

Particulate matter reduction in Eindhoven



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High traffic intensities in cities are a cause of high particulate matter (PM) concentrations due to tailpipe emissions and tire and brake wear. The objective of this study, is to assess whether PM removal in parking garages by implementation of electrostatic precipitation, can reduce PM concentrations in the wider urban surrounding.

Keywords: Air quality; Air pollution; Fine dust; Particulate matter; Computational fluid dynamics (CFD); Electrostatic precipitation; Positive ionization; Urban physics.

The effects of particulate matter exposure

The collection of all solid and liquid particles suspended in the atmosphere, known as particulate matter (PM), is currently one of the most dangerous forms of air pollution. According to the World Health Organization

(WHO), daily and long-term exposure to PM is strongly related to human morbidity and mortality [1]. Health effects are closely related to the size of the inhaled particles [1]; large particles can be filtered by the nose and throat, however, particles smaller than 10 μm (PM_{10}) can enter the bronchi and lungs. Particles smaller than 0.1 μm

(PM_{0.1}) can directly be transported into the bloodstream [1]. Many studies have linked PM exposure to lung cancer, respiratory, cardiovascular and cardiopulmonary diseases (e.g. [2-3]) (an extensive overview of references is given in the paper by Blocken et al. [3]). Furthermore, links with Alzheimer, Parkinson, dementia, multiple sclerosis and stroke incidences are found (e.g. [2-4]). Groups with pre-existing lung or heart diseases, elderly people and children are especially vulnerable [2]. PM exposure affects lung development of children; i.e. lung functioning is impaired and lung growth rate is chronically reduced [5]. According to the Organization for Economic Cooperation and Development (OECD), air pollution will become the world's top environmental cause of premature mortality by 2050 when no measures are taken [6]. According to the European Environment Agency (EEA), the world-wide number of premature deaths due to PM exposure, as presented in **Figure 1**, will climb from approximately 1.5 million today, to 3.5 million in 2050 [7]. Given that good health and a long life are highly valued in society, analysis shows that economic costs of air pollution are significant [8].

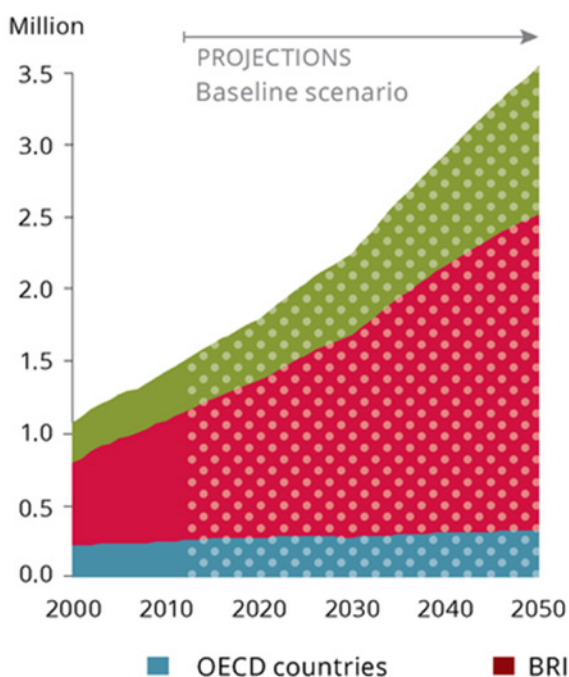
Air pollution in the city

The WHO provides limits for the annual mean PM concentrations. i.e. for PM₁₀ the annual mean is set at 20 µg/m³ and the 24 hour mean is set at 50 µg/m³

[9]. For PM_{2.5} these values are set at 10 and 25 µg/m³ respectively [9]. Worldwide, more than 80% of the people that live in urban areas are exposed to air quality levels that exceed the WHO limits [10]. While in Asia all the global cities fail to meet the 10 µg/m³ PM_{2.5} limit, in Europe few are able to pass (e.g. Helsinki, Edinburgh and Stockholm) [10]. In a global context, ambient PM_{2.5} concentrations in European cities seem relatively low. For example, when considering PM_{2.5} concentrations, annual mean concentrations in Paris are exceeded by a factor 1.8 while in Delhi this is a factor 12.2 [10]. Although the WHO limits are defined strictly, it is important to keep in mind that epidemiological studies were unable to define a specific threshold for which PM concentrations have no effect on human health [2]. It is expected that there is a very wide range in susceptibility; some individuals might be at risk when exposed to very low concentrations [2].

High ambient concentrations of PM are found in regions with high traffic intensity, including urban areas, due to tailpipe emissions and tire and brake wear [11]. Other studies showed that PM is accumulated in parking garages [12–13]. In the surroundings of parking garages the ambient PM concentrations are highly dependent on parameters such as traffic intensity, meteorological conditions and urban geometry.

