A NOVEL APPROACH FOR THE MODELLING OF AIR QUALITY DYNAMICS IN UNDERGROUND RAILWAY STATIONS

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ABSTRACT
Indoor air quality in subterranean train stations is a concern in many places around the globe. However, because of the specificity of each case, numerous parameters of the problem remain unknown, such as the braking disc particle emission rate, the ventilation rate of the station or the complete particle size distribution of the emitted particles. In this study the problem of modelling PM10 concentration evolution is hence addressed with a particle-mass conservation model which parameters are fitted using a genetic algorithm. The parameters of the model allow to reproduce the dynamics and amplitude of the measured data and comply with realistic bounds in terms of emissions, deposition and ventilation rate.
Keywords: conservation model, identification, PM10, underground air quality

1 INTRODUCTION

Indoor air quality in subterranean railway station is an increasing concern of public health. Numerous measurement campaigns and numerical comparisons have been undertaken worldwide, e.g. Strak et al. [1] in the Netherlands, Ma et al. [2] in Japan, Park et al. [3] in Korea or Gomez et al. [4] in Mexico City, as they help to understand the mechanisms that create such indoor/outdoor pollutions, with the aim to reduce them. However, these studies mainly measure the pollution levels and provide design or operation recommendations, without a quantitative analysis of the link between train traffic and particulate matter concentration.

The clear weekly pattern of PM10 concentration in subterranean railway stations and the similar behaviour of particle concentration evolution and train movement frequency observed in Gustafsson et al. [5], as well as in the measurement data exhibited in Fig. 1, led us to investigate the modelling of this relationship.

The difficulty of this enterprise resides in the unknowns around the two key phenomena:

– the source of particles divided in direct emission by abrasion and resuspension of deposited particles, and
– the dilution mechanism, which in underground stations strongly depends on the piston effect as well as comfort ventilation. The piston effect is indeed responsible for sporadic, violent drafts in the tunnels and complex, sometimes counterintuitive, air flows on the platforms, with generated dynamic pressures reaching about a thousand pascal upon arrival in the station [6] and air velocities of about 1/5th of the train velocity [7].

Different sources have shown that iron is the dominant element in underground stations [8], or the review by Qia et al. [9] in which mass concentration in iron is superior by one order of magnitude to all other elements for eight suburban stations over the globe. Determining a value for the direct emission term, i.e. how many particles are emitted by the components of the trains that are subject to abrasion (braking system, wheels, pantograph and catenary), can be achieved by exploiting the maintenance's wear data. In the underground context, resuspension is more complicated to evaluate independently of direct emission, especially without

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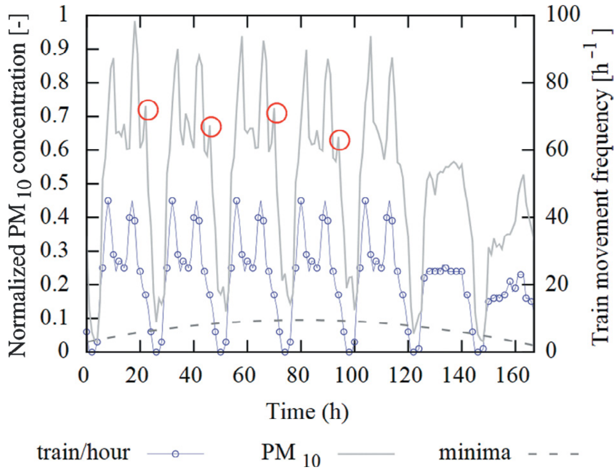

Figure 1: Comparison between PM10 concentrations and train traffic – Saint-Michel station (average 2005 data).

using a tracer such as in [10]. However, an attempt was undertaken by Fortain [11] for a Parisian subterranean station.

As for the ventilation phenomenon, it appears that it is strongly influenced by wind pressure, air transfer between tunnels and the piston effect. The latter has been studied by Kim et al. [12], whose approach allows for an estimation of the amount of ventilation due to train movement. Piston effect is, however, largely driven by the pressure drop between the underground and the exterior environment, which depends on the geometry of the stations. An attempt at classification of the stations relating to geometry and air quality was led by Moreno et al. [13] for Barcelona's underground.

Airborne particle dynamics are also influenced by the particle size distribution. A difference of one order of magnitude between the particles diameter may result in more than two orders of magnitude discrepancy of deposition rates [14, 15]. For the underground context, large particles above 2.5 μm represent about 70% of the mass concentration [11, 16, 17].

Based on these elements, it appears that the modelling options are limited in the subterranean railway environment. CFD is impeded by the lack of information about particle size and distribution as well as the orders of magnitude of the key phenomena such as resuspension and deposition. It is also unclear where the resuspension occurs, although Moreno et al. [13] have observed that the extremities of platforms exhibit higher PM concentration levels in comparison with the centre. The current computing capacity is also a drawback as it reduces the computable duration of particle dispersion to a narrow span that does not allow for the sizing of air quality equipment (for instance, ventilation or filtration), which rely on the daily values of concentration.

