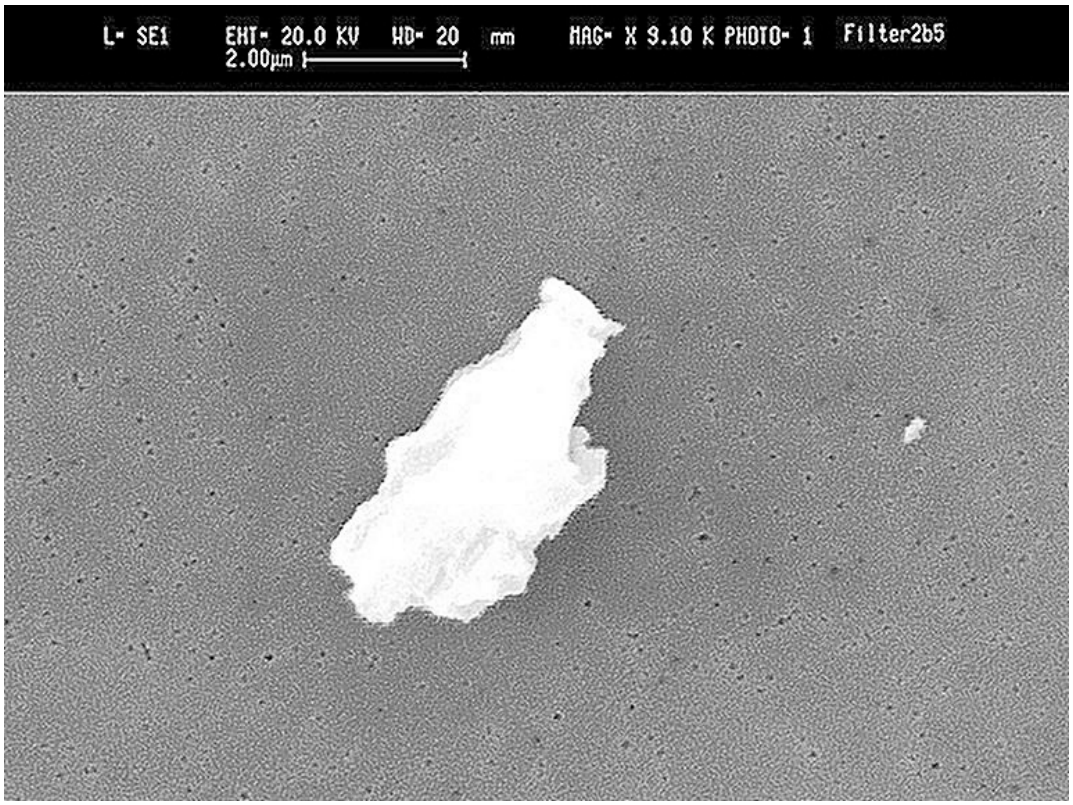
PARTICLES -
sources and dispersion in Stockholm

by

Anna Wallin



An aeroplane engine particle.

Department of Meteorology
Stockholm University

Master of Science thesis in Meteorology

Date **980520**
Supervisor **Christer Johansson**

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Foreword

This thesis work includes the development of an emission database for particulate matter and evaluation of model calculations for particles. The database and model may be used in air quality assessment and supervision by the municipalities within the counties of Stockholm and Uppsala.

The emission data base (edb) for particles, used for the dispersion calculations with the Gauss model, is administrated by the Air Quality Management Association for Uppsala and Stockholm counties. It is a non-profit organization. The members consists of about 30 municipalities and the two county councils. The activity is operated by the members in co-operation with the county administrative board in the county of Stockholm. The goal of the activity is to coordinate the air environment work in the two counties with the help of an air environment supervision system, consisting of among other things measurements, emission databases and dispersion models. Stockholm Air Quality and Noise Analysis runs the system today commissioned by the Air Quality Management Association.

Only some of the calculations that have been made are presented in this report. Dispersion calculations are also made for the SHAPE project -The Stockholm study on Health effects of Air Pollution and their Economic consequences-. The general aim of the project is to contribute to the development of a method for economic valuation of health effects of air pollution. The results should be possible to use in cost-benefit analyses for air pollution control measures, in investment analyses for the transport sector etc.

The more specific aims are:

- To estimate the current exposure to NO_2 and PM10 for the population of Stockholm.
- To chose appropriate dose-response relationships for health effects of NO_2 and PM10 from literature.
- To estimate the health effects of NO_2 and PM10 in Stockholm based on the above.
- To give economic valuations of health effects caused by changes in NO_2 and PM10 concentrations in Stockholm.

The SHAPE study was initiated by the National Institute of Public Health and is a collaboration of experts from:

- The allergy programme, National Institute of Public Health
- The Swedish Environmental Protection Agency
- The Department of Applied Environmental Health, Stockholm County Council
- The Department of Applied Environmental Science, University of Göteborg
- Department of Community Medicine, University of Lund
- Stockholm Air Quality and Noise Analysis at the Environment and Health Protection
- Environment and Natural Resources Division, Swedish National Road Administration

Abstract

An emission data base (edb) covering the county of Stockholm and Uppsala has been created with information on the emission of particulate matter. The main sources in the county of Stockholm are: Wood combustion (55%), Remaining heating and industry (19%), Working machines (12%), Road transport (7%) and shipping (6%) .

Diesel vehicles contribute with 77% to the direct emission from road transport.

Data from the edb has been used for particle dispersion calculations with a Gaussian model for the inner city of Stockholm during the winter of 1995-96. The calculations are made for resuspension, direct emissions from vehicles and the remaining sources. In the vicinity of roads resuspension is the main source of particles from November until May. The contribution lies between 2 and 5 $\mu g/m^3$. Residential heating (principally wood combustion) is the main particle source distant from roads. Its maximum contribution is between 2 and 6 $\mu g/m^3$ in residential areas.

The resuspension part of the traffic related particle concentration is between 30-50 % in the summer and autumn and 70-90% during the spring. It reaches its maximum in March/April right before the streets are cleaned.

The emission of particles due to resuspension was evaluated by comparing with direct emission and varying the parameters that control resuspension. The relation between resuspension and directly emitted particles at Hornsgatan in Stockholm was studied during two winter seasons and one summer season. It is clear that the precipitation is very important for the contribution from resuspension, especially the number of precipitation events. It is important that the instruments for precipitation measurements are good even for snow, since the maximum resuspension amounts occur during the winter season.

A comparison has been made between particle measurements in Stockholm and the background location Aspvreten. The correlation between hourly mean values is very small (0.23-0.52), due to the local traffic emissions. It is better if daily mean values are used, since the variations caused by local traffic are smeared out.

The correlation and relation between PM10 and PM2.5 in Stockholm has been compared to urban areas in Canada. Particle concentrations in Stockholm are much lower than in urban areas in Canada, although the correlations between PM10 and PM2.5 ($\approx$0.80) and relative amounts of PM2.5 and PM10 ($\approx$ 0.5) are quite the same.

Finally, Uncertainties in emission processes and model estimates and future model development is also discussed.

Contents

Introduction

The purpose of this study is to examine how much the resuspension affects the total amount of particles in Stockholm. It is also of interest to find out how much of the vehicle generated particles that are due to resuspension in relation to direct emission and to determine the main sources of uncertainty.

Particle emissions include different combustion processes, heating and energy production, car exhausts, industrial processes, dumps, storing of raw material etc. Particles can also originate from resuspended dust, from roads, or they can be of the natural kind from land and oceans. Different atmospheric processes transform SO_2 to sulphates and NO_x to nitrates, which can form particles too. Ammonium from farms is also an important source of particles, through the formation of ammonium sulphate and ammonium nitrate. Organic compounds can also be reformed to particles through photochemical reactions (Naturvårdsverket, 1990).

The composition and size of the particles vary with origin. The ones that are formed from, for example, wood combustion are small, while the natural ones are quite large.

Considering health effects, the smallest particles are the most dangerous ones. The smaller they are, the further down in the air passages they can get. There they irritate the lung tissues and can cause diseases like asthma and cancer. Concentrations above 20 $\mu g/m^3$ increase the illness among asthmatics at long time exposure (NUTEK, Naturvårdsverket, 1993).

The time of exposure is important, since low concentrations during a long time can give more serious effects than high concentrations during a short time.

In an ordinary indoor working environment the air is filtered. This filter normally let small particles through, which means that the outdoor pollution affects the air in the working premises. The efficiency of filters to remove particles from ambient air varies, but is usually between 30 and 70% (Kyrklund et al, 1998).

Rosendahl (1996) found that the total economic cost for Oslo, due to particle pollution, was 157 million Norwegian crowns in 1994. The cost can be divided into three parts: direct economic costs (for example lost workdays), indirect economic costs (for example that sick leave reduces the access of manpower), and reduced quality of life.

The size of the particle can be described in many different ways. The easiest, but not the most appropriate way is the projected area radius, r_p. It is the diameter of a circle having the same area as the particle silhouette. A measurement in this manner can not account for variation in particle density or shape.

The radius measured by the TEOM instrument, used in Stockholm (see Appendix B), is the equivalent aerodynamic size, r_e, which is more useful. The radius of a sphere having the same falling velocity as the particle and a density equal to 1 g/cm^3.

The ratio between r_p and r_e for particles collected from a sample of Pittsburgh air (Stern, 1976) ranges from 0.25 to 2.4 for most particles, but in an extreme sample is equal to 8.0 (See Figure 1).

Figure 1: *The ratio between the area radius and the equivalent aerodynamic radius was in an extreme sample equal to 8.0.*

Particles are often divided into two groups; fine, with a diameter < 2.5μm, and coarse, with a diameter > 2.5μm.

The fine particles are split up into three sub groups: the nuclei mode (≈5 nm), the Aitken mode (≈50 nm) and the accumulation mode (≈200 nm). The coarse mode has its maximum around 5 μm. The number of particles are largest in the Aitken and the accumulation modes, while the mass is largest in the accumulation and the coarse mode.

Two groups of particles will be studied here. The first group contains particles with an aerodynamic diameter of 10 μm or less, called PM10 (PM = Particulate mass), and the second group contains particles with an aerodynamic diameter of 2.5 μm or less, called PM2.5. For both groups, the dominating removal processes in the atmosphere is wet and dry deposition. Particles are added to the coarse mode by growth or direct emission, while sulphate is the main origin for the smallest ones (Wexler et al, 1994).

There are also other terms describing particles.

- Suspended particulate matter (SPM): All particles surrounded by air in a given, undisturbed volume of air.
- Black smoke (BS): Strongly light-absorbing particulate material suspended in the ambient air. By convention measured by light reflectance of a filter stain.
- Total suspended particulates (TSP): By convention the estimate of SPM concentration as provided by the classical US-High Volume Samplers.
- Fine particulate matter: Can be divided in PM10 and PM2.5.
- Thoracic fraction: The mass fraction of inhaled particles, which penetrate beyond the larynx.

The PM10 particles can be hypothetically divided into three groups, according to their geographical origin. The groups are small-scale (<5 km), meso-scale (50 km) and large-scale (500 km) dispersion. The substances in the groups are different depending on how far they are transported. In Figure 2 Filliger (1998) illustrates this for Switzerland. It would essentially be the same for Sweden.

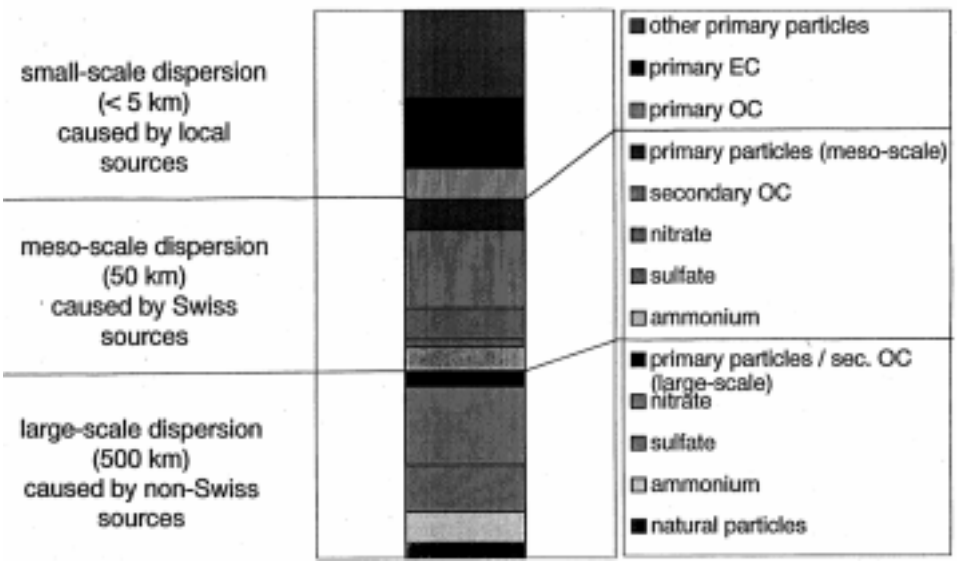


Figure 2: *The PM10 particles are hypothetically parted into three groups for Switzerland, according to their origin geographically seen (Filliger, 1998).*

Schaug et al. (1990) have measured the particle amount at four places in Oslo. Both fine and coarse mode particles were measured. Some substances were principally bound to the coarse fraction. These were for example aluminium, silicon, calcium, titanium, iron, strontium, zirconium and barium from mineral dust and chlorine from sea salt. In the fine fraction there was sulphur, nickel and vanadium from burned oil products and lead and bromine from soil. Potassium, copper and magnesium, for example, had the same concentrations in the fine and the coarse fractions. The most important sources for the fine fraction were oil and wood combustion and for the coarse fraction resuspension.

There is no limit value for particles in Sweden yet. There are, however, guide lines that say that the 24 hour average value should not be higher than 110 $\mu g/m^3$ as a 98 percentile, and the mean value should not be higher than 50 $\mu g/m^3$ in a winter season (October to March). There are also no legal requirements for the amount of particles a petrol car is allowed to emit. Diesel vehicles however are restricted not to emit more than a certain amount of particles per vehicle kilometre. The limits are:

Vehicle	Limit
Passenger car	0.08 g/vkm
Truck <3.5 tons	~ 0.15 g/vkm
Truck >3.5 tons	0.15 g/kWh

In Scandinavia PM10 is generally a factor of 10-50 higher than assumed levels at remote locations for example in the Arctic (Kyrklund et al, 1998). The highest concentration in Sweden is probably found in cities. During periods of long distance pollution transport from central Europe, the particle amount can get high (about ten times the usual background level) also outside these areas. Long distance transport is responsible for 40-60% of the total particle amount and about 15% of the amount near roads (Larssen et al., 1997).

