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# A Framework to Estimate the Potential and Costs for the Control of Fine Particulate Emissions in Europe

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# Contents

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## Abstract

This paper presents a methodology for estimating primary PM emissions in Europe and the costs involved to reduce these emissions from the various sources in the European countries. The framework developed is compatible with existing approaches to estimate emissions and costs for $SO_2$, $NO_x$, $NH_3$ and VOC in the RAINS model.

Emissions of PM are released from a large variety of sources with significant technical and economic differences. The emission characteristic of the sources is also strongly influenced by country-specific conditions. The method applied considers the crucial parameters and allows sectoral and regional variation. The emissions of particulate matter (PM) in the RAINS model are calculated for three different size classes (i) fine fraction ($PM_{2.5}$), (ii) coarse fraction ($PM_{10}$ - $PM_{2.5}$) and (iii) large particles (PM_>10 μm).

A methodology has been developed to estimate emission control costs of standard technologies under the specific conditions characteristic for the various European countries. Based on the assumption of the general availability of control technologies with equal technical properties and costs, a number of country-specific circumstances (level of technological advancement, installation size distribution, labor costs, etc.) are used to estimate the costs for the actual operation of pollution control equipment.

Based on the developed methodology, a first estimate of the PM emissions in Europe was derived for the years 1990, 1995 and 2010. This estimate must be considered as preliminary, since many of the emission factors need revision and update with additional information. The projections for the year 2010 assume full implementation of the current legislation on emission controls, e.g., the EURO-IV emission standards resulting from the Auto Oil process for mobile sources, and regulations relating to the large combustion plant directive of the European Union. Major reductions in PM emissions occurred between 1990 and 1995, mainly because of the economic restructuring in Eastern Europe where many old coal power stations were retired. Between 1990 and 1995, TSP emissions declined by 41 percent; for 2010 a decline of 58 percent is projected. Emission reductions are most efficient for larger particles; for 2010, $PM_{10}$ is calculated to decline by 56 percent, and $PM_{2.5}$ by 48 percent. Consequently, fine fraction ($PM_{2.5}$) will be relatively more important in the future (38 percent of TSP in 2010) compared to 31 percent of TSP in 1990.

In 1990, combustion in energy industries, small non-industrial combustion sources, production processes and road transport contributed about 20 percent each to total TSP emissions in the EU-15. In the non-EU countries, small sources and power plants were responsible for more than 30 percent each, while road transport contributed only three percent of TSP. In those countries, small sources (domestic coal and wood combustion) are expected to increase their share to 45 percent in 2010, while in the EU-15 mobile sources will become the most important source category for TSP emissions (45 percent).

For $PM_{2.5}$, mobile sources were the largest contributor in 1990 in the EU-15 countries (31 percent). This share is expected to decline slightly by 2010 (28 percent) due to the strict

regulations that were recently introduced. In the non-EU countries, industrial production processes were the largest source of $PM_{2.5}$ emissions (36 percent), while in 2010 small combustion sources in the domestic sector will dominate (38 percent).

The present implementation (version 1.03) of the RAINS PM module on the Internet (http://www.iiasa.ac.at/~rains/PM/pm-home.html) provides free access to the input data and results to facilitate interaction with national experts.

# A Framework to Estimate the Potential and Costs for the Control of Fine Particulate Emissions in Europe

## 1 Introduction

There is growing concern related to the health effects of fine particles. Recent studies have demonstrated a consistent association between the concentrations of fine particulate matter (PM) in the air and their adverse effects on human health (respiratory symptoms, morbidity and mortality) for concentrations commonly encountered in Europe and North America.

Airborne suspended particulate matter can be either primary or secondary in nature. Primary particles (PM) are emitted directly into the atmosphere by natural and/or anthropogenic processes whereas secondary particles are predominantly human made in origin and are formed in the atmosphere from the oxidation and subsequent reactions of sulfur dioxide, nitrogen oxides, ammonia and volatile organic compounds.

Strategies for controlling particle concentrations in ambient air have to take into account their different origins and address the control potentials for the various sources in a targeted way. However, to strike a balance among control measures for various pollutants in different economic sectors in several countries is a demanding task, and a large body of information must be taken into account.

Integrated assessment models have been used in the past to identify least-cost strategies that can control multiple precursor emissions leading to acidification, eutrophication and ground-level ozone (Amann and Lutz, 2000). Johansson *et al*. (2000) have also presented an initial attempt to extend the existing framework of the RAINS [**R**egional **A**ir Pollution **In**formation and **S**imulation, developed at the International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria] model to address control strategies for fine particulate matter.

The objective of this paper is to present a methodology for estimating primary PM emissions in Europe and the costs involved to reduce primary PM emissions from the various sources in the European countries. The remainder of this introductory section reviews the context in which the emission and cost estimates should serve. Section 2 introduces the methodology for estimating emission and explores the appropriate level of aggregation for a Europe-wide analysis. Section 3 reviews the available literature sources for the individual source categories and outlines how emission factors were derived for the RAINS model. Cost calculations are the subject of Section 4. Provisional results from the analysis are presented in Section 5, and conclusions are drawn in Section 6. Annex I provides a glossary of frequently used terms.

## 1.1 An Integrated Assessment Model for Fine Particulate Matter

Over the last few years, the RAINS model has been used to address cost-effective emission control strategies in a multi-pollutant/multi-effect framework. For this purpose, the RAINS model now includes the control of $SO_2$, $NO_x$, VOC and $NH_3$ emissions as precursors for acidification, eutrophication and ground-level ozone.

For fine particulate matter (PM) there is evidence that several emission sources contribute via various pathways to the concentrations in ambient air. While a certain fraction of fine particles found in the ambient air originates directly from the emissions of those substances (the "primary particles"), a second fraction is formed through secondary processes in the atmosphere from precursor emissions, involving $SO_2$, $NO_x$, VOC and $NH_3$.

Consequently, the search for cost-effective solutions to control the ambient levels of fine particles should balance emission controls over the sources of primary emissions as well as over the precursors of secondary aerosols. Thus, the control problem can be seen as an extension of the "multi-pollutant/multi-effect" concept applied for acidification, eutrophication and ground-level ozone (Table 1.1).

Table 1.1: Air quality management as a multi-pollutant, multi-effect problem.

| | $SO_2$ | $NO_x$ | $NH_3$ | VOC | Primary PM emissions |
|---|---|---|---|---|---|
| Acidification | √ | √ | √ | | |
| Eutrophication | | √ | √ | | |
| Ground-level ozone | | √ | | √ | |
| Health damage due to fine particles | √ | √ | √ | √ | √ |
| | via secondary aerosols | | | | |

Further, a more sophisticated assessment framework could be used for more than just balancing measures for the five pollutants to control fine particles. Such a framework could consider the possible policy objectives for fine particles together with targets for acidification, eutrophication and ground-level ozone, and thereby search for least-cost solutions to simultaneously accommodate for all four environmental problems.

The present implementation of the RAINS model contains modules to describe emissions and emission control costs for the four substances. The atmospheric dispersion models employed by RAINS also include the processes leading to the formation of secondary aerosols. Additional

modules are necessary to capture primary emissions, control potential and control costs for fine particles, the dispersion of the fine particles in the atmosphere and the formation of secondary aerosols from the “conventional" precursor emissions. Ultimately, a module should be developed to assess the health impacts resulting from a certain emission control strategy.

The conceptual extension of the present structure of the RAINS model is illustrated in Figure 1.1, where the additional elements required for the analysis of fine particulate matter are highlighted (Johansson *et al.*, 2000).

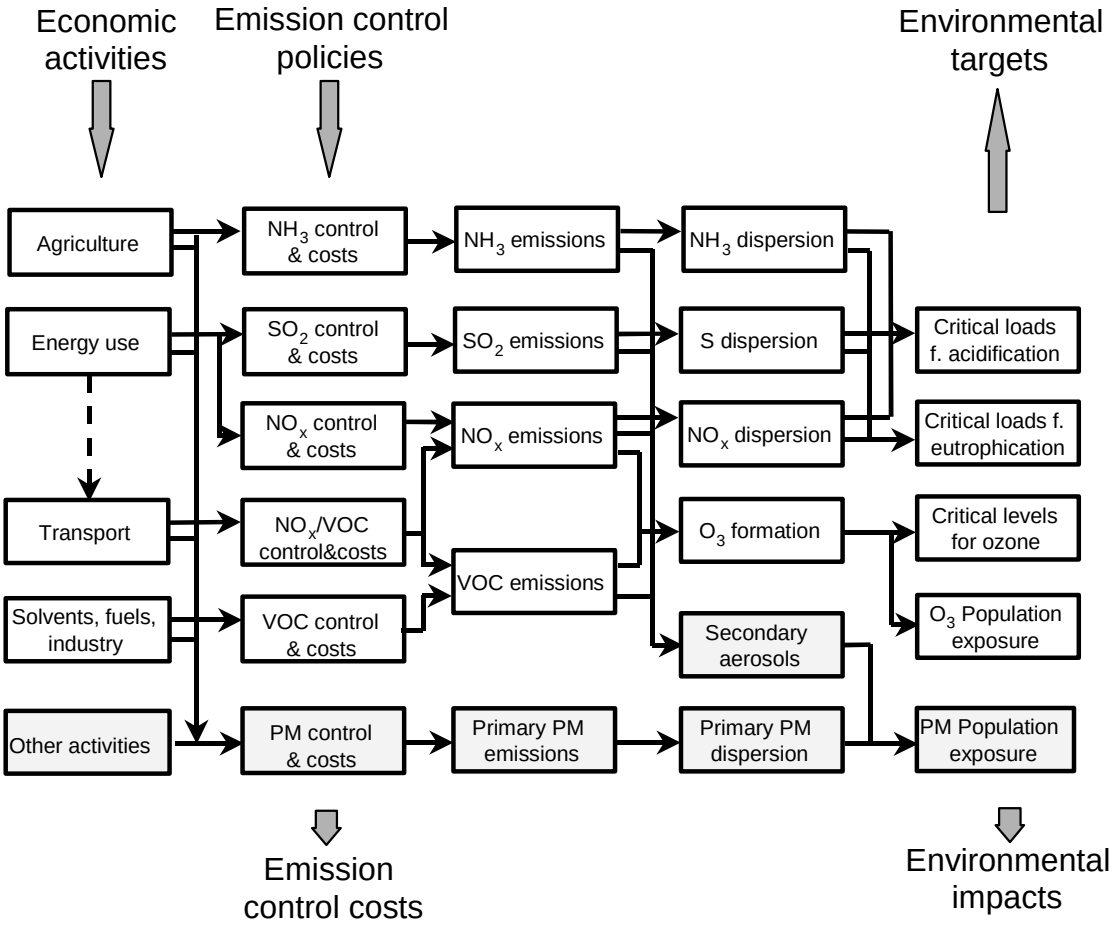


Figure 1.1: Flowchart of the extended RAINS model to address particulate matter.

## 1.2 The Objectives of an Emission Control Cost Module within the Framework of an Integrated Assessment Model

A central objective of integrated assessment models is to assist in the cost-effective allocation of emission reduction measures across various pollutants, several countries and different economic sectors. Obviously, this task requires consistent information about the costs of emission control at the individual sources, and it is the central objective of this cost module to provide such information.

The optimal cross-country allocation of emission control measures is crucially influenced by differences in emission control costs for the individual emission sources. It is therefore of utmost importance to systematically identify the factors leading to differences in emission control costs among countries, economic sectors and pollutants. Such differences are usually caused, *inter alia*, by variations in the composition of the various emission sources, the state of technological development and the extent to which emission control measures are already applied.

In order to systematically capture these differences across Europe, a methodology has been developed to estimate emissions and emission control costs of standard technologies under the specific conditions characteristic for the various European countries. Based on the basic assumption of the general availability of control technologies with equal technical properties and costs, a number of country-specific circumstances (level of technological advancement, installation size distribution, labor costs, etc.) are used to estimate the costs for the actual operation of pollution control equipment.

# 2 A Module to Estimate Emissions of Fine Particulate Matter

## 2.1 Methodology

The emissions of particulate matter (PM) in the RAINS model are calculated for three different size classes:

- fine fraction ($PM_{2.5}$),
- coarse fraction ($PM_{10}$ - $PM_{2.5}$) and
- large particles (PM_>10 μm).

Thereby, $PM_{10}$ is calculated as the sum of fine and coarse fractions and total suspended particles (TSP) as the sum of fine, coarse and PM_>10 fractions.

The methodology includes the following three steps:

- In a first step, country-, sector- and fuel-specific "raw gas" emission factors for total suspended particles (TSP) are derived:
  - For solid fuels the mass balance approach is used where ash content (*ac*) and heat value (*hv*) of fuels and ash retention in boilers (*ar*) is considered:

$$ef_{TSP} = ac/hv * (1 – ar)$$

  - For liquid fuels, industrial processes and transport TSP emission factors are taken from the literature.
- In a second step, "raw gas" emission factors for each of the size fractions are estimated. This is done based on size fraction profiles reported in the literature for a variety of installations. They are typically given for $PM_{10}$ and $PM_{2.5}$ and are fuel- and installation (sector)-specific. The typical profiles are applied to the country-, fuel- and sector-specific "raw gas" TSP emission rates (see first step) to derive the size-specific emission factors used in RAINS.
- In a third step, actual PM emissions are calculated for the three size fractions. For a given country (*i*), PM emissions of size fraction (*y*) are calculated by applying a general formula across every fuel and sector, taking into account the application rates of control technologies and size fraction specific emission removal efficiencies,

$$EPM_{i,y} = \sum_{j,k,m} EPM_{i,j,k,m,y} = \sum_{j,k,m} \{A_{i,j,k} * ef_{i,j,k,y} * (1- eff_{m,y}) * X_{i,j,k,m}\} \quad (1)$$

where:

| | |
|---|---|
| *i,j,k,m* | Country, sector, fuel, abatement technology; |
| *Y* | Size fraction, i.e. fine, coarse, PM_>10; |
| *EPM* | Emissions of particulate matter; |
| *A* | Activity in a given sector, e.g. coal consumption in power plants; |
| *Ef* | "Raw gas" emission factor; |
| $eff_y$ | Reduction efficiency of the abatement option for size class *y*, and; |
| *X* | Actual implementation rate of the considered abatement, e.g., percent of total coal used in power plants that are equipped with electrostatic precipitators. |

If no emission controls are applied, the abatement efficiency equals zero (eff = 0) and the application rate is one (X = 1). In that case, the emission calculation is reduced to simple multiplication of activity rate by the "raw gas" emission factor.

## 2.2 Aggregation of Emission Sources

Emissions of PM are released from a large variety of sources with significant technical and economic differences. Conventional emission inventory systems, such as the CORINAIR inventory of the European Environmental Agency, distinguish more than 300 different processes causing various types of emissions.

In the ideal case, the assessment of the potential and costs for reducing emissions should be carried out at the very detailed process level. In reality, however, the necessity to assess abatement costs for all countries in Europe as well as focus on emission levels in 10 to 20 years from now restricts the level of detail which can be maintained. While technical details can be best reflected for individual (reference) processes, the accuracy of estimates on an aggregated national level for future years will be seriously hampered by a general lack of reliable projections of many of these process-related parameters (such as future activity rates, autonomous technological progress, etc.). For an integrated assessment model focusing on the pan-European scale it is therefore imperative to aim at a reasonable balance between the level of technical detail and the availability of meaningful data describing future development, and to restrict to a manageable number of source categories and abatement options.

### 2.2.1 Criteria for Aggregations

For the RAINS PM module, an attempt was made to aggregate the emission producing processes into a reasonable number of groups with similar technical and economic properties. Considering the intended purposes of integrated assessment, the major criteria for aggregation were:

- The importance of the emission source. It was decided to target source categories with a contribution of at least 0.5 to two percent to the total anthropogenic emissions in a particular country.
- The possibility of defining uniform activity rates and emission factors.
- The possibility of constructing plausible forecasts of future activity levels. Since the emphasis of the cost estimates in the RAINS model is on future years, it is crucial that reasonable projections of the activity rates could be constructed or derived.
- The availability and applicability of "similar" control technologies.
- The availability of relevant data. Successful implementation of the module will only be possible if the required data are available.

It is important to carefully define the appropriate activity units. They must be detailed enough to provide meaningful surrogate indicators for the actual operations of a variety of different technical processes, and aggregated enough to allow a meaningful projection of their future development with a reasonable set of general assumptions. As explained later in the text, some of the RAINS sectors contain a number of PM emitting processes. It is often the case that for such aggregated sectors some emission control options are not necessarily applicable to all processes (emission sources) that are represented by the activity.

Table 2.1 presents the major sectors included in the RAINS PM module and their contribution to total European PM emissions that are estimated in this study for 1990. The RAINS source structure shown distinguishes nine emission categories for mobile and 17 for stationary sources that are split by relevant fuels (see Table 2.3). Some categories are further disaggregated distinguishing, for example, between existing and new installations (for a full list of RAINS sectors see Table 2.2, Table 2.4, Table 2.5).

The sectoral structure of the RAINS model is not directly compatible with that of CORINAIR. Tables presented in this section provide a broad reference to the CORINAIR SNAP'94 categories. In several cases the relation can be established only for a primary sector, i.e., the sum of all RAINS categories for power and district heating plants can only be compared with the sum of several SNAP entries. RAINS contains a feature to aggregate emissions into the CORINAIR SNAP level 1.

The following sections define the source categories distinguished in the RAINS model in more detail and provide the equivalent SNAP source sectors of the CORINAIR inventory.

### 2.2.2 Stationary Combustion Sources

Stationary combustion is by far the most important source of PM emissions. An attempt has, therefore, been made to design an emission source structure that represents the most important sources and factors influencing emissions of PM. The following tables present the RAINS model sectors used in the PM calculation and for the most part they are compatible with the structure of the other RAINS modules although new elements are introduced. More details are given in Section 3.

Table 2.1: Major sectors included in the RAINS PM module and their contribution to total European PM emissions in 1990 as estimated in this study.

| RAINS sector | | Emissions [kt] | | | Share of total European emissions in 1990 [%] | | |
|---|---|---|---|---|---|---|---|
| Primary | Secondary | TSP | $PM_{10}$ | $PM_{2.5}$ | TSP | $PM_{10}$ | $PM_{2.5}$ |
| Stationary combustion | Conversion combustion | 139 | 89 | 33 | 1.0 | 1.0 | 0.8 |
| | Domestic combustion | 4324 | 2493 | 993 | 30.1 | 27.9 | 22.9 |
| | Industrial combustion | 993 | 620 | 215 | 6.9 | 6.9 | 4.9 |
| | Power plants | 3849 | 2676 | 975 | 26.8 | 29.9 | 22.5 |
| Process emissions | Pig iron | 1596 | 1059 | 792 | 11.1 | 11.8 | 18.2 |
| | Coke production | 292 | 147 | 93 | 2.0 | 1.6 | 2.1 |
| | Sinter process | 391 | 107 | 42 | 2.7 | 1.2 | 1.0 |
| | Cement production | 1017 | 621 | 342 | 7.1 | 6.9 | 7.9 |
| | Petroleum refining | 40 | 39 | 33 | 0.3 | 0.4 | 0.8 |
| | Aluminum production | 67 | 45 | 24 | 0.5 | 0.5 | 0.6 |
| | Pup and paper | 54 | 51 | 48 | 0.4 | 0.6 | 1.1 |
| | Fertilizer production | 11 | 11 | 8 | 0.1 | 0.1 | 0.2 |
| Material | Material handling | 199 | 69 | 3 | 1.4 | 0.8 | 0.1 |
| Road transport | Heavy duty vehicles | 230 | 222 | 199 | 1.6 | 2.5 | 4.6 |
| | Light duty vehicles | 214 | 207 | 184 | 1.5 | 2.3 | 4.2 |
| | Motorcycles, mopeds | 31 | 31 | 26 | 0.2 | 0.3 | 0.6 |
| | Leaded gasoline | 93 | 78 | 62 | 0.7 | 0.9 | 1.4 |
| | Tire wear | 330 | 32 | 1 | 2.3 | 0.4 | 0.0 |
| | Brake lining wear | 22 | 18 | 8 | 0.1 | 0.2 | 0.2 |
| | Road abrasion | 67 | 34 | 19 | 0.5 | 0.4 | 0.4 |
| Other transport | Off-road | 110 | 98 | 86 | 0.8 | 1.1 | 2.0 |
| | Shipping | 140 | 138 | 136 | 1.0 | 1.5 | 3.1 |
| Agriculture | Poultry farms | 35 | 25 | 12 | 0.2 | 0.3 | 0.3 |
| | Pig farms | 25 | 10 | 3 | 0.2 | 0.1 | 0.1 |
| | Cattle farms | 17 | 7 | 2 | 0.1 | 0.1 | 0.0 |
| | Other | 55 | 22 | 7 | 0.4 | 0.2 | 0.2 |
| TOTAL | | 14342 | 8948 | 4344 | 100.0 | 100.0 | 100.0 |

Table 2.2: RAINS sectors related to stationary sources with energy combustion.

| RAINS sector | RAINS code | SNAP sector |
|---|---|---|
| **Centralized power plants and district heating** | | |
| New power plants | PP_NEW | |
| New power plants, grate combustion | PP_NEW1 | |
| New power plants, fluidized bed combustion | PP_NEW2 | |
| New power plants, pulverized fuel combustion | PP_NEW3 | 0101, 0102, 020101, 020102, 020201, 020301 |
| Existing plants[(1)], wet bottom boilers | PP_EX_WB | |
| Wet bottom boilers, < 50 MW | PP_EX_WB1 | |
| Wet bottom boilers, 50-300 MW | PP_EX_WB2 | |
| Wet bottom boilers, > 300 MW | PP_EX_WB3 | |
| Existing plants [(1)], other types (of boilers) | PP_EX_OTH | |
| Other types, grate combustion | PP_EX_OTH1 | |
| Other types, fluidized bed combustion | PP_EX_OTH2 | |
| Other types, pulverized fuel combustion | PP_EX_OTH3 | |
| **Fuel conversion** | | |
| Energy consumed in the fuel conversion process | CON_COMB | |
| Fuel conversion process, grate combustion | CON_COMB1 | 0104 |
| Fuel conversion process, fluidized bed combustion | CON_COMB2 | |
| Fuel conversion process, pulverized fuel combustion | CON_COMB3 | |
| **Residential, commercial, institutional, agricultural use** | DOM | 020103-06, 020202-03, 020302-05 |
| **Fuel combustion in industrial boilers** | | |
| Combustion in boilers | IN_BO | |
| Combustion in boilers, grate combustion | IN_BO1 | 010301-03, |
| Combustion in boilers, fluidized bed combustion | IN_BO2 | 010501-03, |
| Combustion in boilers, pulverized fuel combustion | IN_BO3 | 0301 |
| Other combustion | IN_OC | |
| Other combustion, grate combustion | IN_OC1 | 010304-06, |
| Other combustion, fluidized bed combustion | IN_OC2 | 010504-06, |
| Other combustion, pulverized fuel combustion | IN_OC3 | 0302, 0303 |

[(1)] Refers to all sources that came on line before or in 1990.

Table 2.3: Fuel categories distinguished in the RAINS PM module.

| Fuel type | RAINS code |
|---|---|
| Brown coal/lignite, grade 1 | BC1 |
| Brown coal/lignite, grade 2 | BC2 |
| Hard coal, grade 1 | HC1 |
| Hard coal, grade 2 | HC2 |
| Hard coal, grade 3 | HC3 |
| Derived coal (coke, briquettes) | DC |
| Heavy fuel oil | HF |
| Medium distillates (diesel, light fuel oil) | MD |
| Light fractions (unleaded gasoline, kerosene, naphtha) | LF |
| Leaded gasoline | LFL |
| Liquefied petroleum gas | LPG |
| Natural gas | GAS |
| Wood, biomass | OS1 |
| High sulfur waste | OS2 |

### 2.2.3 Stationary Non-combustion Sources

A number of industrial processes emit significant amounts of particulate matter that does not originate from fuel combustion (e.g., metallurgical processes, ore processing, refining, etc., but also agriculture or material handling). Table 2.4 lists the categories distinguished in the RAINS model. A more detailed description is provided in Section 3.

### 2.2.4 Mobile Sources

Table 2.5 and Table 2.6 list the categories distinguished in the RAINS model to estimate emissions and costs of controlling PM emissions from exhaust and non-exhaust mobile sources. This structure is broadly compatible with that of other RAINS modules with exception of non-exhaust sources that are not relevant for emissions of the other pollutants ($SO_2$, $NO_x$, VOC) considered in RAINS.

