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Uncorrelated components in noise and PM exposure give opportunities to disentangle health effects of noise and air pollution

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ABSTRACT

Traffic emits noise and air pollution simultaneously but the emission dynamics of noise and air pollution differ significantly. Even within the mixture of air pollutants, important differences occur. Gaseous emissions relate to fuel consumption while particulate matter emissions relate to incomplete combustion. The dispersion and propagation dynamics of noise, gaseous pollutants and PM differ as well. Especially the life-time and accumulation of Ultrafine particles is, due to many removal mechanisms, very short (coagulation and wind speed). The differences in the distance to source relation for different road types (with specific dynamics) influence the spatial impact of noise, gaseous components and traffic related PM (BC/UFP). Dwellings at moderate distance of highways are highly exposed to noise but relatively less exposed to BC. The highest exposure to BC is found near dwellings close to in-city roads with high traffic dynamics while night-time noise exposure is lower compared to dwellings near highways. A pilot experiment will illustrate these interesting features. A population based impact assessment estimates the size of the uncorrelated subpopulations.

1. INTRODUCTION

One of the most challenging issues in the traffic related health effects is the potential mutual confounding of the effects of noise and air pollution [1, 2]. Tétreault reviewed the existing literature in 2013 and the topic get a lot of attention in more recent publications as well [2, 3, 4, 5]. At this moment there is little scientific evidence of the confounding but most authors agree on the fact that the exposure assessments and the available epidemiological datasets are not strong enough to give conclusive evidence. The scarce set of data is also based on PM10, a pollutant that is strongly linked to traffic. Recent literature has shown that Black Carbon and UFP are expected to be better indicators for the traffic related component of the air pollution related health effects. The complexity of the particulate matter emission and exposure is extensively covered in a review by the Health Effects Institute in Boston [6]. The scientific community is also aware of the large uncertainties in the current practices of the exposure assessments [6, 7, 8, 9].

To disentangle health effects, epidemiologists require subpopulation with contrasting exposure for the investigated burdens [7]. Noise and air pollution is emitted simultaneously. At first sight it is impossible to find the subpopulations with contrasting exposures for these two burdens.

When looking more in detail, multiple dimensions of the exposure can be identified that can provide the required contrast. This will be addressed in section 2. The focus of this paper will be on only one of these dimensions: the dwelling based component of the personal exposure. Section 3 will quantify the subpopulations in each of the potentially distinctive groups of exposure for the dwelling based component. In section 4, different sets of noise and air pollution data will be mapped on the identified subpopulations and will illustrate the contrast in the exposure to noise and air pollution in the space and the time dimension.

2. MULTIPLE DIMENSIONS OF EXPOSURE TO NOISE AND AIR POLLUTION

Exposure is a complex combination of spatial and temporal factors and the correlation between noise and air pollution across these factors changes in time and space. Four dimensions can be identified. Those dimensions will be detailed further in this section.

- Personal mobility affects personal exposure
- The temporal and spatial exposure differences between noise and the divers set of air pollutants are significant
- The conversion from external to internal exposure (or dose) to in-body and organ specific impact differ for each pollutant
- In-body chemical pathways for noise and air pollution express at the same time very distinctive pathways, both with long-term and short-term effects. At the same time many of the health effects are shared and sometimes highly entangled (stress-related processes, blood pressure, inflammation, arterial stiffness etc.).

The first dimension is related to the concept of personal exposure [7]. Exposure estimates should take the differences of the time-activity patterns into account. This dimension will identify people with similar at home exposures and a strong contract related to the personal mobility of the individual. This dimension also includes an important long-term component. Many sources of air pollution related to industrial activities and power generation are eliminated or have significantly reduced their emissions since 1990. In that same time span, the personal mobility has increased dramatically [6]. The background concentrations have dropped due to the reduction of the stationary sources but the traffic related contribution has increased. More people have lower exposure at the dwelling, but more people get more exposure due increased mobility. The in-traffic exposure component of the exposure has grown in time [6].

The second dimension, the actual focus of this paper, is the contrast in exposure to noise and air pollution at the level of individual dwellings. The main differential is the differences in propagation and meteorological influences on the exposure to noise and air pollution. This combined variation in propagation and meteorological perturbations affect the noise and air pollution exposure differently. The distinctive diurnal patterns of noise and air pollution introduce relevant uncorrelated features in the exposure at the dwelling. To distinguish the second dimension from the next, the end-point of the second dimension is the dwelling, the typical result of physical exposure models.

The third dimension is the step from external exposure to internal exposure, typically referred to as ‘dose’. For air pollution, internal exposure is a combination of outdoor-indoor ratios, lung ventilation rate and in-body deposition and transitions to different organs [6, 7]. All of these processes are sensitive to the chemical and physical properties of the different components of the air pollution. In addition, ventilation rate and activity types interact. While sleeping, the ventilation rate drops, and as a consequence, the impact of the night-time exposure to TRAP is reduced [6]. For sleep disturbance, the dwelling noise insulation and quiet side effects can be viewed as 'dose corrections'. In contrast to the air pollution exposure, the night-time exposure is the dominant factor in the effects of sleep disturbance. For annoyance, the picture is even more complex: psycho-acoustic aspects, personal noise sensitivity, physical hearing quality, and context/activity dependent attention modelling will affect the stress responses significantly [12,13,14]. In summary, activity specific features are important modifiers of the internal exposure. In the specific case of noise and air pollution, the physical activity related corrections are expected to increase the exposure contrast.

