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OCCUPATIONAL HEALTH AND SAFETY RISK EVALUATION OF PM2.5 AIR POLLUTION DURING THE HEATING SEASON IN BELGRADE, SERBIA

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Abstract: Belgrade has faced persistent air pollution for decades, with particulate matter concentrations frequently exceeding World Health Organization (WHO) limits during the heating season. Among major pollutants, fine particulate matter smaller than 2.5 μm (PM2.5) poses particular risks to health and has gained increasing attention in occupational safety and health research. This study examined the frequency of low-wind-speed days and the distribution of PM2.5 concentrations under such conditions to assess monthly risk levels during the heating season. Results show that October, December, and January are periods of elevated occupational health and safety risk. These findings highlight the need for preventive measures, such as shorter outdoor shifts, increased rest breaks, and task rotation, to reduce worker exposure to hazardous PM2.5 levels.

Key words: risk, occupational safety and health, air pollution, pm2.5, heating season

INTRODUCTION

Air pollution represents one of the most serious public health challenges in modern urban environments. Consequently, all occupations predominantly performed outdoors are significantly affected. Fine particles with a diameter of less than 2.5 micrometers (PM2.5) are particularly dangerous, as their small size allows them to penetrate deep into the respiratory system and enter the bloodstream, causing a wide range of adverse health effects. According to the World Health Organization (WHO) reports indicate that nearly the entire world’s population (99%) lives in areas with air quality below recommended levels. Globally, air pollution ranks as the second most important risk factor for mortality and for deaths in children under five, following malnutrition. In 2021, it was linked to 8.1 million deaths, with 58% caused by PM2.5 exposure [1].

Among the cities in Serbia, Belgrade stands out as a critical hotspot. As the largest urban center and the main administrative, economic, and transportation hub of the country, the city faces serious air quality challenges. During the heating season, the intensive use of fossil fuels in individual boilers and thermal power plants significantly increases emissions of harmful substances. In addition, the specific meteorological conditions characteristic of Belgrade during the winter months further degrades air quality. High atmospheric pressure, weak winds, and frequent temperature inversions, which can extend up to 700 - 1000 meters in height, together with the occurrence of fog and light drizzle, represent the most unfavorable conditions from the standpoint of local air quality [2]. Such conditions lead to the retention of pollutants in the lower layers of the atmosphere and a significant increase in PM2.5 concentrations, which further elevates the health risk for various outdoor occupations, including construction workers, warehouse and logistics staff, maintenance crews and machinery operators in open-pit mines, etc.

The importance of focusing specifically on Belgrade is also confirmed by the results of the World Health Organization. According to a detailed analysis conducted in cooperation with domestic institutions, approximately 3,600 premature deaths are recorded annually in the 11 largest cities in Serbia due to exposure to PM2.5, with Belgrade alone accounting for as many as 1,796 cases – almost half of the total mortality [3]. This clearly indicates that Belgrade is the epicenter of the health burden associated with air pollution in the country.

Recent analyses provide a clearer picture of the health burden and pollution dynamics in the Serbian capital. On the one hand, evidence suggests that exposure to PM2.5 can be linked to

27.2% of ischemic heart disease cases and 19.4% of strokes, with concentrations ranging from an average of 14.8 μg/m³ to daily peaks of 365 μg/m³ [4]. On the other hand, this health impact is reinforced by findings that during the most extreme heating season episodes, PM2.5 concentrations rose to 250 μg/m³, far above the WHO guideline of 15 μg/m³, with some episodes persisting for months and keeping the outdoor occupations under continuous exposure [5].
That being said, all working environments are affected by elevated pollution levels during the heating season, particularly occupations performed outdoors. Therefore, this paper first reviews the relevant literature addressing this issue. It then introduces a unique risk assessment methodology that combines pollution and meteorological data, followed by a discussion of the results.

