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**A** – study design
**B** – data collection
**C** – statistical analysis
**D** – data interpretation
**E** – manuscript preparation
**F** – literature search

# Urban planning solutions in the context of dispersion of road pollution

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## Abstract

Dense road network change the landscape as well as in many different ways affect the environment and living organisms. The works on reducing the exposures to traffic pollutants carried out all around the world. In the last decade, noise barriers in large numbers began to appear along the main streets and became a common feature of urban architecture in Poland. Besides being barriers to the spread of the noise on the neighboring areas these constructions might also contribute to reducing the spread of air pollution, especially road dust particles with associated trace metals (Cd, Cu, Mn, Ni, Pb, Zn).

The aim of the study described in the article was to examine if the extent to which "green walls" noise barriers and transparent acrylic-glass noise barriers located along roads can contribute to a change in the spread of trace elements from the road traffic to outside of the road area. Toxic metals which occur in road dust in significant concentrations (Cu, Fe, Mn, Pb and Zn) were selected and their concentrations in soil samples were examined. The samples were collected at close vicinity of the road edge in an open area as well as in an area with noise barriers.

**Key words:** *noise barriers, soil contamination, trace metals, traffic pollution dispersion*

## INTRODUCTION

Populating of new sites or intensification of the urbanization process inherently involves constant transforming of environment. This is particularly evident in heavily urbanized areas, where the natural environment has been transformed and replaced by an artificial formation created by man – a city. Not only residential or industrial buildings but also all kinds of routes play an important role in the anthropogenically transformed urban space. The expansion of transport infrastructure, in addition to obvious benefits for socio-economic development, generates a number of negative impacts on the environment. The impact of road infrastructure and transport on the environment has been well documented. Dense road networks change the landscape as well as in many different ways affect the environment and living organisms. For many species a network of roads is often a barrier which separates the land into isolated habitat patches having genetic and evolutionary consequences [HANSKI 2011]. In many European urban areas, the road traffic has been found to be the predominant source of noise and most of air pollutions [CAN *et al.* 2011].

The number of passenger cars in Poland has increased exponentially in the last decade. Generally, it was associated with Polish accession to the European Union which contributed to lower prices for used cars. In 2004 the number of registered passenger cars in Poland amounted to 11.975 million, and 10 years later, in 2014, it was 20.004 million [GUS 2015; JAKUBIAK, GRZESIK 2014]. The natural consequence of the increasing number of vehicles in use is the expansion of road infrastructure. Constructing such a dens road

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network entails irreversible changes in the environment [MISIAK 1999]. Throughout their life cycle cars affect the environment in many ways. Mainly through energy and resource consumption, emissions of hazardous gases, trace elements and other substances, generation of waste during production and operation [JAKUBIAK, GRZESIK 2014].

Research on the effects of road transport on the environment especially pay attention to the air pollution generated by cars and the influence of these substances on the climate and roadside soils or plants. The road vehicles emissions comprise exhaust emissions as well as non-exhaust emissions (emissions from wearing parts of a vehicle, such as tires, brakes, clutch, etc.) [PANT, HARRISON 2013]. The transport sector is responsible for a large and growing share of global emissions affecting climate [FUGLESTVEDT *et al.* 2008]. Emissions from road traffic have a significant share of road dust. Road dust have been found to be an important source of particulate matter (PM) – a carrier of many toxic substances, including heavy metals [BUKOWIECKI *et al.* 2010; KARANASIOU *et al.* 2011]. The use of gasoline type fuels, oils, lubricants, grease as well as tire or brake pad wear are sources of metal contaminants like Pb, Cu, Cd and Zn [CHRISTOFORIDIS, STAMATIS 2009]. The wear of metallic parts and chrome accessories are source of Cr and Ni [AL-SHAYEP, SEAWARD 2001].

The road dust consists of pollution from transport and all other urban dust sources. Therefore, contact and ingestion of particles derived from these might effect in serious issues for human health [ACOSTA *et al.* 2014]. The resuspension of road dust from street surfaces could be a big contributor to atmospheric particulate pollution in most metropolitan areas. Polluted road dust can easily be raised into air by passing traffic or wind. Some of the particles can subsequently be redeposited on roads or spread near a road and deposit on soil, plants, as well as be inhaled or ingested by animals and humans [AMATO *et al.* 2009; MARTUZEVICIUS *et al.* 2011; WEI *et al.* 2015; ZHAO *et al.* 2016]. Therefore, air quality degradation due to ambient particulate matter from the street dust has become an environmental issue of public health. Beside the air pollution, road-traffic noise is one of the major environmental stress factors. The road traffic is not only the most annoying noise source in urban environments but also it is a concern for public health and environmental welfare [CALIXTO *et al.* 2003; KASSOMENOS *et al.* 2014]. Apart from direct emissions of pollutants from vehicles also maintenance of roads causes pollution by substances, which can strongly affect some of environmental components. Salinity of road shoulders might be an effect of periodic use of easily soluble salts, usually sodium or calcium chloride, for deicing roads during winter time. Such large amounts of salt entering the environment can change the soil parameters, causing alkalization and reducing the availability of certain elements for plants as well as penetrate into groundwater [MERRIKHPOUR, JALALI 2013; NOVOTNY *et al.* 2008; JAKUBIAK, URBAŃSKI 2015].

