Emission estimates for diffuse sources
Netherlands Emission Inventory

Road traffic brake wear

Version dated June 2008

NETHERLANDS NATIONAL WATER BOARD - WATER UNIT
in cooperation with DELTARES and TNO

Road traffic brake wear

1 Description of emission source

This fact sheet sets out a method for calculating emissions resulting from the wear of brake linings in road traffic. Wear from brake linings and deposition of particulate matter in the environment is primarily a major source of copper.
This emission source is allocated to the governmental target sector “Transport” within the National Emission Inventory.

2 Explanation of calculation method

The emissions are calculated separately for various vehicle categories. Emissions are calculated by multiplying an activity rate (AR), in this case the number of kilometres driven on Dutch roads, by an emission factor (EF), expressed in emission per AR unit.

$$E_s = AR \times EF$$

Where:
E_s = Emission of particulates (kg)
AR = Traffic performance, distance covered on Dutch road network (km)
EF = Emission factor (kg/km).

The copper emission can be calculated as a fraction of the particulates generated:

$$E_X = E_s \times X$$

Where:
E_x = Emission of component X (kg)
X = Content of component X in brake lining (-/-).

The emission calculated in this way is referred to as the total emission. A specific proportion of this ends up in surface water: this is the net pollution of the surface water.

3 Activity rates

The activity rate reflects traffic performance by various vehicle categories. Numbers are supplied by Statistics Netherlands (CBS) to the Task Force Traffic and Transport. The Task Force Traffic and Transport then calculates the division among the various road types (urban driving, rural driving and highway driving).

Table 1: Traffic performance on urban roads per vehicle category, (in millions of km)

Year	Passenger cars	Vans	Lorries	Trucks	Buses	Special vehicles - light	Special vehicles - heavy	Motor-cycles
1985	21,425	3,628	702	276	297	100	224	448
1990	23,040	6,259	759	402	347	63	204	540
1995	22,447	5,221	422	519	250	36	132	639
2000	23,734	8,318	408	696	250	55	176	827
2005	19,647	8,296	372	793	243	66	275	733
2006	20,137	8,204	368	828	238	71	293	753

Table 2: Traffic performance on rural roads per vehicle category, (in millions of km)

Year	Passenger cars	Vans	Lorries	Trucks	Buses	Special vehicles - light	Special vehicles - heavy	Motor-cycles
1985	26,479	649	1,222	521	184	16	35	171
1990	30,115	805	1,159	504	194	13	41	221
1995	32,239	3,133	1,044	498	163	15	55	418
2000	36,181	4,991	1,011	668	163	23	73	541
2005	34,407	6,222	921	761	159	28	114	733
2006	35,163	6,153	912	794	156	30	122	753

Table 3: Traffic performance on highways, (in millions of km)

Year	Passenger cars	Vans	Lorries	Trucks	Buses	Special vehicles - light	Special vehicles - heavy	Motorcycles
1985	20,856	470	1,306	857	113	9	21	83
1990	28,119	716	1,441	1,124	119	8	27	126
1995	34,103	2,089	1,935	1,604	241	9	33	300
2000	37,890	3,327	1,874	2,151	241	14	44	388
2005	42,888	6,222	1,708	2,451	235	17	69	733
2006	43,116	6,153	1,690	2,558	230	18	73	753

4 Emission factors

Particulate Emission factors from brake linings

Emission factors for particulates from brake linings may be calculated as follows:

Weight of brake linings (g) * wear before replacement (-/-) / life (km)

Over the last few years, various research groups have performed studies to estimate the total emission factor from brake linings. Some of these emission factors (for example, Pagotto et al. [1] and Luhana et al.[2]), are based on the mass balance as shown in formula above. Other emission factors are obtained by interpretation of measurements. Particularly with respect to emission factors based on measurements, the results diverge widely from 1 to 100 g/km. In this respect it is important to remember that measurements frequently do not produce an emission factor, but the emission factor to one compartment (see also section 7).