LITERATURE REVIEW

PM2.5 is widely recognized as one of the most harmful air pollutants, and numerous studies have evaluated its health risks. Urban studies in China indicate that chemical composition strongly influences health outcomes. For example, Chen et al. [6] assessed PM2.5-bound components over three years in Beijing and reported average concentrations of 82 μg/m³, corresponding to lifetime carcinogenic risks of 1.9×10^{-4} and hazard quotients of 18, well above acceptable thresholds, with arsenic and chromium (VI) as the main contributors. In another Chinese megacity, source-specific health risks were analyzed using Positive Matrix Factorization (PMF), showing that industrial emissions and coal combustion dominated carcinogenic risk, while traffic-related pollutants led to non-carcinogenic effects, with an overall hazard index of 1.35 [7]. A longer-term study in Jinan applied PMF with the RM-RA model to assess twelve PM2.5-bound metals, revealing that Cr and As exceeded safe thresholds for carcinogenic risk, whereas Mn and Cd drove non-carcinogenic effects [8]. Seasonal contrasts further highlight the impact of chemical composition: in Shijiazhuang, winter PM2.5 and trace metal concentrations were 1.04–1.60 and 1.44–1.97 times higher than in pre-heating periods, resulting in 1.08–1.42 times higher hazard quotients, with Mn, As, and Co as dominant risk drivers [9].
Focusing on occupational safety and health, similar safety principles apply across all outdoor working environments: exposure to PM2.5 should be avoided once concentrations exceed certain thresholds. Accordingly, occupational settings should aim to minimize such exposure wherever possible. However, the nature of certain jobs makes this goal challenging. For example, a study by Yang et al. [10] found that construction workers are exposed to elevated PM10 and PM2.5 concentrations, with pit bottom workers, plasterers, masonry, and putty workers facing the highest occupational health risks. Using health risk assessment and monetization, the study highlighted the urgent need for improved dust control, ventilation, and protective measures on construction sites. Similarly, Shezi et al. [11] assessed occupational exposure to fine particulate matter (PM4 and PM2.5) among artisanal cookware makers in South Africa, finding notably high levels, especially at the workers' breathing zones. Finally, research by Lestari and Wandy [12] shifted the focus to the relationship between particulate matter levels in different occupational environments and weather conditions. It concluded that rain reduces PM2.5 concentrations both indoors and outdoors and highlighted the importance of accurate data analysis and visualization for Occupational Health and Safety management.
Despite these findings, few studies have quantitatively evaluated the influence of meteorological factors, such as wind speed, during the heating season. This study addresses that gap by proposing a quantitative framework for occupational health and safety (OHS) risk assessment related to PM2.5 exposure during the heating season in Belgrade. The findings may provide a foundation for future research and inform the development of public policy measures aimed at improving air quality and protecting workers’ health.

METHODOLOGY

The core idea behind this research lies in creating a methodology which will be used to quantitatively assess the OHS risk which comes along with high PM2.5 air pollution in Belgrade, Serbia. More specifically, pollution data during the critical periods of the heating season will be analyzed and each month will be treated separately. The risk will be perceived as a product of two components: probability of an unwanted event occurring and the severity of consequences it generates. By intuition, there seems to be an obvious relationship between overall wind speed in a specific area and PM2.5 levels. Therefore, the following work will perceive the day with a low average wind speed as an unwanted event. Firstly, the goal is to statistically determine the correlation between the pollution and wind speed and to calculate daily average 'low' wind speed based on the corresponding air pollution threshold. This enables identifying the days that are of interest. Secondly, the probability of such a day occurring will be calculated, which will present the first risk component. Third part of the research will include analyzing the behavior of pollutants during unwanted events by determining the statistical distributions for each month. Fitting the data with distributions will enable extracting expected values which will present the second risk component – severity of the consequences. Finally, risk for each month will be calculated and evaluated inside a 5x5 risk assessment matrix with cautionary statements for each risk category. For this specific research, the data includes the heating seasons during the period 2018-2022 from a measuring station "Novi Beograd" provided by the Serbian Environmental Protection Agency in Belgrade, Serbia.