These widespread and significant impacts of road transport on populations and environment initiates works on reducing the exposures to traffic pollutants carried out all around the world. The technological development of environmentally friendly transport has been focused mostly on improving fuel efficiency, constructing quiet, electric (no exhaust emissions) passenger vehicles as well as on developing support systems to aid the driver in a more eco-friendly driving style. Telemetry traffic control systems are another modern solution that can increase safety and traffic flow on the roads thereby contributing to the reduction of emissions and noise.

Road constructions, such as sound walls (noise barriers), are another technology that could help to reduce road transport nuisance. In the last decade, noise barriers in large numbers began to appear along the main streets and became a common feature of urban architecture in Poland. The primary purpose of sound walls construction is to reduce the impact of traffic noise on residential areas. The road category, intensity of traffic and the type of the immediate neighborhood protected by walls determinate the type of barrier, its shape and dimensions, materials of which it is made and the ability to reflect or absorb sound waves. Due to the fact that barriers have a significant impact on shaping urban space an aesthetic values of walls also plays an important role. One of the method of sound barriers aestheticization is to create a "green wall" by covering barriers with fast growing greenery e.g. climbing plants. Beside being barriers to the spread of the noise on the neighboring areas these constructions might also contribute to reducing the spread of air pollution, especially road dust particles with associated trace metals (Cd, Cu, Mn, Ni, Pb, Zn). Nevertheless, the spread of air pollution in situations characterized by many variables, as in the case of noise barriers in road vicinity, is a complex problem. However, it is important issue for the health of people living or working in such areas. Although there are many studies about road pollution dispersion around noise barrier [BALDAUF *et al.* 2016; ŚWIETLIK *et al.* 2015; TRUJILLO-GONZÁLEZ *et al.* 2016] the influence of road and sound walls configuration has not been fully investigated [JEONG 2015].

The aim of the study described in the article was to examine if the extent to which “green walls” noise barriers and transparent acrylic-glass noise barriers located along roads can contribute to a change in the spread of trace elements from the road traffic to outside of the road area. Toxic metals which occur in road dust in significant concentrations (Cu, Fe, Mn, Pb and Zn) were selected and their concentrations in soil samples were examined. The samples were collected at close vicinity of the road edge in an open area as well as in an area with noise barriers.

## MATERIAL AND METHODS

The research was carried out on the basis of soil material sampled from the previously selected research sites. Content of heavy metals, granulometric composition and pH value were examined in the samples. Marked characteristics of the soil, apart from the cognitive objective, allowed to verify the variability of studied concentration of trace elements. Organic matter is also one of the main parameters affecting the concentration of heavy metals in soils. Due to uniform land use (urban greenery – grassland) in both research areas and the relatively short distance between the sampling points the study of organic matter has been omitted.

### THE RESEARCH AREA

The research area was set in the vicinity of the Opolska Street. This street is part of the so-called "third ring road" of Kraków, which is one of the main connectors between the eastern and western parts of the city. This street, along its entire length, has a minimum of two lanes in each direction, which are usually separated by greenery or metal traffic barrier. The total number of lanes in both directions is increased to a maximum of eight at some junctions or intersections. The two areas of research; one with the noise barrier (area "A") and the other without (area "B"); were designated in the neighborhood of the Opolska Street, in section located between the intersections with Władysława Łokietka Street and Pleszowska Street (Fig. 1).

The study areas were selected taking into account two important features. First of all, both study areas were located close to each other and had similar parameters of land use (excluding noise barriers). Second, both were located near the road with a heavy traffic. Opolska Street, as one of the most important transit routes in Kraków, is characterized by a high average-daily vehicle traffic. Measurements made by the General Directorate for National Roads and Motorways has shown that the maximum daily traffic in both directions might reach up to 50 000 vehicles [GDDKiA 2010]. Such dense road traffic generates nuisance noise, large amount of dust as well as the high road emissions which cause pollution of the surrounding areas.

