

Influence of the Automotive Brake Wear Debris on the Environment - A Review of Recent Research

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ABSTRACT

Automotive brake linings are complex composite materials. Some raw materials used by manufacturers or the compounds created during the friction process might be potentially hazardous and may cause various adverse effects. Different fractions of the brake wear debris can be released during braking: i) the airborne and ii) the nonairborne. Due to the small size and minimum gravitational action, the airborne particles could be spread for long distances from a source and typically remain suspended in the air for long periods of time. Our previous research demonstrated that the airborne fraction contains considerable amounts of different nanoparticulates. On the other hand, the emitted nonairborne fraction typically settles on vehicle/brake hardware surfaces and in the vicinity of roads. The nonairborne particles are considered to be relatively large, but it was shown that nano-sized particles readily attach to them and can be released later. This study is focused on the recent research in the field of brake wear debris detection in the environment (road dust, soil and sediments, water runoffs, air pollution) as well as on the possible impact on plants, animals and human health. The review of recently published papers allowed for the summary of the spectrum of relevant experimental techniques used currently for identification and analysis of brake wear debris, and for the most recent opinions on their impact on the environment and health. It is suggested that consideration of the environmental aspects becomes the necessary aspect of brake/friction materials design.

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INTRODUCTION

Automotive friction materials are complex composites typically consisting of more than 10 ingredients [1,2]. Some of the raw materials used by manufacturers might be potentially hazardous and may cause various adverse effects. More importantly, however, there are newly formed particulates with a different chemistry, when compared to the original bulk materials, released during the friction (braking) processes, accompanied with complex physico-chemical interactions on the surfaces [3,4]. These materials may pose risk to the environment and health. Two different fractions of the brake wear debris are released during the friction process i) airborne and ii) nonairborne. Airborne particles could be spread for long distance from the source and typically remain suspended in the air for long periods of time due to their small size. On the other hand, the nonairborne fraction typically settles on vehicle/brake hardware surface and vicinity of the roads. However, the nonairborne fraction is considered to be large, contains also considerable amounts of the nanoparticles, which could be easily released to the water environment [5].

The evidence shows that road traffic is a main contributor to particulate matter (PM) formation in urban areas and there is a general agreement that PM-associated health risks can be reduced by firstly focusing on vehicle traffic sector. As exhaust emissions control

become stricter, relative contributions of non-exhaust emissions (brake wear) will become more significant and will raise discussions on possible regulatory needs [6]. Study of the brake wear is accompanied by the lack of standardized sampling procedure and measurement techniques. Thus, these different experimental approaches by researchers mostly lead to the non-comparable results and conclusions. Grigoratos and Martini [6] published literature review focused on the information in terms of importance, physicochemical characteristics, emission factors and possible health effects.

This paper summarizes different approaches adapted when addressing the detection of the brake wear in the environment (air pollution, road dust, soil and sediments, water runoffs) and the possible consequences and impact to the plants, animals, and human health as well. Thus, the paper summarizes the most recent findings published in open literature.

AIR POLLUTION

About 400,000 premature adult deaths are attributed to air pollution each year in the European Region and traffic emissions account for a significant share of this burden [7]. Generally, road transport, especially exhaust emissions, is considered to be the major source of

the fine particles, which play a significant role in adverse health effects. However, there are published studies [8, 9, 10, 11, 12, 13, 14, 15] reporting that exhaust and non-exhaust traffic sources contribute almost equally to the total PM_{10} (particulate matter smaller than 10 μm) and airborne PM. They also induce adverse effects on human health, which has been one of the most important concerns regarding air pollution.

As exhaust emissions control become stricter, the emissions from non-exhaust sources will increase in the forthcoming years and the brake wear is one of the most significant sources. According to Gasser et al., brake wear contributes up to 20% to the total traffic emissions [16].

