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Emissions of metals and particulate matter due to wear of brake linings in Stockholm

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Abstract

The total wear of brake linings have been estimated using the total yearly amount of transports and communication for different vehicle types and estimated annual consumption of linings. In order to calculate heavy metal emissions the metal content of different brake linings were analysed. Analyses were performed using plasma – emission spectrometry. This allowed the detection of copper, zinc, chromium, nickel, cadmium and lead. Emission factors for copper and lead were 1,300 and 190 µg per vehicle km. These values are 9 and 5 times higher, respectively, than measured in road traffic tunnels, indicating that less than 20% of the brake wear is airborne.

The calculated total particle emission per vehicle kilometre due to wear of brake linings was 17 mg and 84 mg for passenger cars and heavy-duty vehicles, respectively. If all would be airborne, the particle wear of passenger cars would be comparable to the particle emission in car exhaust of gasoline cars. Diesel passenger exhaust emission is about 10 times higher, making brake wear emission comparatively small. For heavy-duty goods vehicles the emission due to the wear of brake linings is about 60% of that from due to exhaust. The estimate given here for Stockholm is somewhat higher compared to that given by US-EPA of 8 mg per vehicle kilometre for passenger cars. As exhaust emissions decrease in the future due to renewal of the vehicle fleet and cleaner fuels, emissions from brake linings may not change and therefore become relatively more important as a source of PM in urban areas. Compared to other sources, wear of brake linings may be a significant source of copper and lead.

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1 Introduction

There are elevated, sometimes highly elevated, levels of metals in several of the recipients in Stockholm — soil, lake- and seawater and groundwater — as well as sludge from sewage treatment plants. Sometimes, the elevated levels can affect the biological life. Combined sewage system and wastewater treatment plants reduces the use of the sludge as a fertiliser on farmland. It is therefore important to reduce metal contamination of wastewater. This is particularly the case with mercury, cadmium and lead, but also with copper as the agricultural utility of the sludge is reduced by the high copper content. The environment today is to a great extent affected by diffuse sources.

As yet, we do not possess the knowledge necessary to describe connections between sources and conditions in different recipients. Copper water pipes and roofs covered with copper have been identified as large sources for the spread of copper in Stockholm. A further source could be road traffic that, due to wear of copper containing break linings, emits copper to the sewage system, storm-water and soil [1]. Friction material in brake linings for use in passenger cars and heavy goods vehicles/buses consists of compounds where for instance fibres from steel, glass and plastic serve as reinforcements in the material. Cast iron chip can also occur. In addition, some substances have a heat conducting effect. Copper, brass and zinc are also used to conduct heat [2].

Few studies have been made in Sweden of emissions from wear of brake linings. The Malmö Environmental Health Administration made a study of national cadmium emissions deriving from brake linings in 1993 [3]. This study showed that in Sweden approx. 934,000 kg of brake linings were used per year and that approximately 13 kg cadmium was emitted from road traffic. The objective of the present study is to estimate metal emissions in Stockholm that are caused by wear of brake linings.

2 Results

2.1 Estimates of total wear of brake linings

Front brake linings in passenger cars that are used in city traffic conditions are normally replaced after 30,000 - 40,000 kilometres, rear brake linings after 60,000 - 80,000 kilometres [2].

Using the number of passenger cars presently in use in traffic and communications in the City and County of Stockholm as a reference, the average driving distance can be calculated to be 12,000 - 15,000 kilometres per year. The annual driving distance of a passenger car is hereinafter assumed to be 15,000 kilometres. Making the further assumption that both rear and front linings are replaced after 60,000 kilometres driving, this would consequently happen when the car is four years old.

Passenger car linings weigh 0.13 - 0.15 kg at the front of the car and 0.9 - 0.11 kg at the rear [2]. The assumptions are made here that

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- new front linings weigh 0.15 kg,
- new rear linings weigh 0.11 kg,
- all linings are used to 70 % of their total length of life before being replaced [2] and
- front linings are replaced every 40,000 kilometres (four linings) and rear linings every 60,000 kilometres (four linings).

