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Impact of noise barriers on the dispersal of solid pollutants from car emissions and their deposition in soil

Abstract: Despite the existence of various methods aimed at protecting the environment from the negative influence of roads, there is a lack of adequate techniques for monitoring and reducing the spread of roadside pollution into the air and soils. The aim of this study was to assess the impact of noise barriers (sound walls) on the dispersal and soil deposition of solid pollutants from car emissions, based on both quantitative and qualitative analysis. Magnetic susceptibility measurements, trace elements analyses, and platinum (Pt) and rhodium (Rh) content determinations were performed on soil samples collected in the vicinity of various types of noise barrier. Previous investigations have shown that most traffic emissions are deposited in the close vicinity of roads (up to 10 m), with pollution levels decreasing with increasing distance from the road edge. However, the results of the present study indicate that this distribution is disturbed in areas in which noise barriers are located. Moreover, additional soil enrichment with trace elements was observed at approx. 10–15 m behind the barriers. The spatial distribution of trace elements contents in the tested soil samples corresponded to the magnetic susceptibility values. High Fe, Zn, Mn and Pb levels were observed adjacent to noise barriers composed of sawdust concrete and steel panels.

Keywords: roadside pollution, noise barriers, car emissions, trace elements, platinum-group elements, magnetic susceptibility

INTRODUCTION

Although modern roads should be as functional as possible for motorized users, their impact on the environment should be limited to a minimum. A variety of solutions have been developed in order to minimize the negative impact of roads on their surroundings, with protection against noise as the most important aspect. In order to abate noise intensity at locations in which it can be a particular nuisance, noise barriers (sound walls) are frequently used. They can take the form of various walls, earth embankments or green buffers.

The selection and design of noise barriers follow civil engineering principles, but unfortunately, the problem of environmental protection (with the exception of noise pollution) is not considered. Air quality studies concerning the influence of noise barriers on particle size distribution and pollutants concentrations are well known and advanced (Bowker et al. 2007, Ning et al. 2010). There are examples of models and experiments which describe the particulate matter dispersion profiles (e.g. Zhang et al. 2004, Steffens et al. 2013). Unfortunately, among all these air quality studies, there is lack of studies considered deposition of solid pollutants derived from traffic emissions on roadside soil in the vicinity of noise barriers.

Both road traffic and the roads themselves are emitters of dust and aerosol pollutants containing trace elements and polycyclic aromatic hydrocarbons (Hoffmann et al. 1999). These substances originate from car fumes and the abrasion of the road surface, tires, car metal parts, brake linings, etc.

Since 1993, all cars manufactured in the European Union, and earlier in the USA and Germany, have been equipped with catalytic converters, which contain active platinum group metals deposited in the form of very small nanoparticles (Motelica-Heino et al. 2001, Hooda et al. 2007). Although the role of catalytic converters in reducing emissions of harmful substances within car fumes is invaluable (they retain 80–90% of pollutants), their use also has a range of negative effects. Due to the surface abrasion of the device, Pt, Pd and Rh are blown out together with the hot stream of exhaust fumes and are deposited on the road surface and in plants, soil and water, posing a real threat to human health (Schäfer and Puchelt 1998, Boscolo et al. 2004).

As first observed by Hunt et al. (1984) and later confirmed by Hoffman et al. (1999) and Bućko et al. (2010), car emissions are also a source of technogenic magnetic particles (TMPs), which are the main carriers of heavy metals. TMPs are mainly magnetic Fe oxides and hydroxides, which presence in material can be easily detected via magnetic susceptibility measurements. TMPs occur not only in soot, but are also derived from the abrasion and corrosion processes affecting metal parts, brake linings, tires and road surfaces.

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The objective of the present research was to examine the influence of different noise barriers (“green walls”, sawdust concrete and metal panels, earth embankments) and road embankments on the dispersal and soil deposition of solid traffic pollutants, based on both quantitative and qualitative analyses.

STUDY AREA

The research was conducted close to noise barriers located along the Central Katowice-Gliwice Highway (DTS – Drogowa Trasa Średnicowa) between Chorzów and Zabrze cities (spring 2012 – spring 2014). The DTS highway is the second most important road in the Upper Silesian urban area (Fig. 1), and mainly serves as internal agglomeration traffic. The DTS highway comprises two 3-lane roads (divided by green buffers) in both directions, and a grade-separated junction network. Its total length is 31.3 km, with the maximum permissible speed 100 km/h. Daily (24-h) traffic intensity exceeds 50,000 vehicles (MZUIM Chorzów, 2011).