RESULTS AND DISCUSSION

Determination of a low average wind speed threshold

The necessary prerequisite for further analysis was proving that there is a dependency between daily average PM2.5 levels and daily average wind speed. Since the data is not normally distributed, the adequate parameter for measuring correlation is Spearman's correlation coefficient (ρ). The calculations showed a significant value of the coefficient $\rho=-0.69$, indicating a strong correlation between two variables.
Next step was approximating data with a function which fits it best. The results of the regression analysis have revealed that the function which explains the dependency most accurately is a power function shown in the Equation 1. The value of the coefficient of determination $R^2=0.402$ indicates that the generated function moderately approximates the data, as it is shown in Figure 1.

$$f(x) = 234.43 \cdot x^{-0.86} \quad (1)$$

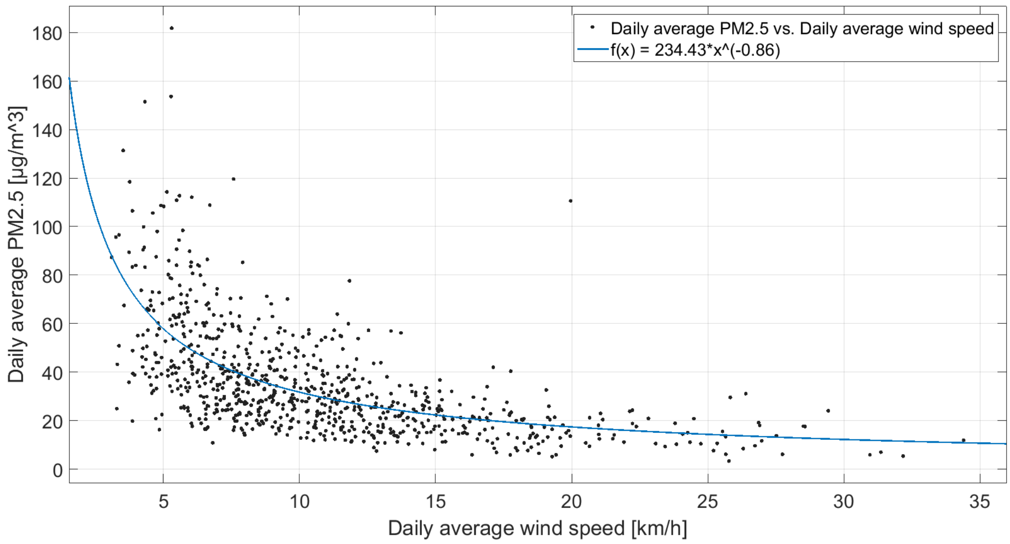

Fig. 1. *Fitted regression function and empirical data*

The generated regression function enabled the determination of a 'low' wind speed threshold. Following the Technical Assistance Document for the Reporting of Daily Air Quality by U.S. Environmental Protection Agency – USEPA [13], the limit for moderate air quality when it comes to PM2.5 is 35.5 µg/m^3 of a daily average and everything above that is considered unhealthy. The average wind speed threshold will be calculated by simply extracting the *x* from the function, for a given *f(x)*, as it is shown in Equation 2.

$$35.5 = 234.43 \cdot x^{-0.86} \rightarrow x = \left(\frac{35.5}{234.43}\right)^{\frac{-1}{0.86}} \approx 9 \quad (2)$$

Therefore, each day which had an average wind speed less than 9 km/h was considered 'an unwanted event'.

Frequency of days with average wind speed below the threshold

The initial dataset had covered the heating seasons (15th October to 15th April) from 2018 to 2022. Subsequently, for each month, the days of interest were counted, and the probability parameter was calculated based on their relative proportion of the total period (Table 1).