The fourth dimension covers the in-body effects for noise and air pollution. The in-body biochemical processes can be split into different pathways and several authors attempted to summarize this complexity [6, 7]. In-body effects are sensitive to the targeted organs and types of health effects. This dimension will be critical in the final evaluation of the potential mutual confounding of the health effects. While all previous dimensions have the potential to disentangle the effects, the in-body processes tend to entangle the potential health effects again. Properly quantifying the first three dimensions is however a prerequisite to disentangle the in-body health effects of noise and air pollution.

The first dimension is the main focus in the PhD of Luc Dekoninck [15]. The generalized methodology presented in the PhD is primarily developed to assess the impact of personal mobility. The second dimension will be covered in the planned improvements of the spatiotemporal models. The implementation includes the step from external to internal exposure and covers the third dimension by design. These dose corrections can be assessed in the same spatiotemporal resolution of the underlying (µLUR) models (10 sec resolution for in-traffic activities). The fourth dimension can be addressed by implementing biomarker or organ specific indicators and will require close cooperation with the epidemiologists and eco-toxicologists.

3. SPATIAL INFORMATION

Different spatial parameters are required to identify the potential subpopulations. In this section, the spatial data is provided and discussed.

Dwelling based population

A dataset with address location is available from the Flemish Government (CRAB) [16]. It includes a point on each parcel with one or more dwellings and the number of dwellings on that parcel. A transition on location quality is ongoing, moving from a centroid of the parcel to the centroid of the main building on the parcel but this action is at this time not completed for the entire Flemish region. This can affect the relative position of the dwelling to the road network. A distance buffer of 50 around the roads will be applied to estimate the dwellings near the targeted road type. For each local neighbourhood, the population is known (base 2011). Each dwelling is attributed with the local neighbourhood based averaged number of inhabitants per dwelling. In the evaluations, the total population is the sum of the population in the selected dwellings.

Road network and distances

Distances to the different road type is the base spatial information. In this evaluation, the open source data OpenStreetMap is used as the underlying layer. This data is freely available in the open source community [17]. The highways are identified as "motorway" and "trunk". The motorways are the actual highways, but the trunks can be 2x2 lane roads with dense traffic as well and are included in the highway network as well. The main connectors between cities are the "primary" roads. Secondary roads connect villages. The tertiary roads are local arteries of the network. This dataset is loaded into a postgis database and the distance to four categories is calculated: HW (motorway + trunk), PRI (primary roads), SEC (secondary roads) and TER (tertiary roads). In an extended evaluation SEC and TER are combined.

Noise map

A noise map is available for the Flemish Region, calculated for the periodic assessment of the state of the environment reports [18]. Screens along highways are included, local screening by dwellings is not available at this scale. The position of the road network is very accurate (traffic data is linked with a network routing procedure to the physical road at any time.

Build-up areas

Exposure to air pollution is affected by the density of the population and traffic. A spatial layer is defined with three categories: city-like dwelling densities, village like dwelling densities and open areas.

Spatial population breakdown

The population can be split in subset matching the spatial parameters: distances to different types of roads and build-up area. For each road type, a distance classification is applied. For easy reporting, only sets of two classifications are used for the distances to the roads types. For highways and primary roads the classes are: 100, 250, 500, 1000, 2000, 6000 and 12000, for secondary and tertiary roads the classes are: 10, 25, 50, 100, 200, 500, 1000 and 12000.

The cardiovascular health effect evidence for air pollution, gathered in recent studies, is communicated on regular basis to the public. The typical announcement is that living within 500 m from a highway has significant health effects [19]. This reference distance will be used as the most relevant distance buffer to identify the subpopulations. Within that dataset, the dwellings within 50 m of the secondary and tertiary roads are identified as potential contrasting population subsets.