A range of noise barrier types have been used in the DTS area, including “green walls”, metal, sawdust concrete and earth embankments. Importantly, most of these barriers were constructed concurrently with the road itself. “Green wall” panels are composed of zinc-plated frame panels filled with a noise-absorption material (mineral wool) covered with green plastic mesh. Metal barriers contain panels made of perforated zinc-plated steel sheets that are filled with the absorption material (mineral wool). Sawdust concrete barriers are constructed from load-bearing slabs (made of reinforced concrete) on which the sawdust concrete slabs themselves are fixed.

MATERIALS AND METHODS

Field measurements of magnetic susceptibility were taken using an MS2D Bartington sensor next to 25 noise barriers with 2–5 m height. Measurements were conducted at different distances from the road edge, including approx. 15 cm from the road (road edge), approx. 15 cm from the barrier (in front) and midway between them. Measurements were also carried out on the other side of the “green walls” barriers (at further distances, perpendicular to the barrier edge). The specific distance from the barrier of these measurements depended on the land development at a given site (sidewalks, roads, buildings, etc.). In order to exclude other local pollution sources, measurements at further distances behind the barriers were conducted only in the areas where buildings with district heating system (blocks of flats) were present.

Additionally, for laboratory analyses topsoil samples containing 500 g of soil were collected from Aan subhorizon at the depths of 0 to 5 cm with the use of plastic shovel at two distances from the road edge (right at the road edge and at the barrier) and, in the vicinity of “green wall” barriers, at three distances

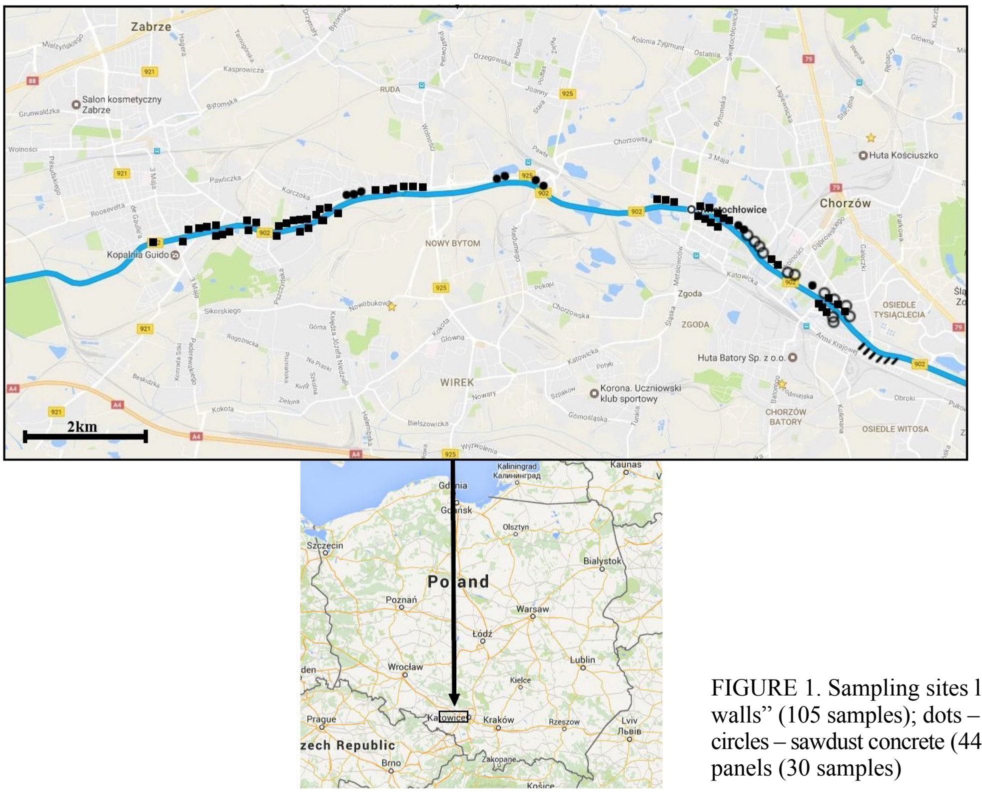

FIGURE 1. Sampling sites location (squares – “green walls” (105 samples); dots – embankments (17 samples); circles – sawdust concrete (44 samples); dashes – steel panels (30 samples)