Given the previous observations, this study is an attempt at coarse modelling of the PM10 dynamics in underground stations using the approach suggested by Nazaroff [14], based on the well-mixed volume hypothesis, with an adaptation to the subterranean railway context. Recently, Song et al. [18] led a similar study aiming at the prediction of CO_2 concentration in the platform and concourse of a station, linking the measurements of CO_2 concentration in the tunnel and an estimation of the train-induced wind after measurements per Kim et al. [12].

It seems, however, that no study couples the analysis of train traffic and PM10 distribution, as underlined by Pan et al. [19]. The originality of this work hence relies in the relation of the

PM10 concentration with piston effect, particle emission and resuspension with train movements. An ordinary differential equation with variable coefficients describes the phenomena. The few parameters of the equation are identified versus available measurement data.

2 MEASUREMENT DATA

The experimental data in this work originates from two main sources:

- The 2005 air quality measurement campaign by the French national railway company 'SNCF' in three of Paris subterranean stations, namely Saint-Michel Notre-Dame, Gare du Nord and La Défense. The data presented here show the weekly pattern averaged over a year of measurements. The data coming from TEOM devices were recorded over a year.
- Measurements from Arlanda C station in Stockholm [5] averaged over two weeks.

2.1 Underground air measurements

Despite the numerous unknowns of the underground context, the measurement data in Fig. 1 exhibit a strong correlation between train movement frequency and PM10 concentration: from Monday to Friday the daily concentration has a similar shape and decreases during weekend, as does the train movement frequency (see also Fig. 3 for Gare du Nord as well as the study by Gustafsson et al. [5] for a station in Sweden).

Additional information may be read from the data: for instance, the overnight peaks circled in red in Fig. 1 stand for the emission of a diesel engine train passing through the station for overnight work that occurred during the year of the measurement.

The concentration decrease starting from the end of service also allows for an estimation of the natural ventilation rate.

2.2 Outdoor air data

Interestingly, the daily minima on a yearly average are not dependent on the theoretical train traffic and exhibit a bell-shaped behaviour (see dotted line in Fig. 1). The same phenomenon can be observed in the measurement campaign done by [11]; however, to the best of the authors' knowledge, this feature has not been described previously, and

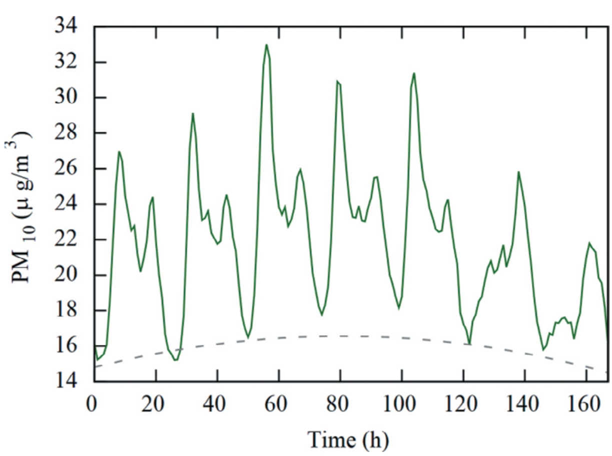

Figure 2: PM10 concentration on the average week (2005 – Paris 1st arrondissement).

is related to the exterior PM10 concentration: on the average Friday early morning, the minimum PM10 is smaller than the previous morning, whereas the train traffic has the same intensity.

The average week of outdoor air PM10 concentration at a nearby station for the year corresponding to the measurements was obtained from the air quality open database AIRPARIF [20] at the station of Paris-Centre (1st district). On the 2005 average week, one can see by the dotted line in Fig. 2 that the PM10 concentration minima also exhibit a bell-curve behaviour. These values are nevertheless lower than the minima of the concentration values for station Saint-Michel plotted Fig. 1.

3 PROPOSED MODELLING

Most of the particle matter evolution studies use a 'two compartment model' that includes both the airborne particles and the particles deposited on the floor. For a stringent closure of the model, the differential equation quantifying the deposition and resuspension rate on surfaces in the station would be necessary, such as in Qian et al. [10] and Nazaroff et al. [21]. As estimating the quantity of particles deposited on surfaces appeared uncertain, surfaces are supposed to be saturated with particles and hence a 'one compartment' model is used, based on the airborne PM10 conservation. Due to the perfect mixing hypothesis, spatial effects described in [13], for instance, cannot be observed. Coagulation or agglomeration as well as thermal effects on particles is also ignored.