Primary particulate emissions from vehicles contain exhaust gasses, and wear particulates released from tires or brakes. The resuspension from roads or unpaved roads also represents a major pollution resource and distinguish between the sources is extremely difficult [17]. Ravindra et al. identified anthropogenic emissions as a major source of fine particles in air in Belgian city, Menen [18]. However, in Japan, Iijima et al. characterized regional and seasonal variations in emissions sources of fine airborne PM in urban, suburban, and mountain areas. They found that nine emission sources contributed to airborne PM: local and continental soils, road dust, coal and oil combustion, waste incineration, steel industry, diesel exhaust and last but not least the brake wear [19]. Grigoratos et al. showed that concentration levels of minerals and most trace metals (brake wear) were higher at urban-traffic site [20].

Mancila and Mendoza estimated that resuspended road dust contributed by 20-25% to the total emissions observed in the Loma Larga Tunnel in the Monterrey metropolitan area in Mexico. $PM_{2.5}$ emissions rates were higher for downhill than for uphill traffic probably because vehicles moving downhill tend to emit additional $PM_{2.5}$ from brake wear [21]. In London, UK, Beevers et al. predicts that brake wear PM_{10} concentration is approximately eight times greater near major roads than at suburban background locations [22]. 11% of the total mass PM_{10} inside the Hatfield Tunnel, UK, corresponds to the brake wear emissions. As traffic volume increases, the non-exhaust emissions contribute significantly to releasing of particles into atmosphere [23]. In selected urban areas at seven locations of USA, Abu-Allaban et al. found that the brake wear contribution was observed mainly in PM_{10} fraction. It was suggested that common source, possibly tire and brake wear, were the origin of Fe-rich components, also containing silicon, sulfur and barium [24]. In Reno, Nevada, USA, Abu-Allaban et al. found that brake wear contributions were highest for the freeway exit sites and less significant for the other locations [25]. Contrary to the daily observation of hazardous trace metal concentrations in Beijing, China, Okuda et al. concluded that the brake wear was the source of specific metals such as copper and antimony, although they do not believe that "transport-related particles" were the major source of hazardous anthropogenic metals [26].

Exhaust gasses were identified as one of the major sources of air pollution around Trans-Alpine highway. Nine different sources were identified and one of them was tire and brake wear, contributing with 1% to total PM_{10} concentration. Concentration levels of Cu, Fe, Zn,

and Pb were elevated in winter periods probably caused by higher wear of winter tires and increased braking frequency due to the weather conditions. Higher wear was also observed on weekdays [27]. The higher concentrations of metals were observed during weekdays and maxima were detected during the traffic hours in Lisbon, Portugal [28]. Barmpadimos et al. showed that coarse mode emissions found in Zürich, Switzerland, were greater on weekdays than on Sundays [29]. Similar situation was observed in India [30,31]. Pengchai et al. studied concentrations of PM_{10} in three provinces of Thailand. The results revealed the same pattern at all locations, in which the PM_{10} increased at the beginning of dry season (December) and reached its peak in March before decreasing by the end of April. These maxima were higher than allowed by Thai ambient standard [32]. The enrichment factors of trace metals showed different seasonal variations in different size ranges, with higher enrichment levels in winter than in summer in New Jersey, USA, which is especially relevant for fine particles. Factor analysis determined brake wear as one of the major sources of metal pollution [33].

Research team in Finland estimated that non-exhaust emissions from road traffic, e.g. from brake and tire wear, correspond to 19% (5.8 kT per year) of the national total $PM_{2.5}$ [34]. Samples of PM collected in Chennai city, India revealed that 4.1% in PM_{10} and 5.4% in $PM_{2.5}$ corresponded to brake and tire wear. Frequent application of brakes at the study site was confirmed by the presence of Zn (40.9%), Cu (69.4%) and Ba (77.4%) in PM_{10} [30,31].

Particulate matter collected at urban site of Pune, India contained toxic metals Cd and Pb, showing higher concentrations in the soluble fraction and thus representing the higher bioavailability index which makes them especially harmful to the environment and the exposed humans. A simple exposure assessment method showed that the cancer risk of the bioavailable fraction of Cd, Cr and Ni were greater than the standard limits [35].

