*Aerosol and Air Quality Research,* 13: 255–265, 2013

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2012.04.0087

# Assessing the Hazardous Risks of Vehicle Inspection Workers' Exposure to Particulate Heavy Metals in Their Work Places

**Peng-Hui Li[1], Shao-Fei Kong[1], Chun-Mei Geng[2], Bin Han[1,3*], Bing Lu[1], Ru-Feng Sun[1], Ruo-Jie Zhao[1], Zhi-Peng Bai[1,2]**

[1] *College of Environmental Science and Engineering, Nankai University, Tianjin, China*
[2] *Chinese Research Academy of Environmental Sciences, Beijing, China*
[3] *College of Mathematics Science, Nankai University, Tianjin, China*

## ABSTRACT

Exposure of on-duty vehicle inspection workers to heavy metals in Beijing was investigated from April 18 to May 17, 2011. Particulate samples were collected by personal environmental monitors during vehicle inspectors' work time, and were analyzed by inductively coupled plasma-mass spectroscopy (ICP-MS) for V, Cr, Mn, Co, Ni, Cu, Zn, As, Cd and Pb. The results showed that in three vehicle inspection lines, Zn was the most abundant element, accounting for over 45% of the total metal concentration. Cr and Pb were the next most abundant compositions. The geoaccumulation index and enrichment factor analysis showed that Cr, Zn, As, Cd and Pb exhibited heavy or extreme contamination and significant enrichment, indicating the influence of anthropogenic sources. Mn and Co were mostly non-enriched and were mainly influenced by crustal sources. Ni and V presented moderate or heavy contamination, and were influenced by both crustal materials and anthropogenic sources. Principle component analysis revealed that the major sources were vehicle emissions, re-suspended dust and industrial processes. Cr and Mn could trigger adverse non-cancer health effects. The median values of incremental lifetime cancer risk (ILCR) of inhalation exposure route were estimated to be $2.59 \times 10^{-5}$, $5.56 \times 10^{-5}$ and $1.01 \times 10^{-4}$, respectively for gasoline, bus, and diesel inspection workers, respectively. The ILCR was higher than the acceptable risk level of $10^{-6}$, indicating an unacceptable potential cancer risk.

***Keywords:*** Heavy metals; Vehicle inspection; Source analysis; Risk assessment.

## INTRODUCTION

Heavy metals are a group of widespread pollutants in the environment, that mostly originate from traffic emission, industrial activities, domestic emission and weathering of buildings and pavements (Chen *et al.*, 2005; Wei and Yang, 2010; Kong *et al.*, 2012). Although some natural sources result in heavy metals emissions, human activities contribute most of their emissions in urban systems (Vassilakos *et al.*, 2007; Sun *et al.*, 2010). Due to their well-known toxicity and low biodegradation, as well as their threat to the environment and public health, heavy metals have been of scientific interest for many years and have been widely studied in various environmental and biological compartments (Hall, 2002; Ferreira-Baptista and De Miguel, 2005; Meza-Figueroa *et al.*, 2007; Khlifi and Hamza-Chaffai, 2010; Ashraf *et al.*, 2012; Batayneh, 2012; Kargar *et al.*, 2012; Mzoughi and Chouba, 2012).

Among various heavy metals emission sources, vehicle emission has been known to be one of the main contributors in urban areas (Vassilakos *et al.*, 2007; Zheng *et al.*, 2010a). On a global basis, anthropogenic inputs of Pb predominate over natural sources, accounting for 96% of the total emissions (Nriagu, 1989). Among these inputs, vehicle emissions of particles are often found to be the most significant source. Although Pb-free petrol has become a popular choice for most transport facilities, Pb is still found to be an important component of airborne particles throughout the world. The association of Pb with vehicle emissions can be explained in terms of Pb contamination in crude oil, which may be of the order of 10–15 mg/L (Vassilakos *et al.*, 2007). Vehicle exhaust is also the primary major source for Cr, Cu, Zn, Cd, Sb, Br, Fe and Ba (Danielsson *et al.*, 1999; Shu *et al.*, 2001; Fang *et al.*, 2010). With rapid economic development in China, the number of motor vehicles has dramatically increased in recent years. In 2010, the number of motor vehicles in China was 190 million, including nearly 80 million cars (China Vehicle Emission Control Annual Report, 2011). Significantly more heavy metals are likely to be emitted

* Corresponding author. Tel.: 86-22-2350-3397;
Fax: 86-22-2350-3397
*E-mail address:* hanbin@mail.nankai.edu.cn

into the urban atmosphere by vehicle emissions. Wei *et al.* (2009a) measured 8-OHdG in the urine of campus security guards exposed to vehicle emissions. After 8-h work-shift exposure, the average concentration of 8-OHdG was increased more than three times than before the work shift, and had a positive association with $PM_{2.5}$ bound metals.

Compare to the general population, occupational exposure of certain groups are of special concern. The potential of continuous exposure to toxic workplace atmospheres makes it necessary for rigorous monitoring of the chemical agents in the environment. It is well known that several occupational illnesses including dermatitis, asthma, bronchitis and cancer are related to the effect of exposure to heavy metals such as Co, Ni, Pb and Cu (Roig-Navarro *et al.*, 1997). In order to prevent damage to health it is necessary to gather information on the atmospheric composition of the workplace, and evaluate exposure to chemical agents. The vehicle inspection system has been widely used all over the world, in which a vehicle is inspected to ensure that it conforms to regulations governing safety and emissions. In particular, vehicle flow rates for the vehicle inspection system have dramatically increased in recent years in China. The number of cars in Beijing was 5 million in 2010 (China statistical yearbook, 2010) and a vehicle inspection worker is expected to inspect nearly 100 vehicles per day. Due to the nature and location of their work, vehicle inspection workers are directly exposed to vehicle emissions. In addition, the re-suspended dust disturbed by the testing of vehicles also contributes to their exposure. Thus the exposure levels and ensuing health risks for vehicle inspection workers are believed to be significantly higher than those of the general population. But to the best of our knowledge, not only in China but also in other countries, heavy metal exposure levels for vehicle inspection workers have never been assessed. In this study, a preliminary assessment of the risk was done in Beijing, China to fill this gap. The main objectives of the present study were: 1) to investigate the occupational exposure levels of vehicle inspection workers, 2) to identify the source of metals, and 3) to assess cancer and other health risks for vehicle inspection workers during work time.

## EXPERIMENTAL WORK

### *Sampling*

All samples were collected in three vehicle inspection factories in Beijing, China from April 18 to May 17, 2011. Beijing is the capital of China, with a population of approximately 20 million and with 5 million cars.

In this type of study, one of the main problems is to obtain a completely representative sample because of the different types of vehicle inspection lines and the variety of vehicle emission characters. At the present time there are three representative vehicle inspection lines in China, the gasoline vehicle line, diesel vehicle line and bus line. One vehicle inspection worker in each of three representative lines was randomly selected for sampling and analysis. Generally two or three workers are assigned in each line, and dozens of vehicle inspection lines exist in different factories. Vehicle inspection workers' tasks included examining cars' equipment, guiding cars to emission inspection places and examining cars' emissions. These tasks were the same for all workers in inspection factories and the volunteers' activities can represent the normal daily work activities during the sampling period. Thus the objects sampled in the present study are representative for large group workers. In addition, though the sampling period did not cover a whole year in this present study, the number of cars inspected in factories did not show evident monthly variability. Thus this vehicle emission intensity would be stable through a year. This present study could reflect the occupational exposure levels of vehicle inspection workers.

