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Air quality mapping in urban environments using mobile measurements

Jan Peters [1,*], Martine Van Poppel [2] and Jan Theunis [2]

[1] VITO, Boeretang 200, BE-2400 Mol, Belgium; E-Mails: jan.peters@vito.be (F.L.)
[2] VITO, Boeretang 200, BE-2400 Mol, Belgium; E-Mails: martine.vanpoppel@vito.be (F.L.); jan.theunis@vito.be (F.L.)

***** Author to whom correspondence should be addressed; E-Mail: jan.peters@vito.be (F.L.);

Abstract: We provide a study on the variability of urban air quality (UFP, PM10) in space and time, and assess the variability characteristics of both pollutants with respect to the practicalities of a mobile monitoring campaign. UFP concentrations showed significant difference within the day and between days, and also between streets along the measurement route. In contrast, PM10 showed a strong temporal variability over longer periods and a limited spatial variability. Consequently, mobile monitoring of UFP mapping should be more dense in time and space, whereas repeated monitoring of a large area on one day is often redundant for PM10.

Keywords: air quality; ultrafine particles (UFP); mobile sensor; monitoring; mapping

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1. Introduction

Mobile platforms are increasingly used to acquire air quality data at a high spatial and temporal resolution in a complex urban environment (e.g. Westerdahl *et al*., 2005). As such, mobile measurements provide a solution for short-term studies to assess spatial variation of pollutants and acquire a data volume that would not be feasible by stationary measurements. This study focuses on mobile monitoring of the ultrafine (UFP) and PM (Particulate Matter) mass in urban environments. UFP contribute little to the mass of the total suspended particles but are highly abundant. UFP come into the air by primary emissions from combustion sources in transportation, industries and power generation, and by secondary formation by atmospheric photochemical reactions and conversion processes (Westerdahl *et al.*, 2005; Seinfeld and Pandis, 2006). These primary ultrafine particles have a very short life time (minutes to hours) and rapidly grow through coagulation and/or condensation to larger complex aggregates (Pope and Dockery, 2006). Therefore, the highest concentrations of UFP are found in the vicinity of the primary sources, for example, near busy roads where particle number concentrations are typically between 10^4 and 10^6 particles cm^{-3} depending on driving speed, fleet composition and meteorology (Nikolova *et al.*, 2011). UFP concentrations decrease rapidly with distance from the emission sources (Zhu et al. (2002)) inducing important differences, in space and

time, of UFP concentrations between urban micro-environments. Typical rural background concentrations are far below the urban UFP concentration, and have a very small contribution to the urban UFP concentration observed near busy streets (Nikolova *et al.*, 2011). PM10 is primarily derived from long range transport, suspension and resuspension of solid material, motor vehicle exhaust and tyre abrasion in urban areas(Lenshow *et al.* (2001)). All these components have their own spatio-temporal dynamics, as have the mechanisms of atmospheric dispersion and particle deposition. Overall, the spatial and temporal variation is lower for PM10 than for UFP (Monn, 2001, and reference therein).

In this study we evaluate the potential to use a mobile monitoring platform to systematically map urban air quality. The tool is evaluated as complementary tool to fixed air quality monitoring networks. Therefore, we compare the variability pattern of UFP and PM10 concentration in urban environments obtained from mobile monitoring with results from the literature. Furthermore, we assess the need for repeated mobile monitoring for UFP and PM10 mapping in urban environments based on the results of the spatio-temporal analyses.

2. Experimental Section

2.1. Mobile platform

A TSI P-Trak ultrafine particle counter was used to measure the number concentration of ultrafine particles (20 nm – 1 μm) within a range from 0 to $5 \cdot 10^5$ particles cm^{-3} at a temporal resolution of 1 sec. A GRIMM 1.108 Dust monitor was used for measuring the PM10 mass concentration (μg m^{-3}) at a 6 second resolution. The P-Trak and the GRIMM Dust monitor were installed on a bicycle monitoring platform which was additionally equipped with a GPS to register measurement location. A similar mobile platform setup was shown to have a robust performance in a similar urban environment (Berghmans *et. al.*, 2009).

2.2. Study area and monitoring campaign

The mobile measurements were performed in Antwerp (51°12'N, 4°26'E), Belgium. Antwerp is a medium-sized city (480 000 inhabitants, 985 inhabitants km^{-2}), and a fixed route was defined in a suburb at the Eastern side (Borgerhout). Although the major part of the mobile route was located in residential area, streets of differing configuration and with differing traffic dynamics were included. Mobile measurements were made by 24 runs on 8 different day in the period between March 16 and April 8, 2009. The monitoring hours ranged from 6 am until 6 pm, but most of the runs were made between 10 am and 4 pm.

