Estimated fine particulate matter exposure reduction potential for urban population using state of the art building envelopes and ventilation systems: example, Helsinki, Finland

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ABSTRACT
The current analysis is based on the microenvironment concentration data collected from Helsinki in the *EXPOLIS* study. The present measured population exposure distribution has been modelled with great accuracy using a validated Monte Carlo simulation framework. Using this same simulation framework we simulate an alternative scenario, where we replace (A) the *EXPOLIS* measured outdoor–indoor penetration distribution which represents the total building stock in Helsinki with (B) the *EXPOLIS* monitored outdoor–indoor penetration distribution from the most modern fraction of the measured building stock. The analysis is done separately for (a) the exposure to $PM_{2.5}$ of ambient origin (which is assumed to be the most harmful for health), and for (b) the exposure to total $PM_{2.5}$ including fine PM from indoor sources.

The results show that the exposure reduction potential using building technology is considerable and probably larger than can be achieved by, e.g. transports policies or other local emission controls.

INDEX TERMS
Air infiltration; Exposure assessment; Modelling; $PM_{2.5}$; Ventilation

INTRODUCTION
Epidemiologists have estimated fine particulate matter ($PM_{2.5}$) exposures to cause hundreds of thousands excess deaths in the developed world (e.g. Pope *et al.*, 2002). These findings are based on ambient air measurements. Although many studies have shown that personal exposures are different from ambient or fixed station concentrations (e.g. Pellizzari *et al.*, 1999; Koistinen *et al.*, 2001) and that indoor sources have remarkable contributions to personal exposures (e.g. Clayton *et al.*, 1993; Wallace, 1996), the health effects found to reflect changes in the ambient PM levels must be caused by either those levels or some other factor associated with them. Additional personal exposures caused by individual behaviour or independent indoor sources cannot explain these findings.

The large numbers of people affected makes the problem severe. Selecting efficient air quality management options requires generation and comparison of scenarios to reduce population exposures to particles. It is commonly known that people in Western societies spend most of their time in indoor environments (e.g. Clayton *et al.*, 1993). The building envelope removes some of the fine particles from the air entering indoors and in mechanical ventilation systems also efficient filters can be added to remove, especially, particulate matter.

The present study uses the microenvironment concentration data collected in the *EXPOLIS* study in 1996–1997 in Helsinki, Finland. Hänninen and Jantunen (2003) analysed the effective penetration factors from the *EXPOLIS*-Helsinki data using elemental analyses of the filters. The collection of the filter data has been described by Jantunen *et al.* (1998) and Koistinen *et al.* (1999) and the ED-XRF-analysis by Mathys *et al.* (2001). Hänninen and Jantunen (2003) used the sulfur concentrations measured residential outdoors and indoors to

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estimate the effective penetration factor for sulfur containing particles. Sulfur data was available for 98 homes and 86 workplaces. These sulphur-based penetration factors were then scaled for the different size distribution of total $PM_{2.5}$ particles. The population average I/O ratio was calculated as the regression slope for residential indoor and outdoor $PM_{2.5}$ concentrations and the scaling coefficient was calculated as the ratio of average sulfur penetration to this $PM_{2.5}$ slope. The results showed that the effective penetrations in homes were slightly higher (0.64 ± 0.18) than in workplaces (0.46 ± 0.23).

Hänninen and Jantunen (2003) also presented a simulation technique to model exposures of ambient origin and of indoor origin. The simulation model was validated by comparing the simulated population exposure distributions to the observed ones for both non-ETS (environmental tobacco smoke) exposed sub-population and the whole population. The model is based on microenvironment approach (e.g. Duan, 1982; Letz *et al.*, 1984; Ryan *et al.*, 1986) and probabilistic simulation (e.g. Ott *et al.*, 1988l; Law *et al.*, 1997). The model is implemented in an Excel (Microsoft, WA) based environment using @Risk add-on software by Palisade (Newfield, NY) (Kruize *et al.*, 2003). Hänninen *et al.* (2003) compared simulation results to observed exposures in pure microenvironment mode (i.e. without using the effective penetration approach).

The current work uses the simulation model to simulate population exposure distribution for Helsinki in a hypothetical scenario, in which all the home and workplace buildings would have been replaced with buildings with ventilation and penetration characteristics of the newest buildings in the study; these buildings were built in 1990–1997.