$PM_{2.5}$ samples were collected on Teflon filters (diameter of 37 mm) by BGI 400 personal environmental monitors (BGITM. Co, USA) during vehicle inspectors' work time (from 8:00 a.m. to 12:00 a.m and from 1:00 p.m to 5:00 p.m.). Compared to other fractions such as $PM_{10}$ or TSP, $PM_{2.5}$ can effectively penetrate into the respiratory system and be deeply deposited in the bronchioles and alveoli of the lungs. Epidemiological studies have demonstrated stronger exposure-response relationships for mortality and morbidity outcomes in association with fine particles ($PM_{2.5}$) than other fractions (Saarnio *et al.*, 2008; Li *et al.*, 2010). Results obtained using a personal sampling technique have proven more reliable than fixed-point sampling for exposure monitoring (Bieniek, 1998). During the sampling period, the samplers were fixed on the inspectors' collars to collect personal samples from the breathing zone, and the samplers operated at a constant flow rate of 4 L/min. A total of 26 samples were collected at 1–2 day intervals. 10 samples were collected in gasoline and diesel lines, respectively, and 6 samples were collected in the bus line. After sampling, the filters were equilibrated in a controlled environment with a relative humidity of 45% and temperature of 22°C for 48 h, before gravimetric analysis to minimize particle volatilization and aerosol liquid water bias. The filters were exposed to a low-level radioactive source prior to sample weighing to remove static charge and were weighed by a sensitive microbalance (Mettler M5) with sensitivity of ± 0.001 mg. After weighing, the filters were stored at –4°C until chemical analysis.

### *Sample Analysis*

Ten metal elements, V, Cr, Mn, Co, Ni, Cu, Zn, As, Cd and Pb, were analyzed by inductively coupled plasma-mass spectroscopy (ICP-MS) (Agilent 7500a, Agilent Co. USA). Each Teflon filter was cut into pieces and placed in a 100 mL polyfluortetraethylene beaker with 5 mL $HNO_3$ (pH = 5.6) and a drop of HF (pH = 5.3) was added. After being covered, the solution was heated on a hot plate at 220°C for 2.5 h. Then the hot plate was shut off and 5 mL hydrochloric acid was added to the solution which was then transferred into a 10 mL plastic bottle. Finally, the digested samples were diluted to 10 mL with deionized water.

Geochemistry reference matter GBW07402 (GSS-2) from the Center for National Standard Matter was simultaneously analyzed to check the reliability of analysis. The relative standard deviations (RSD) were 3.98%, 3.63%, 2.97%, 2.04%, 7.44%, 7.00%, 3.20%, 6.74%, 8.24% and 7.22% for

V, Cr, Mn, Co, Ni, Cu, Zn, As, Cd and Pb, respectively. Background contamination was routinely monitored by using operational blanks (unexposed filters, kept in aluminum foil bags before and after sampling until analysis) which were simultaneously processed with field samples. One standard sample was analyzed per 10 field samples to assure the repeatability of the analytic instrument. Recoveries of the analytes by the utilized technique were from 80% to 120%. One field sample was analyzed twice per ten samples to assure the relative errors were less than 20%.

### *Data Processing Methods*

The geoaccumulation index (Igeo) assessment method results could be useful for regulators and engineers in environmental planning and to develop effective environmental management. In this study, it was adopted to give clear heavy metal contamination levels for particles and to identify the influence of natural or anthropological sources. The geoaccumulation index was calculated by the following equation:

$$Igeo = \mathrm{Log}_2(Cn/1.5\ Bn) \quad (1)$$

where Cn represents the measured concentration of metal n and Bn is the geochemical background value. The constant 1.5 allowed us to analyze natural fluctuations in the content of a given substance in the environment and to detect very small anthropogenic influences (Wei *et al.*, 2009b). In this study, Bn was the background level of metals in Beijing soil (CNEMC, 1990), as listed in Table 1. The Igeo for each metal was classified as: uncontaminated (Igeo ≤ 0), uncontaminated to moderately contaminated (0 < Igeo ≤ 1), moderately contaminated (1 < Igeo ≤ 2), moderately to heavily contaminated (2 < Igeo ≤ 3), heavily contaminated (3 < Igeo ≤ 4), heavily to extremely contaminated (4 < Igeo ≤ 5), and extremely contaminated (Igeo ≥ 5). Igeo values higher than 1 may indicate the influence of anthropologic sources.

The enrichment factor (EF) can be utilized to differentiate between metals originating from human activities and those from natural procedure, and to assess the degree of anthropogenic influence. It was calculated by:

$$EF = (Cn/Cref)/(Bn/Bref) \quad (2)$$

where Cref is the concentration of the reference metal in particles and Bref was the content of the reference metal in Beijing soil. In this study, Mn was chosen as the reference metal. EFs close to 1 pointed to a crustal origin, while those greater than 10 were considered to have a non-crustal source.

## RISK ASSESSMENT METHOD

### *Health Risk Assessment Model*

Health-risk assessments for both inhalatory and dermal exposures of heavy metals were calculated in this study. Although exposure to environmental heavy metals has been based on the assumption that inhalation was the primary route, dermal contact is increasingly taken into account. The models used in this study were based on those developed by the US Environmental Protection Agency and the Dutch National Institute of Public Health and Environmental Protection, which have been widely used around the world (Ferreira-Baptista and De Miguel, 2005;Chen and Liao, 2006; Hu *et al.*, 2007; Shi *et al.*, 2011). Exposure level was separately calculated for each metal and for each exposure pathway by the following formulas.

The incremental risk model for vehicle inspection workers inhalation (IRinh) is defined as,

$$IRinh = C \cdot IR \cdot t \cdot EF \cdot ED/(BW \cdot AT) \quad (3)$$

C = Metal concentration ($mg/m^3$)
IR = Inhalation rate (1.3 $m^3/h$)[a]
t = Daily exposure time span (8 h/d, for two shifts)
EF = Exposure frequency (250 d/year)
ED = Exposure duration (25 years)
BW = Body weight (lognormal (59.25, 1.05)[b], average value)
AT = Averaging time (25 years for non-carcinogens, 70 years for carcinogens)

The incremental risk model for the dermal pathway (IRderm) is defined as,

$$IRderm = Cp \cdot AFd \cdot SA \cdot AB \cdot EV \cdot EF \cdot ED \cdot 10^{-6}/(BW \cdot AT) \quad (4)$$

Cp = particle-bond metal concentration (μg/g)
AFd = particle-to-skin adherence factor ($mg/cm^2$/event), lognormal (0.02, 2.668)[c]
SA = the dermal surface area exposed ($cm^2$), lognormal (3067, 1.06)[c]
AB = the dermal adsorption fraction (dimensionless), 0.001 for V, Cr, Mn, Co, Ni, Cu, Zn, Cd and Pb. And 0.03 for As[d]
EV = the event frequency (1 event/day)
Note: [a] Adapted from USEPA (1997). [b] Adapted from Department of Health, ROC (http://www.doh.gov.tw/cht/index.aspx#). [c] Adapted from USEPA (1992). [d] Adapted from the research of Kong *et al.* (2012).

After the IRinh and IRderm were calculated, a Hazard Quotient (HQ) based on non-cancer toxic risk was then calculated by dividing the average daily value by a specific reference dose (RfD) (Man *et al.*, 2010):

$$HQ = IR/RfD \quad (5)$$

The reference dose (mg/kg/day) is an estimation of the maximum permissible risk on human population through daily exposure, taking into consideration a sensitive group

**Table 1.** Background levels of metals in Beijing soil.

| Metals | V | Cr | Mn | Co | Ni | Cu | Zn | As | Cd | Pb |
|---|---|---|---|---|---|---|---|---|---|---|
| Background levels (mg/kg) | 79.2 | 68.1 | 705 | 15.6 | 29.0 | 23.6 | 102.6 | 9.7 | 0.074 | 25.4 |

during a lifetime. The threshold value of RfD can be used to indicate whether there was an adverse health effect during a life time. For the health effects of the metals are similar, HQ can be added which generated a Hazard Index (HI) to estimate the risk of mixed contaminates as:

$$HI = \Sigma HQi \quad (6)$$

where i corresponds to different contaminates. HI ≤ 1 indicated no adverse health effects and HI > 1 indicated likely adverse health effects (Guney *et al.*, 2010; Zheng *et al.*, 2010a).

For carcinogens, the daily value was multiplied by the corresponding slope factor (SF) to produce an estimate of cancer risk (Zheng *et al.*, 2010b; Kong *et al.*, 2012). The incremental lifetime cancer risk (ILCR) for Co, Ni, As and Cd inhalation exposure route was used for cancer risk assessment by the following equation:

$$ILCR = Inhal.SF \cdot IRinh \quad (7)$$

According to the USEPA, a one in a million chance of additional human cancer over a 70 year lifetime (ILCR = $10^{-6}$) is the level of risk considered acceptable or inconsequential, since this compares favorably with risk levels from several ‘normal’ human activities such as diagnostic X-rays; whereas a lifetime risk of one in a thousand or greater (ILCR > $10^{-3}$) is considered serious and is a high priority for attention.