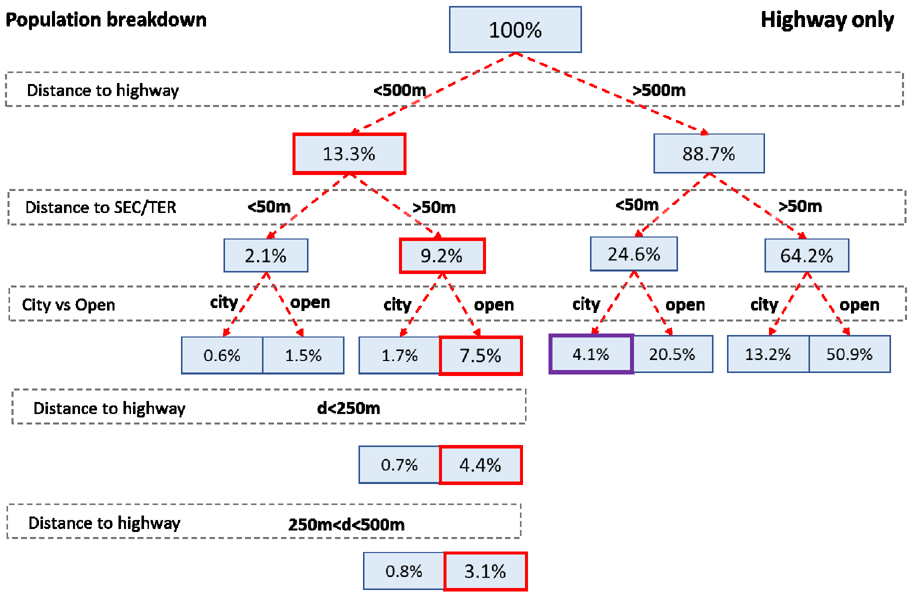

Figure 1: Spatial breakdown of the population Flanders by distance and build-up area.

In Figure 1, the population breakdown is visualized. The main focus will be on the contrast between exposure of highways and exposure along secondary and tertiary roads. 9.2% of the population lives within 500 m of a highway and further away than 50 m from secondary and tertiary roads. When restricting this population to open areas (village like build-up areas and open area) where the highway is expected to be the dominant contribution of the exposure, the group is still 7.5% of the population, 4.4% lives closer than 250 m, 3.1% between 250 and 500 m from the highway. The main contrasting group, living closely to the secondary and tertiary roads is about 24.6% of the population of which 4.1% lives inside the cities. In the next section, these subpopulations will be used to illustrate this contrast.

4. NOISE AND AIR POLLUTION DATA

Black Carbon measurements by the regional government

The regional government organized the air pollution measurements for compliance with the EU regulations (Flemish Environment Agency). Within that network a number of measurement locations also measure Black Carbon. These measurement locations will be used as the reference of TRAP in the spatial evaluation. In this evaluation, the data for the year 2015 is used. Seventeen locations are available but the majority of the measurement locations are grouped near the main air pollution sources in Flanders: the cities of Antwerp and Ghent with each their port area. These locations are classified according to the EU regulations in urban (red), urban background (orange), rural (green), industrial (purple) and traffic sites (grey). Antwerpen Linkeroever was the reference background location in the PhD of Luc Dekoninck and only available background location in 2011 [15] and Houtem is the background location without local traffic influences used in two other publications [20, 15 (section 4.7)]). The distribution of the Black Carbon concentrations, including the outliers is shown in Figure 2. The traffic and in-city locations show the highest levels. A few locations show lower concentrations than Antwerpen-Linkeroever ("aw_link").

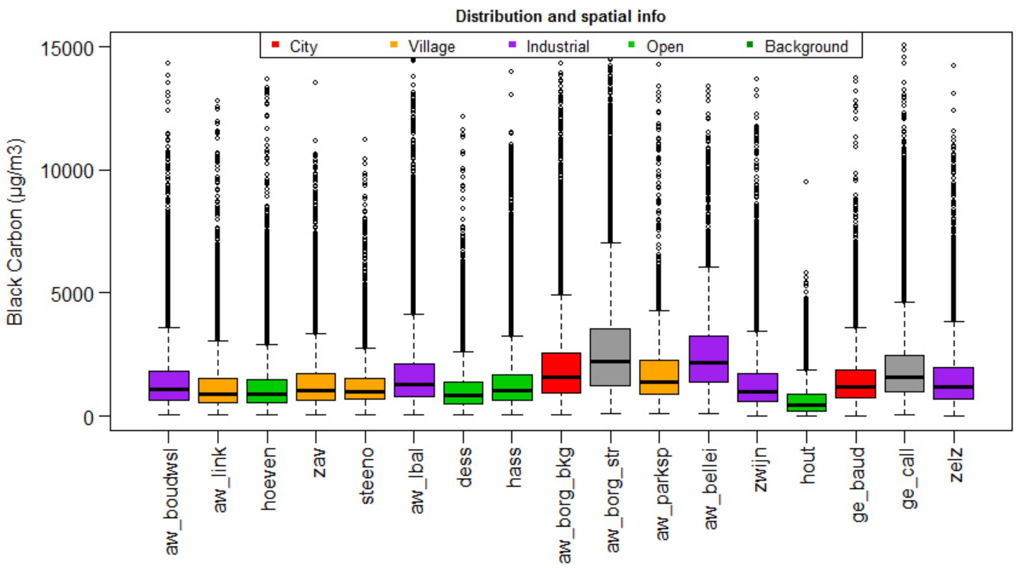

Figure 2: Black Carbon concentration distributions at 17 locations in 2015 (Flemish Institute for the environment – VMM).