According to Cui et al., the traffic sector represents the largest contributor to the copper load (50 - 80%) in the environment and brake linings dominated when copper emissions (80 - 90%) were concerned [36]. According to Hulskotte et al., brake wear from road traffic vehicles is an important source of atmospheric particulate copper emissions in Europe. They estimated the copper emission due to brake wear to be 2.4 kT per year. Also they suggested that 75% of the copper input in the North Sea may be caused by brake wear [37]. Danier van der Gon et al. demonstrated that brake wear emissions with size $PM_{2.5-10}$ may be responsible for 50 - 75% of the total copper emissions to air in Western Europe [38]. When measuring the concentrations of heavy metals in air, Johansson et al. found out that 90% of the road traffic emissions of Cu in Stockholm, Sweden, were due to brake wear. The Cu/Sb ratio was determined to be 3.8. Also a very high correlation between Cu and Cr was found, indicating that brake wear is an important source of chromium [39]. In Belgrade, Serbia, relatively high mean values of 71.3 ng/m³ in PM_{10} and 20.8 ng/m³ in $PM_{2.5}$ were represented by copper in air [40]. At the street locations of Amsterdam, Netherlands, the content of copper in PM was ten times higher than at the urban and regional locations without extensive traffic. More than 75% of Cu particles were distributed in the coarse fraction. The results from Amsterdam also showed that traffic volume has comparable levels of non-exhaust emissions of

Sundays as well during working days. Hence, it was concluded that, under these conditions, the non-exhaust emissions were not significantly reduced by road sweeping/washing [41]. In the $PM_{2.5}$, copper showed 10% increase and in the $PM_{2.5-10}$ fraction, even 100% increase at the urban background in Rotterdam, Netherlands, when compared to the regional background [42].

According to Weckwerth, antimony is one of the main elements of wear of brake linings [43]. Also Varrica et al. determined that road dust and atmospheric PM are composed by an admixture of Sb(III) and Sb(V) and their ratio changes apparently not according to a specific rule [44]. According to a Spanish study, barium concentrations in PM are generally associated with brake wear [45]. Also Dongarrá et al. concluded that a highly significant correlation exists among Cu, Sb, and Mo in the airborne PM in Palermo, Italy [46]. It has been confirmed in the urban area of Rome, Italy, that the brake pad wear is the prevalent source of Sb(III) in PM and that Sb(V) may be formed by oxidation during the braking processes [47]. Cu/Sb ratio was found constant in Barcelona (6.8 ± 0.9); contrary to in Zürich and Girona where the ratio was varying considerably, showing the average values of 13.5 ± 6.1 and 17.0 ± 8.9 , respectively [8]. It was estimated that the brake wear contributes to pollution an average of 15% in Zürich and Barcelona, but less than 10% in Girona [8].

The atmospheric particles were collected at a representative traffic site in the Mediterranean city of Seville, Spain during one year. One of the monitored elements was barium, which is marked as tracer of brake wear, and with occurrence of copper and lead also confirming brake-lining emissions [48]. The brake wear was identified as one of the additional sources of coarse particles, which contribute significantly to PM mass concentration in the Belgrade, Serbia urban area [49]. Birmili et al. suggested that coarse size particles of Cu, Ba, Fe, and Mn originated from mechanically abraded particles from tires, and brakes [50]. Observation of PM in Kaisermühlen Tunnel in Vienna, Austria, also confirmed that particles emitted in the coarse fraction are mainly released from the brake linings and iron, barium, copper and antimony were marked as elements emitted during braking processes [51]. The brake wear emissions were predominantly found in the coarse fraction during measurements of PM in Switzerland [52]. Antimony was determined as element associated with brake wear and its emissions along the interurban freeway with free-flowing traffic were significantly lower, compared to the measured concentration along an urban street canyon with stop-and-go traffic [52]. In the street canyon and freeway in the Zürich, Switzerland, the brake wear tracers (Cu, Zn, Zr, Mo, Sn, Sb, and Ba) were detected to 21% and 3%, respectively [53]. Particle number concentration data have been collected on a very busy road in a central London, UK, and it was estimated that the wear was responsible for 44 - 57% of the total coarse particle emissions [54]. PM samples collected at the Marylebone Road, London, UK, contained $55.3 \pm 7.0\%$ of the brake dust accounting for total of 104.1% of coarse particles mass in the traffic increment above background sites (Regents Park or North Kensington) [55].

