Emission Reduction Scenarios to Control Acidification, Eutrophication and Ground-level Ozone in Europe

Part A: Methodology and Databases

Report prepared for the
22nd Meeting of the UN/ECE Task Force on
Integrated Assessment Modelling

*Markus Amann, Imrich Bertok, Janusz Cofala,
Frantisek Gyarfas, Chris Heyes,
Zbigniew Klimont, Marek Makowski,
Wolfgang Schöpp, Sanna Syri*

November 1998

IIASA International Institute for Applied Systems Analysis A-2361 Laxenburg Austria
Telephone: +43 2236 807 Telefax: +43 2236 71313 E-Mail: info@iiasa.ac.at

Emission Reduction Scenarios to Control Acidification, Eutrophication and Ground-level Ozone in Europe

Part A: Methodology and Databases

Markus Amann, Imrich Bertok, Janusz Cofala,
Frantisek Gyarfas, Chris Heyes,
Zbigniew Klimont, Marek Makowski,
Wolfgang Schöpp, Sanna Syri

Report prepared for the
22nd Meeting of the UN/ECE Task Force on Integrated
Assessment Modelling

November 1998

Interim reports inform on work of the International Institute for Applied Systems Analysis and have received only limited review. Views or opinions expressed herein do not necessarily represent those of the Institute or of its National Member Organizations.

IIASA International Institute for Applied Systems Analysis A-2361 Laxenburg Austria
Telephone: +43 2236 807 Telefax: +43 2236 71313 E-Mail: info@iiasa.ac.at

Acknowledgments

The authors would like to express their gratitude to

- the Swiss Federal Office of Environment, Forests and Landscape, the Netherlands Ministry of Housing, Spatial Planning and the Environment and the Nordic Council of Ministers for providing financial support to this work,
- Arne Drud from ARKI Consulting and Development, Denmark, for making the CONOPT library for the non-linear optimization available,
- Prof. Anton Eliassen from the Norwegian Meteorological Institute, Oslo, and Peringe Grennfelt from the Swedish Institute for Environmental Research, Gothenburg, for offering thoughtful comments on the modeling approach,
- David Simpson from the Nowegian Meteorological Institute for producing the large number of scenarios required as input to the regression analysis,
- Steffen Unger and Prof. Achim Sydow (GMD-FIRST, Berlin, Germany) for transferring the EMEP model to parallel computers,
- Jean-Paul Hettelingh and Max Posch from the Coordination Centre for Effects (CCE) at the National Institute for Public Health and the Environment (RIVM) in Bilthoven, Netherlands, for providing the data bases on ecosystems and population densities.

Emission Reduction Scenarios to Control Acidification, Eutrophication and Ground-level Ozone in Europe

Part A: Methodology and Databases

Table of Contents

1 Introduction

There is substantial concern about the environmental impacts of air pollution on the local, regional and global scale. It has been shown that observed levels of various air pollutants can threaten human health, vegetation, wild life, and cause damage to materials. In order to limit the negative effects of air pollution, measures to reduce emissions from a variety of sources have been initiated.

Once emitted, many air pollutants remain in the atmosphere for some time before they are finally deposited on the ground. During this time, they are transported with the air mass over long distances, often crossing national boundaries. As a consequence, at a given site the concentration of pollutants and their deposition on the ground is influenced by a large number of emission sources, frequently in many different countries. Thus, action to efficiently abate air pollution problems has to be coordinated internationally.

Over the last decade several international agreements have been reached in Europe to reduce emissions in a harmonized way. Protocols under the Convention on Long-range Transboundary Air Pollution focus on reducing emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x) and volatile organic compounds (VOC). Several directives of the European Union prescribe emission standards for large combustion plants, for mobile sources, and limit the sulfur content in liquid fuels.

Most of the current agreements determine required abatement measures solely in relation to technical and economic characteristics of the sources of emissions, such as available abatement technologies, costs, historic emission levels, etc. No relation is established to the actual environmental impacts of emissions. For achieving overall cost-effectiveness of strategies, however, the justification of potential measures in relation to their environmental benefits must also be taken into account. Recently, progress has been made in quantifying the environmental sensitivities of various ecosystems. Critical loads and critical levels have been established reflecting the maximum exposure of ecosystems to one or several pollutants not leading to environmental damage in the long run. Such threshold values have been determined on a European scale, focusing on acidification and eutrophication as well as on vegetation damage from tropospheric ozone.

It is generally expected that the current policies on emission reductions will greatly reduce the levels of tropospheric ozone. However, the measures will not be sufficient to eliminate the problem everywhere in Europe. To meet the environmental long-term targets aiming at the protection of human health and vegetation, as they are currently discussed in the context of the Commission’s ozone strategy, additional- measures will be necessary. Since most of the low-cost options for abating emissions are already adopted in the current strategies, further action aiming at the sustainability of Europe’s ecosystems will have to embark on more costly measures. Cost-effectiveness will be an important argument for gaining acceptance of proposed policies.

1.1 Structure of this Report

This paper prepared for the 22nd Meeting of the UN/ECE Task Force on Integrated Assessment Modelling is a further step in a series of Interim Reports analyzing the features of cost-effective approaches to control European air quality. Its main objective is to provide a concise description of the modelling approach and the recent status of the databases used for the model exercise and to present a range of scenarios to assist the UN/ECE Working Group on Strategies in the (pre-)selection of scenarios which could serve as a starting point for the negotiations on the envisaged Protocol on Nitrogen Oxides and Related Substances.

This study prepared for the UN/ECE Task Force on Integrated Assessment Modelling responds to a request of the Working Group on Strategies and presents a range of optimized emission scenarios addressing acidification, eutrophication and ground-level ozone on a European wide scale. The Report is divided into two parts:

Part A describes the methodology of the analysis and reviews the present state of the databases used for the scenario calculations.

Part B presents the results of the model analysis for a range of environmental targets.

Part A provides a summary of the methodology selected for the integrated assessment exercise and reviews the latest status of the databases used for the analysis. Section 2 presents the main elements of the RAINS model (the emission database, estimates of emission control potentials and costs for SO_2, NO_x, NH_3 and VOC, the atmospheric source-receptor relationships, the critical loads database and the optimization methodology). The data sources (energy and agricultural projections) are described in Section 3. Section 4 reviews the present status of the current emission-related legislation in the European countries, which is adopted as a starting point for the optimization analysis.

In Part A of this report, a gray bar on the right border of the page indicates the most important changes in the description of methodology and databases that have been introduced since the last Interim Report. In addition to the changes marked by the gray bar, all tables and figures were updated, and references to the updated tables were changed in the text.

Detailed information and documentation of the cost curves and the optimization algorithm is available on the Internet under http://www.iiasa.ac.at/~rains.

2 Methodology

The recent progress in quantifying the sensitivities of ecosystems adds an important feature to the analysis and the development of cost-effective strategies to achieve and maintain emission levels that do not endanger the sustainability of ecosystems. Integrated assessment models are tools to combine information and databases on the economic, physical and environmental aspects relevant for strategy development.

2.1 The General Approach for an Integrated Assessment

The Regional Air Pollution INformation and Simulation (RAINS)-model developed at the International Institute for Applied Systems Analysis (IIASA, Laxenburg, Austria) provides a consistent framework for the analysis of emission reduction strategies, focusing on acidification, eutrophication and tropospheric ozone. RAINS comprises modules for emission generation (with databases on current and future economic activities, energy consumption levels, fuel characteristics, etc.), for emission control options and costs, for atmospheric dispersion of pollutants and for environmental sensitivities (i.e., databases on critical loads). In order to create a consistent and comprehensive picture of the options for simultaneously addressing the three environmental problems (acidification, eutrophication and tropospheric ozone), the model considers emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3) and volatile organic compounds (VOC). A detailed description of the RAINS model can be found in Alcamo *et al.*, 1990. A schematic diagram of the RAINS model is displayed in Figure 2.1.

The European implementation of the RAINS model incorporates databases on energy consumption for 38 regions in Europe, distinguishing 22 categories of fuel use in six economic sectors. The time horizon extends from the year 1990 up to the year 2010 (Bertok *et al.*, 1993). Emissions of SO_2, NO_x, NH_3 and VOC for 1990 are estimated based on information collected by the CORINAIR'90 inventory of the European Environmental Agency (EEA, 1996) and on national information. Options and costs for controlling emissions of the various substances are represented in the model by considering the characteristic technical and economic features of the most important emission reduction options and technologies. Atmospheric dispersion processes over Europe for sulfur and nitrogen compounds are modeled based on results of the European EMEP model developed at the Norwegian Meteorological Institute (Barret and Sandnes, 1996). For tropospheric ozone, source-receptor relationships between the precursor emissions and the regional ozone concentrations are derived from the EMEP photo-oxidants model (Simpson, 1992, 1993). The RAINS model incorporates databases on critical loads and critical levels compiled at the Coordination Center for Effects (CCE) at the National Institute for Public Health and Environmental Protection (RIVM) in the Netherlands (Posch *et al.*, 1997).

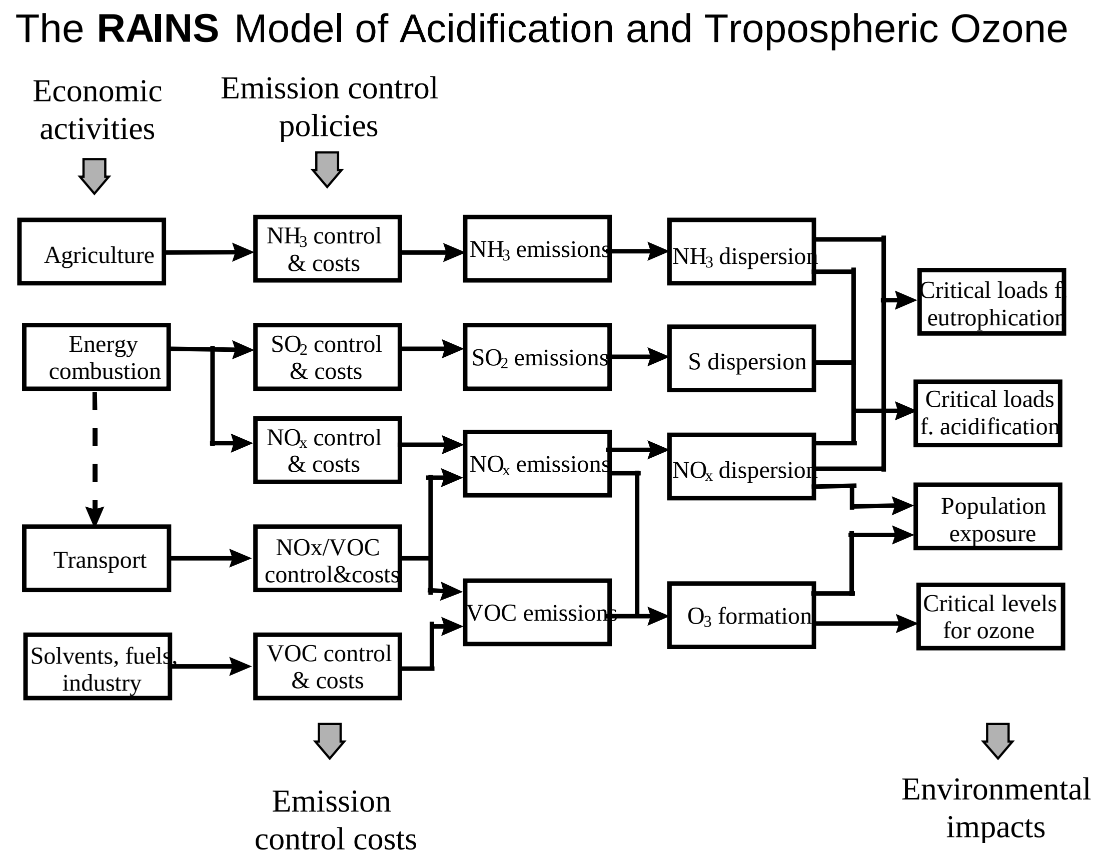

Figure 2.1: Schematic flowchart of the RAINS model framework

The RAINS model can be operated in the ‘scenario analysis’ mode, i.e., following the pathways of the emissions from their sources to their environmental impacts. In this case the model provides estimates of regional costs and environmental benefits of alternative emission control strategies. Alternatively, a (linear programming) ‘optimization mode’ is available for the acidification part to identify cost-optimal allocations of emission reductions in order to achieve specified deposition targets. This mode of the RAINS model was used extensively during the negotiation process of the Second Sulfur Protocol under the Convention on Long-range Transboundary Air Pollution for elaborating effect-based emission control strategies. A non-linear optimization module for tropospheric ozone has been recently completed and was used for this study.