2.3. Experiment

An interesting application of mobile measurements is to obtain an integrated picture of the air quality at a given street or street segment, where peak events are smoothed in space and time. Given the spatio-temporal variability of air quality parameters (UFP and PM10), the question is how many mobile runs should be made to obtain such an integrated picture, and additionally, when should those runs preferably be made? An experiment was conducted to identify a suitable number of mobile runs

needed to representatively map the local air quality (UFP and PM10) over the study period at both locations at street level. First, all the data were used to calculate an aggregated median pollutant concentrations per street over all the measurement runs. This value was assumed as a representative estimate of the pollutant concentration for the 3 week study periods, given the substantial data volume. Subsequently, median pollutant concentrations were calculated per street based on mobile measurements of a cumulatively growing data volume that was obtained by an addition of measurement data from randomly selected runs (random selection without replacement). The convergence pattern of the median concentration in function of the number of runs was assessed for the number and the temporal distribution of the runs needed to allow for convergence. The pseudo-code underneath summarizes the experiment.

Input: mobile measurements of UFP and PM10 concentration made during *k* runs along the same route
Output: median pollutant concentration in function of the number of runs

1. randomly permute the runs (runs = (1,2,...,*k*)), save as permuted_runs (e.g. permuted_runs = (12,*k*,...,3));
2. for *i* = 1 : *k*
    a. select pollutant data from permuted_runs(1:*i*);
    b. calculate median value, save as median_concentration(*i*);
    c. if *i* ∈ {1,2,5,10,16,24}
        i. calculate cumulative distribution function of the measurement time;
        ii. plot cumulative distribution function;
    d. save number_of_runs(*i*) = *i*.

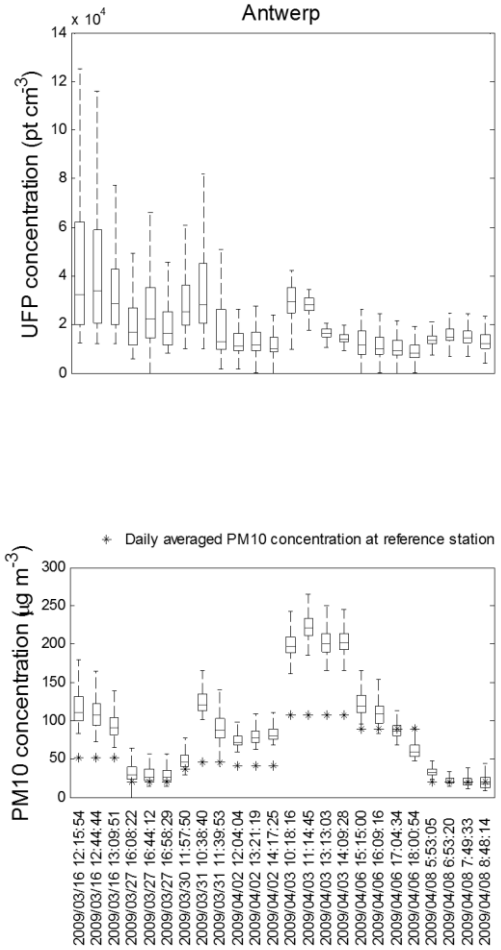
    end
3. plot median_concentration in function of the number_of _runs.

3. Results and Discussion

3.1. Temporal analysis of mobile measurements

Median UFP concentrations along the entire monitoring route were within a range of 8000 pt cm-3 and 34000 pt cm-3. Significant differences in UFP concentration were observed between the measurement dates, but also between several mobile runs on the same measurement date (Chi-sq. = 16240, $p < 0.01$). For example, UFP concentrations were significantly higher on March 16, 2009 than on April 6, 2009. On April 6, 2009 the UFP concentrations were significantly higher during the first run in contrast to the remaining three runs. UFP concentrations showed a high temporal variability, with significant changes in concentrations within hours.

Figure 1. Boxplots of UFP (**a**) and PM10 (**b**) concentration in Antwerp. The labels on the ordinate give the date and starting hour of the mobile monitoring runs.



The temporal variability of the median PM10 concentration is high between measurement dates. Statistical tests indicated significant differences between several measurement dates (Fig. 1, Chi-sq. = 31076, $p < 0.01$). A similar variability pattern between dates is observed from the daily averaged PM10 concentrations measured at reference stations in the vicinity of the mobile measurements. Mostly, reference concentrations were below the median of the mobile measured PM10 concentrations, but the absolute concentration difference ranged from 0 µg m^{-3} to 114 µg m^{-3}. The variability between PM10 concentrations of the mobile runs on a given measurement date were generally less pronounced than for UFP concentrations, and were often non-significant.