Boogaard et al. compared the concentration of a large range of pollutants between major roads and suburban background. A high contrast was observed between busy streets and background locations for chromium, copper, and iron, which were especially present in the

coarse fraction [56]. Two measurement campaigns near busy freeway and suburban crossroad were carried out in Prague, Czech Republic, with simultaneous measurements of suburban background. Results showed that the main contribution of the traffic to ultrafine size range can be attributed to direct exhaust emissions, while the coarse fraction was dominated mainly by regional background aerosol with small traces of brake and tire wear. Most of major elements (Fe, Cu, Mn, and Zn) were found in the coarse fraction and one of the sources could be attributed to the wear of different vehicle parts [57].

Ba, Fe, Cu, and Sb show a large increment of roadside concentrations over the urban background and all pollutants show very similar particle size distributions in roadside air in London, England. Barium is used as a marker element for brake dust particles and it is shown to comprise 1.1% of brake dust emissions. Iron was assumed to arise solely from brake wear, it would represent 75% of the brake dust according to Gietl et al. [58]. In Tokyo, Japan, Suzuki et al. as well concluded that nonspherical iron-rich particles collected from urban atmospheric environment near to road traffic were emitted from brakes as wear particles [59]. In Kawasaki, Japan, Hirabayashi et al. observed that the fine fraction of air PM around major roads contains elements originating from brake wear [60].

PM_{10} samples collected from roadside sites in congestion zone in London, UK, had higher oxidative potential than those from urban background sites. Preliminary evidence suggested that the higher oxidative potential was related to emissions from vehicle exhaust, tire wear and brake wear. In general, it is believed that oxidative potential of PM_{10} is attributable more to the presence of metals than to organic compounds [61,62]. Amount of brake wear PM_{10} total emissions was predicted not to change, but the contribution from tire and brake wear to PM_{10} increased from 29% to 36% in London, UK (2001 - 2004) [61]. Levels of PM_{10} were measured at two different roadside locations in the Stockholm region, Sweden (highway and street canyon in the center). Brake wear was identified as an important contributor to the PM_{10} of the vehicle pollution source [63]. Hjortenkrans et al. also chose Stockholm, Sweden, to compare the emitted metal quantities to the other metal emissions sources. The calculations were based on material metal concentrations, traffic volume, particle emissions factors, and vehicle sales figures. Emissions related to the road traffic sector were dominant, and represented approximately 50% of total metals emissions. The calculated Cu and Zn emissions from brake linings were unchanged in 2005 compared to 1998, indicating that brake linings still remain one of the main emission sources for these metals. Antimony was considered as brake lining emission marker [64].

Han et al. used a mobile sampling system mounted directly on a test vehicle employed to directly collect samples of resuspended road dust generated by a moving vehicle on paved roads. They showed that Cu/Sb ratio decreases almost linearly with the increase in average hourly traffic and the values of Cu/Sb for PM_{10} obtained range 5.5 - 9.5, which clearly implied that some samples contain a fairly large amount of brake wear dust and most of the particles generated from brake wear belong to the fine particle size rather than coarse size [65]. This result contrast with data published by Handler et al. and Bukowiecki et al. [51,52] which concluded that brake wear is predominantly find as a coarse particle fraction.

