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Article

Justification of an Energy-Efficient Air Purification System in Subways Based on Air Dust Content Studies

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Abstract: It is not uncommon that subways count as densely populated areas, so air quality standards, including fine dust concentration, have been established for them. As passengers and subway staff are exposed to potentially harmful airborne particles, addressing this issue is vital to ensuring a safe and healthy environment on the subway. To reduce the dust concentration in subway systems, the authors propose installing filters to capture dust in ventilation failures between subway tunnels near metro stations. A novel aspect of the proposed method is the fact that airflow will be moved through filters by using the piston action of trains passing through the tunnels. The result of this research provides empirical evidence regarding dust content and mass concentrations of PM2.5 and PM10 in subway environments. While some existing literature discusses air quality in subways, the inclusion of specific measurements and data from the experiment strengthens the understanding of the severity of dust-related air quality issues in such environments. The data for this study were collected in the Almaty subway (Republic of Kazakhstan) at four stations: Raiymbek Batyr, Almaty, Baikonur and Alatau. Measuring points were located on passenger platforms, in the halls and at the entrances to the station. The lab scale tests determined the percentage of particles by their diameters relative to the total volume of dust, the percentage of dust particles smaller than a certain diameter, the percentage of various metal oxides and the average dust density. A preliminary energy assessment has been done on the proposed method of air purification from dust. With a frequency of 24 pairs of trains per hour, the energy savings per ventilation failure will be 240.170 kWh.

Keywords: subway; dust; dust concentration; fractional composition; elemental composition; tunnel ventilation; air filter; ventilation connection

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1. Introduction

The subway system is an essential part of the transportation infrastructure in today's megacities. While subways are heavily crowded places, they are also subject to strict health regulations and standards concerning air temperature, humidity, flow rate and concentration of harmful emissions that must never exceed the allowable levels as per metro design codes and the public health code. The harmful emissions also include fine dust. The rates of fine dust concentration per 1 cubic meter are given in the engineering specifications of ventilation and air conditioning systems for public facilities, in the air quality standards for clean enclosures and in the recommendations of the World Health Organization [1,2]. According to these standards, the maximum allowable mass concentration of dust is:

- For fine particles PM2.5 (absorbable into blood)—the daily average value is no more than 20 $\mu g/m^3$ and the average annual value is no more than 10 $\mu g/m^3$;
- For coarse particles PM10 (can penetrate in lungs)—the daily average value is no more than 50 $\mu g/m^3$ and the average annual value is no more than 25 $\mu g/m^3$.

This paper presents for the first time the results of studies on the concentrations and fractional and elemental composition of dust conducted under the operating conditions of premises in the Almaty metropolitan area. The results obtained in this paper will be used as initial data for numerical modeling of the dusty air movement processes in the subway when developing a dust removal system.

The purpose of this study is to substantiate an energy-efficient dust removal system in specific subway conditions, based on the determination of parameters (concentration, number of dust particles, fractional and elemental compositions) of dust content in the air. The application of the obtained results and proposals is possible both in the Almaty subway and for other subways with similar operating conditions and structural design.

Literature Review

According to [1,2], in cases of a short-term exposure, the exceeded concentration of fine particles PM10 per each 10 $\mu g/m^3$ over 50 $\mu g/m^3$ increases mortality by 0.5%. For example, a concentration of 150 micrograms/m3 may result in an increase in mortality by about 5%. It is mostly metro personnel (maintenance workers, train drivers, etc.) who are at risk. This is why research on dust concentrations, sizes and compositions in subway air is vital to the development of high-efficiency dust removal systems.

Previous studies [3] show that the dust concentration in the workplaces of metro personnel exceeds the standard by 1.3–3.4 times. The high concentration of fine dust in the air leads to respiratory diseases [4]. In addition, dust deposition in subway tunnels and underground structures is a favorable medium for bacterial proliferation [5]. A number of studies have been done on the fractional and elemental composition of dust in subway systems in Korea, China, France, Spain, etc. [6–21]. The analysis of the elemental composition of fine dust at a subway station in Seoul (Korea) showed that the predominant element in dust particles smaller than 25 µm is iron, Fe, formed by the wheel-set–rail interaction [6]. Nanjing's subway system has high fine dust concentrations, up to 73.5 $\mu g/m^3$, above WHO recommendations [7]. It was measured that the concentrations of finely dispersed organic compounds reached 1801 $\mu g/m^3$ in the work areas of subway personnel [8]. Work [9] illustrates the change in the concentration of PM10 dust particles for different seasons of the Seoul subway—so, for summer, the concentration is 79.3 $\mu g/m^3$, for autumn—107.8 $\mu g/m^3$ and for winter—138.2 $\mu g/m^3$. In the Barcelona subway (Spain), the fine dust concentrations range from 26 to 86 $\mu g/m^3$, and the dust particulates are mostly ferrous oxide, Fe_2O_3 (30–66%) [10]. It was also shown in [11] that fine dust in the Barcelona subway is mainly represented by iron oxides, Fe_2O_3 and carbon, C. Work [12] is devoted to the study of the concentration of fine dust in passenger cabins of cars of the Seoul subway and it is indicated that it reaches a maximum of 152.8 $\mu g/m^3$. The paper [13] shows the concentrations of PM2.5 dust for the Shanghai subway (China), which are no more than 65.6 $\mu g/m^3$.