2.2 Scenarios of Emission Generating Anthropogenic Activities

Inputs to the RAINS model include projections of future energy consumption on a national scale up to the year 2010. The model stores this information as energy balances for selected future years, distinguishing fuel production, conversion and consumption for 22 fuel types in six economic sectors. These energy balances are complemented by additional information relevant for emission projections, such as boiler types (e.g., dry bottom vs. wet bottom boilers), size distribution of plants, age structures, fleet composition of the vehicle stock, etc..

Agricultural activities are a major source of ammonia emissions, which in turn make a contribution to the acidification problem. Next to specific measures directed at limiting the emissions from livestock farming, the development of the animal stock is an important determinant of future emissions. The projections of future agricultural activities currently implemented in the RAINS model have been compiled from a variety of national and international studies on the likely development of the agricultural system in Europe.

The forecast of the future development of VOC emission generating activities is linked to other information on general economic development. About half of the anthropogenic emissions of VOC originates from combustion and distribution of fossil fuels. Therefore, the information on projected levels of fuel consumption in the countries of the UN/ECE region contained in RAINS is used to estimate future emissions of VOC from relevant sources, i.e. traffic, stationary combustion, extraction and distribution of fuels. The development of the other VOC emitting sectors in the EU is based on information provided in the reports to the European Commission on the development of the EU energy system between 1995-2020 (Capros *et al*., 1997) and on information provided by national experts. The forecasts of GDP values in various industrial sectors, as well as population, were linked to the projected development in the sectors distinguished in the RAINS-VOC module. A similar exercise was performed for non-EU countries.

A detailed description of the actual projections used for this report is provided in Section 3.

2.3 Emission Estimates

The RAINS model estimates current and future levels of SO_2, NO_x, VOC and NH_3 emissions based on information provided by the energy- and economic scenario as exogenous input and on emission factors derived from the CORINAIR'90 emission inventory database and guidebook (EEA, 1996), national reports as well as contacts with national experts. Emission estimates are performed on a disaggregated level, which is determined by the available details of the energy and agricultural projections and the CORINAIR'90 emission inventory. The relations between CORINAIR/SNAP97 categories and the RAINS sectors are shown in Table 2.1 to Table 2.4. Due to the differences in the format of the energy and agricultural statistics and CORINAIR, a direct and full comparison of RAINS estimates with CORINAIR'90 data is only possible at a more aggregated level.

Considering the intended purposes of integrated assessment, the major criteria for aggregation are:

- Contribution to total emissions (compared to total European emissions and to emissions for a particular country). It was decided to aim for individual source categories in a share from 0.5 to 2 percent of total anthropogenic emissions;
- Possibility to define uniform activity rates and emission factors;
- Possibility to construct forecasts of future activity levels. Since the emphasis of the cost estimates is on future years, it is crucial that reasonable projections of the activity rates be constructed or derived;
- Availability and applicability of 'similar' control technologies;
- Availability of relevant data. As far as possible, emission related data should be compatible with the CORINAIR'90 emission inventory.

Table 2.1: RAINS sectors for stationary sources of SO_2/NO_x and their relation to the main activity groups of the CORINAIR'90 inventory

RAINS sector		**CORINAIR**
Primary	**Secondary**	**SNAP97 code**
Power plants and district heating plants	- New boilers - Existing boilers, dry bottom - Existing boilers, wet bottom	0101, 0102
Fuel production and conversion (other than power plants)	- Combustion - Losses	0103, 0104, 0105, 05
Domestic	- Residential, commercial, institutional, agriculture	02
Industry	- Combustion in boilers, gas turbines and stationary engines	0301
	- Other combustion	03 excl. 0301[1]
	- Process emissions[2]	04
Non-energy use of fuels	- Use of fuels for non-energy purposes (feedstocks, lubricants, asphalt)	
Other emissions	- Other sources: (e.g., waste treatment and disposal, agriculture	080501, 080502, 09, 10

---

[1] Also processes with contact from SNAP code 0303 that are treated separately as process emissions are excluded.

[2] Emissions are not directly attributed to fuel consumption. Production processes covered: oil refineries, coke, sinter, pig iron, non-ferrous metals (zinc, lead and copper), cement, lime, sulfuric acid, nitric acid, pulp mills. Other processes are covered in 'Industry-Other combustion'.

Table 2.2: RAINS sectors for mobile sources and their relation to the CORINAIR/SNAP97 codes

	RAINS sector	**CORINAIR**
Primary	**Secondary**	**SNAP97 code**
Road transport	-Heavy duty vehicles (trucks, buses and others)	0703
	- Light duty vehicles, four-stroke (cars, vans, motorcycles)	0701,02,04,05
	- Light duty vehicles, two-stroke (cars, motorcycles)	
	- Gasoline evaporation	0706
Off-road	- Other mobile sources and machinery with two-stroke engines	0801-03 0806-10
	- Other mobile sources and machinery with four-stroke engines	
Air traffic	Domestic and international air traffic (LTO cycles only)	080501, 02
Maritime activities	- Medium vessels - Large vessels	080402, 080403

Table 2.3: Main activity groups distinguished in the RAINS NH$_3$ module and their relation to the CORINAIR'90 SNAP97 code

	RAINS sector	**CORINAIR**
Primary	**Secondary**	**SNAP code**
Livestock	Dairy cows	100501
	Other cattle	100502
	Pigs	100503, 100504
	Laying hens	100507
	Other poultry	100508, 100509
	Sheep and goats	100505
	Fur animals	100510
	Horses	100506
Fertilizer use	Agricultural cultures with fertilizers (except animal manure)	1001-100106
Industry	Production processes in inorganic chem. industry, fertilizer production	040402-040408
Waste treatment and disposal	Waste treatment and disposal	0901-0904
Other	Various activities including stationary combustion, mobile sources and industrial processes	01, 02, 03, 04, 07, 08

Table 2.4: RAINS sectors for stationary sources and their relation to the CORINAIR'90 SNAP97 codes

RAINS sector Primary	 Secondary	CORINAIR SNAP code
Solvent Use	Dry cleaning	060202
	Degreasing	060201,03,04
	Treatment of vehicles	060407,09
	Domestic solvent use (excluding paint)	060408
	Architectural painting	060103
	Domestic use of paints	060104
	Manufacture of automobiles	060101
	Vehicle refinishing	060102
	Other industrial use of paints	060105-09
	Products incorporating solvents	060307-11
	Products not incorporating solvents	060301-05
	Pharmaceutical industry	060306
	Printing industry	060403
	Application of glues, adhesives in industry	060405
	Preservation of wood	060406
	Other industrial use of solvents	060401,02,04,12, 060312-14
Chemical	Inorganic chemical industry	040402,03,07-09,10,11
Industry	Production processes in organic chemistry	040501-21,25-27
	Storage and handling of chemical products	040522
Refineries	Refineries - process	040101-03
	Refineries - storage	040104
Fuel Extraction	Gaseous fuels	0503,0506
and Distribution	Liquid fuels	0502,0504,090206
Gasoline	Service stations	050503
Distribution	Transport and depots	050501,02
Stationary	Public power, co-generation, district heat	0101,0102
Combustion	Industrial combustion	0301-03
	Commercial and residential combustion	0200
Miscellaneous	Stubble and other agricultural waste burning	1003,0907
	Food and drink industry	040605-08
	Other industrial sources	0402,03, 040601-04
	Waste treatment and disposal	09 excl. 0907, 090206

2.3.1 Comparison of RAINS Emission Estimates for 1990 with other Inventories

As indicated above, RAINS generally uses information on emission factors provided by the CORINAIR’90 inventory and its latest national updates. CORINAIR'90 is available for all EU countries as well as for eleven non-EU countries. For some countries, updates to CORINAIR'90 have been recently made available to IIASA and were incorporated into the database. Emission levels calculated by RAINS are usually in good agreement with the CORINAIR’90 inventory with differences typically below five percent.

In a few cases, however, RAINS deviates from the CORINAIR'90 database. This is mainly the case when, in the process of constructing the RAINS database, an inconsistency in CORINAIR'90 was detected, or when countries updated their CORINAIR'90 inventory.

Recent work on the emission database addressed the following issues:

- The updates of national emission inventories for 1990 recently received from Austria, Belgium, Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Italy, Norway, Poland, Sweden and UK were incorporated into the RAINS database.
- The treatment of coastal shipping. An attempt has been made to harmonize the treatment of emissions from coastal shipping. Coastal shipping is now included in the national emissions for the respective countries, and the emissions from international shipping are apportioned to separate categories for the various regional seas.

Table 2.5 compares the 1990 estimates for NO_x and VOC emissions incorporated into the RAINS model with the results from the CORINAIR'90 inventory and with the EMEP/UN-ECE database (UN/ECE, 1998; EMEP, 1998).

It is important to mention that, when calculating ozone concentrations, the EMEP model internally determines natural and agricultural emissions of VOC as a function of temperature, land use, etc. On the other hand, the agricultural emissions are also fully included in the CORINAIR'90 estimates (sector 10). In order to avoid double-counting of these emissions for ozone calculations, the RAINS results presented later on exclude these emissions from the anthropogenic sources (and the cost curves). As a consequence, also the emission levels derived in the subsequent analyses of this report exclude these sources. In order to achieve emission fully comparable to the present CORINAIR methodology, natural and agricultural emissions of VOC must be added to the numbers presented for each scenario.

Close cooperation with several national experts made it possible to remove earlier inconsistencies between the national emission inventories and RAINS estimates. In all cases where national data were sufficiently documented, this revised information was used to improve the RAINS estimate. For some EU countries, however, there remain certain discrepancies between the revised national inventories for 1990 and the data reported by EMEP/UN-ECE, which can partly be explained by the delayed reporting procedures to EMEP/UN-ECE. It was important to confirm, as far as practically possible, that the supplied revisions of national emission inventories for the year 1990 are consistent with the general CORINAIR guidelines.

Compared to the Fifth Interim Report, the most important changes in the emission database occurred for France, Greece and Sweden, due to a different treatment of the emissions from 'Other mobile sources'.

There remain for some non-EU countries a number of unresolved questions:

- There still exist major uncertainties about emissions from the countries of the former Soviet Union, for which no CORINAIR'90 inventory exercise was carried out. Using reported energy statistics, it is in some cases rather difficult to reconstruct the officially submitted emission data. As pointed out by Ryboshapko *et al.* (1996), data reported officially by the former Soviet Union did not always include small and dispersed sources in the residential and commercial sector. This approach is apparently still exercised by Yugoslavia, which reports only emissions from stationary sources to EMEP.
- Compared with CORINAIR'90, RAINS estimates of NO_x emissions in the Czech Republic are more than 30 percent lower. This is due to an extremely high emission factor used in Czech national inventory system for brown coal and lignite. National experts admit that such high emission factors have not been confirmed by the results of measurements. Also the emission factors for mobile sources used in the Czech inventory are much higher than in other countries. Since the Czech vehicles are supposed to meet the pre-1990 UN/ECE emission standards, the highest emission factors reported by EU countries for 1990 were adopted for the calculations in RAINS.
- To some degree, also the 10 percent difference to Slovakia's NO_x estimate can be traced back to the same roots.
- For Poland, the discrepancies between RAINS and CORINAIR'90 estimates are a result of high emission factors applied in the Polish CORINAIR'90 inventory for some industrial processes and for open burning of agricultural waste.
- In other non-EU countries the discrepancies are mainly due to uncertainties of their energy balances.

