PARTICLE CONCENTRATION LEVELS IN A SUBWAY STATION - THE EFFECTS OF VARIOUS LOCATIONS AND DIAMETERS OF RELIEF SHAFTS IN TUNNELS

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ABSTRACT

In this article, we investigate how ventilation shaft diameter and placement in a subway tunnel can influence the concentration of particulate matter (PM) in stations. The trains' rolling and braking systems have been considered the particles' source. The stations have two large escalators, and their doors are open. The airflow in the studied systems is driven exclusively by the piston effect of the moving trains. The IDA Tunnel version 2 software package has been utilized for the simulations.

The results indicate significant fluctuations in PM levels on subway platforms. The average PM concentration on a platform associated with single-track tunnels is almost 5 percent lower than on a platform connected to double-track tunnels, considering similar headway and relief shaft geometry. In the case of single-track tunnels, the shaft location plays a less critical role, while the impact of shaft diameter is more pronounced. For double-track tunnels, the shaft location becomes more crucial. A single relief shaft placed near the stations primarily increases the PM level on the platform, making a shaft location at the tunnel center preferable. The variation in PM levels on the platform for single- and double-track tunnels is approximately 13 percent across shaft locations and cross-sectional areas.

Keywords: Tunnel ventilation- Particulate matter- Subway station, Relief shaft

1. INTRODUCTION

Poor air quality has become a major issue of modern life. In Europe today, air pollution poses a higher health risk than tobacco smoking. Problems with air quality in subway systems have received minimal attention for many years. However, recent studies indicate poor air quality inside these systems, with higher PM concentrations than in the streets above them. The generation and distribution of hazardous particles inside the subway system can severely affect the health of vulnerable groups such as children or older people. Subway particles can be eight times more genotoxic and four times more likely to cause oxidative stress in the lung cells than particles in a busy urban street [1].

Raut et al., 2009 reported that PM10 and PM2.5 concentrations in subway stations in Paris were 5–30 times higher than the outdoor air [2]. Johansson and Johansson's measurements at an underground station in Stockholm revealed that concentrations of PM10 and PM2.5 were 5 and 10 times higher, respectively, than levels observed in one of the busiest streets in central Stockholm [3]. Martins et al. (2015) demonstrated that average PM2.5 concentrations in a subway station in Barcelona exceed those in the surrounding outdoor air [4]. Tu et al. investigated the impact of train type on airborne particle concentrations by analyzing field measurements from six underground metro platforms in Stockholm between 2016 and 2020 [5]. The predominant element in subway particles is iron [6], with brake pads, catenary systems, and abrasion of rail tracks and wheels identified as the primary sources [7]. Three distinct particle size categories exist, with a peak diameter of approximately 100 nm for ultra-fine particles, 0.35 µm for fine particles, and 3–6 µm for coarse particles [8]. In a study closely related to the present paper, Qu et al. (2022) conducted recent field measurements in two stations with Platform Screen Doors (PSDs) from two different subway lines and four air shafts in their connecting tunnels in China [9]. They assessed the effective ventilation and particulate matter discharge efficiency of these air shafts.

Most prior numerical studies have focused on assessing the impact of ventilation systems on thermal comfort and smoke removal. The flow field within a subway system is inherently complex, influenced by both the movement of trains (piston effect) and, if present, the ventilation system [10]. There are very few 3D numerical simulations specifically examining particle transport within subway stations induced by the piston effect. Izadi et al. (2021) investigated the wear particle dispersion due to the train piston effect representing the first 3D numerical investigation into particle distribution due to train braking within a subway system [11]. Another recent study explored the influence of ventilation systems, both with and without under-platform exhaust, on the concentration of braking micro-particles within the subway system [12]. Despite the detailed 3D Computational Fluid Dynamics (CFD) simulations providing valuable information, their coverage is constrained to a specific time interval, typically representing a train's movement between two stations. This limitation stems from the considerable computational cost and time associated with 3D CFD simulations of train motion using dynamic mesh techniques. As previously mentioned, PM measurements within subway stations in Sweden and globally underscore the significance of this issue, rendering it a major concern. Consequently, reducing particle concentrations has become a crucial objective in the design of recently developed subway lines in Sweden. To address this concern and enable the study of particle concentration over a realistic time duration in a subway line, this article employs a 1D numerical simulation. Using the IDA Tunnel version 2 software package, the study investigates how the diameter and placement of ventilation shafts in a tunnel impact PM concentration in stations. Both typical types of single and double-track tunnels have been studied.