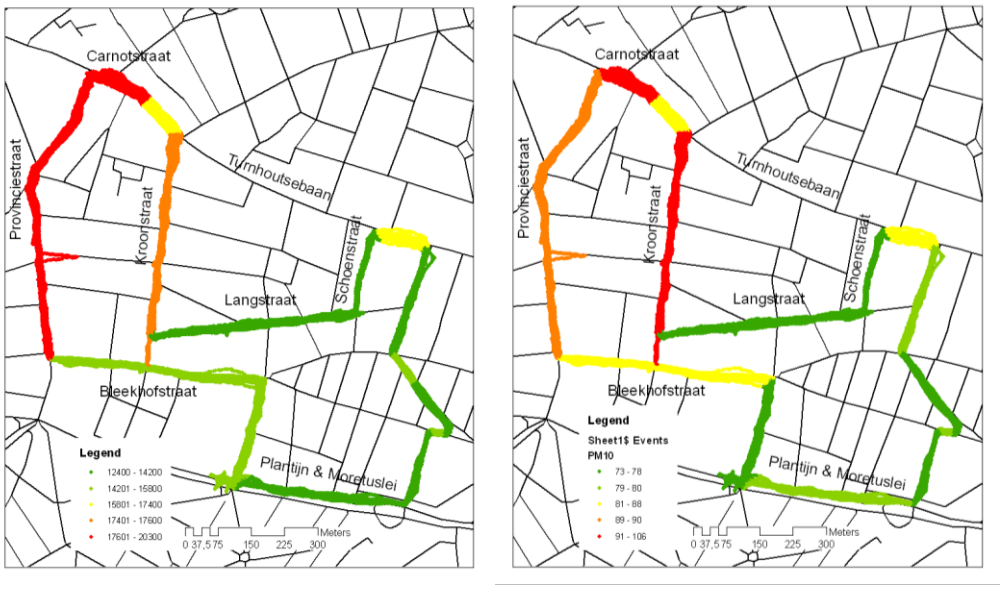
3.2. Spatial analysis of mobile measurements

The mobile measurements were linked to a street database by their geographical coordinates. As such, the mobile UFP and PM10 concentration measurements were attributed to the streets of the mobile routes. A streetwise comparison of the UFP and PM10 concentrations revealed significant concentration differences between the streets of the route (Fig. 3, Chi-sq. = 2711, $p < 0.01$). The highest UFP concentrations were measured in Carnotstraat and Provinciestraat, followed by Turnhoutsebaan and Kroonstraat. The lowest UFP concentrations were found in Schoenstraat and Langstraat. In general, high concentrations correspond to streets with higher traffic numbers and/or

street-canyon like configuration. Lowest concentrations are observed in streets with less traffic or an more open configuration.

The spatial variability of PM10 was lower, but significant (Chi-sq. = 626, $p < 0.01$). In Antwerp, measured PM10 concentrations were significantly higher in Carnotstraat in comparison to Turnhoutsebaan, Provinciestraat and Kroonstraat. In the latter three streets, the PM10 concentration was significantly higher than in all the other streets. The PM10 concentration in these streets, however, were not significantly different.

Figure 2. Maps of the median UFP (**a**) and PM10 (**b**) concentration per street along the route in Antwerp.

