, reporting higher PM concentrations, especially for the larger PM. Thus, for their calibration, after excluding the outliers which bias the calibration process, an exponential regression was applied, considering the effect of RH. This greatly improved the performance of the sensors, achieving for the PM10 the value of $r > 0.60$, while performing a lot better for the smaller sized PM. The BC sensor did not appear to be greatly affected by the environmental conditions, and thus, a linear regression was sufficient to improve its performance.

Finally, for specific projects the Testo DiSCmini was also used. While its price is higher than the other LCS used, it is still significantly cheaper than its research grade counterparts. The Testo DISCmini, is a hand-held UFP counter measuring the number and average diameter of nanoparticles (10 to 700 nm) based on the electrical charge of aerosols. The sensor measures particle counts between 1,000 – 1,000,000 particles/cm^3 with an accuracy of ±100 particles/cm^3. Apart from the particle number, the DiSCmini reports the Lung Deposited Surface Area (LDSA) of particles, a metric used in health studies, as it is considered more important than the PM concentrations to portray the health effect of air pollution. The sensor comes with its own rechargeable battery which can power the device for about 9 hours.

Using multiple setups with these sensors, we collected data from static points (indoors and outdoors) as well as mobile measurements using either walks or cycle sessions in the study area. For both the static and mobile measurements we asked for the help of the local community, setting up sensors at schools and local businesses, as well as of students at the University. The projects will be discussed separately in detail in the following chapters. The aims of the projects were to elucidate the capabilities of LCS for the extension of the current measuring

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network, indoor AQ assessment and identification of air pollution sources. Partial aims of the projects will be discussed in each separate chapter.

3.2 Air quality assessment at neighbourhood scale

3.2.1 Monitoring

We set up 6 static measuring points in the study area in which we installed an OPC-N3 as well as the BC monitor (in two points). The BC sensor was used at the traffic site, as well as at the BAQS (a background site). The points were strategically chosen to cover as much of the studied area as possible, while also collecting data from points of interest. One sampling point was the BAQS, in which the OPC-N3 and BC sensors were placed next to the research grade instruments for quality control and calibration. In addition, we setup sites next to the main road in the area (Bristol Road) to measure traffic emissions, at 2 elementary schools in the block, a local business located within the area with the greatest activity (including markets, restaurants, etc.) and outside a house in the center of the study area and next to the train station. Data was collected for a total period of 3 months, between April and June 2023. Three setups were used for this campaign (Figure 2):

- Two OPC-N3 with the additional sensors using mains for powering;
- Two OPC-N3 with the additional sensors and a BC sensor using mains for powering;
- Two OPC-N3 with the additional sensors powered by a car battery. This setup was powered for about 25 days. An additional car battery was interchanged between the setups to eliminate the charging period.

Figure 2*: From left to right, the three setups used for monitoring.*

To get the help of the local community for finding the appropriate locations/points for measurements we had to ask for the permission to setup by going from door to door. In most cases the answers were positive, and people were happy to cooperate. The main issue in most cases though was finding an outdoor spot that was both safe and had access to mains for powering the OPC-N3. The latter was the most common issue and the reason we came up to the solution of the car battery. Reasons for which we got a negative or no answer were the following:

- Some people did not understand what the RI-URBANS project and monitoring were about, despite our explanations.
- Some people were reluctant to put the sensors in their house, even though they were assured that no harm can come from that.
- Some people were afraid of the electricity cost, even though they were assured that the total cost for the measuring period would barely surpass £1.
- Specific businesses were concerned of the impact on reputation they can get if AQ was not good enough, even though they were assured anonymity of the measurements and outdoor data collection only.

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- Some public businesses never responded to our call. In some cases, we were asked to contact specific personnel resources departments, but we got no answer from them.
- In one case we were declined due to prior negative experience from a previous project done by the University.

3.2.2 Data processing

While data was collected in 10 second intervals, they were averaged over/to 1 hour interval, as this study focused on long-term monitoring. Average, minimum and maximum PM and BC concentrations were reported after calibrated against the research grade instruments at the BAQS. The collocation and calibration were done both at the beginning and at the end of the campaign, assuring at least 2 days of simultaneous measurements. To ensure the best calibration possible, outliers (mostly due to the hygroscopicity effect mentioned in the "Overview" section above) were removed (about 5% of the total measurements) from the obtained dataset. This approach was chosen as the inclusion of extreme outliers tended to negatively impact the calibration of the measurements from the OPC-N3. Furthermore, while the meteorological sensors provided data, which were used for calibrating and reporting, wind data from the meteorological station at the BAQS were used. No additional steps were needed for data processing.

3.2.3 Results

The obtained results included the assessment of the AQ at neighborhood scale within the study area. As 5 measuring points (sites) were located within an area of just 1 km^2, fine spatial resolution was achieved and the effect of local sources of pollution was considered. Additionally, the effect of the meteorological conditions on the AQ, as well as the temporal variation of the pollutants measured were considered and reported. Finally, the long-term performance of the LCS against research grade instruments for pollution monitoring was assessed.

The aftermaths of the carried out specific campaign were multiple. The sensors performed rather well, though the campaign benefitted from the good weather conditions, positively impacting their performance. The shortcomings and calibration of the LCS were discussed earlier. There is a question about the performance of the sensors in cooler seasons though, and the additional steps in their calibration would be needed.

Citizen involvement was crucial for the success of the campaign, as it provided access to multiple sites within the study area. Both elementary schools were very keen to cooperate and interested in the outcomes of the study. The DiSCmini used at one of schools, needed maintenance every 2 days, which led to one person having to deal with it. This caused some annoyance to the school staff, as they had to be present while the maintenance took place. Similar would be the problem if the BC sensor was used. Additionally, there was great skepticism from some people about the safety and purpose of such studies, which should be addressed with increased awareness of the benefits of such studies.

3.3 Street level air quality assessment and pollution source apportionment

3.3.1 Monitoring

For this campaign, two different approaches were used. First, walking sessions were done within the main block, in different times of the day following a specific route covering all the roads of the block. Second, a series of cycling sessions covering a larger area was done in different times of the day. In total, 51 walking and 34 cycling sessions were carried out. The setup used in this case included the OPC-N3 and the additional sensors carried within a backpack and powered by a USB power bank (figure 3). The specific setup can be powered using the power bank for about 2 days, easily sufficient for the needs of each session. In some walking or cycling sessions the Testo DiSCmini and/or the BC sensor were also used. As the sensors are small and lightweight, the whole setup only

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occupied the shoe compartment of the backpack allowing for the rest of the backpack to be normally used without adding too much weight.

Monitoring was done by students at the University, both PhD and MSc, as well as by a PostDoc researcher who was also overseeing the campaign. The campaign was advertised to the MSc students of the Air Pollution Management and Control at the University of Birmingham. A payment was included to promote the offer. For the PhD students and the PostDoc researcher no payment was included as it was part of the student's research.

Figure 3: *Mobile OPC-N3 setup. The sensors were put in the shoe compartment, leaving the rest of the backpack space free, and were powered by a power bank. There was enough space for additional sensors if needed. The total added weight was less than 1 kg.*

3.3.2. Data processing

For the data processing, extra care was taken on the averaging of the obtained data. As several different sensors were used, there were different time scales. All data were averaged to 10 second interval averages, which, for the walking sessions, represented a distance about 15-20 meters. Similarly, the GPS data were also averaged in the same manner. When maps were created using such data, extra care was taken to avoid misalignments due to change of direction while walking or cycling. This is a very important consideration, as GPS data that are not correctly averaged may result in erroneous results.

3.3.3 Results

With this data, we were able to report concentrations and variations, both temporal and spatial, at street level. Furthermore, the data from the walking sessions were used for a source apportionment study. For this, the data from 10 walks were used (these 10 walks were done by a single person following the same route and using the same sensors every time). A longer campaign could produce more comprehensive results, but in our case, we used a shorter campaign, to confirm that only a few walks are enough to get valuable results). Both studies produced very interesting results and can be used as a pilot for further studies, though covering only a part of the day is one shortcoming of this methodology. When a walking or a cycling session is done, a snapshot of the AQ in the area is only taken. Thus, data from such campaign should be used with caution and the results from them should be considered accordingly. Additionally, as such campaigns need people to move around in the streets, there is a safety concern. Accidents may happen when cycling, while the possibility of mugging or assault should be considered

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when doing sessions in late night hours. As late-night hours were avoided in our campaigns, a large part of the day was not covered by our campaigns. Walking sessions of two or more people are suggested if such hours are chosen.