In Figure 3, the distributions of Black Carbon are presented as a function of the distance to the highway (top) and to the primary roads (bottom). Only one location is closer than 300 m from the highways or primary roads. The closest measurement location is placed at a hotspot (Gent, Callierlaan) in the city of Ghent and is positioned under a highway entering the city (locally known as the 'fly-over'). This is technically speaking not a site 'near a highway' but at the crossing of multiple major roads in a city. This spatial evaluation illustrates an important gap in the spatial variation of the Black Carbon measurement sites. The current locations cannot assess the impact of the highways and primary roads.

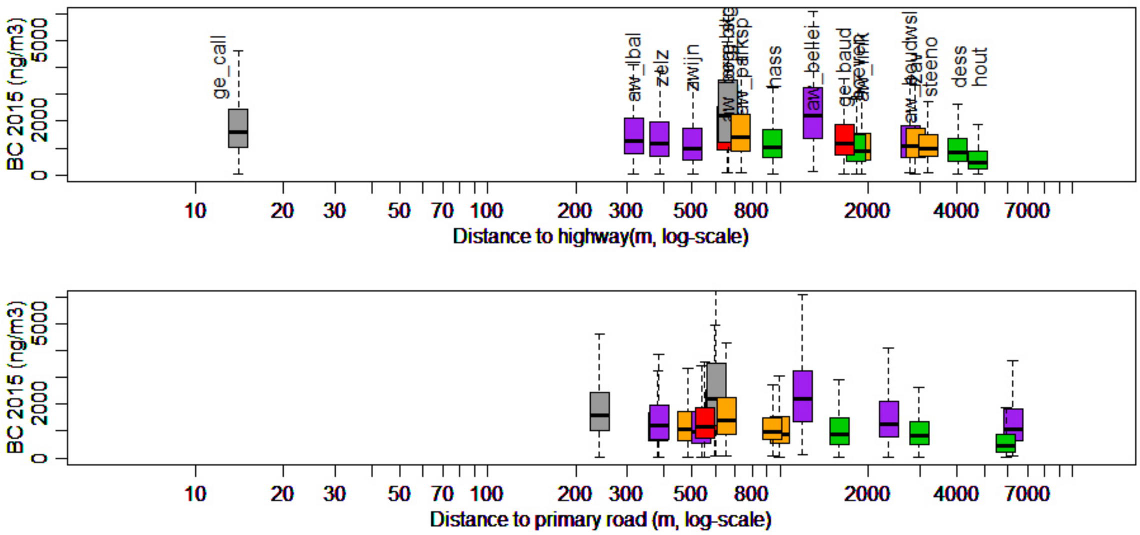

Figure 3: Black Carbon concentration distributions at 17 locations in 2015 and the distance to a highway (top) and primary road (bottom).

In Figure 4, the distributions of Black Carbon are presented in function of the distance to the secondary roads (top), tertiary roads (mid) and for the merged minimum distance to the secondary and tertiary roads (bottom). The spatial distribution of the locations is much better for these parameters. Since traffic densities of secondary and tertiary roads can be of a similar magnitude, the merged evaluation is added. In the merged distance classes, a correlation between distance and BC concentrations is clearly visible, although not all locations fit that pattern (e.g. Zelzate and Hasselt). Notice that the traffic sites are all located inside the cities.

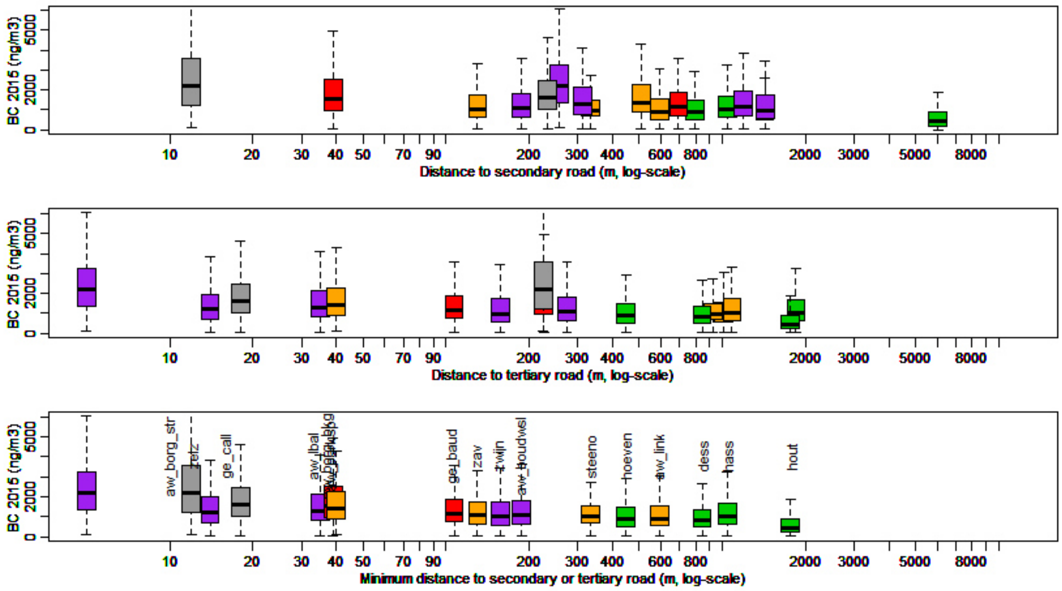

Figure 4: Black Carbon concentration distributions at 17 locations in 2015 and the distance to a secondary road (top), tertiary road (mid) and minimum distance to secondary or tertiary road..