A number of results based on mass balance are set out in table 3. As shown in this table, the differences are quite small. Despite this, there are nevertheless differences in accuracy with respect to the methodology applied. The emission factors calculated by Luhana et al. [2] appear to be the most reliable, because they are elaborated by measuring the weight loss of the brake discs of a number of vehicles over a number of kilometres driven that is assessed precisely. Reference will therefore be made to these emission factors for passenger cars. The emission factors calculated by Pagatto et al. [1] are based on measured weight loss and an estimated number of kilometres driven, and seem to be somewhat less accurate. However, these emission factors are the best available for vans and lorries. The emission factors calculated by Klein et al [4] are based on estimated weight loss and number of kilometres driven, and are therefore based on a less robust approach. However, this is the only value available for motorcycles. The result published by van Hyfte [3] is based on a review of available emission factors in literature, giving average values for the published emission factors, including a number of interpreted deposition measurements. These values do not take into consideration the quality of the emission factor published, with the result that the value of the average values loses quality.

Table 4: Calculation of emission factors for particulates from brake linings per vehicle category, (mg/km)

	Passenger cars		Vans		Lorries		Trucks	Buses	Special vehicles	Motor-cycles
	f[1)]	r[1)]	f	r	f	f				
Weight of brake lining (g)	540	350	770	490	6,700	13,000				
Wear on replacement (%)	75	75	75	75	75					
Life (1000 km)	30	75	30	75	200	400				
EF Pagotto [1]	13.4	3.5	19.4	4.9	25	25				
	8.5		**12.2**		**25**					
EF Luhana [2]	**8.8**									
EF Klein[2)] [4]	8		10		43		43	31		**4**
EF Van Hyfte [3]	6.8		10.6		26.5		26.5	17.2		4

1) f: front brakes; r: rear brakes
2) only relates to proportion of fine particulate

The emission factor for lorries is used for trucks and buses. The emission factor for vans is used for special light vehicles and the emission factor for lorries is used for special heavy vehicles. The selected emission factors are again indicated in bold in table 4.

Emission factors for urban driving, rural driving and highway driving.

There is usually more frequent braking within urban areas than outside these areas. It can therefore be expected that the emission factor per km for urban driving is higher than the emission factor for rural driving and highway driving. Luhana et al. [2] studied the impact of average driving speed on the wear of brake linings in passenger cars. At an average driving speed of 80 kph, the wear per km is still only 40% of the wear per km at 40 kph. Based on these results, if one assumes that the emission factor for rural driving and highway driving is 40% of the emission factor for urban driving, it is then possible to derive the emission factors for urban, rural and highway driving, as shown in table 5, from the number of kilometres driven within urban and rural areas and on highways (table 1 and 2) and the average emission factor in table 4.

Table 5: Emission factors for forming particulates from brake linings in road traffic within and outside urban areas, (mg/km)

	Passenger cars	Vans	Lorries	Trucks	Buses	Special vehicles - light	Special vehicles - heavy	Motor-cycles
EF total	8.8	12.2	25	25	25	12.2	25	4
EF within urban area	16.1	17.4	52.7	48.2	39.7	17.4	52.7	5.9
EF within rural area	6.4	7.0	21.1	19.3	16.1	7.0	21.1	2.3

Particulate matter (PM_{10})

Estimates for the quantity of wear of brake linings emitted as fine particulates (PM_{10}) vary. Van den Brink [5] estimates the quantity of PM_{10} in the brake particulates formed to be 55%; Garg et al. [6] estimate this fraction to be 35%, based on an analysis of particle size distribution of the particulates formed. Sanders et al. [7] reports that in laboratory tests an average of 63% of brake lining wear is released as fine particulate. Fraunhofer [8] estimates the fraction of fine particulates to be 40% based on measurements of particle size distribution. Based on all this data, van Hyfte [3] estimates the quantity of PM_{10}in the brake particulates formed to be 49%, which is the figure used in this study.