Also for the VOC estimates of the EU-15 countries, assistance of national experts helped to eliminate all major discrepancies mentioned in earlier reports, so that there is now a rather good agreement between the national inventories and the RAINS database (typically within ± five percent). For non-EU countries, the following open questions remain:

- Hungary's CORINAIR'90 database does not include emissions from the domestic use of paints;
- The CORINAIR'90 database for Slovenia excludes several important emission sources for VOC, such as evaporative emissions from cars, dry cleaning, degreasing, domestic use of solvents and the storage of products in refineries.

The CORINAIR'94 emission inventory, of which parts became available recently, provides important additional information contributing to a better understanding of VOC emission sources. It is envisaged to further update the RAINS emission calculation using these new data.

Table 2.5: Comparison of RAINS 1990 emission estimates of NO_x and VOC with results from the CORINAIR’90 inventory and the EMEP/UN-ECE databases (in kilotons).

		NO_x			VOC	
	RAINS	EMEP/ UN/ECE	CORINAIR ’90[3]	RAINS	EMEP/ UN/ECE	CORINAIR ’90[3]
Austria	192	196	227	352	367	348
Belgium	351	343	343	374	339/358	364
Denmark	274	282	273	182	178	167
Finland	276	300	269	213	209	207
France	1867	1590/1585	1899	2423	2393/2404	2424
Germany	2662	2654	2980	3100	3181	2937
Greece	345	392/-	344	336	293/-	312
Ireland	113	115	116	110	102/197	102
Italy	2037	2047	2041	2055	2080/2498	2002
Luxembourg	22	23	23	19	19	19
Netherlands	542	596/580	537	490	502	502
Portugal	208	221	215	212	202	202
Spain	1162	1188/1177	1247	1008	1051/1134	1044
Sweden	338	411/338	345	492	526	451
UK	2839	2850/2762	2773	2667	2720/2552	2555
EU-15	13226	13208/-	13632	14032	14162/n.a.	13635
Albania	24	24/-	n.a.	31	32/-	-
Belarus	402	285	n.a.	371	533	-
Bosnia-H	80	80	n.a.	51	101/-	-
Bulgaria	355	376	361	195	187/217	189
Croatia	82	83	n.a.	103	105/-	97
Czech_R.	546	742	773	442	435	435
Estonia	84	93/-	72	45	23	50
Hungary	219	238	191	204	205	148
Latvia	117	90	93	63	63	47
Lithuania	153	158	158	111	111	108
Norway	220	227/222	232	297	299/301	270
Poland	1217	1279	1445	797	797/831	797
Moldova	87	39	n.a.	50	11	-
Romania	518	546	546	503	568/616	571
Russia	3486	2675	n.a.	3542	3566	-
Slovakia	219	225	227	151	149	150
Slovenia	60	62	57	55	35/42	35
Switzerland	163	165	159	278	284/292	282
FYR Maced.	39	39/-	n.a.	19	7/-	-
Ukraine	1888	1097	n.a.	1161	1079/1369	-
Yugoslavia	211	66	n.a.	142	66/-	-
Non-EU	10170	8588/-	n.a.	8609	8656/-	n.a
Atlantic	911	911/-	n.a.	0	0	0
Baltic	80	80/-	n.a.	0	0	0
North_Sea	639	639/-	n.a.	0	0	0
TOTAL	25025	23426/-	n.a.	22641	22818/-	n.a

---

[3] Including the updates received from national experts. Anthropogenic sources only, i.e. excluding sector 10 and 11.

Table 2.6: Comparison of RAINS 1990 emission estimates of SO_2 and NH_3 with results from the CORINAIR'90 inventory and the EMEP/UN-ECE databases (in kilotons).

	SO_2			NH_3		
	RAINS	EMEP/ UN/ECE	CORINAIR '90 3)	RAINS	EMEP/ UN/ECE	CORINAIR '90 3)
Austria	93	93	93	77	85/77	77
Belgium	336	322	317	97	104	79
Denmark	182	182	198	77	122	126
Finland	232	260	227	40	35	41
France	1250	1300	1232	805	700	807
Germany	5280	5263	5257	757	769	739
Greece	504	510	504	80	78/-	471
Ireland	178	178	178	127	126	126
Italy	1679	1678	1683	462	416	466
Luxembourg	14	14	14	7	7	7
Netherlands	201	202	200	233	232/226	195
Portugal	284	283	283	71	93	93
Spain	2189	2266	2206	352	353	331
Sweden	119	136/119	105	61	61/51	74
UK	3805	3764	3787	329	320/333	468
EU-15	16345	16451/16434	16284	3576	3501/-	4101
Albania	72	72/-	n.a.	32	31/-	-
Belarus	843	637	n.a.	219	219/ 4	-
Bosnia-H	487	480	n.a.	31	31/-	-
Bulgaria	1842	2020	2008	141	144	324
Croatia	180	180	n.a.	40	44/37	37
Czech_R.	1873	1876	1863	107	105/156	91
Estonia	275	239/-	275	29	29/-	29
Hungary	913	1010	906	120	164	62
Latvia	121	57	115	43	44	38
Lithuania	213	222	223	80	84	84
Norway	52	53	54	23	23	38
Poland	3001	3210	3273	505	508	539
Moldova	197	231	n.a.	47	47	-
Romania	1331	1311	1311	292	300	300
Russia	5012	4460	n.a.	1282	1191	-
Slovakia	548	543	542	60	62	60
Slovenia	200	194	196	23	24	27
Switzerland	43	43	44	72	72	69
FYRMacedonia	107	106/-	n.a.	17	17/-	-
Ukraine	3706	2782	n.a.	729	729 / 11	-
Yugoslavia	585	508	n.a.	90	90/-	-
Non-EU	21599	20234/-	n.a.	3980	3958/-	n.a
Atlantic	641	641/-	n.a.	0	0	0
Baltic	72	72/-	n.a.	0	0	0
North_Sea	439	439/-	n.a.	0	0	0
TOTAL	39096	37837/-	n.a.	7556	7459/-	n.a

National estimates different from EMEP/UN-ECE and CORINAIR: Belgium 336 kt (SO_2), UK 3782 kt (SO_2), Germany 2678 kt (NO_x). 3) Including the updates received from national experts.

For ammonia emissions, RAINS and CORINAIR/EMEP estimates differ for most of the EU-15 countries typically by less than five percent. Exceptions are Denmark and Portugal:

- The 1997 UN/ECE review of the RAINS ammonia data by Danish experts resulted in significant changes in the 1990 emission estimates for Denmark, which are now 30 percent lower than the Danish numbers originally submitted to CORINAIR'90.
- The Portuguese CORINAIR'90 database contains very high emission factors for fertilizer use. Applying internationally reported values (ECETOC, 1994) reduces the overall estimate by about 17 percent.

For the non-EU countries, major discrepancies (larger than 10 percent) remain only for Hungary. The difference between RAINS and CORINAIR can be traced back to the omission of emissions from pigs and fertilizer use in the CORINAIR database. According to Tajthy & Tar (1997), the high UN/ECE estimate includes emissions from soils, which are not part of the RAINS inventory.

2.4 Emission Control Options and Costs

Although there is a large variety of options to control emissions, an integrated assessment model focusing on the pan-European scale has to restrict itself to a manageable number of typical abatement options in order to estimate future emission control potentials and costs. Consequently, the RAINS model identifies for each of its application areas (i.e., emission source categories considered in the model) a limited list of characteristic emission control options. For each of these measures, the model extrapolates the current operating experience to future years, taking into account the most important country- and situation-specific circumstances modifying the applicability and costs of the techniques.

For each of the available emission control options, RAINS estimates the specific costs of reductions, taking into account investment-related and operating costs. Investments are annualized over the technical lifetime of the pollution control equipment, using a discount factor of four percent. The technical performance as well as investments, maintenance and material consumption are considered to be technology-specific and thereby, for a given technology, equal for all European countries. Fuel characteristics, boiler sizes, capacity utilization, labor and material costs (and stable sizes and applicability rates of abatement options for ammonia) are important country-specific factors influencing the actual costs of emission reduction under given conditions. A detailed description of the methodology adopted to estimate emission control costs can be found in Amann (1990), Cofala *et al.* (1997), Klimont *et al.* (1998) and Klaassen (1991b).

The databases on emission control costs have been constructed based on the actual operating experience of various emission control options documented in a number of national and international studies. Main references are the proceedings of at various UN/ECE Seminars on Emission Control Technologies (e.g., UN/ECE, 1996c, UN/ECE, 1997), the Technical Annexes to the Second Sulfur Protocol (UN/ECE 1994a) and other documentation (e.g., Schärer, 1993, OECD, 1993; Takeshita, 1995; Rentz *et al.*, 1987, Rentz *et al.*, 1996). Data for mobile sources are based on the material developed within the Auto-Oil programme. Country-specific information has been extracted from relevant national and international statistics (e.g., ILO, 1995; IMF, 1995; UN/ECE, 1995a; UN/ECE, 1996a) and was provided by national experts. The list of control options for SO_2, NO_x, NH_3 and VOC and the country-specific data used for the cost calculations were presented to the negotiating parties of the

Convention on Long-range Transboundary Air Pollution for review. All costs are in constant 1990 ECU.

2.4.1 Options for Reducing SO_2 Emissions and their Costs

The national potentials and costs of emission reductions are estimated based on a detailed database of the most common emission control techniques. For a given energy scenario, reduction options for SO_2 emissions considered in RAINS are the use of low sulfur fuel, fuel desulfurization, combustion modification (e.g., lime stone injection processes and fluidized bed combustion) and flue gas desulfurization (e.g., wet limestone scrubbing processes). Structural changes, such as fuel substitution and energy conservation can also be evaluated, although only in interaction with an appropriate energy model.

Table 2.7 to Table 2.9 present, for the major source categories, the available control options and the data applied for the analysis. The basic input data for the SO_2 control technologies used in RAINS have been reviewed in the process of the negotiations for the Second Sulfur Protocol of the Convention on Long-range Transboundary Air Pollution and have recently been updated to take latest operating experience into account. Compared with previous reports, the most important updates are:

- The reduction efficiency of limestone injection has been increased from 50 percent to 60 percent. Such reduction efficiencies are achieved in German plants equipped with this technology (UBA, 1998)
- Following the comments made by CONCAWE, the price differential for low sulfur heavy fuel oil includes was corrected to reflect modified assumptions on capacity utilization of desulfurization plants (CONCAWE, 1993, 1998). It should be stressed that also the new figure is based on a four percent real interest rate used for the economic analysis in the RAINS model.

Table 2.7: Emission control options for SO_2 in the power plant and industrial sector considered in RAINS

Sector/control option	**Removal efficiency**	**Costs[4]**	
		Investment [1000 ECU/MW_{th}]	**Operating and maintenance [%/year][5]**
Retrofit of existing boilers (power plants)			
Limestone injection	60 %	30	4 %
Wet flue gas desulfurization (FGD) - boilers already retrofitted in the base year	90 %	69	4 %
Wet flue gas desulfurization (FGD) - boilers not yet retrofitted	95 %	69	4 %
Regenerative FGD	98 %	165	4 %
New boilers (power plants)			
Limestone injection	60 %	22	4 %
Wet flue gas desulfurization (FGD)	95 %	49	4 %
Regenerative FGD	98 %	119	4 %
Industrial boilers and furnaces			
Limestone injection	60 %	35	4 %
Wet flue gas desulfurization (FGD)	85 %	72	4 %

---

[4] Values are for typical hard coal fired boilers for each source category.

