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HEALTH HAZARD RELATED TO FINE ROAD DUST IN POLAND

Abstract: Air pollution emissions from road vehicles majorly contribute to particulate pollution. This poses significant threats to the environment and human health. Road dust contains various potentially toxic elements, which, when exposed to humans, can lead to severe illnesses such as asthma, cardiovascular diseases, and cancer. This study assessed adult health risks through accidental ingestion, inhalation, and dermal contact associated with heavy metals (Cr, Cu, Ni, Pb, and Zn) in road dust (with a fraction size < 0.1 mm). The analysis covers areas between sound-absorbing screens (S), in open spaces without screens (F), and at highway/express exits (E) with different surfaces: asphalt (A) and concrete (C). Results indicate the highest health risk levels are associated with Zn in road dust in S and E areas, indicating its potential negative impact on human health. When comparing results for all metals, road dust collected from A surfaces might pose a greater health risk than C surfaces. The carcinogenic risk for Cr and Ni found in road dust collected from A and C surfaces at points S, F, and E is medium. The most significant carcinogenic risk (medium-high) is associated with Cr in road dust from A surfaces in the F area, whereas the lowest risk (low-medium) for both A and C surfaces is linked to Ni exposure in the S point. The contributions of Cr and Ni highlight the need to reduce emissions of these elements in areas surrounding heavily trafficked roads.

Keywords: particulate matter, road dust, abrasion of the road surface, exhaust emissions

Introduction

Aspiring to improve quality of life and well-being, a growing number of people are choosing to leave urban environments in favour of more suburban locations. However, research on transportation habits suggests that this trend towards suburbanisation has led to an unexpected increase in car ownership, a decrease in public transportation usage, longer commute times, and greater distances travelled. All these factors contribute to the rise in emissions, primarily of VOCs (volatile organic compounds), NO_x, CO, PM (particulate matter), and minor components responsible for photochemical smog [1, 2]. In highly

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developed countries belonging to the OECD (Organisation for Economic Cooperation and Development), motor vehicles are the primary cause of environmental pollution, releasing over 15,000 chemical compounds [3-5].

The emissions produced by vehicles have been found to be more detrimental to human health than pollutants emitted by industries. This is due to the fact that automotive pollution is dispersed at high concentrations and low altitudes, often in direct proximity to individuals [6]. Research indicates that air pollution concentrations in tunnels, multi-level parking lots, and areas around gas stations can periodically be 4 to 40 times higher than the urban average. Furthermore, research conducted in London, England, has revealed that the concentration of certain identified air pollutants inside vehicles is several times higher than that in the surrounding environment. As a result, driving a specific route in a city can result in significantly higher levels of carbon monoxide in a driver's blood compared to a cyclist who takes the same route [7].

Air pollutant emissions are consistently monitored, and reports from the European Environment Agency highlight Europe's most pressing air quality concerns. These issues primarily revolve around suspended PM, O_3, and NO_2 [8]. Road transport, as the main factor, contributes to significant emissions of harmful substances, such as NO_x (63 %), organic-origin chemical substances (50 %), CO (80 %), PM (10 % - 25 %), and SO_2 (6.5 %) [7, 9].

Street dust, primarily generated by road traffic, mainly originates from tire wear, brake and clutch components, exhaust emissions, and corrosion of vehicle undercarriages and bodies [10-14]. PM particles, whose formation or suspension in the air is linked to mechanical processes during vehicle movement, are typically rich in various heavy metals and organic compounds (some of them are toxic and potentially toxic) [15-20]. A major contributor of heavy metals in road dust comes from the wearing down of road surfaces, corrosion of metal road structures, and use of road maintenance materials. Vehicle malfunctions, such as fuel and oil leaks, as well as issues with greases and other operational fluids, can contribute to the release of heavy metals, although to a lesser degree [21]. As Budai and Clement [22] reported, the abrasion of vehicle components and road surfaces is responsible for 57 % of total Cu and 65 % of total Zn emissions from vehicular transport. Notably, heavy metal pollution is expected to be particularly high in areas directly adjacent to busy roads and exit routes [3, 4, 23].