The total yearly amount of transports and communication in Stockholm equals approx. 3,000 million vehicle kilometres. Passenger cars and light goods vehicles/buses account for 2,880 million vehicle kilometres (96 percent), heavy goods vehicles for 90 million vehicle kilometres (3 percent) and buses for 30 million vehicle kilometres (1 percent) [4]. These assumptions lead to a brake lining consumption of 30,200 kg in the front and 14,800 kg in the rear, per year. This would make the total wear of brake linings in passenger cars 45,000 kg per year.

Data referring to the duration of brake linings for heavy goods vehicles vary between 80,000 - 120,000 kilometres [5] to 100,000 - 120,000 [5]. It will hereinafter be assumed that all brake linings in heavy goods vehicles are replaced every 100,000 kilometres. The number of linings per wheel varies between make and model. Generally, it can be said that, per wheel, linings weigh 2.4 kg in the front and 3.5 kg in the rear [2]. This means that the total linings of four-wheel goods vehicles weigh 12 kg. If the linings are replaced after 70 % of their wear, then 8.4 kg has been used. The total amount of linings consumed per year in goods vehicles would then be equal to 7,600 kg.

According to data derived from weighing new and worn-out linings provided by Stockholm Transport's bus division [9], buses use on average 0.00011 kg per kilometre. This means that 3,300 kg of brake linings are used by buses per year.

2.2 Metal emissions and emission factors

In order to calculate metal emissions from these types of vehicle, it is necessary to measure not just the total amount of brake linings used but also the metal content of brake linings. Analysis of copper, zinc, chromium, nickel, cadmium and lead has been performed by SGAB Analytica. Metal concentrations have been measured by plasma – emission spectrometry. The method used has been to cut out samples using glass or ceramic material, dissolve the samples in aqua regia or hydrofluoric acid and subsequently analyse with HR ICP-MS.

The compilation includes the most frequently represented makes and models in the traffic of Stockholm. The material has been prepared during the autumn of 1997 by the Stockholm branch of the Swedish National Road Administration and is based on random registrations of passenger cars in traffic on Nynäsvägen road, and makes and models have subsequently been checked with the motor vehicle registry. A total of 987 cars were registered.

Table 1 shows the most frequent makes and models and their relative abundance. Only models constituting at least 1 percent of the total amount of cars have been included. It is assumed that the result reflects each model's share of the total passenger car traffic of the city. In all, 63,5 percent of the passenger cars are represented.

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Table 1: Abundance of various car models in Stockholm (Source: Swedish National Road Administration, Stockholm Regional Branch, 1997).

Make	**Model**	**Share %**	**Accumulated %**
Volvo	700, 740, 760	5.8	5.8
	840, 850, S70, V70	5.6	11.4
	940, 960	5.4	16.8
	240	4.7	21.5
	440, 460, S40, V40	2.5	24
	340	1.2	25.2
Saab	900	4.6	29.8
	9000	3.7	33.5
Ford	Escort	3.3	36.8
	Sierra	2.3	39.1
	Scorpio	1.9	41
	Mondeo	1.7	42.7
VW	Golf	2.4	45.1
	Passat	1.3	46.4
	Pick-up	1.2	47.6
Opel	Kadett	2.8	50.4
	Vectra	1.7	52.1
Nissan	Micra	1.4	53.5
	Sunny	1	54.5
Mazda	323	1.8	56.3
	626	1.8	58.1
Audi	100	1.7	59.8
Toyota	Corolla	2.5	62.3
	Carina	1.2	63.5

By including linings from the models above a selection is generated that covers roughly 60 percent of all passenger cars. Samples have been taken from the latest car models and these cars are taken to represent passenger cars impacting on metal emissions from brake linings in the years to come. Front and rear linings for the most sold car models of every make and model/model series were analysed. Altogether 48 brake linings, have been procured.