Table 2.4: RAINS sectors for other stationary sources of PM emissions.

| RAINS sector | RAINS code | SNAP sector |
|---|---|---|
| Industrial process emissions | | |
| Pig iron production | IN_PR_PIGI | 040203 |
| Coke production | IN_PR_COKE | 040201 |
| Sinter production | IN_PR_SINT | 040209 |
| Electric arc and basic oxygen furnaces | IN_PR_FUR | 040206-07 |
| Cement production | IN_PR_CELI | 040612 |
| Petroleum refining | IN_PR_REF | 0401 |
| Non-ferrous metal smelters (aluminum) | IN_PR_NFME | 040301 |
| Others | IN_PR_OTH | |
| | | |
| Agriculture, livestock farming | | |
| Chicken farms | AGR_CHI | 100507-09 |
| Pig farms | AGR_PIG | 100503-04 |
| Cow farms | AGR_COW | 100501-02 |
| Other farm sources | AGR_OTH | |
| | | |
| Other sources | | |
| Other sources of “dust” | DUST | |
| Storage and handling of products | MAH | |

Table 2.5: Categories of PM exhaust emissions from mobile sources considered in RAINS.

| RAINS sector | RAINS code | SNAP sector |
|---|---|---|
| **Road transport** | | |
| Heavy duty vehicles (trucks, buses and others) | TRA_RD_HD | 0703 |
| Light duty cars and motorcycles, two-stroke | TRA_RD_LD2 | 0704 |
| Light duty cars and vans, four-stroke | TRA_RD_LD4 | 0701-02 |
| Light duty cars and vans, four-stroke, gasoline direct injection | TRA_RDXLD4 | 0701-02 |
| | | |
| **Off-road transport** | | |
| Other mobile sources and machinery, two-stroke engines | TRA_OT_LD2 | 0801-02, 0806-10 |
| Other land-based mobile sources and machinery, four-stroke engines | TRA_OT_LB | |
| | | |
| **Maritime activities, ships** | | |
| Medium vessels | TRA_OTS_M | 0803, |
| Large vessels | TRA_OTS_L | 080402-03 |

Table 2.6: RAINS sectors related to non-exhaust PM emissions.

| RAINS sector | RAINS code | SNAP sector |
|---|---|---|
| **Road transport, Tire wear** | | |
| Heavy duty vehicles (trucks, buses and others) | TRT_RD_HD | |
| Light duty cars, motorcycles, two-stroke | TRT_RD_LD2 | |
| Light duty cars and vans, four-stroke | TRT_RD_LD4 | |
| Light duty cars and vans, four-stroke, gasoline direct injection | TRT_RDXLD4 | |
| **Road transport, brake wear** | | |
| Heavy duty vehicles (trucks, buses and others) | TRT_RD_HD | |
| Light duty cars, motorcycles, two-stroke | TRT_RD_LD2 | |
| Light duty cars and vans, four-stroke | TRT_RD_LD4 | |
| Light duty cars and vans, four-stroke, gasoline direct injection | TRT_RDXLD4 | |
| **Road transport, abrasion of paved roads** | | |
| Heavy duty vehicles (trucks, buses and others) | TRD_RD_HD | |
| Light duty cars, motorcycles, two-stroke | TRD_RD_LD2 | |
| Light duty cars and vans, four-stroke | TRD_RD_LD4 | |
| Light duty cars and vans, four-stroke, gasoline direct injection | TRD_RDXLD4 | |

## 2.3 Emission Factors

Emission factors are the key to accurately assess PM emissions. For the present study it has been decided to identify, as far as possible, the main factors that could lead, for a given source category, to justified differences in emission factors across countries. The aim has been to collect country-specific information to quantify such justifiable deviations from values reported in the general literature. When this was not possible or when a source category makes only a minor contribution to total emissions, emission factors from the literature were used.

Within the PM module, unabated emission factors of total suspended matter (TSP) are the basis for deriving emission factors for fractions of the total range of PM mass concentrations. Emission factors of fine PM for two size classes, $PM_{10}$ (ø < 10 μm) and $PM_{2.5}$ (ø < 2.5 μm), are

calculated from the TSP estimates by using typical size profiles available in the literature (Lűtzke, 1982; Ahuja *et al.*, 1989; Houck *et al.*, 1989).

### 2.3.1 Emission Factors for Stationary Sources

Due to the large overall contribution of the stationary combustion of solid fuels to total PM emissions (varying between 50 and 65 percent for $PM_{2.5}$ and TSP), an attempt has been made to derive country-specific emission factors for power plants, industrial boilers, waste processing plants and domestic ovens. Emission factors have been computed by applying a mass balance approach: Country-specific information on the ash contents of different fuels (IEA, 1998), heat values (RAINS database), and the fraction of ash retained in the respective boiler type was used (e.g., Kakareka *et al.*, 1999; EPA, 1998a) (compare Equation 2). Emission factors for total suspended particulate matter (TSP) are estimated in a first step:

$$ef_{TSP} = ac/hv * (1 - ar)*10 \quad (2)$$

where:

| | |
|---|---|
| *ef* | unabated emission factor [g/MJ], |
| *ac* | ash content [%], |
| *hv* | lower heat value [GJ/t], |
| *ar* | fraction of ash retained in boiler . |

In a second step, the emissions of fine particulate matter (for two size fractions: $PM_{10}$ and $PM_{2.5}$) were calculated from the TSP estimates by using typical size profiles available in the literature (Ahuja *et al.*, 1989; Houck *et al.*, 1989). The order of magnitude of the emission factors obtained with this method was checked against values reported in the literature, summarized by Dreiseidler *et al.* (1999).

For PM emissions from the combustion of liquid fuels (gasoline, diesel, heavy fuel oil) and natural gas, emission factors from the literature have been used (for details see Section 3.1.3).

### 2.3.2 Emission Factors for Mobile Sources

For mobile sources, RAINS derives emission factors from the studies carried out in connection with the Auto Oil 1 and 2 Programmes (EC, 1999). Thus, the emission factors used in RAINS for the various vehicle categories are based on the full range of country specific factors such as driving pattern, fleet composition, climatic conditions, etc. that was considered in the Auto Oil analyses. For the RAINS assessment, fuel-related emission factors were obtained by dividing the volume of PM emissions calculated in the Auto Oil project for the RAINS vehicle categories by the respective fuel consumption.

Non-exhaust emission factors for road transport were extracted from various literature sources (see Section 3.3.2). Since such emission factors are usually reported in grams per kilometer (g/km), the fuel-efficiencies of the various vehicle categories have been used to convert them into the fuel-related emission factors. Time-dependent and country-specific fuel efficiencies are taken from the studies conducted for the Auto/Oil 2 Programme (EC, 1999).

Although highly uncertain, the RAINS model treats emissions from tire lining wear, brake wear and abrasion of paved roads as separate sources (see Sections 3.3.2.1, 3.3.2.2, 3.3.2.3).

### *2.3.3 Emission Factors for Other Sources*

In the RAINS model emission factors for industrial non-combustion emissions cover all contributions from a given sector defined (Section 3.2). Emission factors used in this study are mainly based on U.S. data (EPA, 1998a), reviewed by Passant *et al.* (2000).

## 2.4 Emission Control Options

### *2.4.1 Stationary Sources*

In addition to the obvious "structural changes" that lead to a lower consumption of emission generating fuels, there are several end-of-pipe options for reducing particulate matter emissions from stationary sources (Darcovich *et al*., 1997). The following paragraphs briefly review the main options and their technical characteristics.

#### *2.4.1.1 A Review of Available Control Options*

***Inertial Settlers and Cyclones***

The general principle of cyclones is the inertial separation of particles and gas stream. Particulate laden gas is forced to change direction, and the inertia of the particles causes them to continue in the original direction. In Western Europe (multi-)cyclones are usually only used as pre-dedusters (pre-cleaners) for the collection of medium-sized and coarse particles. The net downward motion of particles will arise at sizes larger than 5 μm. Thus gravity settling will be efficient only on large particles (40 to 50 μm). The removal efficiency drops if the fines content of the particulate matter is significant and generally does not lead to a substantial reduction of $PM_{0.1}$ emissions.

***Wet Scrubbers***

In the most widely used Venturi scrubber, water is injected into the flue gas stream at the Venturi throat to form droplets. Fly ash particles impact with the droplets forming a wet by-product, which then generally requires disposal. The process can also have a high energy consumption due to the use of sorbent slurry pumps and fans.

The efficiency of wet scrubbing for particulate removal depends on the particle size distribution. The system efficiency is reduced as the particle size decreases. Many of the wet scrubbers are designed to control both $SO_2$ and particulates by utilizing the alkaline fly ash as sorbent material. Lime is frequently used to boost $SO_2$ removal efficiencies (see also the RAINS $SO_2$ module; Cofala and Syri, 1998a).

***Fabric Filters***

Dust particles moving through fabric filters often form a porous cake on the surface of the fabric. This cake normally does the bulk of the filtration. Conventional reverse-gas-cleaned fabric filters (baghouses, RGB) are quickly replaced by pulse-jet fabric filters (PJFF). Periodic short, powerful bursts of air are used to clean the fabric mounted in cylindrical bags.

Interception (fibrous or granular filter media) is effective on particles down to 2-3 μm. Effective processes to remove particles smaller than 0.2 μm are thermal precipitation (cold collection system) and diffusional deposition (fibrous or granular filter media and small liquid droplets).

***Electrostatic Precipitators (ESP)***

In electrostatic precipitators (ESP), particles are given an electric charge by forcing them through a region in which gaseous ions flow. Electrodes in the center of the flow channel maintain a high voltage, forcing particles to move out of the flowing gas stream onto collector plates. The particles are removed from the plates by knocking them loose or by washing with water. Updating of ESP technology aims especially at improving the collection of ultra-fine particles. ESP can tolerate temperatures as high as 400 $^{o}$C.

The performance of fabric filters and some scrubbers can also be enhanced with electrostatic charging. Electrostatic force is the strongest process commonly used as PM removal technology that can act on fine particles smaller than 2-3 μm.

***High Temperature, High Pressure (HTHP) Particulate Control***

During the last decade there have been significant advances towards the commercialization of combined cycle systems, such as the integrated gasification combined cycle (IGCC) and pressurized fluidized bed combined cycle (PFBCC). Commercial- and demonstration-scale designs are currently used for power generation in the United States, Europe and Japan. An important component in combined cycle power systems is a high temperature, high pressure (HTHP) particulate control device.

Efficient hot gas particulate filtration is necessary to protect the downstream heat exchanger and gas turbine components from fouling and erosion to meet emission requirements. A range of technologies has been proposed for hot gas particulate filtration but few have been developed sufficiently to enable commercial exploitation in combined cycle power systems.

### 2.4.1.2 Control Options Implemented in the RAINS Model

In the interest of keeping a European-scale analysis manageable, the RAINS model considers a limited number of emission control options reflecting groups of technological solutions with similar emission control efficiencies and costs. For large boilers in industry and power stations, six options are distinguished:

- Gravity / inertial settlers;
- Cyclones (centrifugal separators);
- Wet scrubbers;
- Electrostatic precipitators;
- Fabric, packed, bed or rigid barrier filters;

High temperature, high pressure particulate control.

In addition, RAINS includes a non end-of-pipe measure for industrial and residential emission sources:

- Regular maintenance of oil fired industrial and residential boilers.

For wood burning, which is a major source of PM emissions, improved burning technologies are considered for new stoves:

- Improved wood burning technologies (e.g., catalytic combustor, primary and secondary air deflectors), three stages.

The RAINS model considers size-fraction specific removal efficiencies for these control options (Table 2.7).

Table 2.7: Removal efficiencies for the size fractions > $PM_{10}$, COARSE, FINE (= $PM_{2.5}$) considered in RAINS.

| Control technology | Removal efficiency | | |
|---|---|---|---|
| | > $PM_{10}$ | COARSE | FINE |
| Cyclone | 90.0% | 70.0% | 50.0% |
| Bag houses | 99.9% | 99.0% | 96.0% |
| Electrostatic precipitator, 1 field | 97.0% | 95.0% | 93.0% |
| Electrostatic precipitator, 2 fields | 99.9% | 99.0% | 96.0% |
| Electrostatic precipitator, 3 fields and more | 99.95% | 99.9% | 99.0% |
| Wood fired boilers, stage 1 | 50.0% | 50.0% | 50.0% |
| Wood fired boilers, stage 2 | 60.0% | 60.0% | 60.0% |
| Wood fired boilers, stage 3 | 76.0% | 76.0% | 76.0% |
| Coal fired stoves, stage 1 | 30.0% | 30.0% | 30.0% |
| Coal fired stoves, stage 2 | 50.0% | 50.0% | 50.0% |
| Oil fired stoves, regular maintenance | 30.0% | 30.0% | 30.0% |

### 2.4.2 Mobile Sources

Primary particle emissions from mobile sources have two entirely different origins: exhaust due to fuel combustion and non-exhaust emissions, i.e., tire and brake wear and road abrasion or re-suspension (dust swept up or entrained into the air by passing traffic). In this section options to control exhaust emissions of PM as well as their implementation in RAINS are discussed.

#### 2.4.2.1 A Review of Available Control Options

Emission control options for mobile sources can be divided into the following categories:

- ***Changes in fuel quality***, e.g., decreases in sulfur content. Changes in fuel specifications may provide engine manufactures with greater flexibility to use new emission reduction technologies.
- ***Changes in engine design***, which result in better control of the combustion processes in the engine.
- ***Flue gas post-combustion treatment***, using various types of trap concepts and catalysts to convert or capture emissions before they leave the exhaust pipe.
- ***Better inspection and maintenance***. Examples are: in-use compliance testing, in-service inspection and maintenance, on-board diagnostic systems.

***Diesel Fuels and Clean Diesel Engines***

High sulfur or aromatics contents have an impact on the quantity and quality of particulate matter emissions. They also interfere with several technologies controlling diesel exhaust. A reduction of fuel density lowers $NO_x$ and PM emissions, but on the other hand it increases hydrocarbon (HC) and carbon monoxide (CO) exhaust. The use of synthetic diesel fuel, gained from feedstock such as gas or coal, significantly reduces all pollutant emissions, including PM. Other measures, which may result in lower PM emissions, are the use of biodiesel, derived from various vegetable oils, and of dimethyl ether (DME), made for example from natural gas and coal (http://www.dieselnet.com).

Changes in diesel engine design have reduced emissions from diesel vehicles by more than 90 percent. Important improvements are electronic controls and fuel injectors to deliver fuel at the best combination of injection pressure, injection timing and spray location, air-intake improvements, combustion chamber modifications, exhaust gas recirculation and ceramic in-cylinder coatings (see also Cofala and Syri 1998b).

***Diesel Catalyst Technology***

Catalysts increase the rate of chemical reaction. In emission control applications heterogeneous catalysts are used, which are supported on high surface area porous oxides. Two processes may

cause malfunction of emission control catalysts: poisoning and thermal deactivation. The catalyst's active sites can be chemically deactivated or the catalytic surface can be mask, mainly by sulfur and phosphorus. High temperature can result in a sintering of the catalytic material or the carrier.

Diesel oxidation catalysts were first introduced in the 1970s in underground mining as a measure to control CO. Today catalysts are used on many diesel cars in Europe, primarily to control PM and hydrocarbon emissions. Early diesel catalysts utilized active oxidation formulations such as platinum on alumina. They were very effective in oxidizing emissions of CO and HC as well as the organic fraction (SOF) of diesel particles.

However, catalysts also oxidize sulfur dioxide, which is present in diesel exhaust from the combustion of sulfur containing fuels. The oxidation of sulfur to $SO_2$ leads to the generation of sulfate particulate matter. This may significantly increase total primary particle emissions although the SOF PM fraction is reduced. Newer diesel oxidation catalysts are designed to be selective, i.e., to obtain a compromise between sufficiently high HC and SOF activity and acceptably low formation of $SO_2$.

***Diesel Particulate Traps***

Diesel particulate traps physically capture diesel particles preventing their release to the atmosphere. Diesel traps work primarily through a combination of deep-bed filtration mechanisms, such as diffusional and inertial particle deposition. The most common filter materials are ceramic wall-flow monoliths and filters made of continuous ceramic fibers. A number of methods have been proposed to regenerate diesel filters.

Passive filter systems utilize a catalyst to lower the soot combustion temperature. Active filter systems incorporate electric heaters or fuel burners to burn the collected particles.

The regeneration of a diesel filter is characterized by a dynamic equilibrium between the soot being captured in the filter and the soot being oxidized. The rate of soot oxidation depends on the filter temperature. At temperatures that are typically found in diesel exhaust gases, the rate of soot oxidation is small. Therefore, to facilitate filter regeneration, either the exhaust gas temperature has to be increased or a catalyst has to be applied. The catalyst can be applied directly onto the filter media or dissolved in the fuel as a fuel additive.

**Wall-flow monoliths** became the most popular diesel filter design. They are derived from flow-through catalyst supports where channel ends are alternatively plugged to force the gas flow through porous walls acting as filters. The monoliths are made of specialized ceramic materials. Most catalyzed diesel traps utilize monolithic wall-flow substrates coated with a catalyst. The catalyst lowers the soot combustion temperature, allowing the filter to self-regenerate during periods of high exhaust gas temperature. Filters of different sizes, with and without catalysts, have been developed and are available as standard products.

The **CRT (Continuously Regenerating Trap)** system for diesel particulate utilizes a ceramic wall-flow filter to trap particles. The trapped PM is continuously oxidized by nitrogen dioxide generated in an oxidation catalyst, which is placed upstream of the filter. The CRT requires practically sulfur free fuel for proper operation.

**Fuel additives** (fuel soluble catalysts) can be used in passive diesel trap systems to lower the soot combustion temperature and to facilitate filter regeneration. The most popular additives include iron, cerium, copper, and platinum. Many laboratory experiments and field tests have been conducted to evaluate the regeneration of various diesel filter media using additives. Cerium additive is utilized in a commercial trap system for diesel cars.

**Electric regeneration** of diesel traps has been attempted in off- and on-board configuration. On-board regeneration by means of an electric heater puts a significant additional load on the vehicle electrical system. Partial flow layouts or regeneration with hot air are more energy efficient. An on-board, hot air regenerated diesel trap was tested on over 2000 urban buses in the U.S. A system with off-board electric regeneration has also been developed and commercialized.

Diesel **fuel burners** can be used to increase the exhaust gas temperature upstream of a trap in order to facilitate filter regeneration. Fuel burner filters can be divided into single point systems and full flow systems. The full flow systems can be regenerated during regular vehicle operation but require complex control strategies to ensure a thermally balanced regeneration. An advanced system featuring electronically controlled full flow burner regeneration has been developed.

Diesel soot has microwave absorption properties and there are filter substrate materials that are transparent to **microwave irradiation**. Microwave heating is another method to regenerate diesel particle filters.

#### *2.4.2.2 Control Options Implemented in the RAINS Model*

The options to control diesel vehicle emissions considered in the present RAINS PM module are listed in Table 2.8.

It has been assumed that for gasoline exhaust catalytic converters lead to a reduction of PM emissions of 50 percent (Euro I to Euro V). This percentage is based on the difference in emission factors for unleaded fuel with and without three-way catalysts as reported by APEG (1999).

Table 2.8: Control options for PM emissions from diesel vehicles.

| | Control technology / EU standards [(1)] | PM emission standard |
|---|---|---|
| Diesel - | Euro I - 1992 / 94 | 0.14 g/km |
| passenger cars and light duty vehicles | Euro II - 1996 | 0.08 g/km |
| GVW < 1305 kg | Euro III - 2000 | 0.05 g/km |
| | Euro IV - 2005 | 0.025 g/km |
| | Fuel additive | --- |
| | PM traps | --- |
| Diesel - | Class II - 1994 | 0.16 g/km |
| light duty vehicles | Class II- 2001 | 0.07 g/km |
| GVW 1305 to 1760 kg | Class II - 2006 | 0.04 g/km |
| | Fuel additive | --- |
| | PM traps | --- |
| Diesel - | Class III - 1994 | 0.25 g/km |
| light duty vehicles | Class III - 2001 | 0.10 g/km |
| GVW > 1760 kg | Class III - 2006 | 0.06 g/km |
| | Fuel additive | --- |
| | PM traps | --- |
| Diesel - | Euro I - 1992, <85 kW | 0.61 g/kWh |
| heavy duty trucks and bus engines | Euro I - 1992, >85 kW | 0.36 g/kWh |
| | Euro II - 1996 | 0.25 g/kWh |
| | Euro II - 1998 | 0.15 g/kWh |
| | Euro III - 2000 | 0.10 g/kWh |
| | Euro IV and V - 2005 & 2008 (fitted with PM traps) | 0.02 g/kWh |

[(1)] Directive 98/69/EC (Diesel Cars and Light-Duty Trucks); Directive 88/77/EEC (Heavy- Duty Diesel Truck and Bus Engines).

# 3 Emission Source Categories

The following sections briefly characterize the PM source categories included in the RAINS model. This includes the origin of the emissions, their contribution to primary particulates, the activity data used in the model, emission factors and a list of applicable control options.

## 3.1 Fuel Combustion in Stationary Sources

The combustion of fossil fuels in stationary installations is a major source of PM emissions in Europe. It is estimated that in 1990 about 65, 66, and 52 percent of TSP, $PM_{10}$, and $PM_{2.5}$, respectively, were emitted from these sources. Nearly 50 percent originate from small residential and domestic combustion installations.

Primary particulate emissions from combustion processes can roughly be divided into two categories (Flagan and Seinfeld, 1988):

- ash, i.e., a combustion product formed from non-combustible mineral constituents in fuel; typically containing from about two to 30 percent of non-combustible mineral material (McElroy *et al.*, 1982), and
- carbonaceous particles, e.g., char, coke and soot, which are formed by pyrolysis of unburned fuel molecules.

The largest particles of ash and unburned fuel remain in the boiler and are extracted from the process with bottom ash. Smaller particles, typically <100-300 μm, entrain in the combustion gas, forming so-called combustion aerosols or fly ash. Part of the combustion aerosol particles might deposit onto the boiler walls or heat exchanger surfaces. Power and heat generating plants produce enormous quantities of by-product fly ash and PM emission controls are therefore essential to minimize the emissions particles to the atmosphere. In today's power plants and industrial boilers, emission control appliances, such as cyclones or electrostatic precipitators, capture the major part of particles leaving the boiler.

This section is divided into three sub-sections, focusing on solid fuel combustion (excluding fuelwood burning), wood combustion in small residential and domestic boilers and stoves, and the combustion of liquid fuel in stationary sources.

### RAINS Sectors

| | | |
|---|---|---|
| PP_EX_OTH | IN_BO | DOM |
| PP_EX_WB | IN_OC | |
| PP_NEW | CON_COMB | |

### *3.1.1 Emissions from Combustion of Solid Fuels*

Ash-forming species are the main source of particles of solid combustion under controlled conditions, e.g., in power plants and large industrial boilers. For instance, the share of unburned fuel in total particulate emissions of combustion of pulverized coal is normally less than five percent (Lammi *et al.*, 1993). Emissions from fluidized bed combustion also contain particles of the bed material and, if limestone injection into the boiler is applied, also particles originating from limestone. For small-scale boilers and stoves that are mainly used in the domestic sector the share of unburned fuel is usually high.

#### Description

Activity: Burning of solid fuels (excluding fuelwood) in stationary sources (power plants, industry and residential sector).

Unit: **kt/PJ** fuel consumed.

#### Emission factors

To reflect the differences in fuel qualities across countries, TSP emission factors for solid fuels are calculated with a mass balance approach using country-specific data on ash content, heat value and the fraction of ash retained in the boiler following the methodology of Section 2.3.1.

Combustion conditions, especially in large boilers, have a strong influence on mass concentrations of TSP, $PM_{10}$ and $PM_{2.5}$ in the flue gas and on PM size distribution profiles (e.g., Flagan and Seinfeld, 1988; Moisio, 1999). Ash-forming minerals account for most of the particulate matter emissions from solid fuels and form particles of different sizes depending on e.g., mineral matter composition and combustion conditions. Mineral matter, occurring as mineral inclusions or heteroatoms present in the coal molecules, consists of refractory metal oxides ($SiO_2$, MgO, FeO, $Al_2O_3$ *etc.*) and more volatile species (Na, K, Cd, As, Pb, etc.). Refractory compounds are not directly volatilized at the temperatures of normal combustion processes, and they form mainly relatively large sized particles (1-50 μm). Volatile compounds volatilize in high temperatures. A small part of the refractory species might also volatilize in reductive high temperature conditions. Volatilized species mainly form very small particles (0.01-0.5 μm) via nucleation, condensation, agglomeration and coagulation (Flagan and Seinfeld, 1988).

The source sector split distinguished in RAINS does not allow including all these combustion parameters. However, a distinction was made for power plants and industry between three types of boilers, which are characterized by significantly different ash retention as well as particle size distribution (Lind, 1999):

- Grate combustion (e.g., PP_EX_OTH1). Typically smaller installations. Industrial coal plants are slowly replaced with fluidized bed combustion but remain important for

biomass combustion. Particles from grate combustion are usually relatively large, with a mean size of 60-70 μm (Lammi *et al.*, 1993).

- Fluidized bed combustion (FBC) (e.g., PP_EX_OTH2), typically mid-size (up to 100 MW) installations. The theories of fine particle formation presented in the literature (*e.g.*, Lind, 1999) suggest that particle size distributions in fluidized bed combustion are different to pulverized fuel combustion. Since boiler temperatures in atmospheric fluidized bed combustion installations are lower, volatilization of ash takes place at a lesser extent and less fine particles are formed. In the coarse particle mode (particles larger than 2.5 μm), FBC produces larger ash particles than pulverized fuel combustion (Moisio, 1999). In addition, some relatively large particles of bed material and, if limestone injection is used, particles originating from limestone are also entrained with the flue gas. Mean fly ash particle sizes before ESP in circulating FB combustion of coal of 20-30 μm have been measured (Lind *et al.*, 1995, 1996).
- Pulverized fuel combustion (e.g., PP_EX_OTH3). Globally, pulverized coal combustion is a very common way of energy utilization, and the particle formation in these types of boilers has been widely studied. Coal is first milled to a fine powder (40-80 μm) and then blown into the boiler. Combustion temperatures are high, reaching up to 2000 K. Because of these high temperatures, volatile species and a small fraction of the refractory components of the ash-forming species are effectively volatilized. Volatilized species mainly form small particles (0.01-0.5 μm) via nucleation, condensation, agglomeration and coagulation (Flagan and Seinfeld, 1988). The fraction of the volatilized ash is usually less than ten percent. The non-volatilized mineral compounds form larger ash particles, usually above 1 μm (Moisio, 1999). Pulverized fuel combustion of peat is somewhat analogous to coal (Moisio, 1999).

