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PERSONAL EXPOSURE ASSESSMENT THROUGH MEASUREMENT AND MODELLING

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Abstract: Modelling is commonly used to evaluate population exposure to atmospheric pollution. It allows one to assess how many people reside in a zone where pollution levels are above a certain threshold but, to the extent of our knowledge, it does not take the indoor contribution into account. In this study, we propose to compare the cumulated personal exposure as measured by about 60 different persons in the city of Liège (Belgium) during one-week experiments in the years 2018-2020, and various modelling approaches. The measurements were carried out by the citizens with a set of portable devices including the Antilope sensor system developed at the Institut Scientifique de Service Public (ISSeP). The most complex modelling system used here consists of a three-component outdoor model, working at a hourly rate and a spatial resolution of about 10 m. It is combined to an infiltration model that aims at estimating the indoor concentrations based on the outdoor concentrations, some meteorological parameters and the building ventilation properties.

Key words: *Pollutant exposure, Outdoor/indoor concentrations, Low-cost sensor, Modelling, Black carbon,* $PM_{2.5}$

INTRODUCTION

Because of their important population and pollutant emission sources, it is essential to monitor accurately pollutant concentrations and their evolution over time in urban environments and to develop reliable models of personal pollutant exposure. Yet, exposure to pollutants is usually evaluated using atmospheric pollutant concentrations with a low spatio-temporal frequency on the one hand, and, on the other hand, population density maps typically generated on the basis of residency information which do not reflect population movement over time. Intersecting such information to estimate population exposure implicitly makes the assumption that everybody lives outdoors, in front of one's door, whereas we spend in general more than 80% of our time indoors (Dons, 2013). In order to achieve more accurate and consistent estimates of exposure, it is therefore essential to develop high-frequency measurements (at 1-minute rate or faster) and to assess procedures that account for population dynamics and allow one to discriminate between indoor and outdoor exposure. In this context, a low-cost versatile air monitoring device, suitable for fixed and itinerant measurements, both indoor and outdoor, named Antilope, has been developed at the Institut Scientifique de Service Public (Lenartz *et al.*, 2021; 2022). In the framework of OIE (Outdoor and Indoor Exposure) project, we aimed to improve the assessment of personal exposure combining real time itinerant measurements and outdoor/indoor modelling.

MATERIALS AND METHODS

Exposure measurement campaigns

For the mobile personal exposure campaign (2018-2020), subjects were provided with a set of portable devices (set at a 1-minute rate) for seven days: an Antilope low-cost sensor system with an optical sensor for the measurement of $PM_{2.5}$ and electrochemical sensors for the indication of nitrogen oxides (NO and NO_2) and ozone (O_3) approximate levels (Figure 1), a portable AethLabs AE51 aethalometer for the measurement of black carbon (BC) and a GlobalSat DG200 GPS to track the subject location. All the measurement equipment was placed in a backpack to easily shadow the subjects in their daily activities.

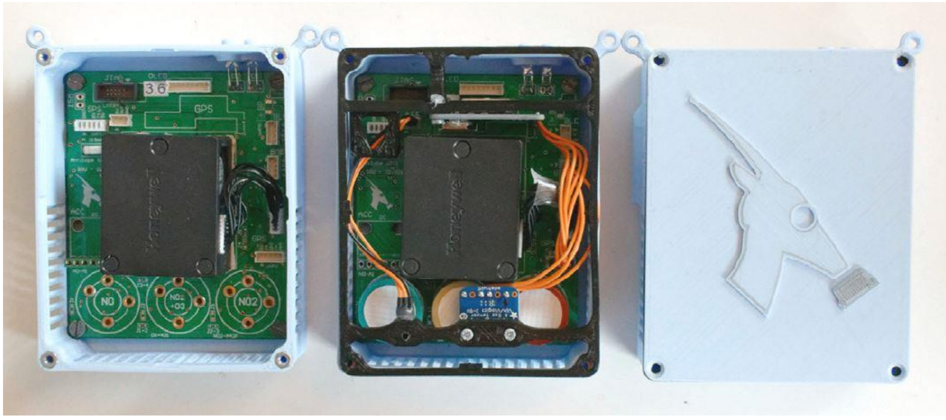

Figure 1. Enclosure of the Antilope (Lenartz *et al*., 2021).