### *Statistical Method*

Statistical analysis of the data was conducted using Microsoft Excel 2003 for windows to generate descriptive statistics, with all other statistical procedures conducted using SPSS 16.0 for windows.

In the risk assessment, high variability was expected for the values of variables in Eq. (3), Eq. (4) and Eq. (7) which would result in high uncertainty in the risk estimation. If only the average values of these variables were used to calculate the risk, the result of a single average risk value might lose a lot of useful information about the uncertainty of the risk. So the Monte Carlo simulation, a tool for combining distributions, was used to deal with the great uncertainties in the risk assessment in this study. It uses random number generation, rather than analytic calculations and thereby mines more data than just summary statistics. The Monte Carlo simulation was implemented using Crystal Ball 7.2 software. The software randomly selected a value of each variable according to its distribution function, and calculated one risk value based on Eq. (3), Eq. (4) and Eq. (7). This step was repeated thousands of times and all the calculated risk values formed a risk distribution. So not only the average risk value, but also the risk values at any desired levels were presented. To test the convergence and the stability of the numerical output, we performed independent runs at 1000, 3000, 5000, and 10,000 iterations with each parameter independently sampled from the appropriate distribution at the start of each replicate. The result showed that 5000 iterations were sufficient to ensure the stability of results.

## RESULTS AND DISCUSSION

### *Concentrations of PM and Heavy Metals*

The average mass concentrations of particulate matter (PM, reported in μg/m$^3$) and particulate metals (reported in ng/m$^3$) collected at three vehicle inspection lines (bus, gasoline and diesel line) are given in Table 2, in terms of their mean, min and max concentrations with the corresponding standard deviations.

As can be seen from the table, the average concentration of $PM_{2.5}$ measured during the work time was highest in the diesel line (315.2 ± 55.2 μg/m$^3$), followed by the bus line (294.8 ± 239.9 μg/m$^3$) and then the gasoline line (152.1 ± 78.3 μg/m$^3$). The China Environmental Protection Agency recently established the $PM_{2.5}$ National Ambient Air Quality Class 2 Standard at 35 μg/m$^3$ for the annual standard and at 75 μg/m$^3$ for the 24 h standard. Though the $PM_{2.5}$ mass concentration inside the vehicle inspection factory was much lower than that specified in the U.S. Occupational Health and Safety Administration (OSHA) and the American Council of Governmental Industrial Hygienists (AGGIH) (Charles *et al.* 2005), it exceeded the 24 h standard by more than 200% during work hours. Since the National Ambient

**Table 2.** PM and heavy metal concentrations in three vehicle inspection lines and various proposed standards.

| Metals | Gasoline line | | | | Bus line | | | | Diesel line | | | | TLV | PEL | TCA |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (ng/m$^3$) | Mean | Min | Max | SD | Mean | Min | Max | SD | Mean | Min | Max | SD | | | |
| V | 52.5 | 25.8 | 98.1 | 26.2 | 123.1 | 56.5 | 221.9 | 72.5 | 179.5 | 101.0 | 279.2 | 60.7 | $5 \times 10^4$ | $5 \times 10^4$ | – |
| Cr | 266.2 | 103.1 | 517.4 | 168.8 | 652.5 | 151.9 | 1250.8 | 520.1 | 831.6 | 394.1 | 1407.3 | 324.6 | $5 \times 10^5$ | $1 \times 10^6$ | $6 \times 10^4$ |
| Mn | 171.8 | 62.0 | 347.9 | 85.5 | 112.3 | 60.1 | 179.6 | 41.1 | 217.4 | 108.3 | 318.2 | 77.6 | $2 \times 10^5$ | $1 \times 10^6$ | – |
| Co | 2.9 | 1.5 | 5.2 | 1.1 | 3.3 | 2.1 | 4.2 | 0.8 | 10.4 | 4.4 | 22.2 | 5.9 | $2 \times 10^4$ | $5 \times 10^4$ | $5 \times 10^2$ |
| Ni | 50.4 | 14.0 | 101.1 | 28.7 | 100.2 | 31.8 | 200.7 | 59.6 | 208.0 | 132.8 | 320.2 | 70.3 | $1.5 \times 10^6$ | $1 \times 10^5$ | $5 \times 10^1$ |
| Cu | 61.1 | 33.2 | 98.1 | 17.7 | 107.8 | 70.2 | 138.1 | 29.9 | 185.6 | 96.8 | 305.2 | 67.5 | $2 \times 10^5$ | $1 \times 10^5$ | $1 \times 10^3$ |
| Zn | 705.5 | 332.2 | 1605.7 | 432.2 | 917.1 | 382.5 | 1450.3 | 417.3 | 2212.7 | 555.6 | 4692.3 | 1427.2 | – | – | – |
| As | 33.9 | 16.2 | 44.6 | 8.2 | 76.7 | 63.8 | 87.0 | 8.3 | 135.1 | 85.3 | 259.7 | 52.3 | $1 \times 10^4$ | $1 \times 10^4$ | $1 \times 10^3$ |
| Cd | 2.7 | 1.4 | 5.0 | 1.4 | 2.7 | 0.9 | 6.0 | 1.8 | 3.7 | 2.0 | 7.8 | 1.7 | $2 \times 10^3$ | $5 \times 10^3$ | – |
| Pb | 190.9 | 77.8 | 570.9 | 178.5 | 182.3 | 71.0 | 347.2 | 118.3 | 235.6 | 108.3 | 779.2 | 213.4 | $5 \times 10^4$ | $5 \times 10^4$ | – |
| $PM_{2.5}$ (μg /m$^3$) | 152.1 | 72.3 | 273.2 | 78.3 | 294.8 | 90.0 | 722.0 | 239.9 | 315.2 | 91.6 | 698.1 | 55.2 | – | – | – |

standards are set to protect public health with an adequate safety margin, exceeding the 24 h $PM_{2.5}$ standard indicated that potential health risks exist for vehicle inspection workers during work hours.

The profiles of metal exposure for vehicle inspection workers are shown in Fig. 1, In general, the profiles for the three inspection lines were similar. Zn was the most abundant composition, accounting over 45% of the total metal concentration. Cr and Pb were the next most abundant compositions. These three elements were mainly linked to vehicle emissions (Fang *et al.*, 2010; Li *et al.*, 2012), and together accounted for over 75% of the total.

In this study, the measured mean exposed concentrations of metals for the workers in the diesel line were highest among three lines, followed by the bus line and gasoline line. To further evaluate the exposure of vehicle inspection workers to metals, their occupational exposure levels were compared with three standards/guidelines for inhalation exposure to metals, which are: (1) the threshold limit values-time weighted average (TLV-TWA) recommended by the American Conference of Industrial Hygienists (denoted as TLV in the table), (2) the permissible exposure limit-time weighted average (PEL-TWA) regulated by the Occupational Safety and Health Administration (PEL), (3) the tolerable concentration in air (TCA) proposed by Research for Man and Environment (RIVM) (See and Balasubramanian, 2006). The standards were used as benchmarks for assessing the acceptable levels of the concentrations of airborne metals for vehicle inspection workers. The concentrations of metals were much lower than those specified in the three standards and guidelines except for Ni which was higher than TCA during work hours. However, the exposure of metals for vehicle inspection workers is of concern since toxic metals can slowly bioaccumulate in biological systems and become a health hazard after chronic exposure to low levels. Exposure to Zn can cause arteriosclerosis, hypertension and heart disease, while exposure to Pb and Cd can lead to itai-itai disease, blood poisoning and anemia respectively. Cr is carcinogenic and can lead to nasal septum perforation, asthma and liver damage. Ni can cause nasal and lung cancer. Additionally Cu can cause nasal septum perforation, pulmonary granuloma, pulmonary interstitial fibrosis and lung cancer (Fang *et al.*, 2010). It has recently been reported that heavy metals present on particles' surfaces plays a role in the generation of reactive oxygen species (ROS) (Valavanidis *et al.*, 2000; Dellinger *et al.*, 2001). ROS in turn could cause damage to DNA and thus induce deleterious health effects. Hence, emissions of metals-containing particles in the vehicle inspection lines and human exposure to such emissions should be limited as much as possible.