behind barriers (at about 0.15 m, 10 m and 15 m). In each distance at least 5 subsamples were collected. They were then mixed into one sample representative for each point. The preliminarily prepared soil samples (air-dried and sieved through 2-mm plastic mesh) were placed in plastic containers (10 cm^3) and examined with the MS2B Bartington sensor in order to determine their volume magnetic susceptibility (κ) (given in 10^{-5} SI units), and to calculate the mass-specific magnetic susceptibility (χ) ($\times 10^{-8} \cdot m^3 \cdot kg^{-1}$). As the applied method was non-destructive, the same samples were analysed for contents of Fe, Mn, Zn, Pb, Cd, Cu, Cr, Ni and Co (in this article named trace elements) in accordance with the PN-ISO 11466 standard (as described in Wawer et al. 2015) using an atomic absorption spectrometry. Additionally, platinum and rhodium contents were determined for selected soil samples using inductively coupled plasma mass spectrometry after microwave digestion with aqua regia. Multivariate statistical evaluation, including Pearson's correlation coefficient analysis and principal component analysis (PCA), was carried out in the STATISTICA 12 (StatSoft) software.

RESULTS

In most cases, soils studied were anthropogenic formations related to road construction. Field measurements revealed that soils located right at the road edge were associated with the highest volume magnetic susceptibility values (κ = 250–610 ×10^{-5} SI), decreasing at a shorter distance from the noise barriers and increasing again approx. 10–15 m behind the barrier (Fig. 2). The only exception was the sites with metal panels, where the κ values observed in their direct vicinity were higher (up to 410×10^{-5} SI). For other noise barrier types, κ values were more than twice as low.

The above results were confirmed by the laboratory measurements, with the highest χ values obtained at the road edge (max. 770; mean value 430×$10^{-8} \cdot m^3 \cdot kg^{-1}$). In the direct vicinity of the barriers, values were lower: 260×$10^{-8} \cdot m^3 \cdot kg^{-1}$ (max. 1,500×$10^{-8} \cdot m^3 \cdot kg^{-1}$) and the lowest were obtained behind the barriers (approx. 180×$10^{-8} \cdot m^3 \cdot kg^{-1}$), with a slight increase recorded at 10–15 m (195×$10^{-8} \cdot m^3 \cdot kg^{-1}$) (Fig. 3).

The obtained χ values differed depending on the sampling point, being higher (more than twice as high) in the vicinity of metal and sawdust concrete barriers (approx. 565×$10^{-8} \cdot m^3 \cdot kg^{-1}$) than in the vicinity of "green walls" (260×$10^{-8} \cdot m^3 \cdot kg^{-1}$) and earth embankments (210×$10^{-8} \cdot m^3 \cdot kg^{-1}$).

The spatial distribution of trace elements in the soil samples collected at different distances from the road edge corresponded to that observed regarding χ values (Fig. 4). The analyses revealed Fe to be the main metal present in roadside soil, with the highest levels (max. 54,900; mean value 22,000 $mg \cdot kg^{-1}$) recorded at the road edge. Similar to χ, Fe contents were lower behind the barriers; the average at 10 m was 12,650 $mg \cdot kg^{-1}$, increasing to 14,400 $mg \cdot kg^{-1}$ at 15 m. The chemical analyses also revealed high Zn, Mn, and Pb contents in the research area, with the highest values measured in the soil collected in the vicinity of the steel and sawdust concrete barriers (3,000; 1,200 and 400 $mg \cdot kg^{-1}$ for Zn, Mn and Pb, respectively). Levels of the remaining trace elements were much lower: 30–60 $mg \cdot kg^{-1}$ for Cu; 10–17 $mg \cdot kg^{-1}$ for Ni; 6–7 $mg \cdot kg^{-1}$ for Co; and 1.5–4 $mg \cdot kg^{-1}$ for Cd (10 m from the barriers and at the road edge,