World premature deaths from exposure to particulate matter



Megacities of 2025



World premature deaths due to ozone pollution

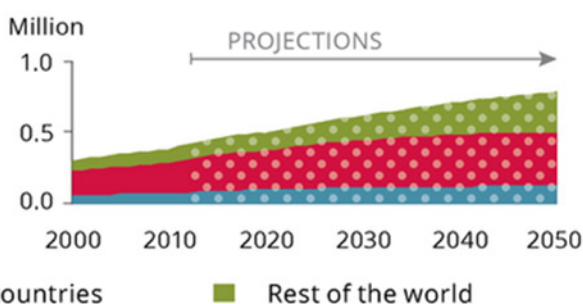


Figure 1. Projected premature deaths due to PM and ground-level ozone [7].

Exposure to high ambient PM concentrations does not only occur outside, in streets where the traffic intensity is high, but also in buildings due to ventilation. Since people roughly spend 85–90% of their time indoors [14], PM exposure is certainly a very serious problem, putting health at risk.

Air purification in garages

Various solutions are available to limit ambient PM concentrations, such as porous media filters, cyclonic separators, wet scrubbers and electrostatic precipitators (ESP). ENS Technology [15], a manufacturer of ESPs based on a positive ionization technology, applied two of their ESP units in a parking garage in Cuijk (the Netherlands). The technology captures fine particles and ultrafine particles without the use of traditional filtering techniques. In the ESP, particles are bound together, forming coarse dust that cannot be inhaled (since it is not airborne). One of the advantages of this system is that most of the energy penalty, associated with the pressure drop across media filters (traditional technique), is eliminated. Furthermore, it is found that the applied systems do not add to the normal background ozone level, unlike several other ESP-based technologies. In Cuijk it is found that PM₁₀ concentrations are strongly reduced in the parking garage, but also in the shopping mall connected to the garage [16]. This leads to the idea of large-scale application of ESP units in parking garages, which would thus function as ‘lungs of the city’.

CFD model Eindhoven city center

A computational fluid dynamics (CFD) case study is conducted for the city center of Eindhoven (the Netherlands), including ESP units in 16 parking garages. Eindhoven is located in the south of the Netherlands and it is the fifth largest city of the Netherlands with 225,020 inhabitants [17]. The city center of Eindhoven is characterized by a mixture of low-rise and a few high-rise buildings, both commercial and residential, with open areas such as roads, parks and squares. The generated computational grid consisting out of 65.7 million cells, as presented in **Figure 2**, covers an area of about 5.1 km².

To determine sources of PM₁₀ in the model, traffic intensity, traffic emission data, parking garage use and background PM₁₀ concentrations are considered. Terrain roughness is taken into account by assigning the correct aerodynamic roughness height (y_0), equivalent sand-grain roughness height (k_s) and roughness constant (C_s) to the wall surfaces. Simulations are performed for a reference wind speed (U_{ref}) of 1 m/s at 10 m height and a south-east wind direction. The southeast wind direction is chosen because ambient concentrations in Eindhoven are generally higher for this wind direction [18]. Thermal effects are not taken into account.

ESP units are implemented in the garages by means of a PM₁₀ sink term. The units run at a volume flow rate of 9,000 m³/h and a PM₁₀ removal efficiency of 70%