Noise barriers constructed in certain parts of the Opolska Street may contribute to the targeted pollutant dispersion and modify their distribution in comparison to areas without such protective systems. The noise barrier (about 180 m long and 3 m high) was designed and constructed in the last decade on one of the research areas (area "A"). This barrier is located about 3–4 m from the road edge and separates the dense multi- and single-family residential area from the road. Some parts of the barrier are made of transparent acrylic glass panels on a concrete foundation. The transparent barriers are to reduce the impact of traffic noise while not limiting sunlight and view. However, the main part of the noise barrier was constructed as a "green wall", which is the most widely used technological solution in the cities (Phot. 1). "Green wall" has a good acoustic properties and is also one of the cheapest solutions. These screens should become spontaneously overgrown with climbing plants, although in Polish climat and the adverse impact of the proximity of communication routes (eg. salinity) this is not always possible.

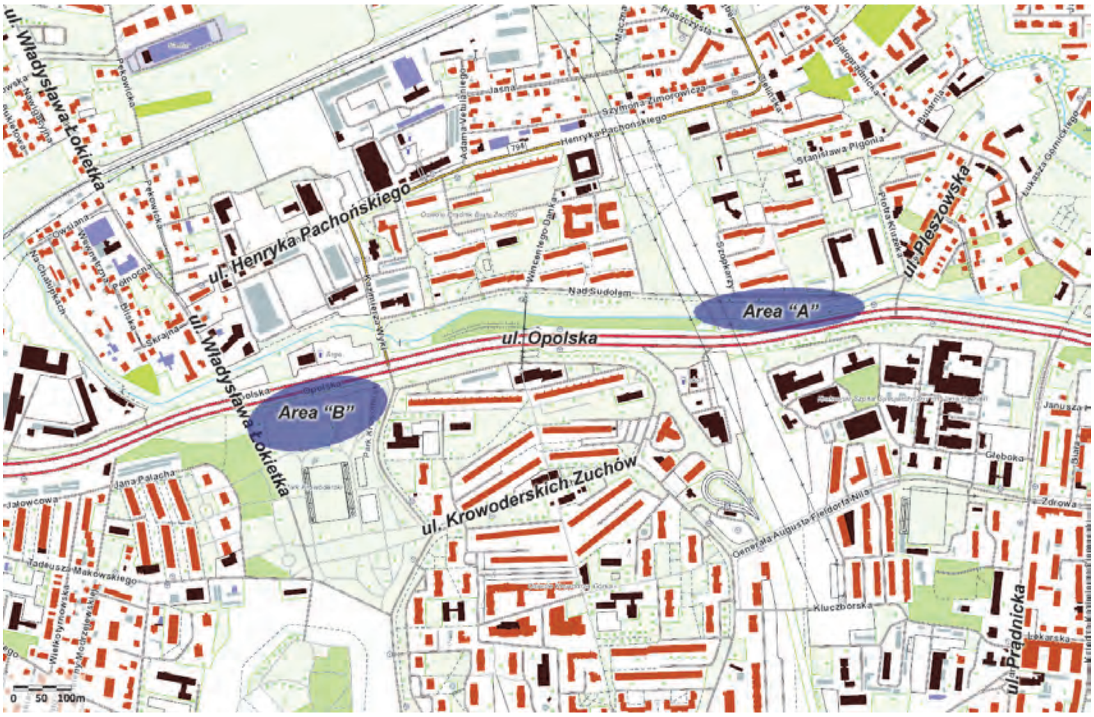

Fig. 1. Location of "A" and "B" research areas; source: own elaboration

Phot. 1. The noise barrier in the research area "A": "green wall" and transparent acrylic glass panels (photo *M. Jakubiak*)

## THE FIELD STUDY

The field part of experiment was based on soil samples collection. Samples were taken in three lines parallel to the road. In both research areas, the lines were established at a distance of 2, 8 and 22 m from the road edge. Five samples were collected on each line in area "A", while in case of area "B" – four samples were collected on each line. The length of the line along which samples were taken was 180 m (area "A") and 100 m (area "B") (Fig. 2). The distance between sampling points on the research areas amounted respectively to 45 and 33.3 m. The total number of samples collected from the area with the noise barrier was 15 and from the area without the barrier – 12. Soil material was collected from a depth of 0–30 cm, which is referred to as the root layer. The soil layer used in the research is compatible with the soil layer specified in the Regulation of the Minister of the Environment of 9 September 2002 on soil and ground quality standards [Rozporządzenie… 2002].