Copper content and content of other metals

The particulates originating from brake linings have a complex composition. It contains residue of brake linings comprising metal fibres (in particular copper, zinc, lead and antimony), inorganic filler material (for example cheap metal oxides such as barium oxide or clay-like material) and friction modifiers (carbon, graphite) bound to each other by means of a wide range of phenol-formaldehyde resins. The particulates also contain residue of the brake disc (usually iron-nickel-zinc alloys) and brake fluid (specific organic components such as n-alkanoic acids or polyalkene glycol ethers). The organic components may be converted into PAH by heat released during braking.

There is considerable information available in the literature about copper content in brake linings. Compared to many other metals, estimates of this copper content are reasonably consistent, varying from 5% (for example, Harrison [9]) to 15% (for example, Pagotto [1]). Van Hyfte [3] provides a list of available literature and estimates the average copper content to be 10%, based on the available European studies. This 10% is also in line with interpretations of increased concentrations of fine particulates and copper within this fine particulates in the Maas tunnel [10].

The most significant other metal pollutants in terms of scope and toxicity are Cu, Cd, Ni, Pb, Sb and Zn.
A number of studies are available focusing on the brake lining itself (for example, van Brewer [11] and Westerlund [12]). There are also a number of studies assessing the composition of brake particulates based on results of particulates collected in the environment (such as van Luhana et al., [2]; Hildeman, [13]). Reference [14] focuses specifically on lead and calculates this content based on the composition of a typical brake lining and the lead content of the brake lining.
Metal contents based on interpretations of composition of particulates deposition by Luhana et al., and Hildeman, deliver results in values that likely are to be considered as too low: approximately 300 times lower compared to the analyses of the actual brake linings. The particulate samples taken by Hildeman and Luhana were probably highly contaminated with particulates from other sources, for which the findings were not sufficiently adjusted. Analyses of the actual brake linings (Brewer [11] and Westerlund [12]) appear to produce better results, but probably underestimate the content of Ni and Zn because these components may also come from the brake disc. In lack of better information, these analyses of brake linings are used as emission factor. The Okopol study [14] appears to provide the best information for lead. The emission factors selected in this fact sheet are entered in the last column of the table below. The emission factors of metals other than copper are very uncertain and only provide an estimate of the order of magnitude of emissions, as indicated by the expression of numbers.

Table 6: Metal content of brake lining particulate, (mg/kg of particulates formed)

	Hildeman [13]	**Brewer [11]1)**	**Westerlund, [12]1)**	**Ökopol, [14]1,2)**	**Lulana [2]3**	**Selected emission factor**
copper	370	15,000-140,000	50,000-120,000	200,000	430	100,000
cadmium		3-30	3-8		-	10
nickel	660	200-850	70-180		260	100
lead	50	2,000-4,000	9,000-19,000	7,000	320	10,000
antimony		10,000		100,000	40	10,000
zinc	270	300-22,000	7,000-24,000		4600	10,000

1) Refers to brake lining.
2) Interpretation of Okopol's specifications: 20% brass fibres, 10% antimony compound and a total of 0.7% lead in the brake lining
3) Lulana reports on metal/copper ratios. 10% copper in the particulates is assumed.

5 Effects of policy measures

No developments are found in the literature consulted with respect to emission factors and copper content of brake linings.

6 Emissions calculated

Tables 7, 8 and 9 below show the primary emissions of brake particulates for various categories of vehicle per year. The emissions are calculated by multiplying the emission factors in table 4 by the activity rates in tables 1 and 2 and 3.

Table 7: Formation of particulates within urban areas, (tonnes)

Year	Passenger cars	Vans	Lorries	Trucks	Buses	Special vehicles - light	Special vehicle - heavy	Motorcycles	Total
1985	345	89	37	13	12	2	12	3	512
1990	371	109	40	19	14	1	11	3	568
1995	361	91	22	25	10	1	7	4	521
2000	382	145	22	34	10	1	9	5	607
2005	316	144	20	38	10	1	14	4	548
2006	324	143	19	40	9	1	15	4	557

Table 8: Formation of brake lining particulates within rural areas, (tonnes)