Computational modeling methods are widely used to predict the processes of dusty air flow movement [22–25], which make it possible to determine the parameters of dust transfer processes and the effectiveness of dust collection methods and perform air quality assessment in buildings and structures [26,27]. In general, it is possible to note the high interest of scientists around the world in studies of the dustiness of air in subways [6–21,28] and methods of reducing dust concentrations.

2. Methods

The number of particles and the bulk concentration of dust were measured at the Raiymbek Batyr, Almaty, Baikonyr and Alatau Stations in the Almaty subway. This subway is equipped with single-track railway and open-type stations; currently the average frequency of trains is 12 pairs per hour; the maximum speed of the train is 70 km/h. Figure 1 depicts the measurement layout: the measurements are taken in the center of a passenger platform (I), in the station halls (II) and outwardly (III), at a distance of 50 m from the entry to the test subway stations.

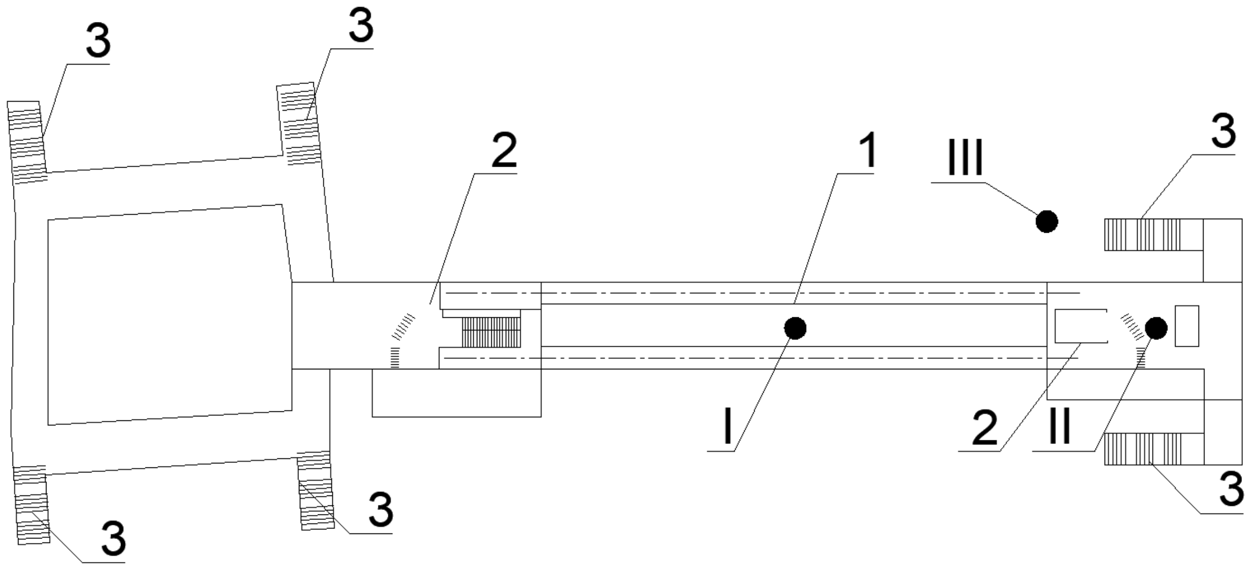

Figure 1. Arrangement of measurement points (in terms of Raiymbek Station): 1—passenger platform; 2—hall; 3—exit to ground surface; I, II, III—measurement points.

The measurement was implemented in August 2021. At each measurement point (I, II, III in Figure 1), three measurements of each test parameter were taken in the morning (7–10 am), in the afternoon (2–5 pm) and in the evening (7–10 pm).

The environmental control device CEM DT-9881M (SHENZHEN EVERBEST MACHINERY INDUSTRY CO., LTD, Location: China, 19th Building, 5th Region, Baiwangxin Industry Park, Songbai Road, Baimang, Xili, Nanshan, Shenzhen, China P.C. 518108) (Figure 2) was used to measure the number of dust particles, bulk concentrations and CO concentrations in the air. This device determines the concentration of suspended solid particles, relative humidity and the temperature of ambient air. The measurement channels for the concentrations of suspended solid particles are 0.3, 0.5, 1.0, 2.5, 5.0 and 10 µm. The bulk concentration measurement range is from 0 to 2000 µg/m^3. In terms of temperature and relative humidity, the measurement range is 0 °C–50 °C and 0–100%, respectively.

Figure 2. Environmental control device CEM DT-9881M.

To exclude anomalous values from the results, an Irwin's criterion is introduced in the form given by:

$$I_i = \frac{y_i - y_{i-1}}{S}, \tag{1}$$

where

$$S = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \overline{y})^2}{n-1}},\ \overline{y} = \frac{\sum_{i=1}^{n} y_i}{n}. \quad (2)$$

In Formulas (1) and (2), n is the number of measurements; y_i is the current measurement; y_{i-1} is the previous measurement; S is the standard deviation; $\overline{y}$ is the arithmetic mean of the measurements.

In a case wherein I_i exceeds the limit value I_{lim}, the measurement y_i is assumed as an anomalous value at an error probability α. The detected anomalous value must be removed from the time series and replaced by an average of the two neighbor measurements. Thus, the results of all measurements at all stations are verified.