Table 1. *The probability of occurence for each month*

Month	Measurement period 2018-2022 [days] (d_a)	'Low' wind speed periods [days] (d_{lws})	Probability of occurrence ($p = d_{lws}/d_a$)
October (2nd half)	85	58	0.682
November	150	74	0.493
December	155	72	0.464
January	155	72	0.464
February	141	53	0.376
March	155	63	0.406
April (1st half)	75	29	0.387

Statistical testing of PM2.5 level distributions

Further analysis has filtered the initial dataset according to the calculated wind speed threshold. Given that the current day had been considered an 'unwanted event', the goal was to determine which statistical distribution best fits the pollution data during such events. Eventually, the extraction of expected values from each theoretical distribution enabled the creation of the second risk parameter, which will present the rank of the consequences an unwanted event generates. The results of the Kolmogorov–Smirnov test indicated that hourly values of PM2.5 levels during the days when the average wind speed is low can be approximated by the Gamma theoretical distribution, with 95% confidence (α=0.05). The theoretical cumulative distribution function (CDF) is given in Equation 3 [14], whereas the results of testing with the parameters of fitted functions are given inside Table 2.

$$F(x;a,b) = \frac{\gamma(a,\frac{x}{b})}{\Gamma(a)} = \frac{\int_0^{x/b} t^{a-1}\,e^{-t}dt}{\int_0^{\infty} t^{a-1}\,e^{-t}dt} \tag{3}$$

The visual representations of KS testing are given through empirical and theoretical fitted Gamma CDFs, in Figure 2. Besides that, Figure 3 shows the probability density functions (PDFs) and the movements of expected values with different periods of the year.

Table 2. *The results of KS statistical testing and parameters of the Gamma distribution*

x		p value	KS score	a	b	E(x)	V(x)
PM2.5 (μg/m³)	October (2nd half)	0.075	0.035	2.773	14.882	41.263	614.065
	November	0.702	0.017	4.190	8.928	37.411	334.018
	December	0.070	0.033	2.850	20.580	58.655	1207.130
	January	0.131	0.031	3.482	18.381	64.013	1176.648
	February	0.439	0.027	2.590	20.235	52.405	1060.427
	March	0.186	0.030	2.886	13.531	39.055	528.467
	April (1st half)	0.266	0.042	3.482	7.448	25.938	193.197

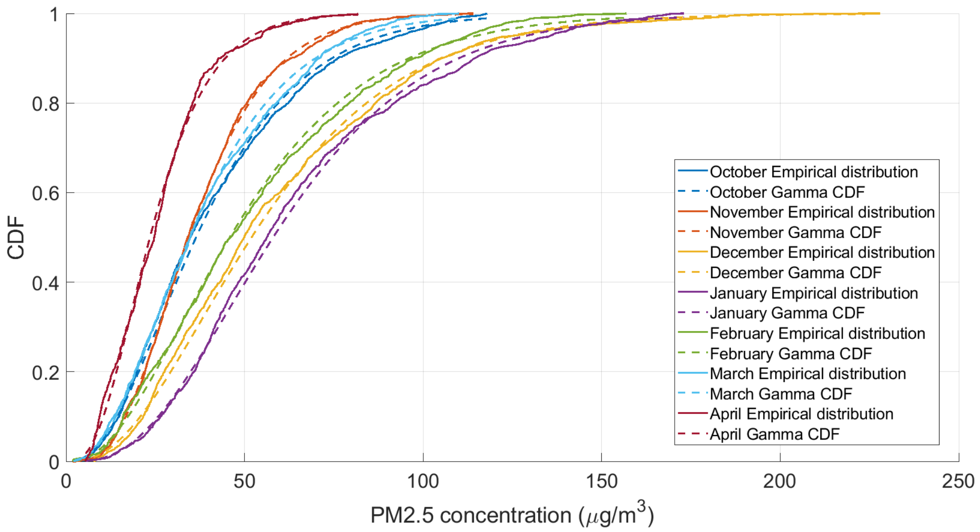

Fig. 2. *Empirical data and theoretical Gamma CDFs for each month during the heating season*