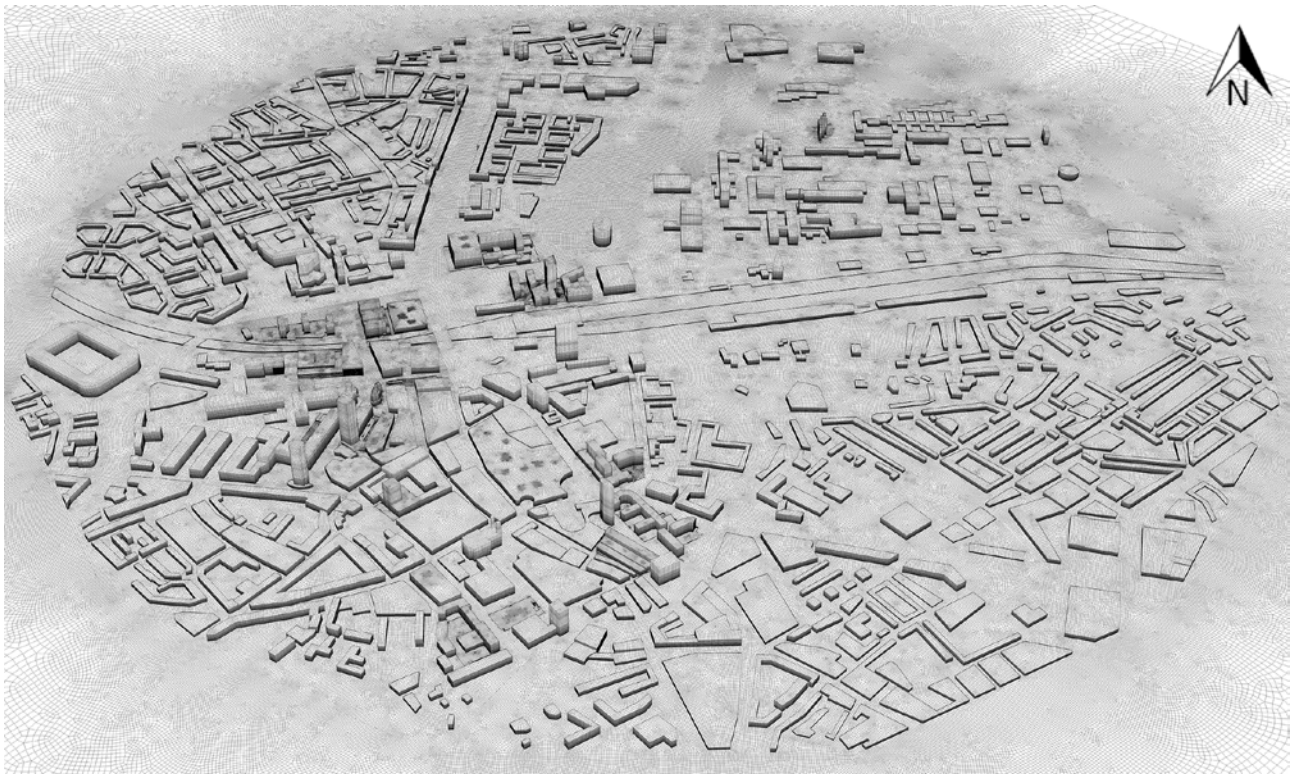


Figure 2. Overview of the computational grid of the city center of Eindhoven (65.7 million cells) [3].

[16]. Three different cases are modeled: a reference case without ESP units, a case including 99 units (one unit per 65 parking spots) and a case including 594 units (six units per 65 parking spots) spread over the 16 parking garages. Garage ventilation is imposed based on the Dutch building regulations ($10.8 \text{ m}^3/\text{m}^2\text{h}$).

In this study, the steady Reynolds-averaged Navier-Stokes (RANS) approach is used in combination with the realizable k- ϵ turbulence model [19] for turbulence closure. A sub-configuration validation study is conducted using wind tunnel measurements of gas dispersion in regular arrays of rectangular building blocks by Garbero et al. [20]. The reader is referred to Blocken et al. [3] for more information on this validation study.

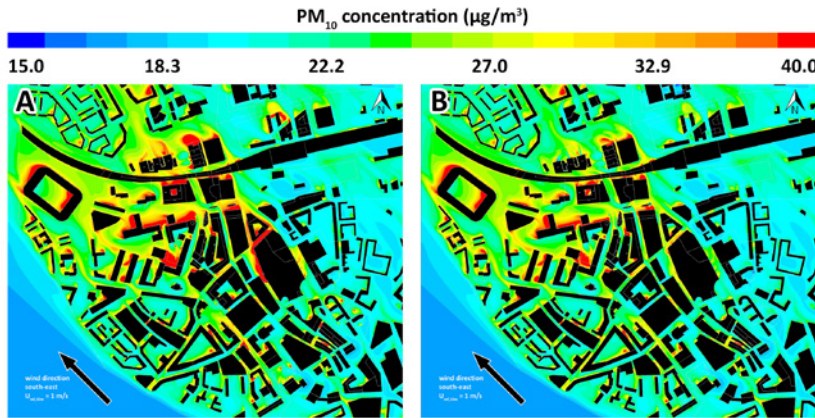


Figure 3. Contours of PM_{10} concentrations ($\mu\text{g}/\text{m}^3$) in a horizontal plane at 1.75 m height without units (a) and including 594 units (b) installed over 16 parking garages in the city center of Eindhoven. Wind direction South-East $U_{\text{ref},10\text{m}} = 1 \text{ m/s}$.

Case study results

Figure 3 presents the PM_{10} concentration contours at a height of 1.75 m (pedestrian level) for the reference case without ESP units (**Figure 3a**) and for the case including 594 ESP units (**Figure 3b**). Results are presented for the region where most of the parking garages are located and where the urban density is relatively high. The concentrations exceed $60 \mu\text{g}/\text{m}^3$ but in this case the maximum concentration shown is limited to $40 \mu\text{g}/\text{m}^3$ for visualization purposes.