The ash retention parameter is used in addition to the fuel characteristics to enable a more accurate reflection of “raw gas” emission rates. Table 3.1, Table 3.2 and Table 3.3 below present an overview of reported emission factors and measured size fraction distributions.

Table 3.1: Uncontrolled emission factors reported in the literature for coal combustion [kt/PJ].

| Source | Installation type | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| BUWAL, 2001 | Small furnaces | | | 0.110 | | 0.270 |
| | Domestic boilers | | | 0.090 | | 0.150 |
| | Industrial boilers | | | 0.045 | | 0.050 |
| UBA, 1999a | Domestic furnaces, hard coal | | | | | 0.250 |
| | Domestic furnaces, brown coal | | | | | 0.350 |
| EPA, 1998a | Small boilers, top loading | | | | | 0.291 |
| | Small boilers, bottom loading | | | | | 0.273 |
| | Pulverized coal, dry bottom boilers | | | | | 1.818 |
| | Pulverized coal, wet bottom boilers | | | | | 1.273 |
| | Hard coal, stoker firing | | | | | 1.200 |
| | Pulverized lignite boilers | | | | | 1.105 |
| Lammi *et al.*, 1993 | Pulverized | | | | | 3.6 – 5.4 |
| | Fluidized bed | | | | | 4.3 – 7.2 |
| Meier and Bischoff, 1996 | Grate firing, lignite | | | | | 2.237 |

Table 3.2: Size fractions reported in the literature for coal combustion [percent of TSP emissions].

| Source | Installation type | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| UBA, 1999a | Domestic furnaces, hard coal | | | 90 % | | 100 % |
| EPA, 1998a | Small boilers, top loading | 14 % | | 37 % | | 100 % |
| | Small boilers, bottom loading | 25 % | | 41 % | | 100 % |
| | Pulverized hard coal, dry bottom, no control | 6 % | | 23 % | | 100 % |
| | Pulverized hard coal, wet bottom, no control | 21 % | | 37 % | | 100 % |
| | Pulverized lignite, no control | 10 % | | 35 % | | 100 % |
| Moisio, 1999 | Pulverized, hard coal, no control | 6 % | | 52 % | | 100 % |
| | Fluidized bed, hard coal, no control | 5 % | | 26 % | | 100 % |

Table 3.3: Size fractions used in RAINS for solid fuel combustion [percent of TSP emissions].

| Fuel | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|
| Coal | 13 % | 39 % | 52 % | 48 % | 100 % |
| Derived coal | 30 % | 40 % | 70 % | 30 % | 100 % |
| Biomass | 93 % | 3 % | 96 % | 4 % | 100 % |
| Waste | 60 % | 30 % | 90 % | 10 % | 100 % |

### Applicable Control Options

The control options used in the RAINS model includes end-of-pipe techniques for industrial installations, i.e., cyclones, bag filters and electrostatic precipitators. For small coal combustion installations in the residential and domestic sector, two types of modern boilers/stoves (see Table 2.7) are included to simulate the gradual replacement of old facilities (no end-of-pipe options are considered for this sector).

### *3.1.2 Emissions from Wood Burning*

The available literature suggests wood burning is a major source of PM emissions. However, it is rather difficult to accurately estimate PM emissions from wood burning for a number of reasons:

- There are serious questions about the accuracy of wood consumption statistics, since the non-commercial use of fuelwood is difficult to quantify;
- There are hundreds of types of wood burning devices in use, especially in the residential and domestic sector;
- Several tree species are used for fuelwood and the literature suggests a strong dependency between PM emissions and wood type;
- Practices of storing and seasoning fuel wood vary (affecting wood moisture);
- The variation of household altitude;
- The variation of chimney conditions between different homes; and
- The large variations in the operation of wood burning devices, i.e., burn rate, burn duration, damper setting, etc.

Each of these parameters has significant impacts on combustion conditions and will change emissions (Houck *et al.*, 2001).

#### Description

Activity: Combustion of fuel wood in industry and residential and domestic sector.

Unit: **kt/PJ** fuel consumed.

#### Emission Factors

So far, only limited measurement data have been used to represent a large number of appliances and variables. Some of the older emission rates reported in, for example, EPA (1998a,b) are not always appropriate for representing present European conditions because there has been a considerable improvement in the performance of devices leading to lower emissions (Houck *et al.*, 2001). As demonstrated in Table 3.4, the emission rates reported in the literature vary greatly reflecting the large differences in combustion parameters of inspected appliances.

Another very important aspect of PM emissions from the domestic combustion of wood is the size distribution of particulate matter. Several studies indicate that up to 95 percent of the particulate mass emitted from this source is in the fine fraction (e.g., Smith, 1987; Ahuja *et al.*, 1989; Houck *et al.*, 1989; Tullin and Johansson, 2000; Baumbach *et al.*, 1999; Dreiseidler *et al.*, 1999). This might have consequences for the importance of this source when evaluating the health effects of PM emissions. Examples of the size distribution for wood combustion installations are shown in Table 3.5.

The emission factors used in the RAINS model were derived from the values reported in the literature (see Table 3.4 and Table 3.5) and are shown in Table 3.6. It was decided to use different values across European countries reflecting different operating practices, age of installations, etc.

Table 3.4: Uncontrolled emission factors reported in the literature for wood burning [kt/PJ].

| Source | Installation type | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| BUWAL, 2001 | Domestic open fire places | | | 0.150 | 0 | 0.150 |
| | Domestic furnaces | | | 0.150 | 0 | 0.150 |
| | Domestic small boilers, wood pieces | | | 0.050 | 0 | 0.050 |
| | Small boilers, automatic loading | | | 0.080 | | 0.080 |
| Karvosenoja, 2000 | Domestic furnaces | | | | | 0.2-0.5 |
| Dreiseidler, 1999 | Domestic furnaces | | | | | 0.200 |
| Baumbach, 1999 | Domestic furnaces | | | | | 0.05-0.10 |
| TNO, 2001 | Domestic heating | 0.09-0.18 | | 0.095-0.19 | | 0.1-0.2 |
| NUTEK, 1997 | Single family house boiler, conventional | | | | | 1.500 |
| | Single family house boiler, modern with accumulator tank | | | | | 0.017 |
| Smith, 1987 | Residential heating stoves <5 kW | | | | | 1.350 |
| | Residential cooking stoves <5 kW | | | | | 0.570 |
| | Industrial boilers | | | | | 0.350 |
| BUWAL, 1995 (1992 Swiss limit value) | up to 1 MW | | | | | 0.106 |
| Zhang *et al*., 2000 | Firewood in China | | | | | 0.76-1.08 |
| EPA, 1998b [(1)] | Open fireplaces | | | 0.805 | | 0.875 |
| | Wood stove | | | 0.724 | | 0.787 |
| EPA, 1998a | Boilers, bark | | | | | 2.266 |
| Lammi *et al*., 1993 | Fluidized bed in large boilers | | | | | 1.0-3.0 |
| | Grate firing in large boilers | | | | | 0.25-1.50 |

[(1)] Original factors in lb/ton, for recalculation heating value of 16 GJ/tonne was assumed.

Table 3.5: Size fractions reported in the literature for wood burning [percent of TSP emissions].

| Source | Sector | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Dreiseidler, 1999 | Domestic furnaces | | | 90 % | | 100 % |
| | Wood pellets | 84.4 % | | 94.6 % | | 100 % |
| EPA, 1998b | | | | 92 % | | 100 % |
| Baumbach, 1999 | Domestic furnaces | 96 % | | 99.7 % | | 100 % |
| UMEG, 1999 | Small boilers | 79 % | | 92 % | | 100 % |

Table 3.6: Emission factors used in the RAINS model for wood burning [kt/PJ].

| Sector | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|
| Domestic, Western Europe | 0.145-0.28 | 0.005-0.012 | 0.15-0.29 | 0.006-0.012 | 0.15-0.30 |
| Domestic, Eastern Europe | 0.465 | 0.015 | 0.48 | 0.02 | 0.50 |
| Industry | 0.26–0.49 | 0.01 | 0.27–0.5 | 0.01-0.02 | 0.28-0.52 |

### Applicable Control Options

The control options considered in the RAINS model include end-of-pipe techniques for industrial installations, i.e., cyclones, bag filters and electrostatic precipitators. For small installations in the residential and domestic sectors three types (stages) of modern boilers/stoves (see Table 2.7) are included to simulate the gradual replacement of old facilities (no end-of-pipe options are considered for this sector).

## *3.1.3 Emission Factors for Liquid Fuels, Natural Gas and LPG*

Normally, liquid fuels contain less ash-forming species than coal. For example, the major parts of emitted particulate mass from heavy fuel oil boilers are unburned carbonaceous coke particles (Flagan and Seinfeld, 1988).

### Description

Activity: Burning of liquid and gaseous fuels in stationary sources (power plants and industry).

Unit: **kt/PJ** fuel consumed.

## Emission Factors

Coke particles from heavy fuel oil combustion are relatively large (1-50 μm). In comparison, soot particles are very small (0.01-0.5 μm) and can be produced during the combustion of gaseous fuels and from the volatilized carbonaceous components of liquid and solid fuels (Flagan and Seinfeld, 1988). An overview of the reported emission rates for the stationary combustion of heavy and light fuel oils is provided in Table 3.7 and Table 3.10. Only a few studies have reported the size distribution of PM emissions (Table 3.8 and Table 3.11).

At this stage of development, the RAINS model uses uniform emission factors across all countries (Table 3.9 and Table 3.12). However, comparing heavy fuel oil combustion in the former German Democractic Republic (GDR) and West Germany shows that there is a potentially significant international difference of up to a factor of three (Dreiseidler *et al.*, 1999). Thus, the current RAINS values might represent a lower end estimate for Eastern Europe, although it is not always possible to determine the level of control for the emission rates reported in the literature.

***Heavy Fuel Oil***

Table 3.7: Uncontrolled emission factors reported in the literature for stationary combustion of heavy fuel oil [kt/PJ].

| Literature source | Type | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| BUWAL, 2001 | Industrial boilers | | | 0.023 | | 0.0239[(1)] |
| BUWAL, 1995 | Power plants | | | | | 0.023[(1)] |
| BUWAL, 1995 | Refineries, after control | | | | | 0.043 |
| EPA, 1998a in Dreiseidler *et al.*, 1999 | Large boiler, no control | | | | | 0.238 |
| EPA, 1995 in Berdowski *et al.*, 1997 | Power plants | | | 0.038 | | |
| | Industry | | | 0.020 | | |
| UBA, 1989 | Power plants | | | 0.015 | | 0.016 |
| | Conversion | | | 0.028 | | 0.031 |
| | Industry | 0.023 | | 0.027 | | 0.030 |
| | Residential | | | 0.045 | | 0.050 |
| UBA, 1998 in Dreiseidler *et al.*, 1999 | Power plants | | | 0.0065 -0.021 | | 0.0068-0.0219 |
| | Conversion & residential | | | 0.008-0.027 | | 0.009-0.030 |
| | Industry | 0.0028 -0.012 | | 0.0033 -0.014 | | 0.0037-0.0156 |
| Lammi *et al.*, 1993 | 5-50 MW | | | | | 0.025-0.15 |
| Ohlström, 1998 | 5-50 MW | | | | | 0.001-0.390[(2)] |
| Berdowski *et al.*, 1997 | Power plants | 0.025 | | 0.038 | | |
| | Industry | 0.014 | | 0.020 | | |
| | Residential | 0.030 | | 0.050 | | |

[(1)] Emission limit value in Switzerland.

[(2)] Average value 0.032 kt/PJ.

Table 3.8: Size fractions reported in the literature for stationary combustion of heavy fuel oil [percent of TSP].

| Source | Sector | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| EPA, 1998a | Large boiler, no control | 52 % | | 71 % | | 100 % |
| | Industry, no control | 56 % | | 86 % | | 100 % |
| | Residential boilers | 23 % | | 62 % | | 100 % |
| Lützke, 1987 | Industry, no control | 76 % | | 92 % | | 100 % |
| Berdowski *et al.*, 1997 | Power plants and industry | 75 %[(1)] | | | | |

[(1)] As a percent of $PM_{10}$.

Table 3.9: Emission factors used in the RAINS model for stationary combustion of heavy fuel oil [kt/PJ].

| Sector | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Power plants | PP_NEW, PP_EX | 0.0093 | 0.0039 | 0.0132 | 0.0023 | 0.0155 |
| Conversion | CON_COMB | 0.0117 | 0.0049 | 0.0166 | 0.0029 | 0.0195 |
| Industry | IN_BO, IN_OC | 0.0104 | 0.0043 | 0.0147 | 0.0026 | 0.0173 |
| Domestic | DOM | 0.0070 | 0.0112 | 0.0182 | 0.0098 | 0.0280 |

***Heating Oil (Light Fuel Oil, Middle Distillates)***

Table 3.10: Uncontrolled emission factors reported in the literature for stationary combustion of light fuel oil (middle distillates) [kt/PJ].

| Source | Sector | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| BUWAL, 2001 | Domestic furnaces | | | 0.001 | | 0.001 |
| | Domestic boilers | | | 0.0002 | | 0.0002 |
| | Industrial boilers | | | 0.0003 | | 0.0003 |
| UBA, 1989 | Power plants, conversion | | | | | 0.0033 |
| | Industry, residential | | | | | 0.0015 |
| UBA, 1998 | All | | | | | 0.0015 |
| Ohlström, 1998 | 0-50 MW plants | | | | | 0.003-0.100[(1)] |
| Berdowski *et al.*, 1997 | Power plants | 0.005 | | 0.005 | | |
| | Industry | 0.004 | | 0.004 | | |
| | Residential sector | 0.03 | | 0.03 | | |
| EPA, 1998a | Conversion, industry | | | | | 0.0047 |

(1) Average value 0.070 kt/PJ.

Table 3.11: Size fractions reported in the literature for stationary combustion of light fuel oil (middle distillates) [as a percent of TSP, except APEG, 1999 and Berdowski *et al.*, 1997].

| Source | Sector | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| EPA, 1998a | Domestic boilers | 42% | | 55% | | 100% |
| | Conversion, industry | 12 % | | 50 % | | 100% |
| APEG, 1999 [(1)] | Power plants | 43 % | | | | |
| | Industry | 25 % | | | | |
| | Residential sector | 76-94% | | | | |
| Berdowski *et al.*, 1997 [(1)] | Domestic | 60 % | | | | |

(1) The values refer to $PM_{10}$ and not to TSP

Table 3.12: Uncontrolled emission factors used in the RAINS model for stationary combustion of light fuel oil (middle distillates) [kt/PJ]

| Sector | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Power plants | PP_NEW | 0.0004 | 0.0007 | 0.0011 | 0.0011 | 0.0022 |
| | PP_EX | 0.0007 | 0.0011 | 0.0018 | 0.0018 | 0.0036 |
| Conversion | CON_COMB | 0.0004 | 0.0014 | 0.0018 | 0.0018 | 0.0036 |
| Industry | IN_BO, IN_OC | 0.0003 | 0.0008 | 0.0011 | 0.0011 | 0.0022 |
| Domestic | DOM | 0.0009 | 0.0001 | 0.0010 | 0.0009 | 0.0019 |

***Natural Gas***

Table 3.13 reviews the emission factors reported in the literature for the combustion of natural gas in stationary sources. Although there is some variation between the reported rates they are all relatively small and the overall contribution of this source to total PM is marginal. Only two studies have reported size fraction distribution (APEG, 1999; Berdowski *et al.*, 1997) and in both cases the assumption is that all particles are emitted in the $PM_{2.5}$ range. The same is assumed in the RAINS model (Table 3.14)

Table 3.13: Uncontrolled emission factors reported in the literature for stationary combustion of natural gas [kt/PJ].

| Literature source | Sector | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| BUWAL, 2001 | Domestic furnaces | | | 0.0005 | | 0.0005 |
| | Domestic boilers | | | 0.0002 | | 0.0002 |
| | Industrial boilers | | | 0.0001 | | 0.0001 |
| UBA, 1989; UBA, 1998 | All | | | | | 0.0001 |
| EPA, 1998a | All, no control | | | | | 0.0009 |

Table 3.14: Emission factors used in the RAINS model for stationary combustion of natural gas [kt/PJ].

| Sector | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Power plants | PP_NEW, PP_EX | 0.0001 | 0 | 0.0001 | 0 | 0.0001 |
| Conversion | CON_COMB | 0.0001 | 0 | 0.0001 | 0 | 0.0001 |
| Industry | IN_BO, IN_OC | 0.0001 | 0 | 0.0001 | 0 | 0.0001 |
| Domestic | DOM | 0.0001 | 0 | 0.0001 | 0 | 0.0001 |

### Applicable Control Options

For the combustion of heavy and light fuel oil in industrial installations, the RAINS model foresees primary measures (regular inspection and maintenance program) and end-of-pipe options (bag filters). For small installations in residential and domestic sector a regular inspection program (for example, obligatory check-ups, tuning and exchange of exploited parts as required annually in Austria) is included.

The RAINS model does not include any control options for gas-fired installations.

## 3.2 Stationary Non-Combustion Sources

### *3.2.1 Industrial Processes*

A wide variety of industrial processes emit particulate matter. These emission rates vary substantially among the processes and among the countries due to differences in technological development. Unfortunately, there is very little process- and country-specific information available, so the RAINS model uses, for the time being, uniform unabated emission factors for all countries. As in other inventories (e.g., Berdowski *et al.*, 1997), emission factors were derived for entire industrial branches and not for specific processes. The source sector split is compatible with a recent UK study reviewing available process emission factors (Passant *et al.*, 2000) and includes all those sources that are major contributors to PM emissions according to other studies (APEG, 1999 and Berdowski *et al.*, 1997).

It is estimated that industrial processes are probably the second largest source of particulate matter emissionsafter stationary combustion. According to RAINS calculations, industrial processes contributed about 24 percent of TSP and $PM_{10}$ and 31 percent of $PM_{2,5}$ in 1990 in Europe. About 65 percent of the emissions from this category originated from the iron and steel industry, nearly 30 percent from cement production and the remaining five percent from other industries. Other studies have produced similar results (e.g., APEG, 1999, TNO, 2001).

#### *3.2.1.1 Coke Production*

Coke is produced in ovens by pyrolysis of coal. There are a number of stages involved in coke production, i.e., crushing, screening, blending, charging and finally carbonization or coking when the coal is heated for several hours under low air conditions. After coking is completed, the coke is removed from the oven and moved to the quench tower where coke is cooled. After this, coke is transported on a conveyor for crushing and screening. All of these stages are potential sources of particulate matter (Table 3.15). It is estimated that about two percent of European PM emissions originate from this source.

**RAINS Sector:**

IN_PR_COKE

**Description**

Activity: Coke production for use in iron and steel industry, in foundries and as smokeless fuel.

Unit: **kg/t** coke produced.

## Emission Factors

Emission factors from the literature are listed in Table 3.15. The fact that there are considerable differences between the reported values and the background information does not always allow identifying between the processes included in the estimates and the level of emission controls that are applied to the various production stages. Table 3.17 illustrates the derivation of the emission factors used in the RAINS model, which is on EPA, 1998a and Passant *et al.*, 2000.

The size distribution examples given in Table 3.16 are derived from a more detailed analysis of the size fractions reported for specific processes in coke production. However, since this information is not readily available for all processes, and size distribution varies greatly between the processes, the reported values should be used with great care. Passant *et al.* (2000) concludes that $PM_{10}$ makes up about half of TSP, while there is more uncertainty about the share of $PM_{2.5}$. There are indications, however, that most $PM_{10}$ emissions are in the small fraction.

Table 3.15: Uncontrolled emission factors reported in the literature for coke production [kg/ton coke], excluding emissions from fuel combustion.

| Source | Abatement | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| UBA, 1989 | Unknown controls | | | | | 0.5 |
| UBA, 1989 [(1)] | Unknown controls | | | 0.5-1.1 | | |
| EPA, 1998a | Uncontrolled | | | | | 5.46 |
| EPA, 1995 [(1)] | Uncontrolled | | | 2.8 | | |
| Passant *et al.*, | Moderate control [(3)] | 0.55 | | 0.75 | | 1.40 |
| 2000 | Best control [(3)] | 0.30 | | 0.35 | | 0.70 |
| EEA, 1999 [(2)] | Uncontrolled | | | | | 0.8 – 5.0 |
| IPPC, 2000a[(2)] | Old plants | | | | | 0.48–0.75 |
| Berdowski *et al.*, | Uncontrolled | 0.15 | | 0.6 | | |
| 1997 | | | | | | |

[(1)] As quoted in Berdowski *et al.*, 1997.

[(2)] As quoted in Passant *et al.*, 2000.

[(3)] Estimated on the basis of EPA data and assumes door leaks uncontrolled.

Table 3.16: Size fractions reported in the literature for coke production [percent of TSP].

| Source | Installation | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Passant *et al.*, | UK coke plant, controlled | | | 54 % | | 100 % |
| 2000 | Moderate control [2] | 40 % | | 54 % | | 100 % |
| | Best control [2] | 43 % | | 50 % | | 100 % |
| Berdowski *et* | Uncontrolled | 25 % | | | | |
| *al.*, 1997 [1] | | | | | | |

[1] Relates to $PM_{10}$ and not to TSP emissions.

[2] Estimated on the basis of EPA data and assumes door leaks uncontrolled.

Table 3.17: Calculation of the emission factors for the RAINS model for coke production [kg/ton coke].

| Production stage | $PM_{2.5}$ | % of TSP | $PM_{10}$ | % of TSP | TSP |
|---|---|---|---|---|---|
| Coal pre-heater | 1.00 | 59.5 % | 1.70 | 97.5 % | 1.75 |
| Oven charging | 0.11 | 39.1 % | 0.12 | 48.9 % | 0.24 |
| Oven door leaks | --- | --- | --- | --- | 0.27 |
| Oven pushing | 0.10 | 16.7 % | 0.25 | 43.3 % | 0.58 |
| Quenching (dirty water) | 0.51 | 19.3 % | 0.60 | 22.8 % | 2.62 |
| Quenching (clean water) | 0.06 | 11.1 % | 0.17 | 30.1 % | 0.57 |
| Quenching with baffles (dirty water) | 0.13 | 20.4 % | 0.21 | 32.3 % | 0.65 |
| Quenching with baffles (clean water) | 0.02 | 6.0 % | 0.03 | 9.8 % | 0.27 |
| SUM: dirty water, without baffles | 1.34 | 24.5 % | 2.28 | 41.8 % | 5.46 |

Table 3.18: Emission factors used in the RAINS model for coke production [kt/ton coke].

| Sector | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Coke Production | IN_PR_COKE | 1.34 | 0.94 | 2.28 | 3.18 | 5.46 |

### Applicable Control Options

The IIASA RAINS model foresees several end-of-pipe control options for coke production (cyclones, bag filters and electrostatic precipitators) for this industry (Passant *et al.*, 2000;

Berdowski *et al.*, 1997). However, oven door and battery top leaks can be a source of significant fugitive PM emissions that cannot be controlled with such end-of-pipe techniques. Adopting good operational practices to prevent or reduce fugitive losses can minimize these emissions. At this stage, however, the RAINS model does not include such options but allows specifying the share of total unabated emissions that belong to this category (fugitive). The user can adjust this value in the control strategy for every five-year period.

#### *3.2.1.2 Pig Iron Production*

There are a large number of processes involved in iron production (see Table 3.19). A detailed description of these processes is not subject of this report. Instead, the reader is referred to EPA, 1998a; Passant *et al*., 2000 for more information. However, all stages of pig iron production are potential sources of particulate matter (see Table 3.19).

Based on RAINS estimates, about 11 percent of European PM originated from this source in 1990, and there are great differences between the countries. Berdowski *et al*. (1997) estimated a lower share of emissions from this source to total national PM emissions, but it is not possible to give an exact number since only total emissions from the iron and steel industry are reported.

**RAINS Sector:**

IN_PR_PIGI

**Description**

Activity: Iron and steel foundries, melting and refining of iron and steel, preparation of moulds, production of castings. Use of electric arc furnaces as part of iron and steel production.

Unit: **kg/t** iron/steel produced.

**Emission Factor**

Table 3.19 and Table 3.20 list the emission factors from the literature. There are considerable differences between the studies and the background information does not always allow linking the emission factors to the processes and determining the underlying level of emission controls for each stage of iron production. This is especially true for the numbers included in Table 3.20, where total emission rates for the whole sector are given. Table 3.21 shows how the emission factors of the RAINS model were estimated relying on data from EPA, 1998a and Passant *et al.*, 2000. These emission factors only included the activities and processes listed in this table. It must be kept in mind that these are only theoretical values, since the emissions from several of the processes, even at older plants, are usually controlled.