***Contamination Assessment***

The calculated results for Igeo of heavy metals in particles collected in three vehicle inspection lines are presented in Fig. 2. The Igeo values for most metals were all higher than zero with the exception of Co for the bus line (Igeo = –1.37), and Mn for bus and diesel lines (Igeo was –1.81 and –0.69, respectively), suggesting that these metals were mostly above the threshold level. For Mn in the gasoline line, and Co in gasoline and diesel lines, their average Igeo values were between 0 and 1, indicating uncontaminated to moderate contamination. While for V and Ni, the Igeo values were higher than 1 with extreme values higher than 3, suggesting moderate or heavy contamination. For Cr, Cu, Zn, As, Cd and Pb, the Igeo values were higher than 3 with extreme values higher than 5, indicating heavy or extreme contamination.

The EFs for heavy metals in particles collected in the three vehicle inspection lines are presented in Fig. 3. The EFs for Mn and Co ranged close to 1, suggesting that they were mainly non-enriched and were from crustal origin. For V in the three lines, and Ni and Cu in the gasoline line, the EF values were a little lower than 10, implying that they were mostly influenced by anthropogenic sources. For Cr, Zn, As, Cd, Pb, the EF values were higher than 10, confirming significant enrichment.

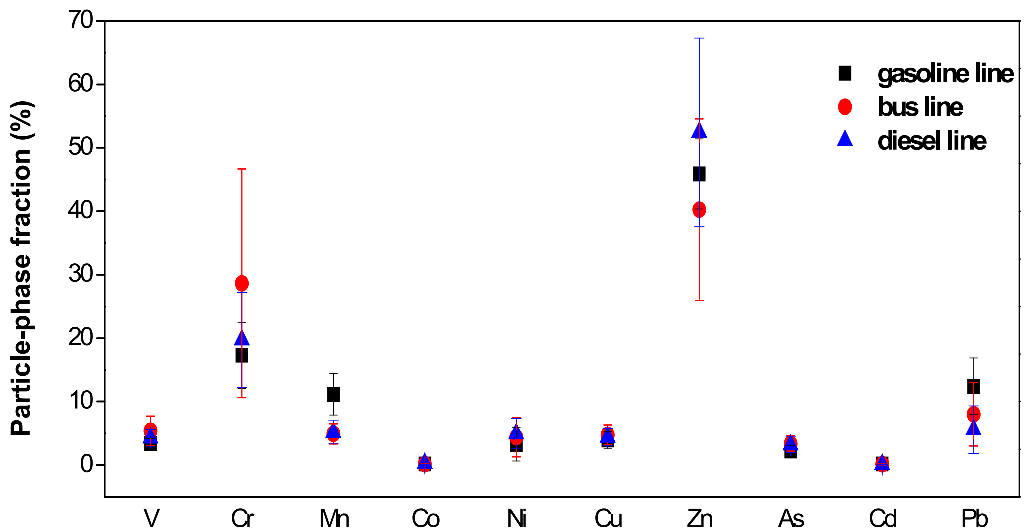


**Fig. 1**. Fractions (with standard deviations) of particulate metals exposure to vehicle inspection workers in three inspection lines.

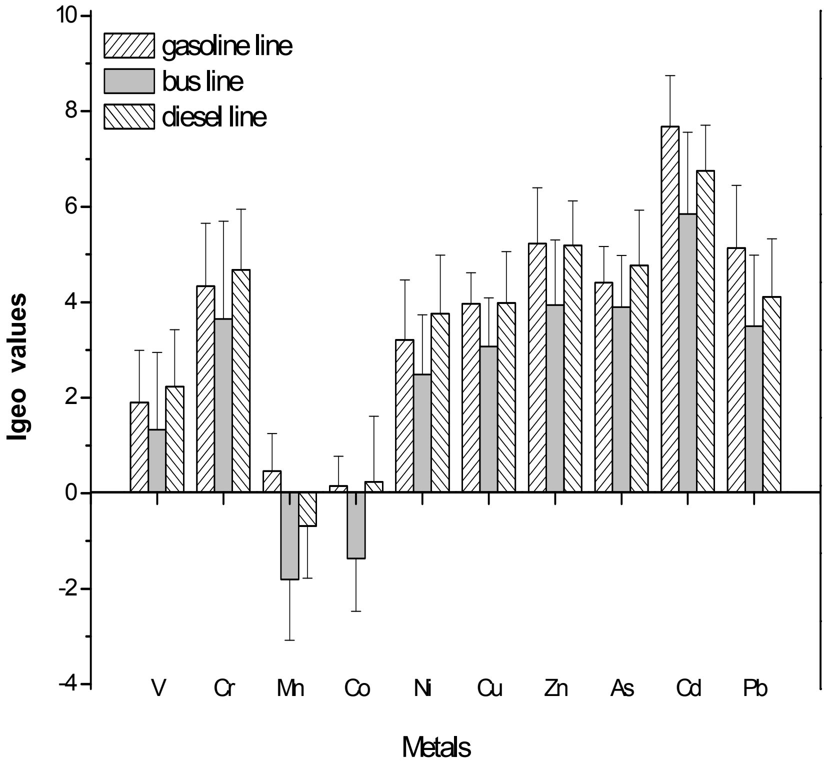


**Fig. 2.** Geoaccumulation index values for particulate metals in three inspection lines.

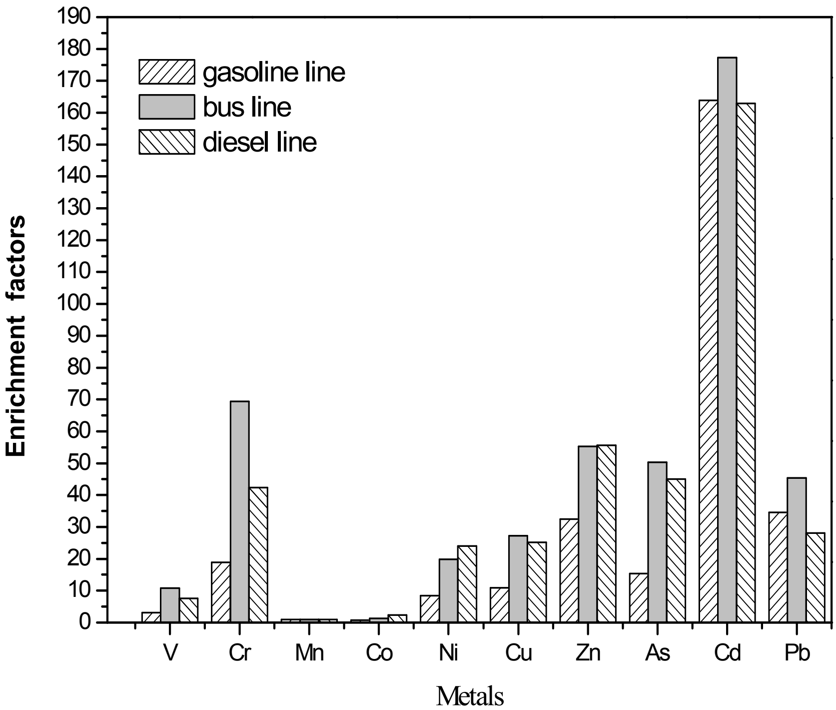


**Fig. 3.** Enrichment factors for metals in particles in three inspection lines.

From the Igeo and EF analysis, we concluded that Mn and Co in particles were mainly influenced by crustal materials. For V and Ni, they were influenced by both crustal materials and anthropogenic sources, while for Cu, Cr, Zn, As, Cd and Pb, anthropogenic sources may be dominant.

***Source Analysis***

Vehicle emission was thought to be the dominant source of particulate metal exposure for vehicle inspection workers. However, the re-suspended dusts disturbed by the testing vehicles would also contribute to their exposure. The vehicle inspection factories are naturally ventilated. Outdoor particles would also influence their exposure burden. In order to provide further insights into the origin of metals, the metal compounds analyzed in this study were subjected to principal component analysis with Varimax rotation using SPSS version 16 (SPSS Inc.). The results are listed in Table 3.