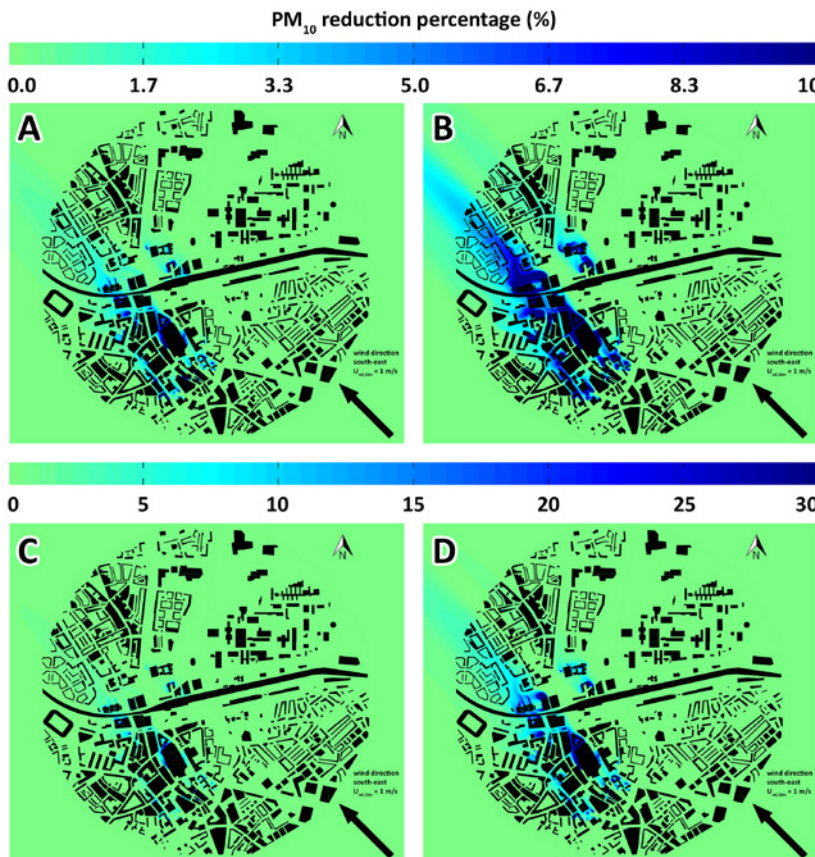


Figure 4. Contours of PM_{10} concentration reduction percentage at a height of 1.75 m for the case with 99 units (a, c) and 594 units (b, d) relative to the reference case without units. Wind direction South-East $U_{\text{ref},10\text{m}} = 1 \text{ m/s}$. [3]

Figure 3 shows that relatively high PM_{10} concentrations are found near the exhaust openings of the parking garages ($> 40 \mu\text{g}/\text{m}^3$). High PM_{10} concentrations are found in the area with a high concentration of parking garages. Furthermore, in this area the urban density is relatively high compared to the rest of the city, resulting in relatively low wind velocities. **Figure 3** shows that PM_{10} concentrations are significantly reduced near the garages and in the exhaust flow from the garage. This is also shown in **Figure 4** where the PM_{10} concentration is compared with the reference case. **Figure 4a, c** presents the PM_{10} reduction percentage for the case including 99 ESP units and **Figure 4b, d** presents the PM_{10} reduction for the case including 594 ESP units. For the case with 99 ESP units, reductions of up to 10% are found near the garage. However, further away from the garages the reductions are insignificant. For the case with 594 ESP units, reductions of up to 30% are found near the garages (locally even up to 50%). Further away from the garages reductions of up to 10% are found.

Discussion and conclusion

Although the study has some limitations, it can be concluded that local removal of PM in parking garages can be an effective strategy towards higher outdoor air quality. As previously mentioned, studies have shown that PM exposure is strongly related to human morbidity and mortality. For this reason the presented work could be very interesting for cities in which problems related to PM exposure are severe (e.g. where the urban density is high). Further research will focus on the limitations of the current study. First of all, the maximum PM₁₀ concentrations in the current simulations are rather limited (< 80 µg/m³). This is due to the fact that all the emissions are uniformly

distributed over the subdomains (instead of assigning them to the exact locations of streets) and the emissions are averaged over a period of 10 hours. It can be expected that during rush hours local concentrations are higher. For this reason unequal spreading, both in time and space, of traffic and thus of PM emissions will be taken into account. In addition, thermal effects can be included in future studies. In this way, the dispersion of emissions can be taken into account in a more accurate way and different meteorological situations can be analyzed. While the current research work and suggestions will certainly not solve the PM city problem completely, at least it can be a significant step in the right direction. ■

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