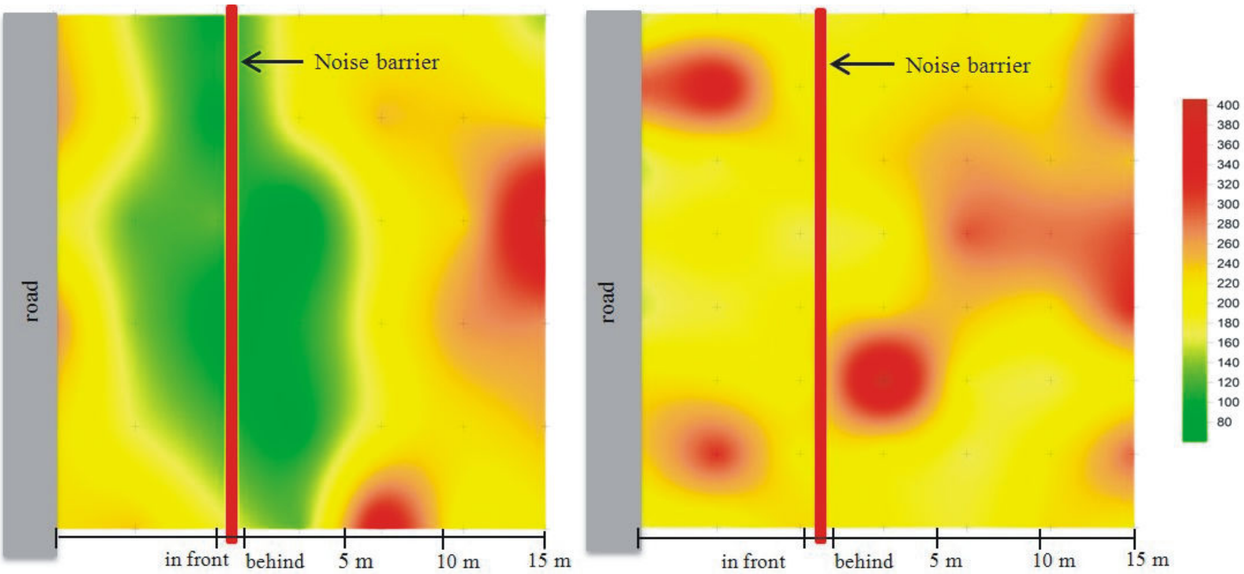

FIGURE 2. Spatial distribution of κ (10^{-5} SI)

respectively). In each case, the trace elements contents was lower with decreasing distance from the noise barrier, but increased at 10–15 m behind. Analysis of the soil samples collected in the vicinity of particular barrier types revealed that those soils sampled at sites with steel and sawdust concrete barriers contained the highest levels of all the analyzed elements (Fig. 5). In contrast, soils in the vicinity of "green walls" and earth embankments demonstrated the lowest trace elements contents. The Pt and Rh contents of all analyzed soils were low, with mean values of 7.4 µg·kg^{-1} (max. 30 µg·kg^{-1}) and 3.7 µg·kg^{-1} (max. 9.2 µg·kg^{-1}), respectively. In this case, the highest levels of Pt and Rh were observed in soils collected right at the road edge. Values decreased with distance from the road edge, but increased again at 15 m behind the barrier (Fig. 6).

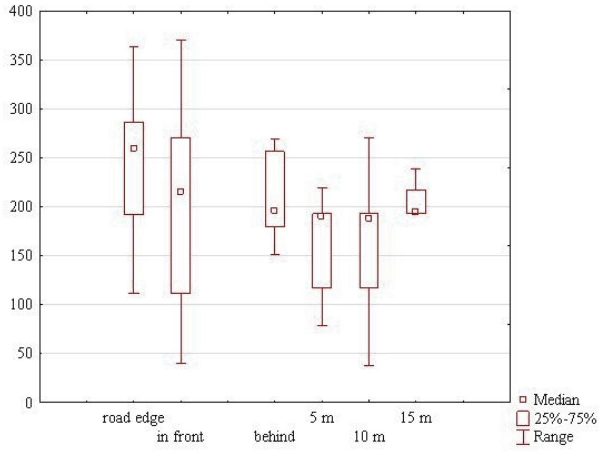

FIGURE 3. Distribution of κ values of soil (10^{-8} m^3·kg^{-1}) depending on the distance from the road edge