Most of the pollutants emitted from road transport settle within a distance of up to 50 m from roads [24]. Outside of this area, extending on both sides of the street, the metal concentration decreases by approximately 90 %. An increase in Pb content within soil samples taken from areas situated in close proximity to heavily traversed roadways has been observed in the past. Dust particles containing Pb tend to remain suspended in the air for extended periods and can be transported over longer distances. However, rain and snowfall have the ability to remove lead from the atmosphere. It is important to acknowledge that other metallic elements such as Zn, Cd, Cr, Ni, and V are also prevalent in addition to Pb. These metals are formed due to exhaust emissions and dust from tire abrasion (e.g. ZnO is incorporated into rubber during the vulcanisation process) [25]. Moreover, soil contamination with Cr is linked to its emission into the atmosphere during coal combustion and chrome steel production [26].

Studies have demonstrated that the particles produced by mechanical processes, such as the wear of brake linings and road surfaces, are of exceedingly small size and have the capability to deeply penetrate living organisms [27-30]. Considering the protection of human health and life, it’s important to note that PM with an aerodynamic diameter below 2.5 µm, referred to as PM2.5 (similarly, we define PM10 or PM0.1), is considered a harmful substance present in the air. Besides particle size and shape (especially surface area), the chemical composition of PM can also affect human health, and this composition primarily relies on the source [31, 32].

Breathing in dusty air for short periods is linked to conditions such as chronic obstructive pulmonary disease (COPD), coughing, breathlessness, wheezing, asthma, respiratory illnesses, and higher rates of hospitalisation. Over the long term, exposure to dust can lead to chronic asthma, reduced lung function, and cardiovascular diseases [31, 33, 34]. Furthermore, air pollution contributes to the development of visual impairment, kidney disease, and disruptions in the hormonal and central nervous systems, causing growth retardation and reduced immunity to bacterial infections. For instance, exposure to Pb disrupts brain function and can be fatal at high concentrations. Lung cancer occurs much more frequently in urban populations than rural areas due to higher air pollution levels in cities [8]. Additionally, studies conducted in Sweden through cohort research have shown that prolonged exposure to air pollution could lead to the development of diabetes [35]. Furthermore, pollution seems to have various adverse health effects early in human life, such as respiratory, cardiovascular, and psychological disorders, as well as perinatal complications [36]. These early health problems can ultimately result in mortality or chronic diseases during adulthood [34, 37].

Regrettably, Poland grapples with some of Europe’s most polluted air [38-40]. This contributes to declining health among the Polish population and a rise in healthcare expenses. Consequently, it is imperative to take resolute steps to address this issue. Education plays a pivotal role in increasing awareness about the health repercussions linked to exposure to polluted air and the available means of curbing detrimental emissions [41, 42].

The objective of this study was to assess the health risks for adults associated with the presence of heavy metals such as Cr, Cu, Ni, Pb, and Zn in road dust. This assessment includes the potential risks from unintended ingestion, inhalation through ambient air, and dermal contact. The analysis focused on dust particles smaller than 0.1 mm [43]. Dust samples were collected at three control points: in the space between sound-absorbing screens, in open areas without screens, and at highway/expressway exit points. Furthermore, the analysis considered a road maintenance worker exposed to both asphalt and concrete surfaces, spending 250 days each year in close proximity to roads. Health risk assessment relied on the calculated hazard index (*HI*) and the estimation of cancer risk (*ILCR*) by the commonly employed model developed by the U.S. Environmental Protection Agency [44, 45].

Materials and methods

Dust samples were collected from sections of highways and expressways with two types of surfaces, asphalt and concrete, located in Poland’s central and southern parts. For each highway/expressway section, six sampling locations were chosen for material collection. Samples were taken on both the left and right sides of the road at three control points: in the space between sound-absorbing screens (S), in an open space without screens (F), and at road exits (E).