The confidence intervals are defined in each measurement series. The final value of the measured value is determined by the Formula:

$$y = \overline{y} \pm t_\alpha \frac{S}{\sqrt{n}}, \quad (3)$$

where t_α is the t-Student's criterion at a preset probability (in our study, the preset probability $p = 0.95$). For the measurement numbers $n = 6$ and $n = 3$, $t_\alpha = 2.571$ and $t_\alpha = 4.3$, respectively.

For estimating the percentage of dust particles by their diameters, q, %, relative to the total volume Q, %, and percentage of dust particles smaller than a certain diameter, Q, %, air was sampled at the Raiymbek Batyr Station (10 g of dust was obtained once from the pocket filter of the ventilation system of the station's office premises, the air entering from the tunnel near stations). The value of q was determined on laser diffraction particle size analyzer Shimadzu SALD-7500 (Shimadzu Europa GmbH, Location: Germany, Albert-Hahn-Str. 6-10, D-47269, Duisburg) (measurement range from 7 nm to 800 µm). The density of the sample p, kg/m3, was determined using a Quantachrome pycnometer (PROFCONTROL GmbH, Location: Germany Schönwalde-Glien, Am Rosengarten 5, 14641), high purity helium was used as a gas: the volume fraction of helium was 99.99%. The oxide mass ratio, q_o, % was determined using atomic absorption spectrophotometer SOLAAR S2 (Thermo Fisher Scientific, Location: USA. 81 Wyman Street, Waltham, MA 02454), and the metal mass concentration, c_m, mg/kg was estimated using inductively coupled plasma emission spectrometer Shimadzu ICPE-9820 (Shimadzu Europa GmbH, Location: Germany, Albert-Hahn-Str. 6-10, D-47269, Duisburg).

3. Results

During measurements at the stations of the Almaty subway, quantitative values of the following parameters were obtained:

- Number of dust particles, units/L;
- The volume of dust concentration, µg/m^3.

Figures 3–6 show the measured values for various stations (Rayymbek Batyr, Almaty, Baikonyr, Alatau) of the Almaty subway.

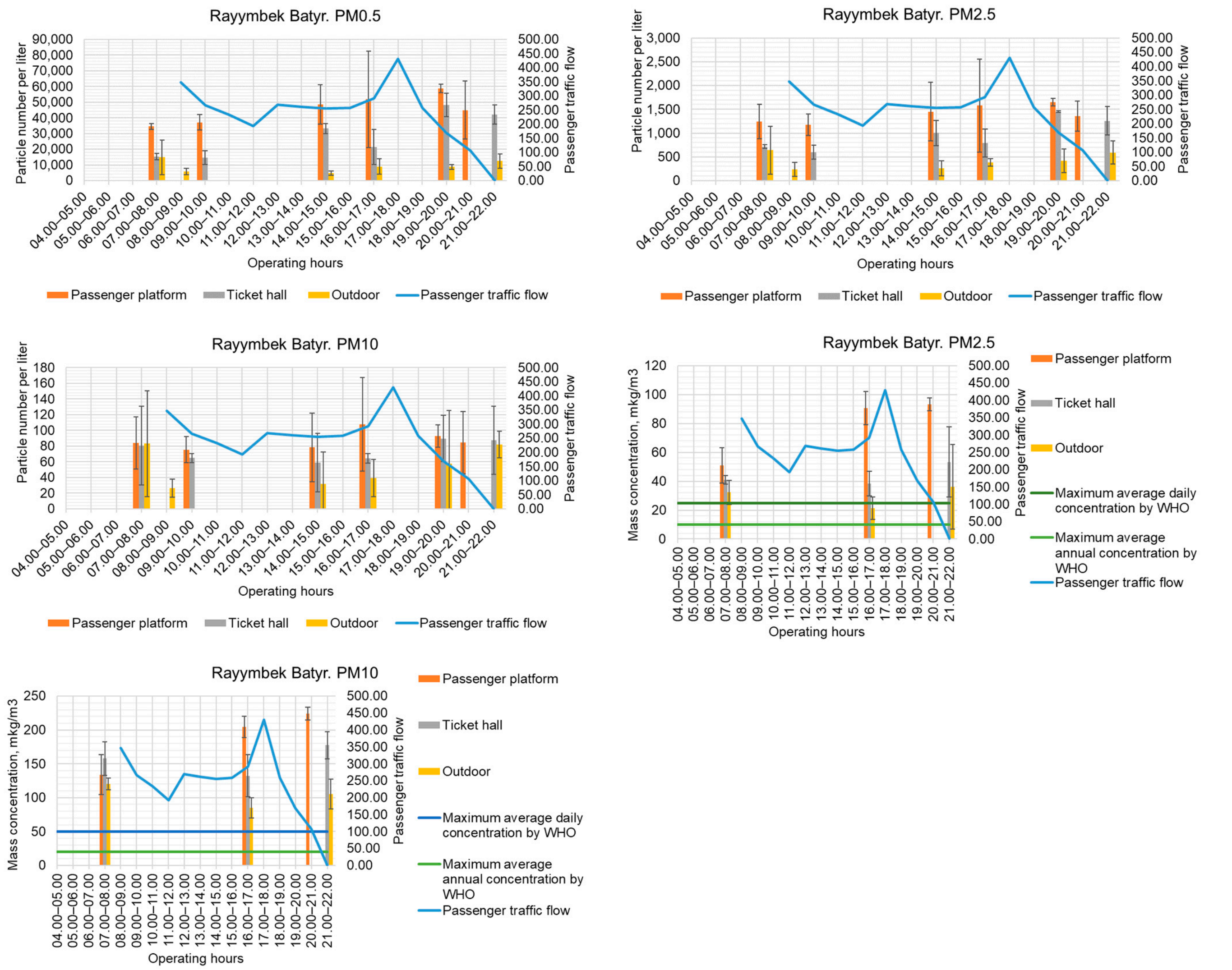

Figure 3. Particle number, dust mass concentration and CO concentration in air at Raiymbek Batyr Station.

