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CASE STUDY

Dispersion modelling of particulate matter concentrations of sand product plants in a mineral complex

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ABSTRACT

BACKGROUND AND OBJECTIVES: Sand and gravel product plants are among the significant sources of dust pollutants. This study was conducted to estimate dust concentrations released from these plants in a mineral complex in the southwest of Tehran.

METHODS: Initially, the amount of silt and moisture content of the samples taken from these plants were determined according to the American Society for Testing and Materials C136 and D2216 methods, respectively. Accordingly, the rates of particulate matter emissions from these plants were determined by the AP-42 dust emission estimation methods published by the United States Environmental Protection Agency. Next, a Gaussian model was used to estimate the particulate matter concentrations in the surrounding residential areas. Finally, the simulated concentrations were compared with the United States Environmental Protect Agency and World Health Organization standards.

FINDINGS: Results showed that hauling operations, with producing 70%, 86%, and 90% of total $PM_{2.5}$, PM_{10} and total suspended particulates, respectively, were the major sources of dust emission in the sand and gravel product plants. The lowest dust emission was related to stockpiling handling, producing 0.24%, 0.33%, and 0.16% of the total $PM_{2.5}$, PM_{10} and total suspended particulates. The results of the presented model indicated that 24-hour average concentrations of $PM_{2.5}$, PM_{10}, and total suspended particulates produced by mining activities were about 36, 183, and 690 $\mu g/m^3$ in the working zone and less than 30, 100, and 400 $\mu g/m^3$ beyond the mineral complex boundary, respectively. Thus, annual average dust concentrations were negligible. The concentrations of $PM_{2.5}$ and PM_{10} produced by these plants in the mineral complex ambient air were higher than the standard average values recommended by the United States Environmental Protect Agency and World Health Organization. However, the concentrations of $PM_{2.5}$ and PM_{10} from these plants in the residential areas around the complex, were below the standard limits proposed by the Environmental Protection Agency.

CONCLUSION: Sand and gravel mining activities increased the concentrations of particulate matter in the air of the surrounding areas and, to some extent, farther cities. $PM_{2.5}$ and PM_{10} resulting from the sand and gravel mining activities could damage the workers in the mineral complex. They exceeded the 24-hour average permissible limits proposed by the United States Environmental Protection Agency about 1 and 33 $\mu g/m^3$, respectively. This study showed the necessity of changing the industrial policies adopted to decrease dust emission rates. The results of this study can help the air pollution experts develop proper strategies for improving the air quality in the vicinity of surface mines.

NUMBER OF REFERENCES
46

NUMBER OF FIGURES
7

NUMBER OF TABLES
6

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INTRODUCTION

Fugitive dust is the major pollutant produced by the sand and gravel industry (Leili *et al.,* 2008). Particulate matter (PM) that affects the health of miners and people living in the vicinity of these industries is considered a critical pollutant (USEPA, 2020a). PM is classified according to the particle diameter size of the component particles as fine inhalable particles ($PM_{2.5}$) and inhalable particles (PM_{10}). The diameters of $PM_{2.5}$, PM_{10} are less than or equal to 2.5 and 10 microns, respectively (US EPA, 2021a). Particles with an aerodynamic diameter of fewer than 30 microns (PM_{30}) are referred to as total suspended particulate matter (TSP) (Lashgari and Kecojevic, 2016). Acute and chronic diseases are caused by inhaling the particles such as PM_{10} and $PM_{2.5}$ (Ezeh *et al.,* 2012). Dust can cause cardiovascular and cerebrovascular diseases, respiratory stress, oxidative stresses (Anderson *et al.,* 2012), hypertension, prematurity, neonatal weight loss, and infant mortality (Ruckerl *et al.,* 2011). Onabowale and Owoade (2015) showed that indoor air particulate was responsible for 28% of illnesses and deaths in developing countries. According to Heger and Sarraf studies (2018), $PM_{2.5}$ was responsible for 4000 annual premature deaths in Tehran, Iran. Particulates can also be emitted from natural and anthropogenic sources such as pollen and quarrying (Owen Harrop, 2005; Lohe *et al.,* 2015). Particulates may also be classified according to their origin as 1) primary particles which are emitted directly from a process to the atmosphere (traffic, road dust, sea spray and etc.); and 2) secondary particles which are subsequently formed by a chemical reaction (sulphates, nitrates, ammonium, etc.) (Theodore, 2008). The sand and gravel industry is a mineral industry for the processing and storage of granular media. Granular materials obtained from natural deposits in the river bed or sea are transferred by, for example, movable loaders, motor buckets, and safety carriers from where they were removed (Cho, 2006). These industries are often located near residential centers (Van Der Meulen and Salman, 1996). Based on product specifications, crushing, screening, washing, and stockpile handling are considered complementary operations of sand and gravel processes. Main sources of fugitive dust in sand and gravel product plants include crushing, aggregate handling and storage piles, vehicle travelling on paved and unpaved roads, wind erosion of open storage piles and open areas (USEPA, 1995a). Emission rates of pollutants from different operations in mines and their negative effects on the environment have attracted the attention of many researchers during recent years. Sastry *et al.,* (2015) predicted and analyzed the dispersion of particulate matter from drilling operations in opencast coal mines using USEPA models. Lashgari and Kecojevic (2016) estimated the dust emission from digging and loading equipment in a surface coal mine using the AP-42 dust emission estimation methods. Gautam and Patra (2014) investigated the dispersion of particulate matter from a copper open cast mine. Badr and Harion (2007) predicted the concentrations of dust from stockpiles in an open-pit mine. Naveen Saviour (2012) investigated the effects of sand mines on the environment and showed the harmful effects of sand and gravel mining activities on air quality, water quality, land use, soil quality, flora, fauna, etc. Ako *et al.,* (2014) studied the effects of sand and gravel mining on the environment using field observations and analysis of soil samples. They finally showed that the pollutants emitted from these mines negatively affected humans, animals, and plants. Neshuku (2012) believed that it was essential to have a comprehensive approach to understand the air pollution caused by different mining operations. Holmes and Morawska (2006) indicated that several dispersion air quality models, such as Gaussian models, including California Puff Model (CALPUFF), American Meteorological Society/Environmental Protection Agency Regulatory Model Improvement Committee Dispersion Model (AERMOD), and United Kingdom Atmospheric Dispersion Modeling System (UK-ADMS) and SCREEN3); Lagrangian/Eulerian models including Graz Lagrangian Model (GRAL), and The Air Pollution Model (TAPM), box models including Air Quality Modeling in Urban Regions using an Optimal Resolution Approach (AURORA), Canyon Plume Box (CPB) and Photochemical Box Model (PBM); and Computational Fluid Dynamic (CFD) models including Microscale flow and dispersion model (MISKAM), and Microscale California Photochemical Grid Model (MICRO-CALGRID), were used to predict air quality. Neshuku (2012) analyzed PM_{10} emission from a uranium mine using the ADMS model. Trivedi *et al.* (2009) estimated the concentrations of the TSP emitted from a coal mine using a fugitive dust model. CALPUFF and AERMOD have been approved by the