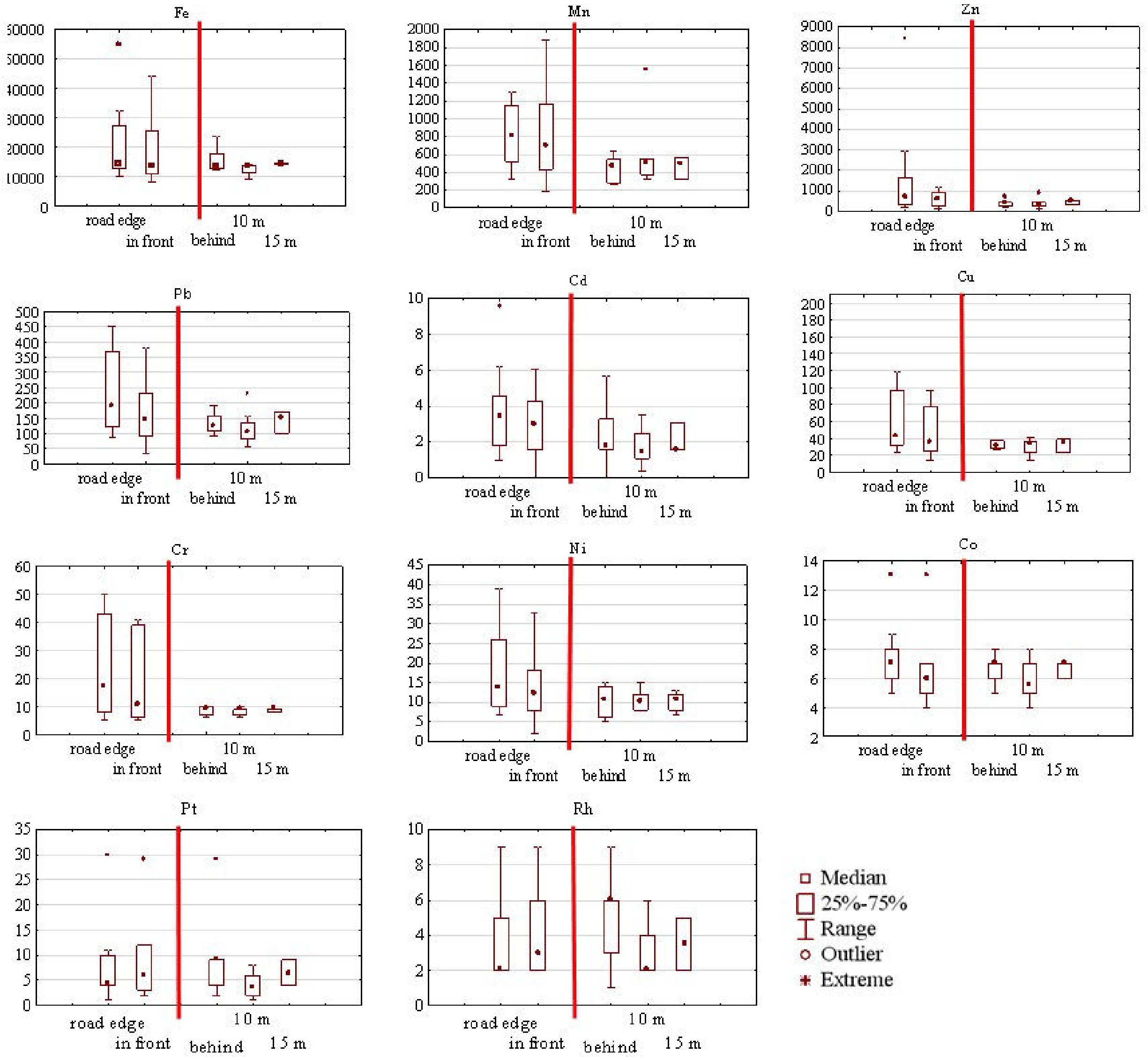

FIGURE 4. Spatial distribution of heavy metal contents (mg·kg^{-1}) in soil (red lines – noise barriers)