At the beginning of their week campaign, subjects had to answer some questions about their profile (age, gender, professional status, *etc*.) and their health in general (allergy or asthma, frequency of physical activities, smoking exposure, *etc*.). They also had to describe their everyday environment through questions about their housing (heating type, ventilation, kitchen and floor equipment, *etc*.) and habits (most occupied rooms, vacuum frequency, *etc*.) as well as their place of work if relevant.

Every day during the week, participants had to fill in a journey logbook with all their activities. Each activity had to be characterized by a start time, an end time, a type (work, shopping, staying at home, cooking, sport, leisure, *etc*.) and an environment (indoor or outdoor). Travels are considered as an activity with an indoor/outdoor type according to the mode of transport (car, bus, train, walk, *etc*.). Every day, subjects also had to report any respiratory discomfort or crisis. Such information is very useful to evaluate exposure to air pollution according to activities and modes of transport as well as to corroborate some of the measurements such as the location provided by the GPS or the lack thereof.

Two measurement campaigns were also carried out in order to validate the indoor model. The first one took place in August and September 2017 in two different stores in Liège and the second in April and May 2021 in an apartment in Liège as well (Hozay, 2021).

Outdoor model

ATMO-Street (Lefebvre *et al*., 2013) simulates the dispersion of pollutants (PM_{10}, $PM_{2.5}$, BC and NO_2) from their main emission sources, *i.e*. large industries and the road network, taking meteorological conditions (temperature, wind direction/speed and solar radiation) into account. ATMO-Street was created by coupling the IFDM bi-gaussian dispersal model (Immission Frequency Distribution Model) with the OSPM (Operational Street Pollution Model). The pollutant concentrations are calculated at different receptor points of the studied territory and then interpolated to the whole area.

Regarding industry, only the most polluting industrial sources within the municipal perimeter are considered by the IFDM model, the impact of the industrial fabric as a whole being taken into account in the background concentrations. For the road network, polluting emissions are assigned to each road segment on the basis of the measured traffic. Each vehicle is assigned a COPERT emission factor depending on its category (light or heavy vehicle, engine, Euro standard) and driving mode (urban, rural or motorway).

The model also takes the configuration of the streets into account. In the case of urban canyons, which are narrow streets with a high building height, the IFDM is replaced by the OSPM. The OSPM distinguishes between the direct contribution of traffic emissions and the contribution due to recirculation caused by the presence of vortices. Within these streets, poor dispersion and therefore local accumulation of pollutants is generally observed.

Model simulations were performed on the same period as the personal exposure campaign (2018-2020) at a hourly rate and a spatial resolution of about 10 m. As background concentrations, we used the concentrations measured at the Herstal station in the suburban area of Liège (Wallonair, 2022). We used the vehicle fleet in 2019 and estimated the traffic from the HERE floating car data for 2018.

Indoor model

The model used to assess the outdoor-indoor transfer of pollutants has been developed by Cenaero (Aeronautics Research Center). The tool « OpenModelica », which is an open-source modelling and simulation environment, was chosen to develop this model. Three different models have been developed to assess indoor black carbon (BC) concentrations respectively in a building, a car and a bus. Only the model dedicated to the building environment is used here.

The building model is a two-zone model, allowing to represent the BC concentrations in two adjacent rooms with only one of them in direct contact with the outside environment. It takes several driving forces (indoor-outdoor temperature difference and mechanical ventilation) as well as different building factors (leakage, natural ventilation, *etc.*) into account. A simplified scheme of this model and its parameters is shown in Figure 2. For the simulations, we made several assumptions (Hozay, 2021): a ventilation flow of 1 volume hour^{-1} in the stores only (absence of ventilation in the appartment), a ventilation filtration rate of 50 % (in the stores only), an air infiltration surface of 0.01 m², *etc*.

