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Correlation between vehicular traffic and heavy metal concentrations in road sediments of Bogotá, Colombia

Relación entre tráfico vehicular y concentraciones de metales pesados en sedimentos viales de Bogotá, Colombia

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| Abstract |

Introduction: Diseases such as asthma and lung cancer are associated with heavy traffic in urban areas. A deep understanding of the pollutants generated by road traffic is relevant to public health control.

Objective: To analyze the correlation between vehicular traffic intensity and heavy metal concentrations in road sediments in the city of Bogota, Colombia.

Materials and methods: A descriptive observational study was performed. The degree of road pollution was assessed based on reference legislation for the protection of human health (inhalation, ingestion, and dermal contact). Heavy metal concentrations (lead, zinc and copper) were determined by flame atomic absorption spectrometry. Regression models between traffic intensity and metal concentrations were developed.

Results: The size fraction <250 µm of the road sediment was representative to analyze the correlation between traffic intensity and heavy metal concentrations. Lead was the heavy metal of greatest concern from the view point of public health in Bogotá.

Conclusions: The following public health limits for control decision-making regarding lead are proposed: lower limit =4 850 vehicles/day; upper limit =11 300 vehicles/day.

Keywords: Environmental Pollution; Heavy Metals; Lead; Public Health; Vehicle Emissions (MeSH).

| Resumen |

Introducción. Enfermedades como el asma y el cáncer de pulmón se han asociado al tráfico vehicular intenso de áreas urbanas. Un entendimiento profundo de los contaminantes generados desde este fenómeno es relevante para el control de la salud pública.

Objetivo. Analizar la relación entre intensidad de tráfico vehicular y concentración de metales pesados en sedimentos viales en la mega ciudad de Bogotá, Colombia.

Materiales y métodos. Se realizó un estudio observacional descriptivo en el que se evaluó el grado de contaminación vial con respecto a la legislación de referencia para la protección de la salud humana (inhalación, ingestión y contacto dérmico). La concentración de metales pesados (plomo, zinc y cobre) en sedimentos viales se determinó mediante espectrometría de absorción atómica con llama. Se desarrollaron modelos de regresión entre intensidad de tráfico y concentraciones de metales.

Resultados. La fracción de tamaño <250µm del sedimento vial fue representativa para analizar la relación entre intensidad de tráfico y concentración de metales pesados. Plomo fue el metal de mayor atención desde el punto de vista de la salud pública en Bogotá.

Conclusiones. Se proponen los siguientes límites para la toma de decisiones de control por contaminación con plomo: límite inferior 4 850 vehículos/día y límite superior 11 300 vehículos/día.

Palabras clave: Contaminación ambiental; Emisiones de vehículos; Metales pesados; Plomo; Salud pública (DeCS).

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Introduction

The density of vehicles used to transport passengers and consumer goods has increased significantly with the rapid growth of urban areas. (1,2) Vehicular traffic in these areas is one of the major sources of soil contamination, as the terrain near the roads is a drain for pollution from vehicles that could easily come into direct contact or by suspension with pedestrians and residents of surrounding areas. (3) In addition, vehicular traffic emits a wide range of hazardous pollutants, including heavy metals. (4,5) With this in mind, a deep understanding of the pollutants generated by vehicular traffic is relevant due to their harmful effects on public health. Moreover, studying the correlation between traffic intensity and heavy metal concentration in road sediments would allow the formulation of strategies to reduce the impact on urban public health.

Respiratory diseases such as asthma and lung cancer are associated with intense vehicular traffic in urban areas. (6,7) Atmospheric aerosols and sediments deposited on the surface of urban soil have increased with population concentration, leading to increased levels of pollution along road corridors. (1) Road sediments, on the other hand, are a potentially toxic medium since they contain heavy metals and hydrocarbons originating from a wide variety of sources of diffuse pollution, including dry and wet atmospheric deposition (rain), vehicle exhaust systems and parts (brake pads, tire wear and oil leaks), pavement wear, road demarcation paint, accidents, abrasion of construction materials and soil erosion. (8-10) Thus, road sediment has often been used as an indicator of heavy metal pollution in urban environments. (7,10,11)

Chen *et al.* (3) and McKenzie & Irwin (12) reported that the deposition of heavy metals on road surfaces was proportional to traffic intensity (vehicles/day). In this regard, Bannerman *et al.* (13) and Zafra *et al.* (14) observed that the amount of lead, zinc and copper present in runoff and road sediment could be related to the intensity of vehicular traffic. However, Barrett *et al.* (15) suggested that traffic intensity was only significant at the local scale (road neighborhood) and that the variation of metal concentration was attributable to other factors such as emissions from industrial sources at a large scale (regional).