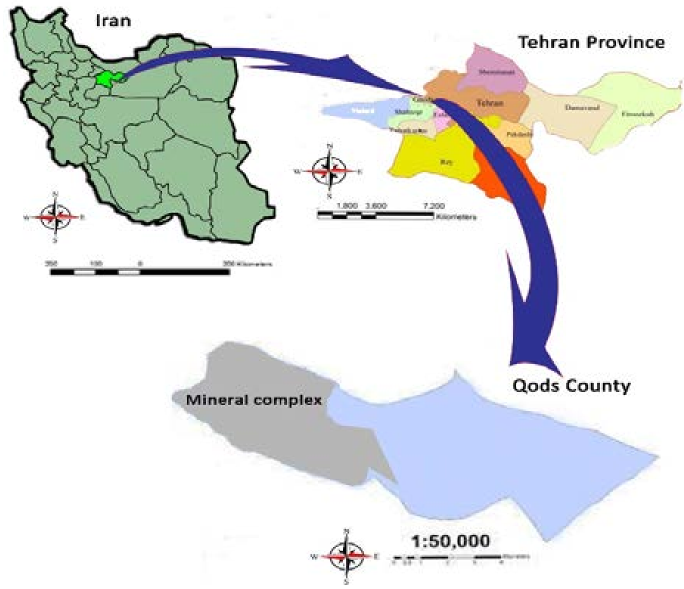


Fig. 1: Geographic location of the study area in Shahre Qods in the southwest of Tehran, Iran

USEPA and can deal with the deposition of pollutants (Cimorelli et al., 2005). Compared to other models, the Gaussian models are easier to use (Asif et al., 2018). Lilic *et al.,* (2012) indicated that the Gaussian AERMOD model could be efficiently used in planning for decreasing the dust impact on air quality around open-pit mines. Sand and gravel product plants, located southwest of Tehran, are one of the major sources of dust in the city. These plants, which emit a large amount of dust to the atmosphere, have been developed in recent years. To the best of the authors' knowledge, no study has been done to investigate the dust emission rate from these plants so far. Therefore, it seems necessary to estimate the dust emission rate from these plants to the atmosphere and dust concentrations reaching the surrounding cities. Such estimation may have an important role in urban planning programs and policies, regional development, land use, health and environment, air quality management, and development of surface mines in the future. The main objective of this study was to analyze the distribution of particulate matters emitted from the sand and gravel product plants in the southwest of Tehran. The hypothesis followed in this study is that the fugitive dust emission from the sand and gravel product plants in the southwest of Tehran significantly increases the airborne levels of particulate matter in nearby areas. This study aims to estimate the particulate matter emission rates using the emission factors suggested by the USEPA, simulate the particulate matter concentrations at a distance of 50 km away from the pollution source using AERMOD model, describe the results of dispersion modelling, and compare the simulated values with the EPA and WHO standard values. This study was performed in Shahre Qods in the southwest of Tehran, Iran, in 2020.

MATERIALS AND METHODS

The study area

This study was performed in a mineral complex in the southwest of Tehran, Iran. The mineral complex has been set up on the alluvium of an old branch of Karaj riverbed. It covers an area of about 2500 ha in Shahre Qods, which is a small part of Shahriar County (Fig. 1). The complex lies between the longitude of 51° 02' and 51° 06' E and latitude of 35° 41' and 35° 45' N and includes 62 sand and gravel product plants covering an area of about 1200 ha. These plants are evenly distributed all over the complex. In addition to sand and gravel product plants, there are other industries such as asphalt factories, moulding factories, and a military barrack. Furthermore, many cities and townships exist in different directions at 1-9 km from the mineral complex.

At the mineral complex, sand and gravel processing operation are performed five days (except

Table 1: Types of vehicles travelling on paved/unpaved roads in the mineral complex

Vehicle	Vehicle class	Average daily traffic [#/day]		Full weight (ton)	Empty weight (ton)
		Paved road	Unpaved road		
Mercedes-Benz 608	Light truck	298	837	7	4
Budsun 6B	Light truck	155	435	7	4
Dong Feng 106C	Light truck	103	289	6	3.330
Isuzu 75 NPR	Light truck	91	256	7.5	3.650
Mercedes-Benz 1921	LK truck 2 Axles-6 Wheels	117	328	20	6.530
Mercedes-Benz 1924	LK truck 2 Axles-6 Wheels	453	1274	20	6.530
Mercedes-Benz 2624	LK truck 3 Axles-10 Wheels	92	259	28	8.930
Mercedes-Benz 2628	LK truck 3 Axles-10 Wheels	39	109	28	8.930
Volvo N10	LK truck 3 Axles-10 Wheels	10	28	28	9.1

on public holidays) a week (Saturday to Wednesday) for eight hours a day (07:00 am-03:00 pm). This operation generally occurs 230 days per year. Aggregate production amounts to approximately 8.5 million tons per year. About 30% and 70% of this production are natural sand and gravel (2.55-million-ton) and broken sand and gravel (2.55-million-ton sand and 3.4-million-tons gravel). The produced gravels are 6-12, 12-19, and 19-25 mm in size, and the produced sand is in the dimension of 0-6 mm. Operations proceed on the same schedule during the year, but the production level is lower in winter (22 September-19 March) than in summer (20 March-21 September). The average number of conveyor transfer points in each plant is 6. The average length of the paved road among the plants for travelling of all vehicles is about 3 km. Also, the average estimated length of unpaved roads in each plant is 1.2 km. The unpaved roads in these plants are watered once or twice a day to prevent the dust emissions caused by vehicular traffic. Usually, nine types of vehicles travel on roads in the mineral complex (Table 1).