Similar to coke production, information on the size distribution of PM emissions is very scarce and data were not found for all processes. Hence, RAINS factors had to rely on EPA information (EPA, 1998a).

Table 3.19: Uncontrolled emission factors reported in the literature (EPA, 1998a; as quoted in Passant *et al.*, 2000) for pig iron production [kg/ton pig iron]

| Process | $PM_{2.5}$ | % of TSP | $PM_{10}$ | % of TSP | TSP |
|---|---|---|---|---|---|
| Cupola furnace | 5.80 | 84 % | 6.20 | 90 % | 6.90 |
| Electric arc furnace | 57.50[(1)] | 3.7 % | 5.80 | 90 % | 6.40 |
| Melting, electric arc | | | | | 6.50 |
| Melting, open hearth | | | | | 5.50 |
| Pouring and casting | | | 1.40 | | |
| Casting cleaning | | | 0.85 | | |
| Casting cooling | | | 0.70 | | |
| Charge handling | | | | | 0.18 |
| Scrap and charge handling, heating | | | | | 0.40 |
| Core making, baking | | | | | 0.60 |
| Basic oxygen furnace, top blown, melting, refining | | | | | 14.25 |
| Basic oxygen furnace, charging | 0.07 | 22 % | 0.14 | 46 % | 0.30 |
| Basic oxygen furnace, tapping | 0.17 | 37 % | 0.21 | 45 % | 0.46 |
| Blast furnace, slip (in g/t slip) | | | | | 39.50 |
| Blast furnace, furnace (in g/t hot metal) | 0.10 | 15 % | 0.16 | 24 % | 0.65 |
| Blast furnace, cast house emissions (in g/t hot metal) | 0.07 | 23 % | 0.15 | 51 % | 0.30 |
| Blast furnace, hot metal desulfurization (in g/t hot metal) | 0.06 | 11 % | 0.10 | 19 % | 0.55 |

(1) $PM_{2.0}$

Table 3.20: Emission factors reported in the literature for pig iron production [kg/ton pig iron].

| Literature source | Abatement | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| BUWAL 1995 | Controlled | | | | | 1.3 |
| UBA, 1989 (1) | Unknown | | | | | 1.8 – 4.5 |
| Berdowski *et al*., 1997 | Unknown | 0.1 | | 0.2 | | |

(1) as quoted in Berdowski *et al.*, 1997

Table 3.21: Calculation of emission factors used in the RAINS model for pig iron production [kg/ton pig iron].

| Source | $PM_{2.5}$ | % of TSP | $PM_{10}$ | % of TSP | TSP |
|---|---|---|---|---|---|
| Melting and refining, Electric arc furnace (carbon steel) | 8.17 | 43% | 11.02 | 58% | 19.00 |
| Charging, tapping, slagging (carbon steel) | 2.58 | 43%[1)] | 3.40 | 58%[1)] | 6.00 |
| Reverberatory | 0.23 | 20%[2)] | 0.55 | 50%[2)] | 1.10 |
| Pouring, cooling | 0.50 | 24% | 1.03 | 49% | 2.10 |
| Shakeout | 0.67 | 42% | 1.12 | 70% | 1.60 |
| SUM | 12.15 | 40% | 17.12 | 57% | 29.80 |

(1) Assumption: same fractions as for melting and refining.

(2) Assumptions based on similar processes.

Table 3.22: Emission factors used in the RAINS model for pig iron production [kg/ton pig iron].

| Sector | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Pig iron production | IN_PR_PIGI | 12.15 | 4.97 | 17.12 | 12.68 | 29.80 |

### Applicable Control Options

The RAINS model includes cyclones, bag filters and electrostatic precipitators as end-of-pipe control options for pig iron production (Passant *et al.*, 2000; Berdowski *et al.*, 1997). Similar to coke production, the issue of fugitive emissions is potentially very important. Adopting good operational practice to prevent or reduce fugitive losses can minimize these emissions. At this stage, however, the RAINS model does not include such options, but allows specifying the

share of total unabated emissions that belong to this category (fugitive). The user can adjust this value in the control strategy for every five-year period.

#### *3.2.1.3 Sinter Plants*

Sinter plants convert basic raw materials (iron ore, coke, limestone, etc.) into agglomerated products (sinter) of suitable size (and with other special properties) for charging into the blast furnace. More details about emissions from sinter processes can be found in, e.g., EPA (1998a) and EEA (1999).

Windboxes, crushing, raw material handling, belt charging and discharging from the breaker and hot screens, handling and transportation of raw materials are major sources of particulate emissions (Passant *et al.*, 2000). Typically, collectible emissions from these sources are ducted to the abatement equipment. Fugitive losses, e.g., from handling and transportation of raw materials, are difficult to treat.

Based on RAINS estimates, between one and three percent of European $PM_{2.5}$ and $PM_{10}$, respectively, originated from this source in 1990 and differences among countries are large.

**RAINS Sector:**

IN_PR_SINT

**Description**

Activity: Sintering in the iron and steel industry (non-ferrous processes not included).

Unit: **kg/t** iron/steel produced.

**Emission Factors**

Table 3.23 lists emission factors from the literature. As for other industrial processes there are considerable differences between reported numbers and it is difficult to allocate the reported values to the individual production processes and to conclude about underlying emission controls. Table 3.25 presents the calculation of the RAINS emission factor based on EPA, 1998a and Passant *et al.*, 2000. The emission factors include only the activities and processes listed in this table.

Similar to the other iron and steel categories, information on the size distribution of PM emissions is very scarce and data were not found for all processes (Table 3.24). The reported size profiles often refer to the controlled situation, which is important for determining the efficiency of abatement, but is of limited use for establishing the size fraction profile for uncontrolled emission factors. RAINS uses information from EPA (1998a).

Table 3.23: Uncontrolled emission factors reported in the literature for sinter processes [kg/ton iron/steel produced].

| Source | Abatement | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| IPPC, 2000a [1] | | | | | | 0.23-1.2 |
| EPA, 1995 [2] | Uncontrolled | | | 0.83 | | |
| EEA, 1999 [1] | Uncontrolled [3] | | | | | 7.5 |
| Berdowski *et al.*, 1997 | Unknown | 0.38 | | 0.5 | | |

[1] As quoted in Passant *et al.*, 2000.

[2] As quoted in Berdowski *et al.*, 1997.

[3] Includes sintering (4 kg/t) and cooling (3.5 kg/t).

Table 3.24: Size fractions reported in the literature for sinter processes [percent of TSP].

| Source | Abatement | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Passant *et al*., 2000 | Controlled | | | 79 % | | 100 % |
| EPA, 1998a (windbox) [1] | Uncontrolled | 6.5 % | | 15 % | | 100 % |
| | Cyclone | 52 % | | 74 % | | 100 % |
| | Baghouse | 27 % | | 69 % | | 100 % |
| | ESP | 33 % | | 59 % | | 100 % |
| Berdowski *et al*., 1997 [2] | Unknown | 75 % | | | | |

[1] average for $PM_{10}$ for controlled processes is estimated at 66 percent (as quoted in Passant *et al.*, 2000).

[2] relates to $PM_{10}$ and not TSP.

Table 3.25: Calculation of emission factors used in the RAINS model for sinter processes [kg/ton iron/steel produced], based on EPA, 1998a.

| Source | $PM_{2.5}$ | % of TSP | $PM_{10}$ | % of TSP | TSP |
|---|---|---|---|---|---|
| Windbox | 0.28 | 6.5% | 0.83 | 15% | 5.56 |
| Sinter discharge | 0.37 | 11% [1] | 1.09 | 32% [1] | 3.40 |
| RAINS: SUM | 0.65 | *7.3 %* | 1.92 | *21.4 %* | 8.96 |

[1] Assumption: size distribution baghouse = uncontrolled.

Table 3.26: Emission factors used in the RAINS model for sinter processes [kg/ton iron/steel].

| Sector | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Sinter processes | IN_PR_SINT | 0.65 | 1.26 | 1.92 | 7.04 | 8.96 |

### Applicable Control Options

The RAINS model includes cyclones, bag filters and electrostatic precipitators for sinter plants (Passant *et al.*, 2000; Berdowski *et al.*, 1997). However, similar to the other iron and steel sectors, fugitive emissions might contribute a significant portion of total PM. Adopting good operational practice to prevent or reduce fugitive losses can minimize these emissions. At this stage, the RAINS model does not include such options but allows specifying the share of total unabated emissions that belong to this category (fugitive). The user can adjust this value in the control strategy for every five-year period.

## *3.2.1.4 Aluminum Production*

Aluminum is produced from electrolytic reduction of alumina using the Hall-Heroult process. Details of this process can be found in EPA (1998a), EEA (1999) and Passant *et al.* (2000). Main sources of emissions include baking of the pre-baked carbon anodes, electrolytic process, tapping and casting of the aluminum product.

Aluminum production is estimated to contribute about 0.5 percent to the total European PM emissions.

### RAINS Sector:

IN_PR_NFME

### Description

Activity: Primary aluminum from aluminum production (not included: production of aluminum from bauxite).

Unit: **kg/t** aluminum produced.

### Emission Factors

The following tables present emission rates reported in the literature. In several cases it was not possible to fully explain the level of control and therefore it was decided to base the RAINS emission factors (Table 3.29) on EPA (1998a). It is important to notice, however, that even the controlled values are relatively high, indicating a significant amount of fugitive emissions.

Indeed, Passant *et al.* (2000) points out that possibly two thirds of the controlled (remaining) emissions are fugitive

Table 3.27: Uncontrolled emission factors reported in the literature for aluminum production [kg/ton aluminum produced].

| Source | Abatement / process | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| BUWAL, 1995 | Unknown | | | | | 0.9-1.7 |
| Passant *et al*, 2000 | Controlled, pre-baked anodes | | | 2.38 | | 3.43 (1) |
| | Controlled, vertical stud Soderberg anode | | | | | 9.85 (1) |
| EPA, 1998a | *Factors given in* Table 3.29 | | | | | |
| UBA, 1989 (2) | Unknown | | | 1.7-7.5 | | |
| Berdowski *et al.*, 1997 | Unknown, Western Europe | 1.4 | | 3 | | |
| | Unknown, Eastern Europe | 3.2 | | 7 | | |

(1) Passant *et al.* (2000) estimates that about 2/3 of the emissions are fugitives.

(2) as quoted in Berdowski *et al.*, 1997.

Table 3.28: Size fractions reported in the literature for aluminum production [percent of TSP].

| Source | Abatement / process | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| EPA, 1998a | Uncontrolled, Pre-baked anodes | 28 % | | 58 % | | 100% |
| | Uncontrolled, horizontal stud Soderberg anode | 17 % | | 31 % | | 100% |
| Berdowski *et al.*, 1997 (1) | Unknown | 45 % | | | | |

(1) relates to $PM_{10}$ and not to TSP.

Table 3.29: Calculation of emission factors used in the RAINS model for aluminum production [kg/ton aluminum produced].

| Source | $PM_{2.5}$ | % of TSP | $PM_{10}$ | % of TSP | TSP |
|---|---|---|---|---|---|
| Prebake cells | 13.16 | 28 %[(1)] | 27.26 | 58%[(1)] | 47.00 |
| Prebake cells, fugitive only | 0.70 | 28 % | 1.45 | 58 % | 2.50 |
| Vertical stud Soderberg | | | | | 39.00 |
| Vertical stud Soderberg, fugitive only | | | | | 6.00 |
| Horizontal stud Soderberg | 8.33 | 17 %[(1)] | 15.19 | 31 %[(1)] | 49.00 |
| Horizontal stud Soderberg, fugitive only | 0.85 | 17 % | 1.55 | 31 % | 5.00 |
| SUM, prebake cells | 13.16 | 28 % | 27.26 | 58 % | 47.00 |

[(1)] Assumption: size distribution for total emissions is the same as for uncontrolled emissions, since the majority of emissions are fugitives

Table 3.30: Emission factors used in the RAINS model for aluminum production [kg/ton aluminum].

| Sector | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Aluminum production | IN_PR_NFME | 13.16 | 14.10 | 27.26 | 19.74 | 47.00 |

### Applicable Control Options

The RAINS model includes end-of-pipe control options for aluminum production plants (bag filters and electrostatic precipitators) that are typically used in this industry (Passant *et al.*, 2000). However, as already mentioned in the introduction to this section, the fugitive emissions contribute a significant portion of total PM. Adopting good operational practice to prevent or reduce fugitive losses can minimize these emissions. At this stage, however, the RAINS model does not include such options but allows specifying the share of total unabated emissions that belong to this category (fugitive). The user can adjust this value in the control strategy for every five-year period.

### *3.2.1.5 Cement and Lime Production*

#### RAINS Sector:

IN_PR_CELI

#### Description

**Non-fuel related emissions**

Activity: Cement production, production of lime (calcium oxide) from limestone.

Unit: **kg/t** cement or lime produced.

Detailed description of both processes can be found in e.g., EEA (1999) and EPA (1998a).

#### Emission Factors

Table 3.31 lists emission factors for cement and lime production. RAINS assumes equal emission factors for lime and cement production, although TSP emissions from lime production are much higher than from cement production. $PM_{10}$ emissions, however, seem to be in the same order of magnitude. Using these factors, $PM_{2.5}$ emissions from lime production may be overestimated in RAINS.

Table 3.31: Uncontrolled emission factors reported in the literature for cement and lime production [kg/ton cement or lime produced].

| | Process | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| EPA, 1998a | Cement production, kilns, wet process | | | | | 65.0 |
| | Cement production, kilns, dry process | | | | | 65.0 |
| | Lime production, coal-fired rotary kiln | | | | | 180.0 |
| | Lime production, gas-fired calcimetric kiln | | | | | 48.0 |
| | Lime production, coal-fired rotary pre-heater kiln | | | | | 42.0 |
| BUWAL, 1995 | Cement production, diffuse emissions | | | | | 0.10 |
| | Lime production, combustion emissions | | | | | 0.16 |
| | Cement production, combustion emissions | | | | | 0.17 |
| UBA, 1989 (1) | Unknown | | | 0.5-2.2 | | |
| IPPC, 2000b (2) | Controlled | | | | | 0.01-0.4 |
| EEA, 1999 (2) | Unknown | | | | | 0.12-0.25 |
| Berdowski *et al.*, 1997 | Unknown | 0 | | 0.15 | | |

(1) As quoted in Berdowski *et al.*, 1997.

(2) As quoted in Passant *et al.*, 2000.

Table 3.32: Size fractions reported in the literature for cement and lime production [percent of TSP].

| Source | Abatement / process | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| EPA, 1998a | Uncontrolled, cement production, kilns, wet process | 7 % | | 24 % | | 100% |
| | Uncontrolled, cement production, kilns, dry process | 18 % | | 42 % | | 100% |
| | Lime production, coal-fired rotary kiln | 1.4% | | 12 % | | 100% |
| | Lime production, gas-fired calcimetric kiln | | | | | 100% |
| | Lime production, coal-fired rotary pre-heater kiln | | | | | 100% |

Table 3.33: Calculation of emission factors used in the RAINS model for cement and lime production [kg/ton cement or lime produced]. The dry process is taken as representative.

| Process | $PM_{2.5}$ | % of TSP | $PM_{10}$ | % of TSP | TSP |
|---|---|---|---|---|---|
| Cement production, kilns, wet process | 4.55 | 7 % | 15.60 | 24 % | 65.00 |
| Cement production, kilns, dry process | 11.70 | 18 % | 27.30 | 42 % | 65.00 |
| Lime production, coal-fired rotary kiln | | | 22.00 | 12 % | 180.00 |
| Lime production, gas-fired calcimetric kiln | | | | | 48.00 |
| Lime production, coal-fired rotary pre-heater kiln | | | | | 42.00 |

Table 3.34: Emission factors used in the RAINS model for cement production [kg/ton cement or lime produced].

| Sector | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Cement production | IN_PR_CELI | 11.70 | 15.60 | 27.30 | 37.70 | 65.00 |

With these emission factors cement and lime production would be one of the more important sources of industrial PM emissions, contributing approximately 30 percent to the total PM from industrial processes and about seven to eight percent to total European emissions in 1990.

Other studies, however, do not confirm such high shares of this sector. For instance, APEG (1999) estimated for 1995 the contribution to the total UK $PM_{10}$ at about two percent and Berdowski *et al.* (1997) suggests that cement production contributes typically less than one percent to total national emissions of $PM_{10}$. Such differences can be explained by different assumptions about the control level and the combined treatment of cement and lime production in RAINS.

### Applicable Control Options

The RAINS model considers cyclones, bag filters and electrostatic precipitators as control options for cement and lime production plants (Passant *et al.*, 2000). Fugitive emissions are normally captured in the ventilation system and ducted to the emission control system, e.g., the electrostatic precipitators. However, if this is not the case, the RAINS model allows specifying

the share of total unabated emissions that represent fugitive emissions. The user can adjust this value in the control strategy for every five-year period.

#### *3.2.1.6 Petroleum Refining*

The petroleum refining industry converts crude oil into more than 2500 refined products, including liquid fuels (gasoline, diesel, residual oil), by-product fuels and feedstocks (e.g., asphalt, lubricants), and primary petrochemicals (e.g., ethylene, toluene, xylene) (EEA, 1999). Detailed descriptions of the specific processes can be found in EPA, 1998a.

Refineries are not a major source of particulate emissions; their contribution to total PM is typically estimated below one percent (APEG, 1999; this study). Berdowski *et al*. (1997) calculated higher shares of this source for the Eastern European countries (see also emission factors in Table 3.35).

**RAINS Sector:**

IN_PR_REF

**Description**

Activity: Refining of petroleum.

Unit: **kg/t** petroleum refined.

**Emission Factors**

Very few sources of information on emission factors and size distribution were found so far (Table 3.35, Table 3.36) and it was a difficult decision to choose one of the reported values. It was decided at this stage to use the value from the Dutch inventory (TNO, 1996) combined with information on size distribution from Berdowski *et al.* (1997), while acknowledging that these emission factors most likely underestimate emissions in several European countries. We trust that the results of the CEPMEIP program (TNO, 2001) will provide an invaluable input to a better understanding of the emissions from this source.

Table 3.35: Uncontrolled emission factors reported in the literature for refineries [kg/ton crude oil].

| Source | Abatement / process | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| TNO, 1996 (1) | Average, uncontrolled | | | 0.12 | | |
| | Dutch plants | | | | | |
| EPA, 1998a | Fluid cooking units | | | | | 1.71 |
| | Catalytic cracking units | | | | | 0.79 |
| Berdowski et al., | Unknown, Western Europe | 0.16 | | 0.2 | | |
| 1997 | Unknown, Eastern Europe | 1.8 | | 2.25 | | |

(1) as quoted in Dreiseidler *et al.*, 1999.

Table 3.36: Size fractions reported in the literature for refineries [percent of $PM_{10}$]

| Source | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|
| Berdowski *et al.*, 1997 | 80 % | | | | |

Table 3.37: Emission factors used in the RAINS model for refineries [kg/ton petroleum refined].

| Sector | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Petroleum refining | IN_PR_REF | 0.096 | 0.02 | 0.120 | 0.002 | 0.122 |

### Applicable Control Options

The RAINS model includes cyclones, bag filters and electrostatic precipitators as control options for refineries.

### *3.2.1.7 Fertilizer Production*

The estimation of emissions from this sector in RAINS is very preliminary and at this stage includes only emissions from the production of nitrogen fertilizers.

The contribution of this sector to the total PM emissions is relatively low, estimated at about 0.1 to 0.2 percent (APEG, 1999; this study).

### RAINS Sector:

IN_PR_FERT

### Description

Activity: Fertilizer production.

Unit: **kg/t** fertilizer produced.

### Emission Factors

To date only one source of emission factors for this activity has been found (Berdowski *et al.*, 1997). Since only the emissions from nitrogen fertilizer production are considered, the present calculations most likely underestimate emissions from fertilizer production.

Table 3.38: Uncontrolled emission factors reported in the literature for fertilizer production [kg/ton fertilizer produced].

| Source | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|
| Berdowski *et al*., 1997 | 0.18 | | 0.25 | | |

Table 3.39: Size fractions reported in the literature for fertilizer production [percent of $PM_{10}$].

| Source | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|
| Berdowski *et al*., 1997 | 70 % | | | | |

Table 3.40: Emission factors used in the RAINS model for fertilizer production [kg/ton fertilizer produced].

| Sector | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Fertilizer production | IN_PR_FERT | 0.65 | 0.35 | 1.00 | 0.02 | 1.02 |

### Applicable Control Options

Similarly to other industrial process sectors, the RAINS model includes several end-of-pipe control options for fertilizer production plants (cyclone, bag filters and electrostatic precipitators).

#### *3.2.1.8 Pulp Production*

### RAINS Sector:

IN_PR_PULP

### Description

Activity: Pulp production.

Unit: **kg/t** pulp produced.

### Emission Factors

No original information was found on PM emissions from pulp and paper production. Instead, the default emission factors based on EEA (1999) listed below were used for the calculations.

Table 3.41: Emission factors used in the RAINS model for pulp production [kg/ton pulp produced].

| Sector | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Pulp production | IN_PR_PULP | 10.0 | 1.0 | 11.0 | 1.0 | 12.0 |

### Applicable Control Options

At the moment no control options for the pulp industry are considered in RAINS.

## *3.2.2 Agriculture*

Several agricultural activities contribute to the emissions of particulate matter. Examples are livestock buildings, arable farming, managing crops, energy use (combustion), burning of agricultural waste and unpaved roads. Some of these sources are dealt with in other sections of

this document. The following section is related to livestock farming, which is believed to be the largest source of PM from agriculture (ICC and SRI, 2000).

### *3.2.2.1 Emissions from Livestock Farming*

Most of the measurements of PM concentrations were performed on poultry and pig farms (e.g., Takai *et al.*, 1998; Donham *et al.*, 1986 and 1989; Louhelainen *et al.*, 1987), which are believed to be the major source of PM from animal housing (Berdowski *et al.*, 1997; ICC and SRI, 2000). Dairy and beef cattle are less important. The predominant sources include feed and faecal material and possibly bedding. Lower contributions originate from skin, hair, mould, pollen grains and insect parts. The ICC and SRI (2000) review indicates that the mass median diameter of dust collected in pig and poultry buildings is in the range between 11 and 17 μm. The proportion of $PM_5$ in total dust for pigs and poultry farms was estimated at about four to 16 percent (e.g., Heber *et al.*, 1988; Louhelainen *et al.*, 1987; Cravens *et al.*, 1981). The ICC and SRI (2000) reports used, for all animal categories, the size fraction distribution given in Louhelainen *et al.*, 1987, i.e., eight and 45 percent for $PM_{2.5}$ and $PM_{10}$, respectively (see Table 3.43). A recent and thorough review of the emissions from this source is available in the ICC and SRI (2000) study.

Berdowski *et al.* (1997) estimated the contribution of agriculture to total European emissions of $PM_{10}$ and $PM_{2.5}$ at nearly nine and seven percent, respectively, indicating however that this might be on the high end. Indeed, a comparison between that study and more recent work of ICC and SRI (2000) suggests the differences for the UK to be larger[1] i.e., for $PM_{10}$ 11.5 kt by ICC and SRI (2000) and 30 kt by Berdowski *et al.* (1997), for $PM_{2.5}$, two and 13 kt, respectively. The preliminary estimates of the RAINS model for the UK give 4.7 and 1.7 kt $PM_{10}$ and $PM_{2.5}$, respectively. The variation for specific animal categories is larger and has to be evaluated in view of the new evidence (ICC and SRI, 2000) that was not available at the time when the emission factors for RAINS were prepared.

**RAINS Sectors:**

| | |
|---|---|
| AGR_CHI | AGR_PIG |
| AGR_COW | AGR_OTH |

**Description**

Activity: Animal numbers.

Unit: kg/animal/year.

[1] The estimates are for different years, i.e., 1990 (Berdowski *et al.*, 1997) and 1998 (ICC and SRI, 2000) but the change in the number of animals (excluding cattle) was not that significant.

### Emission Factors

Examples of emission factors and size distributions reported in the literature are given in the tables below. The ICC and SRI (2000) study based its emission rates on the study by Takai *et al.* (1998) assuming size distribution as given in Table 3.43. The values currently implemented in RAINS are based on the Dutch inventory (CBS, 1998) (Table 3.44). These are somewhat different from values reported in other studies, although the size distribution is consistent with Berdowski *et al.* (1997). One exception is poultry, for which a higher (70 percent) share of $PM_{10}$ was assumed. The data presently implemented in RAINS will be reviewed along the findings of the ICC and SRI (2000) study[2].

Table 3.42: Uncontrolled emission factors reported in the literature for livestock farming [kg/animal/year].

| Source | Animal type | $PM_{2.5}$ | $PM_5$ | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Takai *et al.*, 1998 (1) | Cattle | | 0.17 | | | 0.96 |
| | Pigs | | 0.12 | | | 0.97 |
| | Poultry | | 0.02 | | | 0.11 |
| Berdowski *et al.*, 1997 | Pigs | 0.75 | | 2.2 | | |
| | Poultry | 0.043 | | 0.086 | | |

(1) as cited in ICC and SRI (2000)

Table 3.43: Size fractions reported in the literature for livestock farming [as percent of TSP].

| Source | Sector | $PM_{2.5}$ | $PM_5$ | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Louhelainen *et al.*, 1987 | Pigs | 8 % | 14 % | 45 % | | 100 % |
| Cravens *et al.*, 1981 | Poultry | | | 15-16 % | | |
| Heber *et al.*, 1988 | Pigs | | 3.7 % | | | |
| ICC and SRI, 2000 | All animals | 8 % | | 45 % | | 100 % |
| Berdowski *et al.*, 1997 | Pigs | 12 % | | 40 % | | 100 % |
| | Poultry | 20 % | | 40 % | | 100 % |

[2] This study was not available when the RAINS emission factors were developed.