3.1 Explanation of the model

The box-model proposed in the next paragraphs relies on a concentration balance in the spirit of Nazaroff [14] publication and considers only three main phenomena:

- The emission of particles is modelled with an 'apparent emission' term α that includes emission by friction (brakes, catenary, etc.) and particle resuspension due to train movement.
- Ventilation is composed of the natural ventilation rate τ_0 and of the train-induced ventilation β.
- Deposition δ is chosen in the range given in [14] for the settling of PM_{10} in the specific subterranean station environment.

C being the concentration in PM10, the mass balance is expressed as follows:

$$\frac{dC(t)}{dt} = \alpha N^2(t) - \tau\left(C(t) - C_{ext}\right) - \delta C(t) \tag{1}$$

This ordinary differential equation is solved numerically with a semi-implicit Crank-Nicholson second-order scheme using a time step of 60 seconds. The initial condition is the measured initial concentration. All terms of the equation are explained in the following paragraphs.

In the box-model approach, we consider that the average velocity in the station is proportional to train movement. The kinetic energy being proportional to the square of velocity, the mass of resuspended particles increases with the square of train frequency, as suggested in Martins et al. [22]. The emission term is then proportional to the apparent emission

α [μg/m3] and to the square of train movement N(t) [1/h] such that the apparent source of particles is $\alpha \times N^2(t)$.

The ventilation rate $\tau(t)$ in air changes per hour [1/h] is composed of a base rate τ_0 plus the piston effect–driven ventilation term $\beta \times N$:

$$\tau(t) = \tau_0 + \beta N(t), \tag{2}$$

β [–] is the ratio of volume of air that is moved by train circulation divided by the station's air volume. In the cases presented in this study, the geometry of the station and the complex interconnections with other tunnels at different depths make it hard to have an *a priori* a value of the piston effect per train. Nevertheless, an order of magnitude of $\beta \sim 1$ can be derived from [12] for a station volume of about 10,000 m^3. A similar order of magnitude is obtained from the analytical derivation by [23].

In still environments, the order of magnitude of the deposition rate:

$$\delta C(t), \tag{3}$$

is dependent on the particle diameter, which defines the underlying physical phenomena (Brownian diffusion, turbulent diffusion or gravitational deposition). Analytical derivations of this parameter can be found in [24, 25]. The deposition rates in the domestic context were determined experimentally in [26]. As underground stations are subject to important air velocities, a correction for the increase of deposition related to turbulent flows should hence be implemented in the spirit of [27]. This increase is mostly noticeable for very fine particles, and does not affect large ones significantly. In this first approach δ_a, δ_b will hence be bounded between 0.035 and 7 [1/h] as found in [14].

Other physical phenomena occurring in polydisperse aerosol are neglected, e.g. particle size changes by condensation and coagulation as in [25, 28] or thermal effects.

4 IDENTIFICATION RESULTS AND DISCUSSION

Prior to the optimization procedure, the natural ventilation rate has to be estimated using the concentration decrease overnight, which provides the base ventilation rate τ_0 [vol/h]. This preliminary calculation also takes into account the deposition phenomena and allows for the identification of the correct order of magnitude of natural ventilation. After this step, the identification procedure is launched over parameters α, β, δ and τ_0.

The model was tested against data sets of three of Paris underground railway stations. Fitting the parameters to the measurement was not straightforward, and three different methods were tested:

- The *Levenberg–Marquardt* algorithm [29] proved to be the fastest but is also very dependent on initial conditions and sometimes gave unphysical results (negative values of piston ventilation).
- A least squares method was much slower and in many cases the algorithm did not converge.
- The method giving the best results in terms of computational time and diversity of the minima proved to be a genetic algorithm [30], available in the Scilab software.

The identification procedure for Gare du Nord and Saint-Michel stations gave a correct representation of the phenomenon, as presented in Fig. 3.

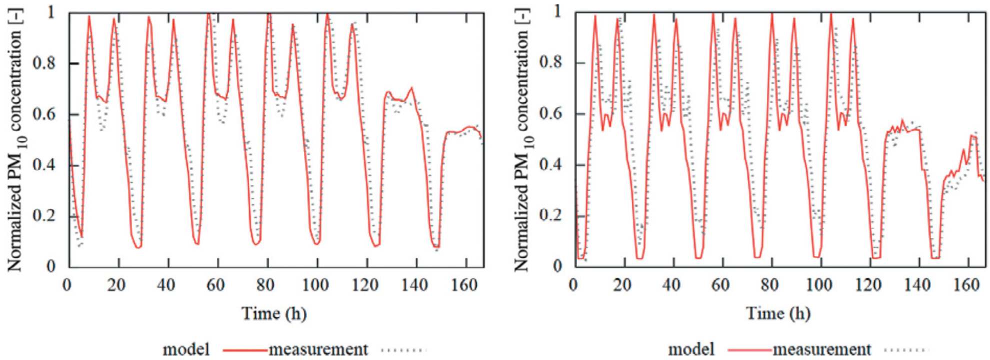

Figure 3: Comparison between model and measurements for Gare du Nord (left) and Saint-Michel (right).