2. SIMULATION MODEL

2.1. Model description

Two single- and double-track tunnel models (Figures 1 and 2) are developed and studied here. Both consist of four 40-meter-deep stations with platforms measuring 145 m x 15 m x 5 m. Each platform includes two symmetrical escalators (70 m length, 15 m² cross-section) to the ground level, with open doors. The tunnels are 2 km in both models. The double-track model comprises five tunnels (40 m² cross-section), connecting stations and the portals at the ground level. The single-track model includes ten 2 km tunnels with a 25 m² cross-section. In both models, each tunnel is equipped with a relief shaft. The shafts have a height of 40 meters. The cross-sectional area of all shafts is 10 m². These shafts are positioned at the tunnel center, except for the tunnels between the second and third stations, where a parametric study introduces variations. In this section, the placement of the shaft shifts from a short distance to the neighboring stations (15 m) to the center of the tunnel. The cross-sectional area of the shaft changes, ranging from 5 to 20 m².

2.2. Boundary conditions and train data

Mass, momentum, energy, and particle mass conservation equations have been solved by the IDA Tunnel version 2 software package [13]. Standard atmospheric pressure and the ambient temperature of 10°C were assumed for portals and all shafts' grills. The train's relevant parameters include a length of 140 m, a front area of 9 m², a perimeter of the front area at 13 m, a nose drag coefficient of 0.5, and a skin friction coefficient of 0.012 aligning closely with the geometrical data of the C20 train. The total mass of the train, including occupants, is 306 tons. The particle source is the train's rolling and braking systems. The mass flow rate of the emitted particles from the train to the tunnel and platform depends on the train velocity, braking, and traction force. Two coefficients, k_b and k_r (g/kWh) play a crucial role in determining the quantity of released particles, and they can be calibrated individually for each metro line. In this study, the values $k_b = 0.234$ g/kWh and $k_r = 0.378$ g/kWh were assumed to achieve an almost equal share of particle concentration on the platform to see the effects of particles released from both braking and rolling systems. The particles corresponding to braking are released only during effective braking. The train headway in each route is 5 minutes, but stochastic delays were introduced to train departures to disrupt perfect adherence to timetables. The maximum velocity of the train in the tunnels is 72 km/h, with acceleration and deceleration rates of 1 and -1 m/s², respectively. The number of trains passage per hour is 24 on both routes.