Furthermore, the use of students, as with any citizen, for such campaigns may have several shortcomings. These individuals, may consider such campaigns as opportunities for an extra income, often ignoring the instructions given. Cases when power banks were not properly charged, or the equipment was not given the proper attention were observed. Detailed and precise instructions should be given and progress meetings during the measuring period are suggested. Furthermore, extra care should be given on the anonymity of such studies. An ethical review and detailed explanation of the campaign and its aims are essential for such campaigns. Finally, data security is essential to ensure anonymity, as personal information may leak by the processing of GPS and air pollution data.

3.4 Predicting PM2.5 concentrations

3.4.1 Monitoring

For this project a combination of the data collected from the aforementioned monitoring activities was used. Additionally, traffic count, topography and demographic data were used. These data were acquired either by the Birmingham City Council, or through internet repositories. As the data from multiple (total of 10) OPC-N3 were used, a collocation of these sensors would be a more appropriate calibration method. While these sensors measure very similarly between them, their performance against a single research grade instrument may vary. This is because LCS, while responding similarly to different meteorological conditions, the intensity of their effect on them may vary significantly. Thus, discrepancies and erroneous data may be observed. Data from multiple sources were used as an input to different machine learning (ML) methodologies, with which we tried to predict PM concentrations and fill gaps when data was not available.

3.4.2 Data processing

For the calibration of the OPC-N3 in this case, though we had one-on-one data with them against the research grade instruments at the BAQS, a collocation and calibration of the OPC-N3 against each other, and then a calibration of one of them against the research grade instruments was found to have the best outcome.

The dataset in this case consisted of multiple different types of data which needed to be inputted to the ML methods. Data were combined and used in 10 seconds resolution. This was done to include detailed data from the mobile measurements.

For the training and testing of model performance we used the 80-20 approach. This meant that we used 80% of the data to train the model and 20% from PM for model evaluation. This was done in multiple repetitions using resampling to assure the uniformity and repeatability of the results.

3.4.3 Results

The results we obtained from the analysis of the data helped in creating a model which can be used to fill data gaps and predict PM concentrations when measured data is not available. The analysis indicated that the models performed better when predicting $PM_{2.5}$ than PM_{10}, data, which was more difficult to model. Communication and data acquisition from the Birmingham city council was easy. City councils are usually willing to provide data. Demographic data were acquired using open online repositories and were very helpful in developing the models. The comments for the mobile measurements and citizen involvement apply for this campaign as well.

3.5 Indoor air quality assessment

3.5.1 Monitoring

For this campaign we used the basic OPC-N3 setup in three bedrooms of three student houses for a period of about two weeks in spring /summer/ of 2023. The houses were in a relatively close proximity to each other (a couple of

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hundred meters) within the study area of Selly Oak. A similar setup was used in three classrooms of an elementary school. With these studies we wanted to assess the personal exposure of the students and pupils in these environments and elucidate the effect of the indoor and outdoor sources on AQ. For the data collection we asked students at the University for the house campaign, and we asked staff at the school to help collect the data there. In both cases, anonymity of the subjects and the locations needed to be assured. Specifically, the school requested the results of this analysis to better understand what affects the AQ there, and how they can improve it.

The measurements were collected in the default 10-second resolution of the OPC-N3. For both reporting and further analysis, the data were averaged in 1-hour intervals. As with any application of LCS, calibration was done in two stages. First stage was the collocation of the OPC-N3 for a day, and then the calibration against a research grade instrument. The calibration of the PM LCS for indoor measurements is a lot easier than that for outdoor ones. As meteorological conditions (and especially high RH) are usually responsible for the deterioration of the measurements, indoor measurements are usually very consistent without significant discrepancies from the research grade instruments' measurements. Thus, in the specific case a linear regression between the OPC-N3 and the research grade instrument used was enough to greatly improve the data.

3.5.2 Data processing

No further data processing was needed. The obtained dataset was fully used, and no outliers needed to be removed. To fully understand the effect of the different sources and distinguish the background conditions, in both cases we made sure that periods when no activity occurred within the indoor environments were included. For example, for the two-week period at the school, we chose one week of normal activity and one week when the school was closed for the Easter holidays.

3.5.3 Results

As mentioned earlier, PM LCS perform a lot better in indoor conditions. This was the case for both indoor studies, and air quality assessment and the source apportionment methodology previously used in outdoor studies were successful. Using the results from this analysis we identified and calculated the effect of the outdoor sources on the indoor environment. More importantly though, we successfully identified the indoor factors that affect AQ The level of activity, the use of the different rooms and the presence of carpeting had a decisive effect, especially on the PM_{10} concentrations.

Such campaigns are very useful when citizen involvement is achieved. People are interested in AQ of the spaces they spend most of their time in, and the factors that affect their quality of life. By sharing and explaining the results, the subjects of the campaigns are better informed and (according to other studies) make changes to improve their footprint on AQ.

In previous indoor studies we collected simultaneously data from both the indoor environment studied, as well as from the outdoor environment in the area. This helps in better understanding the outdoor sources and identification of the ones with the greater impact. Unfortunately, this was not possible in this case, but it is suggested for any future similar study. Finally, as the variation of the indoor environment is great, we would suggest for similar future studies, the simultaneous collection of data from as many indoor environments as possible. In our case, the three houses as well as the three classrooms had significant differences between them, even though they were located very close to each other. Such variability can be better understood with an increased number of simultaneous measurements. As with all studies, the anonymity of the subjects is emphasised and should be carefully protected to avoid future rejections.

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4. ROTTERDAM: CITIZEN-BASED MOBILE MONITORING

Employees from the (1) city of Rotterdam and (2) DCMR conducted mobile monitoring following the airQmap (https://airqmap.com/en) procedure, with portable instruments for black carbon (BC) to map their exposure to BC and derive representative long-term average AQ maps during commuting hours. Monitoring campaigns were conducted in both winter season (2022) and summer season (2023) whilst cycling from and to work (typically during rush hour periods) with a combination of portable GPS and Micro Aethalometer AE51 (Aethlabs microAeth) instrumentation. The campaign was coordinated by VITO in collaboration with DCMR and University of Utrecht. DCMR arranged the supervision of monitoring.

4.1. Monitoring strategy

What was the aim of the study (research question)? [Yearly average, personal exposure, etc.]

To evaluate personal exposure variability to BC along different commuting trajectories and to derive representative long-term average BC map from the repeated measurements along those trajectories.

Which approach was followed? [Dedicated (controlled sampling) vs opportunistic approach]

This approach can be considered opportunistic, as participants could choose freely how they cycled to work. However, we tried to select participants based on following trajectory criteria:

- At least, ~10 min through the Rotterdam city center.
- At least, twice per week, for 2 weeks periods (minimal 6 repeats per route).
- Long commuting trajectories.
- Trajectories from multiple directions into the city (spatial coverage) across participants.

What was the involvement of citizens? Was recruitment satisfactory? What could be improved?

Recruitment was performed with a recruitment letter, which was deemed satisfactory. The response included 27 DCMR and 11 city of Rotterdam participants for the winter period (November - December 2022) and 29 DCMR participants for the summer campaign (May – July 2023). A local coordinator at DCMR and the city of Rotterdam was identified as the local point of contact for all participants, and who was in charge of the distribution of the instrumentation and trained by VITO to handle the instrumentation, conduct filter strip changes and upload the data. This set-up worked very well.

Lessons from communication with citizens?

We noticed that some participants were a bit opportunistic in terms of following the number of repeats, logging, and cycling route. Some varied their cycling route, reducing the number of repeats along the same trajectories. We might have to constrain the sampling routes and expected number of repeats a bit more clearly in the future.

Feedback provided to citizens (general, individual report, lunch talk/presentation etc.)

An overview report (including the representative long-term average maps) was provided by mail to all participants and a lunch talk was provided at the DCMR office to share results and gather participants' feedback on the monitoring campaigns.

Feedback from citizens (questionnaire, e-mail, ...)?

Feedback was gathered during the lunch talk and an additional questionnaire is planned.

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For mobile campaigns, how was driving/cycling arranged? Who was driving/cycling (local technicians, staff, students) and was this satisfactory?

Citizens, but in this case employees from the city of Rotterdam/DCMR which are already involved or interested in the AQ theme in their city.

Communication with drivers/cyclists

Through the local coordinator and provided manual along with the instrumentation.

Which route was followed (dedicated/predesigned vs opportunistic)?

The route was chosen by the participants as their regular route from home to work. Therefore, the approach is opportunistic.

Which number of repeats needed for the goal? Enough or could have been less? How was this validated?