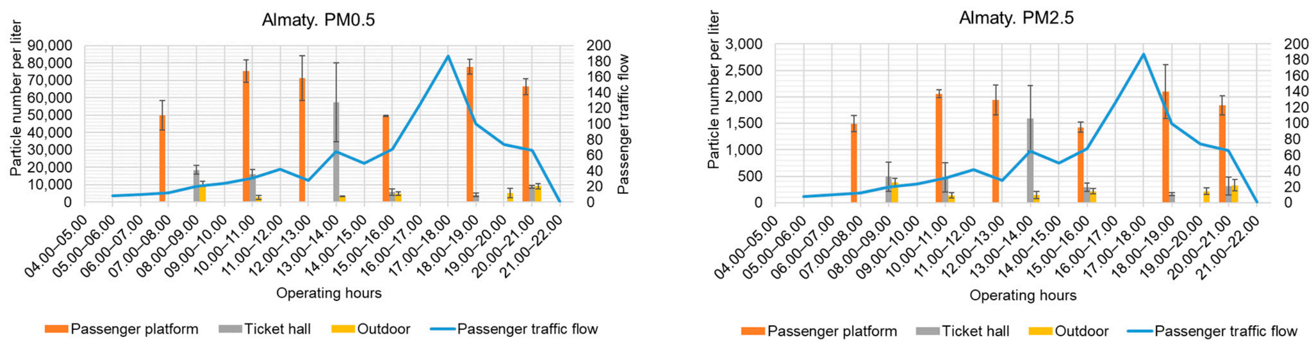

Figure 4. *Cont.*

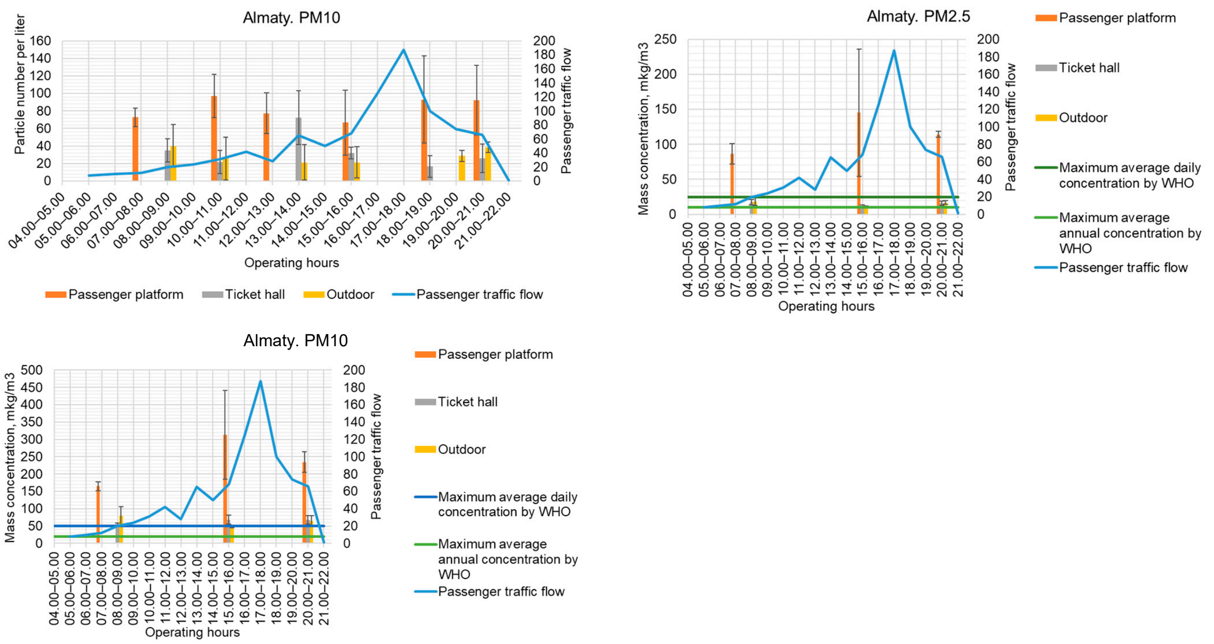

Figure 4. Particle number, dust mass concentration and CO concentration in air at Almaty Station.