[5] Percent of investments per year

Table 2.8: Options for low sulfur fuels considered in RAINS

Fuel type	**Price difference [ECU / GJ / %S]**[6]	**Costs [ECU / t SO_2]**[7]
Hard coal and coke, 0.6% S	0.28	397
Heavy fuel oil, 0.6%S	0.20	463
Gas oil, reduction to 0.2% S	0.68	1440
Gas oil, reduction from 0.2% to 0.045% S	2.04	4330
Gas oil, reduction from 0.045% to 0.003% S[8]	6.69	14200

Table 2.9: Emission control options for industrial process emissions of SO_2 considered in RAINS

Control option	**Removal efficiency [%]**	**Costs [ECU / t SO_2]**
Stage 1	50	350
Stage 2	70	407
Stage 3	80	513

---

[6] Percent sulfur reduced compared to original fuel.

[7] Per ton of SO_2 removed. Since the costs depend on the heating value of the fuel, values given in the table are indicative.

[8] Only available for transport sources

2.4.2 Options for Reducing NO_x Emissions from Stationary Sources and their Costs

Table 2.10 to Table 2.15 present the measures for controlling NO_x emissions from stationary sources as contained in the RAINS database. Depending on the source category, the following main control options are assumed:

- Primary measures (low NO_x burners, re-burning, staged combustion). In the power plant sector this option is considered as a retrofit measure. For new installations, the use of primary measures is assumed by default at no extra costs.
- Selective catalytic (SCR) and non-catalytic (SNCR) reduction (always in combination with primary measures).

Table 2.10: Control options for NO_x emissions from the power plant sector considered in RAINS

Sector/control option	Removal efficiency [%]	Costs[9] Investment [kECU/MW$_{th}$]	Costs[9] Operating and maintenance [%/year]
Retrofits of existing boilers:			
Combustion modification and primary measures (CM)[10]			
Brown coal and lignite	65	6.8	-
Hard coal	50	3.9	-
Heavy fuel oil	65	4.7	-
Gas	65	5.0	-
CM + Select. Cat. Reduction (SCR)			
Brown coal and lignite	80	28.9	6 %
Hard coal	80	23.0	6 %
Heavy fuel oil	80	22.9	6 %
Gas	80	24.7	6 %
New boilers [11]			
SCR			
Brown coal and lignite	80	14.1	6 %
Hard coal	80	12.2	6 %
Heavy fuel oil	80	9.8	6 %
Gas	80	12.9	6 %

---

[9] Values are for typical boilers for each source category.

[10] Combination of various measures (e.g., low NO_x burners, overfire air, etc.)

[11] Low-NO_x burners are assumed by default; thus, new boilers have lower emission factors than the existing ones.

Table 2.11: Control options for NO_x emissions from the residential and commercial sector

Sector/control option	**Removal efficiency [%]**	**Costs** **Investment [kECU/MW_{th}]**	 **Operating and maintenance**
Residential and commercial sector[12]			
Combustion modification, low-NO_x burners (CM)			
Heavy fuel oil	50	5.6	-
Medium distillates	30	12	-
Natural gas	50	16.3	-

Table 2.12: Control options for NO_x emissions from industrial boilers considered in RAINS

Sector/control option	**Removal efficiency [%]**	**Costs**[13] **Investment [kECU/MW_{th}]**	 **Operating and maintenance [%/year]**[14]
Combustion modification and primary measures (CM)			
Brown coal and lignite	50	5.6	-
Hard coal	50	5.6	-
Heavy fuel oil	50	5.0	-
Medium distillates and gas	50	5.7	-
CM + Selective Non-catalytic Reduction (SNCR)			
Brown coal and lignite	70	11.0	6
Hard coal	70	11.0	6
Heavy fuel oil	70	9.1	6
Gas	70	10.6	6
CM + Select. Cat. Reduction (SCR)			
Brown coal and lignite	80	26.0	6
Hard coal	80	25.3	6
Heavy fuel oil	80	18.5	6
Gas	80	21.4	6

Table 2.13: Control options for NO_x emissions from industrial processes

Control option	**Removal efficiency [%]**	**Costs [ECU/t NO_x]**
Stage 1	40	1000
Stage 2	60	3000
Stage 3	80	5000

---

[12] Weighted average for the residential and commercial sector. Unit control costs for gas and gas oil fired boilers in the commercial sector are 40 - 50 % lower.

[13] Values are for typical boilers for each source category.

[14] Percent of investment cost per year

2.4.3 Options for Reducing VOC Emissions from Stationary Sources and their Costs

Emissions of VOC originate both from mobile and stationary sources. Emission reduction measures for the mobile sources are described in the section on nitrogen oxides as they are the same as for controlling VOC emissions. The only exceptions are carbon canisters and oxidation catalysts for two-stroke gasoline engines. Although in reality they are installed in vehicles, they are included in the “stationary” part of the model, since they effect only VOC emissions.

There is a wide range of literature describing the available options for controlling VOC emissions from stationary sources, i.a., Jourdan and Rentz (1991), EPA (1994), OECD (1990, 1992). EEC (1990), ERM (1996), Hein *et al.* (1994), CONCAWE (1987-1990), KWS 2000 (1989-1997), VROM (1995a,b, 1997), IFARE (1998a,b).

Commonly employed methods for reducing VOC emissions from stationary sources include modification of the production process or storage tanks, improvement of the management practices (e.g., good housekeeping, leak monitoring and repair programs), solvent substitution, and finally add-on technologies, such as thermal or catalytic incineration, adsorption, absorption, condensation/refrigeration, and bio-oxidation. Major reduction measures and RAINS-VOC sectors to which they apply are listed in Table 2.14. Note that the listed efficiencies refer to the assumed technical efficiency of the option. In reality, the most efficient options in a sector often have only limited applicability.

The applicability of a given technology for the processes aggregated within a sector in the RAINS model is a very important element of the abatement module. There are many reasons for differences in applicability:

- In many cases the applicability will depend more on the characteristics of a specific source of emissions (e.g., drying oven) rather than on the type of the source category (e.g., automobile manufacturing/ surface coating);
- Some sectors (e.g., products incorporating solvents) include several processes (e.g., paint manufacture, ink manufacture) and the applicability of a selected technology depends on the parameters of the specific process;
- The size distribution of the installations considered in a given category;
- Reformulated products may not be available for all applications within a given source category;
- Variable parameters of emission streams, e.g., too low or too high concentrations of VOC in the stream gas or too low or high flow rates limiting the application of particular add-on techniques such as oxidation/incineration;
- Mixture of solvents used in the process, making some of the add-on technologies less effective or economic, e.g., carbon adsorption, condensation.

Table 2.14: Major categories of VOC abatement measures (remaining options for transport are presented with NO$_x$ controls). Costs in ECU/t VOC.

Sector	***Technology***	***Efficiency [%]***	***Cost range***
Solvent use			
Dry Cleaning	Good housekeeping and adsorption	60	~600
	Closed circuit conventional or new machines	76/92	550/1200-4500
Metal degreasing	Basic emission management techniques	20	< 200
	Carbon adsorption	80	1300-2000
	Low temperature plasma process	98	1300-2300
	Conveyored degreaser with integrated adsorption	95	1700-2200
	Water based systems	99	2500-4000
Domestic solvent use	Substitution	~25	<4300
Non-industrial paint use	Water based paints	70-80	400-800
	High solids	40-60	1200-3000
Industrial paint use (car manufacturing)	Good housekeeping, application technique modification	20-45	<100
	Process modification and substitution	55-70	0.6-0.8/2-4*10^3
	Adsorption, incineration	95	1.5-1.8/3-7*10^3
Vehicle refinishing	Good housekeeping, application technique modification	15-30	< 0
	Housekeeping, application technique, substitution	72	300-800
Products incorporating solvents	Substitution	50	<50
	Basic emission management and end-of-pipe	95	600-900
Products not incorporating solvents	Solvent management plan and substitution	50	~200
	Basic emission management and end-of-pipe	60	1200-2500
Printing	Low solvent inks and enclosure	50-75	<30
	Water based inks	75-95	30-600
	Adsorption	75	150-1000
	Incineration	75	1000-10000
Glues and adhesives in industry	Good housekeeping	15	<50
	Substitution	85	350
	Incineration	80	~600
Preservation of wood	Double vacuum impregnation & dryer enclosure	40	~2800
	as above plus end-of-pipe	75	4300-7500
Other industrial use of solvents	Process modification and biofiltration	75	~600
	Water based coating (leather tanning)	~60	~350
	New agrochemical products	~40	~0
Chemical industry			
Organic chemical industry, processing and storage	Quarterly, monthly inspection and maintenance programs	60/70	~1600/~6000
	Flaring	85	~350
	Incineration	96	~800
	Internal floating covers and secondary seals	90	~2800
	Vapor recovery units	95-99	5600-6200
Pharmaceutical ind.	Good housekeeping and end-of-pipe	85-90	2500-6000
Refineries	Quarterly, monthly inspection and maintenance programs	60/70	<50/300-1000
	Covers on oil/water separators	90	~200
	Flaring / Incineration	98/99	200-300
	Internal floating covers and secondary seals	85	<100
	Vapor recovery units (Stage IA)	95-99	500-2500
Liquid fuel extraction and distribution			
Fuel extraction, loading and transport	Venting alternatives and increased recovery	90	1800-2200
	Improved ignition system on flares	62	4500-5500
	Vapor balancing on tankers and loading facilities	78	50-200
Fuel distribution	Internal floating covers and secondary seals	85	<100
	Vapor recovery units (Stage IA)	95-99	500-2500
	Stage II	85	1500-3000
	Stage IB	95	200-800
Gasoline evaporat.	Small carbon canister	85	50-500
2-stroke engines	Oxidation catalyst	80	900
Residential combustion	New boilers	80	100-500
	Catalyst	50	1000-7000
Miscellaneous			
Food and drink industry	End-of-pipe	90	10000
Agriculture	Ban on burning waste	100	60
Other industrial	Good housekeeping	20-60	<100
	Bitumen substitution (asphalt)	92	<50
Waste disposal	Improved landfills	20	400

2.4.4 Options for Reducing Emissions from Mobile Sources and their Costs

Also for mobile sources there exists a wide variety of fuel- and vehicle-related measures for reducing emissions. In order to keep the overall analysis manageable, RAINS aggregates individual measures into packages, following as far as possible the legislative proposals for emission standards discussed in the European context.

Table 2.15 presents the packages for controlling NO_x and VOC emissions for mobile sources as contained in the RAINS database. Data for mobile sources have been derived from various reports developed within the Auto/Oil program (EC, 1996b, Touche-Ross & Co., 1995) and from other national and international sources (i.a., Gorißen, 1992, HMSO, 1994, McArragher *et al*., 1994, Rodt *et al*., 1995, 1996, UN/ECE, 1994b, UN/ECE 1994c). The assistance of consultants participating in the Auto/Oil study helped to incorporate the suggested measures on fuel quality improvement and inspection and maintenance schemes into the RAINS model in a fully consistent way (Barrett, 1996).

The costs and control efficiencies of technologies used for the calculations presented in this report include the decisions of the Environment Council of October 1997 regarding the common positions on the quality of petrol and diesel fuels as well as on pollution control measures from motor vehicles (OJ 97/C 351/01, 1997a and OJ 97/C 351/02, 1997b). In particular, the following measures have been included in addition to the original Auto/Oil proposal:

- Change in petrol characteristics. For the year 2000, a reduction of the sulfur content to 150 ppm, of benzene to 1 percent and of aromatics to 42 percent. For 2005, further reductions to 50 ppm for sulfur and 35 percent for aromatics.
- Reduction of the maximum sulfur content in diesel oil to 50 ppm. It has been assumed that this low sulfur diesel fuel will be progressively introduced between 2005 and 2015. Additional costs of that fuel are allocated to the SO_2 control.
- For petrol cars and light commercial vehicles, Stage 3 controls from the year 2000 and Stage 4 controls after 2005, taking into account the costs of the cold start test.
- Stage 4 controls for diesel cars and light commercial vehicles, including the requirement for on-board diagnostic systems.
- Costs of Stage 4 controls have been assessed based on information provided in Rodt *et al*. (1995, 1996).