The yearly mean particle concentrations of PM10 at Swedish background sites range from 3 to 12 $\mu g/m^3$ (Kyrklund et al, 1998). In Swedish cities, the mean concentration ranges from 10 to 40 $\mu g/m^3$, where the range 10-20 is found at roof level. Higher concentrations are found at

street level with intensive traffic, see values for Hornsgatan (page 21). The background mean concentration of PM10 at Aspvreten is approximately 11 μg/m^3 (Sjöberg et al., 1996).

Very few measurements are being made, especially long term measurements. Thus it is very hard to see if there is an increasing or decreasing trend for particles. It seems like the contents in Gothenburg have been halved since the middle of the 70´s (Brandberg, 1995), though it is very uncertain. No *significant* reduction seems to have taken place during the last 10 years.

EMISSION DATA BASE (edb)

A particle emission data base was created with information from the literature. The data in the edb is divided into three kinds of sources: point sources, area sources and line sources. A point source is for example a factory chimney, while an area source can be a petrol station. The main part of the line sources are roads.

Road transport

Vehicle emissions

The highest specific emission (i.e. per vehicle) of fine particulate matter comes from heavy duty diesel fuelled vehicles and the lowest from light vehicles with a three-way catalytic converter (TWC). As combustion is very often ineffective, large quantities of organic matter are emitted. International traffic with heavy diesel vehicles is increasing in Sweden. How this will affect the particle amount is not known. The gradual shift from leaded to unleaded petrol results in an almost proportional reduction in the concentration of lead in dust particles in urban environments (de Miguel et al, 1997).

Another important change that may affect the amount of fine particles is the new environmentally classified diesel fuel that was introduced in Sweden in 1991 (Kyrklund et al, 1998).

The vehicles are divided into three different groups, according to the EVA model (Effect calculations at road analyses), initiated by the National Road Administration (Hammarström, 1994).

Type of vehicle		Vehicle subset
Pc A	Passenger car	Without catalytic converter, 86 year model
Pc B		Catalytic converter, environmental class 3
Pc C		Catalytic converter, environmental class 1
T A	Truck	1986 year model
T B		Environmental class 3
T C		Environmental class 1
T/T A	Truck with trailer	1986 year model
T/T B		Environmental class 3
T/T C		Environmental class 1

Particles from diesel engines can be divided into three categories: Condensation nuclei from sulphates (which are dependent on the amount of sulphur in the fuel), volatile unburned hydrocarbons (created when the power on the engine is low), small graphite-like carbon particles (formed during high power on the engine). The last ones do not burn efficiently when they once are formed (Björklund, 1996).

Only 2-3% of the passenger cars in Sweden are diesel driven (Andersson, 1998). The share is probably larger in the city of Stockholm (≈5%), since almost all taxis are diesel driven and the taxi amount in Stockholm is quite large. The amount is increasing, since 12% of the new car sales are diesel cars. The amount of passenger diesel cars is much bigger in the rest of EC than in Sweden. This is partly due to beneficial taxes. As the taxes become more standardised within EC, the amount of diesel cars in Sweden will probably increase too. The mean emission from new diesel passenger cars are about 0.07 g/vkm (grams per vehicle kilometre) and 0.40 from old cars (calculations from EMV, Statens Naturvårdsverk and Vägverket). The total emission from diesel passenger cars in Stockholm is about two times the total emissions from petrol passenger cars (See Table 1). The emission factors for trucks and petrol passenger cars are calculated with the edb.

There are plans to lower the limit of emission of particles from diesel driven cars by the years 2000 and 2005. The new limits are not decided yet, but will probably contain limitations for the number and size of particles (Karlsson, 1998).

Type of vehicle	**Emission factor (g/vkm)**	**Emission in the city of Stockholm (tons/year)**	**Traffic work (Mvkm/year)**
Truck	0.3	42	148 (5.1 %)
Passenger car diesel	0.2	40	132 (4.5 %)
Passenger car petrol	0.01	25	2638 (90.4 %)

Table 1: *Diesel emissions from trucks and cars in the city of Stockholm.*

The emission factors can be compared to the ones used in the British model for West-Midlands (Hutchinson et al, 1996). There the trucks are assumed to emit 1.10 g/vkm i.e. a factor three higher than the value in Stockholm. Diesel passenger cars emit 0.18 g/vkm, similar to the value in Stockholm. The petrol passenger cars are divided into three groups. Cars without three way catalysts (TWC) and with leaded fuel, cars without TWC but with unleaded fuel and cars with TWC. They are assumed to emit 0.06, 0.02 and 0.01 g/vkm respectively.

The traffic is described in the edb by the size, the signposted speed, the share of heavy traffic, the number of stops per kilometer and the variation in time over the year, the week and the day. The emission factors for vehicles come from the EVA-model (Hammarström, 1994) and are based on the composition of the vehicle fleet, an estimated traffic rhythm and estimated contributions from cold starts.

When vehicles are first started it takes some time before the engine reaches its normal operating temperature. During this period the emissions are substantially higher than when the engine is hot. The problem increases the colder it is, though it can be reduced using an engine preheater (Björklund, 1996). This is true both for petrol engined vehicles without catalysts and those with three-way catalytic converters. Catalytic converters do not operate effectively until

they have reached their normal operating temperature. During driving in heavily congested traffic in cold weather the vehicles may not reach their full operating temperature throughout their journey (Hutchinson et al, 1996).

The additional emission due to cold starts in the model is large for small roads (a journey of about 10-20 km for each cold start) and almost zero for motorways (a journey of about 300 km for each cold start).

Measurements show that the emission of particles from heavy duty vehicles has decreased with 10-15% since the new environmental diesel fuel was introduced in 1991. Due to the use of cars with a catalytic converter and the technical development of diesel, the emissions from traffic are expected to decrease further. It has been estimated is that the total emission will decrease with about 80% by year 2020, compared with 1990 (Sjöberg, 1996).

Resuspension of road dust

Except the exhaust pipe discharge, the particles on the roads, that are already deposited, will also get resuspended. When the roadways are dry, this resuspension is important and approximately 10 times larger than the direct emission from the exhaust pipe. Measurements during wintertime in Oslo showed that the contribution from resuspension was about 3 g/vkm, when the roadway was dry. The direct emission from vehicles with TWC is about 5 mg/vkm and from heavy diesel vehicles up to 1.3 g/vkm (Sjöberg et al, 1996).

The origin and nature of street dust was investigated in Madrid and Oslo between 1990 and 1994 (de Miguel et al, 1997). Two distinct ”sources” could be identified:

- ‘Urban’ elements include exhaust and wear of tyres, breaks and weathering and corrosion of building material.
- ‘Natural’ elements include sanding, salting, wear to asphalt, transport into the road by the wind and by tyres.

Road dust deposit may come from mechanical wear of, and dirt on, vehicles (tyre and brake lining wear), debris from loads on vehicles, influx of soil material, wear of the road surface and sanding/salting of roads. The size of these particles is normally larger than 10 μm, but the contribution to the PM10 levels in air may be substantial. The emissions from brake wear is recently studied by Westerlund (1998).The consumed amount of brake wear is about 29 tons a year in the city of Stockholm. The emission factor for passenger cars is 6.25 mg/vkm, which is about the same as from direct emission. Buses and trucks emit 90 mg/vkm, which is about a third of the direct emitted amount. The brake wear emissions include all sizes of particles.

The wear from studded tyres is also an important source (10-25 g/km, Björklund, 1996), which increases with the moisture. It is 2-6 times larger for a wet road than for a dry (Folkeson, 1992). The roads dry up faster at high vehicle speeds than at low.

The wear from studded tyres also increases due to salting, since the street remain wet for longer periods. It also increases with vehicle speed (v^2), the power on the shaft, the tyre pressure and decreasing temperature. As the temperature decreases the tyre becomes less elastic, with the result that the roadway gets more worn (NTNU, 1997).

The resuspension due to the vehicles without any influence from meteorological factors can be calculated with equation 1:

$$E_{resusp}^{vehicle} = \frac{\%cars}{100} \cdot 6.7 \cdot \left(\frac{v}{110}\right)^{2} + \frac{\%trucks\ /\ buses}{100} \cdot 6.7 \cdot \left(\frac{v}{110}\right)^{0.5} \qquad \textbf{eq. 1}$$

The emissions, due to resuspension, with consideration to meteorological influences are:

$$E_{resusp} = E_{resusp}^{vehicle} \cdot fqe \qquad \textbf{eq. 2}$$

The largest resuspended particles are deposited on the roadway or within about ten meters away from it (Folkeson, 1976; Lygren & Gjessing, 1984; Lygren et al, 1984). Only a small fraction of the particles are transported farther away from the road (NVF, 1992). Particle size, topography, wind speed, the design of the road and the structure of the vegetation are very important for how the particles will be dispersed. The amount also decreases logarithmically with height.

A paving more hard-wearing and new types of studded tyres will endure these discharges. Concrete as paving hold about 2-3 times as long as asphalt does, but the concrete particles are finer and therefore more dangerous (NTNU, 1997).

Emissions from ships

Ships emit about 2 000 tons of particles in Sweden each year. Cargo ships are responsible for about 15% of the total emissions. Ferries are responsible for about 23% and pleasure boats for the rest (Burman et al, 1997).

The emission factors for ferries are assumed to be the same as for an old type of truck with a trailer. The emission factor for merchant ships is taken from Skogö (1992).

Most of the pleasure boats use two-stroke engines, which do not combust more than 75% of the fuel (Burman, 1997). Sailing boats usually use diesel engines. They emit about 5% of the total particle emissions from pleasure boats, while two-stroke engines emit about 85% (See Table 2).

	The county of Stockholm (ton/year)	**The city of Stockholm (ton/year)**
Sailing boats	2	<1
Motor boats	103	15
Total:	105	≈16

Table 2: *The total emissions of particles in Stockholm city and county.*

Since the emissions take place below water surface there might be some scavenging in the water, which means less emission to the air.

The emissions from pleasure boats occur during daytime in the summer months. The ferries to Gotland, Finland and to the Baltic States are included in the ferry emissions. The emissions are described for the territorial waters.

Motorized tools and working machinery

Emissions from motorised tools, such as air compressors, snowmobiles, power saws and power lawn mover, are not regulated by law. These diesel engines are often running during long periods. Therefore they may emit significant amounts of particles, for example at road and house construction sites (Björklund, 1996). Since the geographic position varies during

the year, especially for the ones used at roadworks, they are not included in the dispersion calculations.

Working machines include, among other things, excavators. Since no emission factor can be found, the same is used as for diesel engines in old type trucks.

Residential heating

Wood combustion

Emissions from wood combustion are probably more uncertain than traffic emissions. The emissions depend on how the wood is combusted. The emissions vary from 200 to 1500 mg/MJ (Kyrklund et al, 1998). There is also a large uncertainty of the total use of wood as fuel for small-scale heating. Particles that originate from wood combustion are more toxic than traffic related ones (Sjöberg, 1996).

Although the amount of wood-heated houses is relatively small in urban areas, they may account for as much as 25% of the total wood consumption. The total use of wood for domestic heating in Sweden has been estimated to be from 2.1 to 2.8 Mtons per year in 1994, but could be 3-7 times higher. It is comparable to a production of 12 TWh (Kyrklund et al., 1998). In the edb for Stockholm the emissions are allocated to residential districts (Ekström et al, 1995).

Five to six percent (5-6%) of the boilers in Sweden are environmentally authorized (NUTEK, Naturvårdsverket, 1993) and 39% are connected to an accumulation tank. The big difference between accumulated combustion (40 mg particles/MJ) and direct combustion (about 900 mg particles/MJ) depends on the combustion temperature. The temperature in direct combustion is too low to burn the wood completely, while accumulated combustion can occur at a higher temperature.

Only 42% of the newly installed boilers are in accordance with environmental recommendations.

Heating oil

The emission factor for houses heated with an oil boiler is assumed to be 20 mg/MJ. The emissions are allocated to residential areas (Ekström et al, 1995).

Construction dust

Construction and maintenance work, including new building construction, demolition and redevelopment, major building refurbishment and routine maintenance is another source of dust. Even quite modest operations such as rubbing down paintwork prior to redecoration produces considerable quantities of fine dust. Dust is also produced as a result of highway maintenance and other civil engineering works (Hutchinson, 1996). Street dust samples collected in the proximity of buildings which were being renovated show high concentrations of Ca, suggesting that cement dust is a major component of street dust in these locations (de Miguel et al, 1997). Paint flakes from the facade are very likely responsible for the unusually high lead content, while corrosion of metal structures can explain the anomaly for some of the other trace elements. Since the geographic position of the emissions vary, they are not included in the dispersion calculations.

Air traffic

The discharge from aeroplanes consists of two kinds of very small particles (<<2,5μm), soot and engine wear (Ström, 1998). Particle emissions from aeroplane engines has been studied by (Petzold, Schröder). The measurements were performed in the exhaust of a Rolls Royce/SNECMA M45H Mk501 engine, which emits about five times more particles than most modern engines. The emissions vary only by a factor less than two at between 11% and 70% power, which indicates that the variations of the emissions during a flight, except take-off, are relatively small. The emission index (g total coal/kg fuel) is at least ten times higher for take-off than for the rest of the flight (Ström, 1998). The total fuel consumption for the LTO-phase (Landing and take-off) at Arlanda and Bromma has been calculated by Anette Pålsson at FFA (The aeronautical research institute of Sweden).

In the edb air traffic is described by a variation during the day, the week and the year. Only Arlanda and Bromma are described (Ekström et al, 1995).