The next step is to replace the distance to the road by the simulated noise level from the noise maps of Flemish Environmental Agency. In Figure 5, the evaluation for L_{den}, L_{day} and L_{night} is presented. A good correlation is found between noise levels and BC distributions. The location 'Zelzate' fits better compared to the distance to the road graph (Figure 4). The 'hotspot' location "Gent, Callierlaan" has the highest noise exposure, but not the highest BC exposure. The differences between the L_{den}, L_{day} and L_{night} are small.

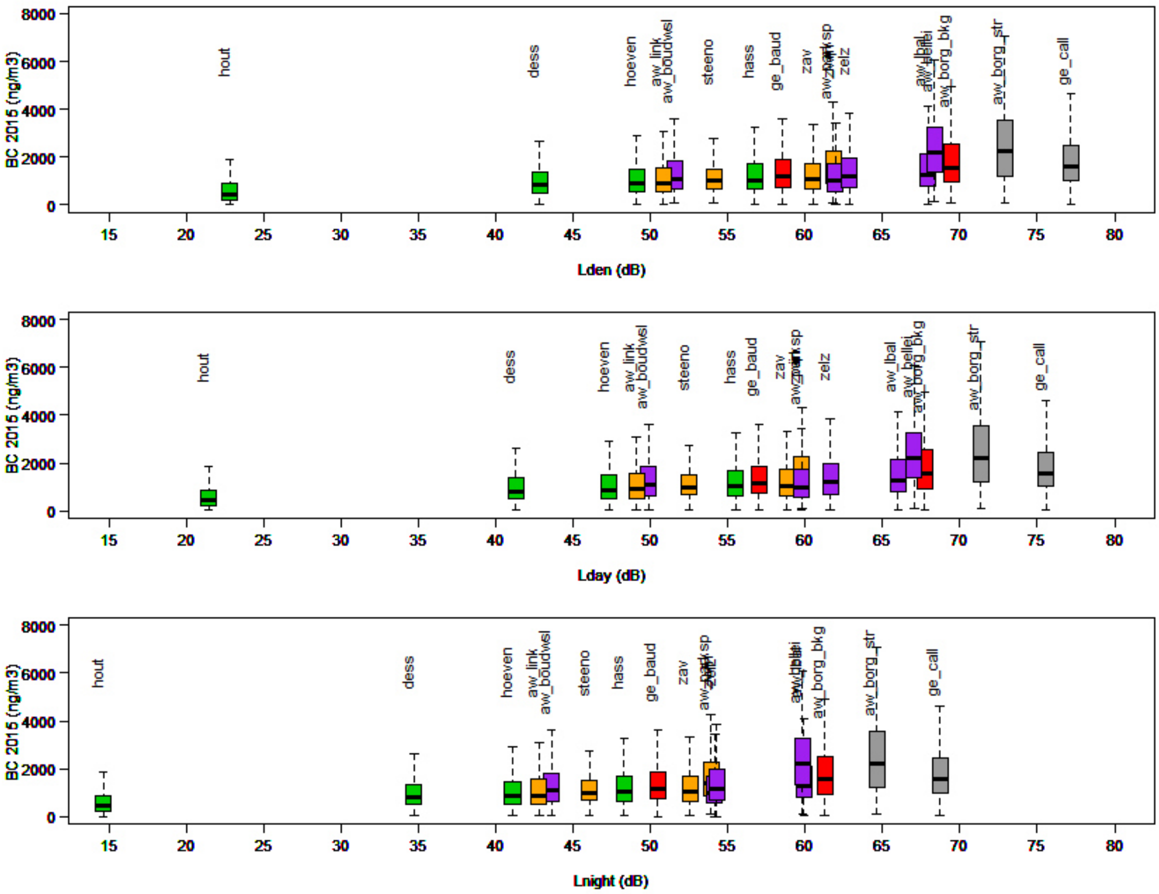

Figure 5: Black Carbon concentration distributions at 17 locations in 2015 and noise level according the noise map for 2015 (VMM).

PILOT MEASUREMENTS IN-CITY and NEAR HIGHWAY

The governmental measurement locations show important gaps in source selection and spatial selection. This is partially linked to physical restrictions. These setups cannot be placed inside narrow street canyons. Assessing the façade exposure of dwellings within a few meters from the traffic is not possible. To investigate the contrast in the BC exposure of dwellings near a highway in open area and at a typical distance of an in-city dwelling to a busy in-city road, three locations were selected to perform a test.

Table 1: Noise exposure in the three test locations.