Emission factor and estimation of dust emission

The emission factor is a ratio between the emissions generated and the outputs of production. Emission factors are considered as one of the crucial tools for air quality management. These factors facilitate the estimation of emissions from different air pollution sources. Compilation of Air Pollutant Emission Factors (AP-42) published by US EPA. AP-42 suggested a large number of equations to estimate fugitive dust emission factors. The latest version of these equations is available on the EPA website (US EPA, 2020b). In this study, the emission factors suggested by the US EPA were used to estimate the dust emission rates resulting from sand and gravel processing operations. Multiplication of activity rate by emission factors is widely used for determining the air pollutant emission rate from non-stack sources as expressed by Eq. 1 (US EPA, 1995b).

$$E = A \times EF \times (1 - ER/100) \qquad (1)$$

Where, E is the emission rate of the pollutant; A is the activity rate; EF is the pollutant's emission factor, and ER is the efficiency reduction percentage (%). The activity rate represents the degree of using the source within the analysis period. The efficiency reduction percentage represents the reduction of emissions before releasing them into the atmosphere, and it can be achieved through some processes or activities that seek to reduce emissions. This study calculated the dust emission rate for each mining activity (crushing, handling of piles, hauling in paved/unpaved roads). In addition, dust emission rate from open area wind erosion in the sand and gravel product plants was also considered. The empirical formulas (Eqs. 2-5) recommended by the US EPA in the fifth edition of AP-42 were used to calculate the emission factor of particulate matter (Table 2).

In Eq. 2, k is particle size multiplier which was 0.053, 0.35, and 0.74 for $PM_{2.5}$, PM_{10}, and TSP, respectively; U is average wind speed (m/s) at the height of 10 m, and M is material moisture content (%). In Eq. 3, k is particle size multiplier which was 0.15, 0.62, and 3.23 for $PM_{2.5}$, PM_{10}, and TSP, respectively; sL is road surface silt loading of the travel surface (g/m^2) (typical

Table 2: Emission Factor equations for sand and gravel mining processes

Activities	Empirical equations	unit	Eq.	Reference
Aggregate handling and storage piles	$EF = k(0.0016)\frac{(U/2.2)^{1.3}}{(M/2)^{1.4}}$	kg/ton	(2)	US EPA, 2006a
Paved roads	$EF = k(sL)^{0.91} \times (W)^{1.02}$	g/VKT	(3)	US EPA, 2011
Unpaved roads	$EF = k\left(\frac{S}{12}\right)^{a} \times \left(\frac{W}{3}\right)^{b}$	lb/VMT	(4)	US EPA, 2006b
Wind erosion	$EF = k\sum_{i=1}^{N} P_i$, $P = 58(u* - ut*)2 + 25(u* - ut*)$; $P = 0$ for $u* \le ut*$	g/m^2	(5)	US EPA, 2006c

the mean silt loading value for paved roads at sand and gravel processing is 70 g/m^2). W is the average of empty and full vehicle weights travelling on paved roads (ton). In Eq. 4, k, a, and b are empirical constants based on the stated aerodynamic particle sizes; k is particle size multiplier which is 1.5, 0.15, and 4.9 for $PM_{2.5}$, PM_{10}, and TSP, respectively; a is 0.9, 0.9 and 0.7 for $PM_{2.5}$, PM_{10}, and TSP, respectively; b is 0.45, 0.45 and 0.45 for $PM_{2.5}$, PM_{10}, and TSP, respectively; S is surface material silt content (%), and W is average of empty and full vehicle weights travelling on unpaved roads (tons). In Eq. 5, N is the number of disturbances per year (365 per year); Pi is erosion potential of a dry surface (g/m^2); k is particle size multiplier which was 0.075, 0.5, and 1.0 for $PM_{2.5}$, PM_{10}, and TSP, respectively; u* is friction velocity (m/s), and u_t* is threshold friction velocity (m/s). Since the emission factor for the dust from the vehicles travelling on unpaved roads is in lb/VMT (Eq. 4), lb/VMT was converted to metric conversion (g/VKT) using Eq. 6.

$$1\left(\frac{lb}{VMT}\right) = 281.9\left(\frac{g}{VKT}\right) \quad (6)$$

Moreover, VKT/VMT was calculated based on Eq. 7.

$$VKT / VMT = ADT \times \text{Length of roads} \times \text{Operating days / year} \quad (7)$$

Fleet average weight for vehicle classes on the segmented road (WFLEET) is necessary for calculations. “WFLEET” is the calculated mean weight multiplied by the percentage of traffic on the road segment. u* in Eq. 5 was calculated based on Eq. 8.

$$U^{*} = 0.053U_{10}^{+} \quad (8)$$

Where, u^{+}_{10} is the average wind speed at the height of 10 m (m/s). u_t* was calculated from the aggregate size distribution mode. This study estimated wind emission based on a continuously exposed open area (12 million m^2). The wind erosion rate was calculated using Eq. 9.

$$E = EF \times S \quad (9)$$

Where, E is wind emission rate (g), and EF is emission factor (g/m^2), S is surface area (m^2).

In this study, the emission factors for handling and storage piles activities were 4.082E-05, 2.693E-04, and 5.695E-04 kilogram of $PM_{2.5}$, PM_{10}, and TSP per ton of the material processed (uncontrolled), respectively. The emission factors for paved roads were 75.339, 311.401, and 1622.301 g of $PM_{2.5}$, PM_{10}, and TSP per vehicle kilometer travelled, respectively. The emission factors for unpaved roads were 0.062, 0.623, and 2.109 kilograms of $PM_{2.5}$, PM_{10}, and TSP

Table 3: Emission factors for crushed stone processing operations (US EPA, 2004)

Crushed stone processing operations	Emission factor (kg/ton material throughput)		
	$PM_{2.5}$	PM_{10}	TSP
Truck unloading-fragmented stone	2.25E-06	8.0E-06	1.5E-5
Aggregate scalping screen	0.0018	0.0043	0.0125
Crushing	0.0012	0.0012	0.0023
Fines crushing	0.0029	0.0075	0.0195
Screening	0.0018	0.0043	0.0125
Fines screening	0.0225	0.036	0.15
Conveyor transfer points	2.25E-04	5.5E-4	0.0015
Truck loading	1.5E-05	5.0E-5	9.8E-5

per vehicle kilometer travelled. According to the aggregate size distribution mode, the threshold friction velocity for the study area was 0.71 m/s. Meteorological data for 2019 were used to calculate the erosion potential (P_i). According to the data, the annual total erosion P_i was 4.26 g/m^2. The emission factors for wind erosion were 0.32, 2.13, and 4.26 g of $PM_{2.5}$, PM_{10}, and TSP per square meter of open area (uncontrolled), respectively. The dust emission factors related to crushing stone processing operations are presented in Table 3.