For samples collected in the gasoline line, three factors accounted for 92.26% of the total variance in the data. Factor 1, which explained 62.12% of the variance, showed high loading for Cr, Zn and Pb. The presence of these compounds was considered the major component of the vehicle tailpipe emissions (Vassilakos *et al.*, 2007; Kong *et al.*, 2012; Li *et al.*, 2012). Zn can also be from vehicle tire wear (Apeagyei *et al.*, 2011). Thus, factor 1 represented vehicle emission sources. Factor 2, which explained 19.68% of the variance, had high loadings for Mn, Co and Cu. Mn and Co have been linked to re-suspended dust (Kong *et al.*, 2012), and Cu could point to brake emission (Xie *et al.*, 2008). Factor 3, which explained 10.46% of the variance, showed high loading for Cd, suggesting an influence from industrial processes (Fang *et al.*, 2010). For samples collected in the bus line, three factors were determined in the analysis: Factor 1, which explained 55.28% of the variance, was mostly associated with metals including Zn, As and Pb, as were detected in vehicle emission sources (Balakrishna *et al.*, 2011). Thus these compounds indicated sources from vehicle emissions. Factor 2, which explained 27.33% of the variance, showed high loading for Mn, V, Ni and Cu. Mn, V, Ni indicated re-suspended dust sources, and Cu pointed to brake emission. Factor 3, which explained 8.26% of the variance, showed high loading for Cd, suggesting an influence from the metal industry. For the diesel line, it can be seen that vehicle emission, re-suspended dust and tire wear emission were the sources with different factor loading of 50.53%, 23.64% and 15.21%, respectively.

Based on principal component analysis, some sources from either re-suspended dust or industrial process sources could increase metals concentrations in particles. However, vehicle emission including tailpipe, tire wear and brake emission was the predominant source of metals for vehicle inspection workers' exposure.

### *Human Health Risk Assessment of Exposure to Heavy Metals*

The relative toxicity values used in the analysis were summarized from the literature as shown in Table 4 (Man *et al.*, 2010; Zheng *et al.*, 2010a, b). V, Ni, Cu, Zn, As, Cd and Pb toxicity values considered for the inhalation route were substituted by the corresponding oral reference doses with the assumption that, after inhalation, the absorption of the particle-bound toxicants will result in similar health effects as if the particles had been ingested.

The non-carcinogenic risk assessment results for vehicle inspection workers, according to exposure to particulate metals during work time are listed in Table 5. For all three lines, inhalation of particles appeared to have much higher risks for Cr, Mn and Co, which were one to four orders of magnitude higher than the corresponding risks of the dermal exposure route. For V and Cd, dermal contact appeared to be the main exposure route that results in a higher risk. The highest non-carcinogenic risk of inhalation appeared to occur for Cr, followed by Mn and Co. For the dermal contact pathway, Cr and As presented higher non-carcinogenic risks for all three fractions. For 5% of the high-risk population, HIs of Cr were the highest, with 2.70, 6.66 and 6.19 for the gasoline, bus and diesel inspection workers respectively. For Mn, HIs were also higher than 1 for workers of the three lines. Occupational exposure to these two metals could trigger adverse health effects for vehicle inspection workers.

Fig. 4 presents the results of the Monte Carlo simulation

**Table 3.** Principal component analysis results for particulate heavy metals.

| Metals | Gasoline | | | Bus line | | | Diesel line | | |
|---|---|---|---|---|---|---|---|---|---|
| | Factor 1 | Factor 2 | Factor 3 | Factor 1 | Factor 2 | Factor 3 | Factor 1 | Factor 2 | Factor 3 |
| V | 0.894 | 0.392 | –0.097 | –0.351 | **0.885** | 0.087 | 0.827 | 0.172 | 0.435 |
| Cr | **0.896** | 0.336 | –0.144 | –0.445 | 0.836 | 0.071 | **0.767** | 0.121 | 0.451 |
| Mn | 0.425 | **0.853** | 0.123 | 0.098 | **0.942** | –0.288 | 0.597 | **0.718** | 0.072 |
| Co | 0.185 | **0.944** | –0.108 | 0.889 | 0.184 | 0.247 | 0.133 | **0.963** | 0.103 |
| Ni | 0.322 | 0.084 | –0.837 | –0.314 | **0.732** | 0.271 | 0.155 | **0.884** | 0.380 |
| Cu | 0.367 | **0.840** | 0.294 | 0.582 | **0.681** | –0.315 | **0.837** | 0.174 | 0.447 |
| Zn | **0.864** | 0.336 | 0.361 | **0.905** | 0.121 | –0.149 | 0.146 | 0.284 | **0.827** |
| As | 0.610 | 0.631 | –0.224 | **0.898** | 0.400 | –0.133 | **0.915** | 0.244 | 0.228 |
| Cd | 0.426 | 0.114 | **0.873** | 0.735 | –0.060 | **0.657** | **0.875** | 0.286 | 0.080 |
| Pb | **0.768** | 0.318 | 0.519 | **0.962** | –0.171 | 0.159 | **0.949** | –0.041 | –0.159 |
| % of Variance | 62.12 | 19.68 | 10.46 | 55.28 | 27.33 | 8.26 | 50.53 | 23.64 | 15.21 |
| Cumulative (%) | 62.12 | 81.80 | 92.26 | 55.28 | 82.61 | 90.87 | 50.53 | 74.17 | 89.38 |
| Sources | vehicle tailpipe and tire wear emission | re-suspended dust and brake emission | industrial processes | vehicle tailpipe and tire wear emission | re-suspended dust and brake emission | industrial processes | vehicle tailpipe and brake emission | re-suspended dust | tire wear emission |

**Table 4.** Relative toxicity values used in this study.

| Category | V | Cr | Mn | Co-Non-cancer | Co-cancer | Ni-Non-cancer | Ni-cancer | Cu | Zn | As-Non-cancer | As-cancer | Cd-Non-cancer | Cd-cancer | Pb |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Inhal. RfD | 7.00E-03 | 2.86E-05 | 1.43E-05 | 5.71E-06 | | 2.00E-02 | | 4.00E-02 | 3.00E-01 | 3.00E-04 | | 1.00E-03 | | 3.50E-03 |
| Dermal RfD | 7.00E-05 | 6.00E-05 | 1.84E-03 | 1.60E-02 | | 5.40E-03 | | 1.20E-02 | 6.00E-02 | 1.23E-04 | | 1.00E-05 | | 5.25E-04 |
| Inhal. SF | | | | | 9.80E+00 | | 8.40E-01 | | | | 1.51E+01 | | 6.30E+00 | |

RfD: reference dose (mg/kg/day); SF: slope factor ($[mg/kg/day]^{-1}$).

**Table 5.** Non-cancer risk derived from the Monte Carlo simulation for each element and exposure pathway in three vehicle inspection lines.