Table 3.44: Emission factors used in the RAINS model for livestock farming [kg/animal/year].

| Sector | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Chicken farms | AGR_CHI | 0.0055 | 0.0055 | 0.011 | 0.0047 | 0.0157 |
| Pigs | AGR_PIG | 0.0129 | 0.0301 | 0.043 | 0.0645 | 0.1075 |
| Cows | AGR_COW | 0.0282 | 0.0658 | 0.094 | 0.141 | 0.235 |
| Other animals | AGR_OTH | 0.0183 | 0.0427 | 0.061 | 0.0915 | 0.1525 |

### Applicable Control Options

A discussion of abatement options to reduce PM concentrations in animal buildings, as well as in the neighborhood of farms, is available, e.g., in Visschedijk *et al.* (1997) and ICC and SRI (2000). At this stage, however, technical control options to reduce PM emissions in livestock farming are not considered in the RAINS model.

## 3.3 Mobile Sources

This section includes both exhaust and non-exhaust emissions from mobile sources. Mobile sources are important contributors to total emissions of PM, especially fine particulate matter. Berdowski *et al.* (1997) estimated that 16 and 19 percent of total European emissions of $PM_{10}$ and $PM_{2.5}$, respectively, in 1990 originated from transport (mainly from road transport). RAINS calculations also indicate similar contributions, i.e., about ten and 16 percent of $PM_{10}$ and $PM_{2.5}$, respectively. The picture, however, differs largely among countries and the contribution varies greatly depending on the development of the transport sector and the level of control of stationary sources. For example, in the UK the share of transport is estimated at about 32 to 37 and 40 to 45 percent for $PM_{10}$ and $PM_{2.5}$ in RAINS and Berdowski *et al.* (1997), respectively. The APEG (1999) study also suggests that nearly 28 percent of $PM_{10}$ in the UK in 1995 derives from transport sources.

This section is divided into two major parts dealing with exhaust and non-exhaust emissions, the latter being more uncertain but presumably contributing only ten to 20 percent of PM emissions from transport. This might, however, change in the future since vehicle exhaust is subject to stringent legislation and it is expected that in spite of growing car numbers emissions from this source should decline.

The emission factors developed in RAINS for various vehicle categories rely to the maximum extent possible on the Auto-Oil studies (EC, 1999). Activity statistics of the transport sector (fuel consumption) are taken from the energy database of the RAINS model and are supplemented by additional data from the Auto-Oil Programme, i.e., average kilometers driven, size structure of the fleet, etc.

### *3.3.1 Exhaust Emissions*

Exhaust emissions from transport activities represent between 80 to 90 percent of the total emissions from transport. The primary contribution comes from heavy duty diesel vehicles, but in several countries light duty vehicles might also contribute substantial amounts of PM. Emissions from spark-ignition engines are typically of lower concern for particulate matter, but they are important when the number and size of particles is considered.

#### *3.3.1.1 Road Transport, Light Duty Vehicles, Diesel Engines*

Light and heavy duty diesel vehicles are a major contributor to PM emissions from road transport. In the last decade, the number of light duty diesel vehicles has grown dramatically, especially in France and Austria, where they currently represent about 50 percent of new registrations. There is a large number of published papers providing the characteristics of PM emissions from diesel engines (especially from heavy duty vehicles) and there is ongoing research to reduce these emissions and improve the "bad" environmental image of diesel vehicles.

**RAINS Sectors:**

TRA_RD_LD4

**Description**

Activity: Road transport, light-duty vehicles.

Unit: **kt/PJ** of diesel fuel consumed.

**Emission Factors**

Diesel exhaust particles are mostly submicrometer agglomerates of carbonaceous spherical particles ranging from ten to 80 nm. Larger particles contain up to 4000 individual spherical particles clustered as agglomerates up to 30 μm (Morawska *et al.*, 1998). The fuel injection process is one of the most important factors in pollutant formation in diesel engines. The distribution of fuel injected in the cylinder is non-uniform, and the generation of unwanted emissions (not only PM) is highly dependent on the degree of the non-uniformity (Yanowitz *et al*., 2000). PM formation is expected to increase under conditions that cause incomplete combustion, such as lower combustion temperature or poor mixing. The main problem in lowering diesel emissions is the inverse correlation between $NO_x$ and PM emissions (Yanowitz *et al*., 2000). Apart from engine operating conditions, which strongly influence the total mass and number of particles emitted, typically increasing with load (Morawska *et al.*, 1998; Durbin *et al.*, 2000), there is a range of other factors that might play a role, for example, altitude, humidity, temperature and inertial weight (Yanowitz *et al*., 2000; Bishop *et al*., 2001).

A significant proportion (estimated at about 90 percent) of diesel PM is smaller than 1 μm, (e.g., Harrison *et al.*, 2000).

In this study, the country-specific unabated $PM_{10}$ emission factors for light duty diesel vehicles are based on the Auto-Oil II study (EC, 1999). For these regions not included in the Auto-Oil II study, factors for countries with a similar per capita GDP and/or from the same climate zone were chosen (Table 3.45). Information on the $PM_{2.5}$ and TSP ratios was taken from Ahuja *et al.* (1989) and Houck *et al*. (1989).

Table 3.45: Uncontrolled emission factors considered in the RAINS PM Module for diesel light-duty vehicles [kt/PJ].

| | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|
| Albania | 0.0895 | 0.0099 | 0.0994 | 0.0040 | 0.1034 |
| Austria | 0.0914 | 0.0101 | 0.1015 | 0.0041 | 0.1056 |
| Belarus | 0.0895 | 0.0099 | 0.0994 | 0.0040 | 0.1034 |
| Belgium | 0.0914 | 0.0101 | 0.1015 | 0.0041 | 0.1056 |
| Bosnia-Herzegovina | 0.0895 | 0.0099 | 0.0994 | 0.0040 | 0.1034 |
| Bulgaria | 0.0984 | 0.0110 | 0.1094 | 0.0044 | 0.1138 |
| Czech Republic | 0.0984 | 0.0110 | 0.1094 | 0.0044 | 0.1138 |
| Croatia | 0.0895 | 0.0099 | 0.0994 | 0.0040 | 0.1034 |
| Denmark | 0.0914 | 0.0101 | 0.1015 | 0.0041 | 0.1056 |
| Estonia | 0.1143 | 0.0128 | 0.1271 | 0.0050 | 0.1321 |
| Finland | 0.104 | 0.0115 | 0.1155 | 0.0046 | 0.1201 |
| France | 0.0999 | 0.0102 | 0.1101 | 0.0053 | 0.1154 |
| Germany | 0.0914 | 0.0101 | 0.1015 | 0.0041 | 0.1056 |
| Greece | 0.0761 | 0.0084 | 0.0845 | 0.0052 | 0.0897 |
| Hungary | 0.0984 | 0.0110 | 0.1094 | 0.0044 | 0.1138 |
| Ireland | 0.0991 | 0.0110 | 0.1101 | 0.0044 | 0.1145 |
| Italy | 0.0815 | 0.0091 | 0.0906 | 0.0036 | 0.0942 |
| Latvia | 0.1143 | 0.0128 | 0.1271 | 0.0050 | 0.1321 |
| Lithuania | 0.1143 | 0.0128 | 0.1271 | 0.0050 | 0.1321 |
| Luxembourg | 0.0934 | 0.0104 | 0.1038 | 0.0042 | 0.1080 |
| Macedonia, FYR | 0.0895 | 0.0099 | 0.0994 | 0.0040 | 0.1034 |
| Moldova, Rep. of | 0.0984 | 0.0110 | 0.1094 | 0.0044 | 0.1138 |
| Netherlands | 0.0934 | 0.0104 | 0.1038 | 0.0042 | 0.1080 |
| Norway | 0.104 | 0.0115 | 0.1155 | 0.0046 | 0.1201 |
| Poland | 0.0984 | 0.0110 | 0.1094 | 0.0044 | 0.1138 |
| Portugal | 0.0814 | 0.0090 | 0.0904 | 0.0036 | 0.0940 |
| Romania | 0.0895 | 0.0099 | 0.0994 | 0.0040 | 0.1034 |
| Russia, St. Petersburg | 0.1143 | 0.0128 | 0.1271 | 0.0050 | 0.1321 |
| Russia, Kola-K., Kaliningr. | 0.1143 | 0.0128 | 0.1271 | 0.0050 | 0.1321 |
| Remaining Russia | 0.0984 | 0.0110 | 0.1094 | 0.0044 | 0.1138 |
| Slovakia, Rep. of | 0.0984 | 0.0110 | 0.1094 | 0.0044 | 0.1138 |
| Slovenia | 0.0814 | 0.0090 | 0.0904 | 0.0036 | 0.0940 |
| Spain | 0.0865 | 0.0096 | 0.0961 | 0.0038 | 0.0999 |
| Sweden | 0.104 | 0.0115 | 0.1155 | 0.0046 | 0.1201 |
| Switzerland | 0.0914 | 0.0101 | 0.1015 | 0.0041 | 0.1056 |
| Ukraine | 0.0984 | 0.0110 | 0.1094 | 0.0044 | 0.1138 |
| United Kingdom | 0.0982 | 0.0109 | 0.1091 | 0.0044 | 0.1135 |
| Yugoslavia | 0.0895 | 0.0099 | 0.0994 | 0.0040 | 0.1034 |

### Applicable Control Options

The control options included in the RAINS model are provided in Table 2.8. They are compatible with the EURO-I to EURO-V EC standards for light duty vehicles.

#### *3.3.1.2 Road Transport, Heavy Duty Vehicles, Diesel Engines*

Exhaust particulate matter emissions from heavy duty vehicles are the most important source of PM from road transport. This is also a category that faces the most stringent emission standards in the EU.

### RAINS Sectors:

TRA_RD_HD

### Description

Activity: Road transport, heavy-duty vehicles.

Unit: **kt/PJ** of diesel fuel consumed.

### Emission Factors

PM emissions from new heavy-duty vehicles are by about an order of magnitude lower (in g/km) than from the vehicles in the 1970s, but particles emitted from a modern diesel consist of smaller particles (the cluster structures are similar though) (Harrison *et al.*, 2000). A number of important factors influencing emissions from diesel engines is listed in the previous section. In the context of heavy-duty vehicles it may be important to add that the deterioration factor is of great importance since such vehicles are typically driven several thousands of kilometers between the obligatory check-ups.

The country-specific unabated $PM_{10}$ emission factors for diesel heavy-duty trucks (Table 3.46) are based on the Auto Oil 2 study (EC, 1999). Information on the $PM_{2.5}$ and TSP ratios is taken from Ahuja *et al.* (1989) and Houck *et al*. (1989).

Table 3.46: Uncontrolled emission factors used in the RAINS PM Module for diesel heavy-duty vehicles [kt/PJ].

| | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|
| Albania | 0.0567 | 0.0063 | 0.0630 | 0.0025 | 0.0655 |
| Austria | 0.0436 | 0.0048 | 0.0484 | 0.0019 | 0.0503 |
| Belarus | 0.0567 | 0.0063 | 0.0630 | 0.0025 | 0.0655 |
| Belgium | 0.0436 | 0.0048 | 0.0484 | 0.0019 | 0.0503 |
| Bosnia-Herzegovina | 0.0567 | 0.0063 | 0.0630 | 0.0025 | 0.0655 |
| Bulgaria | 0.0623 | 0.0070 | 0.0693 | 0.0027 | 0.0720 |
| Croatia | 0.0567 | 0.0063 | 0.0630 | 0.0025 | 0.0655 |
| Czech Republic | 0.0623 | 0.0070 | 0.0693 | 0.0027 | 0.0720 |
| Denmark | 0.0436 | 0.0048 | 0.0484 | 0.0019 | 0.0503 |
| Estonia | 0.0583 | 0.0065 | 0.0648 | 0.0026 | 0.0674 |
| Finland | 0.053 | 0.0059 | 0.0589 | 0.0024 | 0.0613 |
| France | 0.0468 | 0.0052 | 0.0520 | 0.0021 | 0.0541 |
| Germany | 0.0436 | 0.0048 | 0.0484 | 0.0019 | 0.0503 |
| Greece | 0.0521 | 0.0058 | 0.0579 | 0.0023 | 0.0602 |
| Hungary | 0.0623 | 0.0070 | 0.0693 | 0.0027 | 0.0720 |
| Ireland | 0.0484 | 0.0054 | 0.0538 | 0.0022 | 0.0560 |
| Italy | 0.0529 | 0.0059 | 0.0588 | 0.0024 | 0.0612 |
| Latvia | 0.0583 | 0.0065 | 0.0648 | 0.0026 | 0.0674 |
| Lithuania | 0.0583 | 0.0065 | 0.0648 | 0.0026 | 0.0674 |
| Luxembourg | 0.0485 | 0.0054 | 0.0539 | 0.0022 | 0.0561 |
| Macedonia, FYR | 0.0567 | 0.0063 | 0.0630 | 0.0025 | 0.0655 |
| Moldova, Rep. of | 0.0623 | 0.0070 | 0.0693 | 0.0027 | 0.0720 |
| Netherlands | 0.0485 | 0.0054 | 0.0539 | 0.0022 | 0.0561 |
| Norway | 0.053 | 0.0059 | 0.0589 | 0.0024 | 0.0613 |
| Poland | 0.0623 | 0.0070 | 0.0693 | 0.0027 | 0.0720 |
| Portugal | 0.0515 | 0.0057 | 0.0572 | 0.0023 | 0.0595 |
| Romania | 0.0567 | 0.0063 | 0.0630 | 0.0025 | 0.0655 |
| Kaliningrad, Kola-Karelia | 0.0583 | 0.0065 | 0.0648 | 0.0026 | 0.0674 |
| Remaining Russia | 0.0623 | 0.0070 | 0.0693 | 0.0027 | 0.0720 |
| Slovenia | 0.0515 | 0.0057 | 0.0572 | 0.0023 | 0.0595 |
| Slovakia, Rep. of | 0.0623 | 0.0070 | 0.0693 | 0.0027 | 0.0720 |
| Spain | 0.0495 | 0.0055 | 0.0550 | 0.0022 | 0.0572 |
| St. Petersburg | 0.0583 | 0.0065 | 0.0648 | 0.0026 | 0.0674 |
| Sweden | 0.053 | 0.0059 | 0.0589 | 0.0024 | 0.0613 |
| Switzerland | 0.0436 | 0.0048 | 0.0484 | 0.0019 | 0.0503 |
| Ukraine | 0.0623 | 0.0070 | 0.0693 | 0.0027 | 0.0720 |
| United Kingdom | 0.0528 | 0.0059 | 0.0587 | 0.0023 | 0.0610 |
| Yugoslavia | 0.0567 | 0.0063 | 0.0630 | 0.0025 | 0.0655 |

### Applicable Control Options

The control options included in the RAINS model are given in Table 2.8. They are equivalent to the EURO-I to EURO-V standards for heavy duty vehicles.

### *3.3.1.3 Road Transport, Light Duty Vehicles and Motorcycles, Gasoline Engines*

Although PM emission levels from gasoline engines are significantly lower than those of diesel engines (and consequently more difficult to measure accurately), they are still important. In some countries, where light duty diesel vehicles do not form a major share, e.g., Scandinavia, their contribution to total exhaust PM emissions might be more important than diesel. Another important element of PM emissions from gasoline engines is the size distribution. Studies indicate that they are smaller than from diesel engines (e.g., Cadle *et al.*, 2001; Ristovski *et al.*, 1998) and therefore potentially more harmful to human health.

#### RAINS Sectors:

TRA_RD_LD4 TRA_RDXLD4

TRA_RD_LD2

#### Description

Activity: Road transport, light-duty vehicles and motorcycles (4-stroke and 2-stroke).

Unit: kt/PJ of gasoline consumed.

#### Emission Factors

Particulate matter is formed as a result of the incomplete combustion of gasoline. The particles are mostly carbonaceous spherical submicron agglomerates ranging from ten to 80 nm, consisting of a carbon core with various associated organic compounds (Ristovski *et al.*, 1998). Apart from the design of the spark-ignition engines, several other parameters describing engine operating conditions influence the amount of PM emissions. Kayes and Hochreb (1999a) found that fuel type and fuel/air ratio are among the most important ones. The same authors demonstrate in another paper (Kayes and Hochreb, 1999b) that the difference in PM emissions with and without catalytic converters is not statistically significant. Although in some cases a reduction of PM up to 85 percent was measured, in other cases catalyst cars showed increased emissions – a phenomenon not yet fully understood. This also contradicts a few other studies that show lower emissions from catalytic cars (e.g., APEG, 1999) and different size distributions (e.g., EPA, 1995; APEG, 1999).

Data on the size distribution of PM emissions from gasoline is sparse. In a very recent study, Cadle *et al.* (2001) measured the size distribution for 30 light duty gasoline vehicles (1990-1997 models) and estimated that on average 95.1, 88.7 and 83.6 percent of particle mass was smaller than 12.2, 3.0, and 1.2 μm, respectively.

In this study, the unabated emission factors for gasoline are based on the APEG (1999) report. The higher emission factors for two-stroke engines were calculated using information from the

CBS (1998) report. The values (Table 3.47) are not country specific. It is also assumed that emission factors and size distribution for LPG is the same as for gasoline. However, Ristovski *et al.* (1998) measured higher emissions from LPG-fueled cars in the sub-micrometer range than from modern gasoline-fueled cars. This will be considered in the review of the RAINS model data.

Table 3.47: Uncontrolled emission factors for unleaded gasoline (LF), liquefied petroleum gas (LPG) and natural gas (GAS) considered in the RAINS PM Module [kt/PJ].

| Category | RAINS Code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Light duty vehicles, gasoline four stroke engines | TRA_RD_LD4, TRA_RDXLD4 | 0.0085 | 0.0015 | 0.0100 | 0.0001 | 0.0101 |
| Light duty vehicles and motorcycles, gasoline two stroke engines | TRA_RD_LD2 | 0.0944 | 0.0167 | 0.1111 | 0.0006 | 0.1117 |
| Light duty vehicles, LPG | TRA_RD_LD4 | 0.0085 | 0.0015 | 0.0100 | 0.0001 | 0.0101 |
| Light duty vehicles, natural gas | TRA_RD_LD4 | 0.0120 | 0 | 0.0120 | 0 | 0.0120 |

Although leaded gasoline is not sold anymore in the majority of European countries, it is important to recognize its contribution to PM emissions in the past. Tetramethyl lead has been used as a petrol additive to enhance octane rating. Due to the adverse effects of lead on human health and the growing use of catalytic converters, which are poisoned by lead, the use of leaded gasoline is declining rapidly. Lead added to gasoline results in higher PM emissions. To address this issue, additional PM emission factors for light-duty and heavy-duty vehicles (Table 3.48) were introduced. These factors describe the *incremental difference* in PM emissions between unleaded and leaded fuel. They are based on data (in g/km) given by APEG (1999).

Table 3.48: (Incremental) emission factors used in the RAINS model for lead in leaded gasoline [kt/PJ].

| | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Leaded gasoline | LFL | 0.0096 | 0.0006 | 0.0120 | 0.0024 | 0.0144 |

### Applicable Control Options

Although there are no PM emission standards for gasoline vehicles, the RAINS model takes the effects of introducing three-way catalyst and oxidation catalysts on PM emissions into account.

The options for cars are compatible with the abatement levels necessary to meet EU legislation for other regulated pollutants (EURO-I to EURO-V). Oxidation catalysts are also considered for two-stroke mopeds and motorcycles.

#### *3.3.1.4 Off-road Transport, Machinery and Ships*

**RAINS Sectors:**

| | | |
|---|---|---|
| TRA_OT | TRA_OT_LB | TRA_OT_LD2 |
| TRA_OTS_M | TRA_OTS_L | |

**Description**

Activity: Fuel used in off-road machinery and national sea shipping.

Unit: **kt/PJ** of fuel consumed.

**Emission Factors**

For "other transport" sectors, the emission factors used for gasoline and natural gas are the same as those listed for stationary sources. For solid fuels, the mass balance approach described in Section 2.3.1 was applied. The emission factors for heavy fuel oil and diesel for off-road sources are based on averages taken from the literature. For shipping, data from the Lloyd's Register study (Lloyd's Register, 1995) are used.

Table 3.49: Summary of emission factors for off-road activities.

| Source | Type | $PM_{10}$ | TSP |
|---|---|---|---|
| BUWAL, 2001 | Railways | 13.9 g/km | |
| | Trams | 0.33 g/km | |
| | Aircrafts LTO | 191 g/LTO | |
| | Construction machinery | 15.4 g/h | |
| | Agricultural machinery | 39.1 g/h | |
| | Industrial machinery | 1.92 g/h | |
| | Military vehicles | 40.7 g/h | |

Table 3.50: Emission factors used in the RAINS PM module for heavy fuel oil (HF) for off-road sources and shipping [kt/PJ].

| Sector | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Other land-based machinery | TRA_OT_LB | 0.0582 | 0.012 | 0.0594 | 0.0006 | 0.0600 |
| Ships, medium vessels | TRA_OTS_M | 0.1212 | 0.012 | 0.1234 | 0.0016 | 0.125 |
| Ships, large vessels | TRA_OTS_L | 0.1212 | 0.012 | 0.1234 | 0.0016 | 0.125 |

Table 3.51: Emission factors used in the RAINS PM module for diesel (MD) off-road sources and shipping [kt/PJ].

| Sector | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Other land-based machinery | TRA_OT_LB | 0.0436 | 0.0030 | 0.0466 | 0.0019 | 0.0485 |
| Ships, medium vessels | TRA_OTS_M | 0.0277 | 0.0004 | 0.0283 | 0.0003 | 0.0286 |
| Ships, large vessels | TRA_OTS_L | 0.0277 | 0.0004 | 0.0283 | 0.0003 | 0.0286 |

#### Applicable Control Options

The control options included in the RAINS model reflect the requirements of EU legislation for off-road diesel machinery (EURO-I to EURO-V). The RAINS model also includes options to control emissions from gasoline engines, equivalent to the EURO-I to EURO-V standards for gasoline cars. Abatement options for ships include the switch to low sulfur fuel that affects emissions of PM (Lloyd's Register, 1995).

### *3.3.2 Non-exhaust Emissions from Mobile Sources*

Non-exhaust emissions from mobile sources make significant contributions to total PM emissions in Europe. The importance of this source will grow in the future since effective control programs are in place to reduce exhaust emission from transport.

The RAINS model distinguishes three categories of non-exhaust emissions from mobile sources; tire wear, brake wear and road abrasion.

### *3.3.2.1 Tire Wear*

According to current estimates, tire wear contributes between 0.3 and 2.5 percent to total European $PM_{10}$ and TSP, but less than 0.1 percent to $PM_{2.5}$ (this study and TNO, 2001). Excluding re-suspension, tire wear is probably the largest source of non-exhaust TSP and $PM_{10}$ emissions from road transport. Approximately half of the non-exhaust $PM_{10}$ originates from this source and possibly as much as 80 percent of TSP.

In the last decades, emission rates per kilometer declined due to the introduction of radial tires that replaced traditional bias plies. Radial tires are characterized by lower wear rates. However, recent research indicates that the particles from radial tires are smaller than from bias plies and may have greater health impacts (SENCO, 1999)[3]. Measurements reported by Rautenberg-Wulff (1998) and Weingartner *et al.* (1997) found relatively low shares of $PM_3$.

#### RAINS Sectors:

TRT_RD_LD4 (TRT_RDXLD4)

TRT_RD_LD2

TRT_RD_HD

#### Description

| | |
|---|---|
| Activity: | Road transport, light-duty vehicles and motorcycles (4-stroke and 2-stroke) and heavy-duty vehicles. |
| Unit: | g/km driven. |

#### Emission Factors

The emission factors for tire wear used in the RAINS PM module (Table 3.54) are based on a summary of the TSP and $PM_{10}$ emission factors shown in Table 3.52 and Table 3.53. Most of the available inventories or measurements programs do not provide detailed size fractions, which makes estimating the $PM_{2.5}$ fraction difficult. Older studies indicated that the $PM_{2.5}$ emissions from tire wear are important, e.g., EPA (1995) (based on EPA 1985 estimates), Berdowski *et al.* (1997) and Israel *et al.* (1994), while more recent measurements (Rautenberg-Wulff, 1998; Weingartner *et al.*, 1997; Israel *et al.*, 1996 and later versions of PART5 model of EPA) do not confirm this. Accordingly, the assumed $PM_{2.5}$ emission factors in RAINS are relatively low, i.e., five percent of $PM_{10}$.

[3] There is no precise definition of "smaller" and consequently the following sentence referring to the measurements of $PM_3$ does not have to be in contradiction with this statement.