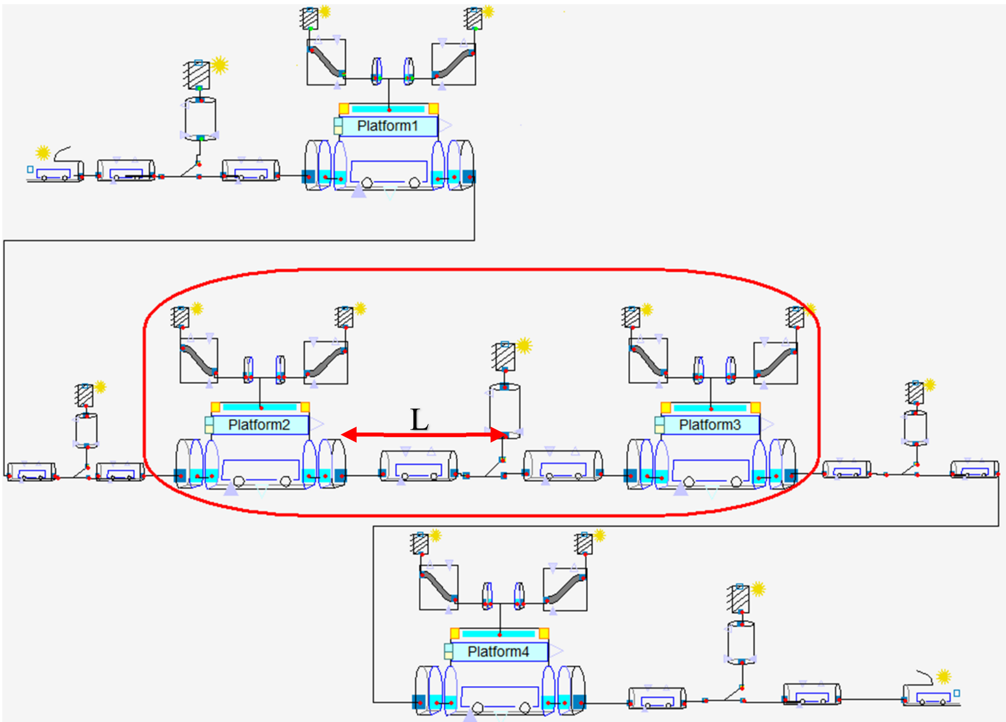

Figure 1: Model for simple metro line with double track tunnels

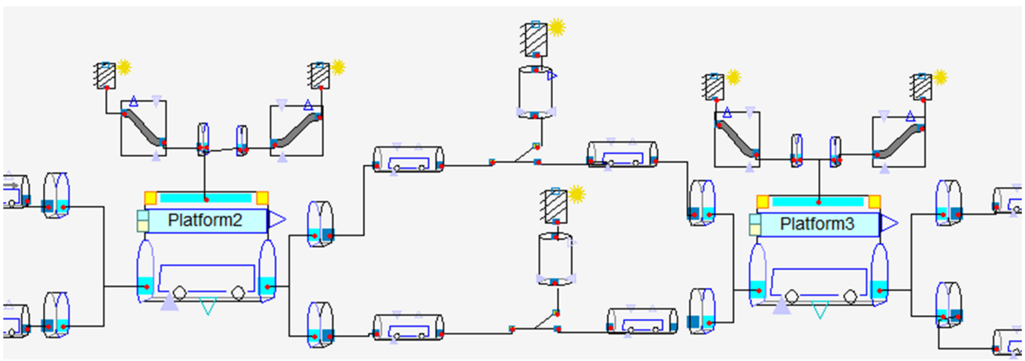

Figure 2: Model for simple metro line with single-track tunnels
(Only the second and third stations with connecting tunnels are shown)

3. RESULTS

Due to the stochastic nature of train departures and the varying airflow caused by the train piston effect at the platform, particle concentrations fluctuate significantly on the platforms. Fig.3 shows a sample of the results for the platform in station 3 for the double-track tunnel model. The simulation is performed for 6 hours. Since the simulation commences with zero concentration in the tunnels and stations, it takes nearly two hours to reach a stationary condition in the platform PM level. The graph also displays a moving average with a time scale of one hour. The average PM level for the final four hours of the simulation is calculated and serves as the basis for comparing the different scenarios studied. Testing revealed that extending the time duration did not significantly alter the statistical average and the trend of the results.

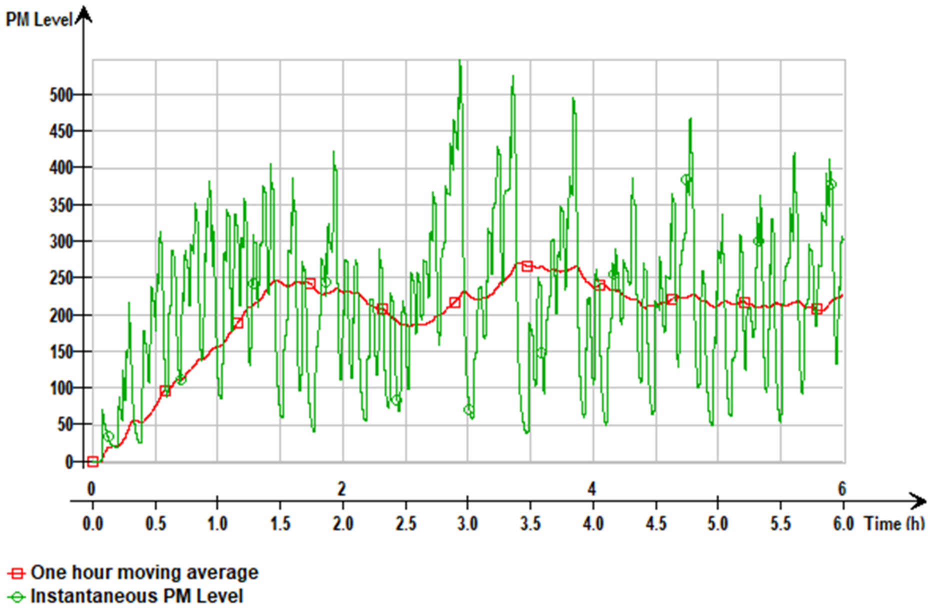

Figure 3: A sample of variation of PM level in the platform for one of the studied cases

The parametric run module of IDA Tunnel 2 is used to study the effects of shaft placement and diameter on the level of particle concentration in the platforms. In this module, the range of the parameters and the number of data points in each range are defined, and the software package performs the simulation for all cases defined in this parametric study.