Year	Passenger cars	Vans	Lorries	Trucks	Buses	Special vehicles - light	Special vehicle - heavy	Motorcycles	Total
1985	169	5	26	10	3	0	1	0	215
1990	193	6	24	10	3	0	1	1	237
1995	206	22	22	10	3	0	1	1	265
2000	232	35	21	13	3	0	2	1	306
2005	220	44	19	15	3	0	2	2	305
2006	225	43	19	15	3	0	3	2	310

Table 9: Formation of brake lining particulates on highways, (tonnes)

Year	Passenger cars	Vans	Lorries	Trucks	Buses	Special vehicles - light	Special vehicle - heavy	Motorcycles	Total
1985	133	3	28	17	2	0	0	0	183
1990	180	5	30	22	2	0	1	0	240
1995	218	15	41	31	4	0	1	1	310
2000	242	23	40	42	4	0	1	1	353
2005	274	44	36	47	4	0	1	1	408
2006	276	43	36	49	4	0	2	2	411

7 Release into environmental compartments

To quantify the distribution among the compartments, the method published by Van Hyfte [3] was used, based on mass balance:

emission to soil and groundwater = formation of brake particulates - share remaining on vehicle - share emitted as fine particulate

The share that stays behind on the vehicle is estimated by Sundberg [15] to be 25%. Based on results of laboratory measurements, Sanders [7] concludes that 22-47% of the brake lining particulates remains on the vehicle. Based on this data, van Hyfte [3] estimates that 31% stays behind on the vehicle, and is partially removed in carwashes, garages and breaker's yards, so it no longer contributes to emissions to atmosphere, soil or water.
The share emitted as fine particulates is estimated by van Hyfte [3] to be 49% based on data published in the literature. This data is substantiated in section 4. Van Hyfte [3] estimates that 20% of brake particulates (100% - 31% remaining behind on the vehicle - 49% emitted as fine particulate) precipitates to soil and surface water.

The distribution worked out by Klein et al. [4] is taken as the distribution to soil and surface water: Within urban areas, 60% is transported to the surface water via the sewer system. On rural roads and on highways, 90% ends up in the soil and 10% directly in the surface water: i.e. 18% and 2% respectively of the total.

Table 10: Distribution of emissions among compartments in %

Compartment	Minimum	Maximum	Average on urban roads	Average on rural roads and on highways
Remains on vehicle	25	36	31	31
To atmosphere (especially PM_{10})	35	63	49	49
To soil			8	18
To sewers or surface water			12	2

The copper pollution can be calculated from the quantity of particulates formed from brake linings as shown in tables 6, 7 and 8, the copper content of brake linings and the share of particulates emitted to the sewer system or surface water.
The resultant calculations of copper pollution to surface water and sewers are shown in tables 11 and 12. The corresponding formulae show how these emissions were calculated.

copper emission on urban roads to sewers =
*formation of particulates from brake linings * copper content of the particulates * share emitted to water =*
*formation of particulates from brake linings in table 7 * 10% * 12%*

Table 11: Emission of copper from brake linings on urban roads to sewers, (tonnes)

Year	Passenger cars	Vans	Lorries	Trucks	Buses	Special vehicles	Motor-cycles	Total
1985	4.1	1.1	0.44	0.16	0.14	0.17	0.04	6.1
1990	4.4	1.3	0.48	0.23	0.17	0.14	0.04	6.7
1995	4.0	1.2	0.27	0.31	0.12	0.09	0.05	6.0
2000	3.6	1.4	0.26	0.42	0.12	0.13	0.04	6.0
2005	3.8	1.7	0.24	0.46	0.12	0.19	0.05	6.6
2006	3.9	1.7	0.23	0.48	0.11	0.20	0.05	6.7

copper emission on rural roads and on highways to surface water =
*formation of particulates from brake linings * copper content of the particulates * share emitted to water =*
*formation of particulates from brake linings in table 8 * 10% * 2%*

Table 12: Emission of copper from brake linings on rural roads, to surface water, (tonnes)