To arrive at an overview of metals in the brake linings of older passenger cars, samples have been taken of front and rear linings from two downstream market suppliers for Volvo 800 and 400, Saab 900, Ford Escort and VW Golf. The linings, 20 in total, have been procured from two of the largest suppliers OK and Biltema. To facilitate the calculation of metal emissions passenger cars have been divided into, cars that are up to four years old and are assumed to be equipped with the original linings, and cars that are older than four years and are

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assumed to be using downstream market linings. About 40 percent of all passenger car traffic is due to four years or younger cars, while 60 percent derives from older cars [4].

2.2.1 Old passenger cars

A measurable cadmium content was only found in a small number of the linings (Table 2). The metal content is low in linings for several car models, particularly among those purchased at OK. This is the case with for instance front and rear linings for VW Golf as well as rear linings of Volvo 850, Saab 900 and Ford Escort. All of these linings were manufactured by BBA Friction Sweden AB. The annual metal emissions are calculated as the amount of brake lining used per year times metal content. As a measure of the metal content, the mean value is used for each metal. Rear and front brake emissions are calculated separately and added.

Table 2: Metal concentrations in brake linings for old passenger cars.

Make	Front linings						Rear linings					
Model	Cd mg/kg	Cr mg/kg	Cu g/kg	Ni g/kg	Pb g/kg	Zn g/kg	Cd mg/kg	Cr mg/kg	Cu g/kg	Ni mg/kg	Pb g/kg	Zn g/kg
Volvo	<9.9	83.9	123	87.6	46.5	23.9	41.4	91.4	0.10	81.9	0.63	17.4
850	<10.1	53.2	121	62.4	0.07	0.04	<10.1	96.8	123	109	<0.06	0.19
Volvo	<9.99	151	37.3	164	35.9	26.9	<9.99	31.2	143	36	62.1	12.1
440	<10.2	102	120	118	<0.06	0.16	<19.1	83.0	4.05	78.4	<0.12	16.5
Saab	<9.97	74.9	76.5	491	3.56	51.0	<1.98	48.0	0.08	34.7	0.09	0.21
900	<10.4	84.5	132	110	0.10	0.03	<10.1	237	122	248	0.10	0.22
VW	<1.99	69.8	0.10	66.6	0.23	0.24	<9.87	234	0.05	117	0.35	12.6
Golf III	12.5	60.9	33.0	164	1.70	22.6	<10.2	274	120	302	0.13	0.21
Ford	11.8	150	31.4	295	33.2	21.3	<10.1	252	0.04	138	0.37	12.5
Escort	14.2	89.6	45.6	257	1.61	30.8	<2.03	164	0.09	73	<0.01	0.04
Mean content	8.60*	92.0	72.0	182	13.7	17.7	3.50*	151	51.2	122	9.11	7.20

* *Cd content is below the detection limit in most linings*

2.2.2 New passenger cars

It is well known that Cd and Zn goes together as they belong to the same group in the periodic system. In order to estimate mean content of Cd in Table 3, the relation between Cd and Zn has been calculated for those linings in which both elements have been analysed. The mean value for this relation is 0.49 milligrams of Cd per gram of Zn. This relation has been used to calculate mean concentrations of Cd in Tables 2 and 3. The metal concentrations are consistently lower in some linings when compared with others. This is for instance the case with rear linings for Volvo 340 and rear and front linings for Nissan Micra.

Table 3: Metal concentrations in brake linings for new passenger cars.