This research was developed in Bogotá, a megacity of Latin America (8.85 million inhabitants in 2015) recognized as the most densely populated urban center (26 000 inhabitants/km^2) and the third city with the worst air pollution in the region. (16,17) There are few studies worldwide aimed at assessing the correlation between vehicular traffic and heavy metal content in urban sediments in developing countries, thus leading to the interest in developing this research.

The objective of this article is to present an analysis of the correlation between vehicular traffic intensity and heavy metal concentrations in sediments accumulated during the dry season on Bogotá road corridors. Furthermore, the city's heavy metal concentrations and traffic intensities are compared and analyzed with those reported internationally by similar investigations. Linear regression models were developed to predict and evaluate the degree of pollution in road surfaces with respect to reference legislation for the protection of human health in urban soil. This study is based on the three heavy metals most reported by research on road sediments: lead, zinc and copper. (18)

Materials and methods

Research sites

The research sites were located in the megacity of Bogotá, central Colombia (Table 1), on road surfaces in the towns of Fontibón (A1), Barrios Unidos (A2), Kennedy (A3), Puente Aranda (A4), the Southern Highway road corridor or Autopista Sur (A5), and the Soacha conurbation (A6). In addition, nine road surfaces with traffic intensities between 4 200 and 187 600 vehicles per day were used for forecasting the concentration of heavy metals in road sediments in Bogotá: Avenida Boyacá between Avenida Primero de Mayo and Calle 13; Avenida Suba with Calle 100; Avenida Boyacá with avenida Jorge Gaitán Cortés; Autopista Norte with Calle 200; Avenida Jorge Gaitán Cortés with Avenida Boyacá; Carrera 24 with Calle 80; Carrera 13 with Calle 59; Calle 45 between Carrera 13 and Avenida Caracas; and Carrera Séptima with Calle 183. Information on traffic intensity was provided by the District Department of Transportation of Bogotá D.C.

Table 1. Characteristics of road surfaces under study.

Characteristic		Fontibón A1	Barrios Unidos A2	Kennedy A3	Puente Aranda A4	Autopista Sur Road corridor A5	Soacha A6
Coordinates		04°40'09"N 74°08'33"O	4°39'36"N 74° 4'42"O	04°35'45"N 74°08'48"O	04°37'49"N 74°07'06"O	4°33'04"N 74°14'22"O	4°35'05"N 74°13'12"O
Population density (inhabitants/hectare)		600	600	480	160	< 25	600
Land use		I-R	R	R-I	I-C	I-RU	R
Average daily traffic (Vehicles/day)		650	1600	12300	13500	40100	2750
Average speed (km/h)		20	20	50	40	70	20
Traffic composition (%)	Cars	93	81	77	83	62	65
	Light trucks	5	16	4	3	7	0
	Bobtail trucks	1	1	2	2	5	0
	Trailer Trucks	0	0	0	1	7	0
	Buses	1	2	17	11	10	35

R: residential; I: industrial; C: commercial; RU: rural
Source: Own elaboration.

Ethical considerations

The information collection and analysis systems used in this study had no effect on human or animal dignity and had no impact on the environment. The information was used for academic purposes only. This study was ethically endorsed by the Centro de Investigación y Desarrollo Científico of the Universidad Distrital Francisco José de Caldas through Minutes 030 of November 24, 2009.

Collection of road sediment

This was a descriptive observational study. Road sediment samples were taken in dry weather, at one side of the curb (0.50m), at the same time for one year (between 8 May 2010 and 8 May 2011) in A1, A2, A3 and A4, and for 127 days (between 7 January 2010 and 14 May 2010) in A5 and A6. The mean sampling frequency was 10 days for A1, A2, A3 and A4, and 3 days for A5 and A6. However, there were slight variations in sampling frequency due to the occurrence of precipitations that prevented the collection of sediment in dry weather.