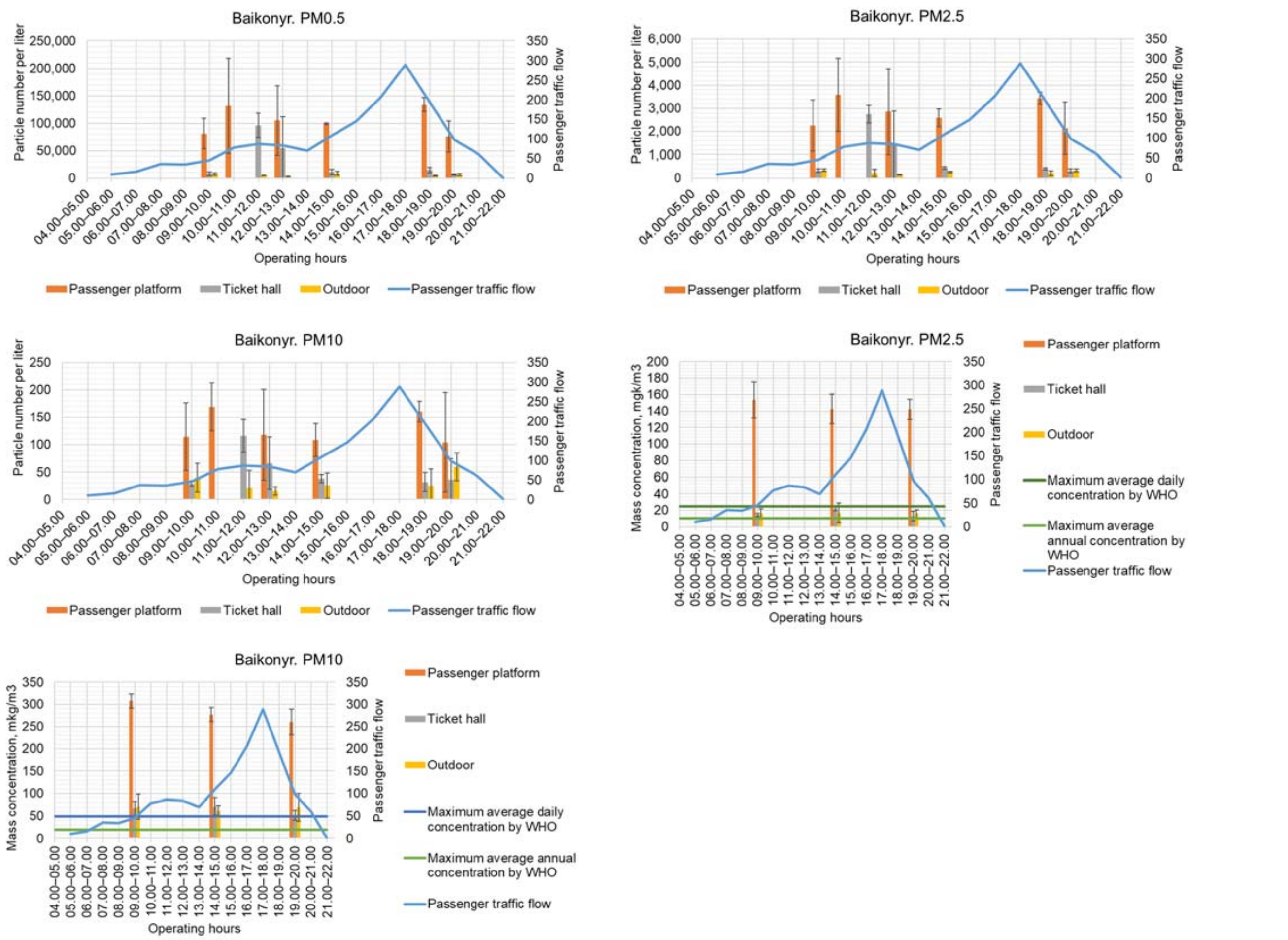

Figure 5. Particle number, dust mass concentration and CO concentration in air at Baikonyr Station.