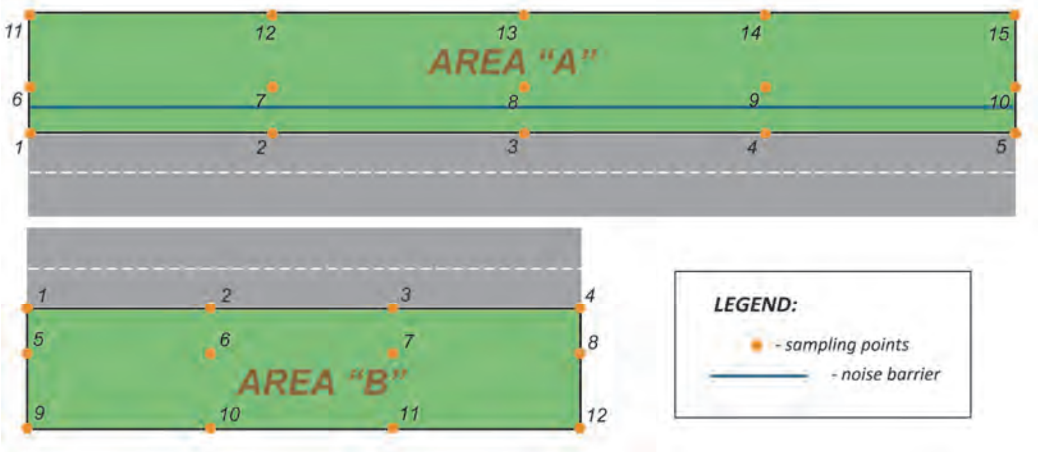

Fig. 2. The schemes of sampling on research areas A and B; source: own study

## LABORATORY STUDIES AND DATA ANALYSIS

The soil material was subjected to laboratory analysis. The granulometric composition was measured (Casagrande method) as well as the pH value (in water and in KCl solution). Afterwards, the samples were mineralized in a solution of a mixture of hydrochloric acid and nitric acid in the ratio 3:1. The final solutions were analyzed for heavy metals using flame atomic absorption spectrometry (FAAS) with the spectrophotometer model Hitachi Z 2000. Total concentrations of Cd, Cu, Mn, Ni, Pb, Zn were determined. The verification of the results was performed with use of Statistica software. The Mann–Whitney U test was used for calculations because that non-parametric test is the strongest alternative to the Student's *t*-test.

The data structure that does not have distribution in accordance with the normal distribution and a very small number of sets indicated the use of that test. The assumed significance level was α = 0.05. The tested hypothesis assumed that the relevant parts of roadside are equally contaminated with heavy metals. The following data sets were considered for the study: sets containing measuring points representing lines located 2 m away from the edge of the road (one set for the field with acoustic screen and separately – set I, the second set for the field without screen – set II), whereas next sets included aggregated values for the other two sampling lines – 8 and 22 m from the edge of the road (one set for the field with acoustic screen – set III and the set for the field without screen – set IV). This procedure was applied due to the fact that the vast majority of pollutions were deposited in the immediate vicinity of the road. The following four combinations of sets were compared: set I and set II, set I and set III, set II and set IV, set III and set IV. Additionally, a testing of the hypothesis of equal concentrations of trace elements studied in relation to all areas of research was done. The study also was conducted with use of the Mann–Whitney U test and the assumed significance level α = 0.05.

## RESULTS AND DISCUSSION

The granulometric composition of all soil samples collected in both research areas was similar. The vast majority of the samples had a particle size of sandy clay loam (85.2% of the total sample), while the rest had a composition corresponding to sandy clay (11.1% of the total) and clay loam (3.7%) (according to the PTG of 2008 and the FAO/WBR classification) (Fig. 3). Analysis of granulometric composition also did not show significant differences in this parameter between research areas. This was confirmed by the statistical tests. For the 91.6% of the samples collected in the area "A", the grain size distribution was corresponding to the sandy clay loam. For the samples from the area "B" it was exactly 80.0%. The pH values (in water and in KCl solution) of all samples of soil taken from the both research areas were similar (Fig. 4). Therefore, it may be presumed that the pH value does not affect the differentiation of pollutants accumulation in the soil of both research areas. In terms of the pH value both research areas have slightly acidic soils. Furthermore, the possibility of easy and intensive leaching of heavy metals along with rainwater can be excluded.

Conducted laboratory analysis showed that the content of marked elements in the soil layer from both research areas is relatively low (Tab. 1). All trace elements were within the permissible concentration limits for roadside areas – as defined by the soil quality standards [Rozporządzenie… 2002].