The shaft cross-sectional area has been varied within the 5-20 m² range. Furthermore, the shaft placement shifts from 15 meters from the train departure side of the stations to an equivalent distance on the train arrival side of the next station. Changes in the shaft cross-sectional area and placement necessitate adjustments in corresponding parameters, like shaft diameter or tunnel segment length, which are executed using IDA Tunnel2's graphical script feature.

In presenting the results, the focus has been on the platforms of stations 2 and 3, as well as the relief shafts in connecting tunnels (Figures 1 and 2). While a particular shaft location may reduce the particulate matter (PM) level on one platform, it may increase it at the neighboring station; thus, this study compares the average PM levels at these two stations across various scenarios.

The presentation and discussion of results begin with the double-track tunnel model. The data in Table 1 have been arranged in ascending order from the minimum to the maximum PM level on the platforms. Table 1 provides a detailed breakdown of exhaust and intake air through the relief shaft, along with the PM mass entering and exiting the shaft, and the PM mass exhausted from the station escalators.

Generally, a shaft farther from the adjacent stations correlates with a lower platform PM level. The results highlight that shaft placement significantly influences PM levels, outweighing the impact of shaft size. Even with the smallest studied cross-sectional area of the shaft (5 m²), a low particle level is achieved when it is positioned at the tunnel center. In this scenario, the particle level is only 3 percent higher than when the shaft size is 20 m². Conversely, a shaft close to the station can elevate the particle level by more than 13 percent compared to the central shaft position. Interestingly, increasing the shaft's cross-sectional area can further elevate the PM level on the platforms when the shaft is placed near the stations.

Qu et al. [9] introduced a PM discharge efficiency for the air shaft, denoted as $\eta=(M_{in}-M_{out})/M_{in}$. In this equation, M_{out} represents the PM mass expelled through the outer opening of the air shaft connected to the grill during the exhaust process per train run, and M_{in} is the intake PM mass from the tunnel through the inner opening of the air shaft connected to the tunnel during the exhaust per train run. However, this definition appears problematic, as it yields 100 percent efficiency when no particle mass is exhausted from the shaft grill. In this study, we propose an alternative definition for the PM discharge efficiency of the air shaft.

$$\eta=M_{exh,sh}/ M_{int,sh}$$

where $M_{exh,sh}$ and $M_{int,sh}$ mirror the concepts of M_{ou} and M_{int} in Qu et al.'s work [9], but are considered over an extended time duration (for instance, a couple of hours, where the PM mass existing in the relief shaft at a given moment becomes negligible compared to the total exhaust mass from the shaft). Additionally, we introduce the exhaust/suction air volume ratio, denoted as Q_{exh}/Q_{suc}. This ratio reflects the capacity of the shaft to discharge polluted air relative to its capacity to intake air from the outside. Table 1 presents the PM discharge efficiency and the exhaust/suction air volume ratio for various studied cases.

The results show a strong inverse correlation between the PM level on the platforms and both the exhaust/suction ratio, and the PM mass expelled from the shaft. However, there is no discernible correlation between the shaft's PM discharge efficiency and the platform's PM level. Notably, both the maximum and minimum cases of PM level in the platform have the same PM discharge efficiency. Therefore, this efficiency alone is insufficient to define the PM level conditions on the platforms. One important physical aspect of the relief shaft that one must know is the PM that remained in the shaft at the last moment of the airflow exhaust. This PM returns to the tunnel during the suction phase of the outside air. This return of PM occurs with each train run, and the difference between the first and second columns for the PM mass exhaust in Table 1 approximates the total mass of PM returning to the tunnel from the relief shaft over four hours. The proportion of returned mass relative to the total exhaust from the tunnel to the shaft varies between 12-20 percent for different studied cases.