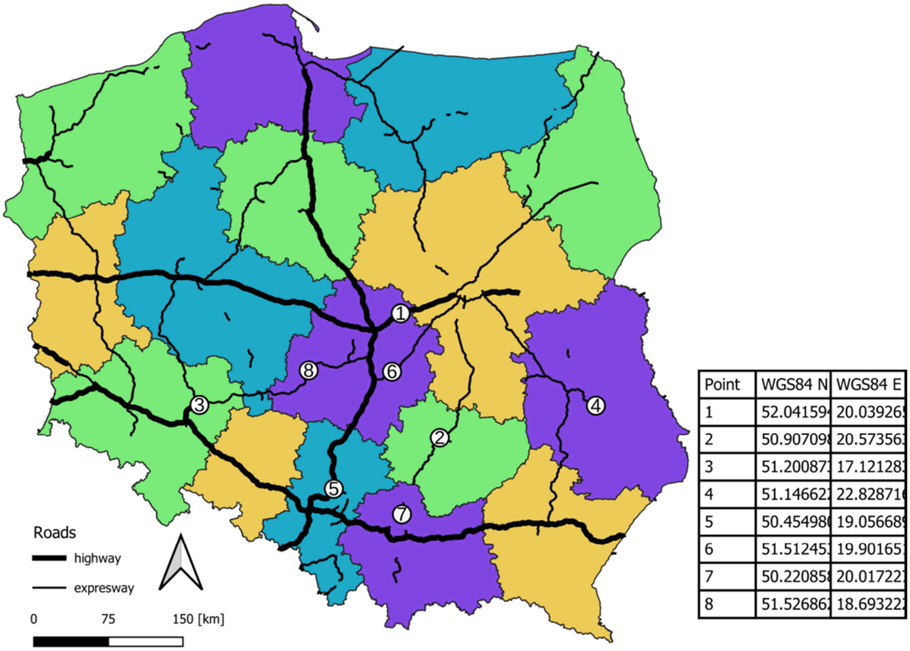
The distances between the control points were approximately 5 km. Points were positioned at relatively the same height on both the left and right sides of the chosen road to collect a representative sample unaffected by wind or vehicle direction. For the space between the sound-absorbing screens, measurement points were selected, covered with screens on both sides and at a distance approximately 2 m from the edge of the screen. The material for analysis was collected manually (using a small brush), each time from an area no less than 2 m² into sterile plastic containers. In total, samples from 48 points were analysed. The collection of materials for the study was conducted during the summer months to minimise the influence of de-icing agents in road dust [29]. The list of roads is provided in Table 1, while the locations of the measurement points are shown in Figure 1.

Table 1

Locations of selected highways and expressways in Poland, with an indication of a chainage and surface type [29, 46]

Measurement point	Road No.	Selected sections	Description of section	Chainage [km]		Surface type
				beginning	end	
1	A2	Warszawa - Lodz	Interchange Lowicz - Interchange Skierniewice	385.95	398.10	asphalt
2	S7	Kielce By-Pass	Interchange Kielce Zachodnie - Interchange Kielce Jaworznia	6.67	15.11	asphalt
3	S8	Wroclaw - Sieradz	Interchange Wroclaw Psie Pole/DK A8 and 98/ - Interchange Olesnica Zachod /DW340/	29.22	51.66	asphalt
4	S17	Lublin - Piaski	Piaski/Przejscie	0.000	1.04	asphalt
5	A1	Czestochowa - Katowice	Interchange Wozniki/DW789/ - Interchange Pyrzowice/S1/	395.34	399.84	concrete
6	S8	Warszawa - Piotrkow Trybunalski	Interchange Wolborz - Interchange Tomaszow Mazowiecki Poludnie	340.30	348.61	concrete
7	S7	Krakow - Widoma	Wesola/Widoma/ - Krakow	642.51	657.89	concrete
8	S8	Sieradz - Wroclaw	Interchange Zloczew - Wezel Sieradz Poludnie	148.67	168.59	concrete

The collected samples underwent granulometric analysis using a mechanical sieve shaker, resulting in seven material fractions: 10 mm - 2 mm, 2 mm - 1 mm, 1 mm - 0.5 mm, 0.5 mm - 0.25 mm, 0.25 mm - 0.1 mm, 0.1 mm - 0.063 mm, and < 0.063 mm. Then, the fractions consisting of particles smaller than 0.1 mm were analysed for their elemental composition using an energy-dispersive X-ray fluorescence spectrometer (EDX 7000, Shimadzu). The X-ray source is a Rh lamp, and the beam irradiates the sample from below. The instrument is utilised for analysing the chemical composition through X-ray excitation. It should be noted that the device does not detect elements with atomic numbers below 11. Approximately 15 g of pre-dried material was placed in the sample cup. The sample did not require crushing before analysis. The instrument settings were as follows: a 10 mm collimator, air atmosphere, and a total radiation exposure time of 60 s. The obtained results were normalised to 100 % (qualitative analysis). The detection limit for each element using the applied method was at the level of 0.01 %. Three measurements were performed from each container of unfractured material, and the percentage results of the elemental composition were input into MS Excel, where the average was calculated. However, for particles with a fraction < 0.1 mm, only one measurement was conducted due to the limited amount of material for analysis.