Numerous additional authors concluded that brake wear represents one of the sources of PM pollution in air: Lough et al. explored metals emissions in two tunnels in Milwaukee, WI, USA, Ning et al. addressed region near two major freeways in Los Angeles Basin, Na and Cocker studied pollutants released in Mira Loma, Southern California, Kummer et al. collected data from European states, Paulino et al. explored area in Rio de Janeiro, Brazil, Oliveira et al. Oporto, Portugal, Minguillón et al. performed their research based on data obtained in Zürich, Switzerland, Singh and Sharma in Taj Mahal, India, Niu et al. in Ottawa, Canada, Andrade et al. in Brazil, Winbruch et al. in Rurh, Germany, Kholdebarin et al. in Tehran, India, Rogula-Kozłowska et al. in Zabrze, Poland [66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79].

ROAD DUST

Road dust (RD), is defined as a suspension of solid particles produced by mechanical disintegration of materials of the vehicle, road, or materials on the road and has four main resources: mineral, motor exhaust, brake, and tire wear [8,80]. It also could be named road deposited sediment and it is a valuable environmental medium for characterizing contaminant levels in urban areas [81]. RD contains potentially toxic pollutants originating from range of anthropogenic activities and consists primarily of soil derived minerals (60%). Potentially toxic pollutants represent about 30% of the build-up [82].

Although Pirjola et al. singled the tire wear as the main source of collected RD in Stockholm, Sweden, the emissions factors included also brake wear [83]. Zafra et al. marked the brake wear debris as the main source of heavy metal in RD [84]. According to Amato et al., brake wear was found to be the largest source of pollution in Utrecht, Netherlands [80].

Data present by Zafra et al. indicated that the concentration of heavy metals diminishes when the distance between the roadway and the sampling site increases (Torrelavega, Spain) [84]. The results from samples collected in Ma'an area in Jordan indicated that dust samples from the urban and industrial sites contained significant levels of metals when compared to the samples obtained from the background site. The variation in concentrations of the heavy metals determined from different locations was in the decreasing order: industrial > high traffic > parks > moderate traffic > hospitals and health centers > schools > gardens > light traffic > background sites [85]. Also Ewen et al. concluded that congestion/stop-start traffic patterns led to increased levels of metal depositions along inner city roads of Thessaloniki, Greece [86].

RD samples collected in the urban area of Palermo, Italy, contained Zn, Cu, and Sb, which are probably results of the wear of tires and brakes [44]. Increasing heavy metal accumulation in the urban environment of Guangzhou, China, poses a serious threat to environment. The presence of high concentrations of Cu, Cd, Cr, Fe, Mn, Pb and Zn is related to the frequent use of brakes [87]. Chen et al. collected RD samples in Beijing, China. More than 94% of Pb, 40 - 61% of Ba, and 62 - 90% of Cu were from traffic pollution sources [88]. Iron was the most abundant metal present in 140 samples of RD samples collected from Aqaba city, Jordan, and also high concentration of Fe was found at RD samples of Amman, the capital

of Jordan [89,90]. Research at Rome, Italy concluded that major contributor to emitted Ba, Fe, Sb, and Sr in RD is brake wear [91]. RD samples collected from three Massachusetts cities (Boston, Somerville and Greenfield) were analyzed and data revealed that barium concentration decreases with increases in traffic volume. Also it is interesting to note that barium concentrations on major roads are lower compared to highways or minor roads [92].

More than 50% of the total variation of Cu, Fe, Cr, and Zr in the analyzed environment can be correlated with the road traffic [93]. RD collected from different areas in Zhenjiang, China, had the highest concentration of Zn (686.93 mg/kg) followed by Pb (589.19 mg/kg) and Cu (158.16 mg/kg). Highest concentrations were found in the areas with an intense traffic [81]. RD samples were collected also along the industrial and residential roads throughout Singapore. Concentration of Cu and Sb was higher than in the upper continental crust. The concentration of Cu was higher in industrial areas, contrary to concentration of Sb which was found higher in residential area [94]. On-road PM was collected during a sampling campaign in 2011 on two major Los Angeles freeways. While emissions rates of the organic species were within the range of values reported by previous studies, the emissions rates of metals were much higher. It was concluded by Liacos et al. that heavy-duty vehicles are grater emitters of barium than the light-duty vehicles, but copper is the most abundant in the brake linings of light-duty vehicles [95]. Also, other authors have found at least one source of metal pollution in RD brake wear. Kuo et al. explored household dust, Saradhi et al. analyzed RD in Mumbai, India and Rajaram et al. in Delhi, India, Jordanova et al. collected RD from 26 urban sites in Bulgaria, Qiang et al. studied RD from Changchun, China, Kamani et al. collected RD in Zahedan, Iran, and Čabanová et al. in Ostrava, Czech Republic [96, 97, 98, 99, 100, 101, 102].