Summary of information in the emission data base

	Type of source	Emission factor	Source
Vehicle	line	0,009-0,381 g/vkm***	Hammarström (1994)
Ferry	point	0,381 g/vkm*	Hammarström (1994)
Pleasure boat	area	2,053 g/kg fuel	Naturvårdsverket 3993
Merchant ship	area	0,638 g/kg fuel	Skogö (1992)
Cargo ship	area	0,551 g/kg fuel	Skogö (1992)
Wood burning, residential heating	area	900 mg/MJ	Ehrenberg et al (1993)
Heating oil, residential heating	area	20 mg/MJ	STOSEB, 1992
Central heating plant	point	**	
District heating	point	**	
Working machine	area	0,7 g/kg fuel*	Hammarström (1994)
Working machine, agricultural	area	173,6 g/kg fuel*	Hammarström (1994)
Air traffic	area	0,51 g/kg fuel	Petzold, Schröder

* The value has been calculated by using the relation between particles and NO_x in the EVA-model. (PM10= NO_x *73,4/1741,5)

** A specific emission factor for each source is used.

***To be compared to the emission factors used in the British model for West Midlands (Hutchinson, 1996). They are 0.01-1.10 g/vkm.

The total emission of particles from different sources 1996.

Source	Discharge from the county of Stockholm (tons/year)	Discharge from the city of Stockholm (tons/year)
Vehicles	220	68
Ferries	44	12
Pleasure boats	100	16
Merchant ships	24	0.4
Cargo ships	24	0.1
Wood burning, residential heating	1 892	324
Heating oil, residential heating	310	166
Central heating plants	58	33
District heating	183	108
Industrial processes	84	20
Working machine (incl. agricultural)	397	150
Air traffic	26	1.2
Total	3 362	898.7

The corresponding emissions from vehicles in Sweden are calculated to 8 800 tons a year. Ships emit about 2 000 tons particles a year in Sweden of which 28.5 tons are emitted in the city of Stockholm. The county of Stockholm is responsible for about 20% of the total emissions (8 600 ton/year) from wood combustion in Sweden.

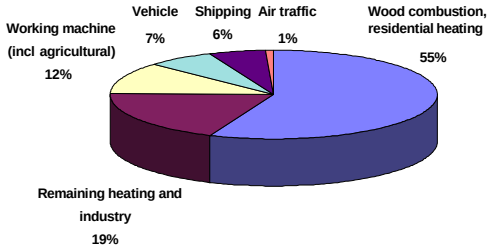


Figure 3: *Emissions from the county of Stockholm.*

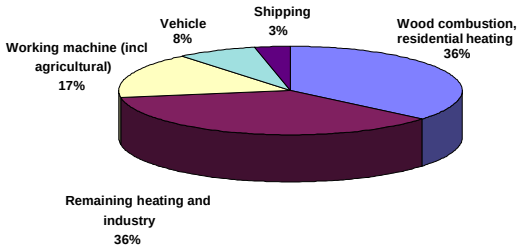


Figure 4: *Emissions from the city of Stockholm.*

The main source of particles in Stockholm is the wood combustion with about 300 tons per year, which is equal to the emissions from the remaining heating and industry. Direct emissions from vehicles do not contribute with more than 7-8%, but the resuspension is not included.

The SMHI resuspension model

In the beginning of the 1990´s the Swedish Environmental Protection Agency initiated the development of a resuspension model for PM10 calculations. The work was done by researchers at SMHI. All information about the model is taken from the paper 'Calculations of PM-10 concentrations in Swedish cities - Modelling of inhalable particles.' (Bringfeldt et al, 1997). The model including parameters can be found in Appendix A.

Model calculations for a street in Stockholm

In order to evaluate the model and compare relative importance of resuspension and direct emission, Hornsgatan was studied as an example. The meteorological parameters have been measured in Högdalen, except the relative humidity and the precipitation, which were measured at Torkel Knutssons street in Stockholm and in Botkyrka south of Stockholm. The air density, the albedo (=0,2) and the cloud amount (=0,6) have been set to constant values in order to simplify.

The dust amount due to traffic is almost zero during the summer months and increases during the winter. It reaches its highest values in February-April before the roads are cleaned. The cleaning day, and the day when the studded tyres are taken off, are set to the 1st of May in this model. This can give too high values during the spring, since the studded tyres are sometimes taken off earlier and the streets may be cleaned more than once a year.

To calculate the emission factor for resuspension, except meteorological influence equation 3 is used:

$$E_{resusp} = \frac{\%cars}{100} * \left(E_{resusp-cars}\right) + \frac{\%trucks\ /\ buses}{100}\left(E_{resusp-trucks/buses}\right) \qquad \textbf{eq. 3}$$

where

$$E_{resusp-cars} = 6{,}7 \cdot \left(\frac{v}{v_0}\right)^2$$

$$E_{resusp-trucks/buses} = 6{,}7 \cdot \left(\frac{v}{v_0}\right)^{0{,}5}$$

v_0=110km/h, since the resuspension is assumed to be equal (= 6,7 g/vkm) for cars and trucks at that speed (Claiborn et al., 1995). These empirical relationships were obtained on two-lane roads with less than 10 000 vehicles a day.

For Hornsgatan, the mean velocity is 45 km/h, 92.8% of the vehicles are passenger cars and 7.2% are trucks/buses. The daily traffic is about 33 000 vehicles, which indicates that the emission factor for resuspension could be even higher and therefore a source of error, since it is based on measurements on roads with less than 10 000 vehicles a day. The resuspension, except meteorological influence, is a constant value:

$$E_{resusp}^{vehicle} = 0.928 \cdot 6.7 \cdot \left(\frac{45}{110}\right)^2 + 0.072 \cdot 6.7 \cdot \left(\frac{45}{110}\right)^{0.5} = 1.35 g\ /\ vkm \qquad \textbf{eq. 4}$$

The emissions, due to resuspension, with consideration to meteorological influences are:

$$E_{resusp} = E_{resusp}^{vehicle} \cdot fqe \qquad \textbf{eq. 5}$$

fqe describes the impact of sanding/salting, tyres and meteorology.

The direct emissions are calculated for three different types of passenger cars and three different kinds of trucks/busses, also described in the emission data base:

Type of vehicle	Vehicle subset	Per cent of the cars/trucks

Pc A	Passenger car	Without catalytic converter, the vehicle fleet of 1986	45%
Pc B		Catalytic converter, environmental class 3	35%
Pc C		Catalytic converter, environmental class 1	20%

T A	Truck	The vehicle fleet of 1986	55%
T B		Environmental class 3	25%
T C		Environmental class 1	20%

$$E_{direct} = \frac{\%cars}{100} \cdot \left(exhaust_{PcA} \cdot \frac{\%PcA}{100} + exhaust_{PcB} \cdot \frac{\%PcB}{100} + \ldots \right) + \frac{\%trucks / buses}{100} \cdot \left(exhaust_{LbA} \cdot \frac{\%LbA}{100} + \ldots \right)$$

This equation gives a constant direct emission per vehicle kilometer at Hornsgatan:

$$E_{direct} = 0{,}928 \cdot (0{,}038 \cdot 0{,}45 + 0{,}025 \cdot 0{,}35 + 0{,}009 \cdot 0{,}20) + 0{,}072 \cdot (0{,}381 \cdot 0{,}55 + 0{,}289 \cdot 0{,}25 + 0{,}114 \cdot 0{,}20) = 47{,}6 mg / vkm$$

All information about Hornsgatan comes from measurements by the EHPA[1] Stockholm (Slb-analys). Emission factors come from the EVA-model (Hammarström, 1994).

The amount of sand/salt in the model is increased by 5% under the following conditions:

1. if there is no precipitation
2. the temperature is between -2°C and +1°C
3. the street is considered as moist, during at least one hour.

The amount is decreased every hour if precipitation occurs, and set to zero on the 1st of May as the streets are assumed to be 'cleaned'. The tyre and pavement amount is increased once a day. In summer the increase is 0.1% and in winter 1%, due to the studded tyres. It is also decreased due to hourly precipitation.

The resuspension has been calculated for two winters (October 1 till March 31), 1994-95 and 1996-97, and for one summer (April 1 till September 30), 1995. In 1994 there was a lack of meteorological data between November the 11th and December the 9th.

[1] Environment and Health Protection Administration

Results

The impact of sanding/salting, tyres and meteorology is described by the factor fqe (See equation 5). It is multiplied by the emission factor for resuspension which gives the resuspension in grams per vehicle kilometre:

$$E_{resusp}^{vehicle} = 0.928 \cdot 6.7 \cdot \left(\frac{45}{110}\right)^{2} + 0.072 \cdot 6.7 \cdot \left(\frac{45}{110}\right)^{0.5} = 1.35 g / vkm$$

The resuspension results are presented in three ways in this report. The fqe-factor, the amount of resuspension and the amount of direct emission from vehicles and finally the relation between the resuspension and the direct emission is presented.

Winter 1994-95

As expected, the resuspension (in Figure 4) is small in the beginning of the season, since neither the sanding/salting nor the tyre-caused resuspension have accumulated enough material yet. (Since these two parameters are set to zero on October the 1st). The maximum is reached at the end of the calculation period, or as can be seen later in the summer calculations, on the 1st of May, right before the cleaning takes place. Every time sanding/salting takes place the road dust amount is increased with 5%. This means that each occasion contribute with a larger amount of sand/salt the later it is in the season. Highest resuspension occur during dry periods.

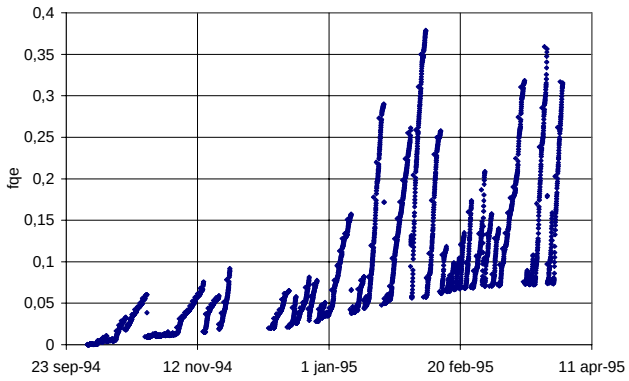
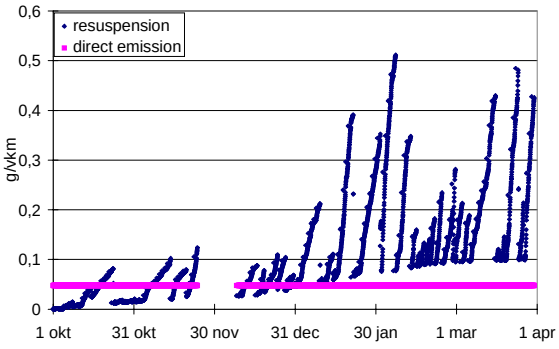


Figure 4: *The fqe-value during the winter 1994-95.*

The longer a dry period is, the higher the resuspension will get. Less than 0.2 mm rain in an hour is enough to reduce the particle resuspension completely. This means that every substantial increase depends upon the length of the dry period, and every substantial decrease depends on occurrence of precipitation. The number of precipitation occasions are more important than the amount of precipitation at one specific occasion. The total amount of precipitation was 229 mm during this period. It was distributed in 331 hours, and during 16 occasions more than 2 mm fell in an hour. The maximum amount was 5.4 mm in one hour.

When SMHI used this model for calculations in Norrköping and Gothenburg the resuspension was high already in the beginning of December. Measurements show that the increase starts late in January or in the beginning of February. In these calculations for Stockholm, the high values starts in the beginning or middle of January, which seems more realistic.



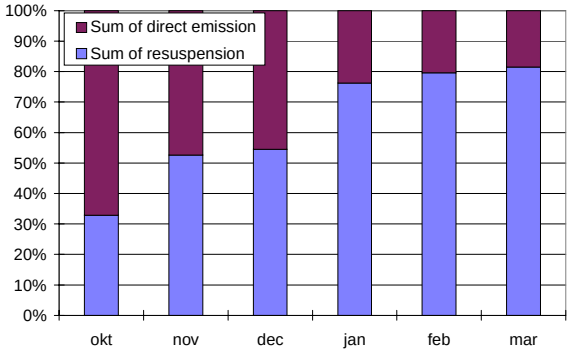


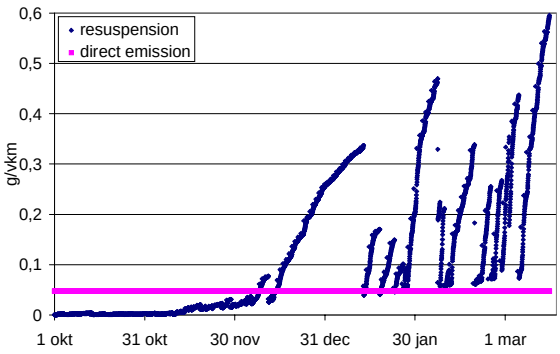
Figure 5: *The resuspension and direct emission during the winter 1994-95.*

Figure 6: *The resuspension and direct emission in percent, winter 1994-95.*

The direct emission is very small compared to the resuspension during the late winter season (Figure 5). According to Figure 6 resuspension is responsible for more than 50% of the road transport related particles from November to March. From January to March it is close to, or even more than, 80%.

Winter 1996-97

The resuspension of particulate matter for the winter 1996-97 is higher compared to the winter 1994-95. In 1994-95 the maximum values were about 0.5 g/vkm, this year it is about 0.7 g/vkm. The increase starts early in the season (see Figure 7). A long period with high resuspension began already in the middle of December. It was caused by a long period without precipitation.



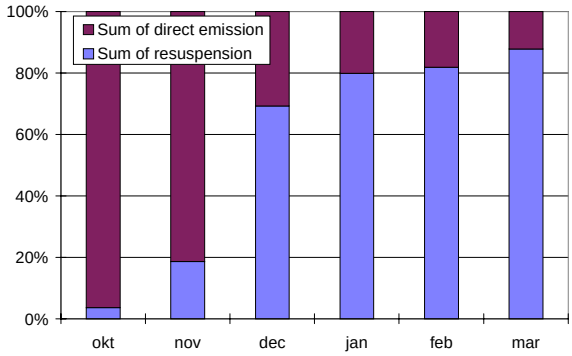


Figure 7: *The resuspension and direct emission during the winter 1996-97.*

Figure 8: *The resuspension and direct emissions in percent, winter 1996-97.*

The total precipitation amount this winter was 179 mm. It fell during 262 hours, with more than 2 mm per hour 12 times. That is 50 mm and 69 precipitation hours less than during 1994-95. The average amount of precipitation during these 262 hours was 0.68 mm/precipitation hour, compared to 0.69 mm/precipitation hour 1994-95, which is not a big difference. This shows that it is not the specific amount per precipitation hour that is important for the resuspension, since the maximal resuspension value is much higher 1996-97 than 1994-95. It is rather the total number of precipitation days.