Sampling and analysis

The guidelines for sampling surface and bulk dust loading (US EPA, 1993a) and laboratory analysis of surface and bulk dust loading samples (US EPA, 1993b) suggested by the USEPA were used to determine the number and volume of the required samples and laboratory analysis methods, respectively. The amount of silt of unpaved roads was determined by measuring the percentage of loose dry particles passing through a number 200 sieve which had a mesh screen with a diameter of 75 µm, according to the ASTM C136 method. Moreover, the moisture content of stockpiles was determined by calculating the percentage of loose dry dust according to the ASTM D2216 method. Finally, the threshold friction velocity for wind erosion was determined using the aggregate size distribution mode. In this study, seven aggregate product plants were randomly selected. From these selected plants, three composite samples weightings of a) 7.2 kg from unpaved roads for estimating silt content, b) 5 kg from stockpiles for estimating moisture content, and c) 5 kg from surface materials for estimating the mode of size distribution to determine the threshold friction velocity were selected. Finally, the composite samples were taken to the laboratory for analysis. The moisture content of the composite sample of stockpiles, the amount of silt of the composite sample of unpaved roads, and the aggregate size distribution mode of the composite sample of open-pit mines were obtained as 4.66%, 10.12%, and 1.3 mm, respectively.

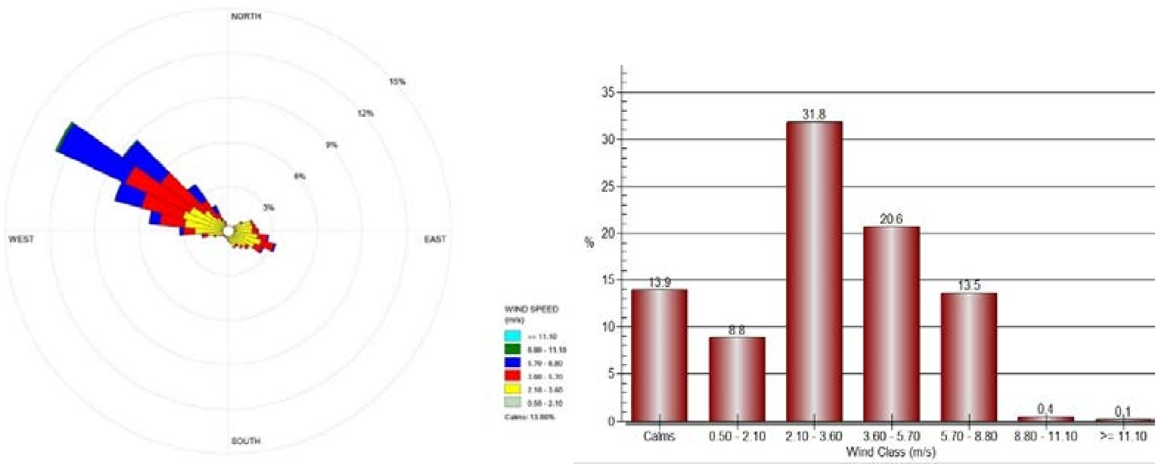
Model description AERMOD

AERMOD, developed by USEPA and AMS, is a steady-state Gaussian plume model for measuring the dispersion of airborne pollutants up to 50 km within the source radius. The Gaussian plume model is used to estimate the dispersion of air pollutants (Cheremisinoff, 2002). The hypothesis of this model is that molecular diffusion causes plum spread and dispersion of pollutants (Thad Godish, 2005). In a coordinate system based on wind orientation, the Gaussian plume model mass balance is expressed using Eq. 10 (Cheremisinoff, 2002).

$$\partial Ci / \partial t + U \partial Ci / \partial x = \partial i / \partial y \left(Ky \partial Ci / \partial y \right) + \partial i / \partial z \left(Kz \partial Ci / \partial z \right) + C1 \qquad (10)$$

Where, Ci is the average concentration (g/m^3 or µg/m^3); U is average wind speed (m/s); t is time; x is the x-axis extending horizontally in the direction of the mean wind; y is the y-axis in the horizontal plane perpendicular to the x-axis; z is the z-axis extending vertically; C1 is the rate of loss or gain by chemical reactions, precipitation (washout), or adsorption by suspended particles; Ky is Uσ2y/2x, and Kz is Uσ2z/2x.

AERMOD model is used in rural and urban areas, flat and complex terrain, surfaces and elevated releases, and multiple sources as points, area, and volume sources. The model input consists of



(a) (b)

Fig. 2: (a) Wind rose diagram and (b) wind class frequency distribution of the study area (2015-2019)

meteorological and topographical data of the study area, source types, emission rates, location of sources, and receptors. Wind speed and direction, temperature, pressure, relative humidity, rainfall, and cloud cover are considered as meteorological data. AERMOD model has a main processor, called AERMOD, and two pre-processors called meteorological pre-processor (AERMET) and terrain pre-processor (AERMAP). AERMET pre-processor processes the meteorological data. AERMET incorporates meteorological observations from the surface and upper stations, calculates the boundary-layer meteorological parameters, and prepares these data in the formats readable by AERMOD (Cimorelli et al., 2004). AERMAP analyzes the terrain and generates receptor grids for AERMOD. The main processor of the model integrates the meteorological and topographical data and source PM emissions to predict the downwind concentrations of the source(s). In this study, the AERMOD model (version 8.9) was used to estimate the 24-hour and annual average concentrations of $PM_{2.5}$, $PM_{10,}$ and TSP from sand and gravel processing operations. Lack of upper air meteorological data was the limitation of using the AERMOD model in this study.

Meteorological data

The required meteorological data during five years (2015 to 2019) was extracted from Shahriar synoptic station, the closest station to the mineral complex. It is located at a distance of 3.5 km at the southwest of the mineral complex between a longitude of 51.01 N and a latitude of 35.40 E. The wind rose plotted by WRPLOT software, and the wind frequency classification of the study area are shown in Fig. 2a and b, respectively. Wind frequency classification shows the percentage of wind with a different speed range. It also shows the time in which a calm situation prevailed.

AERMOD model requires hourly meteorological data to simulate the pollutant dispersion. Since the collected meteorological data were based on three-hour periods, they were converted to hourly data by the weighted interpolation of data with the help of Excel formula functions. To perform calculations, AERMET pre-processor needs three surface characteristics: 1) Bowen ratio (surface moisture determination index), 2) Albedo coefficient (fraction of solar radiation that is reflected into space without being absorbed by the surface), and 3) surface roughness coefficient (altitude that is the average horizontal wind speed). The USEPA values suggested for these surface characteristics are presented in Table 4 (US EPA, 2021b).