	MP1 (Tolhuis)	MP2 (Vlaanderenstraat)	MP3 (Ooievaarsnest)
Highway noise screens	NA	Yes	No
Highway (viaduct)	NA	Height = 6m	Height = 20 m
Orientation to highway		North of highway	South of highway
Traffic (veh/h) Cars + Light + Heavy Weekdays	Day: 382+35+19 Eve: 170+6+5 Night: 72+9+6	Day: 5318+398+1483 Eve: 2937+97+1061 Night: 1483+155+615	
Speed limit	50 km/h	90 km/h	90 km/h
Local traffic	NA	Low	None (dead-end street)
Public transport	Yes	No	No

The first location is located at a dwelling façade at about 4 m from the closest lane along a tertiary road in the city of Ghent (Tolhuislaan). Six weeks of measurements were performed in the spring of 2014. A single dwelling noise-BC model based on this measurement campaign is reported in [12, 6, section 4.7]. To investigate the exposure near a highway, two measurement locations near the edge of Ghent at 300 m at each side of the highway between Jan, 23 2015 and May, 30, 2015. These simultaneous measurements were partially interrupted due to pump failure of the µ-aethalometers (life-time of the pump is about 1500 hours). Results are restricted to filter loadings below 100 ATN. Some additional relevant physical features of the pilot measurement locations are summarized in Table 1.

Black Carbon concentrations

In Figure 6, the BC distributions with valid measurements in the pilot measurement locations are shown in combination with the matching BC concentrations of five typical VMM measurement locations: two background locations (Antwerpen-Linkeroever and Houtem), one in-city background location (Gent-Baudulopark) and two roadside locations (Gent-Callierlaan and Antwerpen-Borgerhout streetside). The top row, gives the absolute concentrations, the bottom row the relative concentration with Gent-Baudulo as a reference. The relative concentration is added to adjust the evaluation to the meteorological sample of individual time series. The relative concentrations is a simple method to adjust for the different sample in meteorological conditions.

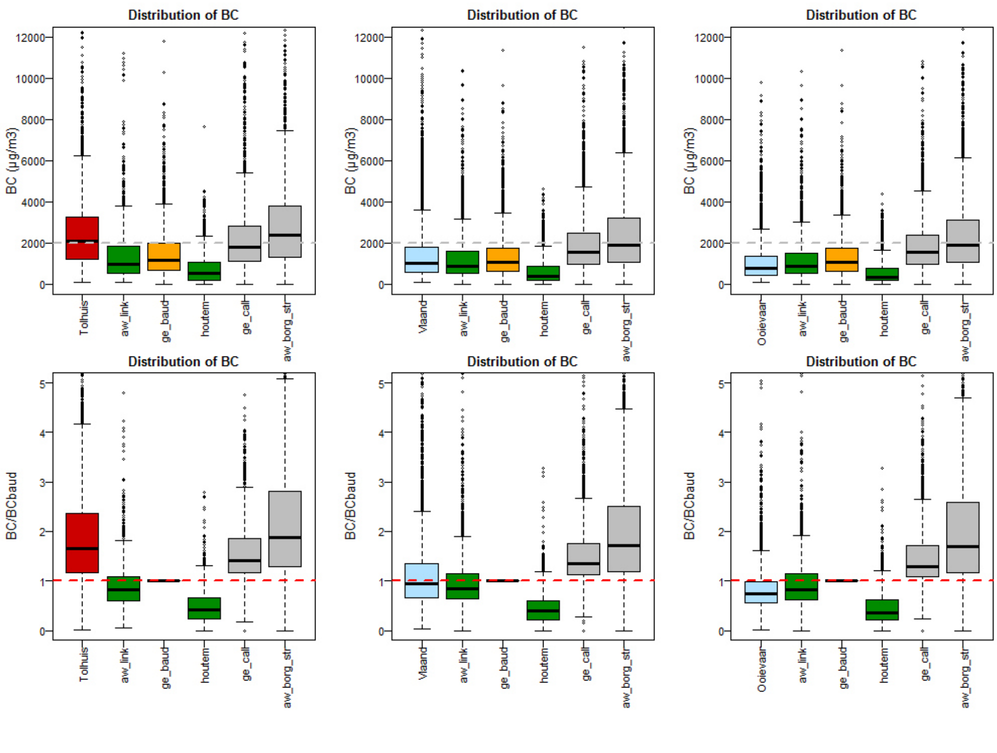

Figure 6: Comparison of the BC concentration distributions at the pilot test sites and five official measurement locations in absolute levels (top) and relative levels (bottom) (ref. Gent Baudulo in-city background).
Left column: in-city facade concentrations near tertiary road, mid and richt, two dwellings in open area at 300 m from highway (Vlaanderenstraat and Ooievaarsnest).

The in-city dwelling at 6 m from the closest lane of the tertiary road reaches similar concentrations as the hotspot traffic locations of the official monitoring network. The concentration is 90% higher compared to the in-city background location Gent Baudulo (mean) and 64% higher for the median. The dwelling Vlaanderenstraat gets similar concentrations as the in-city background location (mean +13% and median -7%). The dwelling at Ooievaarstraat is significant lower (mean -23% and median -28%). For traffic related Black Carbon exposure, the exposure of the inhabitants between 250 m and 500 m from the busiest highway in Flanders, have similar or lower exposure as the typical background exposure of all inhabitants of the city.