The same analysis was conducted for the single-track tunnel model, with similar ranges considered for shaft placement and diameter as in the double-track tunnels. The results are presented in Table 2. Notably, the PM level on the platforms is nearly five percent lower for the single-track model. An important distinction arises between the single- and double-track models: for the single-track model, the shaft cross-section is considerably more influential than the shaft placement (excluding cases with very close proximity to the downstream station). As evident in Table 2, the platforms exhibit the lowest PM levels when the shaft has the maximum cross-sectional area. Neither the PM discharge efficiency nor the exhaust/suction air ratio of the relief shaft correlates with the PM level on the platforms. A crucial observation is that a relief shaft positioned near the train-arriving side of the station, a configuration typical in existing metro lines, exhibits poor overall performance. The PM level on the platform for this case (L=1985 m) is higher than in all other scenarios. The PM mass expelled from the relief shaft is higher than in other cases, but this doesn't translate to a lower PM level on the platform. The primary reason is that the exhaust PM mass from the escalators of the stations is significantly lower in this case. This aligns with the logical consequence of the piston effect of the train entering the station being less pronounced when the relief shaft is placed directly on the train-arriving side of the station. In simpler terms, fewer particles enter the platform, however, the low exhaust airflow through the station's escalators results in a higher PM concentration on the platforms. Additionally, the volume of fresh air intake to the tunnel from the shaft is significantly reduced when the relief shaft is placed at the train-arriving side of the station. It's crucial to emphasize that the discussion here centers around the PM level perspective.

Table 1: Results for double-track tunnel model. The results are summed or averaged for the last four hours of each simulation.

L (m)	A_{sh} (m^2)	PM Platform (μg/m^3)	The volume of air through the shaft (m^3)		PM mass exhaust from (μg)			Shaft PM discharge efficiency	Exh/Suc air ratio
			discharge	intake	Shaft to outside	Tunnel to shaft	Station to outside		
1000	20	234,6	309330	2,97E5	4,09E7	4,95E7	3,83E8	0,83	1,04
1000	15	235,6	270480	2,65E5	3,88E7	4,59E7	3,84E8	0,84	1,02
1000	10	237,4	212658	2,15E5	3,62E7	4,18E7	3,87E8	0,86	0,99
1500	20	239,8	300897	2,90E5	4,50E7	5,37E7	3,79E8	0,84	1,04
1500	15	239,9	259780	2,54E5	4,19E7	4,95E7	3,81E8	0,85	1,02
1500	10	240,8	201128	2,02E5	3,74E7	4,38E7	3,85E8	0,85	1,00
1000	5	241,0	125736	1,31E5	3,15E7	3,57E7	3,95E8	0,88	0,96
500	10	241,2	200452	1,91E5	3,78E7	4,38E7	3,85E8	0,86	1,05
500	15	241,5	260719	2,41E5	4,21E7	4,92E7	3,79E8	0,86	1,08
500	20	242,0	302221	2,77E5	4,45E7	5,26E7	3,76E8	0,85	1,09
500	5	243,2	115002	1,15E5	2,99E7	3,44E7	3,96E8	0,87	1,00
1500	5	243,5	117706	1,21E5	2,99E7	3,42E7	3,95E8	0,87	0,97
15	5	253,1	73915	9,63E4	1,46E7	1,71E7	4,04E8	0,85	0,77
15	10	253,4	135540	1,73E5	2,33E7	2,79E7	3,88E8	0,84	0,78
1985	5	255,0	76369	9,75E4	1,59E7	1,83E7	4,06E8	0,87	0,78
1985	10	256,6	139633	1,76E5	2,52E7	2,95E7	3,91E8	0,85	0,79
15	15	257,1	182838	2,36E5	2,80E7	3,40E7	3,81E8	0,82	0,77
1985	15	259,4	187887	2,42E5	3,00E7	3,57E7	3,83E8	0,84	0,78
15	20	262,2	218732	2,89E5	3,04E7	3,77E7	3,78E8	0,81	0,76
1985	20	263,8	224730	2,97E5	3,21E7	3,88E7	3,80E8	0,83	0,76

In the single-track tunnel model, the airflow pattern is easily predictable since the trains move only in one direction. As the cross-sectional area of the shaft increases, both the intake and exhaust flow through the shaft also increase. With the increase of the shaft distance from the train-leaving side of the station, the intake airflow decreases, and the exhaust airflow increases. The minimum exhaust/suction air ratio occurs when the shaft is at the train-leaving side of the station. This ratio then increases as the shaft is positioned further from this station and reaches its maximum when the shaft is placed close to the train-arriving side of the next station. The proportion of the exhaust PM from the tunnel to the shaft that returns to the tunnel during the suction phase is notably higher than in double-track tunnels, varying between 13 to 35 percent for different studied cases.

Table 2: Results for single-track tunnel model. The results are summed or averaged for the last four hours of each simulation.