Table 3.52: Summary of emission factors for tire wear of light duty vehicles given in the literature [g/km].

| Source | Vehicle type | $PM_{10}$ | TSP |
|---|---|---|---|
| EPA, 1995 | Passenger cars, light-duty vehicles | 0.0050 | --- |
| Environment Australia, 2000 | Motorbikes | 0.0025 | --- |
| Baumann *et al.*, 1997 | Passenger cars | --- | 0.0800 |
| Dannis, 1974 | Cars | --- | 0.024-0.36 |
| SENCO, 1999 | Cars | --- | 0.163 |
| Rautenberg-Wulff, 1998 | Passenger car, station wagon | 0.0061 | --- |
| Garben *et al.*, 1997 | Passenger car | --- | 0.0640 |
| | Light-duty vehicle | --- | 0.1120 |
| | Motorbikes | --- | 0.0320 |
| EMPA (2000) | Light duty vehicles | 0.0130 | 0.0530 |
| | Motorbikes | 0.007 | --- |
| Gebbe *et al.*, 1997 | Passenger car | --- | 0.0528 |
| | Light-duty vehicles | --- | 0.1100 |
| | Motorbike | --- | 0.0264 |
| | Passenger car, petrol | --- | 0.0525 |
| | Passenger car, diesel | --- | 0.0563 |

Table 3.53: Summary of emission factors for tire wear of heavy duty vehicles given in the literature [g/km].

| Source | Vehicle type | $PM_{10}$ | TSP |
|---|---|---|---|
| EPA, 1995 | Heavy-duty vehicles | 0.0075 | --- |
| | Articulated lorry | 0.0225 | --- |
| Baumann *et al.*, 1997 | Heavy-duty vehicle | --- | 0.1890 |
| | Articulated lorry | --- | 0.2340 |
| | Bus | --- | 0.1920 |
| SENCO, 1999 | Truck | --- | 1.403 |
| Rautenberg-Wulff, 1998 | Heavy duty vehicles | 0.0310 | --- |
| Garben *et al.*, 1997 | Heavy-duty vehicle | --- | 0.7680 |
| EMPA (2000) | Heavy duty vehicles | 0.2000 | 0.7980 |

| Source | Vehicle type | $PM_{10}$ | TSP |
|---|---|---|---|
| Gebbe *et al*., 1997 | Heavy-duty vehicles | --- | 0.5394 |
| | Heavy duty vehicles, petrol | --- | 0.0784 |
| | Heavy duty vehicles, diesel | --- | 0.2041 |

Table 3.54: Emission factors for tire wear used in RAINS [g/km].

| Sector | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Light duty vehicles | TRT_RD_LD4 | 0.0003 | 0.0062 | 0.0065 | 0.0596 | 0.0661 |
| Motorbikes | TRT_RD_LD2 | 0.0001 | 0.0031 | 0.0032 | 0.0250 | 0.0282 |
| Heavy duty vehicles | TRT_RD_HD | 0.0020 | 0.0380 | 0.0400 | 0.3808 | 0.4208 |

#### Applicable Control Options

Technical control options to reduce PM emissions from tire wear are not considered in the RAINS model.

### *3.3.2.2 Brake Lining Wear*

This category is not a major source of PM emissions (about 0.1 to 0.2 percent of total and approximately three percent of total road transport), but might grow in the future since tailpipe emissions will be reduced and traffic volumes continue to grow. The shares given are based on the current assessment in RAINS. The lack of a detailed source split (Berdowski *et al.*, 1997) does not allow a comparison, but preliminary results of the CEPMEIP program (TNO, 2001) suggest a total contribution of about 0.2 to 0.7 percent for TSP and $PM_{2.5}$ in 1995.

#### RAINS Sectors:

TRB_RD_LD4 (TRB_RDXLD4)

TRB_RD_LD2

TRB_RD_HD

#### Description

Activity: Road transport, light-duty vehicles and motorbikes (4-stroke and 2-stroke) and heavy-duty vehicles.

Unit: g/km driven.

### Emission Factors

The emission factors for brake wear reported in the literature are summarized in Table 3.55. The values are sometimes difficult to compare because the types of vehicles tested vary; in some cases only aggregated categories are reported (e.g., the sum of cars and trucks), in others background information was not identified. The values used in the RAINS model at this stage (

Table 3.56) are derived primarily from Cadle *et al.* (2000) and Rautenberg-Wulff (1998). The widely used U.S. EPA emission factors (EPA, 1995) rely on fairly old measurements done in 1983 by Cha *et al.* (1983) for asbestos brakes and are therefore not considered in estimating the RAINS rates. Emission factors for motorbikes are assumed to be about 15 percent of that for cars (own assumption), which results in slightly lower values than reported by BUWAL (2001).

The size fraction distribution as reported in several studies varies even more than the emission rates. It was, therefore, decided to use the most recent measurements (Cadle *et al.*, 2000).

Table 3.55: Literature values of emission factors for brake lining wear [g/km].

| Source | Vehicle type | $PM_{2.5}$ | $PM_{10}$ | TSP |
|---|---|---|---|---|
| BUWAL (2001), derived from Carbotech (1999) | Motorbikes | --- | 0.0009 | --- |
| | Passenger cars | --- | 0.0018 | --- |
| | Heavy duty vehicles | --- | 0.0035 | --- |
| | Light duty vehicles | --- | 0.0049 | --- |
| Rautenberg-Wulff (1998) | Passenger cars | --- | 0.0010 | --- |
| | Passenger cars, truck | --- | --- | 0.012 - 0.018 |
| | Heavy duty vehicles | --- | 0.0245 | --- |
| Cadle *et al*., 2000 | Small cars | 0.0018 | 0.0029 | 0.0034 |
| | Large cars | 0.0028 | 0.0045 | 0.0053 |
| | Trucks | 0.0048 | 0.0076 | 0.0088 |
| EPA (1995), Environment Australia (2000), Cha *et al.*, 1983 | Cars and trucks | 0.0037 | 0.0078 | 0.0080 |

Table 3.56: Emission factors for brake lining wear used in RAINS [g/km].

| Sector | RAINS code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Light duty vehicles | TRB_RD_LD4 | 0.0022 | 0.0014 | 0.0036 | 0.0008 | 0.0044 |
| Motorbikes | TRB_RD_LD2 | 0.0003 | 0.0002 | 0.0005 | 0.0001 | 0.0006 |
| Heavy duty vehicles | TRB_RD_HD | 0.0071 | 0.0157 | 0.0228 | 0.0047 | 0.0275 |

### Applicable Control Options

Technical control options to reduce PM emissions from brake wear are not considered in the RAINS model.

#### *3.3.2.3 Road Abrasion*

Estimating the emissions from road abrasion is very difficult since there are no emission factors specifically related to road wear. Any abrasion of paved roads is typically included in total non-exhaust emission rates where tire, break and road wear, as well as re-suspension, are included. There are some studies addressing tire and brake wear (see previous sections), but it is difficult to compare them directly with reported total non-exhaust emissions from traffic.

In the absence of a clearly defined interface between atmospheric dispersion calculations and emission estimates in integrated assessment models, it was decided that the category "road abrasion" in the RAINS model should not include re-suspension at this stage.

Several studies suggest that road abrasion, together with re-suspension, is a major source of PM emissions (Nicholson, 1988). For example, Gaffney *et al.* (1995) and Zimmer *et al.* (1992) estimated that the contribution of emissions from paved roads to total $PM_{10}$ might be as high as 30 percent in California and 40 to 70 percent in the Denver Metropolitan area. A more recent study for France (Jaecker-Voirol and Pelt, 2000) suggests that re-suspension emissions may be three to seven times higher than exhaust emissions from road transport. All these studies used the approach based on the U.S. EPA methodology (EPA, 1995, 1997). It is, therefore, important to mention here that the EPA AP-42 model has recently been the subject of critique, e.g., in an *Atmospheric Environment* journal article (Venkatram, 2000; Nicholson, 2000). It was claimed that this model is not likely to provide adequate estimates of $PM_{10}$ estimates from paved roads and that more research is needed to establish reliable methods for measuring and estimating emissions from this source. A step towards improving the understanding of these sources has been made recently by a TRAKER measurement program started in Las Vegas (Kuhns *et al.*, 2001), but final results are not yet available.

### RAINS Sectors:

TRD_RD_LD4 (TRD_RDXLD4)

TRD_RD_LD2

TRD_RD_HD

## Description

Activity: Road transport, light-duty vehicles and motorcycles (4-stroke and 2-stroke) and heavy-duty vehicles.

Unit: g/km driven.

## Emission Factors

As indicated in the introduction to this section, it is not an easy task to develop a set of emission factors for this category, especially in view of the latest discussions about the AP-42 method (Venkatram, 2000). The emission factors as reported in several studies are presented in Table 3.57, however, a direct comparison is very difficult as the reporting basis varies. In order to derive emission factors appropriate for the RAINS model, an attempt was made to subtract tire and brake wear, and re-suspension, from reported total non-exhaust emission factors. In doing so, tunnel studies were not considered because the various sources of non-exhaust emissions cannot be easily distinguished in such studies and they often include exhaust components.

Another difficulty was to decide about the size fraction split. It has been assumed that 50 percent of TSP is $PM_{10}$ and that $PM_{2.5}$ represents about 50 percent of $PM_{10}$. The current RAINS values should be seen as a preliminary set subject to further review.

Table 3.57: Emission factors for road abrasion given in the literature [g/km].

| Source | Vehicle type | $PM_{10}$ | TSP |
|---|---|---|---|
| CBS, 1998 | Heavy duty vehicles | 0.0380 | --- |
| (including tire, brake and | Light duty vehicles | 0.0090 | --- |
| road wear) | Passenger cars | 0.0070 | --- |
| | Motorbikes < 50cc | 0.0020 | --- |
| | Motorbikes > 50cc | 0.0040 | --- |
| Berdowski *et al*., 1997 | Light duty vehicles | 0.07 | --- |
| (includes tire, brake, road | Motorcycles | 0.023 | --- |
| wear and re-suspension) | Heavy duty vehicles | 1.17 | --- |
| EMPA, 2000 (including | Heavy duty vehicles on paved roads | 0.450 | --- |
| re-suspension) | Light duty vehicles and passenger cars on paved roads | 0.030 | --- |
| Israel *et al*., 1994 | Passenger car & station wagon (tunnel measurement) | --- | 0.12 |
| | Truck (tunnel measurement) | --- | 2.00 |

| Source | Vehicle type | $PM_{10}$ | TSP |
|---|---|---|---|
| Israel *et al.*, 1996 | Passenger car & station wagon (tunnel measurement) | 0.0380 | --- |
| | Truck (tunnel measurement) | 0.5970 | --- |
| Rautenberg-Wulff, 1998 | Passenger car & station wagon (tunnel measurement) | 0.0320 | --- |
| | Truck (tunnel measurement) | 0.8340 | --- |

Table 3.58: Emission factors for road abrasion used in the RAINS model [g/km].

| Sector | RAINS Code | $PM_{2.5}$ | Coarse | $PM_{10}$ | $>PM_{10}$ | TSP |
|---|---|---|---|---|---|---|
| Light duty vehicles | TRD_RD_LD4 | 0.0042 | 0.0033 | 0.0075 | 0.0075 | 0.0150 |
| Motorbikes | TRD_RD_LD2 | 0.0016 | 0.0014 | 0.0030 | 0.0030 | 0.0060 |
| Heavy duty vehicles | TRD_RD_HD | 0.0209 | 0.0171 | 0.0380 | 0.0380 | 0.0760 |

### Applicable Control Options

Technical control options to reduce PM emissions from road abrasion are not considered in the RAINS model.

# 4 Cost Calculations

The basic intention of a cost evaluation in the RAINS model is to identify the values to society of the resources diverted in order to reduce PM emissions in Europe. In practice, these values are approximated by estimating costs at the production level rather than prices to the consumers. Therefore, any mark-ups charged over production costs by manufacturers or dealers do not represent actual resource use and are ignored. Certainly, there will be transfers of money with impacts on the distribution of income or on the competitiveness of the market, but these should be removed from a consideration of the efficiency of a resource. Any taxes added to production costs are similarly ignored as transfers.

As for $SO_2$, $NO_X$, VOC and $NH_3$ emissions, a central assumption in the RAINS PM costs module is the existence of a free market for abatement equipment throughout Europe that is accessible to all countries at the same conditions (see Klaassen, 1991, Klimont *et al.*, 2000, Cofala and Syri, 1998a, 1998b). Thus, the capital investments for a certain technology can be specified as being independent of the country. The abatement costs on a unit basis (EURO/ ton $PM_{10}$, $PM_{2.5}$, TSP removed) of each technology are calculated by using country- or region-specific parameters conditional on variations in average boiler sizes, capacity utilization rates, ash contents of the fuels used etc.

The average annual costs are calculated by taking into account the technical lifetime of the abatement technologies. The expenditures are differentiated into:

- investments,
- fixed operating costs, and
- variable operating costs.

Unit costs are calculated by relating the annual costs to the abated $PM_{10}$, $PM_{2.5}$ or TSP emissions.

Some of the parameters are considered common for all countries, including interest rate and technology-specific data, such as removal efficiencies, basic investments, maintenance costs, and abatement measures specific for the demand of labor, energy, and materials.

Country-specific parameters include the average size of installations in a given sector/class, prices for labor and electricity, and prices of material and annual fuel consumption/mileage for the various vehicle categories.

The following sections introduce the cost calculation principles used in RAINS and explain the construction of the cost curves that will be further used in the optimization module of the RAINS model. The actual parameter values used to calculate country-specific costs and the national cost curves are provided on the RAINS web site (http://www.iiasa.ac.at/~rains).

## 4.1 Stationary Sources

Estimates of costs of dust control for stationary sources in the power plant sector and industrial boilers are based on data published by Rentz *et al.* (1996), Takeshita (1995) and UN/ECE (1996). Costs of controlling pollution from industrial furnaces take into account available estimates from the BAT reference documents prepared by the Integrated Pollution Prevention and Control (IPPC) Bureau (e.g., IPPC, 1999a,b) and by CONCAWE (1999).

### *4.1.1 Investments*

Investments cover the expenditure accumulated until the start-up of an abatement technology. These costs include, e.g., delivery of the installation, construction, civil works, ducting, engineering and consulting, license fees, land requirement and capital. The RAINS model uses investment functions where these cost components are aggregated into one function (Klaassen, 1991, Klimont *et al.*, 2000, Cofala and Syri, 1998a, 1998b). The same approach has been applied for the PM module (see description below). At this stage, however, a simplified method is used to derive the investment costs, i.e., the unit investment costs for including control technologies (ECU/kW) is based on literature review and expert opinions. These unit costs (per kW) are assumed to be independent from the size of the installation. When more data is available, the approach described below (see Equation 1 and 2) is adopted.

The investment costs for the particulate matter control installations for ***combustion processes*** depend on the boiler size *bs* and the (fuel specific) flue gas volume *v* treated. The form of the function is described by its coefficients $ci^f$ and $ci^v$. Coefficients *ci* are valid for hard coal fired boilers. Thus, coefficient *v* is taken to account for the different flue gas volume to be handled when other fuel is used. Coefficients *ci* are estimated separately for three capacity classes: less than 20 $MW_{th}$, from 20 to 300 $MW_{th}$ and above 300 $MW_{th}$. Additional investments, in the case of retrofitting existing boilers/furnaces are taken into account by retrofitting cost factor *r*. The shape of this investment function is given in Equation 1:

$$I = \left( ci^f + \frac{ci^v}{bs} \right) * v * (1 + r) \qquad (1)$$

A similar function can be used for ***industrial process emissions*** when considering the plant capacity *pc* (Equation 2):

$$I = \left( ci^f + \frac{ci^v}{pc} \right) * (1 + r) \qquad (2)$$

The information on classes of plant capacities can be based on the activity rates of different industrial processes (activity given as million metric tons produced). Investments are annualized over the technical lifetime of the plant *lt* by using the real interest rate *q* (as %/100):

$$I^{an} = I * \frac{(1+q)^{lt} * q}{(1+q)^{lt} - 1} \qquad (3)$$

### 4.1.2 Operating Costs

The annual **fixed expenditures** $OM^{fix}$ cover the costs of maintenance and administrative overhead. These cost items are not related to the actual use of the plant. As a rough estimate for annual fixed expenditures, a standard percentage *f* of the total investments is used:

$$OM^{fix} = I * f \tag{4}$$

The **variable operating costs** $OM^{var}$ related to the actual operation of the plant take into account:

- additional labor demand,
- increased energy demand for operating the device (e.g., for the fans and pumps), and
- waste disposal.

These cost items are calculated with the specific demand $\lambda^x$ of a certain control technology and its (country-specific) price $c^x$.

$$OM^{var} = (\lambda^l c^l / pf + \lambda^e c^e) + ef_l * \eta_l * (\lambda^d c^d), \tag{5}$$

$$ef_l = \frac{ac}{hv} * (1 - ar)$$

where

| | |
|---|---|
| $\eta_l$ | removal efficiency for >$PM_{10}$, FINE (= $PM_{2.5}$) or COARSE (=TSP-$PM_{10}$), |
| $\lambda^l$ | labor demand, |
| $\lambda^e$ | additional energy demand, |
| $\lambda^d$ | demand for waste disposal, |
| $c^l$ | labor cost, |
| $c^e$ | electricity price, |
| $c^d$ | waste disposal cost, |
| *pf* | plant factor (annual operating hours at full load), |
| $ef_l$ | unabated emission factor >$PM_{10}$, FINE, or COARSE, |
| *ac* | ash contents, |
| *hv* | lower heat value, and |
| *ar* | ash retention in furnace. |

### 4.1.3 Unit Reduction Costs

***Unit costs per PJ (combustion) or million metric tons (industrial processes)***

Based on the above-mentioned cost items, the unit costs for the removal of PM emissions can be calculated. In Equation 6, all the expenditures of a control technology are related to one unit of fuel input (in PJ). The investment-related costs are converted to fuel input by applying the capacity utilization factor *pf* (operating hours/year):

$$c_{PJ} = \frac{I^{an} + OM^{fix}}{pf} + OM^{var} \quad (6)$$

In Equation 7, all the costs of abatement technologies are related to one unit of industrial products (capacity) produced per year *p*:

$$c_{ton} = \frac{I^{an} + OM^{fix}}{p} + OM^{var} \quad (7)$$

***Unit costs per ton of emissions ( >$PM_{10}$, FINE, and COARSE) removed***

The cost effectiveness of different control options can only be evaluated by relating the abatement costs to the amount of reduced emissions. For this purpose Equations 8 and 9 are used:

$$c_{PMl} = c_{PJ} / ( ef_l * \eta_l) \quad (8)$$

$$c_{PMl} = c_{ton} / ( ef_l * \eta_l) \quad (9)$$

While the fuel- and activity-specific unit costs are unique for each abatement option, emission related unit costs obviously depend on the size fraction of PM emissions considered. This means that the same technology has different unit costs, depending on whether fine, coarse or >$PM_{10}$ is considered.

### 4.1.4 Marginal Reduction Costs

Marginal costs relate the extra costs for an additional measure to the marginal abatement of that measure (compared to the abatement of the less effective option). RAINS uses the concept of

marginal costs for ranking the available abatement options according to their cost effectiveness into so-called “national cost curves” (see Section 4.4).

If, for a given emission source (category), a number of control options $M$ are available, the marginal costs $mc_m$ for control option $m$ are calculated as

$$mc_m = \frac{c_m \eta_{l_m} - c_{m-1} \eta_{l_{m-1}}}{\eta_{l_m} - \eta_{l_{m-1}}} \tag{10}$$

where

$c_m$ unit costs for option $m$ and

$\eta_{lm}$ removal efficiency of option $m$ (for >$PM_{10}$, FINE, or COARSE emissions).

## 4.2 Mobile Sources

Costs of controlling emissions from mobile sources are based on the results of costing studies done within the AUTO OIL Programme (compare EC, 1996; Touche Ross & Co, 1995; Barrett, 1996). The cost data for transport sources are the same as used in the RAINS $NO_x$ module (Cofala and Syri, 1998b).

### *4.2.1 Investments*

The cost evaluation for mobile sources follows the same basic approach as for stationary sources. The most important difference is that the investment costs are given **per vehicle**, not per capacity. The number of vehicles is then computed based on information on total annual fuel consumption by a given vehicle category and average fuel consumption per vehicle per year (Cofala and Syri, 1998b).

The following description uses the indices *i, j, k* and *l* to indicate the nature of the parameters:

*i* denotes the country,

*j* the economic sector,

*k* the control technology,

*l* PM size class fractions.

The **annual costs** are calculated for each sector/control option. The amount of abated >$PM_{10}$, FINE or COARSE emissions is calculated based on the unabated emission factor and the removal efficiency of the control option. The calculation is repeated for every size class fraction considered in the module (fine, coarse, >PM10).

$$rPM_{i,j,k,l}(t) = act_{i,j}(t) * ef_{i,j,l}{}^{N} * \eta_{j,k,l}{}^{N} * af_{i,j.k}(t) \quad (11)$$

where

| | |
|---|---|
| $rPM_{i,j,k,l}(t)$ | emissions removed in country *i* in time step *t* from transport sector *j* with technology *k* and PM size class fraction *l*, |
| $act_{i,j}(t)$ | activity level of sector *j* in time step *t*, |
| $ef_{i,j,l}{}^{N}$ | (unabated) PM emission factor per unit of activity for country *i*, sector *j* and size class fraction *l* expressed in kg pollutant per GJ fuel, |
| $\eta_{j,k,l}{}^{N}$ | PM removal efficiency of technology *k* in sector *j* for size class fraction *l*, |
| $af_{i,j,k}(t)$ | application factor of technology *k* in country *i* for sector *j* in time step *t*. |

The costs of applying control devices to the transport sources include:

- additional investment costs;
- increase in maintenance costs expressed as a percentage of total investments; and
- change (positive or negative) in fuel consumption after inclusion of emission control.

The investment costs $I_{i,j,k}$ are given in EURO/vehicle and are available separately for each technology and vehicle category. They are **annualized** using Equation 12:

$$I^{an}_{i,j,k} = I_{j,k} \cdot \frac{(1+q)^{lt_{i,j,k}} \cdot q}{(1+q)^{lt_{i,j,k}} - 1} \quad (12)$$

where

| | |
|---|---|
| $lt_{i,j,k}$ | lifetime of control equipment. |

### 4.2.2 Operating Costs

The increase in maintenance costs (**fixed costs**) is expressed as a percentage *f* of total investments:

$$OM^{fix}_{i,j,k} = I_{i,j,k} \cdot f_k \quad (13)$$

Finally, the change in fuel consumption after inclusion of emission controls can be calculated as follows:

$$OM^{e}_{i,j,k}(t) = \lambda^{e}_{j,k}\, fuel_{i,j}(t) * c^{e}_{i,j} \quad (14)$$

where:

$\lambda^{e}_{j.k}$ percentage change in fuel consumption in sector *j* caused by implementation of control measure *k*,

$fuel_{i,j}(t)$ fuel use per vehicle in country *i* and sector *j* in time step *t*.

$c^{e}_{i,j}$ fuel price (net of taxes) in country *i* and sector *j*.

Annual fuel consumption per vehicle is a function of the consumption in the base year ($t_0$=1990) and the assumed **fuel efficiency improvement**:

$$fuel_{i,j}(t) = fuel_{i,j}(t_0) * fe_{i,j}(t) \quad (15)$$

where

$fe_{i,j}(t)$ fuel efficiency improvement in time step *t* relative to the base year (1990 = 1).

The unit costs of abatement $ce_{PJ}$ (related to one unit of fuel input) add up to

$$ce_{PJ,i,j,k}(t) = \frac{I^{an}_{i,j,k} \div OM^{fix}_{i,j,k} + OM^{e}_{i,j,k}(t)}{fuel_{i,j}(t)} \quad (16)$$

These costs can be related to the achieved emission reductions. In the current version of the PM module the costs of emissions control in the transport sector are fully attributed to reductions of fine, coarse and >$PM_{10}$ fractions, respectively. The costs per unit of PM abated are as follows:

$$cn_{i,j,k}(t) = \frac{ce_{i,j,k}(t)}{ef^{N}{}_{i,j,k,l} * \eta^{N}{}_{j,k.l}} \quad (17)$$

The most important factors leading to differences among countries in unit abatement costs are: different annual energy consumption per vehicle and, if introduced into the calculation procedure, country-specific unabated emission factors. The latter difference is caused by different compositions of the vehicle fleet as well as differences in driving patterns (e.g., different share of urban vs. highway driving depending on available infrastructure in a given country).

## 4.3 Agriculture

For particulate matter sources from livestock farming, a similar algorithm as that developed for the $NH_3$ module may be used (see Klaassen 1991). Cost calculations are technology-, animal-,

and country specific. The indices *n* (type of animal), *o* (control technology) and *i* (country) are used in the following **investment function**:

$$I_{n,o,i} = \left( ci^{f}_{n,o} + \frac{ci^{v}}{ss_{l,i}} \right) \tag{18}$$

Investment costs of a control technology are a function of the average animal house size, $ss_{l,i}$ is the number of animal places per animal house.

Although some of the $NH_3$ control options, such as animal house adaptations and bio filtration or scrubbing, are certainly also measures for removing PM emissions, they are not yet implemented in the PM module. Cost calculations from the $NH_3$ module may partly be used for the PM module (for details see Klaassen 1991).