The sampling area was 0.49m^2 (0.70m x 0.70m) and the dimensions of the road sediment collection area were guaranteed by placing on the surface a wooden frame with the same dimensions of the sampling area. The sampling site was controlled to avoid repetition and to be close to previous sediment collection points. A plastic fiber brush and a handheld dustpan were used for the collection of the sediment. The number of samples collected in each research area was 36 for A1, A2, A3 and A4, and 43 for A5 and A6. A total of 230 road sediment samples were collected.

Heavy metal concentration

The granulometry of the road sediment (<63-250μm) was determined using the ISO-11277 method. (19) The analysis of heavy metal concentration in the road sediment was performed for the size fraction <250μm because research has reported that this fraction is dominant in weight and has the tendency to record the highest concentrations of heavy metals in road sediments. (14,20,21)

Heavy metal concentration in the road sediment was determined by flame atomic absorption spectrometry (ISO-11047 method). (19) The sediment samples were previously digested in a mixture of hydrochloric acid and nitric acid (3:1, *aqua regia*), method ISO-11466. (19) The heavy metals analyzed were lead, zinc and copper.

Statistical analysis

In order to identify the possible correlation between the variables of the global matrix developed for traffic intensity and heavy metal content in road sediments (literature review), a cluster analysis was applied using the software SPSS version 22.0. Data (variables) were standardized by means of z-scores prior to cluster analysis, and Euclidean distances of similarity between variables were calculated. A hierarchical analysis using Ward's method was then applied to the standardized data. The normal distribution of the data was determined using the Shapiro-Wilk test, while descriptive statistics and r-Pearson were used to deepen the analysis between variables. Finally, mathematical models were developed using linear regression to predict heavy metal concentrations on Bogota roads.

Results

Heavy metal concentration

Table 2 presents a review of the international literature (22-40) on heavy metal concentrations associated with road sediment for different traffic intensities between 1980 and 2015. A cluster analysis allowed the identification of four clusters: 1) zinc and copper concentrations, 2) lead concentration, 3) traffic density, and 4) fraction of size analyzed. Clusters 1, 2 and 3 were grouped at a higher level, perhaps implying a correlation between them. Similarly, a probable correlation between cluster 4 and clusters 1 and 2 was observed. The following are the results of the correlations suggested by the cluster test.

Table 2. International literature review on heavy metal concentration in road sediments (collected in dry weather) from different traffic intensities.

Place (reference)	ADT (vehicles/day)	Size fraction (μm)	Concentration (mg/kg)		
			Lead	Zinc	Copper
Davis/U.S. (22)	130 000	<1 000	110	414	236
Barcelona/Spain (23)	120 000	<10	229	1 252	771
Massachusetts/U.S. (24)	106 000	<2 000	79	381	172
London/England (25)	96 000	<250	2 296	1 212	386
London/England (26)	80 000	<2 000	227	1 145	337
Beijing/China(27)	65 000	<2 000	511	51	126
Baltimore/U.S. (28)	45 575	<63	-	343	196
London/England (25)	42 000	<250	1 826	695	280
Zhenjiang/China (20)	34 512	<2 000	589	687	158
Tokyo/Japan (29)	28 250	<2 000	-	1 500	340
Tokyo/Japan (29)	28 250	<2 000	-	1 525	708
Hamilton/New Zealand (30)	25 000	125-250	251	1 073	184
Christchurch/New Zealand (31)	24 000	<1 000	290	370	73
Hildesheim/Germany (32)	22 000	<2 000	255	120	84
Ulsan/South Korea (7)	20 118	<2 000	153	325	182
Lulea/Sweden (33)	20 000	75-125	68	150	89
Tokyo/Japan (29)	19 600	<2 000	200	1 300	510
Barcelona/Spain (34)	15 000	<100	283	542	216
Jönköping/Sweden (35)	11 200	<250	45	257	282
Jönköping/Sweden (35)	11 200	<2 000	23	125	119
Beijing/China (21)	8 900	150-250	59	280	72
Sydney/Australia (36)	8 800	<200	511	249	124
Aberdeen/Scotland (37)	6 900	63-250	305	345	325
Lulea/Sweden (38)	5 000	75-125	15	80	53
Lulea/Sweden (38)	4 500	75-125	14	100	91
Torrelavega/Spain (11)	3 800	125-250	246	309	90
Torrelavega/Spain (11)	3 800	125-250	299	309	117
Bilbao/Spain (39)	1 800	<2 000	630	200	45
London/England (25)	2 400	<250	978	2 133	91
Singapore/Malaysia (40)	726	<63	297	1 585	465
Median		250	251	358	177
Mean		889	400	635	231
Minimum		10	14	51	45
Maximum		2 000	2 296	2 133	771
Data considered		30	27	30	30