Noise exposure

The noise exposure of the three dwellings is summarized in Table 2. The effect of the noise screen explains the difference of 4 dB between MP2 and MP3. The difference is constant over all parameters. The noise exposure of MP1 is higher than MP2 and MP3 for all parameters except $L_{A95,15min,ngt}$ and $L_{A50,15min,ngt,}$ (after adjusting for the effect of the noise screen in MP2). The nightly background levels at the in-city dwelling MP1 are similar to the locations near the highway.

Table 2: Noise exposure in the three test locations.

		Average Noise Level							
MP	L_{DEN}	$L_{Aeq,day}$	$L_{Aeq,ngt}$	$L_{A95, day}$	$L_{A95, ngt}$	$L_{A50, day}$	$L_{A50,night}$	$L_{A05,day}$	$L_{A05,night}$
MP1 (tol)	72.7	69.0	64.0	57.1	45.6	65.7	54.8	73.3	70.0
MP2 (vla)	59.2	54.3	51.7	48.5	47.0	51.3	50.1	57.9	54.9
MP3 (ooi)	63.4	59.4	55.9	55.9	50.8	58.6	54.9	62.0	59.4

Contrasts in diurnal patterns of Noise and Black Carbon

Despite the similarities between the nightly noise levels in the three pilot measurement locations, the temporal characteristics are quit different (see Figure 7). The diurnal pattern of Black Carbon is strongest in MP1 (Tolhuis) and matches the typical traffic pattern. For MP2 and MP3, the diurnal pattern of the Q1, median and Q3 is not strongly expressed. In the outliers, two phenomena are visible: selected episodes with high exposure at night and and selected peak levels during rush hour. The highest exposure episodes are predominantly linked to stable meteorological conditions and peak emissions are only detected under similar conditions.

For L_{Aeq}, MP1 illustrates a very constant diurnal pattern, while for MP2 and MP3 the distributions are wider. This is a meteorological effect linked to the wind direction. The main distinctive feature between MP1 and the highway locations is the difference between day and night. The traffic dynamics at MP1 is much stronger, while the highway locations suffer from a virtual constant noise level. This difference in the soundscape is visualised in the L_{A05} minus L_{A50} parameter.

Uncorrelated exposures

Based on the BC concentrations, MP2 and MP3 would fit in Figure 5 in the range of VMM locations Dessel and Gent-Baudulo, matching the L_{DEN} range of 35 and 58 dBA. For MP2, the noise and BC exposure match due to the presence of the noise screen. For MP3, the BC and noise are not correlated. In practice, the correlation in MP2 would also fail if the noise screen would not be in place. Detailed information also revealed the influence of local traffic on the BC concentrations at MP2. Two blocks away from MP2, a bus line ends. The low traffic crossing at 8 m from the measurement location is used to manoeuvre the busses into the reverse direction. This information became available after the measurement campaign. It illustrates the sensitivity of exposure assessments. Unforeseen local features of the measurements locations can disturb the evaluations. The local features support the conclusion that noise and air pollution exposure do not correlate as expected.