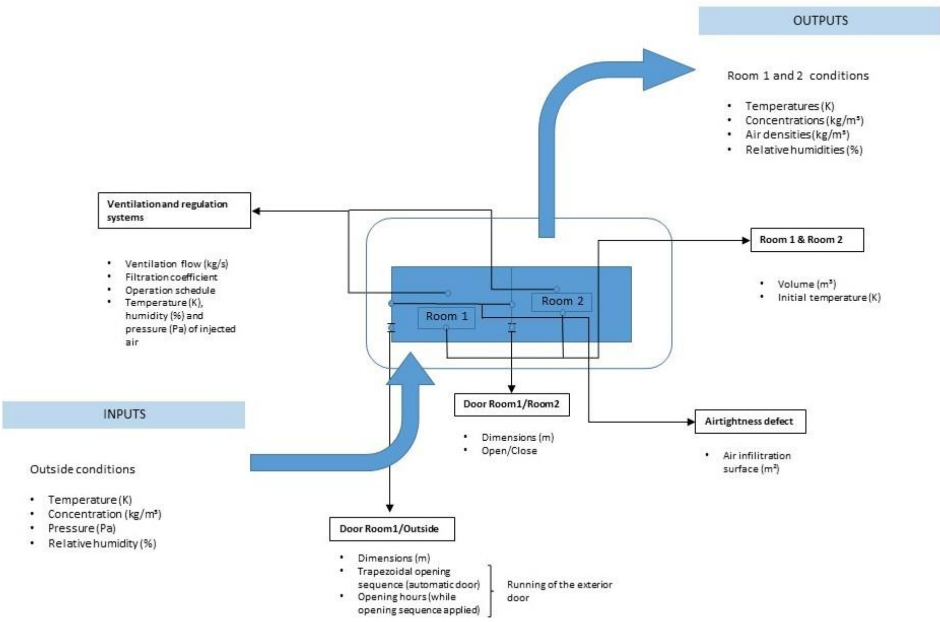

Figure 2. Simplified scheme of outdoor - indoor air pollution transfer model.

RESULTS AND VALIDATION

Mobile personal exposure campaign

Not surprisingly, the participants spent most of their time inside, at home or at work, and in daily travels, with mean exposures to $PM_{2.5}$ of 7, 4 and 6 µgm^{-3} respectively. The highest average exposures are measured during activities indoors: cooking (8 µgm^{-3}) and indoor leisure such as sport (9 µgm^{-3}). It is also during these activities that the highest concentrations were recorded with 64 µgm^{-3} for cooking, 58 µgm^{-3} for indoor leisure and 53 µgm^{-3} when being simply at home. Regarding the means of transport, the time spent travelling by car or walking was the highest in the population sample, followed by train, bus and bike. On average, pedestrians and bus commuters were exposed to 9 µgm^{-3} while car drivers, train commuters and cyclists were exposed to 5 µgm^{-3}. The lowest and highest maximum concentrations were respectively recorded for train (14 µgm^{-3}) and for bus (63 µgm^{-3}).

Although not the subject of an European directive, nor a World Health Organization (WHO) recommendation, measuring black carbon (BC), which is the product of incomplete combustion of fossil fuels or biomass, is a good indicator of traffic and heating intensity. The mobile campaign in Liège highlights the high exposure to BC when leaving and picking up children from school (1.0 μgm^{-3} on average and a maximum of 6.7 μgm^{-3}), ahead of travelling (0.9 μgm^{-3} and 4.4 μgm^{-3}), shopping in a mall (0.8 μgm^{-3} and 3.1 μgm^{-3}) and cooking/making a fire (0.7 μgm^{-3} and 4.7 μgm^{-3}). People also seem to be the most exposed to BC during bus trips (1.6 μgm^{-3}, maximum of 7.8 μgm^{-3}), but, unlike for $PM_{2.5}$, the bus is followed by the train (1.4 μgm^{-3}, max of 3.4 μgm^{-3}) and the bike (1.0 μgm^{-3}, max of 5.3 μgm^{-3}).

Outdoor model validation

The hourly pollutant concentrations simulated by ATMO-Street were compared to the concentrations measured by the citizens during their outdoor activities and travels. For this purpose, the 1-minute measurements were first aggregated at a hourly resolution and a 10 m spatial resolution. Figure 3 shows the comparison between the black carbon modelled and measured concentrations corresponding only to citizen travels in 2019 ($[BC]_{travel\_median\_meas}$ = 0.84 μgm^{-3}, $[BC]_{travel\_median\_mod}$ = 0.72 μgm^{-3}, $[BC]_{travel\_standev\_meas}$ = 4.16 μgm^{-3}, $[BC]_{travel\_standev\_mod}$ = 0.73 μgm^{-3}, RMSE = 4.2 μgm^{-3}). Some well-known traffic hotspots or pedestrian zones in the city (Place Saint-Lambert, Boulevard d'Avroy, le Carré) are identified both by the measurements and the model. If we refine the analysis depending on the travel mode, both measurements and model indicate that pollutant exposure is more important for car drivers ($[BC]_{median\_meas}$ = 0.92 μgm^{-3} and $[BC]_{median\_mod}$ = 0.80 μgm^{-3}) than for pedestrians ($[BC]_{median\_meas}$ = 0.65 μgm^{-3} and $[BC]_{median\_mod}$ = 0.54 μgm^{-3}) and cyclists ($[BC]_{median\_meas}$ = 0.60 μgm^{-3} and $[BC]_{median\_mod}$ = 0.69 μgm^{-3}). In ATMO-Street, it means that pedestrians and cyclists take itineraries with surely less traffic density.