Resuspended road dust is a source of inhalable particles in urban environments. High concentrations of metals were detected in samples from 46 locations in the Witbank area, Republic of South Africa. Concentration of metals reached 17.7% [103]. Sweeping, water flushing and use of chemical suppressants are usually more commonly employed to try to diminish emissions. Sweeping vehicles were generally effective in removing sediments. However, no satisfactory results were achieved for removal/collection of the ambient PM [104]. Brake wear also shows the fastest recovery of its mobility after rain (99.5% within 3 days after last rain). In Barcelona, Spain, only 27% of the road dust corresponds to brake wear [80]. It was demonstrated that recovery of road dust mobility depends on the drying road surface and supply of new wear particles, but it is independent on amounts of rain [80].

SOIL AND SEDIMENTS

Urban soils are of increasing significance in world, but the concentrations of several heavy metals (such as Pb, Cr, Cu, and Zn) are often found to be considerably higher in urban soils than in rural or agricultural areas. For example the industrialized areas showed higher metal concentrations in Samsun, Turkey [105], concentrations of trace elements in highway roadside soil were significantly higher than those in local roadside soils in Finland [106], and concentrations of Cu and Zn were lower in agricultural field than along highways in

India [107]. The availability of the heavy metals leads to toxicity in plants, microbes, wildlife, and humans. Metals have entered urban soils primarily through industrial manufacturing, lead based paints, lead based additives to automobile fuel, and the wear of tires, brake linings, building materials, and fencing [108].

Several elements commonly assigned to brake wear detected in soil samples around interstate in North Carolina also occur naturally in soil. However, the Zn and Cu concentrations detected were greater by an order of magnitude than what is considered to be the natural occurrence [109]. Topsoil (0 - 20 cm) samples were collected from the edge of roads to about 200 m off the roads along the four roads in Southwest China. Metals as As, Cd, Cr, Cu, Ni, Pb, and Zn were detected in higher concentrations than levels found in background samples. Specimens collected along the roads with the longest transportation period (20 years) contained higher content of metals compared to the roads with a shorter transportation period [110].

The soil quality of urban parks was evaluated in Islamabad and Rawalpindi, Pakistan. Metals connected with brake wear (Ba, Cu, Zn, and Sb) were found in soil composition [111]. Also soil samples collected by Massas et al. in the children's playground of Athens, Greece contain significant concentrations of metals, which were divided into two main groups. The first group included Cu, Pb, and Zn and was linked to the brake wear and the second group contained Fe, Mn, Co, Ni, and Cr which are considered to be from a different anthropogenic activity [112].

Cu/Sb ratio as one tracer of brake wear was studied by Ozaki et al. in Japan, it was found that median of this ratio is about 30. For example in front of Matsumoto station, the ratio was 17 ± 13 , contrary to ratio detected for soils collected around Kamikochi, widely spreading between 1.67 and 1076 [113]. Hjortenkrans et al. showed that concentrations of Cu and Sb in the topsoils around 18 Swedish roads increased more than eightfold in last 20 years when compared to the background and also demonstrated that the Cu/Sb ratio was ranging between 3.6 and 150, with mean of 20 ± 19 [114]. Wang showed that the “anthropogenic heavy metals” (Pb, Cu, Zn, and Cr) in the soil samples of Xuzhou, China urban area were strongly correlated with amount of the total carbon. Thus, the “anthropogenic heavy metals” are mainly enriched in the organic matter in the Xuzhou urban roadside soils [115].

