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Particulate matter exchange between atmosphere and roads surfaces in urban areas

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ABSTRACT

The deposition and the re-suspension of particulate matter (PM) in urban areas are the key processes that contribute not only to stormwater pollution, but also to air pollution. However, investigation of the deposition and the re-suspension of PM is challenging because of the difficulties in distinguishing between the resuspended and the deposited PM. This study created two Bayesian Networks (BN) models to explore the deposition and the re-suspension of PM as well as the important influential factors. The outcomes of BN modelling revealed that deposition and re-suspension of PM10 occurred under both, high-traffic and low-traffic conditions, and the re-suspension of PM2.5 occurred under low-traffic conditions. The deposition of PM10 under low-volume traffic condition is 1.6 times higher than under high-volume traffic condition, which is attributed to the decrease in PM10 caused by relatively higher turbulence under high-volume traffic conditions. PM10 is more easily resuspended from road surfaces compared to PM2.5 as the particles which larger than the thickness of the laminar airflow over the road surface are more easily removed from road surfaces. The increase in wind speed contributes to the increase in PM build-up by transporting particulates from roadside areas to the road surfaces and the airborne PM2.5 and PM10 increases with the increase in relative humidity. The study outcomes provide a step improvement in the understanding of the transfer processes of PM2.5 and PM10 between atmosphere and urban road surfaces, which in turn will contribute to the effective design of mitigation measures for urban stormwater and air pollution.

Introduction

Particulate Matter (PM) in urban areas has raised significant concerns in relation to public health (Liu et al., 2018). For example, PM in the atmosphere can contribute to respiratory and cardiovascular diseases, resulting in high mortality (Brook et al., 2010; Liu et al., 2019; Yang et al., 2019). Similarly, PM deposited on urban road surfaces can be washed-off by stormwater runoff, leading to non-point source pollution of receiving waters (Ma et al., 2018).

Denby et al. (2018) reported that atmospheric deposition is one of the important sources of road deposited PM. Additionally, PM on road surfaces can re-suspend back into the atmosphere (Amato et al., 2010; Amato et al., 2016). For example, Ramírez et al. (2019) noted that local soils and pavement erosion are the main sources (63%) of the PM10 fraction. Due to the dynamic nature of re-suspension and deposition of PM (Abt et al., 2000), the investigation of the transfer of PM between the atmosphere and road surfaces is challenging.

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Firstly, there are difficulties in distinguishing between PM re-suspension and deposition. This is due to the fact that the fraction of re-suspended or deposited PM is difficult to assess. The PM originating from wear emissions of traffic and road surfaces cannot be differentiated easily using field data (Rissler et al., 2012; Rivas et al., 2020). Secondly, although in recent years, a number of research studies have been undertaken to investigate the re-suspension and the deposition of PM under the influence of anthropogenic and natural factors, these studies have explored the re-suspension process and deposition process separately, despite the fact that these two phases are closely linked. For example, Fang et al. (2010) estimated the deposition of particulate-bound Hg(p) using an improved deposition model, and Moran et al. (2013) investigated the deposition of PM10 under the influences of wind turbulence using a conceptual model. On the other hand, researchers have simply explored the re-suspension process of PM. Ketzel et al. (2007) investigated particulate re-suspension via monitoring the tracer element NOx. Amato et al. (2009) used factor analysis (FA) to estimate the contribution of re-suspension of PM. Zhao et al. (2016) explored the potential pollution contribution of re-suspension to atmospheric PM employing an innovative road dust index model.

In addition, the variation in influential factors such as traffic conditions and weather characteristics further adds to the complexity in understanding the transfer of PM between road surfaces and the atmosphere. Traffic volume is a significant factor that influences the re-suspension of PM. As noted by Hinds (1999), the airflow generated by passing vehicles induces the re-suspension of PM on road surfaces. Factors such as land use, street sweeping frequency, road surface texture depth, and wind speed can indirectly influence the re-suspension of PM by affecting the amount of PM on road surfaces (Keuken et al., 2010; Gunawardana et al., 2012; Amato et al., 2016; Liu et al., 2017; Li et al., 2018; Crilley et al., 2017). Factors such as atmospheric temperature, relative humidity, wind speed and traffic volume also contribute to the transfer of PM between road surfaces and the atmosphere (Artı́ñano et al., 2004; Tai et al., 2010; Amato et al., 2014; He et al., 2017).