Point	WGS84 N	WGS84 E
1	52.04159	20.03926
2	50.90709	20.57356
3	51.20087	17.12128
4	51.14662	22.82871
5	50.45498	19.05668
6	51.51245	19.90165
7	50.22085	20.01722
8	51.52686	18.69322

Fig. 1. Map of Poland with selected measurement point locations for the study (OpenStreetMap under the Open Data Commons Open Database License)

According to the United States Environmental Protection Agency (US EPA) [47], probabilistic methods can be applied to estimate health hazards associated with exposure to heavy metals in road traffic through ingestion, inhalation, and skin contact. The Average Daily Dose (*ADD*) for three exposure pathways can be calculated using the following formulas [23, 48]:

$$ADD_{ingest} = \frac{C \cdot IngR \cdot EF \cdot ED}{BW \cdot AT} \cdot 10^{-6} \tag{1}$$

$$ADD_{inhal} = \frac{C \cdot InhR \cdot EF \cdot ED}{PEF \cdot BW \cdot AT} \tag{2}$$

$$ADD_{dermal} = \frac{C \cdot SA \cdot AF \cdot ABS \cdot EF \cdot ED}{BW \cdot AT} \cdot 10^{-6} \tag{3}$$

where ADD_{ingest}, ADD_{inhal}, ADD_{dermal} represent average daily dose of exposure to heavy metals [$\text{mg} \cdot \text{kg}^{-1} \cdot \text{day}^{-1}$] through ingestion, inhalation, and dermal contact, respectively; C is an average metal content in dust [$\text{mg} \cdot \text{kg}^{-1}$]. Other parameter values are presented in Table 2.

The assessment of health risk, a metric assessing human exposure to toxic substances, was determined through the Hazard Quotient (*HQ*) calculation method as described by Świetlik et al. [10] and Liu et al. [48] using the following formula:

$$HQ_i = \frac{ADD_i}{RfD} \tag{4}$$

where HQ_i represents the Hazard Quotient for exposure pathway i (ingestion, inhalation, or dermal absorption). ADD_i is the average daily dose for each exposure pathway, and RfD is the reference dose. Specific values for each heavy metal are outlined in Table 3.

Table 2

Parameters for assessing health hazards of heavy metals in road dust [10, 48]

Parameter	**Description**	**Unit**	**Value for an adult**	**Reference**
EF	Exposure frequency	$\text{day} \cdot \text{year}^{-1}$	350	[49, 50]
ED	Exposure duration	year	24	[51]
SA	Exposed skin area	cm^2	5700	[51]
AF	Skin adherence factor	$\text{mg} \cdot \text{cm}^{-2}$	0.07	[51]
ABS	Skin absorption factor	–	0.001	[49]
PEF	Particle emission factor	$\text{m}^3 \cdot \text{kg}^{-1}$	$1.36 \cdot 10^9$	[49]
BW	Average body weight	kg	70	[44]
AT	Averaging time	day	–	[52]
$IngR$	Ingestion rate	$\text{mg} \cdot \text{day}^{-1}$	100	[51]
$InhR$	Inhalation rate	$\text{m}^3 \cdot \text{day}^{-1}$	20	[53]

Table 3

Reference dose, *RfD* for different exposure pathways of heavy metals and the slope factors for carcinogenic toxic elements through various exposure routes

Parameter	**Exposure pathway**	**Cr**	**Ni**	**Cu**	**Zn**	**Cd**	**Pb**	**Ref.**
Reference dose *RfD* [mg · kg · day]	RfD_{ingest}	$3.00 \cdot 10^{-3}$	$2.00 \cdot 10^{-2}$	$4.00 \cdot 10^{-2}$	$3.00 \cdot 10^{-1}$	$1.00 \cdot 10^{-3}$	$3.50 \cdot 10^{-3}$	[54, 55]
	RfD_{inhal}	$2.86 \cdot 10^{-5}$	$2.06 \cdot 10^{-2}$	$4.00 \cdot 10^{-2}$	$3.00 \cdot 10^{-1}$	$1.00 \cdot 10^{-3}$	$3.52 \cdot 10^{-3}$	–
	RfD_{dermal}	$6.00 \cdot 10^{-5}$	$5.40 \cdot 10^{-3}$	$1.20 \cdot 10^{-2}$	$6.00 \cdot 10^{-2}$	$1.00 \cdot 10^{-5}$	$5.25 \cdot 10^{-4}$	–
Slope factor *SF* $[\text{kg} \cdot \text{day} \cdot \text{mg}^{-1}]$	SF_{ingest}	$5.01 \cdot 10^{-1}$	$1.70 \cdot 10^{0}$	–	–	–	$8.50 \cdot 10^{-3}$	[50, 56]
	SF_{inhal}	$4.20 \cdot 10^{1}$	$9.01 \cdot 10^{-1}$	–	–	$1.50 \cdot 10^{1}$	$4.20 \cdot 10^{-2}$	[57]
	SF_{dermal}	2.00	4.25	–	–	–	$8.50 \cdot 10^{-3}$	[51, 58]