Terrain elevation data

The mineral complex, marked as dotted lines in Fig. 3, is located at an altitude of 1000 to 1500 m (1200

Table 4: Values for surface roughness length, Albedo, and Bowen ratio

Surface characteristics	Spring	Summer	Autumn	Winter	Land-use
	0.14	0.16	0.18	0.35	Urban
Albedo coefficient	0.14	0.2	0.18	0.6	Cultivated Land
	0.3	0.28	0.28	0.45	Desert Shrubland
	1	2	2	1.5	Urban
Bowen ratio	0.3	0.5	0.7	1.5	Cultivated Land
	3	4	6	6	Desert Shrubland
	1	1	1	1	Urban
Surface roughness	0.03	0.2	0.05	0.01	Cultivated Land
	0.3	0.3	0.3	0.15	Desert Shrubland

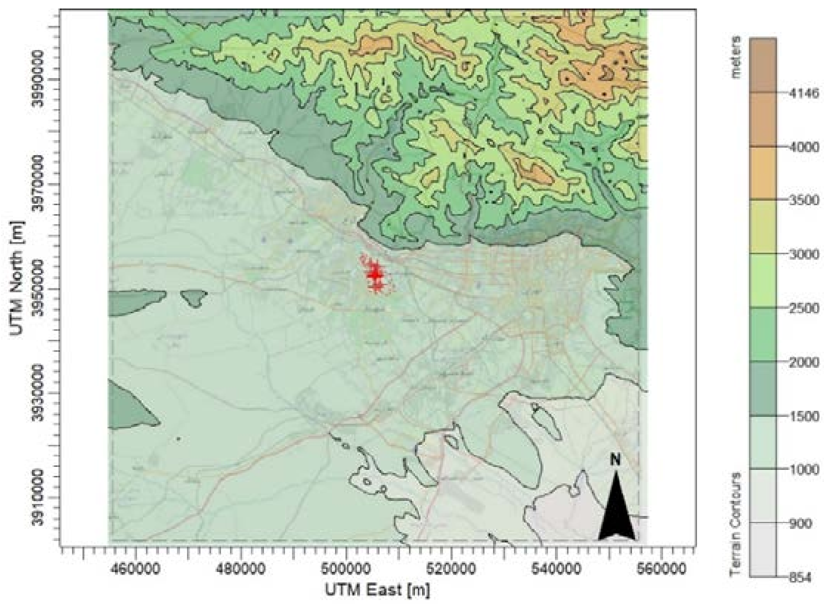


Fig. 3: Map of terrain features of the study area (up to 50 km)

m). There is a relatively complex topography in the northern and northeastern parts of the complex at 3 km. However, in other territories around the mineral complex, the topography is relatively flat. According to the region's topography, a digital elevation model (DEM) with an accuracy of 90 m was used, and the output was fed into the model in XYZ format.

Emission rate

The dust emission rates from different sand and gravel processing operations during the year of operation were calculated based on the experimental equations suggested by USEPA. The required data were gathered from the technical reports of the plants to estimate the rates of dust emission from different mining source activities. 70% control efficiency (C.E.) was assumed for watering at the crushing, screening operation, and conveyors transfer points (USEPA, 1995a) and 55% control efficiency was considered for watering the unpaved roads twice a day (WRAP, 2004). The rates of emission from different sand and gravel mining operations are presented in Table 5.

RESULTS AND DISCUSSION

The rates of particulate matter emission from sand and gravel product plants in a mineral complex were emphasized in this study. The dispersion of these pollutants up to a distance of 50 km was also modelled. The standard values of $PM_{2.5}$ and PM_{10} were compared with the simulated values.

Table 5: Emissions from various pollutant sources in the sand and gravel mining complex

Pollutants	Crushed stone processing operations	Stockpile handling	Unpaved road	Paved road	Open area wind erosion	Total emissions
	ton/y	ton/y	ton/y	ton/y	ton/y	ton/y
$PM_{2.5}$	38.32	0.345	29.377	70.594	3.84	142.476
PM_{10}	71.237	2.289	295.191	291.789	25.56	686.066
TSP	216.54	4.481	999.292	1520.128	51.12	2791.561

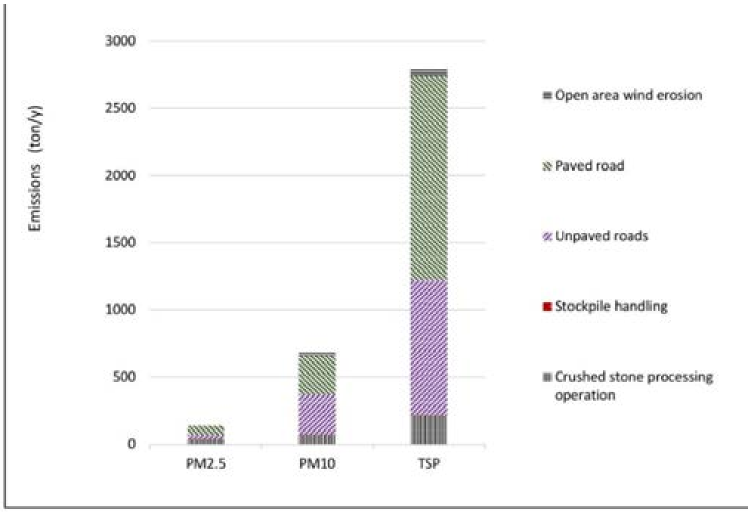


Fig. 4: $PM_{2.5}$, PM_{10} and TSP emissions from the sand and gravel mining processes

Influential parameters

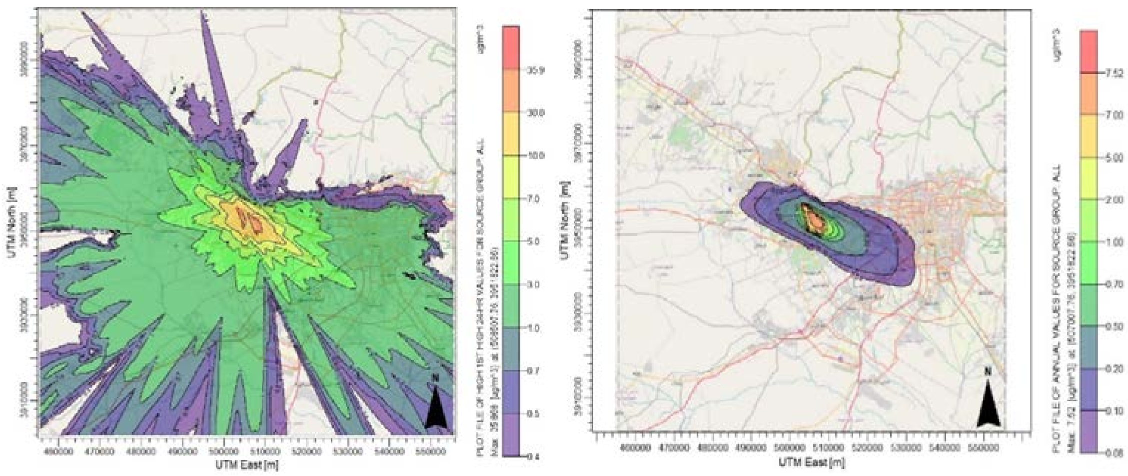
As previously explained by Eqs. 2-5, the wind speed in the area, moisture content of stockpiles, silt content of unpaved roads, silt loading value for paved roads at industrial facilities, and weight of the vehicle travelling on roads were the factors affecting the emission rate of dust from sand and gravel mining operations. The concentration of fugitive dust decreased with a decrease in wind speed, silt content, road surface silt loading, and mean vehicle weight. In contrast, the moisture content is indirectly related to the dust emission from sand and gravel processing operations. Dust emission rate increased with the decrease of moisture content, the weight of particles increased with the increase of moisture content. The moisture made particles heavy and prevented them from dispersing into the atmosphere.