The number of repeats varied between 2-20/sampling route. The spatial coverage was good. In order to derive representative BC maps based upon monitoring alone for long-term exposure, 2 repeats can be considered inadequate. We evaluated the representativity for frequently sampled route segments by means of subsampling.

Temporal variation of measurements (only weekdays, which hours of the day, season, …?) Impact validated?

Sampling was conducted whilst commuting and can, therefore, be regarded representative for commuting hours (rush hour periods; not constrained to 7-9 h and 16-19 h as can be seen on the temporal variability graph below), in both summer and winter season. The seasonal background concentration largely impacted the measured BC concentrations as can be seen on the figure 4.

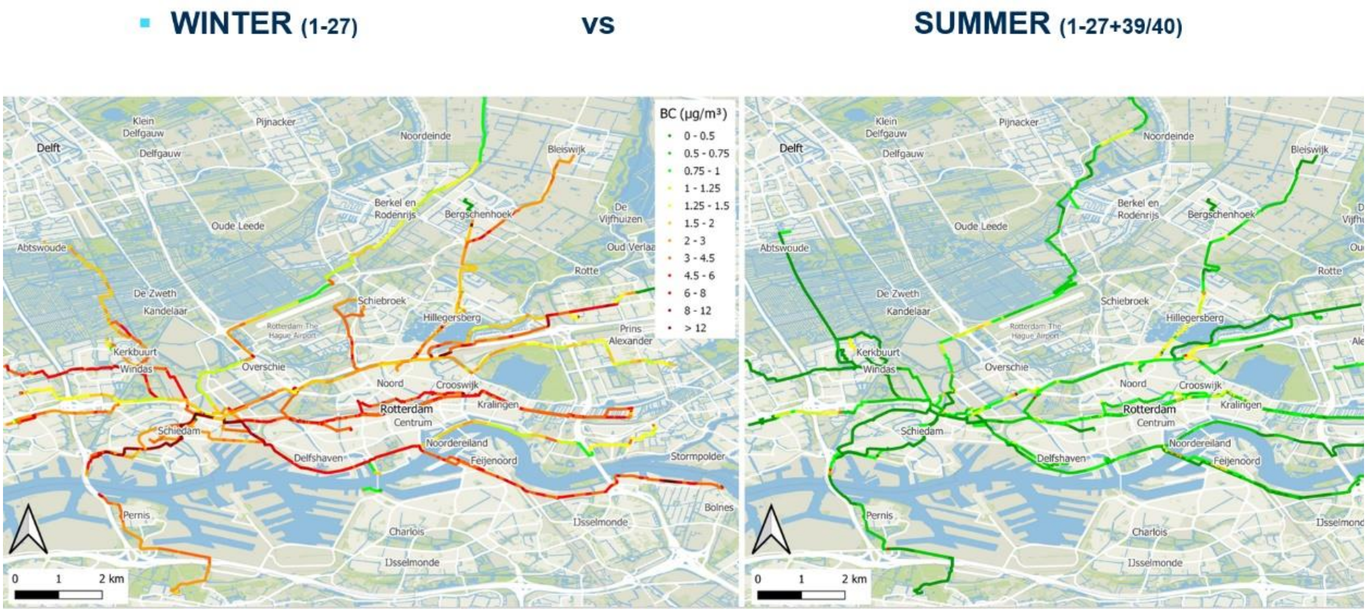

Figure 4: Average BC concentrations (µg/m³) derived from mobile monitoring involving citizens in the Rotterdam area.

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Availability of local partner with expert knowledge. Usefulness? Could this exercise be repeated without expert knowledge/support?

VITO was involved to supply instruments and support. We found that local expert knowledge is needed to successfully perform mobile monitoring. In addition, DCMR which is very knowledgeable in AQ monitoring provided local support.

Which instruments were used?

The airQmap (https://airqmap.com/en) is a mobile platform that measures BC via repeated measurements by bicycle. It comprises a measurement unit consisting of a microAeth® (AE51, AethLabs, San Francisco, CA, USA), a GPS and an automated data processing infrastructure to construct the aggregated BC maps. The microAeth® measures the attenuation of light (880 nm LED) through a Teflon-coated borosilicate glass fiber filter on which light-absorbing particles are sampled continuously. The difference in attenuation (per time base) is converted to a BC concentration using a specific absorption coefficient sigma = 12.5 $m^2 g^{-1}$ (at 880 nm) and the actual sample flow rate. The sample flow rate is set at 150 mL min^{-1}, and the measurements are made at a temporal resolution of 1 sec. To reduce the signal noise at the one second time resolution (especially at low concentrations), the optimized noise-reduction averaging (ONA) algorithm was used with an attenuation threshold of 0.05. Prior to each monitoring campaign, the flow of the instruments is calibrated, and the different instruments used are intercompared by co-location (for at least one day) to check that the inter-instrument variability is less than 10%. A periodic comparison with the AE33 (Magee) is performed.

Time resolution and portability

Both GPS and micro aethalometer are configured to 1 second resolution. Portability was good, with a small pouch including both GPS and micro aethalometer to carry the instruments along.

Accuracy

The accuracy of the instruments was evaluated beforehand at VITO by means of a co-location campaign next to a reference instrument (Aethlabs, AE33 monitor). Inter-instrument variability is less than 10%. When comparing the temporal variability of the mobile BC data to the reference data that was available throughout Rotterdam, we observe similar hourly concentration variability as observed within the existing fixed site of AQMN (Figure 5).

What post processing was needed?

As the mobile measurements consist of point measurements in time and are affected by fluctuating background concentrations, we applied a rescaling method to remove some of the temporal variation.

Validation of measurements, Colocation next to reference station/monitor: How long? Similar environment as sampling environment? When: during, before and/or after sampling

Co-location has been performed with a standard monitor prior to the campaign. For long campaigns, repeated co-location is useful to avoid potential data losses related to malfunctioning equipment. Comparison should be evaluated quickly to avoid using malfunctioning equipment.

Calibration of instruments needed

No

Validation mobile deployment: vibration, GPS, signal noise, high resolution accuracy, …

No, the airQmap procedure (https://airqmap.com/en) was validated before (Van den Bossche et al., 2015).

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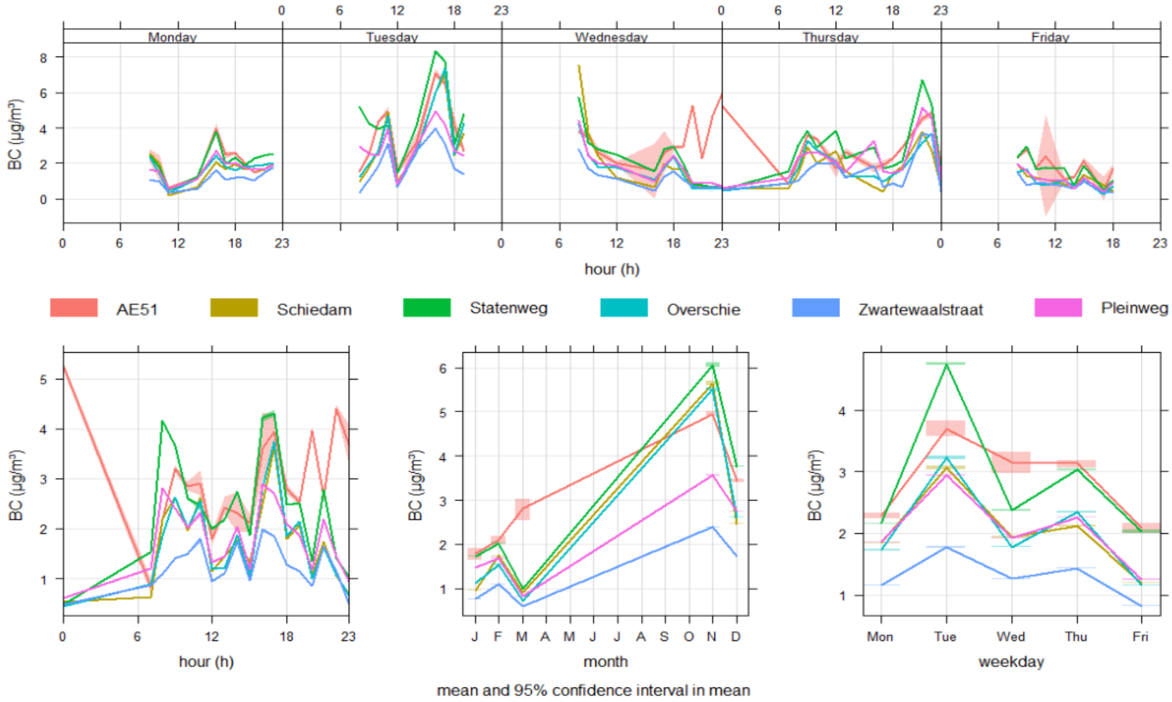

Figure 5: *Diurnal variation of* BC concentrations (µg/m^3) derived from mobile monitoring (AE51) and routine monitoring stations (with AE33 instrument).