## 4.4 Constructing a Cost Curve

Based on the unit cost (see Equations 8, 9, and 17), a cost curve is constructed first for every sector and then for the whole region (country), employing the principle that technologies with higher costs and lower reduction efficiency are considered not cost-efficient and are excluded from further analysis. Marginal costs, i.e., the costs of removing an additional unit of PM by a given control technology, are calculated for each sector along Equation 10. Finally, the remaining (cost-efficient) abatement options are ordered according to increasing marginal costs and thus form the cost curve for the considered region.

Examples of cost curves for TSP, $PM_{10}$, and $PM_{2.5}$ are presented in Table 4.1, Table 4.2, and Table 4.3. The first row in all tables shows initial emissions for a given year and in a given country. The codes of sectors and control technologies are explained in Section 2 of this document. The amount of particulate matter reduced by a particular technology can be derived from comparing the emissions given for this option in the column *"Remaining emissions"* with the preceding value. The *"Total cost"* column displays cumulative costs. This means that for any emission level a cost value in this column represents total costs incurred to achieve this level of emissions. The examples presented in these tables contain only a part of a cost curve, which typically includes some 80 to 150 control options ordered according to increasing marginal costs (such a complete cost curve is presented in Figure 4.2).

A graphical interpretation of Table 4.1 is presented in Figure 4.1. The remaining emissions of TSP are on the x-axis and the total cost on the y-axis. The highest emission value is called the initial emissions and the lowest level is often referred to as maximum feasible reduction (MFR). In the literature, cost curves are often presented in different ways such that instead of showing remaining emissions, the amount of pollutant reduced is shown on the x-axis. As can be seen, the abatement achieved as well as the cost involved, varies substantially from technology to technology. Note the marked points that indicate the technologies appearing in the same order as in Table 4.1.

Comparing the example cost curves for different size fractions also reveals differences which stem from varying unit reduction costs for the same technology but different size fractions (as discussed in Section 4.1.3 of this document). The marginal costs for smaller PM fractions are also consistently higher than for TSP.

Table 4.1: Example of a no control cost curve for TSP (only part of it).

| RAINS fuel code | RAINS sector code | RAINS Control option code | Marginal cost [EURO/kt TSP] | Remaining emissions [kt TSP] | Total cost [Mio EURO] |
|---|---|---|---|---|---|
| | | | | 592.8 | |
| HC1 | PP_NEW2 | ESP1 | 29 | 557.5 | 1.03 |
| HC1 | PP_NEW3 | ESP1 | 30 | 369.0 | 6.63 |
| HC1 | PP_EX_OTH2 | ESP1 | 30 | 360.5 | 6.88 |
| HC1 | PP_EX_OTH3 | ESP1 | 31 | 318.1 | 8.18 |
| HC1 | IN_OC2 | ESP1 | 33 | 315.3 | 8.28 |
| HC1 | IN_OC3 | ESP1 | 33 | 308.5 | 8.50 |
| HC1 | PP_EX_OTH1 | CYC | 36 | 307.5 | 8.54 |
| HC1 | IN_OC1 | CYC | 40 | 305.9 | 8.60 |
| HC1 | DOM | COAL1 | 42 | 304.6 | 8.66 |
| OS1 | DOM | WOOD1 | 45 | 300.5 | 8.84 |
| HC1 | DOM | COAL2 | 63 | 299.6 | 8.90 |
| HC1 | PP_EX_OTH1 | ESP1 | 65 | 299.3 | 8.91 |
| HC1 | IN_OC1 | ESP1 | 76 | 299.0 | 8.94 |
| HC1 | PP_NEW2 | ESP2 | 106 | 297.7 | 9.07 |
| HC1 | PP_EX_OTH2 | ESP2 | 110 | 297.4 | 9.11 |
| HC1 | PP_NEW3 | ESP2 | 111 | 290.9 | 9.84 |
| HC1 | PP_EX_OTH3 | ESP2 | 116 | 289.4 | 10.01 |
| HC1 | IN_OC2 | ESP2 | 129 | 289.3 | 10.02 |
| NOF | IN_PR_FERT | CYC | 130 | 288.8 | 10.08 |
| NOF | IN_PR_REF | CYC | 130 | 287.1 | 10.30 |
| NOF | IN_PR_CELI | CYC | 130 | 101.7 | 34.41 |
| HC1 | IN_OC3 | ESP2 | 135 | 101.5 | 34.44 |
| OS1 | DOM | WOOD3 | 175 | 99.3 | 34.81 |
| NOF | IN_PR_REF | ESP1 | 178 | 98.1 | 35.03 |
| NOF | IN_PR_FERT | ESP1 | 182 | 97.8 | 35.08 |
| … | … | … | … | … | … |

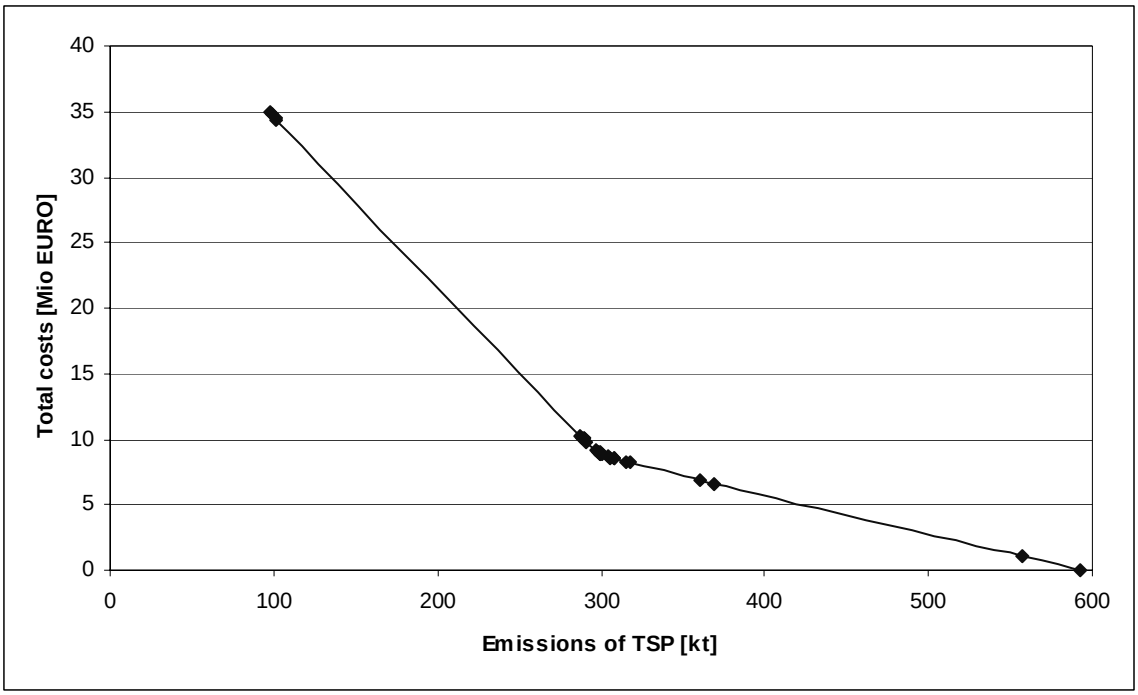


Figure 4.1: Graphical illustration of the part of the TSP cost curve presented in Table 4.1.

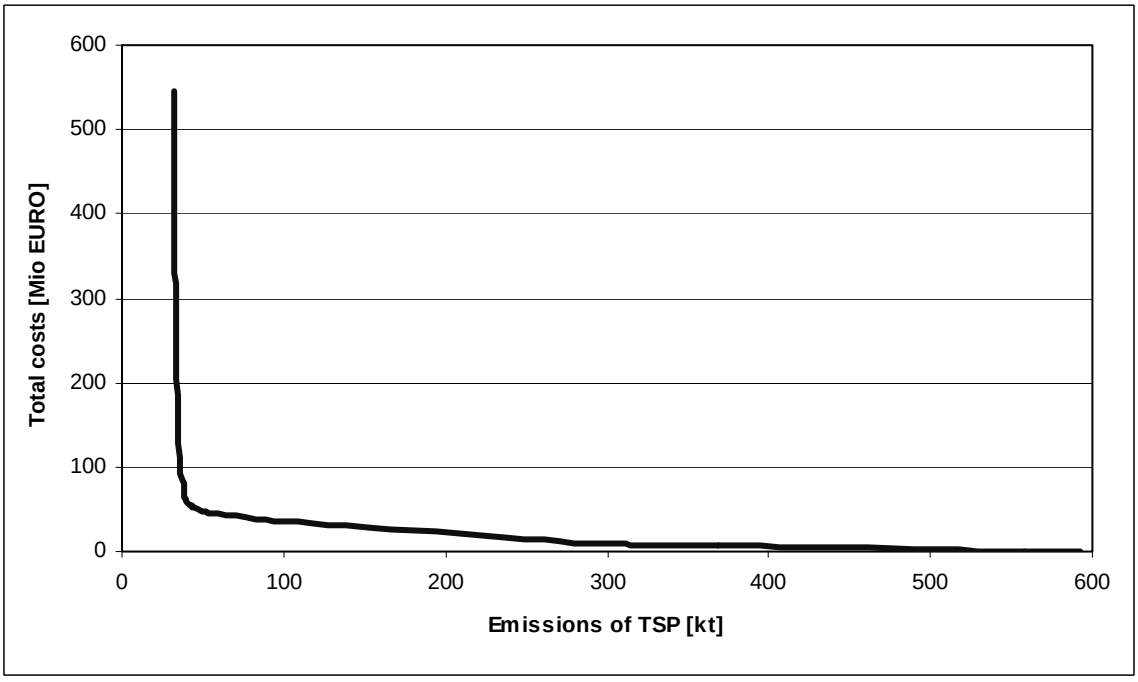


Figure 4.2: Example of the complete no-control TSP cost curve.

Table 4.2: Example of a no-control cost curve for $PM_{10}$.

| RAINS fuel code | RAINS sector code | RAINS Control option code | Marginal cost [EURO/kt PM10] | Remaining emissions [kt PM10] | Total cost [Mio EURO] |
|---|---|---|---|---|---|
| | | | | 300.1 | |
| OS1 | DOM | WOOD1 | 26 | 293.0 | 0.19 |
| HC1 | PP_NEW2 | ESP1 | 57 | 274.9 | 1.22 |
| HC1 | PP_NEW3 | ESP1 | 58 | 178.1 | 6.82 |
| HC1 | PP_EX_OTH2 | ESP1 | 59 | 173.7 | 7.07 |
| HC1 | PP_EX_OTH3 | ESP1 | 60 | 152.0 | 8.37 |
| HC1 | IN_OC2 | ESP1 | 63 | 150.5 | 8.46 |
| HC1 | IN_OC3 | ESP1 | 65 | 147.0 | 8.69 |
| HC1 | DOM | COAL1 | 81 | 146.3 | 8.75 |
| HC1 | PP_EX_OTH1 | ESP1 | 81 | 145.7 | 8.80 |
| HC1 | IN_OC1 | CYC | 91 | 145.0 | 8.86 |
| HC1 | IN_OC1 | ESP1 | 93 | 144.7 | 8.89 |
| OS1 | DOM | WOOD3 | 101 | 141.0 | 9.26 |
| OS1 | PP_NEW | ESP1 | 116 | 138.6 | 9.54 |
| HC1 | DOM | COAL2 | 121 | 138.1 | 9.60 |
| OS1 | IN_OC | ESP1 | 125 | 137.3 | 9.70 |
| OS1 | CON_COMB | ESP1 | 125 | 136.0 | 9.86 |
| OS1 | PP_EX_OTH | ESP1 | 128 | 134.4 | 10.07 |
| NOF | IN_PR_CELI | CYC | 147 | 73.1 | 19.08 |
| HC1 | PP_NEW2 | ESP2 | 182 | 72.4 | 19.21 |
| HC1 | PP_EX_OTH2 | ESP2 | 189 | 72.2 | 19.24 |
| HC1 | PP_NEW3 | ESP2 | 190 | 68.3 | 19.97 |
| HC1 | PP_EX_OTH3 | ESP2 | 198 | 67.5 | 20.14 |
| HC1 | IN_OC2 | ESP2 | 221 | 67.4 | 20.16 |
| HC1 | IN_OC3 | ESP2 | 232 | 67.3 | 20.19 |
| NOF | IN_PR_CELI | ESP1 | 247 | 34.6 | 28.26 |
| … | … | … | … | … | … |

Table 4.3: Example of a no-control cost curve for $PM_{2.5}$.

| RAINS fuel code | RAINS sector code | RAINS Control option code | Marginal cost [EURO/kt PM2.5] | Remaining emissions [kt PM2.5] | Total cost [Mio EURO] |
|---|---|---|---|---|---|
| | | | | 119.2 | |
| OS1 | DOM | WOOD1 | 27 | 112.3 | 0.19 |
| OS1 | DOM | WOOD3 | 104 | 108.7 | 0.56 |
| OS1 | PP_NEW | ESP1 | 120 | 106.4 | 0.84 |
| OS1 | CON_COMB | ESP1 | 129 | 105.1 | 1.00 |
| OS1 | IN_OC | ESP1 | 129 | 104.4 | 1.10 |
| OS1 | PP_EX_OTH | ESP1 | 132 | 102.8 | 1.31 |
| NOF | IN_PR_REF | CYC | 180 | 101.5 | 1.54 |
| NOF | IN_PR_REF | ESP1 | 205 | 100.5 | 1.76 |
| HC1 | PP_NEW2 | ESP1 | 231 | 96.0 | 2.79 |
| HC1 | PP_NEW3 | ESP1 | 235 | 72.2 | 8.39 |
| NOF | IN_PR_FERT | CYC | 235 | 72.0 | 8.44 |
| HC1 | PP_EX_OTH2 | ESP1 | 238 | 70.9 | 8.70 |
| NOF | IN_PR_FERT | ESP1 | 240 | 70.7 | 8.74 |
| HC1 | PP_EX_OTH3 | ESP1 | 243 | 65.3 | 10.04 |
| HC1 | IN_OC2 | ESP1 | 258 | 65.0 | 10.14 |
| HC1 | IN_OC3 | ESP1 | 263 | 64.1 | 10.36 |
| HC1 | DOM | COAL1 | 324 | 63.9 | 10.42 |
| HC1 | PP_EX_OTH1 | ESP1 | 329 | 63.8 | 10.47 |
| HC1 | IN_OC1 | ESP1 | 373 | 63.5 | 10.56 |
| HC1 | DOM | COAL2 | 485 | 63.4 | 10.62 |
| NOF | IN_PR_CELI | ESP1 | 858 | 23.6 | 44.78 |
| HC1 | PP_NEW2 | ESP_PLUS | 906 | 23.3 | 45.04 |
| HC1 | PP_EX_OTH2 | ESP2 | 945 | 23.3 | 45.07 |
| HC1 | PP_NEW3 | ESP2 | 951 | 22.5 | 45.80 |
| HC1 | PP_NEW3 | ESP_PLUS | 954 | 21.8 | 46.53 |
| … | … | … | … | … | … |

# 5 The RAINS PM Web Module

The present implementation (version 1.03) of the RAINS PM module on the Internet (http://www.iiasa.ac.at/~rains/PM/pm-home.html) provides free access to the input data and results to facilitate interaction with national experts.

The following options are available for selected countries and scenarios:

- Display country-specific activity data;
- Display general and country-specific input parameters for the calculation of primary PM emissions at the most resolved level;
- Display general and country-specific input parameters for the calculation of PM control costs at the most resolved level;
- Display control strategy;
- Display resulting emission estimates at the most resolved level and in aggregated form (including CORINAIR SNAP 1 aggregation);
- Display estimates of emission control costs at the most resolved level and in aggregated form; and
- Display "no-control" cost curves for different PM size fractions and years.

Currently, two scenarios are available: (i) a "baseline – current legislation" scenario that can be compared with national emission estimates, and (ii) a (hypothetical) "no control"scenario.

Further features will be added to the Internet version of the RAINS PM module in due course. IIASA continues to work on an implementation that will allow users to develop their own emission inventories and projections in a fully interactive way and to examine the implications on PM emission control cost curves. Ultimately, IIASA aims to provide full access to the RAINS model via the Internet.

# 6 Results

Based on the methodology and data introduced above, a first estimate of the PM emissions in Europe was derived. This estimate must be considered as preliminary, since many of the emission factors need revision and update with additional information.

## 6.1 Emissions

Table 6.1 lists the national total emissions for the European countries for the year 1990, 1995 and 2010. The projections for the year 2010 assume full implementation of the current legislation on emission controls, e.g., the EURO-IV emission standards resulting from the Auto Oil process for mobile sources, and regulations relating to the large combustion plant directive of the European Union. Results are provided for TSP, $PM_{10}$ and $PM_{2.5}$. Major reductions in PM emissions occurred between 1990 and 1995, mainly because of the economic restructuring in Eastern Europe where many old coal power stations were retired. Between 1990 and 1995, TSP emissions declined by 41 percent; for 2010 a decline of 58 percent is projected. Emission reductions are most efficient for larger particles; for 2010, $PM_{10}$ is calculated to decline by 56 percent, and $PM_{2.5}$ by 48 percent. Consequently, fine fraction ($PM_{2.5}$) will be relatively more important in the future (38 percent of TSP in 2010) compared to 31 percent of TSP in 1990.

Table 6.2 presents the hypothetical emissions if no control measures are applied and thereby illustrates the significant extent to which PM emissions are already controlled. In 1990, 92 percent of TSP in raw gas was eliminated by emission control measures, and this share is expected to increase until 2010 to 96 percent. For $PM_{2.5}$, however, control measures reduced PM in raw gas by about 85 percent, and 91 percent of control is anticipated for 2010 with present legislation. The need for accurate information on the status and performance of installed emission control devices is obvious, and minor inaccuracies in such information leads to significant changes in the estimates of overall emissions.

The analysis also reveals that despite the far-reaching emission controls that are implemented today there is a certain potential for further cuts in PM emissions. As illustrated in Table 6.3, in 1990 there was a technical potential for further cuts in PM emissions by about 72 percent below the actual levels. The penetration of more stringent legislation will reduce this potential in the future. However, fully implementing the control measures considered in RAINS would cut PM emissions in 2010 by another 50 percent below that is expected from present legislation.

Table 6.1: Estimates of PM emissions for the years 1990, 1995 and 2010 assuming full implementation of current legislation.

| | TSP | | | $PM_{10}$ | | | $PM_{2.5}$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1990 | 1995 | 2010 | 1990 | 1995 | 2010 | 1990 | 1995 | 2010 |
| Albania | 39 | 20 | 17 | 26 | 13 | 12 | 13 | 7 | 8 |
| Austria | 68 | 53 | 38 | 48 | 39 | 26 | 34 | 31 | 22 |
| Belarus | 112 | 69 | 55 | 74 | 47 | 37 | 42 | 25 | 24 |
| Belgium | 85 | 77 | 45 | 57 | 51 | 26 | 36 | 33 | 18 |
| Bosnia-Herzegovina | 152 | 101 | 81 | 99 | 67 | 57 | 36 | 24 | 23 |
| Bulgaria | 531 | 468 | 340 | 340 | 304 | 231 | 128 | 111 | 97 |
| Croatia | 44 | 30 | 24 | 30 | 21 | 17 | 17 | 13 | 11 |
| Czech Republic | 768 | 476 | 184 | 492 | 312 | 145 | 204 | 135 | 81 |
| Denmark | 31 | 32 | 24 | 23 | 23 | 16 | 16 | 16 | 11 |
| Estonia | 231 | 102 | 30 | 153 | 72 | 26 | 53 | 30 | 16 |
| Finland | 59 | 51 | 39 | 49 | 41 | 29 | 41 | 35 | 25 |
| France | 364 | 343 | 213 | 256 | 242 | 128 | 181 | 179 | 92 |
| Germany | 1969 | 458 | 299 | 1132 | 285 | 151 | 461 | 192 | 103 |
| Greece | 101 | 114 | 97 | 81 | 88 | 77 | 51 | 56 | 50 |
| Hungary | 299 | 131 | 41 | 180 | 87 | 30 | 65 | 39 | 21 |
| Ireland | 61 | 48 | 19 | 34 | 27 | 11 | 13 | 11 | 6 |
| Italy | 241 | 238 | 175 | 166 | 161 | 97 | 122 | 119 | 66 |
| Latvia | 41 | 18 | 12 | 25 | 12 | 9 | 13 | 8 | 7 |
| Lithuania | 66 | 30 | 19 | 40 | 19 | 13 | 20 | 11 | 10 |
| Luxembourg | 9 | 8 | 5 | 6 | 5 | 3 | 4 | 4 | 2 |
| Netherlands | 56 | 54 | 41 | 38 | 36 | 22 | 28 | 27 | 16 |
| Norway | 22 | 23 | 17 | 16 | 16 | 11 | 13 | 12 | 9 |
| Poland | 1405 | 1161 | 724 | 887 | 752 | 490 | 332 | 334 | 257 |
| Portugal | 35 | 39 | 34 | 27 | 29 | 23 | 22 | 24 | 18 |
| R. of Moldova | 76 | 44 | 37 | 43 | 25 | 21 | 13 | 8 | 7 |
| Romania | 589 | 471 | 309 | 376 | 314 | 216 | 173 | 136 | 106 |
| Russia | 2856 | 1510 | 1365 | 1789 | 965 | 883 | 941 | 501 | 483 |
| Slovakia | 248 | 208 | 104 | 152 | 122 | 61 | 59 | 44 | 23 |
| Slovenia | 73 | 43 | 22 | 45 | 30 | 17 | 15 | 15 | 12 |
| Spain | 208 | 213 | 171 | 151 | 155 | 112 | 98 | 110 | 77 |
| Sweden | 65 | 53 | 40 | 52 | 41 | 27 | 45 | 34 | 22 |
| Switzerland | 22 | 20 | 19 | 14 | 12 | 10 | 10 | 9 | 7 |
| FYR Macedonia | 54 | 43 | 26 | 35 | 29 | 18 | 12 | 10 | 7 |
| Ukraine | 2572 | 1145 | 948 | 1455 | 706 | 596 | 704 | 331 | 285 |
| United Kingdom | 404 | 321 | 186 | 265 | 206 | 105 | 149 | 123 | 67 |
| Yugoslavia | 266 | 172 | 126 | 172 | 113 | 87 | 60 | 40 | 36 |
| Atlantic Ocean | 67 | 67 | 67 | 66 | 66 | 66 | 64 | 64 | 64 |
| Baltic Sea | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| North Sea | 46 | 46 | 46 | 45 | 45 | 45 | 44 | 44 | 44 |
| Total | 14342 | 8507 | 6047 | 8948 | 5587 | 3962 | 4344 | 2955 | 2241 |

Table 6.2: Estimates of hypothetical “no-control” PM emissions for the years 1990 and 2010.

| | TSP | | $PM_{10}$ | | $PM_{2.5}$ | |
|---|---|---|---|---|---|---|
| | 1990 | 2010 | 1990 | 2010 | 1990 | 2010 |
| Albania | 274 | 176 | 142 | 90 | 44 | 30 |
| Austria | 1023 | 914 | 512 | 562 | 218 | 327 |
| Belarus | 533 | 582 | 263 | 288 | 111 | 106 |
| Belgium | 1783 | 1177 | 904 | 602 | 360 | 291 |
| Bosnia-Herzegovina | 2933 | 2717 | 1507 | 1397 | 396 | 366 |
| Bulgaria | 8976 | 9151 | 4643 | 4734 | 1211 | 1235 |
| Croatia | 332 | 287 | 171 | 148 | 58 | 51 |
| Czech Republic | 14913 | 11679 | 7706 | 6023 | 2044 | 1613 |
| Denmark | 1334 | 1243 | 691 | 714 | 207 | 281 |
| Estonia | 4898 | 2136 | 2542 | 1102 | 653 | 288 |
| Finland | 1354 | 2221 | 911 | 1467 | 504 | 759 |
| France | 4936 | 4245 | 2431 | 2256 | 980 | 1102 |
| Germany | 29492 | 20422 | 15057 | 10537 | 4326 | 3321 |
| Greece | 9087 | 11107 | 4641 | 5704 | 1240 | 1513 |
| Hungary | 3179 | 1397 | 1631 | 705 | 446 | 216 |
| Ireland | 604 | 601 | 319 | 339 | 96 | 123 |
| Italy | 4576 | 4672 | 2130 | 2255 | 892 | 970 |
| Latvia | 198 | 193 | 98 | 93 | 39 | 36 |
| Lithuania | 414 | 369 | 187 | 163 | 77 | 70 |
| Luxembourg | 207 | 190 | 92 | 83 | 50 | 47 |
| Netherlands | 1329 | 1364 | 674 | 742 | 245 | 311 |
| Norway | 184 | 233 | 105 | 132 | 65 | 80 |
| Poland | 19780 | 17124 | 10189 | 8858 | 2747 | 2484 |
| Portugal | 557 | 931 | 285 | 514 | 119 | 208 |
| R. of Moldova | 465 | 377 | 243 | 197 | 62 | 50 |
| Romania | 8610 | 7957 | 4428 | 4089 | 1228 | 1146 |
| Russia | 12993 | 9007 | 6714 | 4642 | 2408 | 1738 |
| Slovakia | 3086 | 1504 | 1589 | 766 | 435 | 229 |
| Slovenia | 1073 | 725 | 552 | 374 | 146 | 105 |
| Spain | 10657 | 9050 | 5374 | 4783 | 1577 | 1664 |
| Sweden | 746 | 1747 | 420 | 1249 | 264 | 759 |
| Switzerland | 386 | 338 | 172 | 155 | 79 | 74 |
| FYR Macedonia | 1043 | 854 | 542 | 444 | 137 | 112 |
| Ukraine | 15931 | 10739 | 8060 | 5407 | 2506 | 1752 |
| United Kingdom | 13498 | 6010 | 6908 | 3074 | 1976 | 1065 |
| Yugoslavia | 4820 | 4134 | 2488 | 2133 | 644 | 553 |
| | | | | | | |
| Atlantic Ocean | 67 | 67 | 66 | 66 | 64 | 64 |
| Baltic Sea | 7 | 7 | 7 | 7 | 7 | 7 |
| North Sea | 46 | 46 | 45 | 45 | 44 | 44 |
| | | | | | | |
| Total | 186327 | 147693 | 95439 | 76939 | 28707 | 25193 |