During the first two months the resuspension is very low (see Figure 8) in comparison with 1994-95, although the precipitation was small too. For the rest of the period the resuspension is high, due to less precipitation occasions this season. The reason for the low resuspension

values in October is the high temperature, see Figure 9. It was never slippery and no snow fell, which meant (according to the model) that no salting/sanding was needed.

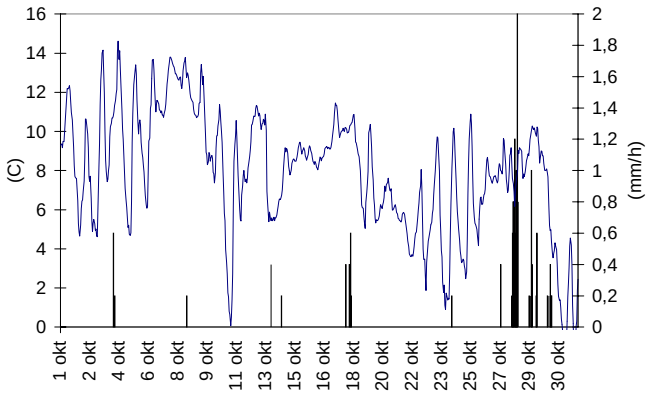


Figure 9: *Rain and temperature in October 1996.*

The first time the conditions for sanding/salting and the use of studded tyres were fulfilled was on November the 11th at 1 a.m. The low resuspension values in November are explained by the large amount of precipitation occasions (Table 3).

Month	Precipitation (mm) 1994-95	Number of sanding/salting occasions	Precipitation (mm) 1996-97	Number of sanding/salting occasions
October	51.2	1	16.6	0
November	14.8	1	79.2	3
December	41.4	5	28.0	3
January	22.8	8	5.6	4
February	59.9	10	38.4	4
March	38.9	6	11.2	1
Total	229	31	179	15

Table 3: *Precipitation and fqe values, winter 1994-95 and 1996-97.*

Summer 1995

There are only very small differences between the months in Figure 10, since there is no sanding/salting or use of studded tyres. The small variation is due to differences in the precipitation. The total amount of precipitation is 391 mm, divided into 212 hours. During 46 hours it fell more than 2 mm rain. The small resuspension values in May are due to the fact that the streets are assumed to be swept on the 1st of May, at the same time as the studded tyres are taken off. Because of that the model parameters are put to zero the 1st of May.

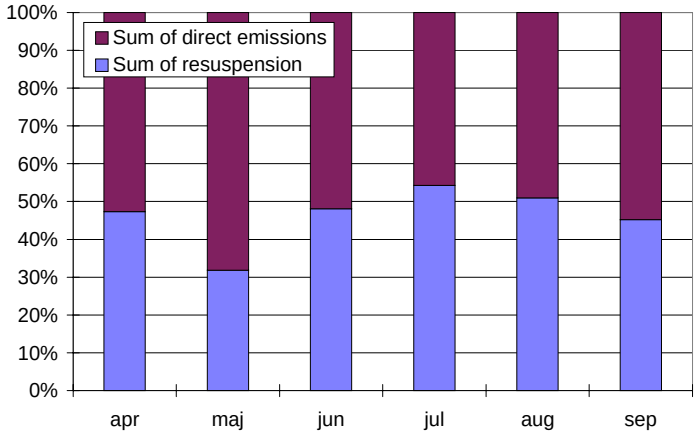


Figure 10: The resuspension and direct emissions in percent, summer 1995.

The importance of precipitation

The precipitation measurements are made both at Torkel Knutssons street (Summer 1995) and in Botkyrka (Winter 1994-95 and Winter 1996-97). This can be of importance since the instrument at Torkel Knutsson street is heated so that the snow melt in the winter. This is not the case in Botkyrka. Due to that snow is not registered as precipitation until it has melted, which can result in large errors. The reason for using the measurements from Botkyrka anyway, is that that there are big gaps in the data from Torkel Knutsson and that it has given incorrect values (like negative amounts) during some periods.

The precipitation in the calculations has been varied in four different ways to examine how sensitive the model is. Precipitation from the years 1993-94 (measurements from Botkyrka), 1994-95 (measurements from Botkyrka), 1995-96 (measurements from Botkyrka) and 1996-97 (measurements from Torkel Knutssons street) have been used.

The first conclusion that can be made is that precipitation is very important. The variation of the resuspension follows the precipitation completely. As an example the model was run using meteorological data for the winter season 1994-95, but with precipitation from 1995-96, will be discussed. This winter was fairly unusual, since the total precipitation amount was only 59 mm divided into 142 hours. There did not fall more than 1.8 mm in one hour.

The season was divided into four parts without any precipitation. These were:

- 951210 16:00 - 960109 15:00
- 960110 17:00 - 960215 15:00
- 960217 06:00 - 960226 13:00
- 960301 13:00 - 960327 16:00

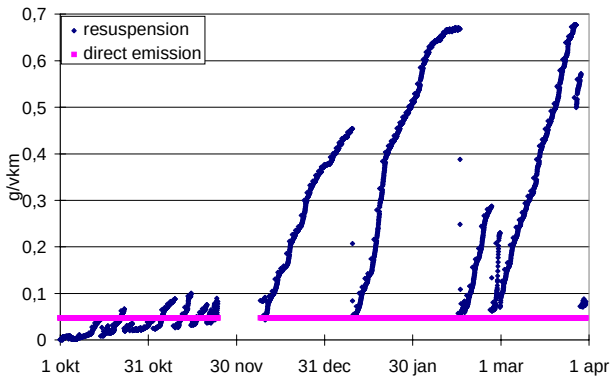


Figure 11: *The resuspension and direct emission for the winter of 1994-95 with the precipitation from the winter of 1995-96.*

As can be seen in Figure 11 resuspension grew to high values during these periods.

Since the importance of the precipitation is now established, some conclusions can be made. The precipitation measurements are quite good when the precipitation comes as rain. When snow falls, the measured amount may be too small. This means that the precipitation is a large source of error, since the major part of resuspension occurs in the cold season.

Variation of the parameters

To do a complete examination of the influence of the model parameters on the results, all parameters should be varied at the same time in some random way. This has not been possible. Instead a number of parameters have been varied once at the time.

The increase or decrease of the resuspension due to the parameter variation is small for the majority of the parameters. The parameters that cause a variation of importance are:

- **resuspa**/**resuspb** are factors for the relation between studded tyres and sanding/salting. This means that **resuspa** is the share of tyre and road particles in the total road dust depot, while **resuspb** is the share of sand/salt particles. Their sum usually equals unity and the assumption in the model is that there are similar contributions from sanding/salting and tyres. The relation between them could be determined more carefully with help of tracers.
- **k** is an empirical factor. It affects the hourly reduction of the amount of material in the street dust and on the street surface. This indicates that the affect of **k** on the resuspension is large only when the ground is wet. SMHI has found **k** to be -0,075 by studying particle concentrations during several days without precipitation.
- **decay** affects the hourly relative decay of the dust depot due to reduction by resuspension. If **decay** is large the reduction of the resuspension due to the moisture is large, and if it is small the reduction is small. SMHI has used different values on **decay** (0.01, 0.003, 0.002, 0.0015, 0.001 and so on). It has been varied to make the model fit the measurements made in Norrköping and Gothenburg.
- **anskid** is the accumulated number of days with slippery conditions- where sanding/salting is assumed to be made- during the winter season. SMHI has normalized **anskid** with 20, except when the highest value of **decay** (=0,01) has been used. Then the normalization was 10. A normalization with 20 means that every sanding/salting occasion increase the road dust amount with 5% (1/20). In the same way the normalization of 10 means an increase with 10% (1/10).

Parameter	Standard values[2]	Temporary value	Percent change in mean resuspension	Percent change in max. resuspension
resuspa/ resuspb	0.5/0.5	0.7/0.3	+4.4%	-0.6%
resuspa/ resuspb	0.5/0.5	0.3/0.7	-4.4%	+0.6%
k	0.075	-0.15	+39.0%	+39%
k	0.075	-0.0375	-24.9%	-34%
decay	0.001	0.01	-36.8%	-38%
Normalization of anskid	20	5	+30.6%	+13%
Normalization of anskid	20	15	+8.8%	+13%

Table 4: *The variation of calculated resuspension caused by the parameters used in the model.*

The maximum value of **resuspa** and **resuspb** is 1. Since the resuspension increase as **resuspa** is increased and **resuspb** is decreased and on the contrary, it seems like resuspa, and therefore the share of tyre and road particles, is more important to the resuspension than **resuspb**.

k is increased and decreased with a factor 2. As **k** decreases the hourly reduction decreases and the resuspension increases.

decay is increased 10 times to 0.01, since it is one of the values used by SMHI when they were evaluating the model. Since the hourly decay of the dust depot increases, the resuspension decreases.

As the normalization of **anskid** changes from 20 to 5 and 15, every sanding/salting occasion increase the road dust with 20% and 7% instead of 5%, which increases the resuspension.

As a conclusion it can be said, that even though the variation of the parameters changes the amount of resuspension a lot, and is adjusted to get the model to fit into reality, it is good quality precipitation measurements and the number of sanding/salting occasions that are most important for the model results and therefore the largest source of errors.

Measured concentrations of PM10 and PM2.5 in Stockholm and comparison with other sites

Very few particle measurements have been made, since particles have not been considered as harmful before. It is now established that particles cause diseases like asthma and cancer, and measurements and calculations are as necessary as ever. Most of the measurements are made of PM10 particles, though the ones smaller than 2.5 μm are more harmful. One of the largest particle sources is road dust.

[2] The values of the parameters used in the model were obtained by SMHI when they matched their calculations with results from measurements in Norrköping and Gothenburg.

A Dutch study

Janssen et al (1997) studied daytime PM10, PM2.5 and black smoke concentrations. Measurements were made simultaneously near a busy road and at a background location in two cities (Wageningen (just PM10) and Arnhem) in the Netherlands. Eight hour averaged samples were taken on weekdays from 10 a.m. to 6 p.m. or from 8.30 a.m. to 4.30 p.m. Sites were chosen distant from other local particle sources such as unpaved roads, construction work or industrial sources, so that no local sources other than traffic were present. The differences found are therefore caused by traffic.

The sampling equipment was located on the pavement, within 0.5 m from the edge of the road. In Wageningen, the background site was in a meadow, on the outskirts of the town about 2 km away from the street site and about 500 m away from the nearest road (rural background). In Arnhem, the background site was located in the city centre in the courtyard of the police station, 200 m away from the nearest busy road and about 1 km from the street site (urban background).

For PM10 the average difference between street and background concentrations was 7.2 $\mu g/m^3$ in Wageningen and 12.7 $\mu g/m^3$ in Arnhem; for PM2.5 the average difference was 7.9 $\mu g/m^3$. The PM10 and PM2.5 concentrations at the street site were on average 30% higher than the corresponding background concentrations.

The same street/background ratio but a smaller mean absolute difference were found for PM2.5 when compared with PM10. This is consistent with a larger contribution of resuspended road dust to the coarse fraction of PM10. Significantly higher iron and silicon concentrations in PM10 samples at the street sites as compared to the background locations, also indicates a contribution of suspended road dust to the coarse fraction of PM10 particles.

The greater part (83%) of the difference in PM2.5 concentrations between the two sites (7.9 $\mu g/m^3$) can be attributed to a difference in elemental carbon (EC) (like graphite) concentrations, emphasizing the contribution of diesel vehicles to traffic emissions of fine particles.

About 50% of the difference in PM10 concentrations could be explained by a difference in EC concentrations. The mean ratio between PM2.5 and PM10 in Arnhem was 0.55.

Vanadium was selected as a tracer for oil combustion, sodium for marine aerosol, silicon and iron as soil-related elements, potassium for wood burning and sulphur for long distance transport. In addition, zinc, copper and magnesium were selected though they may have several sources, both crustal and anthropogenic.

For vanadium, sodium, and sulphur, street site concentrations were about equal to background concentrations. Potassium, magnesium and zinc concentrations were slightly higher at the street sites. The largest differences were found for silicon, iron and copper.

PM2.5/PM10 ratios of less than 0.25 were found for silicon, sodium, iron, copper and zinc; ratios above 0.50 were found for vanadium, magnesium and sulphur.

In addition to lead and bromine, Huang et al. (1994) suggested antimony and zinc as potential marker elements for vehicle emissions. In this study, zinc concentrations at the street sites were only slightly higher compared to background concentration, indicating the dominance of resuspension rather than an anthropogenic source.

A significant positive correlation between particle mass and elemental concentrations was found for most elements. This is probably due to the fact that unfavourable meteorologic conditions lead to increased concentrations of most air pollution components.

In the Netherlands, the highest concentrations of anthropogenic pollutants generally occur with easterly wind directions, due to both the presence of source areas and a higher prevalence of episodic meteorological conditions (like dry air) than at other wind directions. The higher PM10 concentrations measured in Arnhem could be explained by less frequent occurrence of atmospheric conditions that are associated with low particle concentrations.

A Swedish study

The measurements that have been done with TEOM® instruments (See Appendix B) in Stockholm are not made especially for this comparison, and are therefore made during both day and night. PM2.5 measurements are only made during April 1998. Furthermore the background measurements are made at Aspvreten, which is located about 70 km south of Stockholm. The urban measurements are made at street level at Hornsgatan in the city of Stockholm from April to May 1996. The Aspvreten data is also compared with measurements from Rosenlundsgatan (also in the city of Stockholm) during February and March, when the resuspension is expected to have its maximum value. These measurements are made at roof level, and are thus lower than measurements at street level.