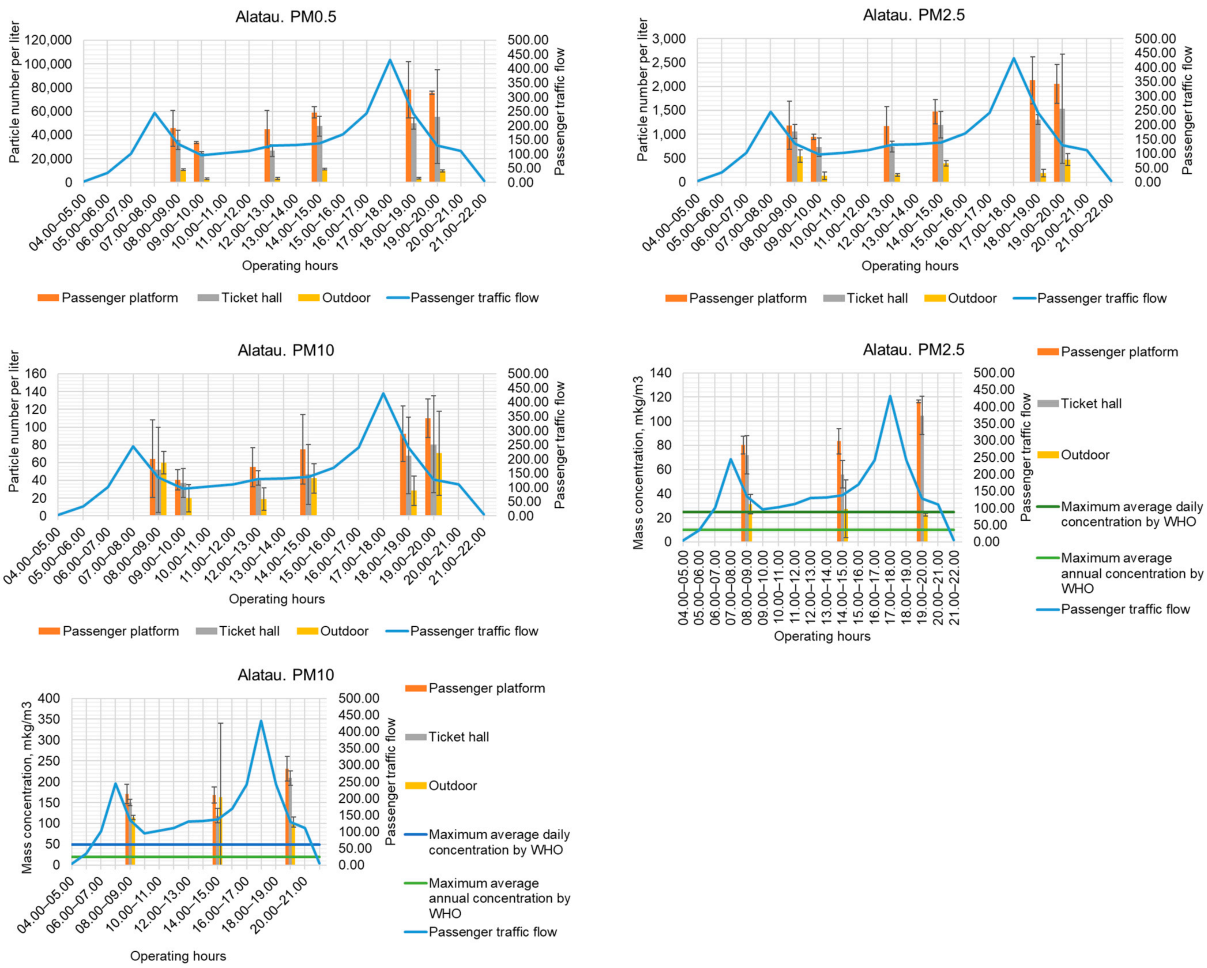

Figure 6. Particle number, dust mass concentration and CO concentration in air at Alatau Station.

Figures 7 and 8 for the Rayymbek Batyr station are shown, respectively:

− The percentage of dust particles by their diameters relative to the total volume, q, %, and the percentage of dust particles smaller than a certain diameter, Q, %;

− The metal mass concentration, C_m, mg/kg;

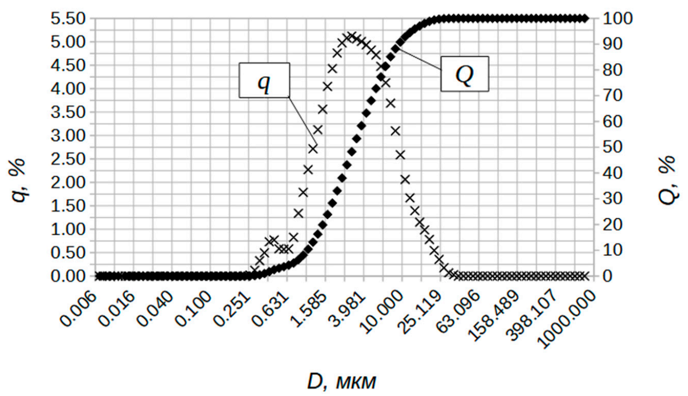

Figure 7. Percentage of dust particles by diameters relative to total volume, q, %, and percentage of dust particles smaller than certain diameter, Q, %, in air sampled at Raiymbek Batyr Station.

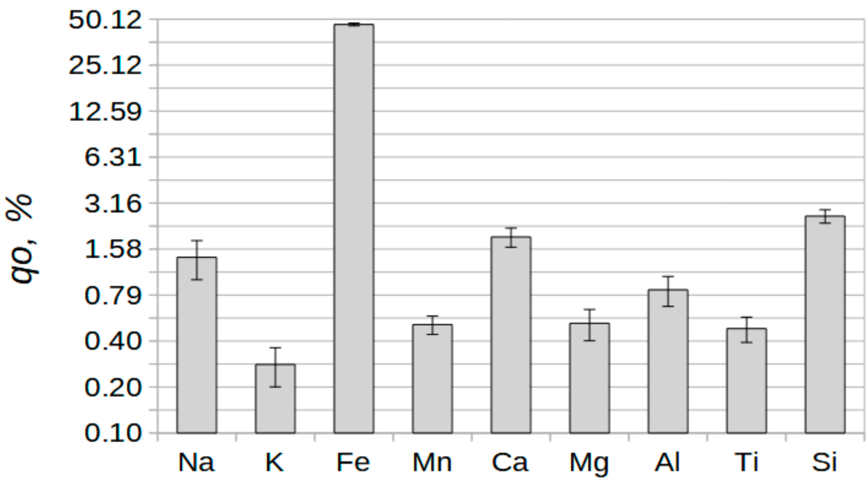

Figure 8. Mass concentrations, C_m, mg/kg, of different metal oxides in dust at Raiymbek Batyr Station.

The average density of dust was 3639 kg/m^3.