Figure 3. Black carbon outdoor concentrations measured during multimodal travels (small circles) and modelled by ATMO-Street (large circles) in May-December 2019.

Indoor model validation

BC measurements were carried out inside and outside a clothing shop in Liège on 24-25 August 2017 ($[BC]_{outdoor\_median\_meas}$ = 1.52 μgm^{-3}, $[BC]_{Room1\_median\_meas}$ = 1.12 μgm^{-3} and $[BC]_{Room2\_median\_meas}$ = 0.65 μgm^{-3}). The more frequent variations in the indoor concentrations during day time suggest that there is a greater influence of the outside concentration during the opening hours (Figure 4). Outside this period, indoor concentrations are more stable, although an overall increase in outdoor concentration (between 7 pm and midnight) leads to a delayed increase in indoor concentrations. The opening of the doors that occurs only during the opening hours seems thus to have a short-term effect on the indoor concentrations while the ventilation (working day and night) would have a more delayed impact. The simulated concentrations for Room 1 (the room with the opening doors) are quite close to the measurements ($[BC]_{Room1\_median\_mod}$ = 0.92 μgm^{-3}) even if the model tends to amplify the concentration variations during the night. For Room 2, the results are not so good; the modelled concentrations are overestimated ($[BC]_{Room2_median_mod}$ = 0.87 μgm^{-3}). If, during the opening hours, the simulated concentrations for the two rooms are different and follow rather well the trend of the measured concentrations, after the store closing, the simulated concentrations for the two rooms converge which is not the case for the measurements.

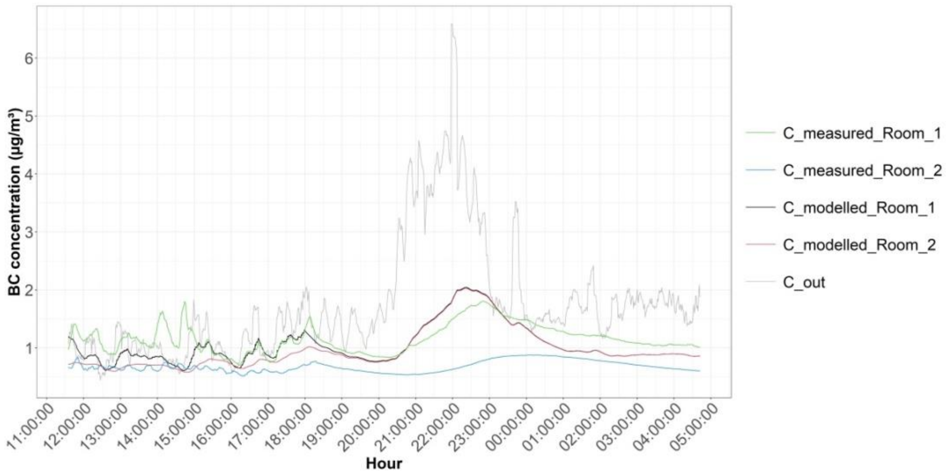

Figure 4. Measured and modelled black carbon concentrations outside and inside a store (24-25 August 2017).

The model presents better results for the store campaign than for the campaign led in the appartment. First, the modelled indoor concentrations in the apartment are less influenced by the outside concentration variations than the measured concentrations, even if we note the influence of opening the outside door on Room 1 concentrations. This suggests that, in absence of mechanical ventilation in the appartment, the model tends to underestimate the influence of the natural ventilation and infiltration. Even if, in reality, we can consider the airtightness defect insignificant compared to the mechanical ventilation, it should still influence the results. Secondly, the indoor BC sources (cooking, candles, *etc.*) more important in the appartment than in the shop are not considered in the model. Further improvements should thus include indoor sources but also deposition and atmospheric chemistry. It would also be interesting to see if the model response would be better with larger particulate matter.

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