The correlation between roof level and background measurements of PM10 was considerably higher than the correlation between street level and background measurements. The roof level values were also less variable than the street level values. The average difference between street and background concentrations was 24.5 $\mu g/m^3$. The concentration of PM10 in the street was 6.1 times the background value. The difference between the concentration at roof level and in Aspvreten was 4.0 $\mu g/m^3$. The concentration at roof level was 1.7 times the background value.

The value mentioned in the Dutch report was 1.3. It can be compared to 6.1 times the background value in these measurements. The main reason for the big difference is probably that our background site is situated further out on the countryside, and is therefore less affected by the pollution from urban areas.

The average difference between street and background concentrations for PM2.5 was 8.9 $\mu g/m^3$. The street level values were 2.9 times the background values.

The first thing that strikes you when comparing the PM10 measurements is the co-variation of the daily averages for the measurements, independent of measuring location. Especially the extreme values. For example, the measurements at Hornsgatan show that almost every peak value also correspond to an increase at Aspvreten.

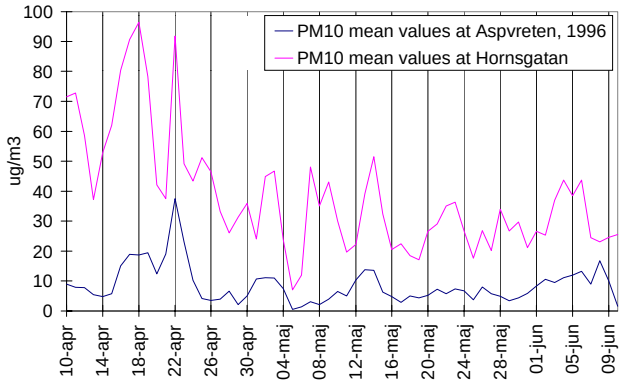


Figure 12: *PM10 values at Aspvreten and Hornsgatan, April and May 1996.*

The values at Aspvreten show much less variation than the city measurements since the main source is long-range transport. The highest background particle amounts occur during southerly winds due to long-range transport from central Europe.

The large variations at Hornsgatan depend mainly on the daily traffic. Precipitation scavenging is the most important loss process for PM10 particles. A rapid decrease in concentrations of PM10 may be seen in Figure 13 as precipitation occur. One millimetre rain (or wet snow) is enough to make the particle amount decrease a lot. The decrease in concentration is also due to the moisture of the street, which cause less resuspension of road dust.

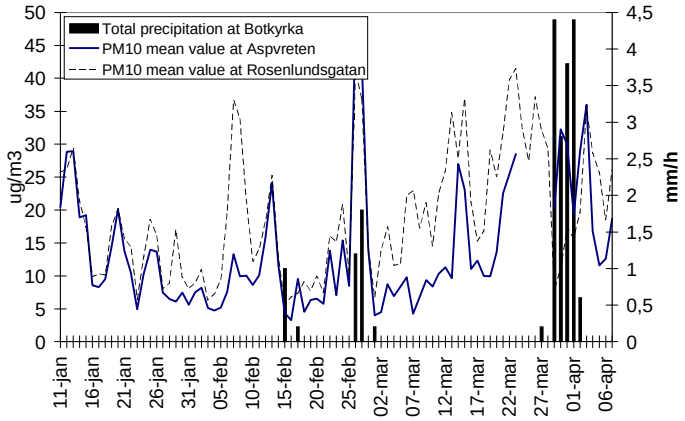


Figure 13: *PM10 values at Aspvreten and Rosenlundsgatan and precipitation from Botkyrka, January until April 1996.*

Sites	Correlation (Hourly values)	Correlation (Daily values)
Aspvreten and street level measurements, PM10	0.32	0.65
Aspvreten and roof level measurements, PM10	0.52	0.76
Roof and street level measurements, PM10	0.68	0.86
Aspvreten and Hornsgatan (street level), PM2.5	0.23	0.39

Table 5: *The correlation between the different measuring sites.*

When the correlation is above 0.6 it may be regarded as good. The correlation between daily averages can be compared to measurements made in Canada (Brook et al, 1997). A mean value of daily averages of PM10 between 6 rural and 6 urban roof sites is 0.63. The PM2.5 correlation for the same sites is 0.72. The Swedish measurements indicate that the measurements at roof level are better correlated to the background measurements than the measurements at street level. Though the roof and street level measurements show best correlation (Figure 14).

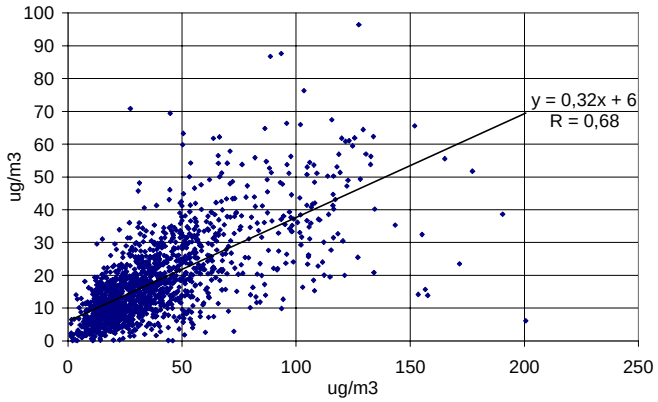


Figure 14: *The correlation between PM10 measurements at roof and street level.*

The PM2.5 correlation between Aspvreten and Hornsgatan is the worst. This shows the importance of local vehicle emissions for the PM2.5 levels in the streets in Stockholm.

It is not surprising that the correlation between Aspvreten and the city based on hourly mean values is worse than the correlation between Aspvreten and roof level values, shown in Figure 15, made for daily mean values. The correlation increase from 0.52 to 0.76, when using daily mean values instead of hourly values. The emissions of PM10, due to traffic variation are smoothed-out using daily mean values.

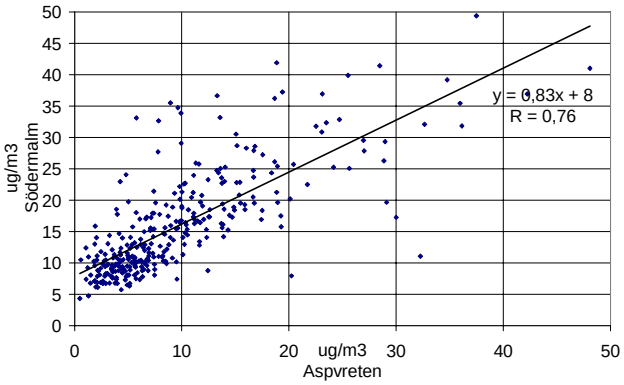


Figure 15: *The correlation between Aspvreten and roof level values.*

The relation between PM2.5 and PM10 has been obtained from linear regression at three different measuring occasions. At roof level at Rosenlundsgatan in the spring 1996 (Figure 16), at street level at Hornsgatan in April 1997 (Figure 17) and at Aspvreten in March in 1998.

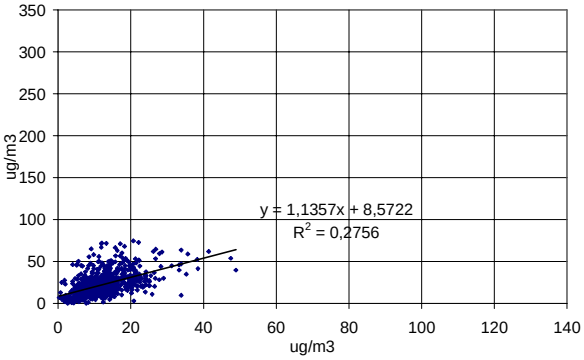


Figure 16: *The relation between PM2.5 and PM10 at Rosenlundsgatan, 1996.*

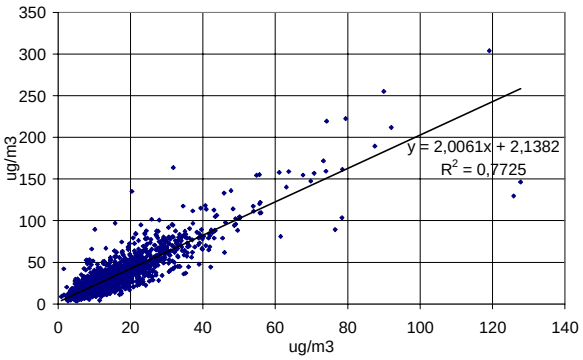


Figure 17: *The relation between PM2.5 and PM10 at Hornsgatan in April, 1997*

In these diagrams PM2.5 is on the x-axes and PM10 is on the y-axes. The resuspension is the reason why the PM10 part is larger for street level measurements (2*PM2.5) than for roof level measurements (1.6*PM2.5). It contributes with mostly particles larger than PM2.5.

At Aspvreten PM10 is 20% higher than PM2.5. The low (PM10-PM2.5) part is due to the fact that the measurements at Aspvreten principally consist of long distance transported particles.

A Canadian study

The relationship between PM10 and PM2.5 has been studied by Brook et al (1997). A maximum of ten and a minimum of two years of data was available for 19 locations in Canada.

On average across all sites, PM2.5 accounted for 49% of the PM10. The PM2.5 tended to increase from summer to winter. A number of factors could explain this. For example, lower mixing heights and higher energy consumption for heating in the winter. This suggests that combustion sources are an important contributor to winter time particle pollution and also shows that fine particles control the seasonal PM10 variability.

On average, coarse particles (2.5 μm<diameter<10 μm) decrease from summer to winter. This may be due to snow cover and/or increase in precipitation, which would inhibit the resuspension of crustal material.

Sites that are close together experience similar fine particle levels, while coarse particle levels differ more between sites.

Measuring place		**Mean**	**95 percentile**	**Linear equation**	**correlation between PM2.5 and PM10**
Canada, urban (19 locations)	PM10	27.6	58.0	PM2.5= -0.59 +0.56*PM10	0.86
	PM2.5	13.9	32.2		
	PM2.5/PM10	0.51	0.80		
Sweden, urban (Stockholm)	PM10	51.1	161.8	PM2.5=-7.55 +0.88*PM10	0.52
	PM2.5	14.8	29.1		
	PM2.5/PM10	0.41	0.84		
Sweden, rural (Aspvreten)	PM10	7.2	15.0	PM2.5=-1.4 +0.93PM10	0.94
	PM2.5	6.0	11.5		
	PM2.5/PM10	0.56	0.96		

Table 6: *A comparison of PM10 and PM2.5 values between Sweden and Canada.*

Processes that affect concentrations of particulate matter

The rate of change of the particle amount in urban areas can be described by six sources/sinks (Wexler et al, 1994). Total amount = condensation/evaporation + spatial diffusion + emissions + nucleation + dry deposition + wet deposition. The condensation/evaporation consists of two parts. Increase/decrease of the particle mass and change of size of the particles. The two main sources of condensation/evaporation are SO_2 and HNO_3. Emitted SO_2 oxidize to SO_4^{2-} which condense onto droplets and particles. HNO_3 is in equilibrium with NO_3^- which is absorbed by droplets and particles. The NO_3^- aerosols is mostly concentrated in particles below 2.5 μm. There is also a contribution from organic material, but Wexler et al (1994) and Lurmann (1997) show that the contribution in San Francisco is small compared to direct emission of organic material. It should be even smaller in Stockholm. Nucleation is a source of new particles under certain conditions. Although a large number of particles can be generated, their mass is sufficiently small that it does not significantly alter the aerosol mass distribution in urban areas. Therefore nucleation may be neglected in urban areas (Wexler et al, 1994, and Lurman et al, 1997).

When haze or fog exists particles grow to larger sizes. Particle growth and shrinkage are determined by the amount of water transferred to and from the aerosol, based on the equilibrium concentrations for specific relative humidity, temperature and aerosol chemical composition. Deposition of fog droplets occur in the same way as for other particles. Fog

reduces photolytic reactions by about 30% within the fog layers and increases the reaction rates by about 30% above the layers (Lurmann et al, 1997).

Wet, dry and cloud deposition

Definition

Wet deposition = Fall out by precipitation.

Dry deposition = Uptake into the surface of the earth by soil, water or vegetation.

Cloud deposition = Deposition of fog or cloud droplets on earth surface or vegetation.

Wet deposition

The most important mechanism for droplets collection of particles is condensation of water on the particles, nucleation scavenging (Rodhe, 1992). Whether a collision between a particle (with the diameter $\tilde{D}p$) and a falling droplet (with the diameter Dp, and the fall velocity Vt) will occur depends on the velocity of the falling droplet, its size, the size of the particle and its mass. The collection can occur in three different ways (Seinfeld, 1986):

- Brownian diffusion
- Interception
- Inertial impaction

Brownian diffusion is the random movement of particles, because of pushes from gas molecules, which will bring them in contact with the droplet. The diffusion increase, as the diameter decrease. The time scale of Brownian diffusion for a particle which is 0.3 μm in diameter is more than an hour. For a 0.1 μm particle and a 10 μm droplet the time scale would be more than a day, since it takes longer time when the droplet and the particle are in different sizes (Wexler et al, 1994).

Interception occurs when the particles follow the streamlines around an obstacle. The particle should not be too small, since its surface has to get in contact with the surface of the droplet. If the streamline lie within Dp/2 from the droplet, interception will take place.

Inertial impaction occur when the particle is too heavy to be able to follow the streamlines around the obstacle. Because of its velocity, the particle will continue towards the obstacle and collide with it.

The size is more important than the weight for particles that deposit due to interception. For impaction it is the opposite.

Figure 18 (Stern, 1976) describes what happens to the particle concentration in an urban atmosphere as a function of time, when it starts to rain. In the beginning the pollutant is unaffected by rain and the amount grow with time. (If the emission is larger than the dispersion and other sink processes). After 10^4s ≈ 3h it starts to rain with 0.2 inches per hour (≈5 mm/h). The dotted-dashed line describes the decrease of particles which are 3-4 μm in diameter.