4. Discussion

Let's have a look at the requirements for the number of fine particles in the air of the working area. So, for the class of premises "9" according to ISO, which corresponds to ordinary office, industrial and other premises that are not clean rooms, the maximum permissible value of the amount of dust particles for the PM0.5 fraction should be no more than 3.52 × 107 particles/m^3. The dust particle number at the Raiymbek Batyr Station is 5.9 × 107 particles/m^3 (which exceeds the norm by 1.67 times), and it is 7.8 × 107 particles/m^3 at the Almaty Station (2.22 times excess), 1.32 × 108 particles/m^3 at the Baikonyr Station (3.75 times excess) and 7.9 × 107 particles/m^3 at the Alatau Station (exceeding 2.25 times). The fine dust number in the outer air and the ticket halls is much lower than at the passenger platforms. The authors explain this fact by the occurrence at a passenger platform of a so-called circulation loop of air flows due to the piston effect [29]. The air circulation loop runs along tunnels up to the distillation ventilation failure on one side and the passenger station and station ventilation failure on the other side. In this circulation ring, the same air moves through the tunnel section with minimal mixing of fresh air, which contributes to the accumulation of dust particles in it. At the same time, the dust that has already settled rises into the air again when the train passes.

The maximum values of dust concentrations for the stations under consideration:

– Raiymbek Batyr: PM2.5—92 µg/m^3 (higher than the WOS allowable daily average value by 4.6 times), PM10—224 µg/m^3 (higher than the allowable daily average value by 4.48 times);
– Almaty: PM2.5—143 µg/m^3 (higher than the allowable daily average value by 7.15 times), PM10—315 µg/m^3 (higher than the allowable daily average value by 6.3 times);
– Baikonyr: PM2.5—153 µg/m^3 (higher than the allowable daily average value by 7.65 times), PM10—309 µg/m^3 (higher than the allowable daily average value by 6.18 times);
– Alatau: PM2.5—116 µg/m^3 (higher than the allowable daily average value by 5.8 times), PM10—230 µg/m^3 (higher than the allowable daily average value by 4.6 times).

Again, the dust concentration is mostly higher at the platforms than in the ticket halls and in the outer air.

The fractional analysis of dust sampled at the Raiymbek Batyr Station shows that the dust consists mostly of particles 0.251–39.811 µm in size, and the highest dust concentration

(5.15%) has the feature of 2.987 μm particles (Figure 7). The major metal in the dust is iron (Figure 8). The elemental composition of the dust represents mostly iron oxides, then follows silicon, Si, sodium, Na and calcium, Ca oxides. Such chemical composition identifies dusting sources as brake shoes of trains, rails, as well as eroded reinforced-concrete and cast-iron tubing and metal structures. Some dust probably comes on dirty shoes of passengers, and this dust quantity depends on the size of the passenger traffic flow. The average density of the dust was 3639 kg/m^3.

It follows from the dust concentration and quantity measurements in the Almaty subway that the dust concentration outside the subway (at the station entries and at the air intake points) is much lower than in the inner rooms, especially at the passenger platforms. For instance, at the Raiymbek Batyr Station, for particulate matters PM2.5 and PM10, the bulk dust concentrations inside subway rooms exceeded those outside by 57–326% and 11–140%, respectively. This confirms the conclusion that dust is mainly formed directly in the subway itself, and does not enter it from the outside through the supply ventilation system, passenger entrances or portals. Therefore, cleaning outside air before it is supplied to the subway premises does not significantly affect the dustiness of the indoor air. A more effective way to combat dust will be to capture particles directly in the subway, near the sources of dust formation—in tunnels, stations and ventilation failures.

The main criteria for installation of filtration equipment in subways are the convenience of operation and maintenance, and zero impact on train traffic. In the authors' opinion, the best sites for the location of filters in full conformity with the listed criteria are the station ventilation connections. These ventilation connections serve to reduce the intensity of air flows induced by the piston effect in the passenger paths. Figure 9 depicts the arrangement of the filtration equipment in the ventilation connections in terms of a standard station in the Almaty subway. These ventilation connections are rather easily accessible for the maintenance of the filters, and no train routes pass along them. Station ventilation connections, along with adjacent tunnels and stations, are part of the air circulation loop, which enables multiple and large air flows to pass through dust-generating points. Due to the repeated passage of the same air volumes through a ventilation connection, the accumulation effect of multiple dust filtrations will be achieved, which allows using filters that are probably not very effective but possess minimal air resistance, and this is critical when there are no other pressure sources besides the piston effect. The novelty of this solution for the filtration equipment arrangement is proved and patented [30].