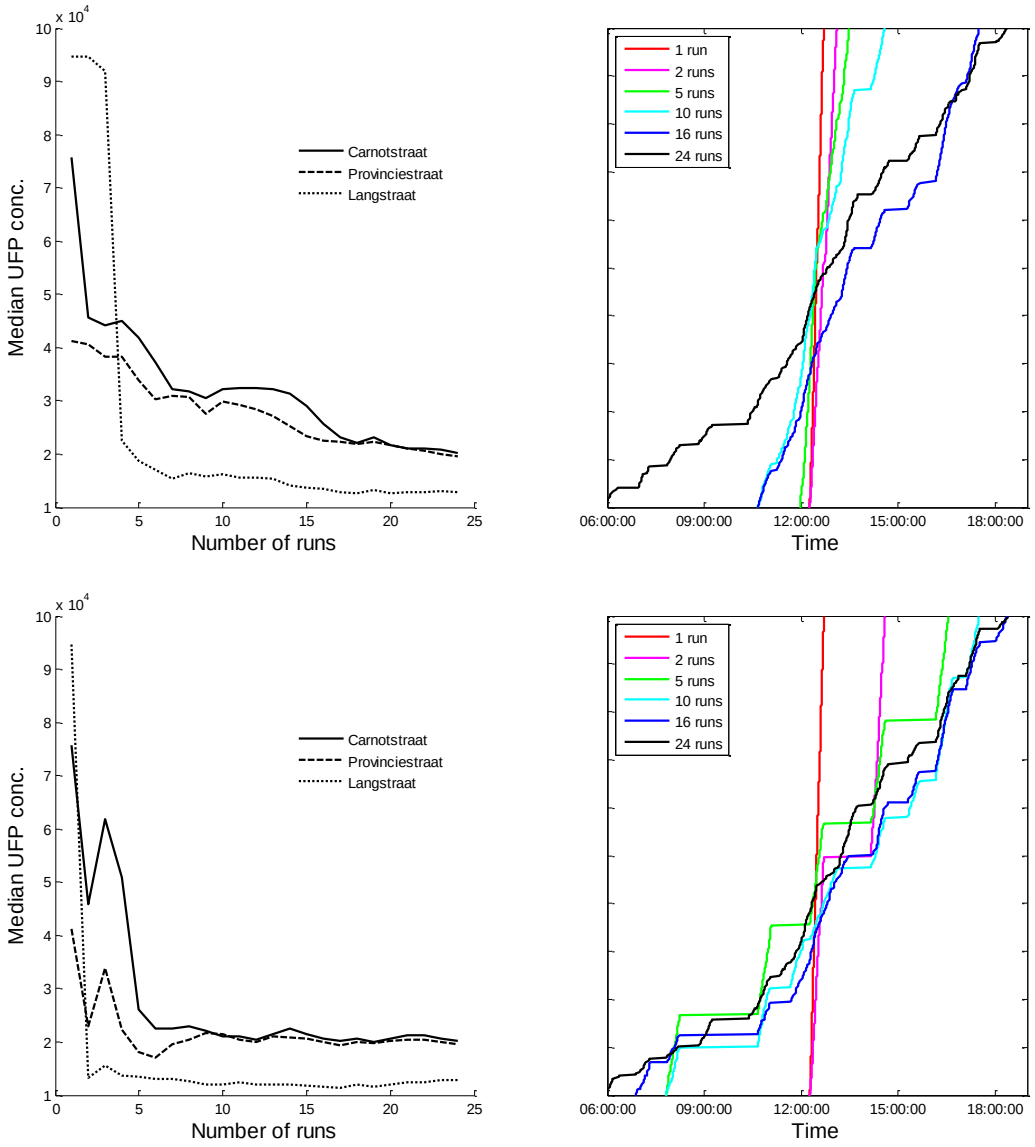


3.3. Experiment: how many runs are needed?

In Antwerp, three streets were selected for this exercise based on the spatial analysis: Carnotstraat and Provinciestraat having high pollutant concentrations and Langstraat, having the lowest concentrations along the route. Results indicated pronounced differences between different streets in the convergence pattern of median UFP concentration (Fig. 3). Two examples of possible combinations of runs are given, and indicate the need for a uniform coverage of the day by mobile measurements. If the measurements are made within a limited time interval, e.g. five runs between 12:00 and 13:30 (Fig. 3., top), then the median UFP concentration calculated from measurements of these five runs differs from the overall median value based on 24 runs. The difference is moderate (6000 pt cm-3) for Langstraat, but substantial for Provinciestraat (14500 pt cm-3) and Carnotstraat (21500 pt cm-3). If the measurement runs are performed on different times of the day, e.g. covering a period from 8:00 until 16:30 (Fig. 3, bottom), these differences are much more limited, and approximately 500 for Langstraat, 1400 for Provinciestraat and 5800 for Carnotstraat. The overall street concentration had an important effect on the number of runs needed to obtain accurate concentration values. Streets of high concentration needed to be monitored more frequently (more than

eight runs) in comparison to the streets of low concentration where two runs may suffice. This can be explained by temporal variation of local sources (traffic) in streets with high concentrations.