| Category | | V | | | Cr | | | Mn | | | Co non-cancer | | | Ni non-cancer | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 5% | medium | 95% | 5% | medium | 95% | 5% | medium | 95% | 5% | medium | 95% | 5% | medium | 95% |
| Gasoline line | HQinh | 1.56E-04 | 9.07E-04 | 1.65E-03 | 1.94E-03 | 1.09E+00 | 2.26E+00 | 2.56E-01 | 1.44E+00 | 2.67E+00 | 2.45E-02 | 5.88E-02 | 9.80E-02 | 1.40E-05 | 3.02E-04 | 5.77E-04 |
| | HQdermal | 8.01E-04 | 1.60E-02 | 6.75E-02 | 1.40E-03 | 9.58E-02 | 4.42E-01 | 1.06E-04 | 1.96E-03 | 6.08E-03 | 1.75E-06 | 3.50E-06 | 1.23E-05 | 5.18E-06 | 1.87E-04 | 9.18E-04 |
| | HI = ΣHQi | 9.57E-04 | 1.69E-02 | 6.91E-02 | 3.34E-03 | 1.19E+00 | 2.70E+00 | 2.57E-01 | 1.45E+00 | 2.68E+00 | 2.45E-02 | 5.88E-02 | 9.80E-02 | 1.92E-05 | 4.89E-04 | 1.50E-03 |
| Bus line | HQinh | 8.01E-06 | 2.09E-03 | 4.17E-03 | 7.20E-02 | 2.71E+00 | 6.30E+00 | 3.84E-01 | 9.44E-01 | 1.51E+00 | 4.42E-02 | 6.86E-02 | 9.80E-02 | 1.40E-05 | 6.02E-04 | 1.19E-03 |
| | HQdermal | 1.60E-03 | 1.24E-02 | 5.40E-02 | 2.33E-03 | 7.42E-02 | 3.56E-01 | 1.22E-04 | 4.56E-04 | 1.46E-03 | 1.75E-06 | 3.50E-06 | 5.26E-06 | 2.59E-05 | 1.19E-04 | 3.89E-04 |
| | HI = ΣHQi | 1.61E-03 | 1.45E-02 | 5.82E-02 | 7.43E-02 | 2.79E+00 | 6.66E+00 | 3.84E-01 | 9.44E-01 | 1.51E+00 | 4.42E-02 | 6.86E-02 | 9.80E-02 | 3.99E-05 | 7.21E-04 | 1.58E-03 |
| Diesel line | HQinh | 1.40E-03 | 3.08E-03 | 4.82E-03 | 1.32E+00 | 3.47E+00 | 5.74E+00 | 7.59E-01 | 1.83E+00 | 2.88E+00 | 9.80E-03 | 2.21E-01 | 4.23E-01 | 5.40E-04 | 1.25E-03 | 1.93E-03 |
| | HQdermal | 2.00E-03 | 2.20E-02 | 7.53E-02 | 2.33E-03 | 1.18E-01 | 4.45E-01 | 1.52E-05 | 9.30E-04 | 3.30E-03 | 1.75E-06 | 7.00E-06 | 2.97E-05 | 1.56E-05 | 2.86E-04 | 1.25E-03 |
| | HI = ΣHQi | 3.40E-03 | 2.51E-02 | 8.01E-02 | 1.32E+00 | 3.59E+00 | 6.19E+00 | 7.59E-01 | 1.83E+00 | 2.89E+00 | 9.80E-03 | 2.21E-01 | 4.23E-01 | 5.56E-04 | 1.53E-03 | 3.19E-03 |

| Category | | Cu | | | Zn | | | As non-cancer | | | Cd non-cancer | | | Pb | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 5% | medium | 95% | 5% | medium | 95% | 5% | medium | 95% | 5% | medium | 95% | 5% | medium | 95% |
| Gasoline line | HQinh | 9.74E-05 | 1.83E-04 | 2.70E-04 | 5.68E-06 | 2.83E-04 | 5.71E-04 | 8.12E-03 | 1.36E-02 | 1.90E-02 | 5.60E-05 | 3.36E-04 | 5.88E-04 | 4.23E-04 | 6.58E-03 | 1.66E-02 |
| | HQdermal | 1.63E-05 | 1.14E-04 | 3.61E-04 | 7.00E-06 | 2.51E-04 | 1.05E-03 | 9.10E-04 | 1.77E-01 | 5.99E-01 | 2.80E-03 | 5.60E-03 | 1.96E-02 | 4.79E-04 | 6.41E-03 | 3.64E-02 |
| | HI = ΣHQi | 1.14E-04 | 2.98E-04 | 6.31E-04 | 1.27E-05 | 5.33E-04 | 1.62E-03 | 9.03E-03 | 1.91E-01 | 6.18E-01 | 2.86E-03 | 5.94E-03 | 2.02E-02 | 9.02E-04 | 1.30E-02 | 5.30E-02 |
| Bus line | HQinh | 1.79E-04 | 3.28E-04 | 4.70E-04 | 9.30E-05 | 3.64E-04 | 6.41E-04 | 2.51E-02 | 3.05E-02 | 3.64E-02 | 2.80E-05 | 3.36E-04 | 6.72E-04 | 4.87E-04 | 6.33E-03 | 1.30E-02 |
| | HQdermal | 1.40E-05 | 6.78E-05 | 2.15E-04 | 4.20E-06 | 1.11E-04 | 4.03E-04 | 1.37E-03 | 1.37E-03 | 5.54E-01 | 2.80E-03 | 5.60E-03 | 1.12E-02 | 4.26E-04 | 2.19E-03 | 9.86E-03 |
| | HI = ΣHQi | 1.93E-04 | 3.95E-04 | 6.85E-04 | 9.72E-05 | 4.75E-04 | 1.04E-03 | 2.65E-02 | 3.19E-02 | 5.91E-01 | 2.83E-03 | 5.94E-03 | 1.19E-02 | 9.13E-04 | 8.51E-03 | 2.29E-02 |
| Diesel line | HQinh | 2.23E-04 | 5.60E-04 | 9.04E-04 | 9.24E-06 | 8.99E-04 | 1.85E-03 | 1.97E-02 | 5.43E-02 | 8.85E-02 | 1.12E-04 | 4.48E-04 | 7.84E-04 | 4.20E-03 | 8.09E-03 | 1.98E-02 |
| | HQdermal | 7.00E-06 | 1.21E-04 | 4.23E-04 | 2.80E-06 | 2.39E-04 | 8.18E-04 | 2.97E-03 | 2.53E-01 | 9.94E-01 | 2.80E-03 | 5.60E-03 | 1.12E-02 | 4.26E-04 | 3.42E-03 | 1.12E-02 |
| | HI = ΣHQi | 2.30E-04 | 6.81E-04 | 1.33E-03 | 1.20E-05 | 1.14E-03 | 2.67E-03 | 2.27E-02 | 3.07E-01 | 1.08E+00 | 2.91E-03 | 6.05E-03 | 1.20E-02 | 4.63E-03 | 1.15E-02 | 3.10E-02 |