Although the relationships between airborne PM concentration and meteorological parameters have been investigated (Gui et al., 2019), so far, no methodological approaches have been established to create an in-depth understanding of PM re-suspension and deposition, namely, the exchange of PM between the atmosphere and road surfaces. Further, the impacts of influential factors on the transfer of PM is not clearly known. Therefore, there is a knowledge gap in relation to the transfer of PM between the atmosphere and road surfaces as well as the role played by the various influential factors.

Accordingly, the primary aim of this study was to understand the exchange of PM between the atmosphere and road surfaces. Accordingly, two statistical models were developed to explore the deposition and re-suspension of PM. The impacts of anthropogenic factors (traffic and road sweeping activity), road surface condition (road texture depth), as well as meteorological factors (wind speed, atmospheric temperature and relative humidity) on the transfer of PM were also investigated. The outcomes of this study present new insights for understanding PM transfer between the atmosphere and road surfaces, and the role played by a range of influential factors on the transfer of PM. Consequently, it will contribute to the formulation of more effective stormwater and air pollution mitigation strategies.

1. Materials and methods

1.1. Study sites and data collection

1.1.1. Study sites

The location of study sites is provided in Fig. S1 in the Supplementary Information. The sampling sites are located in Hebi City, Henan Province, China. Hebi City hosts 1.6 million people and has a sub-humid climate with wet summers and dry winters with 350-970 mm annual rainfall and an average annual atmospheric temperature of about 14°C. Two roads, R1 and R4 were selected as sampling sites. The traffic volume at R4 (36,000 vehicles per day) site is about 20 times the traffic volume at R1 site (1,800 vehicles per day). The road surface texture depth of R1 and R4 is 0.33 mm and 0.28 mm, respectively. The road sweeping frequency of R1 and R4 were twice a day and four times a day, respectively (Wei et al., 2019).

1.1.2. Data collection

Current air quality standards for particulate matter uses the mass concentration of PM2.5 (Particulate matter aerodynamic diameter < 2.5 μm) and PM10 (Particulate matter aerodynamic diameter between 2.5 and 10 μm) as metrics (Janssen et al., 2011), which are supported by health studies, showing it is inhalable (Cao et al., 2014) and are carriers of toxicants such as metals and hydrocarbons (Pandey et al., 2013). Hence, in this study, PM2.5 and PM10 were chosen to investigate the re-suspension and the deposition of PM.

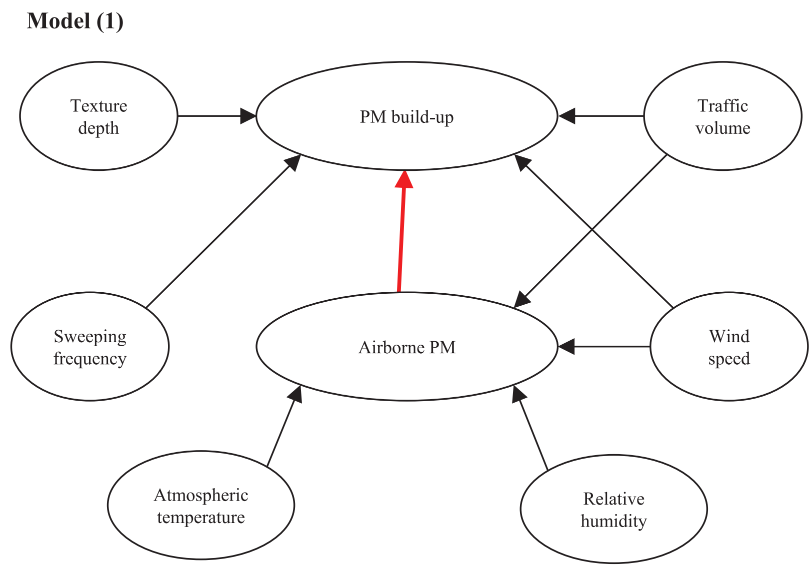
In order to investigate the re-suspension and the deposition of PM2.5 and PM10, data on PM build-up on road surfaces and data on airborne PM in the atmosphere were needed. Accordingly, PM build-up samples were collected from small plots of 2-20 m^2, 0.5 m from the road edge at each road site for antecedent dry periods of 1, 2, 3, 4, 5, 7, 9, 11 and 13 days. Samples were initially collected using a domestic wet and dry vacuum cleaner (Deerma DX132F), which was found to have a removal efficiency of 95% for 0.3 μm particles (confirmed by the supplier). Details on data collection on PM build-up can be found in Wei et al. (2019). The smallest size class of 0-22μm PM was selected to investigate the PM exchange between road surfaces and atmosphere. Data on sweeping frequency at the two road sites were obtained from the road cleaning agency. The road surface texture depth was measured using the Sand Patch Test method (Kim et al., 2013). Data on airborne PM2.5 and PM10 for the 9 antecedent dry periods were obtained from the website of the Ministry of Ecology and Environment of the People's Republic of China (http://www.mee.gov.cn/, date: 2017.10.14-2017.10.31). The hourly PM2.5 and PM10 data are published online, and the mean daily data were collected for this study.