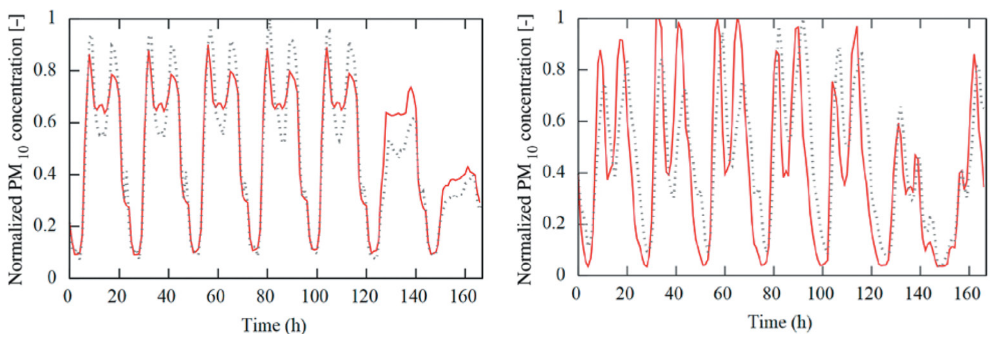

Figure 4: Comparison between model and measurements for La Défense (left) and Arlanda C (right).

The dynamics and amplitude of PM concentration related to train traffic are respected in both cases; however, for Saint-Michel the discrepancy is slightly higher, which is probably due to the overnight work, as explained in Section 2.1.

For stations La Défense and Arlanda C, the results are shown in Fig. 4.

Although the dynamics are respected, the model performs noticeably less accurately for station La Défense, which we believe is due to the geometry of the station: its much larger volume makes the perfect mixing hypothesis irrelevant and makes our representation of the piston effect less effective. Regarding station Arlanda C, the model seems to be 'ahead' of measurements. This is most likely due to fine particles having a longer deposition time, which means that considering only coarse particles is insufficient.

A summary of the identified parameters are summarized in Fig. 5.

The simulation results are in good accordance with the measurements in terms of amplitude and dynamics, with corresponding parameters that fit realistic orders of magnitude of deposition, ventilation. The outcome of this study is also an 'apparent emission' term α that mimics the direct emission and the resuspension phenomena.

Parameter	La Défense	Saint-Michel	Gare du Nord	Arlanda C
α (µg/m^3/train)	1.77	7.47	3.7	24.2
β (m^3/m^3)	0.46	0.75	1.3	0.52
τ_0 (ach/h)	0.24	0.29	0.17	0.14
δ (1/h)	0.45	0.15	0.20	0.12
Aver. error (µg/m^3)	1.56	3.09	1.60	4.10

Figure 5: Summary of the identified parameters for the four stations.

5 CONCLUSION

In this article, a novel approach for the estimation of the PM10 concentration dynamics in underground train station is presented. This method is space- and time-averaged; hence, it does not provide an access to the concentration spatial distribution and requires concentration measurements prior to being used. However, it gives a reasonably simple way to estimate the level of particle concentration originating from train circulation and the level of ventilation or filtration that would be required to reduce air pollution. The particle size distribution function was unfortunately not available, which impeded the modelling of a multi-component aerosol. This modelling would have allowed simulating the difference in dynamics between fine-mode particles (below 2.5 µm) and coarse ones (above 2.5 µm).

6 PERSPECTIVES

It has been shown that the model is tractable to different underground railway stations, which support our idea that the number of fitting parameters is sufficient for this type of train stations. We believe it can be used to generate multiple scenarios with different ventilation rates, and provide engineers with a way to quantify the corresponding air quality increase, given that a new measurement campaign – after implementation of a solution – can attest the validity of our hypotheses and model.

However, the model is still dependent on the identification of the parameters: the source term and the dilution (especially the piston effect) having antagonist effects, one can find several sets of parameters with different orders of magnitude that provide a correct fit on the measured data. A measurement campaign of the piston effect in Saint-Michel's station is to be done at the beginning of 2017 to give the correct order of magnitude of this parameter.

Translating the principle of Nazaroff et al. [31] to the underground environment, an improvement of the model would be to model the behaviour of concentration in the station as a multi-component aerosol. A measurement campaign started in two Paris underground stations with commitment of data's public availability should make this possible in a short-term future.

Although the model seems to be able to represent the dynamics and amplitude of the train-related PM concentration, it fails to catch the overnight low concentration. Indeed the nightly minima over the average week (see Fig. 2) exhibit a bell curve that the model does not manage to reproduce. We suppose that this is linked to the slower deposition rate of fine-mode particles (PM < 2.5 μm). An attempt in this direction is under progress.

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