The estimate of the effects of the Common Position on emission control efficiencies and costs is based on Auto/Oil data (EC, 1996; Touche & Ross, 1995) and on the information available in DG-XI (Mackowski, 1998).

It is important to mention that the European Auto/Oil program used the net present value costing methodology, whereas RAINS expresses costs in terms of total annual costs, based on annualized investments over the entire technical life time of the equipment and the fixed and variable operating costs. Although there is consistency between Auto/Oil and RAINS in the input data of the cost evaluation, the resulting output cost numbers are not directly comparable. Besides, Auto/Oil costs are in 1995 prices, while RAINS uses constant prices from 1990 as a basis for calculations.

The estimates of control efficiencies and costs for reducing emissions from ships are based on Norwegian sources (Klokk, 1995; Selvig, 1997).

Table 2.15: Control options for NO_x and VOC emissions from mobile sources

Fuel/vehicle type/control technology	**Removal efficiency NO_x/VOC [%]**	**Costs**	
		Investments [ECU/vehicle]	**Operating and maintenance [%/year]**[15]
Gasoline 4-stroke passenger cars and LDV[16]			
3-way catalytic converter - 1992 standards	75/75	250	30
3-way catalytic converter - 1996 standards	87/87	300	25
Advanced converter with maintenance schemes - EU 2000 standard	93/93	709	11
Advanced converter with maintenance schemes – EU post-2005 standard (**)	97/97	884	8
Diesel passenger cars and LDV			
Combustion modification - 1992 standards	31/31	150	34
Combustion modification - 1996 standards	50/50	275	19
Advanced combustion modification with maintenance schemes - EU 2000 standards	60/60	780	7
NO_x converter(**)	80/80	1027	5
Heavy duty vehicles - diesel			
Euro I - 1993 standards	33/36	600	42
Euro II - 1996 standards	43/47	1800	14
Euro III - EU 2000 standards with maintenance schemes	60/66	4047	6
Euro IV (NO_x converter) (**)	85/93	8047	3
Heavy duty vehicles – gasoline			
Catalytic converter	85/85	2750	7
Seagoing ships			
Combustion modifications – medium vessels[17]	40/0	115000	4
Combustion modifications – large vessels[18]	40/0	165000	4
SCR – large vessels	90/0	526000	4

(**) - Not yet commercially available. Preliminary cost estimates are based on Rodt (1995), Rodt *et al*. (1996), and UN/ECE (1994b, c).

---

[15] Percent of investment cost per year.

[16] LDV - light duty vehicles.

[17] about 300 kW thermal

[18] about 2500 kW thermal

2.4.5 Options for Reducing Ammonia Emissions and their Costs

Ammonia emissions from livestock occur at four stages, i.e., in the animal house, during storage of manure, its application and during the grazing period. At every stage emissions can be controlled by applying various techniques. Obviously RAINS cannot distinguish all of the several hundred available control options, but considers groups of techniques with similar technical and economic characteristics (Klaassen, 1991b, 1995; UN/ECE, 1996b; EEA, 1996; Menzi *et al*., 1997). The major categories considered in RAINS are

- low nitrogen feed (dietary changes), e.g., multi-phase feeding for pigs and poultry, use of synthetic amino acids (pigs and poultry), and the replacement of grass and grass silage by maize for dairy cattle;
- biofiltration (air purification), e.g., by treatment of ventilated air using biological scrubbers to convert the ammonia into nitrate or biological beds where ammonia is absorbed by organic matter. This option is applicable mainly for pigs and poultry;
- animal house adaptation by improved design and construction of the floor (applicable for cattle, pigs and poultry), flushing the floor, climate control (for pigs and poultry), or wet and dry manure systems for poultry;
- covered outdoor storage of manure (low efficiency options with floating foils or polystyrene, and high efficiency options using tension caps, concrete, corrugated iron or polyester);
- low ammonia application techniques, distinguishing high efficiency (immediate incorporation, deep and shallow injection of manure) and medium to low efficiency techniques, including slit injection, trailing shoe, slurry dilution, band spreading, sprinkling (spray boom system);
- substitution of urea by ammonium nitrate for fertilizer application;
- stripping and absorption techniques in the chemical industry (e.g., during fertilizer production.

The removal efficiencies and costs of the control options are presented in Table 2.16 and Table 2.17. It should be mentioned that, compared to the control options for SO_2 and NO_x, the cost estimates for ammonia abatement techniques are more uncertain, mainly due to the lack of practical operating experience with many of the techniques in most European countries. An overview of national experience is available in the proceedings of the workshop on 'The Potential for Abatement of Ammonia Emissions from Agriculture and the Associated Costs' (Culham, UK, October, 1994; see ApSimon, 1994). More detailed information can be found in country reports, e.g., Menzi *et al.*, 1997; Zimmermann *et al.*, 1997 for Switzerland and Haan, Ogink, 1994; Hartog, Voermans, 1994; Holwerda *et al.*, 1995 for the Netherlands.

Table 2.16: Emission control options for NH_3 considered in the RAINS model and their assumed removal efficiencies

		Removal efficiency [%]			
Abatement option	**Application areas**	**Stables**	**Storage**	**Application**	**Meadow**
Low nitrogen feed (LNF)	Dairy cows	15	15	15	20
	Pigs	20	20	20	n.a.
	Laying hens	20	20	20	n.a.
	Other poultry	10	10	10	n.a.
Biofiltration (BF)[19]	Pigs, poultry	80		n.a,	n.a.
Animal house adaptation (SA)	Dairy cows, other cattle	45	60	n.a.	n.a.
	Pigs	50	60	n.a.	n.a.
	Laying hens	70	70	n.a.	n.a.
	Other poultry	80	70	n.a.	n.a.
Covered storage (CS - low/high)	Dairy cows, other cattle, pigs, poultry	n.a.	50/80	n.a.	n.a.
Low NH_3 application (LNA- low/high)	Dairy cows, other cattle, pigs, poultry, sheep [solid waste]	n.a.	n.a.	40/80	n.a.
	Dairy cows, other cattle, pigs [liquid manure]	n.a.	n.a.	30/70	n.a.
Urea substitution	Fertilizer use	80 - 93			
Stripping/ adsorption	Industry	50			

n.a.: not applicable

---

[19] Although some countries indicated during the UN/ECE review process that this option is also available for cattle (because many animal houses are equipped with mechanical ventilation), it has not yet been implemented in RAINS.

Table 2.17: Costs of emission control options for NH_3 considered in the RAINS model

Abatement option	**Application area**	**Investments** [ECU/animal-place]		**Total costs*** [ECU/animal place/year]	
		Stable size **			
		small	typical	small	typical
Low nitrogen feed	Dairy cows	n.a.		45	
	Pigs	2.7		8	
	Laying hens	n.a.		0.1	
	Other poultry	n.a.		0.12	
Bio-filtration and bio-scrubbers	Pigs	200-300	170	40-60	35-38
	Laying hens	4.7		1.3-2.0	
	Other poultry	4.7		1.5-2.5	
Animal house adaptation	Dairy cows, Other cattle	450-550	400	90-110	75-90
	Pigs	90-94	89	18-20	
	Laying hens	0.8		0.2-0.25	
	Other poultry	1.8		0.28	
Covered storage - high efficiency	Dairy cows	150-350	100-220	20-50	10-20
	Other cattle	80-200	70-150	20-35	9-15
	Pigs	25-80	15-20	6-15	2-4
	Laying hens	0.4		0.05	
Covered storage - low efficiency	Dairy cows	50-100	30-60	10-20	5-7
	Other cattle	40-100	30-40	10-15	4-5
	Pigs	10-40	7-8	3-7	1-2
	Laying hens	0.2		0.03	
Low NH_3 application	Dairy cows	n.a.		40-70	
	Other cattle	n.a.		10-40	
	Pigs	n.a.		4-12	
	Laying hens	n.a.		0.1-0.15	
	Other poultry	n.a.		0.02-0.06	
	Sheep	n.a.		2-4	
Urea substitution	Fertilizer use	350-950 ECU/t NH_3 removed			
Stripping/adsorption	Industry	7000 ECU/t NH_3 removed			

n.a.: not applicable

* - Taking into account fixed and variable operating costs

** - The following stable sizes are assumed:

Pigs	- small (<50 animals/stable), typical (~170)
Dairy cows	- small (<20 animals/stable), typical (~35)
Other cattle	- small (<30 animals/stable), typical (~40)

2.5 Atmospheric Source-Receptor Relationships

2.5.1 Modeling the Dispersion of Sulfur and Nitrogen Compounds in the Atmosphere

The RAINS model estimates deposition of sulfur and nitrogen compounds due to the emissions in each country, and then sums the contributions from each country with a background contribution to compute total deposition at any grid location. These calculations are based on source-receptor matrices derived from a Lagrangian model of long-range transport of air pollutants in Europe, developed by EMEP.

The EMEP model is a receptor-oriented single-layer air parcel trajectory model, in which air parcels follow two-dimensional trajectories calculated from the wind field at an altitude, which represents transport within the atmospheric boundary layer. Budgets of chemical development within the air parcels are described by ordinary first-order differential equations integrated in time along the trajectories as they follow atmospheric motion. During transport, the equations take into account emissions from the underlying grid of a 50 km resolution, chemical processes in the air, and wet and dry deposition to the ground surface. Model calculations are based on six-hourly input data of the actual meteorological conditions for specific years.

In order to capture the inter-annual meteorological variability, model runs have been performed for 11 years (1985-1995, Barret and Sandnes, 1996). For each of these years, budgets of sources (aggregated to entire countries) and sinks (in a regular grid mesh with a size of 150 x 150 km) of pollutants have been calculated. These annual source-receptor budgets have been averaged over 11 years and re-scaled to provide the spatial distribution of one unit of emissions. The resulting atmospheric transfer matrices are then used as input in the RAINS model.

The use of such ‘country-to-grid’ transfer matrices implicitly assumes that the spatial relative distribution of emissions within a country will not dramatically change in the future. It has been shown that the error introduced by this simplification is within the range of other model uncertainties, when considering the long-range transport of pollutants (Alcamo, 1987).

2.5.2 Modeling Ozone Formation

The formation of ozone involves chemical reactions between NO_x and VOC driven by solar radiation and occurs on a regional scale in many parts of the world. The time scale of ozone production is such that ozone concentrations build up in polluted air over several days under suitable weather conditions, and this pollutant and its precursors can be transported over considerable distances and across national boundaries.

An integrated assessment model for ozone needs to be able to relate ozone exposure to changes in the emissions of ozone precursors. For application in an integrated assessment model for ozone, however, the source-receptor relationships need to be valid for a variety of spatial patterns of emission sources and for a range of emission levels, and not restricted to the present-day situation alone. For this reason, attempts to define these relationships solely on the basis of recent ozone measurement data are likely to prove inadequate. Instead, the ozone formation description needs to be based on mathematical models that have gained widespread international acceptance.

Within the framework of an integrated assessment model, source-receptor relationships must be computationally efficient to enable the numerous scenario runs for analyzing costs and benefits from a wide range of control strategies. Extended uncertainty and robustness analyses is necessary to derive solid conclusions from the model, taking into account the gaps and imperfections of the available databases and models. In many cases, methodologies for such analyses require sufficiently simple formulations of the underlying models. In addition, optimization analysis has proven to be a powerful feature in the integrated assessment process for the Second Sulfur Protocol. Optimization of the entire chain from the sources of emissions, over the costs for controlling them, up to the regional impacts on ozone levels, also requires sufficiently simple source-receptor relationships.