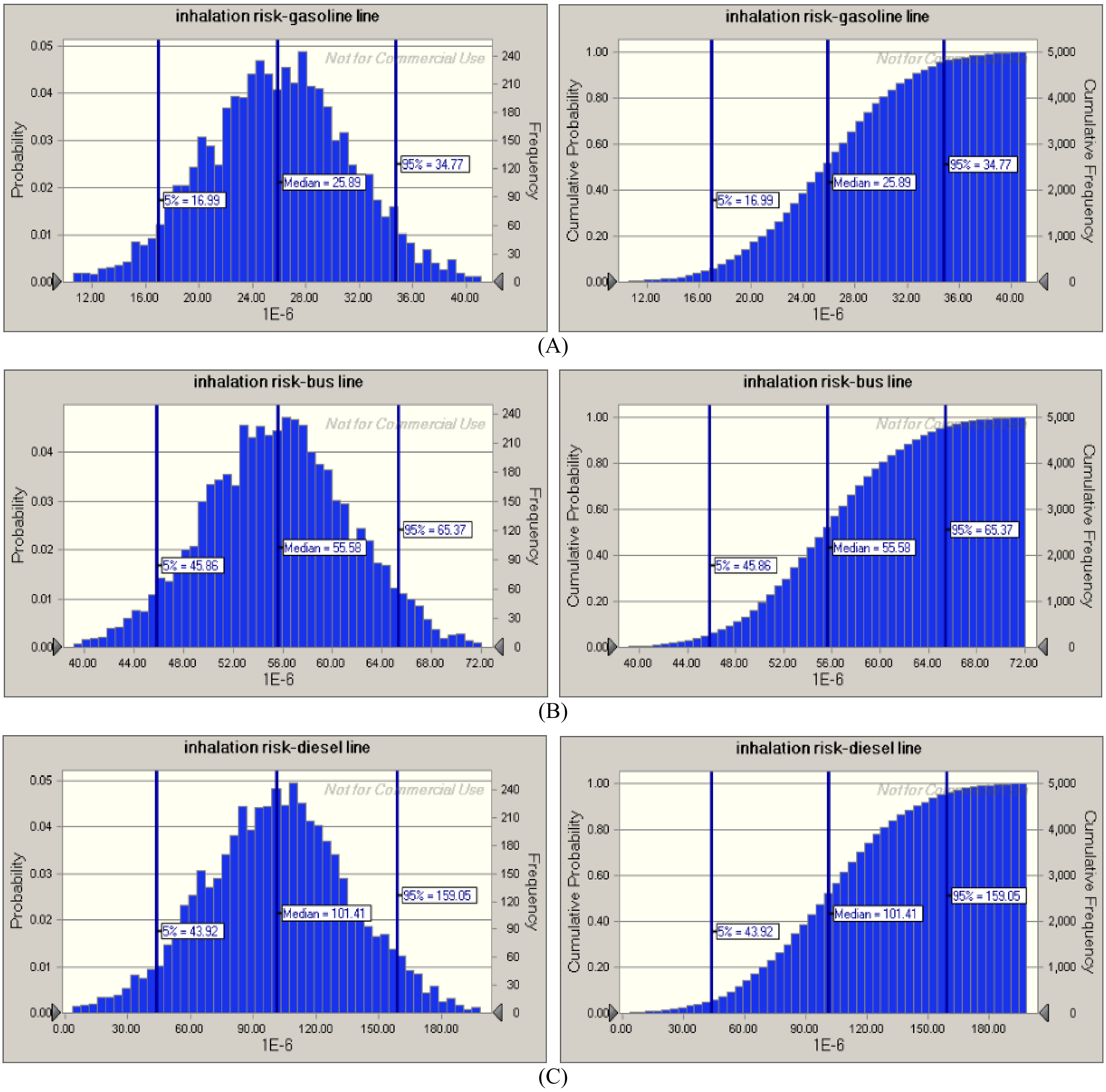


**Fig. 4.** The probability and cumulative frequencies of cancer rates derived from the Monte Carlo simulation on the inhalation exposure to metals for the vehicle inspection workers in gasoline line (A), bus line (B) and diesel line (C).

for vehicle inspection workers' inhalation cancer risk caused by particulate metals including Co, Ni, As and Cd (unit: $10^{-6}$). The probability and cumulative probability distributions of them were presented, and medians as well as 5% and 95% percentile of the calculated risks are shown. For 5% of the high-risk population, the metals induced cancer rates were $3.48 \times 10^{-5}$, $6.54 \times 10^{-5}$ and $1.59 \times 10^{-4}$ for the gasoline, bus and diesel inspection workers respectively. The rates were $2.59 \times 10^{-5}$, $5.56 \times 10^{-5}$ and $1.01 \times 10^{-4}$ for half of the population. Even for the 5% of low-risk population, the rates were still one magnitude higher than the acceptable risk level of $10^{-6}$. Occupational exposure to heavy metals posed an unacceptable, but not high potential cancer risk to the vehicle inspection workers in this present study.

The risk assessment suggested that there was an unacceptable potential of adverse health effects for the vehicle inspection workers in the three lines caused by particulate metals. It was thus clear that the exposure of the vehicle inspection workers and other personnel working in the factories, and possibly the customers, to the fine particles with toxic metal contents is of serious concern. In addition, these fine particles can absorb a host of other harmful pollutants such as polycyclic aromatic hydrocarbons (PAHs) and nitrated PAHs because of their large specific surface area, thus further increasing the health risk for exposed individuals (See and Balasubramanian, 2006).

Appropriate safe particulate guideline should be established to protect these workers, and effective protective measures are suggested to reduce their exposure levels, such as wearing a mask and protective clothing.

## CONCLUSIONS

Particulate samples were collected in three vehicle inspection factories in Beijing, China and were analyzed by inductively coupled plasma-mass spectroscopy (ICP-MS) for V, Cr, Mn, Co, Ni, Cu, Zn, As, Cd and Pb. Zn was the most abundant composition, accounting over 45% of the total metal concentration. Cr and Pb were the next most abundant compositions. These three vehicle emission related elements together accounted for over 75% of the total. Based on the geoaccumulation index and enrichment factors analysis, Cr, Zn, As, Cd and Pb exhibited heavy or extreme contamination and significant enrichment, indicating anthropogenic sources. Mn and Co were mostly not enriched and were mainly influenced by crustal sources. Ni and V presented moderate or heavy contamination and were influenced by both crustal materials and anthropogenic sources. Principle component analysis revealed that the major sources were vehicle emission, re-suspended dust and industrial processes. The risk assessment framework used integrated toxicity values and Monte Carlo simulation approaches to quantitatively estimate the exposure risks. Although the exposure concentrations of particulate heavy metals were much lower than those specified in the three standards/guidelines, unacceptable potential health effects were posed to the vehicle inspection worker. For non-cancer effect, Cr and Mn had HIs higher than 1, which could trigger adverse health effects for vehicle inspection workers. For half of the population, the metals induced cancer rates were $2.59 \times 10^{-5}$, $5.56 \times 10^{-5}$ and $1.01 \times 10^{-4}$, respectively for gasoline, bus, and diesel inspection workers. Even for the 5% of low-risk population, the induced cancer rates were still one magnitude higher than the acceptable risk level of $10^{-6}$, indicating an unacceptable potential cancer risk. Occupational exposure of certain groups should be of special concern, and further research should be conducted.

## ACKNOWLEDGMENTS

We thank Dr. Ji Ya-qin for providing valuable comments and considerable assistance with the experiment. This work was supported by the National Natural Science Foundation of China (Research on characterization and adjustment of ambient particulate matter exposure errors, 20977054) and National Basic Research Program of China (2011CB503801). Thanks to Dr. Edward C. Mignot, Shandong University, for linguistic advice.

## REFERENCES

Apeagyei, E., Bank, M. S. and Spengler, J. D. (2011). Distribution of Heavy Metals in Road Dust along an Urban-rural Gradient in Massachusetts. *Atmos. Environ.* 45: 2310–2323.

Ashraf, M.A., Maah, M.J. and Yusoff, I. (2012). Bioaccumulation of Heavy Metals in Fish Species Collected From Former Tin Mining Catchment. *Int. J. Environ. Res.* 6: 209–218.

Balakrishna, G., Pervez, S. and Bisht, D.S. (2011). Source Apportionment of Arsenic in Atmospheric Dust Fall out in an Urban Residential Area, Raipur, Central India. *Atmos. Chem. Phys.* 11: 5141–5151.

Batayneh, A.T. (2012). Toxic (Aluminum, Beryllium, Boron, Chromium and Zinc) in Groundwater: Health Risk Assessment. *Int. J. Environ. Sci. Technol.* 9: 153–162.

Bieniek, G. (1998). Aromatic and polycyclic Hydrocarbons in Air and Their Urinary Metabolites in Coke Plant Workers. *Am. J. Ind. Med.* 34: 445–454.

Charles, K., Magee, R.J., Won, D. and Lusztyk, E. (2005). Indoor Air Quality Guidelines and Standards, National Research Council Canada, B3312/P7-10

Chen, T.B., Zheng, Y.M., Lei, M., Huang, Z.C., Wu, H.T., Chen, H., Fan, K.K., Yu, K., Wu, X. and Tian, Q.Z. (2005). Assessment of Heavy Metal Pollution in Surface Soils of Urban Parks in Beijing, China. *Chemosphere* 60: 542–551.

Chen, S.C. and Liao, C.M. (2006). Health Risk Assessment on Human Exposed to Environmental Polycyclic Aromatic Hydrocarbons Pollution Sources. *Sci. Total Environ.* 366: 112–123

China Statistical Yearbook (2010). Compiled by National Bureau of Statistics of China, 16/p24-25, http://www.stats.gov.cn/tjsj/ndsj/2010/indexch.htm

China Vehicle Emission Control Annual Report (2011). Ministry of Environmental Protection of the People's Republic of China, p. 1, http://www.es.org.cn/c/cn/news/2012-05/18/news_1725.html

CNEMC (China National Environmental Monitoring Centre) (1990). The background values of Chinese soils, Environmental Science Press of China, Beijing, p. 15–505.

Danielsson, A., Cato, I., Carman, R. and Rahm, L. (1999). Spatial Clustering of Metals in the Sediments of the Skagerrak Kattegat. *Appl. Geochem.* 14: 689–706.