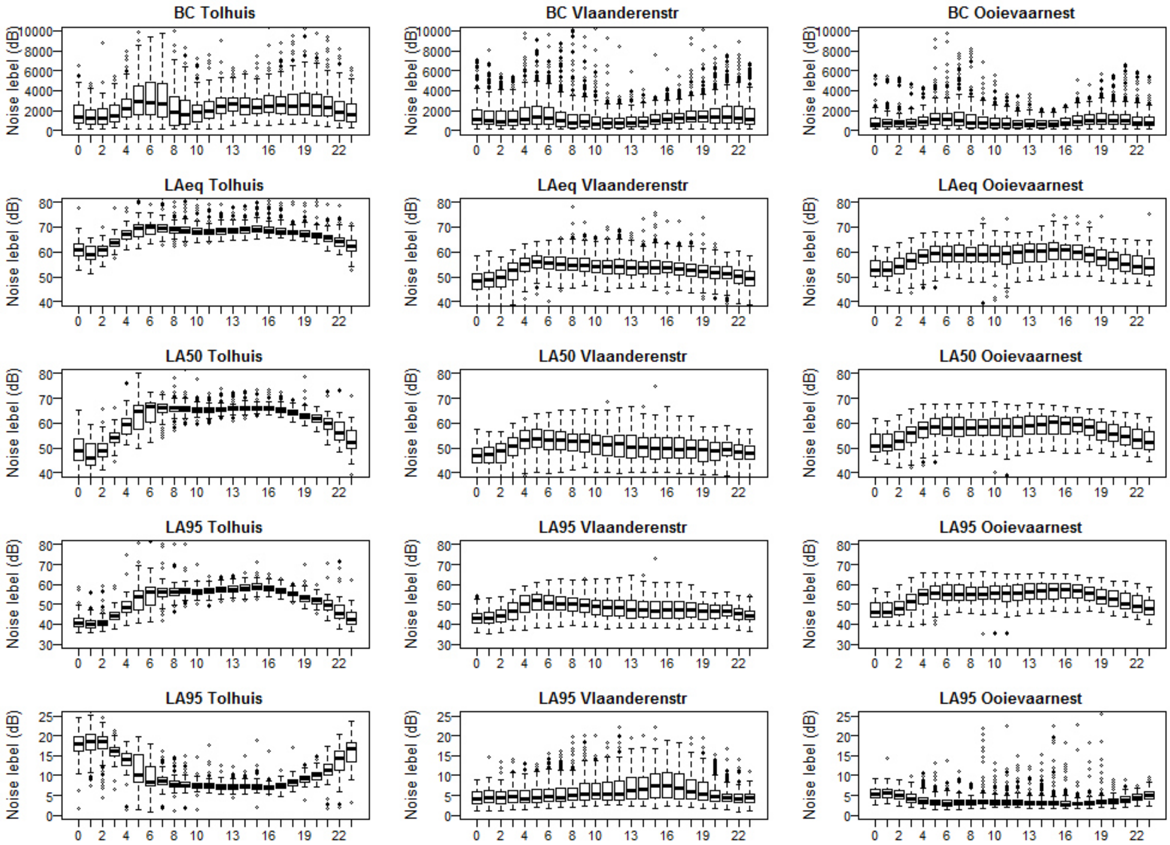

Figure 7: Diurnal patterns of Black Carbon and a selection of noise parameters in the three pilot measurement locations ($L_{Aeq,\ 15min}$, $L_{A50,\ 15min}$, $L_{A95,\ 15min}$ and $L_{A10,15min}$ minus $L_{A50,\ 15min}$)..

DISCUSSION

Particulate matter is a complex mixture of particle sizes and emission sources.PM10 and PM2.5 are not traffic specific and other measures (Black Carbon and UFP) are proposed as better indicators for traffic related exposure [6]. The spatial variability has been assessed in many occasions, but in the monitoring networks, the number of sites measuring Black Carbon and UFP are not as large as for PM10 and PM2.5. In the current situation in Flanders, few of the measurement locations assess the impact of highways without disturbances of the other road types or other influences (industrial or pollution accumulation inside cities). Additional data has to be gathered to identify spatial situation where the correlation between noise and air pollution is valid or invalid. In previous work, the lack of correlation between L_{Aeq} and Black Carbon has been illustrated extensively [21, 22, 23]. In the instantaneous exposure model for of bicyclists it is shown that the engine noise related component is correlating much better with the BC exposure than the overall noise level. This was in itself already a strong indication for the lack of spatial correlation between noise and PM. The dominant local contribution results from peak exposure when biking in dynamic traffic near the exhaust plume, an effect requires spatial resolution of meters to reach accurate exposure assessments [21]. This distance to source effect is even stronger for UFP and was documented in [22].

Instantaneous models also disentangle the local traffic dynamics and provide stable meteorological adjustments for long-term exposure estimates [21, 23]. These techniques require extension to fixed locations (dwellings). These new insights triggered the pilot measurement campaign and the results behave as expected. Dynamic traffic at close distance results in the highest BC levels. BC exposure near highways is relatively low due to a combined effect of free flow traffic and meteorological conditions.

The temporal difference in the noise parameters for the pilot measurement locations also illustrates the necessity to improve the noise indicators. L_{DEN} is clearly not sensitive enough to explain the local variation or diurnal patterns of the noise exposure but this is out of the scope of this paper.

The near highway pilot measurements (300 m) are not identified as high exposed dwellings for Black Carbon. Similar population sizes inside cities and near main local connecting roads have twice the exposures to BC compared to the near highway sites. On top of this, the MP2 is partially influenced by local traffic (including short exposures to manoeuvring diesel busses). Additional assessments are required at dwelling closer to the highways and without noise screen or other disturbing features (like viaducts and speed limits). Effects of the noise screen and viaduct on the Black Carbon exposure are possible.

Two subpopulations of a similar size (3-4%) are identified with similar L_{night}, but distinct Black Carbon exposure: 250-500 m from the highway in open area and less than 50 m from an in city busy connecting road. Within the population breakdown, several groups require similar improvements in exposure assessments for both noise and air pollution.

CONCLUSION

The correlation between noise and traffic related air pollution is not absolute. The main features that trigger the lack of correlation are the non-linear speed and acceleration driven PM emission. On highways, the noise emission is mainly driven by rolling noise, while PM emission is mainly engine regime driven. Dwellings close to highly dynamics traffic flows can be higher exposed than near highway dwellings. The diurnal pattern of the noise emission is also highly distinctive. The noise related health effects for these distinctive exposure situations are unknown at this moment. Improvements of the exposure assessments and the matching health indicators are necessary in both disciplines. Simultaneous measurements are a prerequisite to solve the issue of potential mutual confounding of air and noise pollution.

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