4.2. Data processing

What were the criteria for removal/cleaning of data? Considerations for criteria?

ONA correction for instrument noise, map matching threshold to map point measurements to trajectories and winsorising and background normalization were applied to derive more stable concentration patterns.

Was any spatial correction applied to link point measurements to route segments (map matching, buffer averaging)?

Yes, map matching was applied to map the point measurements to manually drawn trajectories considering a maximal threshold. In a next step the point measurements were aggregated into buffers along the considered trajectories.

Which and why post-processing steps were taken (winsorising, noise, moving average)?

To reduce the signal noise at the one second time resolution (especially at low concentrations), the ONA algorithm was used with an attenuation threshold of 0.05.

Was any temporal correction applied to cope with short-term measurements? If so, how (normalisation, scaling factor, …)? What are the implications?

Yes, we evaluated an additive or multiplicative normalization procedure of the point measurements, based on respective nearby urban background or roadside reference AQ monitoring stations (AQMS).

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$$BC_{norm,i} = BC_i - BC_{bg,i} + \overline{BC_{bg}} \quad \text{(additive)}$$

$$BC_{norm,i} = BC_i / BC_{bg,i} \cdot \overline{BC_{bg}} \quad \text{(multiplicative)}$$

BC_i = BC concentration from mobile monitoring time i

$BC_{bg,i}$ = BC concentration from fixed background station time i

BC_{bg} = BC concentration from mobile monitoring time, average full study period

The additive normalisation procedure was ultimately selected to normalize the collected mobile data and derive representative spatial maps of BC exposure. Based on the background normalisation, maps could be derived showing hotspot locations (Figure 6).

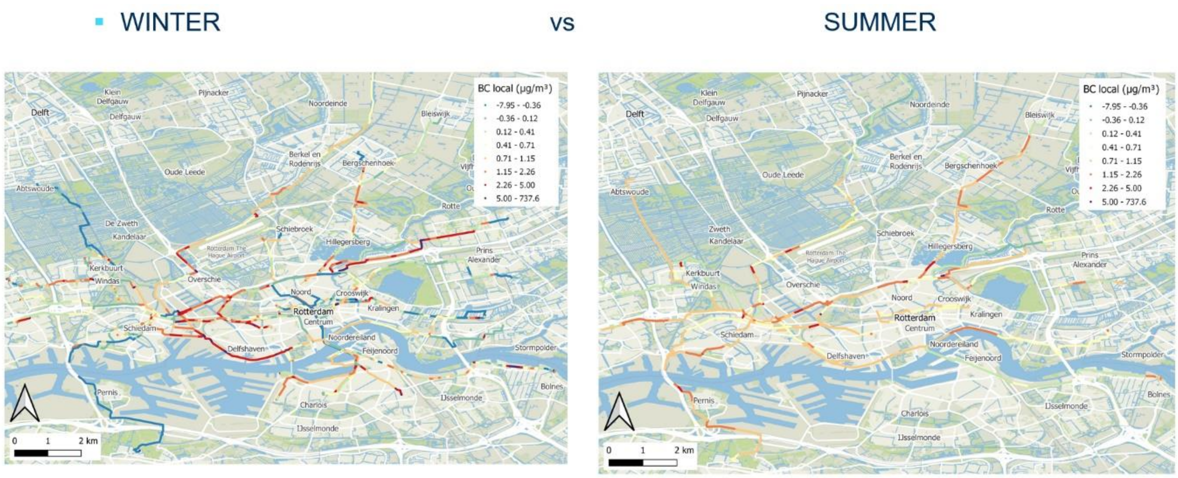

Figure 6: BC concentrations (µg/m^3) derived from mobile monitoring by bicycle.

Locations with highest local contribution coincided with busy road traffic locations and/or cycling infrastructure in between road traffic.

Conversion between pollutants (EC vs BC in summer and winter)

No, we applied the same procedure in both summer and winter seasons: measured attenuation at 880 nm considering specific absorption coefficient sigma = 12.5 m^2 g^{-1} (at 880 nm).

4.3. Results

How did the accuracy of measurements/models impact the results?

We evaluated sensor precision against observed spatial and temporal concentrations gradients and observed spatial gradients were often higher than the inter-sensor uncertainty.

What was the influence of method choices on results?

Opportunistic data collection results in inadequate number of repeated runs on most of the trajectories in order to derive representative long-term average maps based upon monitoring alone.

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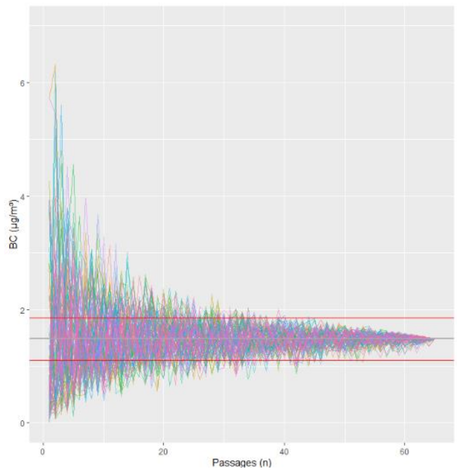
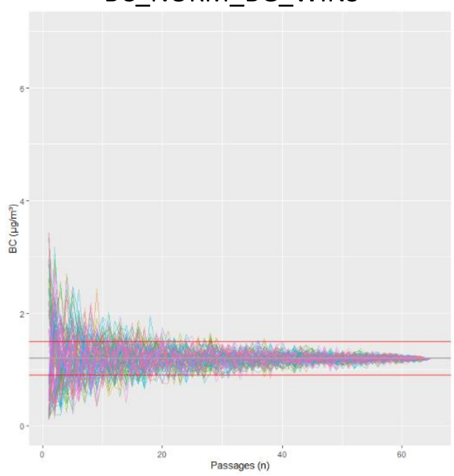
RAW BC



BC_NORM_BG_WINS



SEGMENT 1 WINTER + SUMMER (n=24)

	BC	BC_wins	BC_norm_bg	BC_norm_bg_wins
mean	1.206653	1.018998	1.038778	0.8866859
required passages to be within 25% of mean	24	23	24	22
95% chance of being within 25% of mean	**23**	**23**	**23**	**18**
90% chance of being within 25% of mean	22	22	20	18

SEGMENT 2 WINTER + SUMMER (n=65)

	BC	BC_wins	BC_norm_bg	BC_norm_bg_wins
mean	1.482482	1.306711	1.262775	1.201283
required passages to be within 25% of mean	54	45	39	39
95% chance of being within 25% of mean	**43**	**39**	**31**	**29**
90% chance of being within 25% of mean	43	29	29	29

Figure 7: *BC concentrations before and after normalization. Table insert shows the impact of normalisation on obtaining a stable estimate of the average concentration.*

New insights based on pilot

The minimal number of required repeats for long-term average representativity, based on the subsampling analysis, varied between 24 and 54 (depending on the road segment) to be within 25% of the mean when considering the raw BC values, or between 22 and 39 when applying additional post-processing (winsorising and/or background normalization) (figure 7). Background normalization is also necessary, irrespective of the number of repetitions, to correct for bias due to the fact that the sampling hours were during the morning and afternoon rush-hours (some 40% too high). Use of reference monitoring data is essential to correct for sampling hour bias.

Added value of the mobile monitoring/citizen science strategy when compared to stationary monitoring networks (AQMN)

Awareness raising, identification of hotspot locations, more representative personal exposure assessments in urban environments/during specific activities (e.g., commuting). Derivation of long-term average maps (when enough repeated measurements are considered). Comparing the cycling maps to the available high-resolution modelling produced fairly consistent results. On the one hand this means that there was no added value in Rotterdam, on the other hand it implies that where these modeled maps are not available, the cycling likely produces reliable pollution maps.

Added value of monitoring multiple pollutants? Do pollutant ratios provide new insights (e.g., source attribution)?

Was not tested here.

More impact achieved through citizen involvement?

Yes, more spatial and temporal coverage + awareness raising + expert knowledge on urban environment/relevant monitoring locations.

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What would you do similar/differently when repeating the monitoring campaign?

More stringent monitoring protocol (number of repeats, fixed repeated routes, etc.) or longer-term monitoring campaigns. E.g. the cycling volunteers favored good weather conditions and were more active during the summer campaign. However, the observed concentrations during the summer monitoring were generally very low and hence less relevant for discerning spatial patterns.