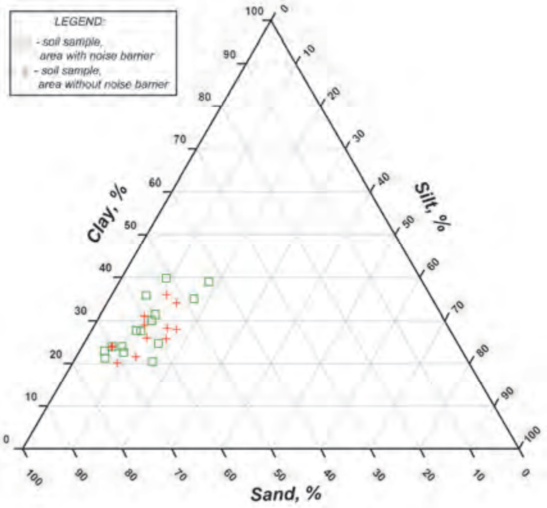

Fig. 3. Grain size distribution of soil samples taken for both research areas; source: own study

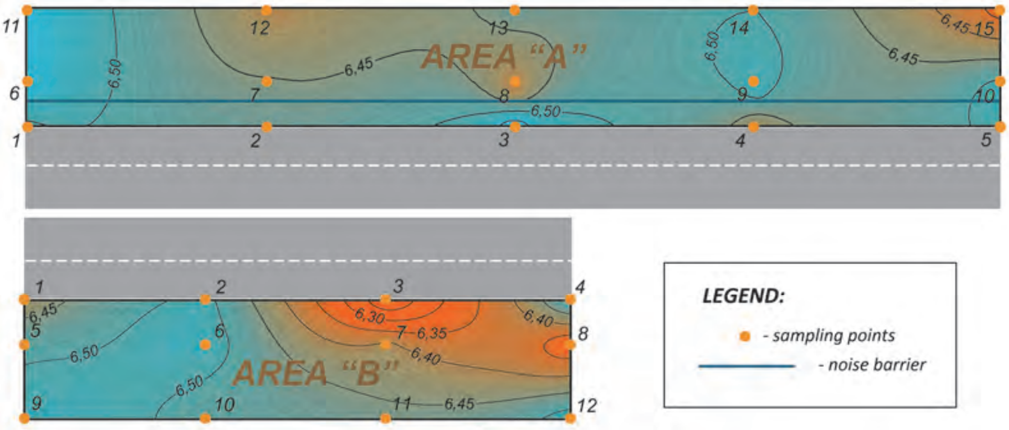

Fig. 4. The distribution of pH value measured in water solution of soil samples for both research areas; source: own study

**Table 1.** Selected statistics of marked soil elements for research areas taking into account all samples collected from both areas as well as samples collected from each area separately

| Research field | Element | Statistics, $mg\cdot kg^{-1}$ d.w. | | | | | |
|---|---|---|---|---|---|---|---|
| | | average | minimum value | maximum value | lower quartile | upper quartile | standard deviation |
| Both areas | Mn | 435.16 | 201.44 | 906.46 | 297.35 | 506.93 | 187.75 |
| | Ni | 11.93 | 4.64 | 18.01 | 9.70 | 14.25 | 3.38 |
| | Cu | 23.02 | 11.57 | 49.27 | 15.62 | 30.88 | 9.89 |
| | Zn | 127.67 | 49.51 | 275.35 | 85.96 | 161.25 | 57.56 |
| | Cd | 0.31 | 0.00 | 1.73 | 0.00 | 0.62 | 0.42 |
| | Pb | 48.93 | 14.28 | 91.00 | 28.60 | 64.92 | 21.86 |
| Area “A” | Mn | 518.99 | 288.04 | 906.46 | 338.94 | 674.15 | 198.90 |
| | Ni | 12.16 | 8.26 | 17.31 | 9.70 | 13.27 | 2.79 |
| | Cu | 23.67 | 11.57 | 49.27 | 14.25 | 34.87 | 11.55 |
| | Zn | 119.19 | 49.51 | 207.03 | 80.00 | 157.85 | 49.71 |
| | Cd | 0.36 | 0.00 | 1.74 | 0.00 | 0.63 | 0.50 |
| | Pb | 37.71 | 14.29 | 63.94 | 24.1546 | 49.29 | 15.63 |
| Area “B” | Mn | 330.38 | 201.44 | 506.93 | 246.68 | 424.27 | 106.78 |
| | Ni | 11.65 | 4.64 | 18.01 | 8.73 | 14.57 | 4.13 |
| | Cu | 22.19 | 15.31 | 36.84 | 16.63 | 27.15 | 7.74 |
| | Zn | 138.28 | 60.53 | 275.35 | 92.98 | 188.40 | 66.82 |
| | Cd | 0.26 | 0.00 | 0.77 | 0.00 | 0.51 | 0.30 |
| | Pb | 62.96 | 31.86 | 91.00 | 45.66 | 82.90 | 20.81 |

Source: own study.