Meteorology

The concentration of pollutants was proportional to the emission rate, wind speed and direction, atmospheric turbulence, and horizontal diffusion direction. In addition to the horizontal flow, the concentration of pollutants was affected by the vertical wind flow. Wind speed changed the concentration of pollutants. Fig. 2 illustrates that the most frequent winds for this period (2015-2019) blew from the northwest direction. The wind speed in the study area varied in the range of 0.5 and 11.10 m/s, and the average wind speed during 2015-2019 was 3.12 m/s. The minimum frequency distribution percentage of the wind speed (0.1%) was related to the speed of over 11.1 m/s, and the maximum frequency distribution percentage of the wind speed (31.8%) was associated with 1.3-2.3 m/s. Calms (wind speed <5 m/s) during the study period occurred 13.9% of the time. The predominant wind direction was towards the southeast direction.

Distribution of particles among aggregate product operations

Fig. 4 shows the total PM2.5, PM10, and TSP emissions from sand and gravel processing operations in the mineral complex. PM2.5, PM10, and TSP



(a) (b)

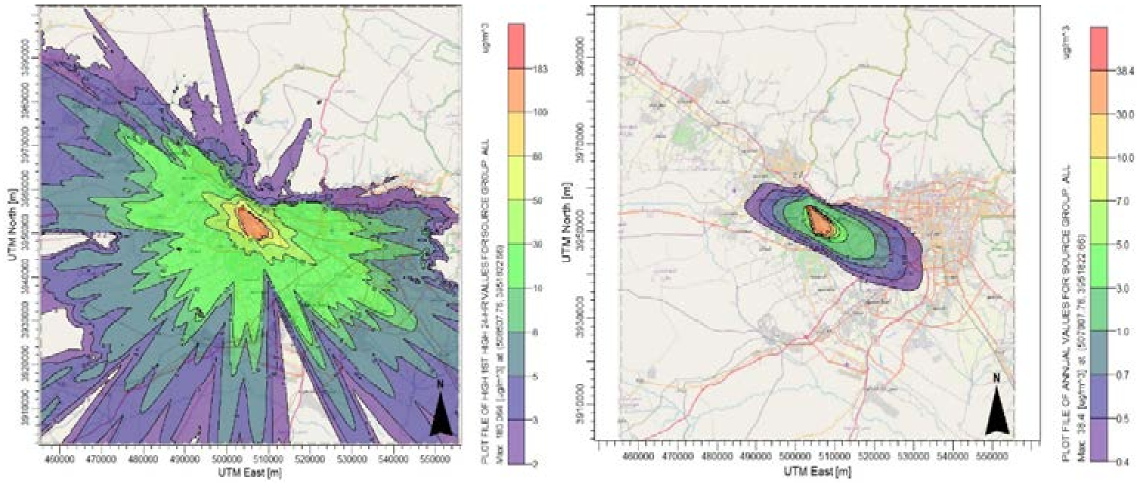
Fig. 5: Dispersion of $PM_{2.5}$ from the sand and gravel product plants: (a) 24-hour average and (b) annual average

emissions were 142.476, 686.066, and 2791.561 tons/y, respectively. Vehicular traffic on paved roads, in the first stand, accounted for 49.55% of the total $PM_{2.5}$ emission, and crushed stone processing operations, which produced 26.90% of the total $PM_{2.5}$ emission, placed the second. Mandal *et al.* (2012) performed a similar study. They found that vehicle travelling on roads was responsible for the highest amount of total dust generation (about 80%) during the operations in opencast mines. In the third stand, Unpaved roads accounted for about 20.62% of the total $PM_{2.5}$ emission, and open area wind erosion contributing to 2.70 % of the total $PM_{2.5}$ emission was in the fourth stand. The highest emission of PM_{10} (43.03%) was related to unpaved roads, followed by paved roads, crushed stone processing operations, and open area wind erosion with 42.53%, 10.38%, 3.73% total PM_{10} emissions, respectively. The highest emission of TSP (54.45%) was related to paved roads, followed by unpaved roads, crushed stone processing operations, and open area wind erosion with 35.80%, 7.76%, and 1.83 % total TSP emissions, respectively. The minimum concentration emitted to the air was due to stockpiles handling with 0.24%, 0.33%, and 0.16% emissions of the total $PM_{2.5}$, PM_{10} and TSP, respectively.