5. ROTTERDAM CAR-BASED MOBILE MONITORING

5.1. Monitoring strategy

What was the aim of the study (research question)? [Yearly average, personal exposure]

The aim was to produce long-term average air pollution concentration maps for the area, by the means of LUR models. A sub-question was to investigate if the industrial sources (mainly port activities) could be adequately captured in the mobile monitoring campaign.

We used a car to measure the ambient concentrations of NO_2, BC and UFP during two seasons in the city of Rotterdam; one campaign in November-December 2022 and another campaign in May-July 2023. The car was equipped with lab-grade 1 Hz NO_2 (CAPS, Aerodyne Research Inc., USA), 1 Hz BC (AE33, Magee Scientific), and 1 Hz UFP (EPC 3783, TSI) monitors measuring simultaneously. A Global Positioning System (GPS) (G-Star IV, GlobalSat, Taiwan) was used to record the location of the car, which was linked to the measuring equipment via date and time. The measurements were mainly carried out between 8 to 22 hours every day in the study period (including some weekend days) in different parts of the city. The study area extended beyond the municipality of Rotterdam to cover sources in the area more broadly, include the harbour, industrial area, and airport. The “route” was discussed in detail with DCMR, the regional authority for the environment. *Which approach was followed? [Dedicated (controlled sampling) vs opportunistic approach]*

The study design was mostly a dedicated approach, but had elements of an opportunistic approach. The dedicated part comes from the fact that the area was divided into 8 polygons, each containing a part of the city center and residential areas as to randomise road characteristics at much as possible in each polygon (see Figure 8). Drivers were instructed to drive in one polygon for each morning or afternoon session. Polygons were driven multiple times, each on a different day of the week and part of the day. The opportunistic part is that there were no specific routes that were followed. Drivers were asked to drive randomly on busy roads, residential roads and in industrial areas. Thus, the campaign does not rely on choices made by individuals for other reasons, such as the shortest route between home and work, as in the citizen-based campaign in section 4.

This way, we made sure there is temporal dependencies in the data and no temporal correction is needed in the data processing. This is because all types of roads and corresponding co-variates were driven at different timepoints throughout the day and week, therefore, effectively nullifying the correlation between the covariates and time of day. The number of repetitions per location is quite low (or absent) complicating measured data interpretation. The number of repetitions was low by design because the main purpose was to develop am model for which repetitions are not essential Though winter and summer campaigns were used some bias arises from the fact that the driving was mainly on weekdays between 9:00 h and 19:00 h.

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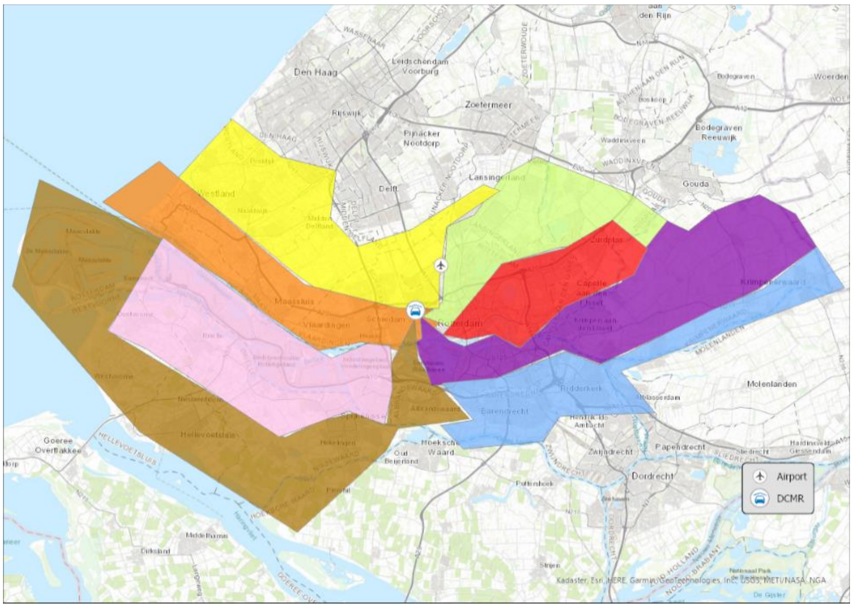

Figure 8: *overview of driving areas in the Rotterdam metropolitan area.*

Next to GPS systems in the car, all routes were tracked on a tablet visible by the driver as well. This app (MyTrack) enabled the drivers to see which streets were already driven, both in the current session and all previous measurement days. All drivers said this was a very useful addition to the system.

What was the involvement of citizens?

Not applicable

For mobile campaigns, how was driving/cycling arranged?

Driving was done by paid students from Rotterdam with no prior knowledge on air pollution monitoring. Having local staff with air pollution knowledge driving the car is likely the preferred option, but the student option worked very well. Since the car was parked in another city (Rotterdam) a local partner (DCMR) handled all practicalities, regarding access to the garage for overnight safe parking. The measurement car was developed in such a way that the least amount of manual interference is needed with the system. Nevertheless, all drivers were given a training at the start of the campaign, meaning almost all measurement days were successful.

Which number of repeats needed for the goal? Enough or could have been less? How was this validated?

Our main goal was to create a LUR model based on all mobile monitoring, so repeats were not strictly necessary. Temporal and spatial variation in the data is more important. All topographies and road characteristics need to be monitored in the area (on different times of the week and day) in order to create robust models. Adding repeats increases the training performance of the model (because training instances are more accurate) but not the testing performance of the model.

As expected, more traditional data interpretation (e.g., comparing observations in different parts of the area; comparing time profiles, comparing simultaneous measurements of the three pollutants) proved difficult. This requires more repetitions and observations during different meteorological conditions (wind directions). The sub-question if the monitoring could be used to detect the influence of port-industrial activities was hard to answer as this implies to explore wind-direction dependent exposure (contrary to the wind independent mapping of traffic exhaust). We suspect that the temporal variation in the data was much higher than the spatial variation, so with

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hardly any repetitions, and two (too) short campaigns covering a large complex area, comparison of situations in different parts of the area under different meteorological conditions proved very difficult.

Temporal variation of measurements (only weekdays, which hours of the day, season, …), impact validated?

In previous research we validated that temporal correction is not needed in mobile sampling, as long as measurements are done in the entire spatial domain and throughout different times of the day and week. Since we did not measure at night our model might not be a yearly-average concentration but a yearly-average day-time concentration level.

It was also emphasised in this study that measurements in two different seasons are crucial to capture the yearly variation of air pollution. Especially for BC, we found almost twice as high concentrations in winter opposed to the summer campaign. In the summer campaign we have seen evidence of new particle formation (NPF) in the afternoon UFP measurements. The diurnal profile of UFP differed between the winter and summer campaigns, with afternoon peaks only present in the summer.

In general, it is better to spread measurements in time and space as much as possible. One hour of mobile monitoring per day is better than one day of driving 24 hours. So, it becomes a practical/theoretical trade-off, as it is practically much more difficult to drive 1 hour each day, let alone spread this over a full year. We found that driving two times for at least 20-25 days in two different seasons is enough to capture most of the variation.

Availability of local partner with expert knowledge. Usefulness? Could this exercise be repeated without expert knowledge/support?

Some level of expert knowledge by a local partner is very helpful in setting up such a campaign. In our campaign, DCMR provided that knowledge. This is especially useful for sources other than traffic, often emitted from larger heights than motorized traffic.

Which instruments were used?

The time resolution of all our instruments was 1 Hz. Though only the UFP device was accurate enough on this time base that no post-processing was needed other than deleting unrealistic values below 500 particles/cm^3 and above 5000000 particles/cm^3. For the BC and NO_2 device the 1-sec resolution gave too much noise, so, a moving average of 6 seconds and 3 seconds was used, respectively.

All instruments used are lab-grade and not very portable by hand. At least, a car is needed to make use of these instruments in a true mobile setup. Colocation with reference measurements was done, but not checked thoroughly enough during monitoring campaign, leading to unreliable NO_2 measurements in the winter campaign. On top of that, we also validated the UFP measurements by driving our measurements car right after another exactly the same measurement car (used in other projects). Results show that a moving platform can very accurately pick up UFP concentrations while driving. Despite this QA-QC, mobile measurements of NO_2 during the winter campaign were lower than during the summer campaign and substantially lower than measured at routine monitoring sites in Rotterdam. Additional QA-QC is needed.