Trace elements concentrations in both research areas followed the sequence: Mn > Zn > Pb > Cu > Ni > Cd (Tab. 1). In some samples presence of cadmium was not confirmed at all, or it was under the lower limit of analytical determination. Also the differences in the concentrations of individual elements for different fields were highlighted. The mean content of Zn and Pb were higher in soil samples from the field without the barrier (area “B”). Whereas the concentrations of Ni, Mn, Cd and Cu had higher levels in the field with the barrier (area “A”). What is important, for all sampling lines (2, 8 and 22 m from the edge of the road) concentrations of elements were changing (Fig. 5). This is particularly evident in the case of Cu, Ni, Zn and Cd. The standard deviation for cadmium exceeds the average value for this element. It was caused by the uneven distribution of the cadmium concentration in soil samples collected in the same line-distance from the road. The concentration of cadmium in one sample significantly differs (being much higher) from the cadmium content of all other samples. This phenomenon was recorded for both research fields. However, higher values (and thus the greater unevenness in concentration of the test element) was observed in the area with acoustic screen (Fig. 5). No clear trend was observed in the standard deviation. Its value varies widely for different elements, as well as research lines in both study areas.

In order to better illustrate the relationships of the mean values and other statistical characteristics block diagrams plotted with use of the “Statistica” were prepared (Fig. 6). Charts graphically highlighted that in case of certain elements the concentration declined together with the increasing distance from the edge of the road, and then the concentration slightly increased (Fig. 6). Such a phenomenon occure in all of the analyzed elements for the field without the barriers (area “B”). While for the area “A” this trend is visible only in cases of cadmium and zinc. For all elements from both research fields the highest concentrations occurred in the nearest sampling line from the roadway – which was 2 m.

The statistical testing was performed because the levels and distribution scheme of trace elements concentration in roadside soils of particular lines were similar. Statistical analysis had to clearly verify the hypothesis about the effect of noise barriers on the deposition of pollutants in soils. Statistical study of the relationship between such two data sets: the values of the line nearest to the road (2 m) and a set of values for the other two lines showed that significant differences were present for almost all the tested items. In case of the area with noise barrier (area “A”) statistically significant differences in the concentration of heavy metals do not occur only in case of cadmium. For the area without barrier (area “B”) statistically significant differences were observed for Mn, Zn, Cd and Pb. Comparing sets of values of concentrations in samples from: the lines nearest to the road in both research areas (set I + set II) and the two other lines form both research areas (set III + set IV), showed statistically significant differences only for Mn and Pb. Testing taking into account all the research areas also showed significant differences in concentration for these two elements.