RfD_{ingest}, RfD_{inhal}, RfD_{dermal} represent the reference doses of heavy metals after ingestion, inhalation, and dermal contact, respectively, while SF_{ingest}, SF_{inhal}, SF_{dermal} is the slope factors of the elements after ingestion, inhalation and dermal contact, respectively. Based on Liu et al. [48]

In situations where the Hazard Quotient (HQ) value is below 1, it is considered that the exposure does not pose a significant health risk. However, when HQ exceeds 1, it is assumed that there is a significant risk of adverse health effects [59]. A more detailed classification of health risks has been provided by Cai et al. [60], as presented in Table 4.

The cumulative effect resulting from exposure to a toxic substance, referred to as the Hazard Index (HI), was calculated by summing the HQ values calculated for each exposure route (ingestion, inhalation or dermal contact) [10, 48]:

$$HI = \Sigma HQ_i \tag{5}$$

where HQ_i represents the Hazard Quotient for exposure route *i* (e.g., ingestion, inhalation, or dermal absorption).

Table 4

Classification of risk into carcinogenic and non-carcinogenic [48]

Type of risk	Range	Risk degree
Non-carcinogenic	< 0.5	No risk
	$0.5 – 1$	Low risk
	> 1	High risk
Carcinogenic	$< 10^{-6}$	Extremely low risk
	$10^{-6} – 10^{-5}$	Low risk
	$10^{-5} – 5 \cdot 10^{-5}$	Low-medium risk
	$5 \cdot 10^{-5} – 10^{-4}$	Medium risk
	$10^{-4} – 5 \cdot 10^{-4}$	Medium-high risk
	$5 \cdot 10^{-4} – 10^{-3}$	High risk
	$> 10^{-3}$	Extremely high risk

When it comes to health risks associated with carcinogenic heavy metals, the Incremental Lifetime Cancer Risk (*ILCR*) is calculated as the additional probability of developing cancer throughout a person's lifetime due to prolonged exposure to these carcinogenic heavy metals [51]. To assess the average daily dose of cancer risk over a lifetime, a weighted arithmetic mean of each exposure route is applied for elements exhibiting carcinogenic risks, such as Cd, Pb, Cr, and Ni. The formula for calculating the risk of developing cancer over a lifetime is as follows:

$$ILCR = SF_{ingest} \cdot ADD_{ingest} + SF_{inhal} \cdot ADD_{inhal} + SF_{dermal} \cdot ADD_{dermal} \qquad (6)$$

Generally, it is accepted that risk management measures should be formulated when *ILCR* values fall within the range [61]. To further investigate the level of risk for each heavy metal, a scale for assessing carcinogenic risk was adopted [48, 62]. Generally, risk management strategies are formulated when *ILCR* values exceed 10^{-4} [61]. For a more detailed examination of the risk level associated with each heavy metal, a standardised seven-level scale for assessing carcinogenic risk (Table 4) has been employed, based on Li et al. [55] and Liu et al. [48].

Results and discussion

In this study, the mass fraction of Cr, Cu, Ni, Pb, and Zn in road dust for eight measurement points at three control points: in the space between sound-absorbing screens (S), in an open space without screens (F), at road exits (E) were determined. The data was collected from dust samples with a particle size of less than 0.1 mm at each measurement point (1-8) on both sides of the road. The collected data were then averaged for each element and surface type (asphalt/concrete), as presented in Table 5.

Health risk assessment based on *HI* risk index calculations

According to standard health risk criteria, when the *HI* is less than 1, exposure is considered not to pose a significant health risk. However, when exceeds 1, there is considered to be a significant risk of adverse health effects [59]. As shown in Figure 2, the health risk for Zn is greater than 1 in two areas: for the E area from an asphalt road and for

S space with a concrete surface. In the case of Cr, Cu, Ni, and Pb, the health risk in all areas (S, F, E) is less than 1 and can be ranked in decreasing order as follows: Cr > Pb > Cu > Ni. Therefore, these elements present in road dust collected from two types of surfaces (asphalt/concrete) do not pose a health risk to people at control points S, F, and E.