Data on wind speed, atmospheric temperature and relative humidity were obtained from the Yinbingguan air quality monitoring station which is managed by the Chinese National Meteorological Information Centre and is the closest to the two build-up sampling sites. In the study sites, wind speed ranges from 0-5.4 m/sec. Daily traffic at each sampling site was video-recorded during peak and non-peak periods, while a 24-hour video was also recorded to infer the daily traffic volume.

1.2. Bayesian networks (BN) modelling

Bayesian networks (BN) are a graphical modelling approach based on Bayesian statistical methods, which characterise systems/processes as a network of collaborations between variables from prime cause to final consequence, with all the cause-effect assumptions made explicitly (Voinov and Bousquet, 2010). It defines relationships between variables in terms of the conditional probabilities included in the network (Borsuk, 2008). The directed acyclic graphical (DAG) structure (i.e. a directed graph without any loops) is a general way to present BN in which variables are represented by the nodes and the dependencies between nodes are represented by directed edges (Phan et al., 2016).

The movement of PM from the atmosphere to road surfaces can be understood by considering how airborne PM influences PM build-up. The transfer of PM from road surfaces to the atmosphere can also be explained by considering how PM build-up influences airborne PM. In addition, the influence of traffic volume, land use, street sweeping frequency, road surface texture



Conditional density
PM Build-up | Traffic volume: Wind speed: Texture depth: Sweeping frequency
Airborne PM | PM Build-up: Traffic volume: Wind speed: Relative humidity: Atmospheric temperature

Fig. 1 – DAG structure for the BN model (1) to investigate PM transfer from the atmosphere to road surfaces.

depth, and wind speed on PM build-up as well as the role of atmospheric temperature, relative humidity, wind speed and traffic volume on airborne PM were also needed to be explained to better understand the transfer of PM. Therefore, in order to identify the exchange of PM, the relationships between the variables noted above were identified using BN.

2. Results and discussion

2.1. *Development of BN models*

2.1.1. *Model set up*

As discussed in Section 2.2, the BN model (1), namely, the deposition model, was proposed to recognize the transfer of PM from the atmosphere to road surfaces, as depicted in Fig. 1. In the BN model (1), the PM build-up was taken as the primary receptor which is directly influenced by airborne PM, as well as factors such as traffic volume, sweeping frequency, texture depth, and wind speed, and indirectly influenced by atmospheric temperature and relative humidity.

BN model (2), namely the re-suspension model, was proposed to distinguish the PM transfer from road surfaces to the atmosphere, as depicted in Fig. 2. In BN model (2), the airborne PM was taken as the main receptor which is directly influenced by PM build-up, as well as factors such as traffic volume, wind speed, atmospheric temperature and relative humidity and indirectly influenced by sweeping frequency and texture depth. Land use was not included in both, BN model (1) and BN model (2) as it was similar for both sampling sites.