MATERIAL AND METHODS

Personal exposures and microenvironment concentrations at homes and workplaces were measured for 201 subjects in Helsinki in the *EXPOLIS* study during a 1-year period in 1996–1997. Kruize *et al.* (2003) developed a probabilistic simulation model based on microenvironment approach to model population exposures. The current work uses the *EXPOLIS* data and the simulation model to compare population exposures to $PM_{2.5}$ in two scenarios: (a) the current building stock in Helsinki, and (b) hypothetical building stock, which would have the ventilation and effective $PM_{2.5}$ penetration characteristics of the newest office buildings in Helsinki during the *EXPOLIS* study.

The current exposure scenario was taken directly from the previous work by Hänninen and Jantunen (2003). Three models were reported for the non-ETS exposed adult sub population and one for the whole adult population. Because the current work is focused on the reduction of exposures to ambient pollution using effective air filtration techniques, only non-ETS models were considered. All three models compared similarly to the observed exposures. Model #2 used hourly ambient concentration distribution as its input and estimated the highest exposure percentiles slightly better than the two other models. Therefore, it was selected to represent the population exposures in the current building stock scenario.

I/O penetration data from the newest workplace buildings were selected for the alternative scenario. The *EXPOLIS*-Helsinki database (Hänninen *et al.*, 2002) contained nine buildings with sulfur penetration data, which were built in the year 1990 or later. The effective $PM_{2.5}$ penetration factors of these buildings (0.35 ± 0.12) were then used for all homes and workplaces in the alternative scenario. Exposures from indoor sources and exposures while outdoors or in transport are not affected by the alternative scenario.

Time activities of the working and non-working sub populations are modelled separately. The simulations include four microenvironments: (i) home indoor, (ii) work indoor (working sub- population only), (iii) traffic and (iv) all other environments grouped together.

Four simulation models were run; for both scenarios the model was run for total $PM_{2.5}$ exposures (including exposures from indoor sources) and for ambient originating exposures only (excluding indoor sources). The models are summarized in Table 1.

Table 1 Summary of simulation models 1–4

Model	Description
0	Observed personal exposures (excluding ETS)
1	Current, with indoor sources
2	Current, exposures of ambient origin only
3	Alternative, with indoor sources
4	Alternative, exposures of ambient origin only

RESULTS

The average simulated population $PM_{2.5}$ exposure levels are listed in Table 2. The total exposure level (excluding ETS exposures) is reduced from 9.2 µg m^{-3} in the current situation down to 7.3 µg m^{-3} in the Building Stock '90-scenario, totalling 22% reduction in the average population exposure level. When looking at the fraction of the exposures of ambient origin only, the current exposure level 6.6 µg m^{-3} goes down to 4.7 µg m^{-3}, a 29% exposure reduction compared to the current level.

Table 2 Summary of simulation results

Modeled exposures	Current Building Stock µg m^{-3}	Building Stock '90 µg m^{-3}	Exposure Reduction %
Ambient	6.6 ± 4.6	4.7 ± 3.3	29
Ambient+Indoor sources	9.2 ± 5.2	7.3 ± 4.0	22

Figure 1 displays the simulated exposure distributions together with observed $PM_{2.5}$ exposures in the *EXPOLIS* study. It can be seen that the exposure reduction affects all percentiles as should be expected. The absolute reduction of total exposures is equal to reduction in ambient particles, but relatively the latter reduction is higher.