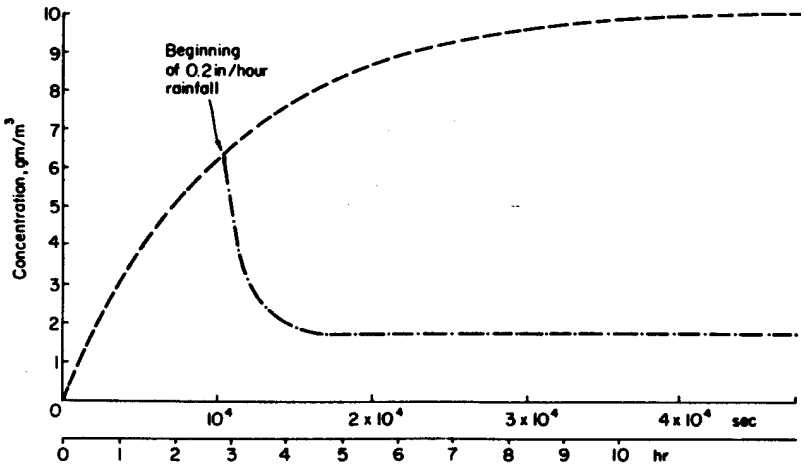


Figure 18: *The decrease of particles due to precipitation. After Stern (1976).*

The amount of particles deposited per time unit due to the precipitation is described by a scavenging coefficient (Λ).Larger precipitation intensity result in larger scavenging coefficient.

$$\frac{dC}{dt} = -\Lambda C$$

assuming constant Λ, this equation may be integrated:

$$\frac{C}{C_0} = e^{(-\Lambda t)} \text{ or } \ln\frac{C}{C_0} = -\Lambda t$$

C is the mass concentration of particles in the air and C_0 is the concentration in air before scavenging begins. At a constant droplet diameter and a given geometric standard deviation the scavenging coefficient (normalized by rainfall rate) can be described as a function of the geometric mean particle radius. Then the coefficient gives the deposited amount of particles per (mm) precipitation. It is calculated by the formula (Seinfeld, 1986):

$$\Lambda(D_p) = \int_0^\infty \frac{\pi}{4}\tilde{D}_p^2 V_t(D_p) E(D_p, \tilde{D}_p) N(\tilde{D}_p) dD_p$$

where

$N(\tilde{D}p)$ is the size distribution function, which can be decided by using known values of the rainfall rate, p_0 (mm/h).

$$p_0 = \int_0^\infty \frac{\pi}{6}\tilde{D}_p^3 V_t(\tilde{D}_p) N(\tilde{D}_p) d\tilde{D}_p$$

Typical values for p_0 is 0,5 mm/h for drizzle and 25 mm/h for heavy rain.

$E(Dp, \tilde{D}p)$ is the empirical collision efficiency. It is the ratio of the total amount of collisions between droplets and particles and the total amount of particles in an area as big as the effective cross-section area of the droplet.

If E=1, all particles in the volume that get swept away by the droplet will be collected by it. In most cases E<0, but it can be E>1 if electric effects exists.

E depends on the three factors, Brownian diffusion, interception and impaction.

The minimum of E occurs when the particles are too large for diffusion, but too small to be efficiently collected by interception or impaction.

Λ is normalized to make it possible to study the removal of particles of different sizes (q=1,2,…).

$$\overline{\Lambda}_q = \frac{\int_0^\infty \Lambda(D_p) D_p^q \tilde{n}(D_p) dD_p}{\int_0^\infty D_p^q \tilde{n}(D_p) dD_p}$$

For example, when q=2, Λ is the mean scavenging coefficient for the particle surface area and when q=3, Λ is the same for the particle volume or mass.

If the geometric mean particle radius $D_{pg} \geq 5$ μm, then E>1, which indicates that the deposition does not depend on q anymore.

The variation of the scavenging coefficient with rainfall rate and particle size is illustrated in Figure 19 (Stern, 1976), where W_p is the same as Λ.

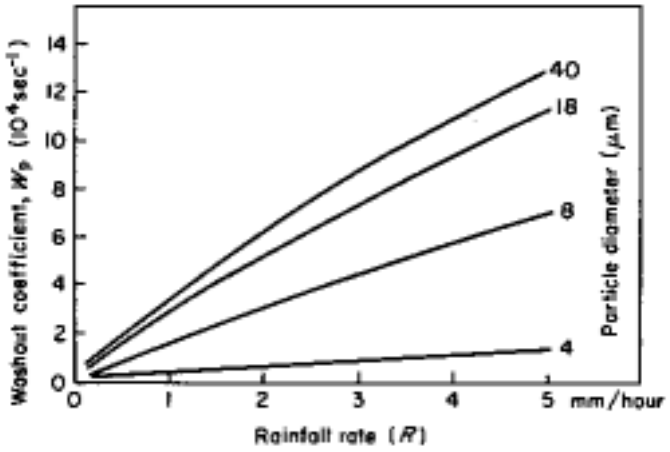


Figure 19: *The scavenging coefficient dependent on the rainfall rate and the particle diameter.*

Dry deposition

Dry deposition occur through three steps.

The first is the transport through the surface layer to the immediate vicinity of the surface. It is called the aerodynamic part of the transport and occur because of turbulent diffusion.

The second step is the diffusion through the laminar layer (10^{-1}-10^{-2} cm thick). This is called the surface component of the transport.

The third step is the solubility or the absorption of the ground. It is called the transfer component.

Large particles (Dp>20μm) deposit principally because of the gravitation (sedimentation), while small particles (Dp<0.1μm) behave like gases and deposit through Brownian diffusion.

The particles that stay longest time in the air has a diameter between 0.1 and 1.0 μm, since they are too small for sedimentation and too big for Brownian diffusion. The uncertainty of the rate of deposition in this interval is very large.

Large particles are except gravity (which affect the settling velocity, v_s) also influenced by inertia (impaction). The inertia depend on the characteristic relaxation time, τ, of the particle. τ indicate the particles tendency to continue its trajectory when the streamline yield. The larger τ is, the larger is the chance for the particle to impact or intercept on the surface.

The deposition velocity (v_d) is not a measurable movement through the air. It is just a proportionally constant, which relate the vertical flux downward to the concentration in the air. $v_d = \frac{\text{Flux}}{\text{Concentration}}$.

It varies with the time of the year, the time in the day and the meteorological conditions. Therefore is the insecurity of the deposition velocity significant (Persson et al, 1986).

Diameter (μm)	Deposition velocity (cm/s)
1	0.01
3	0.06
5	0.4

Table 7: *Examples of theoretical values of the deposition velocity due to the particle diameter (Rodhe 1992).*

$$v_d = \left(r_a + r_s + r_a r_s v_s\right)^{-1} + v_s$$

v_s is the gravitational settling velocity (m/s) of the particles.

r_a is the aerodynamic resistance. It is a function of wind speed, stability, surface roughness and independent of the particles.

$$r_a\left(z_1, z_0\right) = \frac{\left(\ln\left(z_1 / z_0\right)\right)^2}{\kappa^2 \overline{u}\left(z_1\right)}$$

z_0 is the surface roughness, z_1 is a reference level, κ is von Karmans constant and $u(z_1)$ is the time average velocity.

r_s is the surface layer resistance.

$$r_s = A\frac{Sc^{\alpha}}{u_*}$$

A and α are settled experimentally to 1,7 and 2/3 respectively. Sc is the Schmidt number of the particle and U_* is the friction velocity.

Deposition of particles less than 10 μm is dominated by wet deposition. For larger particles dry deposition dominate. The importance of the sedimentation increase with the size of the particle (See Figure 20).

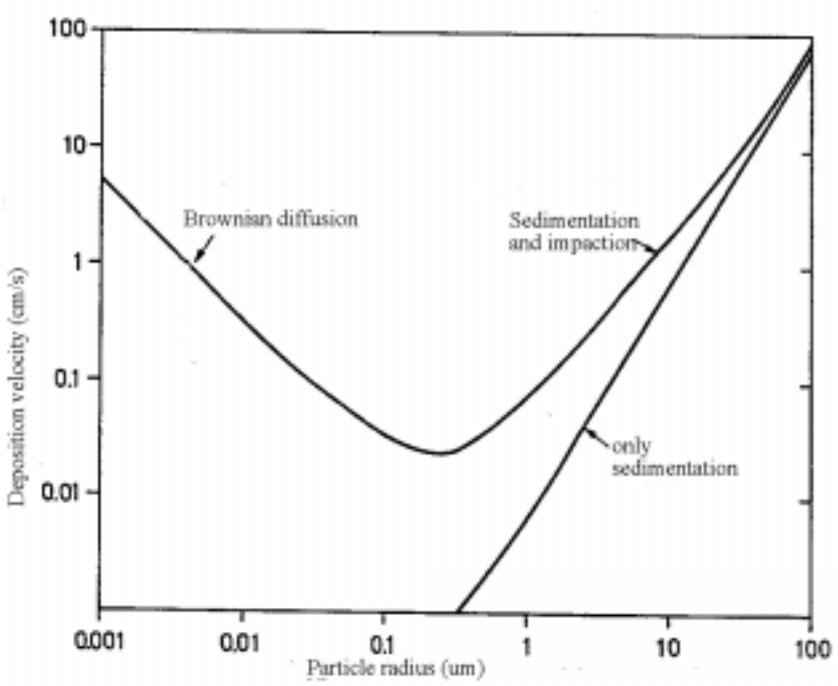


Figure 20: *The dry deposition velocity as a function of the particle radius (Rodhe 1992).*

Cloud deposition

It occurs principally in the mountains through impaction, but also through sedimentation. The cloud deposition is dependent on the moisture amount in the clouds, the wind speed and the surface roughness (Rodhe, 1992).

Time scales for deposition

The residence time $\left(\tau_{od}\right)$ for dry deposition is calculated by (Rodhe, 1992):

$$\tau_{od} = \frac{H}{v_d}$$

where H is a well mixed layer.

The mixing times $\left(\tau_{M}\right)$ in the atmosphere are different for different directions (Seinfeld, 1986). For the entire troposphere

$\tau_{M,Z} \approx 1\text{week}$ (vertical)

$\tau_{M,X} \approx 1\text{week}$ (horizontal, latitudinal)

$\tau_{M,Y} \approx 1\text{year}$ (horizontal, longitudinal)

This means that the troposphere can be seen as a well mixed layer for substances with a residence time longer than a year.

With an one km mixed layer and the deposition velocities suggested by Rodhe (1992) the residence times for dry deposition are shown in Table 8.

Diameter (μm)	Deposition velocity (cm/s)	Residential time
1	0.01	116 days
3	0.06	19 days
5	0.4	69 hours
10	0.8	32 hours

Table 8: *Residence time for particles with different aerodynamic diameters. Mixing height is assumed to be 1 km.*

As an example it can be assumed that some particles are transported northwards from the southern part of the county of Stockholm. With a southerly wind of 4 m/s the particles will be transported through the whole county within a day. This means that the dry deposition only affects the largest particles in this study (10 μm in diameter) since the rest of the particles are too small to be affected by sedimentation.

After some simplifications the residence time for wet deposition (τ_{ov}) can be calculated by (Rodhe, 1992):

$$\tau_{ov} = T_d + \frac{1}{f\Lambda}$$

where T_d is the mean length of the dry periods and f the part of the time during which precipitation falls. T_d is about 40 hours during the winter and 50 during the summer in northern Europe (Persson et al, 1986). f is about 0.15 and 0.07 in the winter and summer respectively (Rodhe, 1992).

If Λ^{-1}=1.15 hours (as for sulphate particles) (Persson et al, 1986), the residence time for wet deposition is about 46 hours in the winter and 62 hours in the summer.

The overall residence time is controlled by the process with the fastest removal time. The mean residence times for particles of different sizes are described by Figure 21 (Rodhe, 1992). The shorter residence times for the smallest particles in polluted air are explained by the relatively fast coagulation to larger particles.

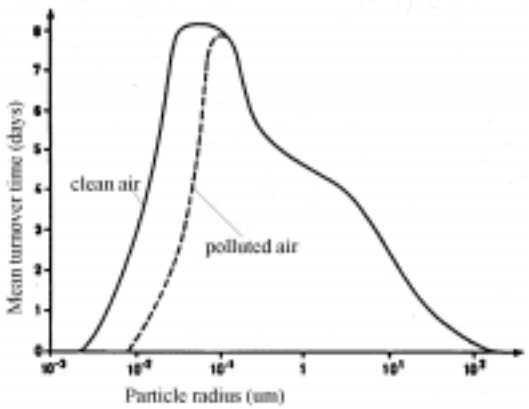


Figure 21: *Mean turnover time in the atmosphere for particles as a function of the radius.*

Meteorological impact on measured particle concentrations

Apart from emissions the variation in the PM10 amount in the air depend on several things. The results of the tests of the resuspension model showed that the particle resuspension depend a lot on the precipitation. In addition to this, airborne particles are scavenged when it rains and the amount in the air decreases. This is studied more closely during a period from the 19th until the 26th of April 1998 (Figure 22).

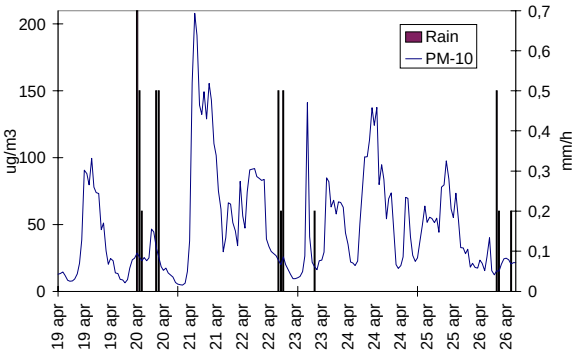


Figure 22: *PM10 concentration at street level at Hornsgatan and precipitation, 19-26 April 1998.*

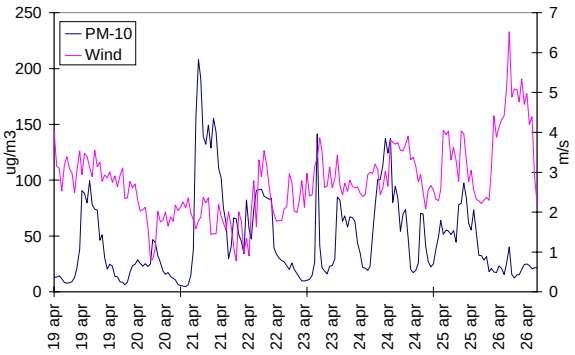


Figure 23: *PM10 concentration at street level at Hornsgatan and wind speed, 19-26 April 1998.*

The precipitation and wind measurements are made at the Torkel Knutsson street.