Table 6.3: Estimates of hypothetical PM emission levels achievable with maximum technically feasible emission reductions for the years 1990 and 2010.

| | TSP | | $PM_{10}$ | | $PM_{2.5}$ | |
|---|---|---|---|---|---|---|
| | 1990 | 2010 | 1990 | 2010 | 1990 | 2010 |
| Albania | 7 | 6 | 4 | 3 | 3 | 2 |
| Austria | 32 | 25 | 18 | 14 | 11 | 11 |
| Belarus | 43 | 19 | 24 | 10 | 12 | 6 |
| Belgium | 36 | 34 | 19 | 15 | 10 | 9 |
| Bosnia-Herzegovina | 11 | 10 | 8 | 6 | 5 | 4 |
| Bulgaria | 76 | 64 | 46 | 39 | 23 | 21 |
| Croatia | 13 | 7 | 7 | 4 | 4 | 3 |
| Czech Republic | 238 | 60 | 136 | 38 | 52 | 23 |
| Denmark | 16 | 17 | 9 | 9 | 6 | 6 |
| Estonia | 19 | 8 | 13 | 6 | 9 | 4 |
| Finland | 22 | 27 | 14 | 18 | 11 | 15 |
| France | 168 | 154 | 91 | 72 | 56 | 45 |
| Germany | 586 | 258 | 276 | 113 | 121 | 72 |
| Greece | 43 | 52 | 28 | 33 | 20 | 24 |
| Hungary | 91 | 18 | 49 | 10 | 17 | 6 |
| Ireland | 32 | 14 | 17 | 7 | 6 | 3 |
| Italy | 123 | 136 | 62 | 60 | 39 | 36 |
| Latvia | 15 | 5 | 8 | 3 | 4 | 2 |
| Lithuania | 23 | 8 | 12 | 4 | 5 | 3 |
| Luxembourg | 3 | 3 | 2 | 2 | 1 | 1 |
| Netherlands | 29 | 35 | 15 | 16 | 10 | 11 |
| Norway | 11 | 13 | 7 | 7 | 5 | 5 |
| Poland | 296 | 306 | 170 | 179 | 71 | 84 |
| Portugal | 15 | 21 | 9 | 10 | 6 | 7 |
| R. of Moldova | 26 | 15 | 14 | 8 | 4 | 3 |
| Romania | 63 | 56 | 40 | 35 | 24 | 22 |
| Russia | 793 | 532 | 449 | 297 | 193 | 130 |
| Slovakia | 79 | 48 | 43 | 25 | 15 | 9 |
| Slovenia | 15 | 9 | 8 | 5 | 3 | 3 |
| Spain | 101 | 114 | 57 | 59 | 35 | 38 |
| Sweden | 28 | 32 | 18 | 19 | 14 | 14 |
| Switzerland | 14 | 15 | 7 | 6 | 4 | 4 |
| FYR Macedonia | 6 | 4 | 4 | 2 | 2 | 1 |
| Ukraine | 457 | 302 | 248 | 163 | 93 | 64 |
| United Kingdom | 207 | 140 | 115 | 64 | 62 | 38 |
| Yugoslavia | 22 | 17 | 14 | 11 | 9 | 7 |
| | | | | | | |
| Atlantic Ocean | 40 | 40 | 39 | 39 | 39 | 39 |
| Baltic Sea | 4 | 4 | 4 | 4 | 4 | 4 |
| North Sea | 27 | 27 | 27 | 27 | 27 | 27 |
| | | | | | | |
| Total | 3829 | 2657 | 2132 | 1446 | 1038 | 806 |

The sectoral origins of PM emissions in Europe (by SNAP code) are listed in Table 6.4 and Table 6.5. In 1990, combustion in energy industries, small non-industrial combustion sources, production processes and road transport contributed about 20 percent each to total TSP emissions in the EU-15. In the non-EU countries, small sources and power plants were responsible for more than 30 percent each, while road transport contributed only three percent of TSP. In those countries, small sources (domestic coal and wood combustion) are expected to increase their share to 45 percent in 2010, while in the EU-15 mobile sources will become the most important source category of TSP emissions (45 percent).

For $PM_{2.5}$, mobile sources were the largest contributor in 1990 in the EU-15 countries (31 percent). This share is expected to decline slightly until 2010 (28 percent) due to the strict regulations that were recently introduced. In the non-EU countries, industrial production processes were the largest source of $PM_{2.5}$ emissions (36 percent), while in 2010 small combustion sources in the domestic sector will dominate (38 percent).

Table 6.4: PM emissions of the EU-15 countries by SNAP sectors.

| | 1990 | 2010 | 1990 | 2010 | 1990 | 2010 |
|---|---|---|---|---|---|---|
| SNAP sector | TSP | | $PM_{10}$ | | PM 2.5 | |
| 1: Combustion in energy industries | 685 | 232 | 523 | 213 | 242 | 151 |
| 2: Non-industrial combustion plants | 871 | 150 | 515 | 127 | 220 | 108 |
| 3: Combustion in manufacturing industry | 463 | 17 | 291 | 15 | 102 | 10 |
| 4: Production processes | 761 | 300 | 485 | 202 | 314 | 144 |
| 7: Road transport | 683 | 544 | 433 | 190 | 349 | 121 |
| 8: Other mobile sources and machinery | 67 | 53 | 65 | 52 | 61 | 49 |
| 10: Agriculture | 63 | 60 | 30 | 29 | 11 | 11 |
| 12: Other (not included in CORINAIR) | 162 | 71 | 45 | 26 | 2 | 1 |
| SUM | 3756 | 1427 | 2385 | 854 | 1302 | 594 |

Table 6.5: PM emissions of the non-EU countries by SNAP sectors.

| | 1990 | 2010 | 1990 | 2010 | 1990 | 2010 |
|---|---|---|---|---|---|---|
| SNAP sector | TSP | | $PM_{10}$ | | PM 2.5 | |
| 1: Combustion in energy industries | 3303 | 1257 | 2242 | 973 | 767 | 431 |
| 2: Non-industrial combustion plants | 3453 | 2018 | 1978 | 1223 | 773 | 575 |
| 3: Combustion in manufacturing industry | 531 | 60 | 329 | 45 | 113 | 22 |
| 4: Production processes | 2707 | 747 | 1596 | 502 | 1067 | 337 |
| 7: Road transport | 304 | 280 | 188 | 153 | 150 | 119 |
| 8: Other mobile sources and machinery | 61 | 37 | 52 | 36 | 43 | 34 |
| 10: Agriculture | 70 | 62 | 34 | 31 | 13 | 12 |
| 12: Other (not included in CORINAIR) | 37 | 37 | 24 | 25 | 0 | 0 |
| SUM | 10465 | 4499 | 6443 | 2988 | 2925 | 1530 |

The lack of data prohibits a comprehensive comparison of these results with emission estimates from other sources. An incomplete comparison is, however, presented in Table 6.6; what is surprising are the matches indicated for some countries, while at the same time astounding differences emerge for other countries. In many cases where national estimates are sufficiently documented, the sources of the differences can be traced back to a few sectoral estimates, here the national estimates used contradict the literature sources listed in the preceding parts of this document. In other cases, national estimates included additional emission sources for which only limited information could be found in the international literature (e.g., railways) or are explicitly excluded from this analysis (e.g., re-suspension).

Obviously, the present analysis considers a restricted set of sources of PM emissions. There is, of course, a potentially large number of other sources that could make substantial contributions to PM emissions, but for which only limited information is available. For instance, the Swiss emission inventory includes railways (estimated to contribute about ten percent to total national $PM_{10}$ emissions) and the manufacturing of wood products (700 g/person). However, insufficient confirmed information was found to be able to include these activities into the RAINS inventory. TNO considers the emissions of waste incineration, differentiating among the (illegal) open burning of domestic waste, burning of agricultural waste, hazardous waste incineration, the burning of construction waste, and sewage incineration as well as the production of asphalt roofs. Further work is therefore necessary to confirm this underlying information and to collect relevant data at an European scale.

Table 6.6: Comparison of national emission estimates with RAINS estimates.

| Country | Year | Substance | National estimate | RAINS estimate |
|---|---|---|---|---|
| Austria | 1990 | TSP | 39 [(1)] | 68 |
| Belgium | 1990 | TSP | 24 [(1)] | 85 |
| Czech Republic | 1990 | TSP | 631 [(1)] | 768 |
| Finland | 1990 | TSP | 86 [(2)] | 59 |
| France | 1990 | TSP | 234 [(1)] | 364 |
| France | 1990 | $PM_{10}$ | 343 [(3)] | 243 |
| Germany | 1990 | TSP | 1881 [(4)] | 1969 |
| Ireland | 1990 | TSP | 105 [(1)] | 61 |
| Netherlands | 1995 | TSP | 36 [(1)] | 56 |
| Norway | 1990 | TSP | 22 [(1)] | 22 |
| Poland | 1990 | TSP | 1337 [(1)] | 1405 |
| Switzerland | 1995 | $PM_{10}$ | 28 [(5)] | 12 |
| UK | 1995 | $PM_{10}$ | 220 [(6)] | 206 |

[(1)] GUS, 1999; OECD, 1998. [(2)] Karvosenoja, 2000 [(3)] CITEPA, 2000 (excluding forest fires estimated by CITEPA at 64.3 kt); [(4)] UBA, 1999b; [(5)] BUWAL, 2001. [(6)] APEG, 1999.

## 6.2 Emission Control Costs

Preliminary cost estimates are presented in Table 6.7. In 1990, about six billion Euro/year were spent in the EU-15 on measures to reduce PM emissions. While this level of expenditure remains similar for stationary sources, the recently adopted EU legislation for mobile sources (the Auto Oil emission standards) will increase total abatement costs to about 48 billion Euro, if the full costs of the PM control measures are taken into account.

Table 6.7: Costs for measures that reduce PM emissions, for 1990 and for present legislation in the year 2010. Note that these costs include the full costs of EURO I-IV in the transport sector, although they also affect other emissions than PM.

| | EU-15 | | Non-EU | |
|---|---|---|---|---|
| | 1990 | 2010 | 1990 | 2010 |
| Power sector | 2274 | 1991 | 2299 | 1842 |
| Industry | 3096 | 3070 | 1722 | 1853 |
| Domestic | 314 | 348 | 26 | 24 |
| Transport | 260 | 43014 | 85 | 4385 |
| Total | 5944 | 48422 | 4133 | 8105 |

## 6.3 PM Emission Estimates for Germany

Table 6.8 to Table 6.10 present the estimates of PM emissions for Germany for 1990, 1995 and 2010, respectively.

Table 6.8: PM emissions in Germany in 1990.

| RAINS sector | | Emissions [kt] | | | Share of total German emissions in 1990 [%] | | |
|---|---|---|---|---|---|---|---|
| Primary | Secondary | TSP | $PM_{10}$ | $PM_{2.5}$ | TSP | $PM_{10}$ | $PM_{2.5}$ |
| Stationary combustion | Conversion combustion | 24 | 15 | 5 | 1.2 | 1.3 | 1.1 |
| | Domestic combustion | 472 | 250 | 68 | 24.0 | 22.1 | 14.7 |
| | Industrial combustion | 367 | 219 | 65 | 18.6 | 19.3 | 14.1 |
| | Power plants | 424 | 289 | 103 | 21.5 | 25.5 | 22.4 |
| Process emissions | Pig iron | 70 | 49 | 38 | 3.6 | 4.4 | 8.2 |
| | Coke production | 18 | 9 | 6 | 0.9 | 0.8 | 1.3 |
| | Sinter process | 17 | 5 | 2 | 0.9 | 0.4 | 0.4 |
| | Cement production | 264 | 155 | 82 | 13.4 | 13.6 | 17.7 |
| | Petroleum refining | 2 | 2 | 2 | 0.1 | 0.2 | 0.4 |
| | Aluminum production | 3 | 2 | 1 | 0.1 | 0.2 | 0.2 |
| | Pup and paper | 3 | 3 | 3 | 0.2 | 0.3 | 0.6 |
| | Fertilizer production | 1 | 0 | 0 | 0.0 | 0.0 | 0.1 |
| Material | Material handling | 136 | 27 | 2 | 6.9 | 2.4 | 0.4 |
| Road transport | Heavy duty vehicles | 19 | 19 | 17 | 1.0 | 1.7 | 3.7 |
| | Light duty vehicles | 39 | 38 | 33 | 2.0 | 3.3 | 7.2 |
| | Motorcycles, mopeds | 10 | 10 | 9 | 0.5 | 0.9 | 1.9 |
| | Leaded gasoline | 15 | 13 | 10 | 0.8 | 1.1 | 2.2 |
| | Tire wear | 49 | 5 | 0 | 2.5 | 0.4 | 0.0 |
| | Brake lining wear | 3 | 3 | 1 | 0.2 | 0.2 | 0.3 |
| | Road abrasion | 10 | 5 | 3 | 0.5 | 0.5 | 0.6 |
| Other transport | Off-road | 11 | 10 | 9 | 0.6 | 0.9 | 2.0 |
| | Shipping | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 |
| Agriculture | Poultry farms | 2 | 1 | 1 | 0.1 | 0.1 | 0.1 |
| | Pig farms | 3 | 1 | 0 | 0.2 | 0.1 | 0.1 |
| | Cattle farms | 2 | 1 | 0 | 0.1 | 0.1 | 0.0 |
| | Other | 2 | 1 | 0 | 0.1 | 0.1 | 0.1 |
| TOTAL | | 1969 | 1132 | 461 | 100.0 | 100.0 | 100.0 |

Table 6.9: Estimated PM emissions in Germany in 1995.

| RAINS sector | | Emissions [kt] | | | Share of total German emissions in 1995 [%] | | |
|---|---|---|---|---|---|---|---|
| Primary | Secondary | TSP | $PM_{10}$ | $PM_{2.5}$ | TSP | $PM_{10}$ | $PM_{2.5}$ |
| Stationary combustion | Conversion combustion | 3 | 2 | 1 | 0.6 | 0.7 | 0.5 |
| | Domestic combustion | 45 | 31 | 17 | 9.9 | 10.8 | 8.8 |
| | Industrial combustion | 4 | 3 | 2 | 0.9 | 1.2 | 1.0 |
| | Power plants | 67 | 61 | 40 | 14.6 | 21.5 | 21.0 |
| Process emissions | Pig iron | 40 | 30 | 24 | 8.8 | 10.5 | 12.4 |
| | Coke production | 2 | 1 | 1 | 0.5 | 0.5 | 0.5 |
| | Sinter process | 8 | 3 | 1 | 1.7 | 0.9 | 0.6 |
| | Cement production | 63 | 41 | 25 | 13.7 | 14.5 | 13.2 |
| | Petroleum refining | 1 | 1 | 1 | 0.2 | 0.3 | 0.4 |
| | Aluminum production | 2 | 1 | 1 | 0.4 | 0.5 | 0.5 |
| | Pup and paper | 1 | 1 | 1 | 0.2 | 0.3 | 0.4 |
| | Fertilizer production | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 |
| Material | Material handling | 57 | 11 | 1 | 12.5 | 4.0 | 0.4 |
| Road transport | Heavy duty vehicles | 21 | 20 | 18 | 4.6 | 7.1 | 9.5 |
| | Light duty vehicles | 49 | 47 | 42 | 10.6 | 16.5 | 21.8 |
| | Motorcycles, mopeds | 2 | 2 | 1 | 0.4 | 0.6 | 0.7 |
| | Leaded gasoline | 2 | 1 | 1 | 0.4 | 0.5 | 0.6 |
| | Tire wear | 59 | 6 | 0 | 12.9 | 2.0 | 0.1 |
| | Brake lining wear | 4 | 3 | 2 | 0.8 | 1.1 | 0.8 |
| | Road abrasion | 12 | 6 | 3 | 2.7 | 2.2 | 1.8 |
| Other transport | Off-road | 9 | 9 | 8 | 2.0 | 3.1 | 4.2 |
| | Shipping | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 |
| Agriculture | Poultry farms | 2 | 1 | 1 | 0.3 | 0.4 | 0.3 |
| | Pig farms | 3 | 1 | 0 | 0.6 | 0.4 | 0.2 |
| | Cattle farms | 1 | 1 | 0 | 0.3 | 0.2 | 0.1 |
| | Other | 2 | 1 | 0 | 0.5 | 0.3 | 0.1 |
| TOTAL | | 458 | 285 | 192 | 100.0 | 100.0 | 100.0 |

Table 6.10: PM emissions in Germany estimated for 2010.

| RAINS sector | | Emissions [kt] | | | Share of total German emissions in 2010 [%] | | |
|---|---|---|---|---|---|---|---|
| Primary | Secondary | TSP | $PM_{10}$ | $PM_{2.5}$ | TSP | $PM_{10}$ | $PM_{2.5}$ |
| Stationary combustion | Conversion combustion | 1 | 1 | 1 | 0.4 | 0.7 | 0.7 |
| | Domestic combustion | 17 | 14 | 13 | 5.7 | 9.6 | 12.4 |
| | Industrial combustion | 3 | 3 | 2 | 1.0 | 1.8 | 1.7 |
| | Power plants | 36 | 32 | 25 | 12.0 | 20.9 | 23.9 |
| Process emissions | Pig iron | 19 | 15 | 13 | 6.5 | 10.1 | 12.6 |
| | Coke production | 1 | 1 | 0 | 0.3 | 0.4 | 0.4 |
| | Sinter process | 3 | 1 | 1 | 1.1 | 0.8 | 0.6 |
| | Cement production | 38 | 23 | 15 | 12.7 | 15.4 | 14.3 |
| | Petroleum refining | 0 | 0 | 0 | 0.2 | 0.3 | 0.4 |
| | Aluminum production | 1 | 1 | 0 | 0.3 | 0.5 | 0.5 |
| | Pup and paper | 0 | 0 | 0 | 0.1 | 0.2 | 0.3 |
| | Fertilizer production | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 |
| Material | Material handling | 46 | 9 | 1 | 15.4 | 6.1 | 0.7 |
| Road transport | Heavy duty vehicles | 3 | 3 | 3 | 1.0 | 2.0 | 2.6 |
| | Light duty vehicles | 17 | 17 | 15 | 5.8 | 11.1 | 14.3 |
| | Motorcycles, mopeds | 1 | 1 | 1 | 0.5 | 0.9 | 1.2 |
| | Leaded gasoline | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 |
| | Tire wear | 76 | 7 | 0 | 25.5 | 4.9 | 0.3 |
| | Brake lining wear | 5 | 4 | 2 | 1.7 | 2.7 | 2.1 |
| | Road abrasion | 16 | 8 | 5 | 5.4 | 5.4 | 4.4 |
| Other transport | Off-road | 6 | 6 | 6 | 2.2 | 4.1 | 5.6 |
| | Shipping | 0 | 0 | 0 | 0.0 | 0.0 | 0.0 |
| Agriculture | Poultry farms | 1 | 1 | 0 | 0.4 | 0.6 | 0.4 |
| | Pig farms | 2 | 1 | 0 | 0.8 | 0.6 | 0.3 |
| | Cattle farms | 1 | 0 | 0 | 0.4 | 0.3 | 0.1 |
| | Other | 2 | 1 | 0 | 0.7 | 0.5 | 0.2 |
| TOTAL | | 299 | 151 | 103 | 100.0 | 100.0 | 100.0 |

# 7 Conclusions

This report introduces a methodology to estimate PM emissions and control costs in an European context, compatible with existing approaches to estimate emissions and costs for $SO_2$, $NO_x$, $NH_3$ and VOC. Thereby, these estimates can be used by the RAINS integrated assessment model to balance the emission control measures for primary and secondary aerosols that could achieve target levels of PM concentrations in ambient air at least costs.

While the numerical implementation and the results available at present must be considered as preliminary, some conclusions can be drawn at this stage:

Small combustion sources, e.g., wood and coal combustion, are major contributors to PM emissions in certain European countries, although they make a relatively low contribution to energy supply. In Eastern Europe, power plants with less efficient emission controls were important in 1990. The ongoing economic restructuring and the upgrading of the environmental performance of these plants will diminish their importance in the future.

The estimates presented in this paper must be considered provisional. For many potential sources of PM emissions work has started only recently and at the moment much of the available information is contradictory (e.g., for non-exhaust emissions from mobile sources, emissions from gasoline cars, industrial processes, etc.). Further work is required.

While the present quantitative estimates of the mass of PM emissions are loaded with significant uncertainties, uncertainties are even larger when the size fractionation is concerned. Only limited information is available that allows drawing robust conclusions about source-specific size distribution profiles. Improved information on this aspect will be crucial if the specific characteristics of PM (e.g., very small particles, $PM_1$, etc.) are specifically associated with health impacts.

Furthermore, utilizing the information presently available raises more confidence in emission estimates than in cost estimates. The present study should, therefore, be seen as an initial step towards a harmonized approach to assess PM emissions and control costs on a European scale; intense interaction with national experts will be essential to arrive at a verified database that could be used as a basis for international agreements to reduce PM pollution in Europe.

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# 9 Annex 1: Basic terminology used in RAINS

Activity data:

Examples of activity data include consumption of hard coal in power plants, kilometers driven by heavy-duty trucks, production of cement, numbers of animals, etc. This kind of data is stored in activity pathways.

Activity pathways:

These are sets of data files that include country- and sector-specific data on energy consumption (energy pathway), agricultural activities (agricultural pathway), other activities like production of steel, cement, etc. The data are available for five-year periods between 1990 and 2010. It is possible to have several alternative development pathways for either single countries or groups of countries that can be used in the subsequent calculations.

Uncontrolled/"raw gas" emission factors:

Since one of the objectives of the RAINS model is to assess the extent and costs of controlling emissions, the emission calculation starts from an unabated level. In other words, even if abatement is considered an integral part of the process, e.g., in the metallurgical industry, the distinction is made between 'raw gas' concentrations (before any abatement) and after the control equipment. The concentration of pollutant in the 'raw gas' is used to derive an uncontrolled ('raw gas') emission factor that is ultimately defined per unit of energy input. The values of these coefficients are either estimated on the basis of fuel type and combustion conditions or taken from the literature.

Size fractions:

Typically, the emitted mass or concentration of particulate matter is given as TSP (total suspended particles), $PM_{10}$ (particles with an aerodynamic diameter less than 10 microns), $PM_{2.5}$, $PM_1$, $PM_{0.1}$, etc. The RAINS model distinguishes three size fractions:

Fine particles - $PM_{2.5}$ - (< 2.5 microns);

Coarse particles (> 2.5 and < 10 microns); and

Larger than $PM_{10}$ - PM_>10 - (> 10 microns).

Of course the model also allows calculation of TSP and $PM_{10}$ emissions.

Control option:

The model distinguishes major categories of abatement equipment for both stationary and mobile sources. Each technique, e.g., cyclone, electrostatic precipitator, EUROI to IV for vehicles, etc. is called a control option and can be used to construct a control strategy or a cost curve. The full list of RAINS control options and their efficiencies is available from the RAINS PM Web model under the option Display Emissions: Regional coefficients: Emission factors & removal efficiency.

Control strategy:

A selection of control options applied to a certain percentage of total capacities in specific sectors and years constitutes a control strategy. A control strategy can be defined for a single country, a group of countries or for the whole of Europe. At this stage, it is possible only to view the illustrative strategies provided.

Initial controls:

Since RAINS also attempts to reproduce the official emission inventories, the initial controls file contains a set of control options that were present in 1990 or 1995. In RAINS PM Web these initial controls can be viewed by displaying the region-specific control strategy.

Emission control scenario:

A set of activity pathway - control strategy pairs for each country defines an emission control scenario. In a future version of the model it will be possible to create “scenarios” in an interactive way. In principle, every calculation of emissions or costs in RAINS is performed for a selected scenario.

Unit cost of emission control:

Unit costs are calculated by relating the annual costs to the abated particulate matter emissions. The average annual costs are calculated considering lifetime of the abatement technologies. The expenditures are differentiated into investments, fixed and variable operating costs.

Marginal cost:

Marginal costs relate the extra costs for an additional measure to the marginal abatement of that measure (compared to the abatement of the less effective option). For details and discussion see and Forsund, 2000.

Cost curve:

The cost curve can be calculated for a selected country, year and scenario. Two principal calculation stages can be distinguished, i.e.

1.the elimination of non-cost-effective control options (techniques that have higher costs and lower efficiency than the preceding option are excluded); and

2.final ranking of the remaining options with increasing marginal cost to form a national cost curve.