Year	Passenger cars	Vans	Lorries	Trucks	Buses	Special vehicles	Motorcycles	Total
1985	0.38	0.01	0.05	0.02	0.01	0.002	0.000	0.43
1990	0.38	0.01	0.05	0.02	0.01	0.002	0.001	0.47
1995	0.38	0.03	0.04	0.02	0.01	0.003	0.002	0.49
2000	0.42	0.07	0.04	0.03	0.01	0.004	0.003	0.57
2005	0.44	0.09	0.04	0.03	0.01	0.005	0.003	0.61
2006	0.45	0.09	0.04	0.03	0.01	0.006	0.003	0.62

Emissions to highways is restricted by the increasing use of very open asphalted concrete (ZOAB) over the years to cover road surfaces. With this type of surface, a large proportion of the released particulates are trapped in the coarse pores on the road surface. To a large extent, this prevents diffusion of the particulates in the environment. Emissions of most metals are reduced by more than 90%, according to a CIW report [16].
This report provides an overview of all measurements performed over the years. The calculations are based on the assumption that where the roads are covered in ZOAB, emissions are reduced by 95%.

Table 13: ZOAB correction factors for metals

Year	ZOAB share on highways (in %)	ZOAB correction factor
1985	0.5	1.00
1990	10	0.90
1995	31	0.71
2000	53	0.50
2005	68	0.35
2006	71	0.33

copper emission on highways to the surface water =
*formation of particulate matter from brake linings * copper content of the particulate matter * share emitted to water =*
*formation of particulate matter from brake linings in table 9 * 10% * 2% * ZOAB correction factor*

Table 14: Emission of copper from brake linings on highways to surface water, (tonnes)

Year	Passenger cars	Vans	Lorries	Trucks	Buses	Special vehicles - light	Motorcycles	Total
1985	0.27	0.01	0.06	0.03	0.004	0.000	0.000	0.37
1990	0.32	0.01	0.05	0.04	0.003	0.001	0.001	0.43
1995	0.29	0.02	0.06	0.05	0.006	0.001	0.001	0.42
2000	0.25	0.04	0.04	0.04	0.004	0.001	0.001	0.38
2005	0.19	0.03	0.03	0.03	0.003	0.001	0.001	0.29
2006	0.18	0.03	0.02	0.03	0.002	0.001	0.001	0.27

In the same way, emissions of other metals can be calculated from the formation of particulates from brake linings, as shown in tables 6, 7 and 8 and the metal content in the particulates as shown in table 6 and the share emitted to the sewers or surface water, as shown in table 9. The results are shown in tables 15 and 16.

Table 15: Emissions of other metals from brake linings on urban roads to sewers, (tonnes)

Year	Cadmium	Nickel	Lead	Antimony	Zinc
1985	0.0006	0.006	0.6	0.6	0.6
1990	0.0007	0.007	0.7	0.7	0.7
1995	0.0006	0.006	0.6	0.6	0.6
2000	0.0006	0.006	0.6	0.6	0.6
2005	0.0007	0.007	0.7	0.7	0.7
2006	0.0007	0.007	0.7	0.7	0.7

Table 16: Emissions of other metals from brake linings on rural roads and on highways to surface water, (tonnes)

Year	Cadmium	Nickel	Lead	Antimony	Zinc
1985	0.00008	0.0008	0.08	0.08	0.08
1990	0.00009	0.0009	0.09	0.09	0.09
1995	0.00009	0.0009	0.09	0.09	0.09
2000	0.00009	0.0009	0.09	0.09	0.09
2005	0.00009	0.0009	0.09	0.09	0.09
2006	0.00009	0.0009	0.09	0.09	0.09

The emissions of brake particulates emitted as fine particulates to atmosphere are calculated by calculating 49% (table 9) on the total primary emissions as entered in tables 6, 7 and 8.