It can be noticed that when it rains the PM10 concentration decreases. The wind speed also effects the particle amount (See Figure 23).As the wind speed increase the particle amount decrease, due to turbulent mixing and advection. But on the other hand increased wind speed also increases resuspension of road dust, which will tend to increase the PM10 concentration. The relative importance will depend on sanding/salting, efficiency of resuspension and background concentration. In the same way, when it is calm and an inversion for example the particle amount rises, since it is concentrated very close to the ground.

One thing that affect the results a lot is where the PM10 measurements are made. Here they are made at street level at Hornsgatan in central Stockholm. If the measurements would have been done at roof level at the same place, the traffic rhythm would not be as important for the variations in the concentrations and the concentrations would have been much lower.

Calculations of concentrations of particulate matter in Stockholm

The only processes considered in the calculations are emission and dispersion of particles. Other processes (see page 24) are not considered in these studies, since only comparisons between different PM10 sources are made. For the Stockholm region, particle import is also very important.

The Gauss model

The model is used to simulate the distribution of ground concentrations of pollutions over urban or industrial areas with a scale from one to a few tenths of kilometres. The upper limit is given by the fact that the conditions shall be more or less stationary for the time it takes for an air parcel to be advected through the area. Each simulation is one hour, as the wind can be assumed to be more or less constant during that period. This should be considered when

simulations are made for areas larger than 20 km x 20 km. The pollution concentrations are assumed to be in steady-state during the simulation.

Calculations are made for specific time periods, for which meteorological data from the emission data base is used. The resolution of the wind field depend on the topographic information. The grid is normally 500*500 m or 250*250 m. If the map is zoomed up to a smaller area, the wind field will be linearly interpolated within the original grid.

Winds, vertical fluxes of momentum and temperature are estimated from measurements in meteorological masts. The horizontal large scale geostrophic wind is assumed to be uniform in the model. When this wind field is estimated, the initial surface pressure field is determined in accordance with a geostrophic balance. The model is not mass conservative and vertical circulation can not be described, since it is a one layer model.

The concentration is calculated with the following equation (SMHI, 1997):

$$C = \frac{Q}{2\pi\sigma_y\sigma_z U} e^{-y^2/2\sigma_y^2}\left[e^{-(z-h_e)^2/2\sigma_z^2} + e^{-(z+h_e)^2/2\sigma_z^2} + e^{-(z+h_e-2h)^2/2\sigma_z^2}\right]$$

where Q describes the sources, y and z are the distances to the sources horizontal and vertical respectively and U is the horizontal wind. The dispersion parameters σ_y and σ_z are calculated on the basis of detailed meteorological measurements of temperature gradient, wind speed, wind direction and vertical wind. h_e is the height of the plume.

The model does not resolve individual buildings. Instead, surface structures like houses and trees enter the model through local roughness values and through the wind field. The calculation height is 2 m above ground in an open area. Over a city the simulation will reflect the concentrations at 2 meters above roof height.

This model is not very good when the accumulation of pollutants is of interest and a time sequence must be simulated, or when the horizontal scales are regional. It will not be good either when the topography is too complicated. In these cases the grid model would be preferable.

Especially for the urban situations, the accuracy of the results depend on the quality of the emission data, the description of the surface and the meteorological data.

All information about the model come from SMHI (1993) and SMHI (1997).

Calculations with the Gauss model

The PM10 concentration has been calculated for the inner city of Stockholm during the winter (1/10-31/3) of 1995-96. Figure 24 shows the mean particle concentration for the whole winter. Figure 24a shows the contribution from resuspension alone, Figure 24b shows the direct emitted particles from vehicles, Figure 24c shows the contribution from the point and area sources and Figure 24d shows the resuspension part in percent of the total particle amount.

The mean resuspension amount (in a) is clearly concentrated to the large thoroughfares. The highest amounts are found close to the E4 southwards from Hornstull, where the contribution is about 3-5 $\mu g/m^3$. This can be compared to the direct emission (in b), which has its maximum values in the same areas as the resuspension. The contributions are never higher than 3 $\mu g/m^3$ anywhere. This is a first indication that resuspension can be the largest local particle source, especially in heavy traffic areas.

The remaining sources (in c) are dominated by wood combustion and other heating processes. This is obvious since the highest values are found away from the busy roads in the residential areas. South of Stockholm the highest contributions are between 4 and 6 $\mu g/m^3$.

The amount of resuspended dust in these areas are very small (0-20%), as can be seen in Figure 24d.

The areas with dominating (>50% of the total particle concentration) resuspension are along Värmdöleden, heading eastwards from Stockholm and along the E4 southwards. The percentage share of resuspension is also more than 30% in the entire inner city.

The winter of 1995-96 is also divided into four parts, for which the resuspended part of the traffic related emissions are shown in **Figure 25**. The parts are October until December, January, February and March. The mean meteorological values for each period are shown in Table 9.

	October till December	**January**	**February**	**March**
Mean wind (m/s)	1.1	1.8	2.4	0.9
Mean temperature (°C)	-4.0	-7.8	-0.8	-1.1
Number of precipitation hours	47 (≈16 per month)	10	17	12
Mean time without precipitation (hours)	37.2	45.9	21.5	12.2
Number of sanding/salting occasions	9 (Oct:0, Nov:6, Dec:3)	7	1	6
Average contribution from resuspension	55%	50%	55%	67%

Table 9: *Meteorological conditions during the winter of 1995-96.*

The resuspension increases during the winter season, especially south-east of the city where the amount raises from 60 to over 80%. During the first part of the winter (Oct. -Dec. **Figure 25**a) resuspension and direct emission contribute with about 50% each to the traffic related emissions. The resuspension is a bit higher (60%) along E4 southwards and between Nynäsvägen and Värmdöleden. During January (see **Figure 25**b) and February (see **Figure 25**c) the areas with the highest resuspension amounts close to the roads expand, though the differences are small.

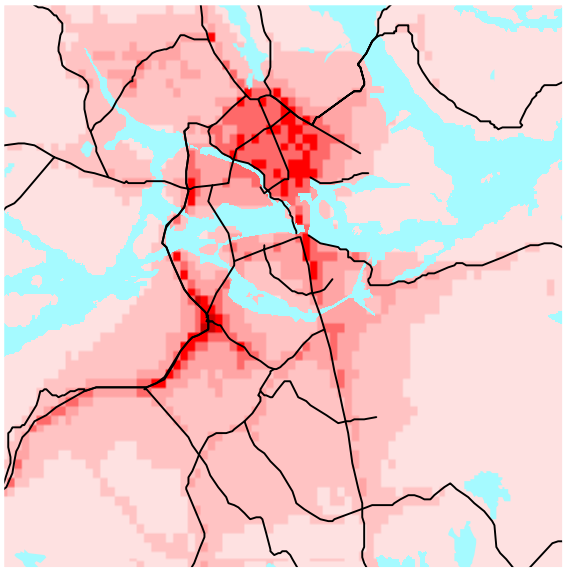
The mean percentage share raises to over 60% for the resuspension during March (see **Figure 25**d). The areas where resuspension is the source of more than 70% of the traffic related emissions, increase south and east of the city. It is in the city of Stockholm that resuspension has least importance. It varies from 45-60% during the winter.

It must be remembered that these dispersion calculations are made for one season only. Since the particle amount in general and the resuspension in particular are dependent upon the meteorological conditions the contributions from the different sources are supposed to vary from year to year.

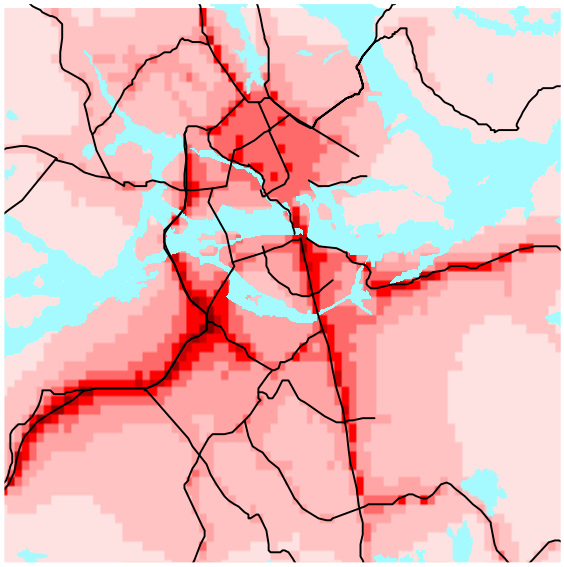
It should be noted that the only parameters that cause a geographical variation of resuspension in the model are traffic flow, vehicle speed and vehicle composition. Sanding/salting and

meteorology have the same effect on all streets in the area. In reality one might expect significant differences in sanding/salting between different roads. Precipitation amount may also vary in the region.

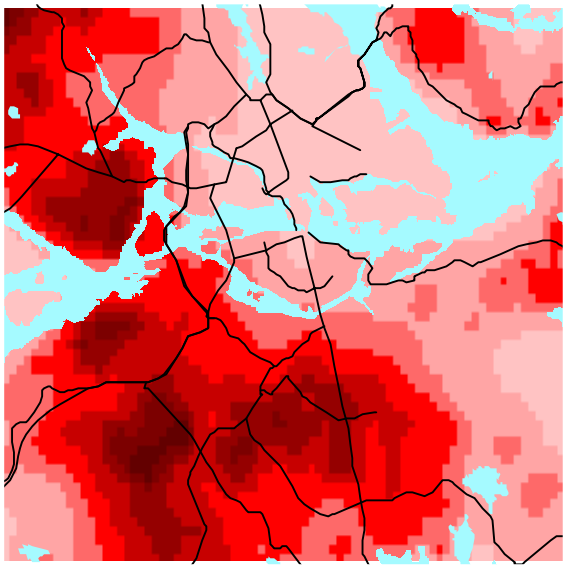
The contribution from import is about 10 μg/m^3, while the total road dust contribution is about 5 μg/m^3. Resuspension contribute with about 2-3 μg/m^3, which is 15-20 % of the total particle concentration, import included.



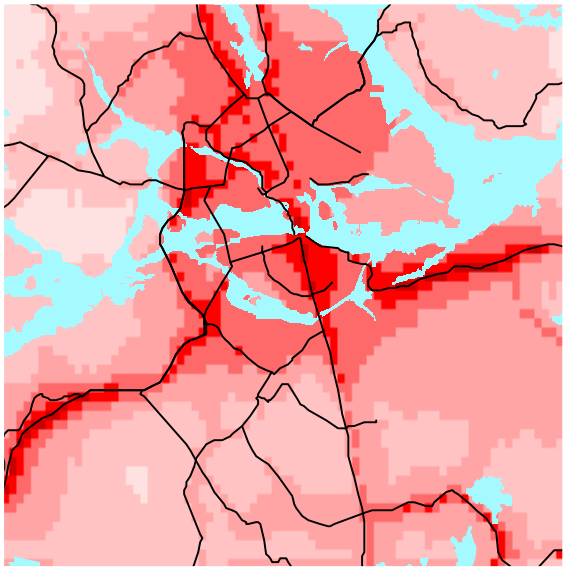
Resuspension (µg/m^3)



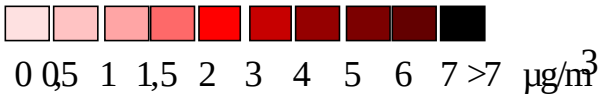
Exhaust emission (µg/m^3)



Point and area sources (µg/m^3)



Percent resuspension of total PM concentration (%)



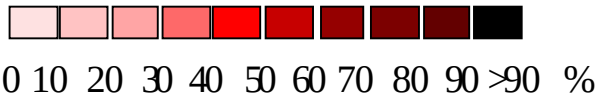


Figure 24. Contributions from local resuspension, vehicle exhaust and point and area sources to the PM levels in central Stockholm. Winter season mean levels.

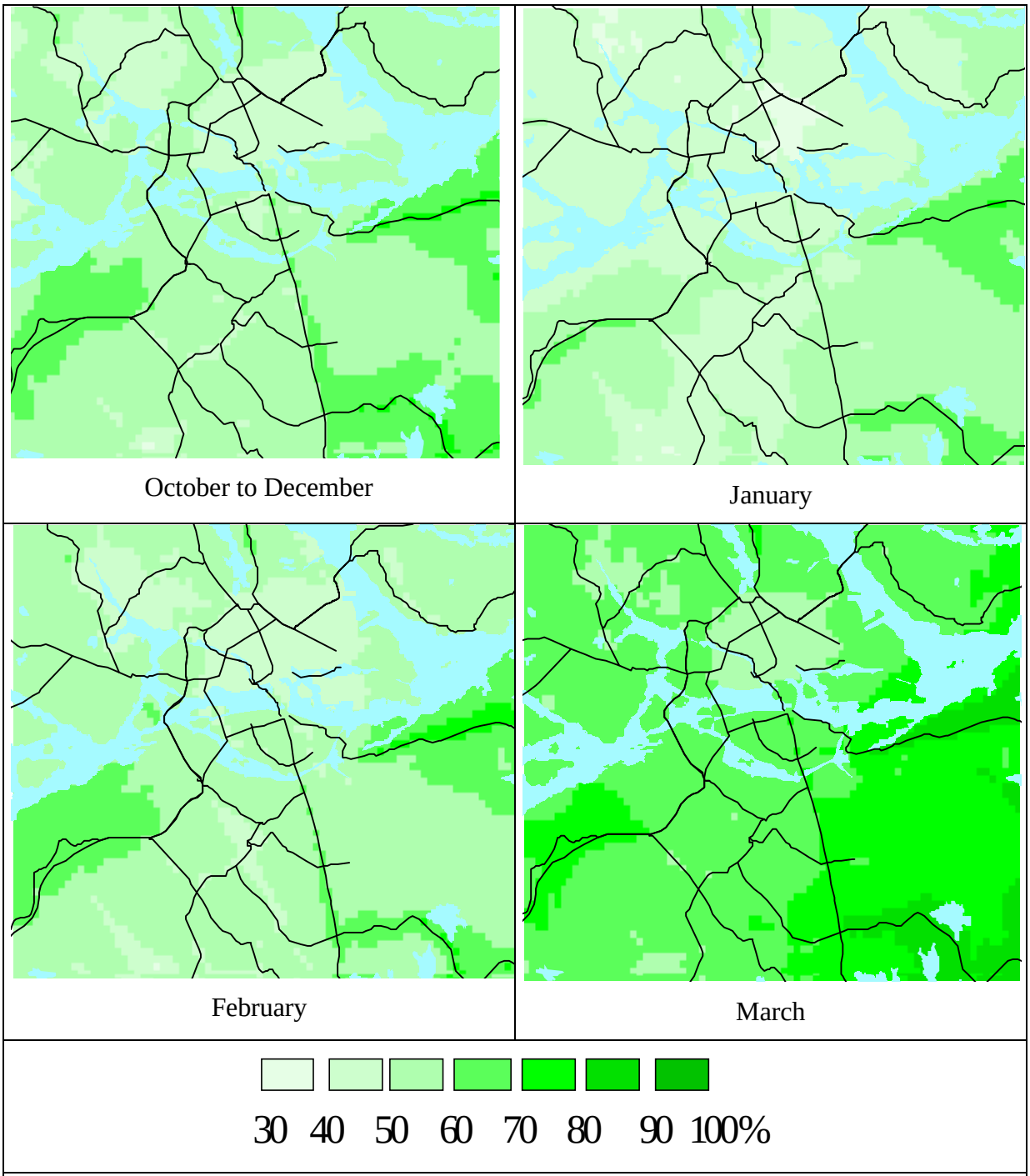


Figure 25. Contribution of resuspension to the concentrations of PM due to local sources in Stockholm, during different months of the winter season.