Table 5

Mass fraction of elements identified in road dust with a particle size of less than 0.1 mm at eight measurement points divided into three control points (S, F, E)

Point	**1**	**2**	**3**	**4**	**Average value**	**5**	**6**	**7**	**8**	**Average value**	**Average value for both types of surfaces**
Road	**A2**	**S7**	**S8**	**S17**		**A1**	**S8**	**S7**	**S8**		
Selected section	**Warszawa - Lodz**	**Kielce By-Pass**	**Wrocław - Sieradz**	**Lublin - Piaski**		**Czestochowa - Katowice**	**Warszawa - Piotrkow Trybunalski**	**Krakow - Widoma**	**Sieradz - Wrocław**		
Surface type	**Asphalt**					**Concrete**					
Element [%]	**Soundproof screens (S)**										
Cr	0.157	<dl	0.121	0.079	0.119	0.052	0.152	0.049	0.107	0.09	0.102
Cu	0.231	0.082	0.195	0.120	0.157	0.086	0.190	0.083	0.160	0.13	0.143
Ni	<dl	<dl	<dl	<dl	<dl	<dl	<dl	<dl	<dl	<dl	<dl
Pb	0.065	<dl	0.095	<dl	0.08	<dl	0.119	<dl	<dl	0.119	0.093
Zn	0.723	0.126	0.760	0.660	0.567	0.126	3.324	0.140	1.722	1.328	0.947
Element [%]	**Free space (F)**										
Cr	0.116	0.083	0.141	0.087	0.107	<dl	0.121	0.052	0.123	0.099	0.103
Cu	0.203	0.095	0.159	0.104	0.14	0.082	0.192	0.087	0.163	0.131	0.136
Ni	0.035	<dl	0.044	<dl	0.039	<dl	<dl	<dl	0.055	0.055	0.045
Pb	<dl	0.046	0.091	<dl	0.069	<dl	0.086	<dl	0.086	0.086	0.077
Zn	1.012	0.360	0.970	0.315	0.664	0.129	0.662	0.172	0.991	0.488	0.576
Element [%]	**Exit from the road (E)**										
Cr	0.112	0.058	0.166	0.075	0.103	0.067	0.134	0.036	0.127	0.091	0.097
Cu	0.220	0.083	0.261	0.102	0.166	0.086	0.146	0.085	0.291	0.152	0.159
Ni	<dl	<dl	0.061	<dl	0.061	<dl	<dl	<dl	<dl	<dl	0.061
Pb	0.077	<dl	0.099	<dl	0.088	<dl	0.075	<dl	0.095	0.085	0.087
Zn	1.056	0.130	1.388	0.356	0.732	0.111	0.842	0.134	1.664	0.687	0.710

< dl denotes detection limit which is 0.01 %

Analysing the data in Figure 2 for Cr, Cu, Ni, Pb, and Zn present in dust from both types of surfaces (asphalt/concrete) at three control points (S, F, E), it was noted that in most cases, the highest health risks were obtained for E area from the asphalt surface (except for Zn), and the lowest for F area with a concrete surface. For Cr and Cu, the health risk at each control point (S, F, E) was higher for the asphalt surface than for concrete. Health risk for Ni in road dust only occurred for areas F and E with an asphalt surface. It is worth noting that the results obtained for area F for both types of surfaces are very similar to each other. In the case of Pb, health risk occurs only for dust from asphalt surfaces and is significantly higher for the E area than for areas S or F.