The use of NO_2 rather than NOx might be a good choice for city LUR AQ mapping but for understanding air pollution mechanisms it is not useful. Normalizing UFP with NOx (to distinguish traffic and other sources) was not possible as NO_2, especially in summer, is strongly impacted by photochemistry.

Since our aim was to create a model, we processed outliers by truncating them to the 5^{th} and 95^{th} percentile of the data. This means that very high or low values are not removed but remain very high (or low) without influencing the model too much.

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Validation of the instruments was done before the campaign, once per year. The instruments are lab-grade reference equipment and do not need to calibrate in between the measurements. Colocation was therefore only done to check values, not calibrating. To properly maintain data quality, longer co-location than the current set-up of 1 hour is useful, though logistically complicated. Immediate evaluation of the comparison results needs to be organized with the data owner of the reference station.

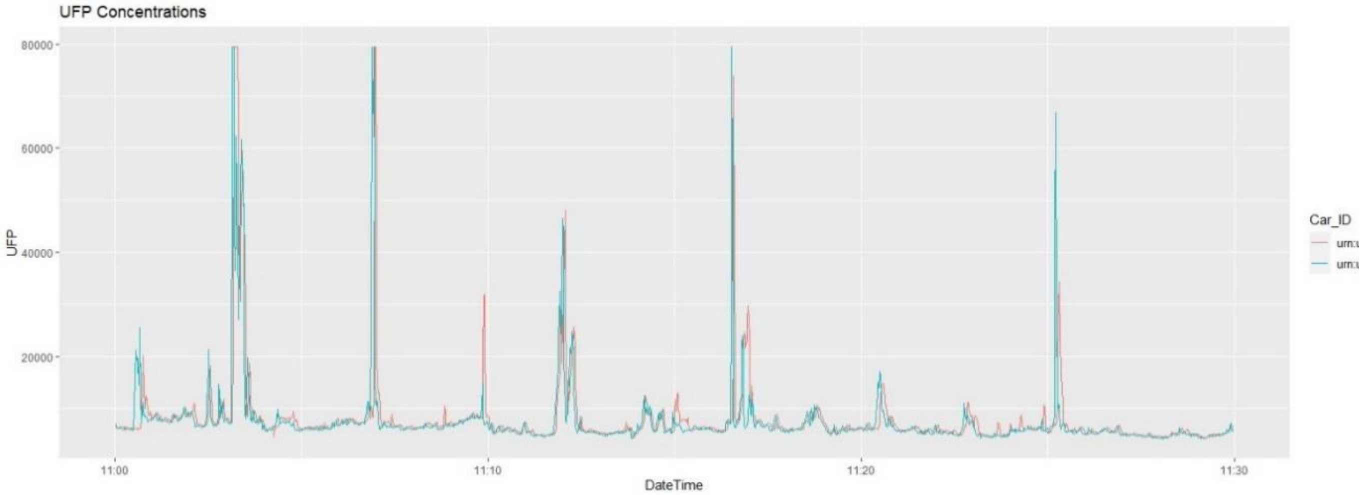

Figure 9: *Example of UFP measurements (particles/cm^3) by two cars.*

What were the criteria for removal/cleaning of data? Considerations for criteria?

We only deleted measurements that were physically unrealistic. Specifically, 1-second UFP concentrations below 500 particles/cm^3 and above 5000000 particles/cm^3 were deleted. NO_2 <0 and >500.

Was any spatial correction applied to link point measurements to route segments (map matching, buffer averaging)?

All measurements were matched to the nearest road segment, as we were sure all measurements were done on the road. Measurements were then averaged over 50 m street segments per driving day. Then measurements were averaged over the entire campaign, creating a mean of means for every street segment.

Conversion between pollutants (EC vs BC in summer and winter)

No conversion was applied.

5.2. Results

How did the accuracy of measurements/models impact the results?

The precision of the average concentration of our measurements per street segment is not high, since we measured most street segments only once or twice. As a data-only point this is far too little, but for creating a model this is not a limitation. The performance of the model therefore needs to be compared with a robust test set, not on the noisy training instances.

What was the influence of method choices on results?

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The measurement periods (2 times 8 weeks) and spatial variation seems to be adequate to create spatial LUR models for UFP, BC and NO_2. For the sub question of identifying port-industrial sources (and their impact on UFP) the amount of data was inadequate given the area covered. A more targeted monitoring campaign is needed.

New insights based on pilot?

This pilot emphasized the seasonal and daytime difference of the pollutants. BC for example was very dependent on the season and meteorology in Rotterdam region, more than other cities measured so far. Though, models based on summer measurements were very similar to models based on winter measurements.

Similar results were found when the car models were compared with models based on the bike campaign.

NFP was probably seen on summer afternoon. As UFP data are scarce in the Netherlands this is an important confirmation of this phenomenon in a rather 'northern town' albeit with many UFP precursors (seagoing ships, refineries, in addition to traffic).

Added value of the mobile monitoring/citizen science strategy when compared to stationary monitoring networks (AQMS)?

Mobile monitoring adds a lot of extra spatial variation in maps of air pollution, provided no high-resolution AQ modelling is available. For UFP, currently not modelled and hardly monitored, the campaign did generate a lot of new/additional data and seemed to confirm NPF. However, due to the scarcity of repetitions the data is hard to compare to existing modeled data (unlike the cycling data). This also limits the interpretation of the new UFP data in relation to the well-established monitored and modeled data on other pollutants (e.g. BC, NOx, PM).

Added value of monitoring multiple pollutants? Do pollutant ratio's provide new insights (e.g. source attribution)?

We had hoped to compare UFP/BC or UFP/NO2 ratio's but due to data issues, few repetitions/ too few observations it is hard to draw conclusions. With systematic mobile monitoring in areas of interest, generating sufficient repetitions the mobile approach could have been more successful in mapping specific source areas. Ratios between pollutants offer new insights into the source contribution of the pollutants. E.g. UFP is often elevated near airports, whereas BC and NO_2 are not. Similarly, one might expect to see areas with the influence of seagoing ships (supposedly the largest UFP source in the area), and the refineries. Figure 10 does seem to suggest some of the expected influences in some parts, but produces unexpected results in others. The area near the airfield has similar colors as Barendrecht to the south of Rotterdam. From the map one could conclude either that there are two airports or that the info on the map is not indicative for an airport.

More impact achieved through citizen involvement?

No citizens helped this campaign, but local knowledge helps a lot in interpreting some of the results. Especially looking at known and unknown hotspots.

What would you do similar/differently when repeating the monitoring campaign?

Creating a dataset with street segments with a lot of repeats or some form of stop-and-go sites would create better validation set for testing models based on true mobile measurements.

If the goal is to interpret the measurements more directly, not 'diluting' the observations over a vast and complex area and performing detailed mapping (considering meteo) to investigate assumptions. More frequent quality control (e.g. not only doing parallel measurements but also daily verification of the parallel measurements and immediate action if required).

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***Figure 10**: Ratio between predicted NO_2 and UFP concentrations in Rotterdam. Each of the four colors in the 2x2 box represent an equal number of road segments.*

6. BUCHAREST PILOT

In the city of Bucharest several summer and winter campaigns in 2022 were carried out using mobile measurements without citizens' involvement. UFP, PMx and gaseous pollutants were measured. Moreover, the ESCAPE Land Use Regression models together with PyLUR tool and QGIS were implemented. Data analysis of the mobile campaigns, highlighting the summer and winter specific concentrations and distribution had been conducted.

6.1 Mobile measurements and data

Two mobile measurements campaigns representative for summer and winter periods have been conducted in Bucharest on 100 km route. The route included heavy traffic roads inside the city, residential, industrial, and commercial areas, as well as sub-urban areas. Portable instruments for UFP, different particle matter fractions (PM_1, $PM_{2.5}$, and PM_{10}) and gaseous compounds (NO_2) have been used during both campaigns. The car measurements took place in the following timeframes: May – July (summer period, thereafter - summer) and January-February (winter period, thereafter - winter).

The measurements duration during one route were approximatively 8 hours starting from 8:30 AM local time in order to catch rush hours, but also less intense traffic during the mid-day of working days. At least, full 15 measurements routes were performed during each campaign, in different temperature conditions representative for the specific season.

6.2 Model

A Land Use Regression model, together with PyLUR tool and QGIS, was set-up in order to create the pollutants maps during both seasons in the city of Bucharest. The goal is to create the air pollution maps for Bucharest area in order to assess the contribution of diverse area to air pollution, the gradients on particle concentrations between areas and related exposure along roads in different seasons or atmospheric conditions. A mixed effect model was also tested, using the mean value from the fixed effect model (LUR) together with the pollutant variability (intercept of mean standard deviation values) for all individual street segments at 1-minute intervals. Individual maps at 100 m grid have been retrieved for each season.