Make	Model	Front linings						Rear linings		
		Cd mg/kg	Cr mg/kg	Cu g/kg	Ni mg/kg	Pb g/kg	Zn g/kg	Cd mg/kg	Cr mg/kg	Cu g/kg
Volvo	745 GL	<10.0	156	132	151	23.1	28.1	16.2	57.7	172
"	854 GLT	<10.0	169	156	217	23.3	29.3	18.2	21.8	216
	945 S 2.3	<10.0	156	132	151	23.1	28.1	16.2	16.2	172
	245 GL	10.1	123	205	-	6.76	26.9	<9.87	<19.7	138
	400	12.1	128	217	186	0.87	11.8	<9.90	72.8	0.19
	340	24.2	167	148	348	20.6	107	<9.62	176	0.83
Saab	900 SE 2.0 T	<9.96	305	168	59.3	0.52	2.65	<9.96	53.4	153
"	9000 150 SE	<10.0	182	128	155	1.37	29.2	<10.1	30.5	229
Ford	Escort 1.6 CLX	<9.92	130	87.8	117	0.18	0.13	<9.99	46.4	19
"	Sierra 2.0 i GLX	<10.0	120	107	108	0.26	37.2	<9.89	43.2	123
"	Scorpio 2.0 CLX	<17.6	132	159	159	1.59	17.5	<9.89	43.2	123
"	Mondeo 2.0 CLX	<17.6	132	159	159	1.59	17.5	<9.95	48.9	107
VW	Golf 1.8 GL	10.8	93.2	165	109	31.3	27.9	<10.1	197	0.17
"	Passat 1.8 GL	<9.89	127	147	113	0.44	24.1	<9.94	149	142
"	Pick up 2.5	22.5	108	112	162	39.7	36.8	19.9	59.6	162
Opel	Astra 1.6 GL	<9.96	158	97.4	121	17.3	32.8	<10.3	248	0.08
"	Vectra 1.8	<9.98	118	104	113	17.8	34.2	<9.93	43.2	124
Nissan	Micra 1.0	<9.1	76	0.064	80.1	0.14	6.6	<1.01	27.1	0.01
"	Sunny 1.6	<9.49	285	0.23	382	0.02	50.00	<0.97	28.2	0.01
Mazda	323 S	<0.10	83	17.4	62	0.16	9.33	<1.00	5.73	0.02
"	626 2.0 GLX	<0.10	77.9	15.2	61.2	0.23	7.69	<0.10	123	18
Audi	A6 1.8	9.86	81.5	43.6	99.4	5.97	5.71	11.8	144	126
Toyota	Corolla 1.6	<0.97	152	98.9	110	0.04	0.76	<0.97	6.07	0.11
"	Carina 1.8	<0.98	23	234	12.4	0.94	0.66	<0.97	6.21	0.03
Mean content		11.6*	137	118	141	9.05	23.8	8.02	73.4	92.2

** Cd content is below the detection limit in most linings*

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Emission factors for brake linings of passenger cars are given in Table 4. Sternbeck et al. [5] measured emissions of metals from road traffic in a traffic tunnel in Gothenburg. For Cu and Pb they found much lower emission factors than estimated for brake linings here; 150 and 36 µg/vehicle km, respectively. This indicates that less than 20% of the brake wear becomes airborne. For Zn and Cd they obtained 220 and 0.25 µg/vehicle km, i. e. similar to the estimates for wear of brake linings. But a significant fraction of the Zn emission found in the tunnel study may be due to tyre wear and a large part of the observed Cd emission may be due to its presence in fuels and motor oil.

Table 4: Metal emissions per year and emission factors for new and old passenger cars (kg) in the city of Stockholm.

	Cd	**Cr**	**Cu**	**Ni**	**Pb**	**Zn**
New	0.19	2.1	1970	2.1	220	386
Old	0.23	3.0	1760	4.4	329	385
Sum	0.42*	5.1	3730	6.5	549	771
Emission factor (µg/veh km)	0.15	1.8	1300	2.3	190	268

* *Cd content is below the detection limit in most linings*

2.2.3 Goods vehicles

There are large variations within the goods vehicle group as regards total weight, with a range between 3.5 tonnes to over 24 tonnes. The group is represented by Volvo and Scania, the two dominant makes among distribution goods vehicles with a weight of 10 tonnes or more. The relationship between the number of Volvo and Scania goods vehicles in the national lorry fleet is approx. 60/4 [6]. This relationship will be used hereinafter. Brake linings have been procured for Volvo FL 614 and Scania P9, the most abundant distribution vehicles in Stockholm from each make, and the front and rear brake linings share the same composition ([7] and [8]). One brake lining from each model has been analysed.

As seen in Table 5 the linings made for Scania (from BBA Friction Sweden AB) show consistently lower metal concentrations than the Volvo linings. This is particularly the case as regards copper and zinc. Metal emissions from goods vehicle traffic is calculated as the metal content times the amount of brake lining used. As a measure of the metal content a weighted mean value is used according to the 40/60 relationship between Volvo and Scania.