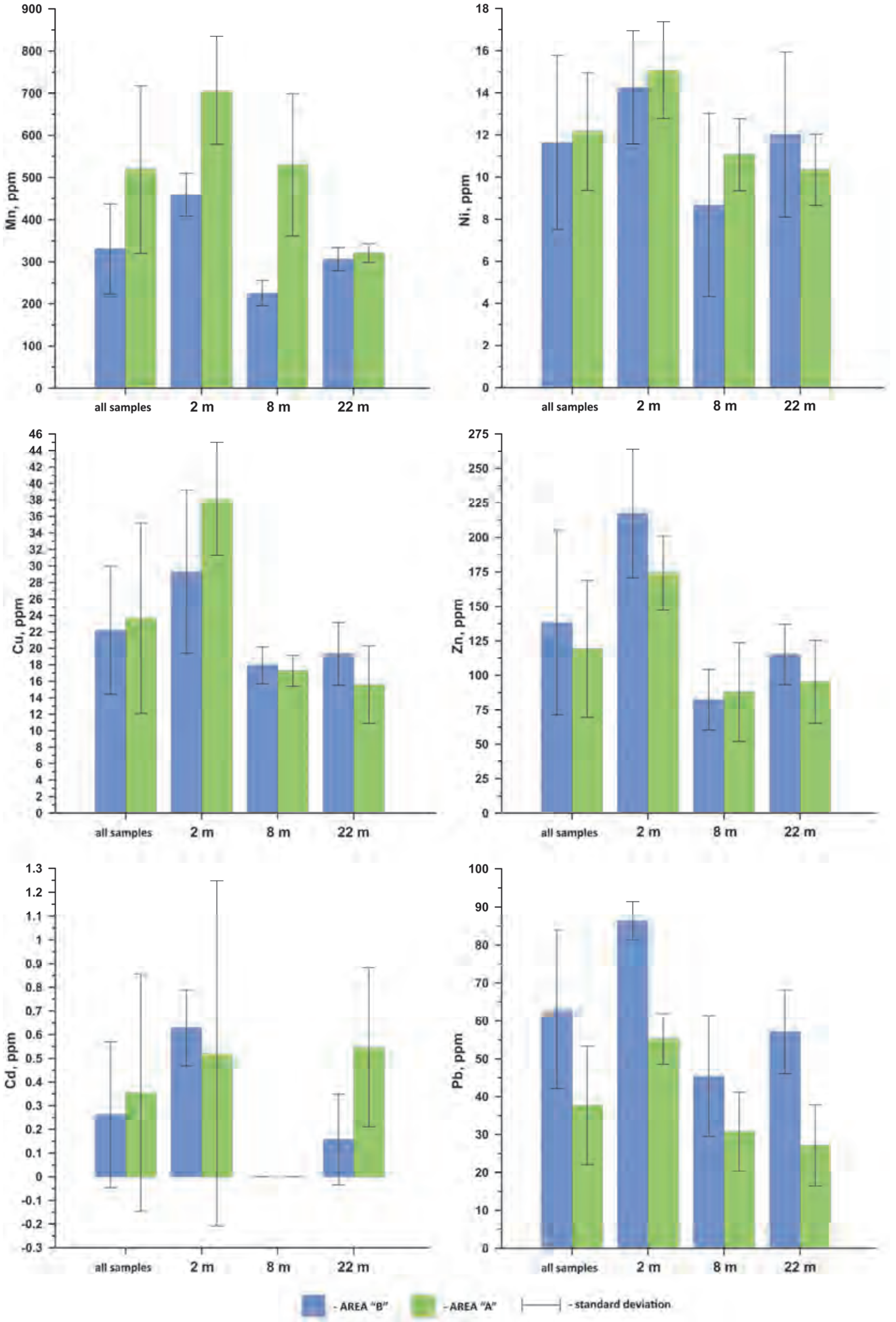

Fig. 5. The mean values and standard deviations of trace elements marked for both research areas taking into account all samples as well as sampling from each sampling line at a distance of 2, 8 and 22 m from the road edge; source: own study

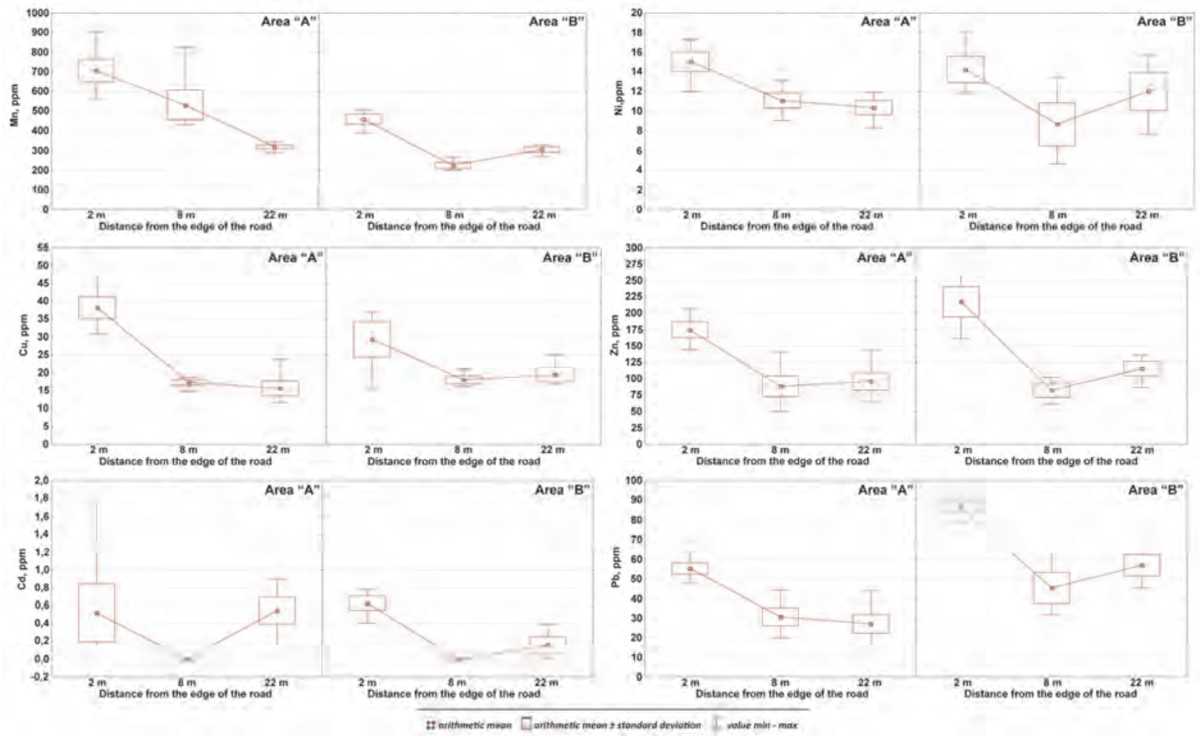

Fig. 6. The distributions of selected statistics, taking into account the different sampling lines; source: own study