ADT: average daily traffic.
Source: Own elaboration.

A Pearson's correlation coefficient analysis was performed in order to evaluate the affinity in the origin of the heavy metals reported in Table 2, for example, the source of contamination. The results worldwide showed that there was a significant positive correlation —average to considerable— between zinc and copper concentrations associated with road sediment (r-Pearson=0.63, p<0.001). In Bogotá, the correlation between these two metals was similar (r-Pearson =0.67, p<0.001). With respect to lead, positive correlations —between weak and average— were observed at both the international and national levels (r-Pearson= lead and copper: 0.16, p=0.044; lead and zinc: 0.38, p=0.025), and the local level (r-Pearson= lead and copper: 0.26, p<0.001; lead and zinc: 0.50, p<0.001).

The results showed that the concentrations in the road sediment had the following sequence at the international level: zinc (358 mg/kg), lead (251 mg/kg) and copper (177 mg/kg) (Table 2). At the local level the sequence was: zinc (136 mg/kg), copper (81 mg/kg) and lead (72 mg/kg) (Table 3). Analyses of heavy metal concentrations in Bogotá focused on the size fraction <250µm of the road sediment because this was the dominant trend at the international level, as shown in Table 2.

Table 3. Heavy metal concentration in road sediments for different traffic intensities.

Metal	Fontibón A1	Barrios Unidos A2	Kennedy A3	Puente Aranda A4	Autopista Sur road corridor A5	Soacha A6	Average	Median
Concentration in mg/kg of dry matter - Size fraction <250µm								
Lead	69±14	60±12	74±15	48±11	217±30	84±22	92	72
Zinc	334±51	145±32	197±29	126±19	110±9	96±13	168	136
Copper	279±38	94±16	110±19	68±11	57±13	41±10	108	81
ADT (Vehicles/ day)	650	1600	12300	13500	40100	2750	14050	12300

ADT: average daily traffic.
Source: Own elaboration.

International results showed no significant correlations between traffic intensity and lead and zinc concentrations in road sediments (size fraction <2 000µm) (Table 2). However, a positive —from weak to average— linear correlation was observed with copper concentration (r-Pearson=0.39, p=0.016). A similar analysis was performed taking into account only the size fraction <250µm of the road sediment. The results showed no significant correlation for zinc. However, at the international level, a positive linear correlation from weak to average between the average daily traffic intensity (ADT = vehicles/day) and concentrations (mg/kg of dry matter) of lead (r-Pearson=0.48, p=0.029, gl=16, Pb=0.0084* ADT+246) was observed. For copper, the results showed a linear correlation between average and strong (r-Pearson=0.73, p<0.001, gl=17, Cu=0.0040*TPD+128). Figure 1 presents the linear models developed for lead and copper based on the information reported worldwide (Table 2) and in Bogotá (Table 3). Geometric and logarithmic models were also tested; however, the linear model showed a better fit (r-Pearson≥0.50).