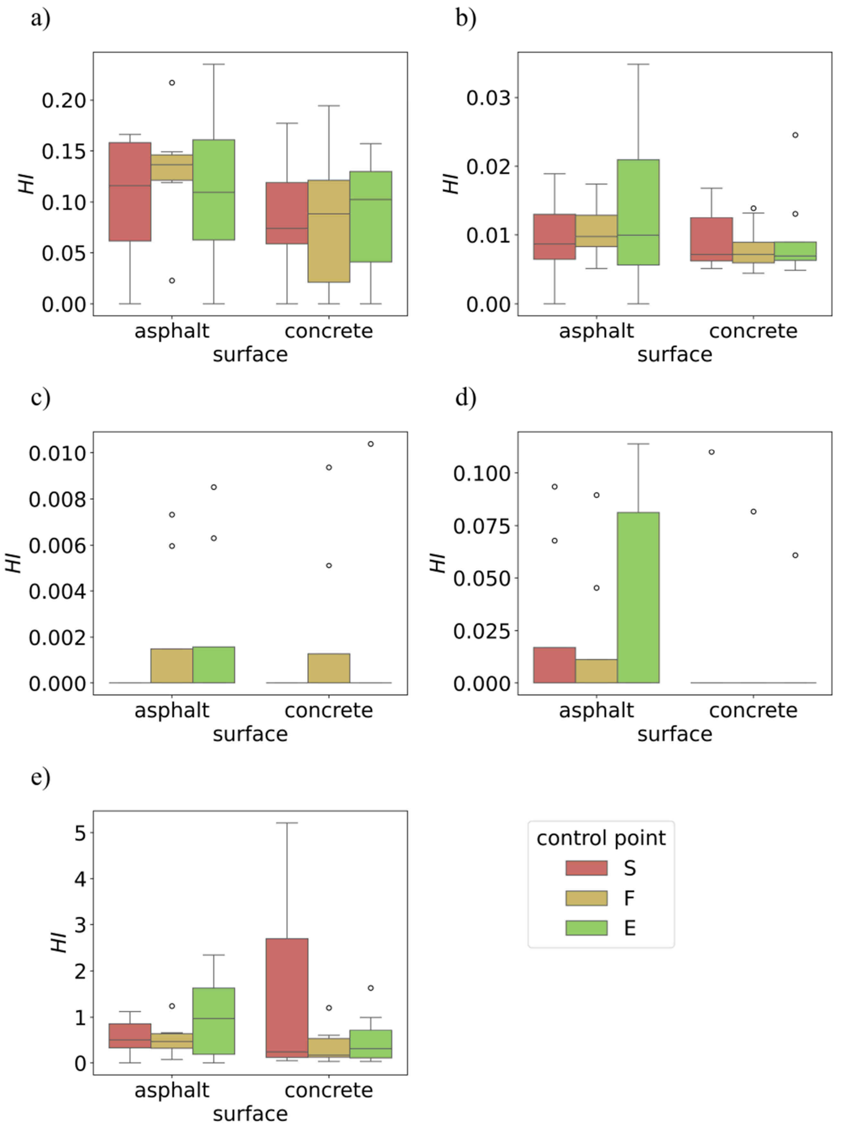


Fig. 2. Health risk assessment based on the hazard index, *HI* for: a) Cr, b) Cu, c) Ni, d) Pb, and e) Zn in road dust using box plots for various study areas with y-scale individual for each element. The outlier points, i.e., further than one and half inter quartile range from box boundaries, are denoted with circles

Health risk assessment based on *ILCR* cancer risk

The study assessed the risk of developing cancer due to long-term exposure to Cr and Ni (known carcinogens) as well as Pb (a potential carcinogen). According to slope factors for carcinogenic elements, Cr, Ni, and Pb are associated with exposure through ingestion, inhalation, and dermal contact, whereas other carcinogenic metals primarily involve inhalation as the exposure route [63]. *ILCR* represents the probability of developing cancer due to lifelong exposure to carcinogenic factors. Based on US EPA recommendations, $ILCR < 10^{-6}$ signifies a negligible risk of cancer, $ILCR > 10^{-4}$ indicates a high cancer risk, and *ILCR* values between 10^{-6} and 10^{-4} represent a tolerated cancer risk [63]. As shown in Figure 3, the carcinogenic risk for Cr and Ni is lower than 10^{-4} but within an acceptable range, whereas the carcinogenic risk for Pb is lower than 10^{-6}, thus can be considered negligible and should not be a cause for concern.