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Table 5: Metal content in brake linings for goods vehicles and metal emissions and emission factors in the city of Stockholm.

	Cd	Cr	Cu	Ni	Pb	Zn
Volvo (mg/kg)	<10.3	171	15,000	118	656	14,900
Scania (mg/kg)	<1.99	157	76.9	110	158	127
Metal emission (kg)	<0.05	1.3	68	0.9	3.9	68
Emission factor (µg/veh km)	<0.6	14	760	10	43	760

2.2.4 Buses

Bus traffic in Stockholm is dominated by the bus division of Stockholm Transport, Busslink AB. Their bus fleet consists of 92 percent Scania buses and 8 percent Volvo [9]. The brake linings share the same composition, both rear and front. One brake lining for each bus make has been analysed.

The content of copper and zinc is many times higher in the brake linings for Volvo, than it is in those for Scania (BBA Friction Sweden AB) (Table 6). The content of chromium and nickel is however higher in Scania's linings. The metal emissions from bus traffic is calculated as metal content times the amount of brake lining used. As a measure of the metal content in brake linings a weighted mean value is used, in accordance with the relationship 92 to 8 percent between Volvo and Scania buses.

Table 6: Metal content in brake linings for buses and metal emissions and emission factors in the city of Stockholm.

	Cd	Cr	Cu	Ni	Pb	Zn
Volvo (mg/kg)	<10.1	<20.1	27,300	140	1,020	18,500
Scania (mg/kg)	<1.98	118	88.3	178	441	172
Metal emission (kg)	<0.01	<0.46	76	0.5	3.2	56
Emission factor (µg/veh km)	<0.33	<15	2530	17	107	1870

2.3 Total emissions of PM

It is also interesting to compare the PM emissions due to wear of brake linings with the direct emissions due to incomplete combustion of diesel and gasoline in vehicles in Stockholm. The average emission factor for heavy-duty vehicles and passenger cars in Stockholm (1996) have been estimated using the emission model EVA (version 2.2) of the National Swedish Road and Transport Administration.

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Table 7: Comparison of emissions from wear of brake linings and from incomplete combustion of diesel and gasoline. Total emissions have been estimated using the total yearly amount of transports and communication in Stockholm.

Vehicle type	Brake linings emission		Exhaust emission	
	mg/veh km	Tonnes/y	mg/veh km	Tonnes/y
Passenger cars Diesel	17	2	172	20
Passenger cars Gasoline	17	50	11	30
Goods vehicles	84	8	140	10
SUM		60		60

As can be seen from Table 7 the calculated emission per vehicle kilometre due to wear of brake linings from this study is comparable to the fleet average emission from gasoline passenger cars and about a factor 10 lower compared to the exhaust emission from diesel passenger cars. It is also seen that from heavy-duty goods vehicles the emission due to the wear of brake linings is about 60% of that from due to exhaust.

The estimate given here for Stockholm is somewhat higher than the US EPA estimate of 8 mg of brake linings per vehicle kilometre for passenger cars [10]. Total particle emissions may then be estimated using the total yearly amount of transports and communication in Stockholm cited earlier. The exhaust particle emissions are calculated to be about 20, 30 and 10 tonnes per year for diesel and gasoline passenger cars, and goods vehicles respectively. These values may then be compared with the particle emissions due to wear of brake linings of 2, 50 and 8 tonnes per year. The total amount emitted is then about equal for these sources. Exhaust particles are much smaller than particles generated by wear of brake linings. Garg et al. [11] found that 86% and 63% of the airborne PM was smaller than 10 μm in diameter or 2.5 μm in diameter, respectively. But they also found that about 35% of the brake pad mass loss was emitted as airborne; a large fraction may thus end up in water and soil recipients. It is important to note that as exhaust emissions decrease in the future due to renewal of the vehicle fleet, emissions from brake linings may not change and therefore become relatively more important as a source of PM in urban areas.

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