Saeedi et al. showed that studied soil samples along the Tehran-Karaj highway, Iran have higher metal content than the acceptable value, and also the toxicity characteristics leaching procedure test results revealed that the studied soils may be hazardous [116]. Cd which is known for its toxicity to humans and could be part of some brake linings entered into the soil ecosystem along three ring roads with high traffic density from Beijing, China [117]. Soils in Lisbon, Portugal urban areas contain anthropogenic elements as Cu, Zn, and Pb, and especially the presence of Cu was marked as related to the brake wear by Cachada et al. [118]. Other high levels of the metals related to the brake wear (Ba, Sb, and Zn) were found in São Paulo, Brazil, nearby high density traffic avenues [119].

Taylor and Owens concluded that sediments in urban river basins have two main sources of metals - natural and anthropogenic (including the brake wear) [120]. Concentrations of traffic related metals were determined in sediment and crustacean samples from eight different aquatic habitats in the Ruhr district, Germany. Traffic related heavy metals could be identified in sediment and biota samples as a combination of heavy metals (Pt, Sb, Cd, Pb for sediments and Pt and Sb for crustacean samples) [121]. A high concentration of Cu and Zn associated with low levels of Pb was found in the stormwater retention ponds sediments (top layer) of Mediterranean region of France [122].

In the Seto Inland Sea of Japan geochemical study of sediments was performed. The distribution and abundances of 13 elements (As, Pb, Zn, Cu, Ni, Cr, Sr, Ca, Fe, Ti, P, Mn, and S) were examined in 40 coastal and river sediment samples. Brake wear was marked as one of the possible sources of copper and the average concentration of Cu was 16 mg/kg at Ube, 3 mg/kg at Suo-Oshima and 8 mg/kg at Kasado Bays. These concentrations were lower compared to the upper continental crust [123]. Metals (Ni, Cu, Zn, Hg, Pb, Br, Ca, Sb, Cd, and Ba) found in soils from Zhuzhou City, China were also marked as traffic related emissions and they were related to brake wear [124].

RUNOFFS AND OTHER WATER SOURCES

As runoff water flows over the land surface, it picks up potential pollutants (bacteria, pesticides, metals, etc.). Thus the polluted runoffs could be harmful to the environment. Runoff water quality was monitored in Southern California and the brake pad wear was identified as one of the runoff pollutants [125]. Sörme and Lagerkvist marked brake and tire wear as one of the major contributors to stormwater [126].

According to Hulskotte et al., Cu from brake wear contributes significantly to pollution of surface waters [37] and the same conclusion was made by Nie et al. [127]. Concentrations of metals in road runoffs were measured at two Swedish field sites during one year. Concentrations of most measured elements increased significantly up to one order of magnitude during the winter. Copper concentrations reached background level at a distance of 5 m and reached high levels to the 1m from the road. In their opinion this indicates an association with brake wear (larger particles), that is not always transported far from the road. In the open site locations the background concentration was reached a little farther away from the road (more than 1 m) [128]. About 25% of the emitted brake wear material becomes entrained by rainfall-runoff in Hungary. Based on the metal concentrations measured in numerous Hungarian road runoff samples, Budai and Clement identified distinct Cu/Zn ratios for free-flow motorways and urban roads characterized by stop-and-go traffic. The ratios were higher for urban regions, reflecting the impact of more frequent braking on Cu emissions [129].

Copper content was determined in five small lakes in Stockholm, Sweden, and the model identified that traffic emission, especially from brake linings, dominated to the total load in all five cases [36]. Thirty stormwater wetlands and wet pond forebays across North Carolina were analyzed for seven metals (Cd, Cr, Cu, Fe, Pb, Ni, and Zn), typically associated with the brake wear. This study showed that