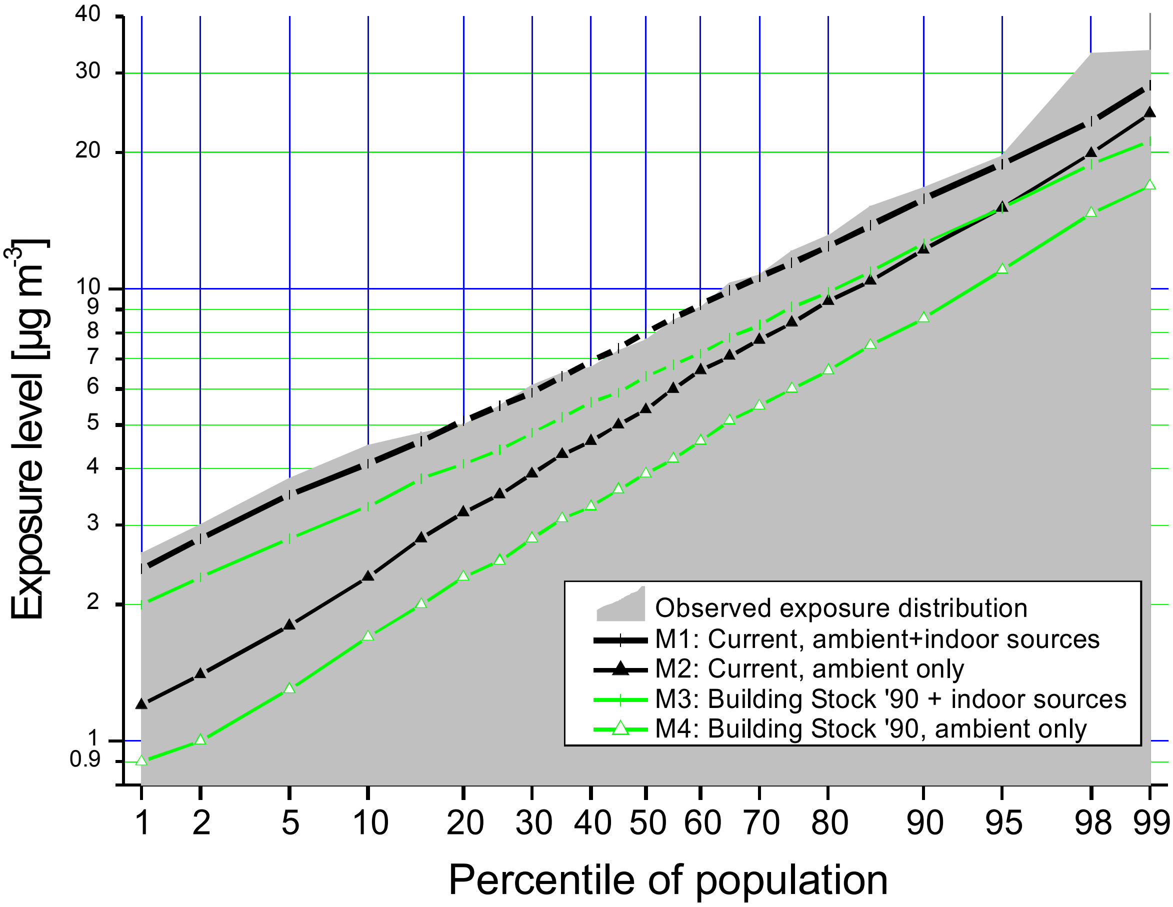

Figure 1 Simulation results for the 48-h $PM_{2.5}$ exposures within the urban population in the current situation and the hypothetical building stock situation. In both scenarios, the exposures have been modelled separately from ambient sources only and including general indoor sources. Validation data (observed population exposures in current situation) in grey.

DISCUSSION

Enhancing building filtration of particles reduces exposures of practically all population members and it does not require any behavioural changes. The populations considered susceptible to health damage caused by particles, newborns and the elderly, spend more of their time indoors and less in traffic compared to active-age general population. Thus, the filtration enhancement would benefit especially susceptible individuals.

Renewing of the building stock of a whole city is extremely expensive and it can be done only gradually along the natural re-construction process. On the other hand, people concerned of air pollution can take this into account and seek their way to live in buildings with good filtration systems. But for them to be able to make right choices, the information on the filtration properties of houses should be available. Several studies have also shown that the ventilation systems themselves can become sources of pollution (e.g. Pasanen *et al.*, 1994); thus it is important to monitor the ventilation system condition.

Enhanced filtration affects all particles of ambient origin. Enhancements of city transportation system, changing local traffic emissions and population time activity, affect mainly exposures to local traffic particles. It has been estimated that in Helsinki the primary local traffic particles contribute approximately 10–20% to the total $PM_{2.5}$ exposures (Koistinen *et al.*, 2003). Compared to the exposure reduction potential estimated in the current work, the tailpipe $PM_{2.5}$ emissions from local traffic would have to be totally eliminated to obtain similar reductions in the total $PM_{2.5}$ exposures. Battery or fuel cell operated vehicles might fulfil even such a fabulous scenario in the decades to come, but even then exposures to soil particles (re-suspended mostly by vehicles) and to industry and energy production generated long-range particles would not be affected. In contrast, filtration by building envelope and in ventilation systems affects all ambient particles from local and regional sources as well as long-range transport.

CONCLUSION AND IMPLICATIONS

Engineering buildings and their ventilation systems in a way that minimizes the penetration of fine particles indoors is probably the most effective way to reduce population exposures. Advantages of filtration by ventilation systems compared to other exposure reduction alternatives include:

- The whole population can be affected, but the reduction can be especially targeted to susceptible sub populations.
- Exposures to all particle fractions of ambient origin are reduced.
- Making building filtration properties known available, people can select their houses according to their concern to air pollution.

The public health benefit potential can be tens of thousands saved lives per year in the Europe and North America, in both of which the number of annual deaths has been estimated to be tens of thousands.

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