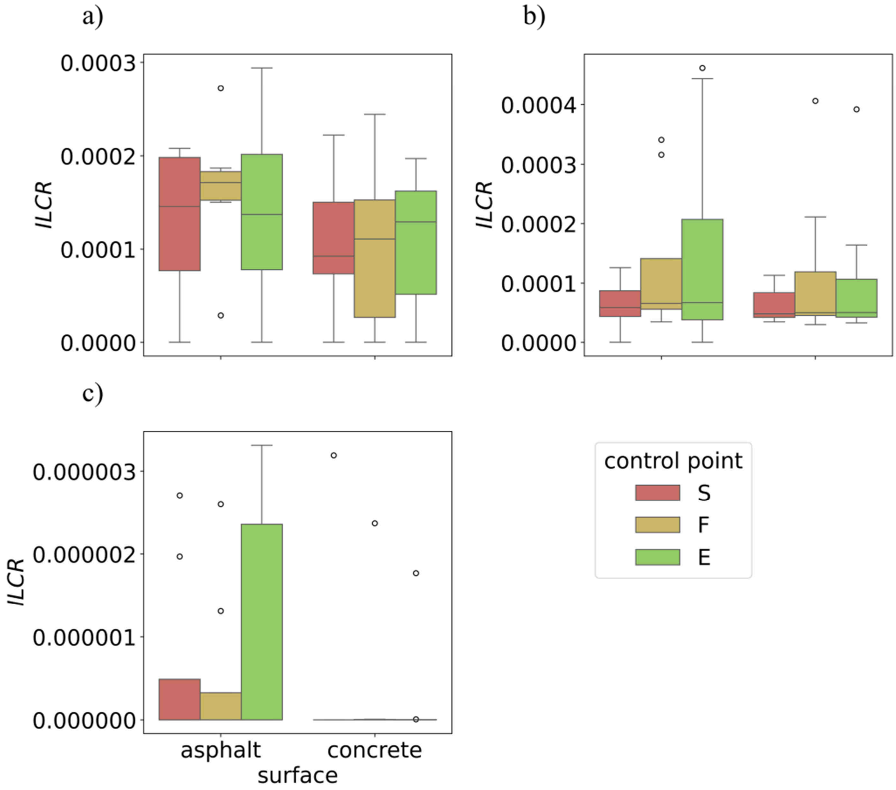


Fig. 3. Carcinogenic risk assessment based on Incremental Lifetime Cancer Risk, *ILCR* for: a) Cr, b) Ni, and c) Pb in road dust using box plots for various study areas with *y*-scale individual for each element. The outlier points, i.e., further than one and half inter quartile range from box boundaries, are denoted with circles

To provide a more detailed examination of the carcinogenic risk for Cr and Ni present in road dust collected from asphalt and concrete surfaces at three control points (S, F, E), a standard 7-level assessment of carcinogenic risk was employed (Table 4). According to this assessment, the harm to the human body increases with higher values of carcinogenic risk.

As indicated in Figure 3, the carcinogenic risk attributed to Cr exhibits a medium level on concrete surfaces across all control points (S, F, E), as well as on asphalt surfaces at locations S and E, ranging from $5 \cdot 10^{-5}$ to 10^{-4}. However, for asphalt surfaces at F area, the risk ranges from 10^{-4} to $5 \cdot 10^{-4}$, which is considered medium-high. The risk of exposure to Ni is medium for points F and E for both types of surfaces. Meanwhile, for S areas on both, asphalt and concrete surfaces, the risk falls within the range of 10^{-5} to $5 \cdot 10^{-5}$, indicate low-medium.

Conclusion

The highest levels of health risk were obtained for Zn present in road dust, particularly in specific areas (S and E), which can have a negative impact on human health. Comparing the results obtained for Cr, Cu, Ni, Pb, and Zn, it appears that dust collected from asphalt surfaces may pose a greater health risk than that from concrete surfaces. Furthermore, analysing the results in terms of control points (S, F, E), it can be concluded that the greatest health risk to humans comes from dust at E areas from highways/expressway, while the lowest risk is associated with dust collected from F areas. Therefore, in the face of potential threats, relevant authorities should pay closer attention and take action to monitor Cr concentrations in road dust. Moreover, the risks associated with human exposure to Pb and Cd should not be ignored. While Cu, Ni, and Zn have a comparatively lower detrimental effect on human health, it remains essential to monitor the presence of these elements in road dust.

The carcinogenic risk for Cr and Ni present in road dust collected from asphalt and concrete surfaces at specific control points (S, F, E) is moderate. The highest risk (medium-high) is observed for Cr present in road dust collected from asphalt surfaces for F areas, while the lowest risk (medium-low)) is for Ni in S for both types of surfaces. Lifetime Incremental Cancer Risk, *ILCR* values are mainly driven by Cr and Ni; therefore, efforts should be made to reduce emissions of these elements in areas near heavily trafficked roadways. Similar observations of carcinogenic risk, primarily from Cr due to exposure to road dust, have been noted in China and India [48, 56].

The issue of assessing human health exposure resulting from heavy metal pollution in street dust is still relatively unexplored and requires careful analysis. Although the scope of this study and the applied methodology are not novel in global literature, it should be emphasised that research in this area has been very limited in Poland. Nonetheless, in Poland, this issue is significant due to the consistently reported high levels of PM concentrations in the atmosphere.

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