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6.3 Maps based on car measurements

Figure 11 and Figure 12 represent maps of spatial variability for NO_2, and UFP in Bucharest during summer and winter periods, respectively. The UFP sources seem to be well distributed during summer period, while winter is characterized by more homogeneous sources. Significantly elevated concentrations are found mainly on the industrial area and urban agglomerations, but also on some important traffic routes. The average UFP number concentration along the mobile route presents a large spatial gradient mostly during summer, with differences up to a factor of 2 in the mean.

The NO_2 concentration shows sharper gradients during summer, when the concentrations are higher on the main roads. On both seasons the main streets, including the Bucharest ring road, represents the main NO_2 source. Also, the city center roads are highlighted, where the intensity of the traffic persists for the entire day. Seasonal variations of pollutants are also related to the height of the planetary boundary layer, linked to summer /winter.

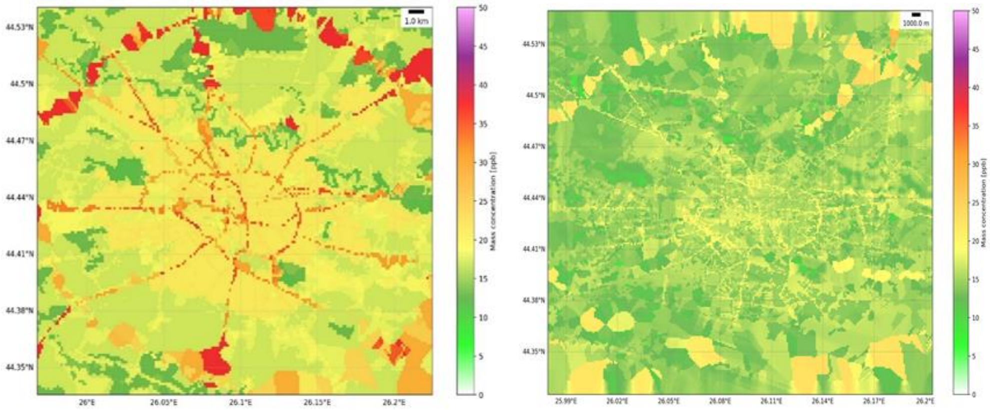

Figure 11: *Model maps for NO_2 concentration levels in Bucharest during summer and winter period*.

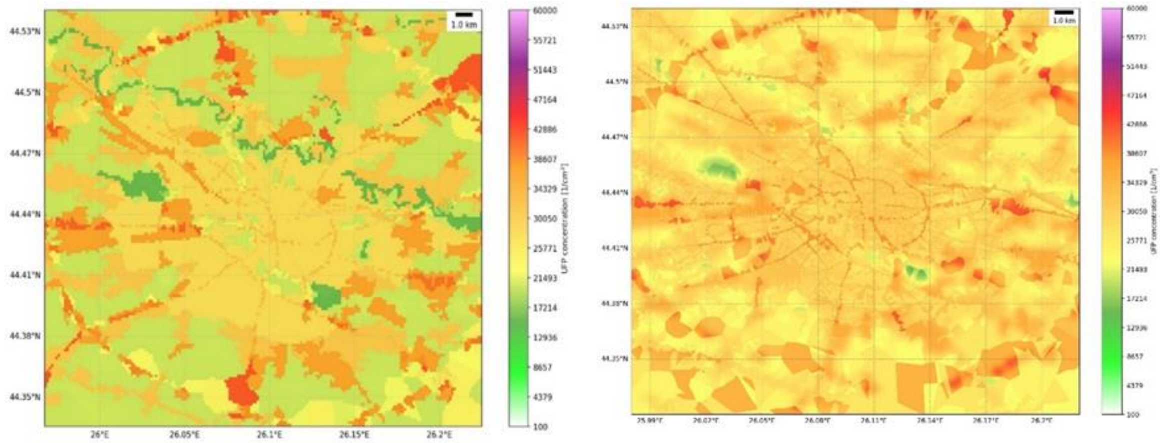

Figure 12: *Model maps for UFP concentration levels in Bucharest during summer and winter period*.

6.3.1 Evaluation of the summer and winter mapping by comparison to fixed measurements

The model performance has been evaluated for NO_2 and PM_{10} concentrations using the hourly data available at the Romanian National Air Quality Monitoring Network (ANPM-8 fixed stations representative for urban, industrial, and suburban areas) and at MARS supersite, which is part of RADO-Bucharest ACTRIS site (PM_{10}/NO_2 for winter). Mean values of root mean square error (RMSE), Mean Fractional Bias (MFB) and Mean Fractional Error (MFE) are evaluated using the data from May-August 2022 and January-February 2023 (timeframe of the mobile

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measurements). Overall, the model performed well, NO_2 values are overestimated, while PM_{10} levels are slightly underestimated (Table 1). As the model is trained with mobile on-road data, it is not surprising that it overestimates NO_2 exposures.

***Table 1**: Model performance metrics for NO_2 and PM_{10} predicted concentration levels in Bucharest (Romania) during summer 2022 and winter 2023, when compared with measurements from fixed sites.*

Pollutant	Season	Observed mean concentration	Modelled mean concentration
NO_2	***summer***	12.58 ± 7.71 ppb	20.35 ± 0.70 ppb
	winter	15.98 ± 9.52 ppb	17.17±0.74 ppb
PM_{10}	***summer***	24.64±13.18 µg/m^3	22.94 ± 0.45 µg/m^3
	winter	26.33 ±18.50µg/m^3	27.81± 5.13 µg/m^3

6.3.2. Variability within 1 km x 1km areas

Winter and summer maps for the normalised standard deviation (NSD) have been computed for all pollutants in order to assess the spatial sub-grid variability of concentrations within 1 km x 1 km areas (Figure 13 and Figure 14). A higher variability of pollutants concentrations is observed during the summer period, in the wintertime important variation are highlighted mostly on the ring road areas.

Similar variability patterns are observed for the particle's concentrations. UFP and NO_2 mean NSD are higher during summer.

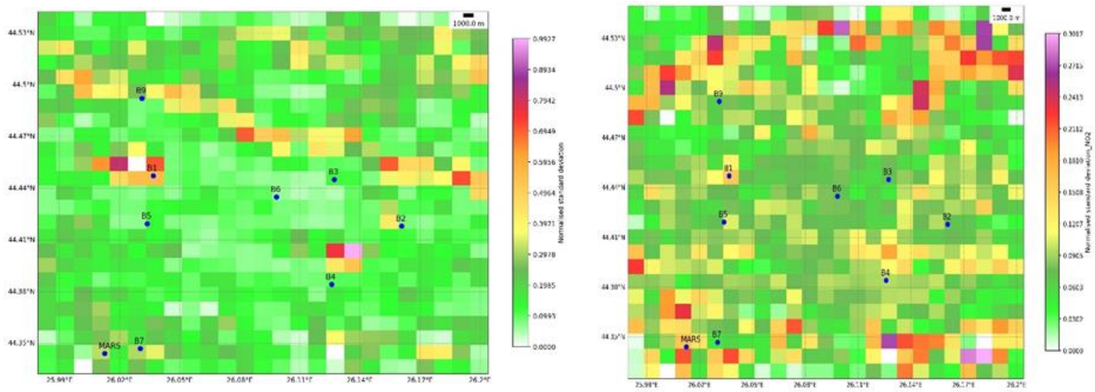

***Figure 13:** Normalised Standard Deviation of the sub-grids for NO_2 concentration levels in Bucharest during summer and winter period.*

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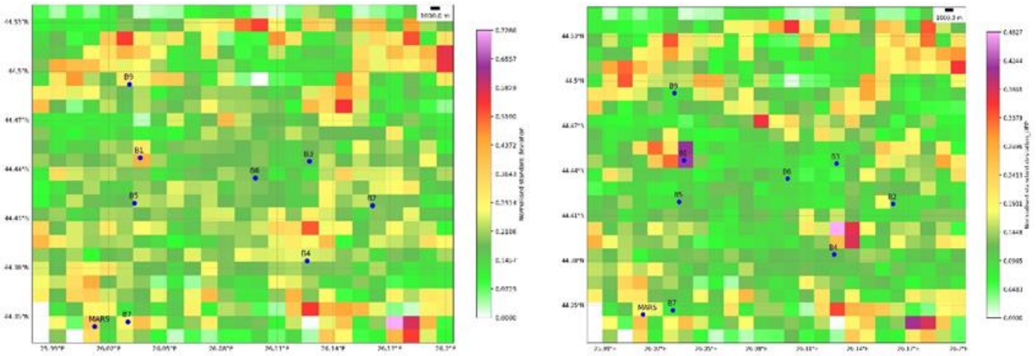

Figure 14: *Normalised Standard Deviation of the sub-grids for UFP concentration levels in Bucharest during summer and winter period.*

7. OVERALL ASSESSMENT

One overall message from the three pilot studies is that substantial new information can be learned by campaigns of mobile monitoring or low-cost sensor (LCS) fixed site indoor and outdoor monitoring of a limited duration (weeks to months) with a proper design. This makes these methods useful as an addition to routine monitoring with reference grade instruments at a small number of fixed sites. Obviously, in a specific domain, the longer the additional campaign, the more precise estimates of air pollution patterns can be obtained. We note that these campaigns are intended to provide additional information to the fixed site monitoring, not replace such measurements, as they provide excellent temporal resolution (at a limited number of locations).