Most of the available models for ozone formation are process-oriented and contain a considerable degree of detail of the chemical mechanisms and meteorological factors relevant for ozone formation. Consequently, their computational complexity makes it impossible to use them directly within the framework of an integrated assessment model. In order to overcome this gap, an attempt has been made to construct a ‘reduced-form’ model, using statistical methods to summarize the reaction of a more complex ‘reference’ model.

To this end, the work was carried out in collaboration with EMEP’s Meteorological Synthesizing Centre-West, and the results of the EMEP ozone model (Simpson, 1993) provide the basis on which a 'reduced-form' model for the source-receptor relationships has been built. The EMEP model has been selected for this analysis, i.a., because (i) it has repeatedly undergone extensive peer review and its structure and results have been compared with other ozone models, and (ii) the EMEP model is readily available for calculating ozone levels over all of Europe over a time period of six months, and the calculation of the necessarily large number of scenarios is a practical proposition with this model.

2.5.3 Ozone Isopleth Diagrams

Before starting the development of the simplified model, the EMEP ozone model was used to investigate the relationships in different areas of Europe between mean boundary layer ozone concentrations and changes in the emissions of NO_x and VOCs. A convenient way to illustrate the results of these investigations is by means of ozone isopleth diagrams (Figure 2.2). Such diagrams have been most commonly used, particularly in North America, to show how maximum ozone concentrations depend on the initial concentrations of NO_x and VOCs on a particular day at a specific location. Lines of constant value, or isopleths, of the maximum ozone concentrations are constructed by connecting points having the same ozone concentration but corresponding to various initial conditions. Ozone isopleth diagrams in this form provide a concise representation of the effect of reducing initial NO_x and VOC concentrations on peak ozone concentrations. In the past, they have been used quantitatively to develop ozone control strategies as part of the U.S. EPA's empirical kinetic modeling approach (EKMA).

The isopleth diagrams used in this section are constructed rather differently, although there are obvious similarities in appearance. Firstly, the ozone statistic depicted by the isopleths is the mean, over the six-month summer period, of the early afternoon ozone concentrations calculated by the EMEP model. Secondly, in the version used here, ozone is shown as a function of the percentage reduction in emissions of NO_x and VOC across Europe. Thus, the top right-hand corner of each diagram represents the base case without any reduction in precursor emissions.

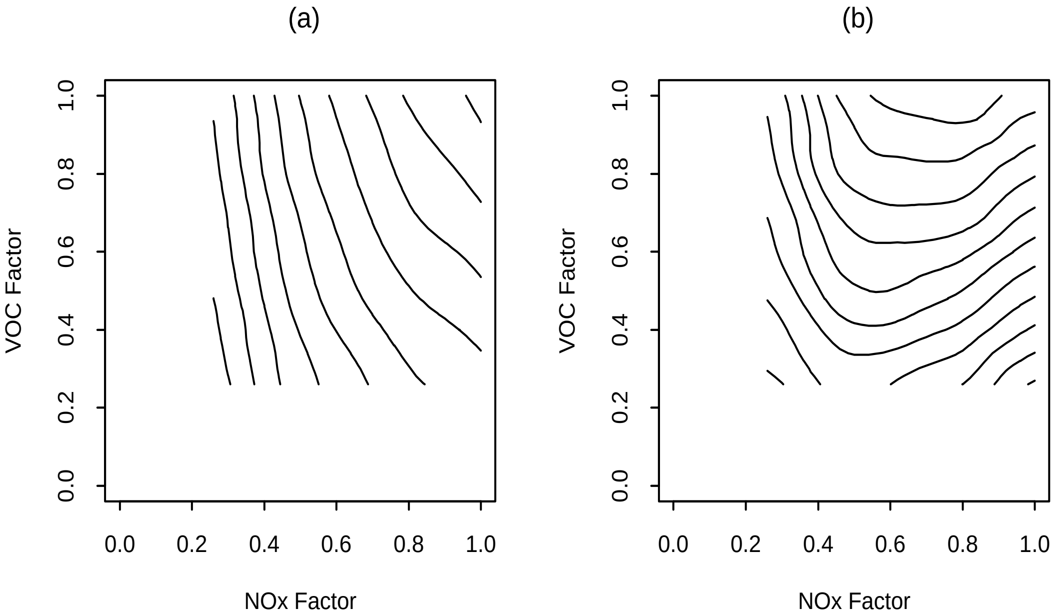

Figure 2.2: Typical patterns of ozone behavior in Europe. The left isopleth sketches the situation for a 'NO$_x$ limited region' in Europe, while the other illustrates the 'ozone hill' occurring in high-NO$_x$ areas.

For regions with comparably low emission densities, reductions in VOC emissions are seen to exert only a minor influence on mean ozone concentrations (Figure 2.2a). In these regions the NO_x / VOC ratio is relatively low and there is an ample supply of peroxy radicals (RO_2 and HO_2) to convert NO to NO_2 and, thus, lead to ozone production. Decreasing the available NO_x leads directly to a decrease in ozone. In these circumstances, ozone formation is limited by the availability of NO_x, and the atmospheric chemistry system is said to be NO_x-limited. In such regions, reductions in emissions of NO_x are likely to be effective in reducing ozone concentrations, but ozone is relatively insensitive to reductions of VOC, and to changes in the VOC species distribution, at constant NO_x.

In areas with sufficiently high emission densities, i.e., in the north-west of Europe, the isopleths form a ridge dividing the diagram into two areas (Figure 2.2b). On the left of the ridge, corresponding to the greatest reductions in NO_x emissions, the system tends towards the NO_x -limited case). On the right of the ridge, the NO_x / VOC ratio is relatively high and the NO_2 concentrations are sufficiently great that NO_2 competes with VOC for reaction with the OH radical. In this region of the diagram, reducing VOC emissions results in lower ozone concentrations; to a large extent, ozone shows a linear dependence on VOC emission changes (Simpson, 1992). However, ozone concentrations may be increased, at least initially, by NO_x reductions in the absence of concurrent reductions in VOC emissions.

2.5.4 A ‘Reduced Form’ Model of Ozone Formation

On the basis of the ideas outlined above a general formulation for the reduced-form "seasonal" model was developed. In subsequent sections the following abbreviations are used for model variables:

v_i - annual national emissions of non-methane VOCs from emitter country i
n_i - annual national emissions of NO_x from emitter country i
ev_j - "effective" emissions of VOCs, including natural sources, at receptor j
en_j - "effective" emissions of NO_x, including natural sources, at receptor j
evn_j - "effective" natural emissions of VOCs at receptor j
enn_j - "effective" natural emissions of NO_x at receptor j

The long-term ozone exposure at receptor *j*, AOT_j, is assumed to be a function of the non-methane VOC and NO_x emissions, v_i and n_i respectively, from each emitter country *i*, and the mean "effective" emissions (of NO_x and VOCs), en_j and ev_j, experienced at the receptor over the period in question. The general model formulation adopted is:

$$AOT_{lj} = k_j + \sum_{i=1}^{M}(a_{ij}v_i + b_{ij}n_i + c_{ij}n_i^{2}) + \alpha_j \overline{en}_j^{2} + g(\overline{en}_j, V) + \overline{en}_j \sum_{i=1}^{M} h_{ij}n_i \qquad (1)$$

where *M* is the number of emitter countries considered,

$$V = \{v1, v2, ..., vM\}, \qquad (2)$$

and the non-linear function *g()* is given either by:

$$g(\overline{en}_j, V) = \overline{en}_j \sum_{i=1}^{M} d_{ij}v_i \qquad (3)$$

or by:

$$g(\overline{en}_j, V) = \beta_j \overline{en}_j \overline{ev}_j \qquad (4)$$

The mean "effective" emissions are given by:

$$\overline{en}_j = \sum_{i=1}^{M} \overline{E_{ij}} n_i + \overline{enn_j} \qquad (5)$$

$$\overline{ev}_j = \sum_{i=1}^{M} \overline{F_{ij}} v_i + \overline{evn_j} \qquad (6)$$

where E_{ij}, F_{ij} depend on the meteorology and are obtained from EMEP model calculations, and enn_j and evn_j represent the "effective" natural emissions of NO_x and VOCs, respectively.

For the initial stages of evaluating this model, an heuristic approach was taken to decide which terms, if any, could be dropped from the model. Such experiments led to the conclusion that the following linear regression model contained sufficient information for the present purpose:

$$AOT_{lj} = k_j + \sum_{i=1}^{M}(a_{ij}v_i + b_{ij}n_i + c_{ij}n_i^{2}) + \alpha_j \overline{en}_j^{2} + \overline{en}_j \sum_{i=1}^{M} d_{ij}v_i \qquad (7)$$

In order to decide which emitter countries should be included in the model, the emitter countries were ranked (i) on the basis of their contribution to the "effective" NO_x emissions experienced at each receptor *j*, and (ii) by how great an ozone reduction was achieved for a given fractional VOC reduction. The most influential twelve countries were included in the equation, i.e. *M* was set equal to 12. This choice was based on an assessment of the EMEP model results for a small number of receptor sites, in an attempt to include in the simplified model all the most influential emitter countries (for a given receptor) yet exclude those which had very little effect.

The formulation of the reduced-form model given in Equation 7 above has been used in the construction of models for 598 European receptor grids.

It is of interest to relate the terms of Equation 7 to the physical and chemical processes that determine ozone formation in the atmosphere. Possible interpretations are:

k_j	includes the effects of background concentrations of O_3 and its precursors, and natural VOC emissions;
$a_{ij}v_i$	provides the linear country-to-grid contribution from VOC emissions in country *i*, allowing for meteorological effects;
$b_{ij}n_i$	provides the linear country-to-grid contribution from NO_x emissions in country *i*, allowing for meteorological effects;
$\alpha_j en_j^2$	takes account of the average non-linearity (in the O_3 / NO_x relationship) experienced along trajectories arriving at receptor *j* and any non-linear effects local to that receptor;
$c_{ij}n_i^2$	serves essentially as a correction term to allow for non-linearities occurring close to high NO_x emitter countries;
$d_{ij}en_jv_i$	allows for interactions between NO_x and VOCs along the trajectories.

The coefficients a_{ij}, b_{ij}, $c_{ij,,}$, d_{ij} and α_I are estimated by the linear regression, and n_i, v_i and en_j are used as variables. The coefficients a_{ij} and b_{ij} may also be regarded as a composite source-receptor matrix.