L (m)	A_{sh} (m^2)	PM Platform (μg/m³)	The volume of air through the shaft (m³)		PM mass exhaust from (μg)			Shaft PM discharge efficiency	Exh/Suc air ratio
			discharge	Intake	Shaft to outside	Tunnel to shaft	Station to outside		
15	20	223,8	7,32E4	4,40E5	1,09E7	1,60E7	4,28E8	0,68	0,17
1000	20	226,6	1,78E5	2,29E5	3,33E7	4,28E7	3,84E8	0,78	0,78
500	20	227,8	1,39E5	3,12E5	2,23E7	3,16E7	4,00E8	0,70	0,44
1000	15	227,9	1,63E5	2,14E5	3,23E7	3,95E7	3,83E8	0,82	0,76
15	15	229,8	6,37E4	3,73E5	1,02E7	1,43E7	4,15E8	0,72	0,17
500	15	229,8	1,28E5	2,82E5	2,20E7	2,92E7	3,95E8	0,75	0,45
1000	10	231,8	1,37E5	1,86E5	2,85E7	3,35E7	3,80E8	0,85	0,74
1500	20	233,9	2,00E5	1,42E5	4,15E7	5,16E7	3,54E8	0,80	1,41
1500	15	234,6	1,80E5	1,36E5	3,86E7	4,65E7	3,57E8	0,83	1,32
500	10	234,7	1,08E5	2,33E5	1,99E7	2,48E7	3,88E8	0,80	0,46
1500	10	237,1	1,46E5	1,23E5	3,27E7	3,82E7	3,61E8	0,86	1,19
15	10	237,7	4,93E4	2,84E5	8,56E6	1,15E7	3,98E8	0,75	0,17
1000	5	241,9	8,70E4	1,25E5	1,93E7	2,19E7	3,73E8	0,88	0,69
1985	20	242,1	2,34E5	9,16E4	5,58E7	6,58E7	3,15E8	0,85	2,55
1985	15	244,2	1,95E5	8,28E4	4,74E7	5,52E7	3,23E8	0,86	2,35
500	5	244,6	6,85E4	1,50E5	1,35E7	1,62E7	3,77E8	0,84	0,46
1500	5	245,2	9,02E4	8,70E4	2,12E7	2,42E7	3,63E8	0,88	1,04
1985	10	247,6	1,44E5	6,93E4	3,58E7	4,13E7	3,33E8	0,87	2,08
15	5	248,2	2,78E4	1,66E5	5,21E6	6,80E6	3,80E8	0,77	0,17
1985	5	253,0	7,84E4	4,59E4	1,99E7	2,29E7	3,46E8	0,87	1,71

4. SUMMARY AND CONCLUSION

The impact of the placement and cross-sectional area of relief shafts on particle concentration in the platforms of two subway line models has been examined. Both single- and double-track tunnels were investigated, considering a naturally driven flow resulting from the trains' piston effects. Each station has two large escalators with their doors kept open. The sources of the particles under study were the rolling and braking systems of the trains, and particle levels were compared between the two models.

The key findings of the current study are outlined below.

- In double-track tunnels, the placement of the relief shaft is more important, whereas for single-track tunnels, the size of the cross-sectional area of the shaft plays the same role. The optimal placement for double-track tunnels is in the middle of the tunnel.
- In double-track tunnel model, the PM level on the platforms exhibits a strong inverse correlation with the exhaust/suction air ratio and the total exhaust PM mass discharged outside of the relief shaft. However, there is no correlation between the PM discharge efficiency and the PM level on the platforms.
- For single-track tunnels, neither the exhaust/suction ratio nor the PM discharge efficiency of the shaft correlate well with the PM level in the platforms. The only weak correlation observed is with the total PM mass exhausted from stations and shafts, which correlates to some extent with the PM level on the platforms.

- A relief shaft placed very close to the train-arriving side of the station results in higher particle levels on the platforms. While this placement reduces the mass of entering particles on the platform, it also decreases the exhaust air from the stations, consequently increasing the PM concentration.

4.1. Limits

In the current 1D model, the entire platform is treated as a control volume with a single value for the PM level, disregarding local variations in particle concentration on the platform. The complex 3D geometry of the station might lead to a high regional variation in the PM level. Additionally, the model excludes consideration of flow driven by temperature differences and mechanical ventilation, focusing solely on naturally driven flow resulting from the train piston effect. Assumptions include typical sizes for tunnels and stations, train and rail specifications, and a typical train headway, all based on a subway line in Sweden. Additionally, it was assumed that the two large escalators in each station are always open during the simulation, so the results should not be interpreted for cases where the escalators occasionally have open doors.

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