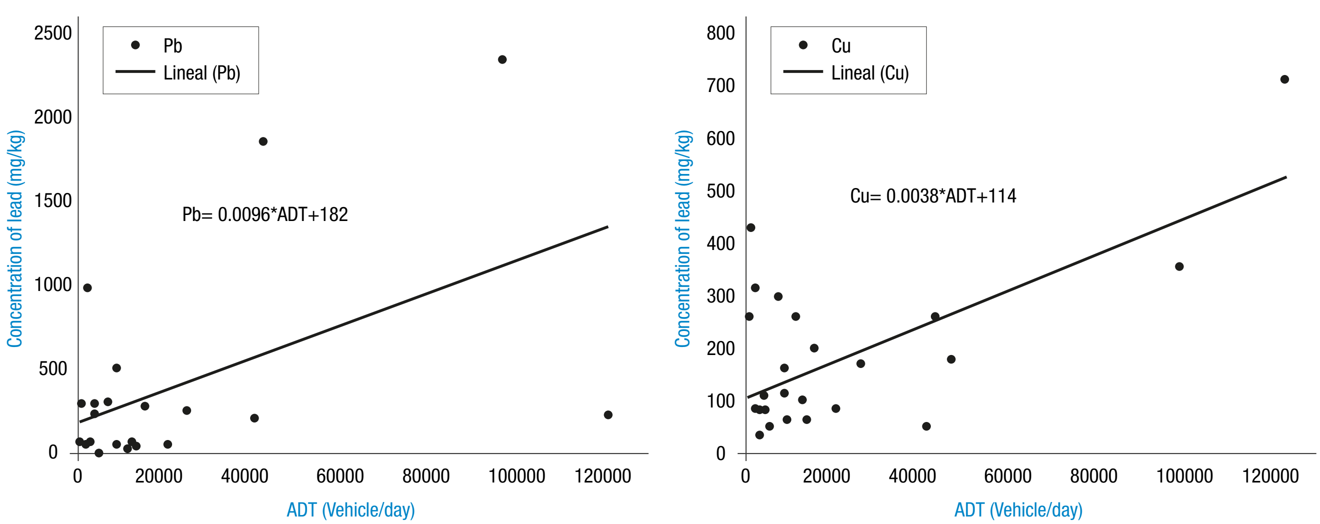

Figure 1. Linear models between lead and copper concentrations in road sediments and average traffic intensity.
ADT: average daily traffic.
Source: Own elaboration.

Forecasts for Bogotá

Based on the linear models obtained, the concentration of metals (lead and copper) was predicted on nine road surfaces of Bogotá, with ADT between 4 200 and 187 600 vehicles/day (Table 4). The results showed that lead and copper concentrations in the sediment of the road with the maximum ADT (Avenida Boyacá between Avenida Primero de Mayo and Calle 13) could reach figures of up to 1 938 mg/kg and 827 mg/kg, respectively. The maximum figures reported internationally were 2 296 mg/kg for lead and 771 mg/kg for copper (ADT between 96 000-120 000 vehicles/day). In contrast, the predictions for the road with lower ADT (Carrera Séptima with Calle 183) allowed observing lead concentrations of 222 mg/kg and copper concentrations of 130mg/kg. International reports on roads with similar ADT (3 800-4 500 vehicles/day) showed lead concentrations of 14-299 mg/kg and copper levels of 90-117 mg/kg (Table 2).

Table 4. Forecasts for heavy metal concentration in Bogotá with respect to reference legislative limits.

Selected forecasts	ADT (Vehicles/ day)	Concentration (mg/kg) linear model (<250 µm)	
		Lead	Copper
Avenida Boyacá - Avenida Primero de Mayo and Calle 13	187 600	1 983±124	827±48
Avenida Suba - Calle 100	157 300	1 692±124	712±48
Avenida Boyacá - Avenida Jorge Gaitán Cortés	55 200	712±124	324±48
Autopista Norte - Calle 200	49 000	652±124	300±48
Avenida Jorge Gaitán Cortés - Avenida Boyacá	26 900	440±124	216±48
Carrera 24 - Calle 80	14 200	318±124	168±48
Carrera 13 - Calle 59	12 500	302±124	162±48
Calle 45 - Carrera 13 and Avenida Caracas	6 900	248±124	140±48
Carrera Séptima - Calle 183	4 200	222±124	130±48
ADT limit for public health *			
ADT upper limit	Pb=11 300, Cu=55 400	140	310
ADT lower limit	Pb=4 850, Cu=11 250	60	63
Reference Legislation			
Catalonia, Spain (41) †	-	60	310
Basque Country, Spain (42) ‡	-	120	-
Canada (43) **	-	140	63

ADT: average daily traffic per flow fluctuation by direction, excluding motorcycles.
* Forecasts with linear models that integrated Bogotá and international information.
† Limits for the protection of human health: urban soil.
‡ Urban ground and children's play area.
** Residential land and parks.
Source: Own elaboration.