Dispersion of particulate matters

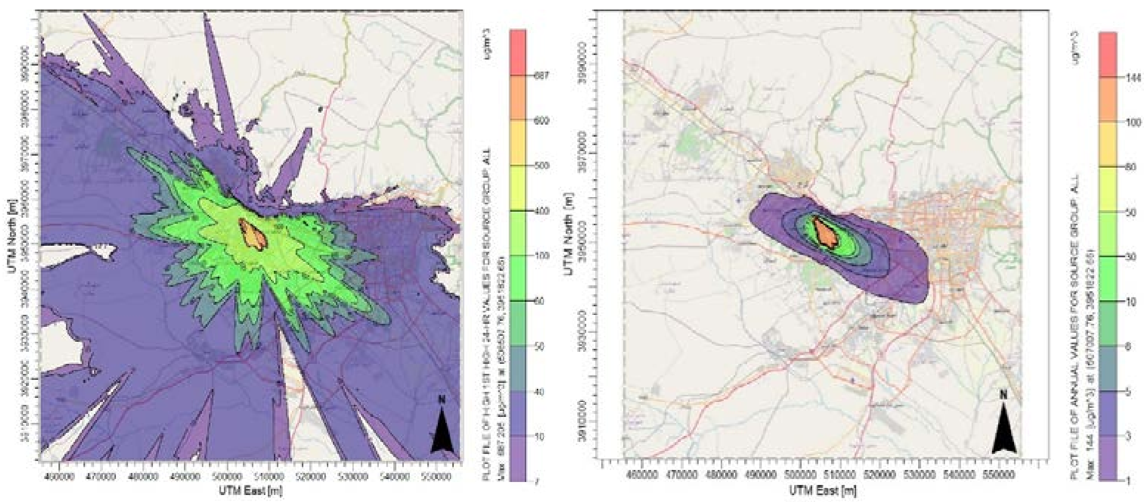
In the Gaussian dispersion model, the concentration of pollutants is directly proportional to the emission rate, wind speed and direction, atmospheric turbulence, horizontal dispersion direction, and vertical wind flow. Vertical and horizontal directions influence concentration. Many factors, such as atmospheric conditions, land use, vegetation cover, and other geographical characteristics, affect atmospheric dust emissions. As shown in Fig. 2, the dominant wind was blowing from northwest to the southeast of the mineral complex, driving the largest particulate matter to residential areas at the southeast of the mineral complex. The dispersion of pollutants concentration in the mineral complex decreased outwards from the source to the point of impact (Fig. 5a-7b) due to wind direction and speed, terrain height, horizontal distance, and other meteorological parameters. Due to the flatness of the study area, particles are uniformly distributed in all areas. Based on the collected data, the sand and gravel product plants in the mineral complex emitted about 36 µg/m^3 of $PM_{2.5}$ (Fig. 5a), 183 µg/m^3 of PM_{10} (Fig. 6a), and 687 µg/m^3 of TSP (Fig. 7a) into the atmosphere in 24-hour average and about eight µg/m^3 of $PM_{2.5}$ (Fig. 5b), 39 µg/m^3 of PM_{10} (Fig. 6b), and 144 µg/m^3 of TSP (Fig. 7b) into the atmosphere in annual average. The maximum 24-hour and annual $PM_{2.5}$, PM_{10}, and TSP concentrations observed in the mineral complex are shown in Table 6.

According to the US EPA reports on ambient air quality, which is valid in Iran as well, the standard values of $PM_{2.5}$ are 35 µg/m^3 (24-hour average)



(a) (b)

Fig. 6: Dispersion of PM_{10} from the sand and gravel product plants: (a) 24-hour average and (b) annual average



(a) (b)

Fig. 7: Dispersion of TSP from the sand and gravel product plants: (a) 24-hour average and (b) annual average

Table 6: Maximum concentrations of PMs emitted from the sand and gravel product plants

Pollutant	Maximum concentration (μg/m^3)	Average time	Geographical coordinates	
			X	Y
$PM_{2.5}$	35.87	24-hour	508507.76	3951822.66
	7.52	annual	507007.76	3951822.66
PM_{10}	183.06	24- hour	508507.76	3951822.66
	38.39	annual	507007.76	3951822.66
TSP	678.2	24- hour	508507.76	3951822.66
	144.12	annual	507007.76	3951822.66

and 12 μg/m³ (annual average), the PM_{10} threshold standard value is 150 μg/m³ (24-hour average), and no standard value is defined for an annual average concentration of PM_{10} (US EPA, 2021c). However, the WHO standard values for $PM_{2.5}$ are 25μg/m³ (24-hour average) and 10 μg/m³ (annual average), and for PM_{10} are 50 μg/m³ (24-hour average) and 20 μg/m³ (annual average) (WHO, 2006). The USEPA and WHO do not have regulated standard values of TSP.

As previously explained, the most frequent winds in 2015-2019 blew from the northwest direction. Dispersion of particulate matter concentrations indicated the significant impact of dust within the mineral complex. This finding was in agreement with the results reported by Lilic *et al.* (2018), who showed that the distribution of PM_{10} from mining operations had a significant impact on the nearby surface mines. In the present study, the modelling results showed that in a wider area around the mineral complex, the 24-hour average concentrations of $PM_{2.5}$, PM_{10}, and TSP decreased from 30, 80, and 400 μg/m³ (immediate vicinity of the mineral complex) to 0.50, 3, and 10 μg/m³ in the Ijdanak and Abyek villages at a distance of about 50 km in the southeast and northwest of the complex, respectively. For example, the 24-hour average concentrations of $PM_{2.5}$, PM_{10}, and TSP, which had reached the areas at distances of 1-9 km from the mineral complex, were approximately in the range of 5-30, 30-80, and 100-400 μg/m³, respectively. The 24-hour average concentrations of the particulate matters reached the residential areas such as Shahre Qods, Andisheh, Shahriar, Malard, and Mohammadshahr townships were approximately 30, 30, 7, 5, and 5 μg/m³ for $PM_{2.5}$, 80, 80, 50, 30, and 30 μg/m³ for PM_{10}, and 400, 400, 400, 100, and 100 μg/m³ for TSP, respectively. In the mentioned townships, the $PM_{2.5}$ concentrations were 5, 5, 28, 30, and 30 μg/m³ less than the EPA standard values, and the PM_{10} concentrations were 70, 70, 100, 120, and 120 μg/m³ less than the EPA standard values, respectively. However, the $PM_{2.5}$ concentrations reached Shahre Qods, and Andisheh townships were 5 and 5 μg/m³ higher than the WHO standard values, respectively. The $PM_{2.5}$ concentrations reached Shahriar, Mallard and Mohammadshahr townships were 18, 20, and 20 μg/m³ lower than the WHO standard values, respectively. Moreover, the PM_{10} concentrations that reached Shahre Qods and Andisheh townships were 30 and 30 μg/m³ higher than the WHO standard values, respectively, and the PM_{10} concentrations in Malard and Mohammadshahr townships were 20 and 20 μg/m³ less than the WHO standard values, respectively. The PM_{10} concentration in Shahriar was almost equal to the standard value. The 24-hour average concentrations of $PM_{2.5}$, PM_{10}, and TSP in Wardavard zone, located in the western part of Tehran, were approximately 7, 50, and 400 μg/m3, respectively, and the 24-hour average concentrations of $PM_{2.5}$, PM_{10}, and TSP reached the center of Tehran, at a distance of 28 km from the mineral complex, were 3, 10, and 40 μg/m³, respectively (lower than the standard values). The 24-hour average concentrations of $PM_{2.5}$, PM_{10}, and TSP reached Hakimiyeh district, at the eastern part of Tehran, were 0.5, 3, and 10 μg/m³, respectively. The 24-hour average concentrations of $PM_{2.5}$ and PM_{10} reached Tehran were below the EPA and WHO standard values. The dispersion of annual average dust concentrations showed a significant decrease. The distributed concentrations of $PM_{2.5}$, PM_{10}, and TSP were 0.1, 0.5, and 3 μg/m³, respectively, towards the southeast of the study area up to Ahmadabad Mostoufi village at a distance of about 9 km from the mineral complex. The annual average concentrations of particulate matters reached Shahre Qods, Andisheh, Shahriar, Malard, and Mohammadshahr townships were approximately 0.7, 0.5, 0.2, 0, and 0.1 μg/m³ for $PM_{2.5}$, 5, 3, 0.7, 0 and 0.5 μg/m³ for PM_{10}, and 30, 10, 3, 0 and 3 μg/m³ for TSP, respectively (lower than the EPA and WHO standard values). Alkas (2016) monitored the suspended particulate matter and settleable particulate matter parameters in Turkey's sand and gravel industry. He showed that the average values for these parameters in the plant were equal to the standards. Sozaeva and Kagermazov (2020) studied the harmful effects of dust emissions from extraction and sand and gravel processes on air quality. Their findings showed that the dust emissions in the study area exceeded the threshold value and became lower than it was only outside the study area. Although the $PM_{2.5}$ and PM_{10} concentrations reached the residential areas around the mineral complex and Tehran were acceptable, these pollutants, along with the pollutant particles emitted from other emission sources, such as vehicles and other industries, could increase the airborne levels of particulate matters and cause air pollution and threaten the health of the people living in the vicinity of the studied mineral complex. Therefore, reducing dust emissions seemed to be essential for reducing air pollution, and it was suggested to be more careful in locating, constructing and developing sand and gravel product plants. Asphalting the unpaved access roads in sand and product plants, which lead to dust emission due to vehicle travelling, was also suggested. Application of some efficient methods, such as using trucks with higher capacity to carry aggregates, spraying water on paved and unpaved roads, storage piles and crushed stones before loading; choose the best strategy to preserve the moisture content of sand and gravel, reducing the silt content of the unpaved roads, and constructing a green belt around the mineral complex, can be followed to mitigate the dust emission. Moreover, the government and responsible organizations should set up and apply laws, regulations and standards related to the sand and gravel processing operations. They should also monitor the aggregate production plants to ensure that they perform all commitments according to the laws and regulations. The government should improve the urban design to protect public health and move the industries with heavy pollutions into the industrial zones.