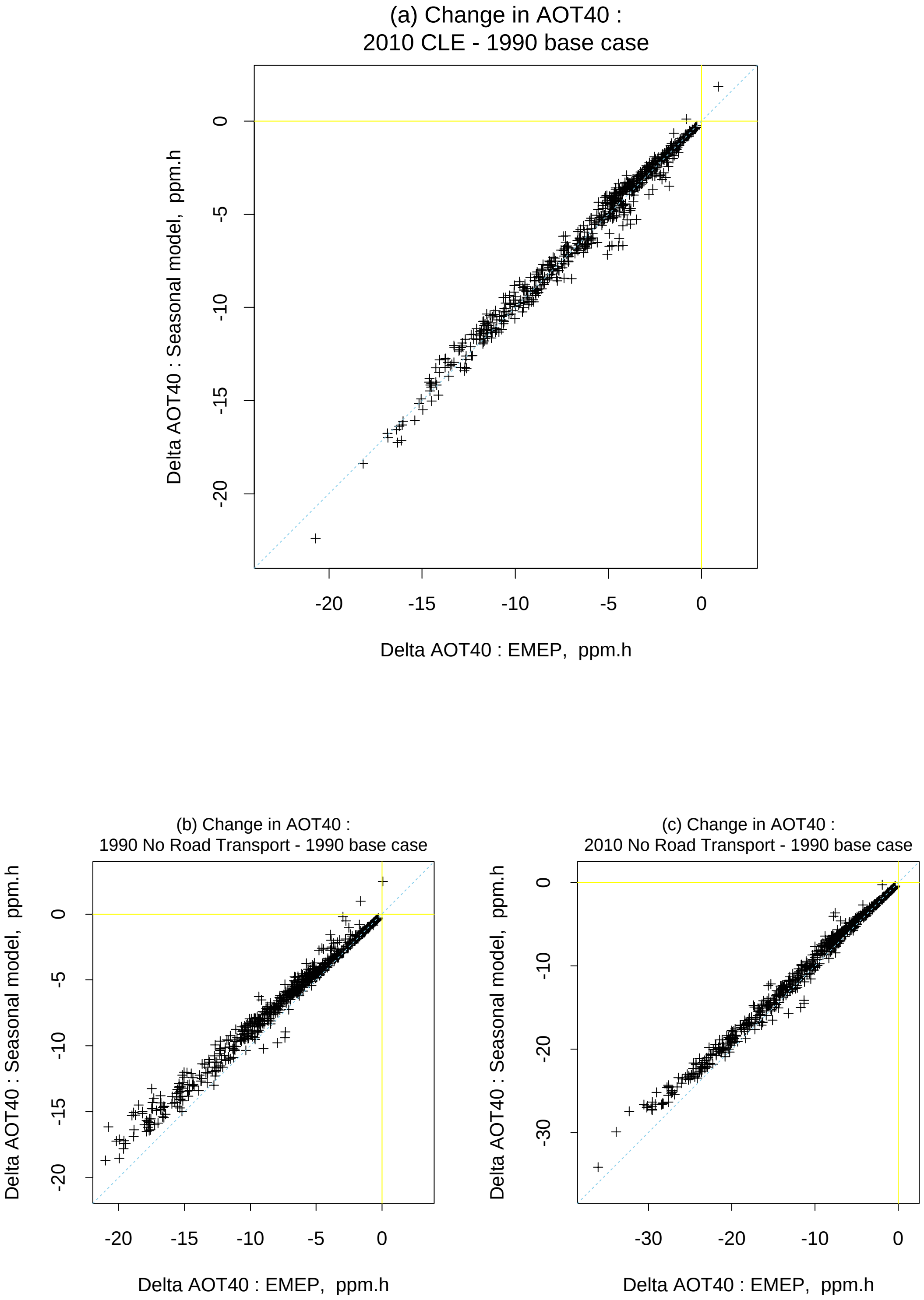

Figure 2.3: Comparison of the results from the reduced-form model for three scenarios with the corresponding EMEP model calculations

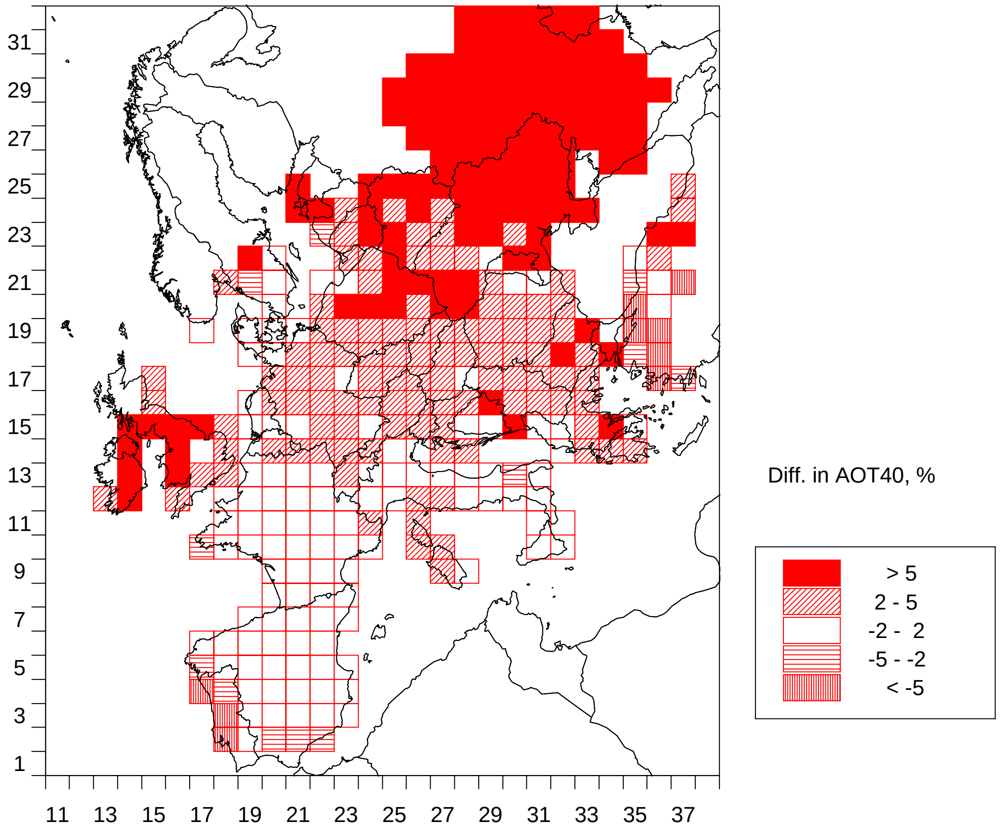

Figure 2.4: Spatial distribution of differences between a reduced-form and the full EMEP models for those receptor grids at which the 1990 base case AOT40 value for forests - as calculated using the 1995 version of the EMEP model - exceeds the critical level of 10 ppm.hours.

2.6 Critical loads and Critical Levels

2.6.1 The Concept of Critical Loads for Acidification and Eutrophication

A critical load for an ecosystem is defined as the deposition "below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge". Over the past years methodologies for computing critical loads have been elaborated for acidification and eutrophication and compiled by the Mapping Programme under the Working Group on Effects which operates under the UN/ECE Convention of Long-range Transboundary Air Pollution (LRTAP) (UBA, 1996).

Acidification is caused by the deposition of both sulfur and nitrogen, and both compounds "compete" for the counteracting (neutralizing) base cations, which are mostly provided by deposition and weathering. And, in contrast to sulfur, for nitrogen there are additional natural (sources and) sinks such as uptake by vegetation, immobilization and denitrification. Consequently, it is not possible to define a single critical load for acidity, as was the case when looking at sulfur alone, but a (simple) function, called critical load function. This function defines pairs of sulfur and nitrogen deposition for which there is no risk of damage to the ecosystem under consideration, thus replacing the single critical load value used earlier. The critical load function for each ecosystem has a trapezoidal shape and is defined by three quantities: $CL_{max}(S)$, $CL_{min}(N)$ and $CL_{max}(N)$: $CL_{max}(S)$ is essentially the critical load of acidity (as defined earlier), $CL_{min}(N)$ summarizes the net nitrogen sinks, and $CL_{max}(N)$ is the maximum deposition of nitrogen (in case of zero sulfur deposition) taking into account CLmax(S) and deposition-dependent nitrogen processes ($CL_{max}(N)>=CL_{min}(N)+ CL_{max}(S)$).

In addition to acidification, nitrogen deposition also acts as a nutrient for ecosystems. Consequently, in order to avoid eutrophication, critical loads for nutrient nitrogen, $CL_{nut}(N)$, have been defined and calculated for various ecosystems.

2.6.2 The European Critical Loads Database

Following standardized methodologies, critical loads data are compiled on a national level. Each year the Coordination Center for Effects (CCE)) located at the Dutch National Institute for Public Health and the Environment (RIVM) invites countries to submit revised national critical loads calculations, so that the integrated assessment modeling groups participating in the LRTAP Convention may work with up-to-date critical loads data. The following paragraphs describe the status of the critical loads databases as of August 1998.

For the 1998 version of the critical loads databases, the number of countries which submitted data has increased to 24 (see Table 2.18 and Table 2.19). National focal centers have selected a variety of ecosystem types as receptors for calculating and mapping critical loads. For most ecosystem types (e.g., forests), critical loads are calculated for both acidity and eutrophication. Other receptor types, such as streams and lakes, have only critical loads for acidity, on the assumption that eutrophication does not occur in these ecosystems. For some receptors, like most semi-natural vegetation, only critical loads for nutrient nitrogen are computed, since the sensitivity to acidifying effects is less than the eutrophication effects.

Table 2.18 shows for the EU countries the ecosystem types and the number of individual ecosystems for which critical loads data were submitted by the national focal centers. Out of the 15 EU countries, 12 countries submitted critical load calculations to the CCE, providing details about 595,566 ecosystems. No data were supplied by Greece, Portugal and Luxembourg. Table 2.19 complements this information with the critical load statistics for the non-EU countries.

For those countries which did not provide their national critical loads estimates to the CCE, the European background database for critical loads (de Smet *et al.*, 1997) is employed. The European background database is constructed at the CCE by applying the consensus methodology for calculating critical loads to internationally published information, such as the 1994 digital soil map of the FAO and the RIVM European land use maps.

Figure 2.5 shows the fifth percentile of $CL_{max}(S)$ for the EMEP modeling domain.

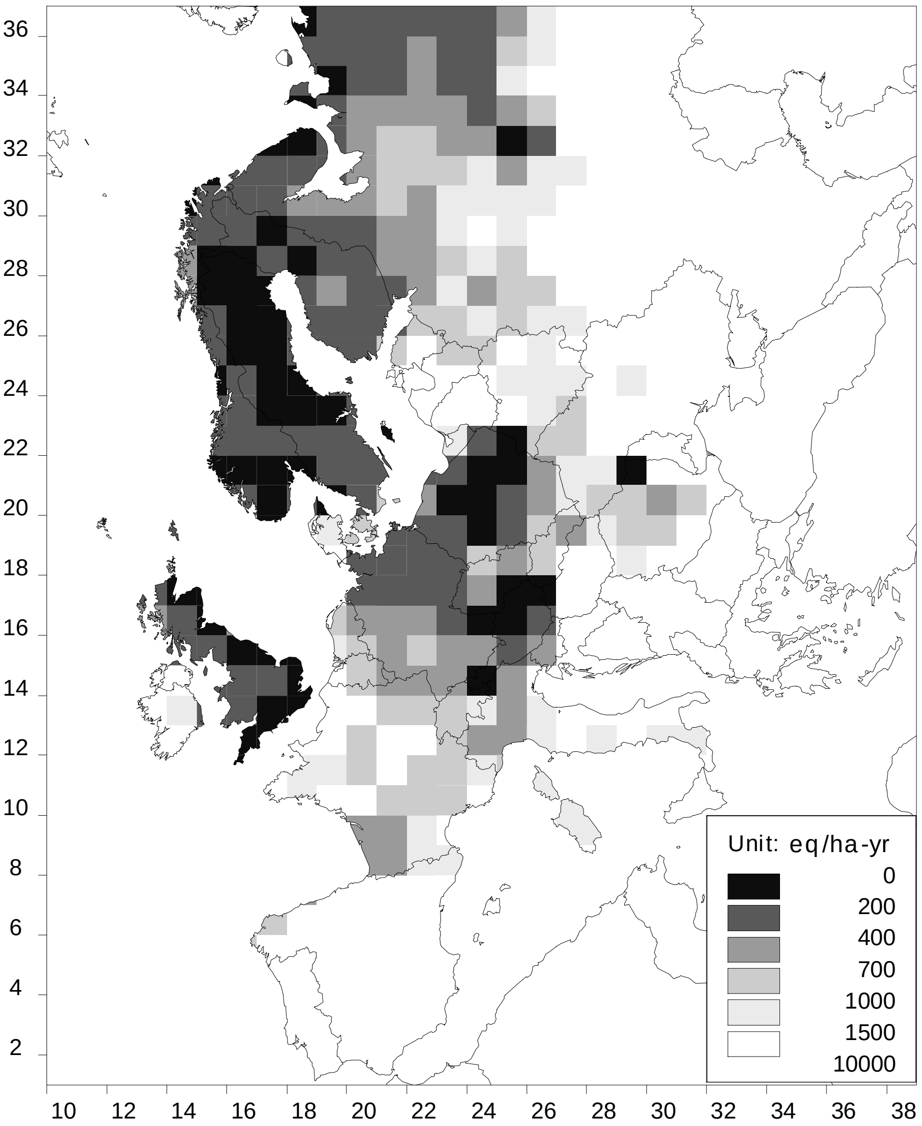

Figure 2.5: The fifth percentile of the critical loads for acidity ($CL_{max}(S)$)