A comparative analysis of the forecasts based on reference legislation on inhalation, ingestion and dermal contact with contaminated soil (41-43) showed that all the selected roads exceeded the more flexible limit for lead (Canada, 140mg/kg). The ADT of all roads under evaluation were >4 200 vehicles/day (Table 4). On the other hand, only three of the nine selected road surfaces exceeded the most flexible limit for copper (Catalonia, 310 mg/kg). The roads that exceeded this limit had an ADT >55 200 vehicles/day.

Two new linear models were developed with origins in heavy metal concentration and ADT equal to zero, integrating the international (Table 2) and local (Table 3) reports. This sought to forecast the ADT associated with the limits established by the reference legislation for lead and copper. (41-43)

The following models were obtained: Pb=0.0124*ADT (r-Pearson=0.43, $p<0.001$, gl=22) and Cu=0.0056*ADT (r-Pearson=0.63, $p<0.001$, gl=23). The results for lead showed that ADT associated with the most stringent (Catalonia, 60 mg/kg) and more flexible (Canada, 140 mg/kg) legislative limits were 4 850 and 11 300 vehicles/day, respectively. With respect to copper, the ADT associated with the most stringent (Canada, 63mg/kg) and most flexible (Catalonia, 310mg/kg) legislative limits were 11 250 and 55 400 vehicles/day, respectively (Table 4). The results showed that lead was the most critical heavy metal when increasing the ADT of the roads under study. Finally, the limit ADT for public health for lead was lower or more restrictive than those for copper.

Discussion

Heavy metal concentration

The results suggest the existence of a common or dominant source for zinc and copper in Bogotá's road sediments, probably vehicular traffic. This is supported by an average to considerable correlation between the concentrations of these two heavy metals (r-Pearson=0.67). In contrast, various sources of pollution are suggested for lead (r-Pearson= lead and copper: 0.26, lead and zinc: 0.50) such as vehicle exhaust gas, road paint, pavement wear, traffic accidents, urban furniture and industrial emissions. (11,20,33) On average, the most abundant metal in the road corridors under study is zinc (Table 3). The order of presentation of heavy metal concentrations in Bogotá is zinc (96-334 mg/kg), copper (41-279 mg/kg) and lead (48-217 mg/kg). A similar trend is reported worldwide (Table 2).

At the international level, the determination of heavy metal concentration in the road sediments focuses on the size fraction <250µm. Studies suggest that this fraction is representative to analyze the correlation between traffic intensity and heavy metal concentration in road sediments (Table 2). The results show that the correlation between traffic intensity and concentrations of lead and copper in road sediments is more evident for the size fraction <250µm rather than for the fraction <2 000µm.

Particles emitted from lead and copper sources in the road environment may be associated with sizes <250µm. Ball *et al.* (36) report a similar behavior for heavy metals (lead, zinc, copper, chromium and iron) in the finer fraction of road sediment.

Forecasts regarding reference legislation

The linear model has the best fit to represent the correlation between traffic intensity and the concentrations of lead and copper in road sediments (r-Pearson≥0.50). However, zinc concentrations do not show a significant correlation with traffic intensity in the road corridors under study. Forecasts with the linear model developed for lead concentrations in road sediments suggest that the nine roads selected in Bogotá exceed the most flexible legislative reference limit (Canada, Pb=140mg/kg in residential land and parks). In the case of copper, forecasts show that three of the nine routes selected exceed the most flexible legislative limit (Catalonia, Cu=310mg/kg on urban land). The selected roads recorded an ADT >4 200 vehicles/day. Therefore, these results suggest lead as the heavy metal of greatest public health concern in the Bogotá road corridors; on average, the concentrations of this metal in the road sediments exceed between 1.59 and 14.2 times the most flexible legislative reference limit (Table 4).

Conclusions

The findings of this research are a reference for the development and implementation of strategies for the control of heavy metal pollution in urban roads. In this regard, the following ADT for public health limits are proposed for decision-making on lead contamination control on urban roads in Bogotá: lower public health limit of 4 850 vehicles/day and upper public health limit of 11 300 vehicles/day.

Conflicts of interest

None stated by the authors.

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