7.1 Monitoring strategy

Detailed frequent quality control is essential, both in studies employing LCS and in studies using reference grade instruments. Comparisons with routine monitoring stations prior to and after mobile monitoring studies are important. Results need to be evaluated immediately such that potential errors can be detected before embarking the campaign.

The pilots also delivered a large number of practical considerations to make low-cost monitoring near homes possible, including the observation that connection to the main electricity network was a limitation and therefore (car) batteries were a viable solution.

Experiences with specific instruments suitable for mobile monitoring and citizen monitoring were obtained:

- The AE51 portable BC monitor provided useful information in both Birmingham (UK) and Rotterdam (The Netherlands). Though this device only works well when the moving speed is low and/or pollution levels are high. To reduce the noise in the instrument, concentrations often need to be averaged over about a minute, meaning you should not cover too much space in this time frame. In the studies above, the device was used while walking or cycling, meaning the averaging time was appropriate.
- In a car-based platform, experiences with the AE33 were very good as well. This device was capable of much higher temporal resolution than the AE51, need when large distances are covered within seconds. Though a moving average of 6 seconds was still needed to get rid of the noise. Another advantage of the AE33 is that it can calculate different wavelength, meaning it can distinguish traffic related soot from wood burning for example. Newer versions of the device doe calculate this percentage automatically.
- The frequent required maintenance of the DiSCmini instrument was burdensome for citizens and schools, rendering the instrument less useful for longer-term monitoring.

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- The PM sensor needed much less attention. Comparability of different LCS sensors is an issue when comparing data.

In the three pilots, mobile campaigns were performed with cars, bicycles, and pedestrians. All these options resulted in informative campaigns. It depends on the research question and the size of the study area which platform is most suitable. Cars lend themselves more easily to included non-portable reference grade instruments such as the AE33 aethalometer instead of the cheaper and portable AE51. With cars, also a larger study area can be covered, such as in the Rotterdam where measurements were conducted in the wider Rijnmond area. In general, the faster the platform, the higher temporal resolution and response time of the instruments are needed.

As there is well-documented seasonal variability, and the aim is to create long-term average estimates, conducting monitoring in at least two seasons is crucial. If the interest is in specific sources e.g. wood burning than a season-specific campaign could be sufficient. In the summer season, optical low-cost PM sensors tend to perform better than in the winter, because of less days with high relative humidity. For the same reason, indoor measurements are less problematic with low-cost PM sensors than outdoor measurements.

In none of the pilots, it was feasible to perform mobile monitoring at night, hence the measured concentrations primarily reflect daytime averages. In the Rotterdam car pilot, a limited number of monitoring days were performed in the weekend, but as in the other pilots monitoring was mostly performed in weekdays. Night-time monitoring raises safety concerns when performed by cycling or walking.

7.2 Involvement of citizens

The approach of involving citizens in mobile monitoring of air pollution worked well, both in Birmingham and Rotterdam. In Rotterdam, these were employees of the DCMR and municipality of Rotterdam. These were more knowledgeable than the average citizen. In addition, it made it easy to have a local coordinator from DCMR organizing and supervising the campaign. In Birmingham citizens were invited from the population, sometimes with a reward for participation added. The latter increased the response rate, but also resulted in students primarily interested in the reward. The approach with incorporating employees of the organization responsible for air monitoring is a relatively easily scalable approach, as recruitment and project organization cost less time. This is at the expense of a less representative population and less variability in covered commuting routes (same endpoint).

The Birmingham pilot obtained useful experiences for interacting with citizens for LCS monitoring in or near their home. Building trust between citizens and researchers is an important issue. Respecting anonymity is another requirement for both citizens and schools and other organizations. Providing relevant feedback is important as citizens often participate because they are interested in the topic. Reimbursement of costs, even if small, may increase collaboration. Citizens did not always follow instructions.

The Birmingham indoor air quality (AQ) showed that people were interested in the AQ of the spaces they spend most of their time in, and the factors that affect their quality of life. In Birmingham, houses as well as the three classrooms had significant differences between them, even though they were located very close to each other. Differences in indoor sources and infiltration factors between homes may contribute to these differences.

Awareness raising, identification of hotspot locations, more representative personal exposure assessments in urban environments/during specific activities (e.g., commuting) were identified as added value of involving citizens in the Rotterdam pilot.

7.3 Data processing

For calibration of the low-cost PM sensors, a simple linear relationship between sensor and reference grade instrument may not be optimal. Consideration of outliers related to high humidity is another key consideration.

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As mobile measurements consist of point measurements in time and are affected by fluctuating background concentrations, in the cycling Rotterdam pilot we applied a rescaling method to remove some of the temporal variation, using data from a continuous reference site. Whether this is needed, depends on using the measured data directly or using the data as input for further empirical models. In the latter case, rescaling contributes less.

Mobile measurements were assigned to the nearest road segment using GIS tools. This added a limited amount of uncertainty. Careful graphical evaluation of the original GPS readings is needed in addition to scripted procedures to avoid potential large errors, as we observed on a single day in the Rotterdam car pilot.

7.4 Modelling strategy

The monitoring in itself was useful to document variability in space, e.g. between different homes in Birmingham using longer-term monitoring with LCS or along routes frequently driven by DCMR employees in Rotterdam. In addition, the monitoring served as data to derive empirical models. This was done in Birmingham using machine-learning, and in Rotterdam using a manually guided stepwise linear regression, based on a variety of land use predictors.

Machine-leaning models in Birmingham performed better when predicting $PM_{2.5}$ than PM_{10} data, which were a lot harder to model, possible related to the lower quality of PM_{10} data from the specific sensor used.

In the Rotterdam pilot, we compared the map based on mobile monitoring with results from dispersion modelling from our partner DCMR. Both types of models were moderately correlated. Integration of the two approaches may be optimal. Evaluating locations, where the two types of models disagree, may give useful hints at modelling issues in both approaches.

7.5 Results

Mobile monitoring was an effective tool for characterizing spatial variation in the three pilot cities Rotterdam, Birmingham and Bucharest. Substantial variation was found within 1x1 km grid cells in all cities (Deliverable 27, WP4.3 and figures 14 and 15 included from the Bucharest pilot).

As mobile monitoring involves on-road monitoring (especially for car and cycling-based campaigns), using the data directly to map air pollution concentrations across the city will overestimate the concentrations experienced at the façade of homes and other buildings. The overestimation likely depends on the distance of homes from the road. The overestimation is less for models based upon model monitoring, as the predictors of these models (e.g., traffic load in a 50 m buffer) have lower values when homes are located at a larger distance from roads. In Dutch studies, an overestimation of about 30% of UFP was found for mobile monitoring models (Kerckhoffs, 2016; Kerckhoffs, 2017). The daytime monitoring also plays a role here.

In the Rotterdam pilot, we identified the impact of motorised traffic as in many previous mobile monitoring studies. In addition, by linking wind direction data, source locations and the individual measurements (that is, not averages across measurement days), we also found influences of the harbor, industrial area, and airport on the measured air pollution variables.

Indoor measurements were usually very consistent without significant discrepancies from the research grade instruments' measurements. A simple linear regression between the OPC-N3 sensor in Birmingham and the research grade instrument used was enough to greatly improve the data.

Opportunistic data collection in the Rotterdam citizen pilot, resulted in an inadequate number of repeated runs on most of the trajectories in order to derive representative long-term average maps based on measurements alone. The minimal number of required repeats for long-term average representativity, based on the subsampling analysis, varied between 24 and 54 (depending on the road segment) to be within 25% of the mean when considering the

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raw BC values, or between 22 and 39 when applying additional post-processing (winsorising and/or background normalization). This number is consistent with values found in other studies.

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