Table 17: Emissions of fine particulates (PM10) as a result of wear from brake linings to the atmosphere, (tonnes)

Year	Urban roads	Rural roads	Highways	Total
1985	251	105	90	446
1990	275	115	117	506
1995	247	119	145	511
2000	243	140	186	569
2005	270	150	199	619
2006	273	152	201	626

The total emissions of metals to atmosphere are calculated by combining the total emissions in table 17 with the metal content values set out in table 6.

Table 18: Emissions of metals as a result of wear from brake linings to the atmosphere, (tonnes)

Year	Copper	Cadmium	Nickel	Lead	Antimony	Zinc
1985	44.6	0.045	0.45	4.5	4.5	4.5
1990	50.6	0.051	0.51	5.1	5.1	5.1
1995	51.1	0.051	0.51	5.1	5.1	5.1
2000	5.69	0.057	0.57	5.7	5.7	5.7
2005	6.19	0.062	0.62	6.2	6.2	6.2
2006	6.26	0.063	0.63	6.3	6.3	6.3

8 Description of emission pathways to water

It is assumed that 60% of emissions to soil and water within urban areas enters the sewers indirectly and 40% goes into the soil. On rural roads and on highways 90% of emissions is assigned to the soil compartment, and 10% of emission is assigned to the surface water directly.

9 Spatial allocation

Emissions on rural roads and on highways are spatially allocated on the basis of data on traffic intensities and emissions on urban roads on the basis of the number of inhabitants, as recorded in the National Emission Inventory database

10 Comments and changes in regard to previous version

Various changes were made in 2006. Previously only fine particulates as a result of brake wear were calculated by the Task Force Traffic and Transport. The currently presented emission factors for emissions to the atmosphere are lower than the emission factors of fine particulates previously applied by the Task Force Traffic and Transport, because only 49% of emissions of brake particulates is considered to be fine particulate matter, whereas previously this figure was 100%. This report now also calculates emissions to soil and water.
In the methodology report of the Task Force Traffic and Transport, Klein et al. [4], the copper content measured in particulate matter collected outside the vehicle, as measured by Hildeman [13], was used. According to this inventory, the actual content of copper in brake linings is approximately 300 times higher. This prompted the calculation to be revised. In 2003, the calculated emission of copper from brake linings to atmosphere was approximately 66 tons Cu (in 2004, a total of 1350 tons of particulate matter was formed from brake linings. 49% of this amount is fine particulate matter emitted to atmosphere; 10% is copper). Until that time, the estimated amount of copper emissions was 0.5 tons Cu [17].

In 2008, the distribution among compartments within and outside urban areas was adjusted. It is now assumed that 60% of emissions within urban areas enters the sewers and 40% goes into the soil, whereas before it was assumed that all emissions enter the sewers. This is now equated in the same manner as the distribution of emissions due to tyre wear.

11 Accuracy and indicated subjects for improvements

The method used in Emission Inventory publications has been followed as far as possible in classifying the quality of information [18]. It is based on the CORINAIR (CORe emission INventories AIR) methodology, which applies the following quality classifications: CORINAIR uses the following quality classifications:

- A: a value based on a large number of measurements from representative sources;
- B: a value based on a number of measurements from some of the sources that are representative of the sector;
- C: a value based on a limited number of measurements, together with estimates based on technical knowledge of the process;
- D: a value based on a small number of measurements, together with estimates based on assumptions;
- E: a value based on a technical calculation on the basis of a number of assumptions.

In general, we can conclude that emission factors are based on a number of studies carried out in the Netherlands and internationally. There is reasonable to good consistency in the results of these studies. This means that we can classify the emission factors in category B. The activity rate is updated by the Traffic and Carriage task group regularly, and can be classified under category A. The division of emissions among individual compartments is very uncertain, so category D applies here. In this respect, there is again less uncertainty with emission pathways into water, so they are classed as B. Finally, the spatial allocation of emissions is fairly reliable, so it comes into reliability class B.

Element of emission calculation	Reliability classification
Activity rates	A
Emission factor for copper	B
Emission factors for other metals	D
Distribution among compartments	D
Emission pathways to water	B
Spatial allocation	B

12 Request for reactions

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