Dellinger, B., Pryor, W.A., Cueto, R., Squadrito, G.L., Hegde, V. and Deutsch, W.A. (2001). Role of Free Radicals in the Toxicity of Airborne Fine Particulate Matter. *Chem. Res. Toxicol.* 14: 1371–1377.

Fang, G.C., Huang, Y.L. and Huang, J.H. (2010). Study of Atmospheric Metallic Elements Pollution in Asia during 2000-2007. *J. Hazard. Mater.* 180: 115–121.

Ferreira-Baptista, L. and De Miguel, E. (2005). Geochemistry and Risk Assessment of Street Dust in Luanda, Angola: A Tropical Urban Environment. *Atmos. Environ.* 39: 4501–4512.

Guney, M., Zagury, G.J., Dogan, N. and Onay, T.T. (2010). Exposure Assessment and Risk Characterization from Trace Elements Following Soil Ingestion by Children Exposed to Playgrounds, Parks and Picnic Areas. *J. Hazard. Mater.* 182: 656–664.

Hall, J.L. (2002). Cellular Mechanisms for Heavy Metal Detoxification and Tolerance. *J. Exp. Bot.* 53: 1–11.

Hu, Y., Bai, Z., Zhang, L., Wang, X., Zhang, L., Yu, Q. and Zhu, T. (2007). Health Risk Assessment for Traffic Policemen Exposed to Polycyclic Aromatic Hydrocarbons (PAHs) in Tianjin, China. *Sci. Total Environ.* 382: 240–250.

Kargar, M., Khorasani, N. A., Karami, M., Rafiee, G.H. and Naseh, R. (2012). An Investigation on As, Cd, Mo and Cu Contents of Soils Surrounding the Meyduk Tailings Dam. *Int. J. Environ. Res.* 6: 173–184.

Khlifi, R. and Hamza-Chaffai, A. (2010). Head and Neck Cancer due to Heavy Metal Exposure via Tobacco Smoking and Professional Exposure: A Review. *Toxicol. Appl. Pharmacol.* 248: 71–88.

Kong, S., Lu, B., Ji, Y., Zhao, X., Bai, Z., Xu, Y., Liu, Y. and Jiang, H. (2012). Risk Assessment of Heavy Metals in Road and Soil Dusts within $PM_{2.5}$, $PM_{10}$ and $PM_{100}$ Fractions in Dongying City, Shandong Province, China. *J. Environ. Monit.* 14: 791–803.

Li, P.H., Wang, Y., Li, Y.H., Wang, Z.F., Zhang, H.Y., Xu, P.J. and Wang, W.X. (2010). Characterization of Polycyclic Aromatic Hydrocarbons Deposition in $PM_{2.5}$ and Cloud/Fog Water at Mount Taishan (China). *Atmos. Environ.* 44: 1996–2003.

Li, P.H., Han, B., Huo, J., Lu, B., Ding, X., Chen, L., Kong, S.F., Bai, Z.P. and Wang, B. (2012). Characterization, Meteorological Influences and Source Identification of Carbonaceous Aerosols during the Autumn-winter Period in Tianjin, China. *Aerosol Air Qual. Res.* 12: 283–294.

Man, Y.B., Sun, X.L., Zhao, Y.G., Lopez, B.N., Chung, S.S., Wu, S.C., Cheung, K.C. and Wong, M.H. (2010). Health Risk Assessment of Abandoned Agricultural Soils Based on Heavy Metal Contents in Hong Kong, the World's Most Populated City. *Environ. Int.* 36: 570–576.

Meza-Figueroa, D., De la O-Villanueva, M. and De la Parra, M.L. (2007). Heavy Metal Distribution in Dust from Elementary Schools in Hermosillo, Sonora, Mexico. *Atmos. Environ.* 41: 276–288.

Mzoughi, N. and Chouba, L. (2012). Heavy Metals and PAH Assessment Based on Mussel Caging in the North Coast of Tunisia (Mediterranean Sea). *Int. J. Environ. Res.* 6: 109–118.

Nriagu, J.O. (1989). A Global Assessment of Natural Sources of Atmospheric Trace Metals. *Nature* 338: 47–49.

Roig-Navarro, A.F., Lopez, F.J., Serrano, R. and Hernandez, F. (1997). An Assessment of Heavy Metals and Boron Contamination in Workplace Atmospheres from Ceramic Factories. *Sci. Total Environ.* 201: 225–234.

Saarnio, K., Sillanpaa, M., Hillamo, R., Sandell, E., Pennanen, A.S. and Salonen, R.O. (2008). Polycyclic Aromatic Hydrocarbons in Size-segregated Particulate Matter from Six Urban Sites in Europe. *Atmos. Environ.* 42: 9087–9097.

See, S.W. and Balasubramanian, R. (2006). Risk Assessment of Exposure to Indoor Aerosols Associated with Chinese Cooking. *Environ. Res.* 102: 197–204.

Shi, G., Chen, Z., Bi, C., Wang, L., Teng, J., Li, Y. and Xu, S. (2011). A Comparative Study of Health Risk of Potentially Toxic Metals in Urban and Suburban Road Dust in the Most Populated City of China. *Atmos. Environ.* 45: 764–771.

Shu, J., Dearing, J.A., Morse, A.P., Yu, L.Z. and Yuan, N. (2001). Determining the Sources of Atmospheric Particles in Shanghai, China, from Magnetic and Geochemical Properties. *Atmos. Environ.* 35: 2615–2625.

Sun, Y.B., Zhou, Q.X., Xie, X.K. and Liu, R. (2010). Spatial, Sources and Risk Assessment of Heavy Metal Contamination of Urban Soils in Typical Regions of Shenyang, China. *J. Hazard. Mater.* 174: 455–462.

US EPA (1992). Dermal Exposure Assessment: Principles and Applications, Office of Health and Environmental Assessment, EPA/600/6-88/005Cc.

US EPA (1997). Exposure Factors Handbook, Update to Exposure Factors Handbook, EPA/600/8-89/043-May 1989, EPA/600/P-95/002Fa.

US EPA (2001). Risk Assessment Guidance for Superfund, Volume I: Human Health Evaluation Manual (Part E, Supplemetal Guidance for Dermal Risk Assessment), EPA/540/R/99/005, Washington DC, USA Office of Emerage and Remedial Response.

Valavanidis, A., Salika, A. and Theodoropoulou, A. (2000). Generation of Hydroxyl Radicals by Urban Suspended Particulate Air Matter. The Role of Iron Ions. *Atmos. Environ.* 34:2379–2386.

Vassilakos, C., Veros, D., Michopoulos, J., Maggos, T. and O' Connor, C.M. (2007). Estimation of Selected Heavy Metals and Arsenic in $PM_{10}$ Aerosols in the Ambient Air of the Greater Athens Area, Greece. *J. Hazard. Mater.* 140: 389–398.

Wei, B., Jiang, F., Li, X. and Mu, S. (2009b). Spatial Distribution and Contamination Assessment of Heavy Metals in Urban Road Dusts from Urumqi, NW China. *Microchem. J.* 93: 147–152.

Wei, Y., Han, I. K., Shao, M., Hu, M., Zhang, J. and Tang, X. (2009a). $PM_{2.5}$ Constituents and Oxidative DNA Damage in Humans. *Environ. Sci. Technol.* 43: 4757–4762.

Xie, S.D., Liu, Z., Chen, T. and Hua, L. (2008). Spatiotemporal Variations of Ambient $PM_{10}$ Source Contributions in Beijing in 2004 Using Positive Matrix Factorization. *Atmos. Chem. Phys.* 8: 2701–2716.

Zheng, N., Liu, J., Wang, Q. and Liang, Z. (2010a). Heavy Metals Exposure of Children from Stairway and Sidewalk Dust in the Smelting District, Northeast of China. *Atmos. Environ.* 44: 3239–3245.

Zheng, N., Liu, J., Wang, Q. and Liang, Z. (2010b). Health Risk Assessment of Heavy Metal Exposure to Street Dust in the Zinc Smelting District, Northeast of China. *Sci. Total Environ.* 408: 726–733.

*Received for review, April 13, 2012*
*Accepted, September 4, 2012*