2.1.2. *Model input*

Before data input into the BN models, the distribution and correlation of the data were investigated using SPSS. It was found that: (1) sweeping frequency and road texture depth are constant; (2) the daily traffic volume changes with the study sites, but does not change obviously with sampling date. Hence, data relating to traffic volume, sweeping frequency and road texture depth were input into the BN model as qualitative data. Data on PM build-up, airborne PM10 and PM2.5, wind speed, atmospheric temperature and relative humidity were quantitative data. The qualitative data were input as Yes/No. In order to present the impact of traffic volume, sweeping frequency and road texture depth more directly, “Yes” was considered as high-volume traffic conditions $>$ 10,000 vehicles/day, high sweeping frequency $>$ 3 times/day, and shallow texture depth $<$ 0.3 mm, and “No” was regarded as low-volume traffic condition (low traffic volume $<$ 10,000 vehicles/day, low sweeping frequency $<$ 3 times/day, and deep texture depth $>$ 0.3 mm).

2.2. *Case study: the transfer of PM*

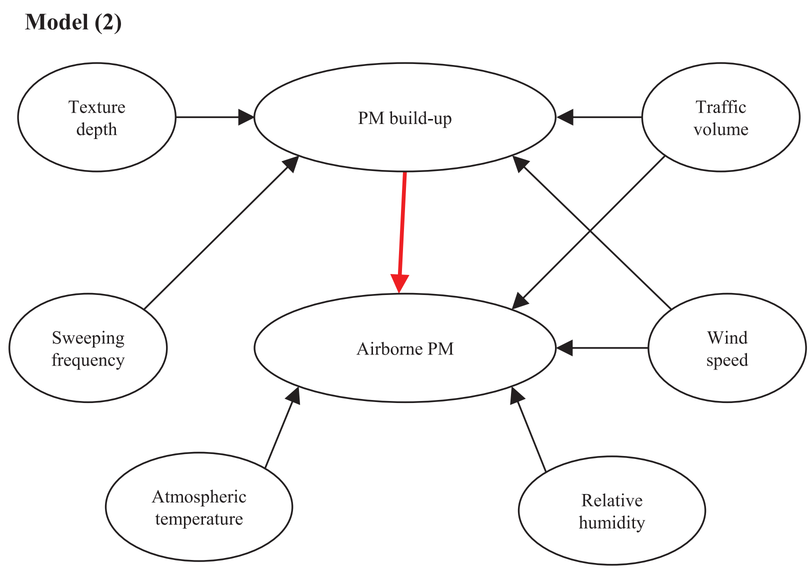
2.2.1. *Performance of the BN modelling*

The data collected were input into the two BN models to explore the deposition of airborne PM2.5 and PM10 and the re-suspension of the PM build-up. The results of the simulation of the BN model (1) and BN model (2) are given in Fig. S2 and Fig. S3 in the Supplementary Information. From these figures, it is evident that model simulations are satisfactory for the PM build-up, airborne PM2.5 and airborne PM10.

The conditional regression coefficients for the influential factors of the BN model (1) are shown in Table 1, which indicates the deposition of airborne PM. The conditional regression coefficients of BN model (2) are shown in Table 2, which indicates the re-suspension of build-up PM. As shown in Table 1 and Table 2, the coefficients under high-volume traffic condition and low-volume traffic conditions were obtained.

2.2.2. *Analysis of the deposition of PM*

The positive/negative coefficients in Table 1 relates to the positive/negative impact on airborne PM2.5, PM10 from influential factors on PM build-up; the relative humidity, atmospheric tem-



Conditional density
PM Build-up | Traffic volume: Wind speed: Texture depth: Sweeping frequency
Airborne PM | Build-up PM: Traffic volume: Wind speed: Relative humidity: Atmospheric temperature

Fig. 2 – DAG structure for the BN model (2) to investigate PM transfer from road surfaces to the atmosphere.

Table 1 – Conditional regression coefficients for the influential factors of PM build-up (conditional Gaussian distribution, standardized data) for BN model (1).

Conditional density: PM build-up | Airborne PM2.5: Airborne PM10: Wind speed

Coefficients (Contribution %)	Intercept	Airborne PM2.5	Airborne PM10	Wind speed
High-volume traffic condition	-0.84	-0.42	0.55	0.24
Low-volume traffic condition	0.63	-0.85	0.88	0.53

Note 1: Conditional density refers to the probability density function for the PM build-up, given Airborne PM2.5, Airborne PM10, and wind speed.
Note 2: Data on sweeping frequency, texture depth and traffic volume were fed as qualitative data and the impacts were integrated into high/low -volume traffic conditions.