## CONCLUSIONS

The study of heavy metals distributions in areas under strong and very time-varying anthropogenic influence seems to be a particularly complicated issue. The study, which was conducted on two parts of the Opolska Street was intended to determine the size and extent of the effects of the communication route to the state of quality of soil in adjacent areas. Moreover, the research should allowed to answer the question whether the low noise barriers contribute to the change in the distribution of contaminants in soils on the roadside. The results showed that the highest concentration of pollutants occurred at a distance of 2 m from the road edge. Nevertheless, these values do not exceed the levels set out in the Regulation of the Minister of the Environment [Rozporządzenie… 2002]. The observed increases in the concentrations of selected elements in the soil occurring farther from the edge of the road might be caused by other, unidentified sources of emission in close proximity to the examined terrain. This multiplicity of sources of pollution in urban environments is often found and it may also hinder the clear conclusions. Recorded statistically significant differences in the concentration of only two (Mn and Pb) of the six elements can reliably determine whether the selected noise barriers significantly affect the scheme of the spread of contamination. On the contrary, the observed similar schemes of heavy metals distributions for both research areas and similar values of their concentration appear to contradict earlier assumptions. However, it should be noted that sound barriers were relatively low (height of 3 m only). It is possible that more apparent differentiation would be observed in the distribution of contaminants in the air and thus their subsequent accumulation in soil, should the noise barriers be higher or of other shape. Other studies, pertaining directly to air pollution distribution, showed a significant effect of acoustic barriers on the spread of traffic contamination. Although, the examined barriers in those researches had a height of 4.5 and 6 m [BALDAUF *et al.* 2016; FINN *et al.* 2010]. That could contribute significantly to increasing their influence to change the spatial distribution of pollutants.

To summarize, conducted studies have found that the maximum level of pollutants in roadside soils is undoubtedly in the immediate vicinity of the road. Nevertheless, it is not possible to explicitly conclude that 3 m high barriers would be able to significantly alter the expected trend of spatial differentiation of pollutants in the soil.

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## Rozwiązania urbanistyczne w kontekście rozprzestrzeniania się zanieczyszczeń drogowych

### STRESZCZENIE

Funkcjonowanie przestrzeni zamieszkałych przez człowieka nierozerwalnie wiąże się ze stałym ich przekształcaniem. Szczególnie widoczne jest to na obszarach silnie zurbanizowanych. Oprócz zabudowy mieszkaniowej czy przemysłowej istotną rolę w antropogenicznie przekształconej przestrzeni miejskiej odgrywają wszelkiego rodzaju szlaki komunikacyjne. Rozbudowa infrastruktury komunikacyjnej, poza niewątpliwymi korzyściami dla rozwoju społeczno-gospodarczego, generuje również niekorzystne oddziaływania na środowisko. W ostatniej dekadzie wzdłuż głównych ulic dość licznie zaczęły pojawiać się ekrany akustyczne, które stały się powszechnym elementem architektury miejskiej. Podstawowym celem budowy tych konstrukcji jest ograniczenie oddziaływania hałasu komunikacyjnego na tereny zabudowy mieszkaniowej. Z uwagi na swoją konstrukcję mogą one także przyczyniać się do ograniczania rozprzestrzeniania się zanieczyszczeń znajdujących się w pyle drogowym, takich jak metale śladowe (Cd, Cu, Mn, Ni, Pb, Zn). Zanieczyszczenia te, przenoszone przez powietrze, są deponowane na powierzchni terenów przydrożnych, wpływając na jakość środowiska glebowego.

Celem prezentowanych badań było sprawdzenie, w jakim stopniu wybrane ekrany akustyczne, zlokalizowane wzdłuż tras komunikacyjnych na terenach miejskich, mogą przyczyniać się do zmiany rozprzestrzeniania się zanieczyszczeń pierwiastków śladowych pochodzących z ruchu pojazdów kołowych.

Jako teren badań wytypowano jedną z głównych arterii miasta Krakowa. Próbki glebowe pobrano z obszarów sąsiadujących z jezdnią w wybranych terenach otwartych, jak i z wybudowanymi barierami dźwiękochłonnymi. Przeprowadzono analizy koncentracji metali śladowych, a uzyskane wyniki poddano analizie statystycznej. Wyniki te umożliwiły jedynie częściowe potwierdzenie hipotezy o wpływie ekranów akustycznych na rozprzestrzenianie się metali ciężkich i tym samym ich zawartość w glebach terenów przydrożnych. Zanotowano statystycznie istotne różnice w koncentracji manganu i ołowiu w odniesieniu do całych pól badawczych. W przypadku pola z ekranem różnice – w oznaczonych zawartościach w poszczególnych strefach poboru próbek – nie były statystycznie istotne jedynie dla kadmu (pola z ekranem) i niklu (pola bez ekranu akustycznego).

**Słowa kluczowe:** *dyspersja zanieczyszczeń drogowych, ekrany akustyczne, metale śladowe, zanieczyszczenie gleby*