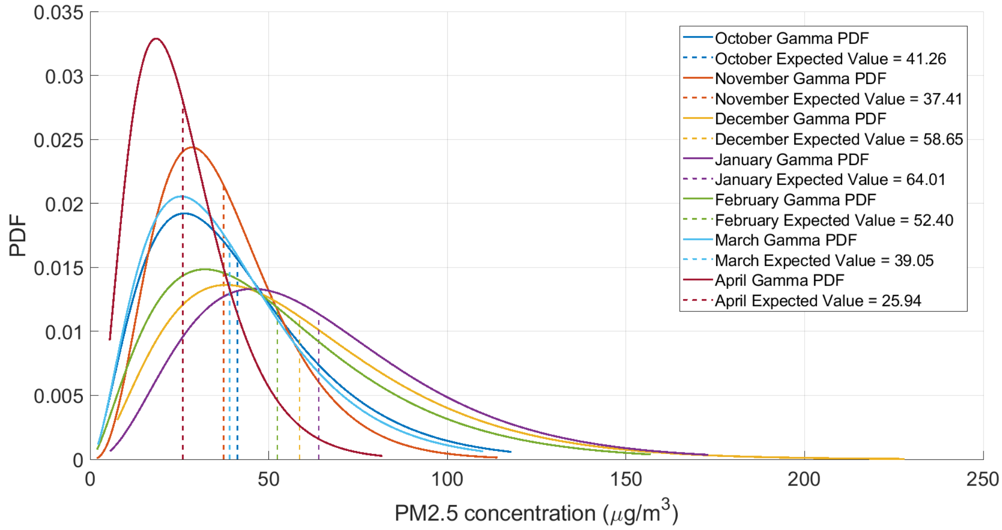

Fig. 3. *Theoretical Gamma PDFs for each month during with their expected values*

Risk evaluation model

The most basic risk evaluation models perceive risk as a measure of the probability and severity of adverse effects. In other words, risk is the product of the likelihood of an event occurring and its consequences which go along [15]. Therefore, the following assessment framework did not deviate from such approach, as final risk is calculated following Equation 4.

$$R = Likelihood \cdot Severity \tag{4}$$

The first component is evaluated with accordance to relative frequency of events during each month, respecting the defined categories in Table 3.

Table 3. *Likelihood of occurence evaluation*

Criterion	Likelihood	Rank
$p \leq 0.2$	Very Low	1
$0.2 < p \leq 0.4$	Low	2
$0.4 < p \leq 0.6$	Medium	3
$0.6 < p \leq 0.8$	High	4
$p > 0.8$	Very High	5

The second component of the product is the severity of consequences. Following the Air Quality Index categories outlined in the USEPA's technical assistance document [13], five severity labels were created.

Table 4. *Severity of consequences evaluation*

Criterion	AQI category	Severity	Rank
$PM2.5 \leq 9\ [\frac{\mu g}{m^3}]$	Good	Very Low	1
$9.1 \leq PM2.5 \leq 35.4\ [\frac{\mu g}{m^3}]$	Moderate	Low	2
$35.5 \leq PM2.5 \leq 55.4\ [\frac{\mu g}{m^3}]$	Unhealthy for Sensitive groups	Medium	3
$55.5 \leq PM2.5 \leq 125.4\ [\frac{\mu g}{m^3}]$	Unhealthy	High	4
$PM2.5 \geq 125.5\ [\frac{\mu g}{m^3}]$	Very Unhealthy	Very High	5

Finally, risk results have been calculated for each month and presented in a 5×5 risk assessment matrix (Figure 4). The final risk categories and suggested actions were derived by following the guidance and standards published by the Washington State Department of Labor & Industries [16], and the cautionary statements by the U.S. Environmental Protection Agency [13] and the Government of Canada [17].

Table 5. *Risk categories interpretation*

Criterion	Risk level	Suggested actions
$1 \leq R \leq 4$	Low	Normal work can continue. Standard monitoring and awareness.
$5 \leq R \leq 10$	Moderate	Sensitive workers (with respiratory/cardiac conditions) should be identified. Employers should monitor exposure and ensure protective masks (e.g. N95/FFP2 respirators) are available.
$11 \leq R \leq 16$	High	Consider all of the above measures. Implement exposure controls, such as using filtered enclosures or vehicles, portable HEPA filters, relocating or rescheduling work to areas/times with lower PM2.5 levels, minimizing activities that generate extra dust or smoke, reducing work intensity, and allowing more rest breaks.
$17 \leq R \leq 25$	Very High	Consider all of the above measures. Suspend or reschedule strenuous outdoor activities. If PM2.5 exceeds extreme thresholds (e.g. 250 μg/m³), suspend outdoor work except for essential/emergency tasks with full PPE. Employers must ensure workers experiencing symptoms get immediate medical attention.