Table 2 – Conditional regression coefficients for airborne PM2.5 and PM10 (conditional Gaussian distribution, standardized data) for BN model (2).

Conditional density: Airborne PM2.5 or PM10 | PM build-up: Relative humidity: Atmospheric temperature: Wind speed

Coefficients (Contribution %)		Intercept	PM build-up	Relative humidity	Atmospheric temperature	Wind speed
Airborne PM2.5	High-volume traffic condition	-0.32	-0.5	1.09	0.11	0.19
	Low-volume traffic condition	-0.14	0.13	0.54	0.50	0.03
Airborne PM10	High-volume traffic condition	0.78	0.75	1.08	-0.14	-0.21
	Low-volume traffic condition	-0.27	0.29	0.70	0.12	-0.19

Note 1: Conditional density refers to the probability density function of airborne PM2.5 or PM10, given PM build-up, relative humidity, atmospheric temperature, and wind speed.
Note 2: Data on sweeping frequency, texture depth and traffic volume were fed as qualitative data and the impacts were integrated into high/low -volume traffic conditions.

perature as well as wind speed. These positive or negative impacts are presented in Table 3.

It is evident from Table 3, that in BN model (1), the impacts of airborne PM10 on PM build-up are positive under both, high-volume and low-volume traffic condition. This suggests that with the increase in airborne PM10, the amount of PM build-up increases, which coincides with the deposition behaviour of airborne PM. This means that PM10 undergoes obvious deposition under both, high-volume and low-volume traffic conditions. It is also evident from Table 3 that under both, high-volume and low-volume traffic conditions, the impact of airborne PM2.5 on the PM build-up is negative. This indicates that the increased

Table 3 – Impact on PM build-up from influential factors.

Relationships		Airborne PM2.5	Airborne PM10	Wind speed
PM build-up	High-volume traffic condition	-	+	+
	Low-volume traffic condition	-	+	+

Table 4 – Impacts on airborne PM2.5 and PM10 from PM build-up as well as influential factors.

Relationships		PM build-up	Relative humidity	Atmospheric temperature	Wind speed
Airborne	High-volume traffic condition	-	+	+	+
PM2.5	Low-volume traffic condition	+	+	+	+
Airborne	High-volume traffic condition	+	+	-	-
PM10	Low-volume traffic condition	+	+	+	-

airborne PM2.5 do not cause an increase in the PM build-up. It implies that the deposition of PM2.5 did not occur under both high-volume and low-volume traffic conditions at the study site.

Table 1 shows that the conditional regression coefficient for PM10 under low-volume traffic conditions (0.88) is 0.6 times higher than it is under high-volume traffic conditions (0.55). This implies that the deposition of PM10 is higher under low-volume traffic conditions. This phenonmenon can be attributed to the fact that high traffic volume would lead to greater re-suspension, which further leads to relatively lower depostion process at the study sites.

2.2.3. *Analysis of the re-suspension of PM*

The positive/negative coefficients in Table 2 means the positive/negative impact on PM build-up from influential factors of airborne PM2.5, PM10 as well as wind speed. These positive or negative impacts are presented in Table 4.

As shown in Table 4, the impact of PM build-up on airborne PM2.5 is negative under high-volume traffic condition, but is positive under low-traffic condition. This indicates the increased PM build-up did not cause the increase in airborne PM2.5 at high traffic volume condition, whereas it causes the increase in airborne PM2.5 at low traffic volume condition. It is also evident from Table 4 that under both, low-volume and high-volume traffic conditions, PM build-up on road surfaces has positive impact on airborne PM10. This suggests the increased PM build-up leading to the increase in airborne PM10 under both, high and low-volume traffic conditions. Hence, the modelling results confirmed that PM10 exhibits re-suspension behaviour under both, high-volume and low-volume traffic conditions at the study sites, whilst PM2.5 exhibits re-suspension behaviour under low-volume traffic conditions, but do not exhibit re-suspension behaviour under high-volume traffic conditions.

It can be inferred from above that PM10 are more easily resuspended from road surfaces compared to PM2.5. This phenomenon agrees with the concept proposed by Hinds (1999) that due to the thin laminar airflow arising from traffic induced turbulence, only the particles that are larger than the thickness of this airflow could be moved and resuspended.