The Walpurgis episode, 1998

From April the 28th until April the 30th 1998 there was an episode of high particle concentrations (PM10) in Stockholm (see Figure 26).

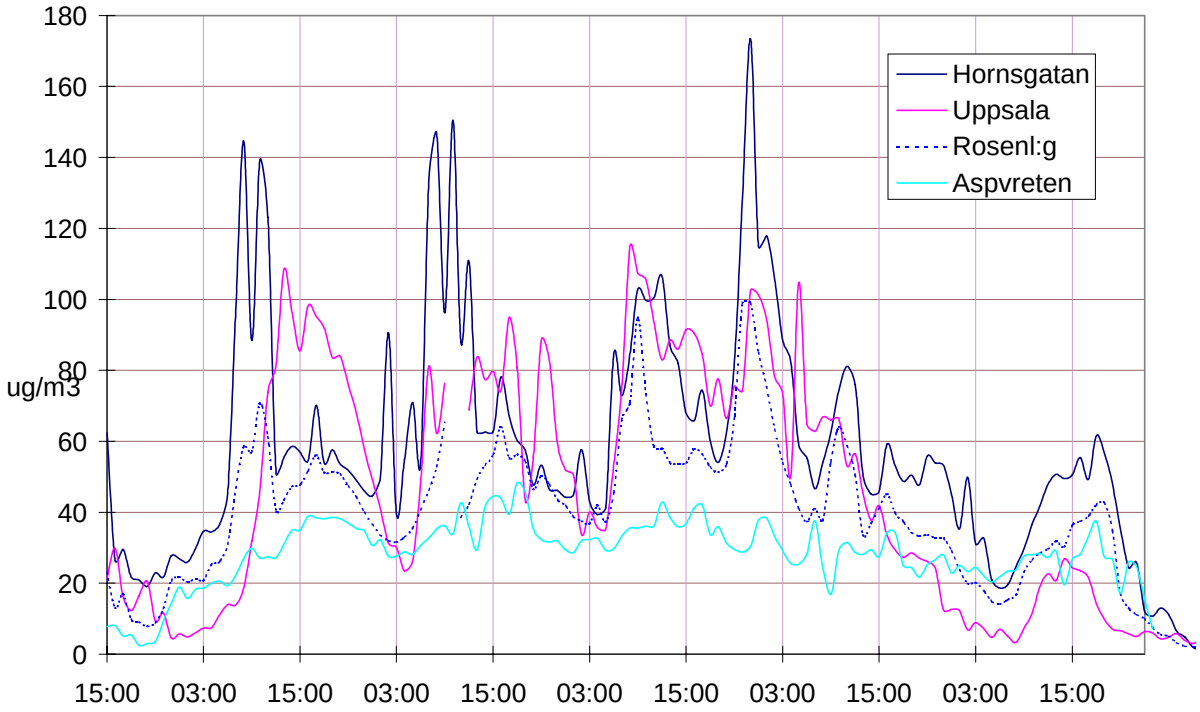


Figure 26: *Particle concentrations at four different measuring sites, the 27th of April until the 2nd of May.*

The measurements at Hornsgatan and in Uppsala are made at street level. The measuring location in Uppsala lies more open than the one at Hornsgatan. Therefore the mixing is better, which is one of the reasons for the lower particle concentrations. At Rosenlundsgatan the measurements are made at roof level, resulting in lower concentrations than in Uppsala. Aspvreten is a background measuring site, located 70 km south of Stockholm.

The mean concentrations were much higher than usual for all four stations during the episode (see Table 10).

Measuring site	**Approximate long term mean concentration (µg/m^3)**	**Mean concentration during the episode (µg/m^3)**
Hornsgatan	≈35	73
Uppsala	≈25	65
Rosenlundsgatan	≈15	50
Aspvreten	≈10	32

Table 10: *Mean concentrations at the measuring sites.*

The main reason to the episode was long range transport from central Europe and the interior of Russia (see Figure 27).

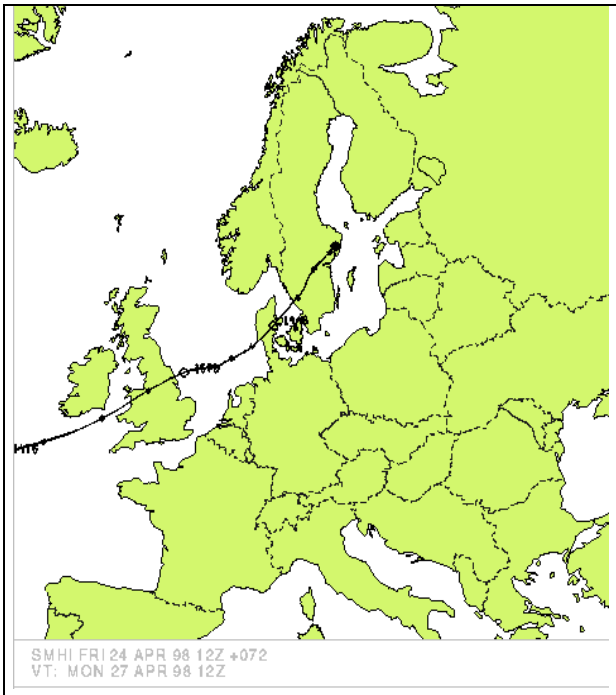


Figure 27a: *The trajectory of particles arriving to Stockholm on April the 27th, 1998.*

Figure 27b: *The trajectory of particles arriving to Stockholm on April the 28th, 1998.*

Figure 27c: *The trajectory of particles arriving to Stockholm on April the 29th, 1998.*

Figure 27d: *The trajectory of particles arriving to Stockholm on April the 30th, 1998.*

On April the 27th the air came from the Atlantic ocean (Figure 27a), and PM10 concentrations were relatively low. The day after, the air mass origin changed (Figure 27b), and the air came from central Europe, with high particle concentrations. This trajectory stayed for three days

(Figure 27c and Figure 27d), until April the 30th. Unfortunately there are no trajectories available to show the change on the first of May. It can though easily be seen in Figure 26 that the particle concentrations are lower that day. During the 28th and 29th the daily traffic variation is clearly seen. It is also interesting to note the effect of the fires at Walpurgis night - on the 30th the highest concentrations occur around ten to eleven p.m.

All trajectories are from SMHI, Norrköping.

Concluding remarks

Resuspension of road dust makes an important contribution to the PM10 concentration in the Stockholm region.

Very little information is available about the amount emitted and how it depend on traffic composition, vehicle speed and meteorological factors. One of the most important meteorological parameters is precipitation amount and duration of dry periods. Accurate measurements with good time and space resolution is needed.

In the SMHI model the most important parameters are 'k', which affects the hourly reduction of the amount of material in the street dust and street surface, and 'decay', which affects the hourly relative decay of the dust depot due to reduction by resuspension. Knowledge of the value of these parameters may be obtained from comparison of calculations with measurements.

Future model development for more accurate calculations of **fine** particles in the Stockholm region would mainly include gathering better information on emission factors. Especially for diesel vehicles and wood combustion.

For **coarse** particles resuspension is one of the most uncertain processes that need further attention.

Since particles also are 'carriers' of a number of toxic substances, like heavy metals, it is also very important to consider the dry and wet deposition of particles. Then size resolved information is needed.

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Appendix A

Parameters that have been used in the SMHI resuspension model:

tyre - Ratio of accumulated depot of tyre and road particles to the highest depot at the end of the season.

anskid - accumulated number of days with slipperiness, when sanding and salting are supposed to occur.

frf - reduce of particles on the roadway, because of rain.

rf - drain (mm)

epot - potential evaporation (mm)

gred - reduction factor for g

rr - precipitation per hour (mm)

td - dew point (°C)

t - temperature (°C)

esat - saturation vapour pressure

gamma - psychrometer constant (hPa/K)

L - latent heat (J/kg)

ra - aerodynamic resistance (s/m)

Δe - esat(t) - esat(td) (hPa)

cp - heat capacity (J/kg*K)

rho - air density (kg/m^3)

rn - incoming net radiation

delta - derivative of saturation vapour pressure with respect to temperature

The constant parameters used in the model:

Heat capacity cp(J/kgK)	1004
Latent heat (J/kg)	2,50E+06
Gamma (hPa/K)	0,4
Decay	0,001
k	-0,075
initialanskid	0
resuspa	0,5
resuspb	0,5
ginitial	0
rfmax	10
rho air density at sea level (kg/m^3)	1,225
von Karmans	0,4
z0	1
zr	20
initialtyre	0
alfa	0,8
N	0,6
albedo	0,2
cett	5,31E-13
ctvå	60
stefan-Boltzmanns constant	5,67E-08
initialpetter	0
initialdag	0

The equations that are used (Bringfeldt et al, 1997):

$$delta = 6{,}11 \cdot \ln 10 \cdot \frac{1782{,}75}{(237{,}7 + T)^2} \cdot 10^{\left(\frac{7{,}5 \cdot T}{237{,}7+T}\right)}$$

$$epot = 3600 \cdot (delta \cdot rn + rho \cdot cp \cdot \Delta e / ra) / (L \cdot (delta + gamma))$$

$$gred = \exp(k \cdot epot / 24)$$

$$g = \min(1.0, g + rr) \cdot gred$$

$$rf = \max((g + rr) \cdot gred, 0)$$

$$fsusp = 1 - decay \cdot fq$$

$$2 < rf < 10 \Rightarrow$$

$$frf = 1 - 0{,}05 \cdot (rf - 2) / (rf\ \max - 2)$$

$$rf < 2$$

or if

$$rr = 0 \Rightarrow frf = 1$$

$$rf > 10 \Rightarrow frf = 0{,}95$$

if

$$rr > 0$$

$$-2 < t < 1$$

$$fq < 0.1$$

$$anskid = anskid + 1$$

else

$$anskid = anskid$$

$$anskid = anskid \cdot frf \cdot fsusp$$

In winter

$$tyre = tyre + 0{,}01$$

At 1:st of May

$$tyre = tyre \cdot 0{,}1$$

and then

$$tyre = tyre + 0{,}001$$

$$tyre = tyre \cdot frf \cdot fsusp$$

$$fq = 1 - 0{,}9273 \cdot g$$

$$d = resuspa \cdot tyre + resuspb \cdot \min(anskid, 20) / 20$$

$$d > 1 \Rightarrow d = 1$$

$$fqe = d \cdot fq$$

Equations used to get the dewpoint from relative humidity and temperature: (www.usatoday.com/weather/whumcalc.htm)

Saturation vapour pressure:

$$E_s = 6{,}11 \cdot 10^{(7{,}5 \cdot T/(237{,}7+T))}$$

The actual vapour pressure:

$$E = \left(RH \cdot E_s\right)/100$$

Dewpoint

$$Td = \left(-430{,}22 + 237{,}7 \cdot \ln(E)\right)/\left(-\ln\left(E\right) + 19{,}08\right)$$

Equations used to get the aerodynamic resistance (Länsstyrelsen, 1997):

L= The Monin-Obukhov length

L<0⇒

$$R_a\left(z_r\right) = \frac{0{,}74}{\kappa \cdot u^*}\left(\ln\frac{\left(x-1\right)}{\left(x+1\right)} - \ln\frac{\left(y-1\right)}{\left(y+1\right)}\right)$$

where

$$x = \sqrt{1 - 9\frac{z_r}{L}}$$

and

$$y = \sqrt{1 - 9\frac{z_0}{L}}$$

L>0⇒

$$R_a\left(z_r\right) = \frac{1}{\kappa \cdot u^*} \cdot 0{,}74$$

Equation used to get the net radiation from the short-wave radiation (Hanna and Chang, 1991):

$$Q = \left(\left(1-A\right) \cdot B + c_1 \cdot T^6 - \sigma \cdot T^4 + c_2 \cdot N\right)/\left(1 + c_3\right)$$

where

A= albedo

B= short-wave radiation

$$c_3 = 0{,}38\left(\left(1-\alpha\right) \cdot S\right)/\left(S+1\right)$$

where

$$S = 1{,}4293 \cdot e^{(-0{,}0561 \cdot T)}$$

APPENDIX B

TEOM® (Tapered Element Oscillating Microbalance)

TEOM® (made by Rupprecht & Patashnick) was designated by the Environmental Protection Agency (EPA) in October 1990 as an equivalent method for measurement of 24-hour mean PM10, (Allen et al, 1997). It calculates the particle weight by measuring the frequency of the oscillation of the filter in the instrument. The weight is calculated with the formula (Hansson et al, 1997):

$$m = k_0\left(f_1^{-2} - f_0^{-2}\right)$$

where m is the weight, k_0 is a calibration constant, f_0 is the frequency of the instrument before the measurement and f_1 is the frequency after. All TEOM data are reported at standard temperature and pressure.