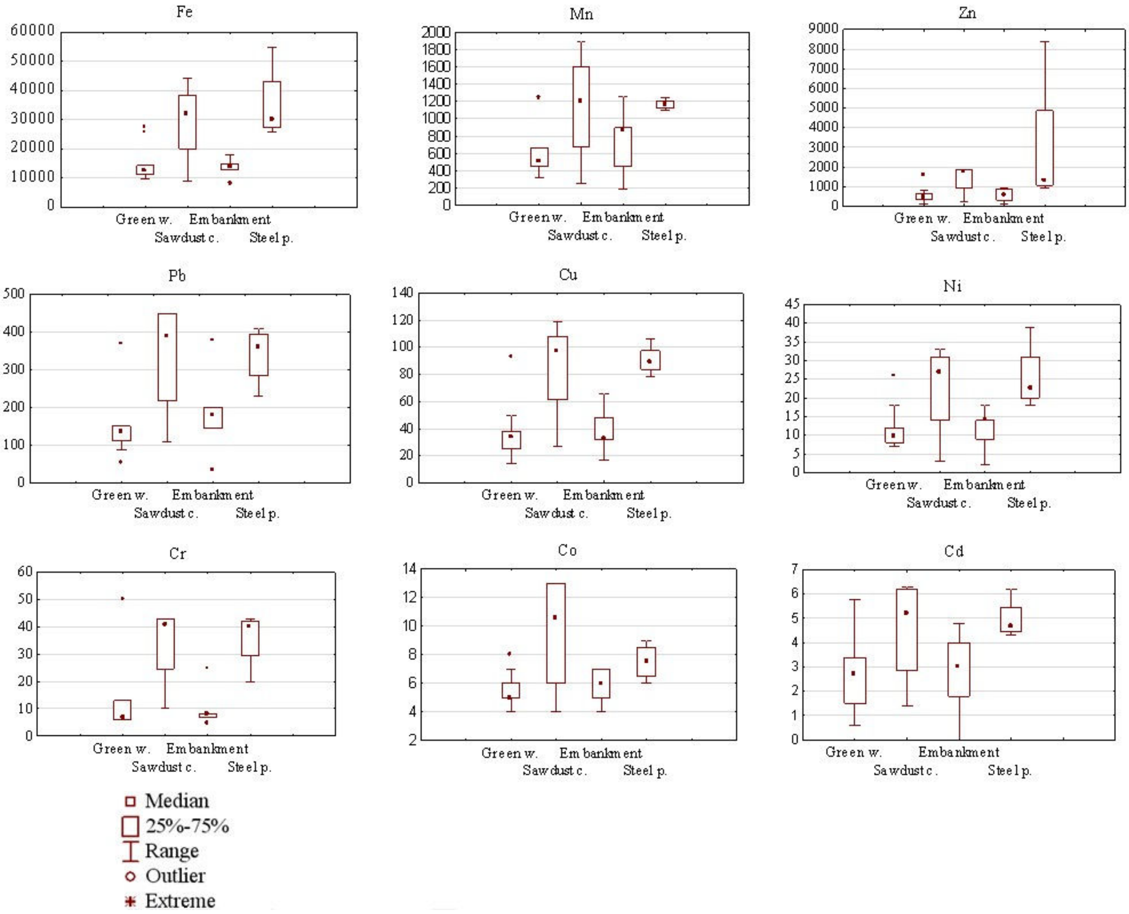

FIGURE 5. Heavy metal contents (mg·kg^{-1}) near different kinds of noise barriers

DISCUSSION

Research conducted so far has demonstrated that most car emissions are deposited in the close vicinity of roads (up to 10 m, with levels decreasing with increasing distance from the road edge (Hoffmann et al. 1999, Bućko et al. 2010, Wawer et al. 2015, Ojha et al., 2016).

However, the present study has revealed that the spatial distribution of pollutants is disturbed at sites containing noise barriers, with χ values and trace elements contents in fact increasing at 10–15 m behind the barrier (Figs. 2, 3 and 4). Such a distribution confirms that TMPs and trace elements present in the studied soils were derived from traffic sources, and also proves the direct influence of the acoustic barriers on the dispersal and soil deposition of solid pollutants. The observed increase in χ values and trace elements contents at greater distances behind the barriers reflects the fact that the pollutants were blown from the road by the wind.

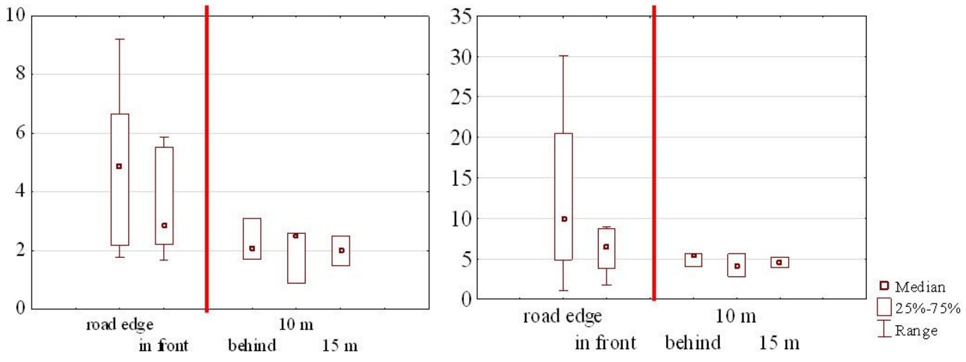

FIGURE 6. Spatial distribution of platinum and rhodium contents (µg·kg^{-1}) in soil samples

The similar spatial distributions of the magnetic susceptibility and trace elements can be explained by the fact that TMPs emitted from traffic can adsorb trace elements onto their surfaces (Hunt et al. 1984). This finding is corroborated by the high correlation coefficients between χ values and those of particular metals (Table 1). Additionally, the high positive correlation coefficients for Fe and χ (> 0.9) confirm that Fe occurred in the analyzed soils in the form of ferrimagnetic particles, typical for anthropogenic sources (Zawadzki et al. 2015).