2.2.4. *Impact of wind speed on PM build-up*

As evident from Table 3, positive coefficients were obtained for wind speed under both, high-volume and low-volume traffic conditions. The positive coefficients suggest that PM build-up increases with increased wind speed. This is attributed to the fact that the increase in wind speed would contribute more fine particles from roadside soil to the samplings sites.

2.2.5. *Impacts of relative humidity, wind speed and atmospheric temperature on airborne PM 2.5 and PM10*

Relative humidity, atmospheric temperature and wind speed were the meteorological factors taken into consideration in the analysis. As evident from Table 3, relative humidity has a positive impact on airborne PM2.5 and PM10 under both, high-volume and low-volume traffic conditions. This suggests that with the increase in relative humidity, the amount of airborne PM2.5 and PM10 increases. Similarly, Zhao et al. (2014) also found that PM10 and PM2.5 increases with increasing relative humidity.

As evident from Table 4, wind speed has a positive impact on airborne PM2.5, but has a negative impact on airborne PM10. This indicates that during the monitored days, the quantity of PM2.5 grew with the increased wind speed ranging from 0-5.4 m/sec, and the amount of PM10 decreased with increasing wind speed. The phenomenon that airborne PM10 decreases with increased wind speed has been confirmed by field observations undertaken by Akyuz and Cabuk, 2009.

As evident from Table 4, both positive and negative relationships between atmospheric temperature and airborne PM2.5 and PM10 were found in this study. The positive relationship means that with the increase in atmospheric temperature, the amount of airborne PM increases. The negative relationship indicates with the increasing atmospheric temperature, the amount of airborne PM declines. The positive relationship between atmospheric temperature and airborne PM has been observed in previous studies, such as the study by Vardoulakis and Kassomenos (2008) in Athens (Greece) and Birmingham(UK) and the study by Zhao et al. (2014) in Beijing. It is worthy to note that during the monitoring days, the atmospheric temperature at the study sites only ranged from 17-24°C. Within this range, no clear effect on airborne PM2.5 and PM10 were observed.

3. Conclusions

This study investigated the re-suspension and deposition of PM2.5 and PM10 by creating a deposition model and a resuspension model based on Bayes Network model. The study outcomes confirmed PM10 displays deposition behaviour under both, high and low-volume traffic condition as well as resuspension. On the other hand, PM2.5 displays re-suspension of under low-volume traffic condition. The study results also revealed that the deposition of PM2.5 under both, high and low-volume traffic condition and the re-suspension of PM2.5 under high-volume traffic conditions did not occur in the study area. In addtion, the positive impact of wind speed on PM build-up, the positive impact of relative humidity on airborne PM2.5 and PM10, the positive impact of wind speed on airborne PM2.5, as well as the negative impact of wind speed on airborne PM10 were noted. The study outcomes provide an in-depth understanding of the re-suspension and deposition of PM, which will contribute to the development of more reliable stormwater treatment and air pollution mitigation strategies.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A Supplementary data

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jes.2020.05.027.