CONCLUSION

The demand for sand and gravel for different purposes in industry and construction is growing every day. Sand and gravel mining activities generate particulate matters, including $PM_{2.5}$, PM_{10}, and TSP, which increase airborne dust levels. Stone crushing, stockpile handling, traffic roads, and wind erosion are among the sources of particulate matter emissions. Due to the impossibility of sampling and direct measurement of dust concentrations at any time and place, the application of dispersion models for estimating the pollutants concentrations in the atmosphere has been highlighted. Investigation of large-scale sand and gravel processing operations in the South-West of Tehran revealed that vehicle traffic on roads with the rates of 70.2%, 85.6%, and 90.2% for total $PM_{2.5}$, total PM_{10}, and total TSP, respectively, was responsible for the maximum dust emission. However, stockpile handling and storage piles, with the rates of 0.24%, 0.33%, and 0.16% for total $PM_{2.5}$, total PM_{10}, and total TSP, respectively, had limited potential for dust emission. These plants emitted 36 μg/m^3 of $PM_{2.5}$, and 183 μg/m^3 of PM_{10} in 24-hour average and eight μg/m^3 of $PM_{2.5}$, and 39 μg/m^3 of PM_{10} in annual average into the atmosphere. The results showed that the particulate matter significantly impacted airborne dust levels within and beyond the studied mineral complex boundaries. The workers/personnel working at these plants were affected by these pollutants. Therefore, the government and the authorities were expected to take immediate actions and adopt proper policies by enacting appropriate laws and regulations. Significant improvements in technology were required to reduce the dust emissions, and windbreaks as product covers and enclosures were necessary to control the pollutant sources. Further study is recommended to estimate the cumulative dispersion of particulate matter produced by all the industries in the study area. It is better to update the emission factors for local use because of the differences in the measuring conditions of these factors, such as vehicle technology, consumption fuel quality, and culture of driving for mobile sources.

AUTHOR CONTRIBUTIONS

Y. Zehtab Yazdi performed the literature review, collected the data, and ran the model. N. Mansouri conceived the original idea, formulated the study goals, analyzed the study data, prepared the manuscript text and performed the manuscript edition. F. Atabi helped in structuring the study and contributed in interpreting the results and editing the manuscript. H. Aghamohammadi elaborated on the maps and figures.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, the authors have entirely witnessed ethical issues, including plagiarism, informed consent, misconduct, data fabrication and falsification, double publication and submission, and redundancy.

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ABBREVIATIONS

%	Percentage
∂	Partial Derivative
ADT	Average Daily Traffic
AERMOD	American Meteorological Society/ Environmental Protection Agency Regulatory Model Improvement Committee Dispersion Model
a.m.	ante meridiem: before noon
AMS	American Meteorological Society
AP-42	Compilation of air emission factor
ASTM	American Society for Testing and Materials
AURORA	Air Quality Modeling in Urban Regions using an Optimal Resolution Approach
°C	Degrees Celsius
CALPUFF	California Puff Model
CE	Control Efficiency
CFD	Computational Fluid Dynamic
CPB	Canyon Plume Box
E	East
EF	Emission Factor
e.g.,	exempli gratia: for example,
EPA	Environmental Protection Agency
etc.	et cetera: and other similar things
Eq.	Equation
et al.	et alia: and others
ER	Efficiency Reduction
FDM	Fugitive Dust Model
Fig	Figure
g	gram
g/m^3	Gram per cubic meters
GRAL	Graz Lagrangian Model
ha	Hectare
ISC-3	Industrial Source Complex 3
Kg	Kilogram
Km	Kilometer
Km^2	Square kilometers
lb	Pound
m^2	Square meters
mm	Millimeter
m/s	Meter per second
$\mu g/m^3$	Microgram per cubic meters
µm	Micrometers
MICRO-CALGRID	Microscale California Photochemical Grid Model
MISKAM	Microscale flow and dispersion model
N	North
OSPM	Operational Street Pollution Model
PBM	Photochemical Box Model
p.m.	post meridiem: Afternoon
PM	Particulate Matter
$PM_{2.5}$	particulate matter with an aerodynamic diameter of less than or equal to 2.5 micrometers
PM_{10}	particulate matter with an aerodynamic diameter of less than or equal to 10 micrometers
TSP	Total suspended particulate

TAPM	The Air Pollution Model
UK-ADMS	UK Atmospheric Dispersion Modeling System
US EPA	United States Environmental Protect Agency
VKT	Vehicle Kilometers Travelled.
VMT	Vehicle Miles Travelled
WHO	World Health Organization
y	Year

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