Importantly, considerably higher χ values (approx. $625\times10^{-8}\cdot m^3\cdot kg^{-1}$) as well as content of Cr, Zn, Cu, Ni and Pb, elements typically emitted from traffic sources (Kennedy 2003, Adachi and Tainosho 2004), were observed in Chorzów and Świętochłowice cities, where the DTS motorway was built in 1986–2006. The χ values at Ruda Śląska and Zabrze cities, a section constructed in 2004–2011, were much lower ($236\cdot10^{-8}\cdot m^3\cdot kg^{-1}$). This difference proves the long-term accumulation of the pollutants containing TMPs, most of which were deposited in the direct surroundings of the road.

Fe and Mn, which dominated in the analyzed soil samples, can occur naturally. However, their co-occurrence with the remaining metals and their spatial distribution in the research area seem to be likely related to car emissions. Both of these elements occur in large amounts in brake linings, tire covering and engine dust, with the Fe content of some types of brake reaching 60% (Kennedy 2003, Chan and Stachowiak 2004).

The Zn present in roadside soils is typically derived from brake linings and tires, to which it is added as ZnO (Hewitt and Rashed 1990, Kennedy 2003, Hjortenkrans et al. 2007), although it is also present in soot and engine lubricants (Huhn et al. 1995, Davis et al. 2001). However, the highest levels were observed in the vicinity of the metal noise barrier, and consequently its presence in the analyzed samples was likely not only caused by car emissions but also by corrosion and abrasion of zinc-plated barrier construction elements exposed to both atmospheric conditions and substances used for winter road maintenance (NaCl). Their effect was particularly visible in Chorzów, where the barriers (approx. 20–25 years old) were highly rusted, their pieces scattered over and forming a thin layer on the soil surface. Thus, the corrosion of zinc-plated panels or crash barriers, rather than traffic, is an important Zn source in the studied roadside soils, a finding confirmed by previous studies carried out by Hjortenkrans et al. (2007) and Świetlik et al. (2013).

Although Pb was present in petrol in Poland until 2005, its emission is currently reduced and its content in roadside soils is mainly related to the erosion of brake linings and engine parts or to earlier deposition (Hoffmann et al. 1999). The high correlation coefficients (> 0.8) observed between Pb and other elements found in vehicle brake linings and tires (particularly Cu, Ni and Cd) indicate that the presence of Pb is likely mainly related to this particular source (Hildemann et al. 1991, Kennedy 2003). Although the obtained values correspond with roadside soil research data recorded in other countries (Nabulo et al. 2012, Wiseman et al. 2013), they are higher than those from other Polish cities (Wiater et al. 2011, Świetlik et al. 2013).

As Pt and Rh levels in the Earth's crust and soils are naturally low, their increased content in roadside soils is normally related to emission from car catalytic converters (Ek et al. 2004). Studies carried out by Jarvis et al. (2001), and Hooda et al. (2007) revealed that levels of platinum group elements decreased significantly with increasing distance from roads. However, the present research performed in the vicinity of the DTS highway has shown that this trend is

TABLE 1. Pearson's correlation matrix for investigated parameters

	χ	Fe	Mn	Zn	Pb	Cd	Cu	Cr	Ni	Co	Rh	Pt
χ	1.00											
Fe	0.82*	1.00										
Mn	0.6*	0.62*	1.00									
Zn	0.56*	0.66*	0.42*	1.00								
Pb	0.73*	0.83*	0.6*	0.74*	1.00							
Cd	0.45*	0.65*	0.40*	0.89*	0.67*	1.00						
Cu	0.79*	0.78*	0.61	0.42*	0.81*	0.25	1.00					
Cr	0.77*	0.53*	0.51*	0.24	0.52*	0.04	0.72*	1.00				
Ni	0.78*	0.77*	0.69*	0.52*	0.66*	0.43*	0.71*	0.5*	1.00			
Co	0.71*	0.82*	0.71*	0.38*	0.66*	0.33*	0.8*	0.47*	0.78*	1.00		
Rh	0.1	0.22	-0.04	0.45*	0.22	0.63*	-0.04	-0.27	0.11	0.03	1.00	
Pt	0.27	0.26	0.03	0.60*	0.26	0.62*	0.07	-0.05	0.29	0.08	0.85*	1.00

* Correlation is significant at the 0.05 level (2-tailed).

disturbed when noise barriers are constructed along the roadside, with a slight increase in Pt and Rh contents observed at a 15-m distance behind the barriers. Interestingly, the highest levels of platinum group elements were observed next to the road bridge over the DTS motorway, where values reflect both bridge traffic emissions and the deposition of pollutants emitted by vehicles going under the bridge.