REFERENCES

Abt, E., Suh, H.H., Allen, G., Koutrakis, P., 2000. Characterization of indoor particle sources: a study conducted in the metropolitan Boston area. Environ. Health Perspect. 108 (1), 35–44.
Akyuz, M., Cabuk, H., 2009. Meteorological variations of PM2.5/PM10 concentrations and particle-associated polycyclic aromatic hydrocarbons in the atmospheric environment of Zonguldak. Turkey. J. Hazard. Mater. 170 (1), 13–21.
Amato, F., Cassee, F.R., Der Gon, H.D, Gehrig, R., Gustafsson, M., Hafner, W., et al., 2014. Urban air quality: the challenge of traffic non-exhaust emissions. J. Hazard. Mater. 275 (1), 31–36.
Amato, F., Favez, O., Pandolfi, M., Alastuey, A., Querol, X., Moukhtar, S., et al., 2016. Traffic induced particle resuspension in Paris: emission factors and source contributions. Atmos. Environ. 129, 114–124.
Amato, F., Nava, S., Lucarelli, F., Querol, X., Alastuey, A., Baldasano, J.M., et al., 2010. A comprehensive assessment of PM emissions from paved roads: real-world emission factors and intense street cleaning trials. Sci. Total Environ. 408 (20), 4309–4318.
Amato, F., Pandolfi, M., Escrig, A., Querol, X., Alastuey, A., Pey, J., et al., 2009. Quantifying road dust resuspension in urban environment by multilinear engine: a comparison with PMF2. Atmos. Environ. 43 (17), 2770–2780.
Artinano, B., Salvador, P., Alonso, D.G., Querol, X., Alastuey, A., 2004. Influence of traffic on the PM10 and PM2.5 urban aerosol fractions in Madrid (Spain). Sci. Total Environ. 334-335, 111–123.
edited by Borsuk, M.E., 2008. Bayesian networks. In: Jørgensen, S.E., Fath., B.D (Eds.), Encyclopedia of Ecology. Academic Press, Oxford, pp. 307–317 edited by.
Brook, R.D., Rajagopalan, S., Pope, C.A., Brook, J.R., Bhatnagar, A., Diezroux, A.V., et al., 2010. Particulate matter air pollution and cardiovascular disease: an update to the scientific statement from the American Heart Association. Circulation 121 (21), 2331–2378.
Cao, C., Jiang, W., Wang, B., Fang, J., Lang, J., Tian, G., et al., 2014. Inhalable microorganisms in Beijing's PM2.5 and PM10 pollutants during a severe smog event. Environ. Sci. Technol 48, 1499–1507.
Crilley, L.R., Lucarelli, F., Bloss, W.J., Harrison, R.M., Beddows, D.C., Calzolai, G., et al., 2017. Source apportionment of fine and coarse particles at a roadside and urban background site in London during the 2012 summer ClearfLo campaign. Environ. Pollut. 220, 766–778.
Denby, B.R., Kupiainen, K.J., Gustafsson, M, 2018. Chapter 9 - review of road dust emissions. In: Amato, F. (Ed.), Non-Exhaust Emissions. Academic Press, pp. 183–203.
Fang, G.C., Yang, I.L., Liu, C.K., 2010. Estimation of atmospheric particulates and dry deposition particulate-bound mercury Hg(p) in Sha-Lu, Taiwan. Aerosol Air Qual. Res. 10 (5), 403–413.
Gui, K., Che, H., Wang, Y., Wang, H., Zhang, L., Zhao, H., et al., 2019. Satellite-derived PM2.5 concentration trends over Eastern China from 1998 to 2016: relationships to emissions and meteorological parameters. Environ. Pollut. 247, 1125–1133.
Gunawardana, C., Goonetilleke, A., Egodawatta, P., Dawes, L.A., Kokot, S., 2012. Source characterisation of road dust based on chemical and mineralogical composition. Chemosphere 87 (2), 163–170.
He, J., Gong, S., Yu, Y., Yu, L., Wu, L., Mao, H., et al., 2017. Air pollution characteristics and their relation to meteorological conditions during 2014-2015 in major Chinese cities. Environ. Pollut. 223, 484–496.
Hinds, W.C., 1999. Aerosol Technology: Properties, Behavior, and Measurement of Airborne Particles. John Wiley & Sons.
Janssen, N.A., Hoek, G., Simiclawson, M., Fischer, P., Van Bree, L., Brink, H.T., et al., 2011. . Black carbon as an additional indicator of the adverse health effects of airborne particles compared with PM10 and PM2.5. Environ. Health Perspect. 119, 1691–1699.
Ketzel, M., Omstedt, G., Johansson, C., During, I., Pohjola, M., Oettl, D., et al., 2007. . Estimation and validation of PM2.5/PM10 exhaust and non-exhaust emission factors for practical street pollution modelling. Atmos. Environ. 41 (40), 9370–9385.