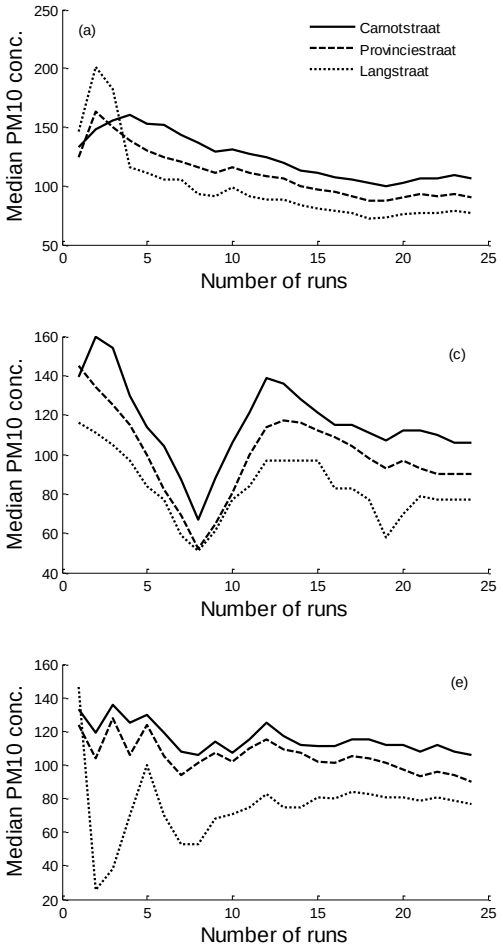
Figure 3. Median UFP concentration (pt cm-3) in function of the number of runs, and the cumulative density plots of measurement time for three streets in Antwerp. The top represents mobile runs that were not uniformly spread during the day (first five runs around noon), whereas the bottom represents a more uniform coverage of the day (first five runs between 8:00 and 16:30).



In contrast to the UFP concentrations, the PM10 concentration did more slowly converge when the runs were randomly selected (Fig. 4(a), same selection order as in Fig. 3, bottom). 20 runs were needed to obtain a median concentration similar to the overall median concentration (Fig. 4(a)). When the selection order of the runs reflected a higher likelihood for a run to be selected and added to the

previously selected ones based on the similarity in date, a high variability in median PM10 values was observed (Fig. 4(b)). When the selection of the runs guaranteed a high dissimilarity between the dates, i.e. runs of different measurement dates had a higher likelihood to be selected, convergence was observed when measurements from 15 runs were combined for Carnotstraat and Langstraat (Fig. 4(c)). The difference between the overall median and the median after 15 runs was 4 µg m-3 for Langstraat and 5.5 µg m-3 for Carnotstraat. The median of 15 runs selected from all measurement dates differed 12 µg m-3 from the overall median for Provinciestraat. 15 runs were not sufficient to allow for convergence at Provinciestraat. The relationship between concentration and the convergence pattern as observed for UFP was not present for PM10.

Figure 4. Median PM10 concentration in function of the number of runs. The selection of the runs shown here used a selection of the runs that guaranteed a significant temporal coverage (in terms of hours of the day) of the runs (**a**), reflected a high similarity between the measurement dates of the runs (for a number of runs of eight, measurements from only two different dates were used) (**b**), or guaranteed a high dissimilarity between the measurement dates of the runs (for a number of runs of eight, measurements from eight different dates were used) (**c**).



4. Conclusions/Outlook

Measurements of the air pollutants UFP and PM10 were acquired by mobile monitoring during a short period (less than one month) along a predefined route in an urban environment. The repetition frequency of the mobile monitoring during this period allowed for a small-scale assessment of the temporal and spatial variability of UFP and PM10 concentrations. In addition, the mobile monitoring tool was evaluated for assessing spatial variation in order to better estimate peoples exposure. The spatio-temporal variability of UFP concentration is high, with significant changes in concentrations within the same day and significant concentration differences over small distances. Nevertheless, a mobile measurement campaign allowed to distinguish streets with overall higher concentrations (and traffic volumes) from quiet streets with lower concentrations. PM10 concentrations display a lower within-day temporal variability and a lower spatial variability. Moreover, a high inter-daily variability was observed, attributed to a high variation in background concentrations. The difference in spatio-temporal variability of UFP and PM10 may affect the survey characteristics of a mobile monitoring campaign. The high spatio-temporal variability of UFP in an urban environment constrains for repeatedly and extensive urban coverage by the mobile measurement runs. For PM10, repeated runs on the same date do sometimes results in redundant measurements. Additionally, the spatial heterogeneity of PM10 is lower in urban environments due to the more inert nature of the larger PM10 particles and the (generally) lower contribution of spatially variable local sources. As a result, a more extensive extrapolation of measured PM10 concentrations from one street to neighbouring streets of similar traffic intensity and configuration may be appropriate in comparison to UFP. These results confirm the added value of mobile air pollution measurements if sufficient attention is paid to sampling period and frequency.

Acknowledgments

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