Principal component analysis (PCA) revealed two main components accounting for 78% of total variance (PC1: 56% and PC2: 22%; the projection of the variables on the bi-plot is shown in Fig. 7). Based on this figure, elements can be classified into the following three distinct groups: Group 1 (most of the investigated elements and χ) represents components that are generally derived from traffic emissions; Group 2 with Zn and Cd lying in a separate group indicates a non-vehicular origin, likely the corrosion of the zinc-plated elements of noise barriers, although an important source of these metals is the wearing of tire treads; Group 3 –Pt and Rh, which are emitted from car catalytic converters.

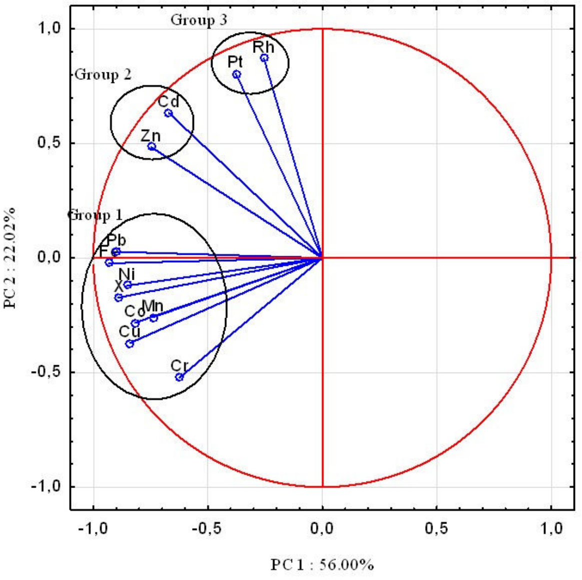

FIGURE 7. PC1 vs. PC2 bi-plot of the investigated elements

CONCLUSIONS

The present study has shown that sound walls have a direct influence on pollutant migration and concentration in soils located in the vicinity of the barriers. The observed increase in magnetic susceptibility values and trace elements contents at greater distances from the road edge is caused by the deflation of dust pollution from the road. The higher concentration of trace elements in soils was also caused by the long-lasting deposition of traffic-derived emissions. Noise barriers containing steel panels or zinc-plated elements constitute an additional threat to the environment, particularly when exposed to the influence of winter road maintenance substances (mainly NaCl) and subjected to rapid corrosion. In such a scenario, the barrier elements are scattered across the local area and are deposited in the soil, leading to an increase in Zn content that is especially problematic because of its mobility. The spatial distribution of the investigated parameters and the high correlation coefficients between κ values and trace elements levels in soils confirm traffic emissions as a major source of pollution in the study area.

ACKNOWLEDGMENTS

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Wpływ ekranów akustycznych na rozprzestrzenianie się i depozycję zanieczyszczeń komunikacyjnych w glebach

Streszczenie: Istnieje wiele metod mających na celu ochronę środowiska przed negatywnym wpływem samochodów i dróg, jednak wciąż brakuje odpowiednich technik monitoringowych oraz ograniczających migrację zanieczyszczeń komunikacyjnych w powietrzu i glebie. Celem badań było określenie wpływu różnych ekranów akustycznych na rozprzestrzenianie i depozycję w glebie stałych zanieczyszczeń pochodzących z emisji drogowych w oparciu o analizy jakościowe i ilościowe. Próbki gleb pobrane w sąsiedztwie różnych ekranów akustycznych zostały poddane pomiarom podatności magnetycznej i analizom na zawartość wybranych metali ciężkich oraz platyny i rodu. Wcześniejsze badania wykazały, że zanieczyszczenia emitowane z dróg deponowane były w bezpośrednim sąsiedztwie pasa drogowego (do ok. 10 m), a stopień zanieczyszczenia gleby malał wraz ze wzrostem odległości od krawędzi drogi. Prezentowane badania wykazały jednak, że w sąsiedztwie ekranów akustycznych przestrzenny rozkład zanieczyszczeń komunikacyjnych w glebie został zaburzony. Wykazano istnienie strefy zwiększonej koncentracji zanieczyszczeń w odległości ok. 15 m od barier drogowych. W miejscach tych obserwowane były zarówno wyższe wartości podatności magnetycznej, jak również podwyższone zawartości pierwiastków śladowych oraz Pt i Rh. Najwyższe zawartości Fe, Zn, Mn i Pb zanotowano w glebach w sąsiedztwie metalowych ekranów oraz ekranów z trocinobetonu.

Słowa kluczowe: zanieczyszczenia komunikacyjne, ekrany akustyczne, emisje drogowe, metale ciężkie, platynowce, podatność magnetyczna