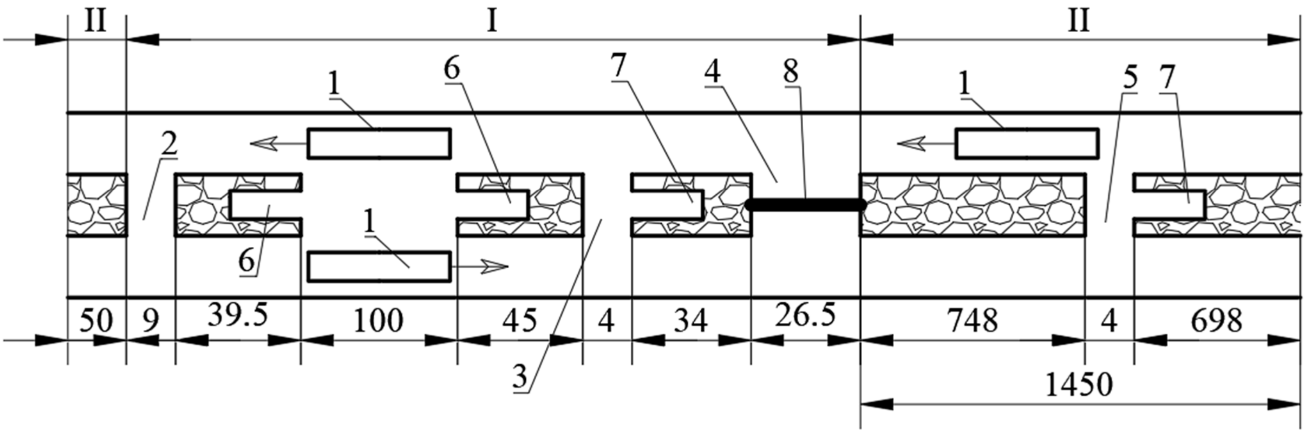

Figure 9. Layout of a subway facility in terms of a standard subway station in Almaty: I—station facility, II—tunnel, 1—train, 2—small ventilation connection, 3—to station air room, 4—large ventilation connection, 5—tunnel ventilation connection, 6—exits, 7—to tunnel air room, 8—filter seat.

The air flows passing through the ventilation connections have a significant impact on the operation of the filtration equipment located there. Accordingly, when there is no additional source of draught, the filtration equipment should have low air resistance so as not to impact air exchange in tunnels and stations. Due to this, inertial and electrostatic filters are deemed to be the most suitable filters. Electrostatic filters are excellent for capturing fine dust, while inertial filters are easy to maintain and inexpensive. In order to design and improve filters, in situ testing results are used as source data for numerical modeling of dust trapping.

A preliminary assessment of the energy efficiency of the application of the proposed system of air purification from dust in subway structures using air flows from the piston action of trains has been carried out. As a result of the conducted studies, it was determined that up to 186 m3 of air passes through the ventilation failure, where filters are planned to be installed, per train passage at a frequency of 24 pairs of trains per hour [29]. When using a traditional air filtration system with minimal aerodynamic drag and pressure losses of 100 Pa, the required power of the installed fans will be 23.25 kW with an efficiency of at least 0.8. With a frequency of 12 pairs of trains per hour, the required fan power will be 13.8 kW. Thus, when using the dust-free air purification system proposed by the authors in the subway, energy savings amount to 240,170 kWh per year per ventilation failure under the currently operating modes of the metro in question.

Along with the filtration equipment, ventilation connections may also accommodate air flow rate regulators (ventilation valves) and adiabatic cooling systems for tunnel air [31]. In this manner, a station ventilation connection serves as an important component of the integrated air handling systems in subways.

5. Conclusions

1. The article substantiates the use of an energy-efficient air purification from dust system installed in a ventilation failure in the subway, through which air movement is carried out due to air flows from the piston action of trains.
2. The research results are correct for subways with single-track tunnels and open-type stations.
3. In situ measurements of fine dust parameters have been accomplished at four stations of the Almaty Metro.
4. The concentration and the number of particles of fine dust in subway air greatly exceed these values in outside air. Accordingly, the main sources of dust exist inside the subways, and cleaning of incoming air at the air intake points can only insignificantly reduce the dust concentration in subway air.
5. The dust concentrations in the air at the subway stations exceed the effective rates and WHO recommendations by 4.6–7.65 and 4.6–6.3 times in terms of particulate dust matters PM2.5 and PM10, respectively. The average density of dust is 3639 kg/m^3. The elemental composition of dust is mostly oxides of iron, Fe, and lesser oxides of silicon, Si, sodium, Na and calcium, Ca, which is reflective of the dust sources represented by train brake shoes, eroded surfaces of metal works and reinforced concrete tubing in tunnels. Some dust comes in the subway on passenger shoes.
6. The dust concentration has the highest value at the passenger platforms in subways. This is connected with the fact that a passenger platform lies in an air circulation loop generated by air flows through the tunnels and adjacent stations. These areas are the main generators and accumulators of dust as these circulation loops involve little fresh air. Therefore, it is most efficient to trap dust and to reduce dust concentration immediately at the points of dust generation—in tunnels, at stations and in ventilation connections.
7. It is proposed to place filtration equipment in the station ventilation connections as they are involved in the air circulation loops, and this contributes to multiple passages of one and the same air volumes through the connections. Moreover, filters placed in the station ventilation connections do not clog the train movement.
8. Air flows through ventilation connections greatly affect the operation of the filtration equipment placed there. In cases wherein air flows under the piston effect only, the filtration equipment should possess a sufficiently low air resistance to have no

influence on air distribution in the subway. For this reason, it is suggested to install inertial and electrostatic filters in ventilation connections.
9. Alongside the filtration equipment, it is possible to place air flow controllers (ventilation valves) and adiabatic cooling systems for tunnel air in ventilation connections. In this manner, a station ventilation connection serves an important component of the integrated air handling systems in subways.
10. A preliminary assessment of the energy efficiency of the proposed method of air purification from dust has been carried out; with a frequency of 24 pairs of trains per hour, energy savings will amount to 240,170 kWh per year per ventilation failure.
11. The in situ testing results work as the source data for numerical modeling of dust trapping by the filters with a view to their design and improvement.

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Data Availability Statement: The data used in this study were collected by the authors, and any questions or clarifications can be addressed to the corresponding author upon a reasonable request (t.irgibayev@satbayev.university).

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Conflicts of Interest: The authors declare no conflict of interest.

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