Keuken, M., Gon, Der, D., H., Der Valk, K.V, 2010. Non-exhaust emissions of PM and the efficiency of emission reduction by road sweeping and washing in the Netherlands. Sci. Total Environ. 408 (20), 4591–4599.
Kim, H.B., Lee, S.W., Hyun, T., Lee, K., 2013. Measurement of texture depth of pavement using potable laser profiler. J. East. Asia Soc. Transp. Stud. 10, 1576–1589.
Li, Y., Jia, Z., Wijesiri, B., Song, N., Goonetilleke, A., 2018. Influence of traffic on build-up of polycyclic aromatic hydrocarbons on urban road surfaces: a Bayesian network modelling approach. Environ. Pollut. 237, 767–774.
Liu, A., Ma, Y., Deilami, K., Egodawatta, P., Goonetilleke, A., 2017. Ranking the factors influencing polycyclic aromatic hydrocarbons (PAHs) build-up on urban roads. Ecotox. Environ. Saf. 139, 416–422.
Liu, A., Wijesiri, B., Hong, N., Zhu, P., Egodawatta, P., Goonetilleke, A., 2018. Understanding re-distribution of road deposited particle-bound pollutants using a Bayesian Network (BN) approach. J. Hazard. Mater. 355, 56–64.
Liu, C., Chen, R., Sera, F., Vicedocabrera, A.M., Guo, Y., Tong, S., et al., 2019. Ambient particulate air pollution and daily mortality in 652 cities. N. Engl. J. Med. 381, 705–715.
Ma, Y., Hao, S., Zhao, H., Fang, J., Zhao, J., Li, X., 2018. Pollutant transport analysis and source apportionment of the entire non-point source pollution process in separate sewer systems. Chemosphere 211, 557–565.
Moran, S., Pardyjak, E.R., Veranth, J.M., 2013. Understanding the role of grid turbulence in enhancing PM10 deposition: scaling the stokes number with Rλ. Phys. Fluids 25 (11), 115103.
Pandey, P., Patel, D.K., Khan, A.H., Barman, S.C., Murthy, R.C., Kisku, G.C., 2013. Temporal distribution of fine particulates (PM2. 5, PM10), potentially toxic metals, PAHs and metal-bound carcinogenic risk in the population of Lucknow City, India. J. Environ. Sci. Health, Part A 48 (7), 730–745.
Phan, T.D., Smart, J.C., Capon, S.J., Hadwen, W.L., Sahin, O., 2016. Applications of Bayesian belief networks in water resource management: a systematic review. Environ. Modell. Softw. 85, 98–111.
Rissler, J., Swietlicki, E., Bengtsson, A., Boman, C., Pagels, J., Sandstrom, T., et al., 2012. Experimental determination of deposition of diesel exhaust particles in the human respiratory tract. J. Aerosol Sci. 48, 18–33.
Rivas, I., Beddows, D.C., Amato, F., Green, D.C., Jarvi, L., Hueglin, C., et al., 2020. . Source apportionment of particle number size distribution in urban background and traffic stations in four European cities. Environ. Int. 135, 105345.
Tai, A.P., Mickley, L.J., Jacob, D.J., 2010. Correlations between fine particulate matter (PM2.5) and meteorological variables in the United States: implications for the sensitivity of PM2. 5 to climate change. Atmos. Environ. 44 (32), 3976–3984.
Vardoulakis, S., P, Kassomenos, 2008. Sources and factors affecting PM10 levels in two European cities: Implications for local air quality management. Atmos. Environ. 42 (17), 3949–3963.
Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environ. Modell. Softw. 25, 1268–1281.
Wei, T., Wijesiri, B., Jia, Z., Li, Y., Goonetilleke, A., 2019. Re-thinking classical mechanistic model for pollutant build-up on urban impervious surfaces. Sci. Total Environ. 651, 114–121.
Yang, Y., Ruan, Z., Wang, X., Mason, T.G., Lin, H., Tian, L., 2019. Short-term and long-term exposures to fine particulate matter constituents and health: a systematic review and meta-analysis. Environ. Pollut. 247, 874–882.
Zhao, C.X., Wang, Y., Wang, Y., Zhang, H.L., Zhao, B.Q., 2014. Temporal and spatial distribution of PM2.5 and PM10 pollution status and the correlation of particulate matters and meteorological factors during winter and spring in Beijing. Environ. Sci. (China) 35 (2), 418–427.
Zhao, H., Shao, Y., Yin, C., Jiang, Y., Li, X., 2016. An index for estimating the potential metal pollution contribution to atmospheric particulate matter from road dust in Beijing. Sci. Total Environ. 550, 167–175.