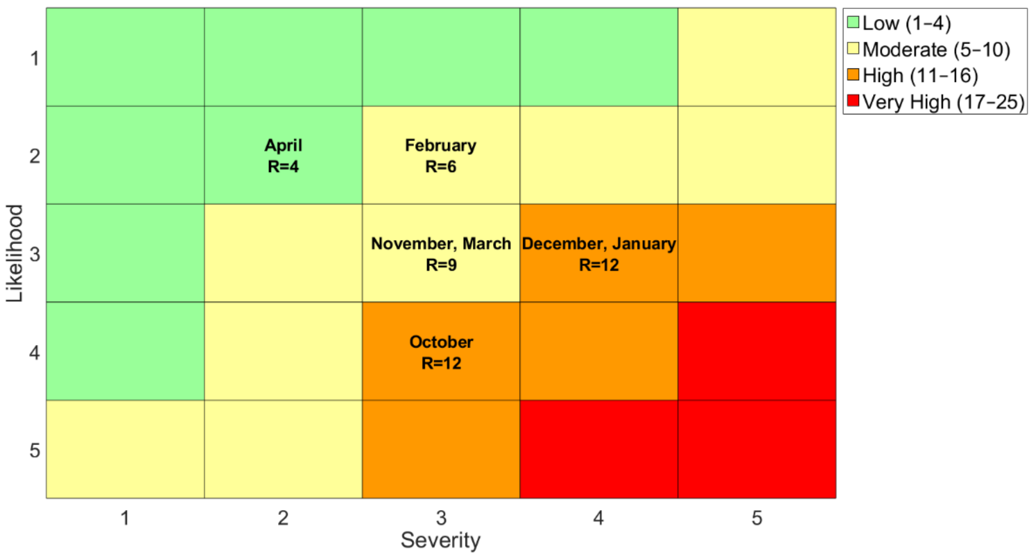

Fig. 4. *Risk visualization for each month in a 5x5 matrix*

CONCLUSION

This study aimed to quantitatively assess occupational safety and health risk associated with fine particulate matter during the heating season, focusing on days without meteorological phenomena that could act as natural urban air purifier. In particular, days with low average wind speed create conditions that allow particulate matter to accumulate in the lower atmosphere, making such events potentially hazardous from OHS risk mitigation perspective. Risk was defined as the product of the likelihood of such days occurring and the severity of their consequences. Scores were calculated separately for each month in the heating season and evaluated using a 5×5 risk assessment matrix. October had the highest probability of low-

wind days (relative share of 0.682 across the full measurement period), corresponding to rank 4 (high likelihood). On the other side, the severity of consequences was highest in December and January, where expected PM2.5 levels were 58.65 μg/m³ and 64.01 μg/m³, respectively (rank 4, indicating high severity). Overall, October, December, and January were classified as periods of high risk (R = 12), whereas April had the lowest risk score (R = 4). These evaluations were followed by practical occupational health and safety recommendations for companies operating in Belgrade, tailored to each month of the heating season.
Future research could diversify the data sources, i.e. use a greater number of monitoring stations which would provide a more realistic representation of air quality in Belgrade. In addition, the risk parameters could be estimated using more advanced approaches, such as simulation and/or different machine learning techniques. Eventually, it could be explored how this framework may be incorporated into intelligent air quality warning systems and adapted to other working environments with similar pollution and meteorological conditions (e.g. opencast mines). Given that occupational safety and health are fundamental, this study contributes by providing a methodological framework for assessing risks during periods of high air pollution, showing how established air quality indices within a risk matrix can offer a clear and actionable framework for communicating air pollution risks across diverse occupational environments.

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