Table 2.18: Types of ecosystems, number of critical loads and ecosystem cover (percentage of total land area) in the critical loads database submitted by EU countries (Status 1997) Source: Coordination Centre for Effects, Posch (1998)

Country	**Ecosystem type**	**Critial loads submitted**		**Land area covered by ecosystems with CL for acidity**
		No. of ecosystems	**Total ecosystems**	
Austria	Forest	6604	7901	71.2 %
	Oligotrophic bog	205		
	Alpine grassland	1092		
Belgium	Coniferous forest	835	2532	23.0 %
	Deciduous forest	1201		
	Mixed forest	490		
	Lake	6		
Denmark	Spruce	5463	18784	9.0 %
	Pine	1033		
	Beech	2814		
	Oak	447		
	Grass	9027		
Finland	Spruce	1004	4533	80.7 %
	Pine	1045		
	Deciduous forest	1034		
	Lake	1450		
France	Coniferous forest	28	591	58.4 %
	Deciduous forest	83		
	Mixed forest	302		
	Grassland (agricultural)	178		
Germany	Coniferous forest	227457	410277	28.7 %
	Deciduous forest	91937		
	Mixed forest	90883		
Ireland	Coniferous forest	10022	26303	9.8 %
	Deciduous forest	8933		
	Moors/Heathland	7348		
Italy	Boreal forest	41	502	39.8 %
	Temperate coniferous forest	22		
	Temperate deciduous forest	165		
	Mediterranian forest	110		
	Tundra	46		
	Acid grassland	118		

Table 2.18: Types of ecosystems, number of critical loads and ecosystem cover (percentage of total land area) in the critical loads database submitted by EU countries (Status 1997) Source: Coordination Centre for Effects, Posch (1998), continued

Country	**Ecosystem type**	**Critial loads submitted**		**Land area covered by ecosystems with CL for acidity**
		No. of ecosystems	**Total ecosystems**	
Netherlands	Coniferous forest	52949	127269	7.6 %
	Deciduous forest	74320		
Spain	Coniferous forest	2237	3409	17.1 %
	Deciduous forest	744		
	Mixed forest	428		
Sweden	Forest	1883	4261	86.9 %
	Lake	2378		
United Kingdom	Coniferous forest	29309	318258	39.2 %
	Deciduous forest	69747		
	Acid grassland	137228		
	Calcareous grassland	24976		
	Heathland	55553		
	Fresh water catchment	1445		
EU-15			890870	

Table 2.19: Types of ecosystems, number of critical loads and ecosystem area (percentage of total land area) in the critical loads database submitted by non-EU countries (Status 1997) Source: Coordination Centre for Effects, Posch (1998)

Country	**Ecosystem type**	**Critial loads submitted**		**Land area covered by ecosystems with CL for acidity**
		No. of ecosystems	**Total ecosystems**	
Belarus	Coniferous forest	234	555	24.2 %
	Deciduous forest	79		
	Grassland	242		
Bulgaria	Coniferous forest	29	84	44.6 %
	Deciduous forest	55		
Croatia	Coniferous forest	18	34	4.8 %
	Deciduous forest	16		
Czech Republic	Forest	29418	29418	33.7 %

Table 2.19: Types of ecosystems, number of critical loads and ecosystem area (percentage of total land area) in the critical loads database submitted by non-EU countries (Status 1997) Source: Coordination Centre for Effects, Posch (199, continued.

Country	**Ecosystem type**	**Critial loads submitted**		**Land area covered by ecosystems with CL for acidity**
		No. of ecosystems	**Total ecosystems**	
Estonia	Pine-podzol	32	140	41.8 %
	Pine-bog	22		
	Spruce-podzol	30		
	Spruce-alvar	15		
	Deciduous-podzol	12		
	Deciduous-wet	14		
	Bog	15		
Hungary	Unspecified forest	7	42	3.1 %
	Coniferous forest	5		
	Deciduous forest	8		
	Grassland / Reed / Marsh	12		
	Heath	4		
	Bog	4		
	Lake	2		
Moldova	Coniferous forest	15	141	35.6 %
	Deciduous forest	32		
	Grassland	94		
Norway	Forest	720	4635	99.0 %
	Lake/stream	2305		
	Semi-natural vegetation	1610		
Poland	Coniferous forest	1957	3914	55.5 %
	Deciduous forest	1957		
Russian Federation	Coniferous forest	4929	14251	74.2 %
	Deciduous forest	2983		
	Other	6339		
Slovakia	Coniferous forest	112440	320891	40.9 %
	Deciduous forest	208451		
Switzerland	Forest	8467	23937	58.0 %
	Alpine lakes	495		
	Semi-natural ecosystem	14975		
Total ECE			1322662	

2.6.3 Using Critical loads for Integrated Assessment Modelling

The European critical loads database as compiled by the Coordination Centre for Effects provides for each cell of the EMEP grid system the cumulative distribution function of the critical loads for all ecosystems of the grid cell. From this information it is possible to derive for each grid cell, for a given deposition value calculated from a certain emission control scenario, (a) the excess deposition for a selected ecosystem (e.g., for the two percentile) and (b) the percentage of ecosystems which experience deposition below their critical loads (i.e., the ecosystems protected against acidification).

Both measures have been used in the past to establish environmental interim targets on the way towards the full achievement of critical loads. The negotiations on the Second Sulfur Protocol of the Convention on Long-range Transboundary Air Pollution postulated for each grid cell a minimum ’60 percent gap closure’ between the deposition in 1980 and the critical load of the ’five percentile’ ecosystem. This strategy relied only on the critical load estimate of one single ecosystem, i.e., it ignored the five percent more sensitive ecosystems and the 94 percent less sensitive ecosystems in each grid cell.

Due to the methodological problems in adding up sulfur and nitrogen deposition, the multi-pollutant context of the EU Acidification Strategy motivated a move towards the second approach by using the percentage of protected ecosystems as the key environmental indicator for shaping the strategy. In practice, the central scenario aimed at a 50 percent reduction (’gap closure’) of the area of unprotected ecosystems in each grid cell, compared to the situation in 1990. Obviously, this criterion addresses the other dimension of the cumulative distribution function (i.e., the full range of ecosystems), but it ignores the extent to which ecosystems receive excess deposition.

Over the last few months, a new measure for evaluating ecosystems protection was developed. This new measure reflects the total excess deposition (above the critical loads) accumulated for all ecosystems in a grid cell (in acid equivalents per year). Starting from a given deposition, this ’accumulated exceedance’ (AE) is calculated by adding up (for each ecosystem) the sulfur and nitrogen reduction needed to achieve non-exceedance by taking the shortest path to the critical load function.

2.6.4 The AOT60 as a Surrogate Indicator for Risk to Human Health

The analysis presented in this report addresses the protection of human health and vegetation against elevated ozone exposure. The appropriate exposure measures for environmental long-term targets for these categories are discussed in detail in the Draft Position Paper on Ozone prepared by the Commission’s Services. For modeling and optimization purposes, however, the use of some of these original criteria proved to be complicated and impractical, and some surrogate indicators have been introduced instead. By no means the use of such surrogate indicators does question the original definition of the criteria. Furthermore, they must not be interpreted as actual damage estimates. The only reason for the surrogate indicators is to facilitate the modeling and optimization exercise.

Following the revised WHO Air Quality Guidelines for Europe (WHO 1997), the Draft Position Paper on Ozone prepared by the Commission's Services proposes a maximum eight-hour average concentration of 60 ppb (120 μg) as the long-term environmental objective for the EU ozone strategy[20]. The ultimate goal would be to eliminate all excess of this criterion.

The modeling of European abatement strategies for individual days over a multi-month period is a rather ambitious task and is not entirely feasible at the moment. In order to simplify the modeling task, and particularly to find a manageable approach for the reduced-form model implemented in the RAINS optimization, the target of no-exceedance of the WHO criterion (60 ppb as maximum eight hours mean concentrations) was converted into an AOT index, which could be handled in a similar way to the AOT40 for vegetation. As a result, an AOT60 (i.e., the cumulative excess exposure over 60 ppb, for practical reasons over a six-month period) of zero is considered as equivalent to the full achievement of the WHO criterion. Any violation of this WHO guideline will consequently result in an AOT60 of larger than zero.

It is important to stress that this AOT60 surrogate indicator has been introduced purely for practical modeling reasons. Given the current knowledge on health effects it is not possible to link any AOT60 value larger than zero with a certain risk to human health. The only possible interpretation is that if the AOT60 is above zero, the WHO criterion is exceeded at least once during the six-month period.

For the actual model exercise, the AOT60 of different emission control scenarios at a given site is calculated as a function of the emission levels of NO_x and VOC in the various European countries (see the description of the 'reduced form' model in Part A). The reduced-form model is derived from a statistical analysis of a large sample of results obtained with the full EMEP model. The EMEP model provides ozone levels at six-hourly intervals (0 GMT, 6 GMT, 12 GMT and 18 GMT) over a six months period. Following the findings of various studies for different parts of Europe (Künzle, 1995; Dumont 1998), the AOT60 has been calculated as the excess ozone over 60 ppb at 12 GMT and 18 GMT, accumulated over the entire period and multiplied by a factor of six.

2.6.5 The AOT40 as a Critical Threshold for Vegetation Protection

In the absence of accepted dose-response curves applicable at the large scale, the analysis in this report uses the concept of critical thresholds as developed within the framework of the UN/ECE Convention on Long-range Transboundary Air Pollution. The Working Group on Effects of this Convention established two long-term related critical levels:

- For agricultural crops and herbaceous plant communities (natural vegetation), the critical level is set at an AOT40 of 3 ppm.hours for the growing season and daylight hours, over a five-year period;
- For forest trees, a critical level of 10 ppm.hours for daylight hours, accumulated over a six-month growing season, is proposed.

---

[20] The maximum is calculated from running eight-hour averages of the one-hour mean concentrations.

The AOT40 is calculated as the sum of the differences between the hourly ozone concentrations in ppb and 40 ppb for each hour when the concentration exceeds 40 ppb, using daylight hours only.

It has been shown elsewhere that for the currently prevailing European ozone regime the critical level for crops and natural vegetation is stricter than the critical level for forest trees. This means in other words, while the critical levels for forest trees are usually met when the critical level for crops and vegetation is achieved, the opposite statement does not hold. Based on this finding it has been decided to restrict the scenario analysis to the critical levels for crops and natural vegetation. If considered necessary, however, there are no methodological problems to prevent exploring scenarios for the achievement of the critical levels for forest trees separately.

For the regression analysis of the reduced-form ozone model, the AOT40 has been calculated from the results of the full EMEP model by multiplying the excess exposures over 40 ppb at 12GMT and 18 GMT, accumulated over a three months period, by a factor of six.

2.7 Optimization

2.7.1 The Formulation of the Optimization Problem

The optimization mode of integrated assessment models can be a powerful tool in the search for cost-effective solutions to combat an air pollution problem. In the RAINS-acidification model, optimization techniques have been used to identify the cost-minimal allocation of resources in order to reduce the gap between current sulfur deposition and the ultimate targets of full critical loads achievement.

In the case of tropospheric ozone, a systematic search for cost-effectiveness appears even more attractive. The facts that several pollutants (NO_x and VOC emissions) are involved, and that important non-linearities between precursor emissions and ozone levels have been recognized, cut the likelihood of 'intuitive' solutions being identified in the scenario analysis mode.

The model distinguishes between a set of *I* sources of various types of air pollution and a set of *J* receptor areas for which various air quality targets are assessed.

Emissions are analyzed for sets of emitters that are located in a region *i*, which is typically a country. NO_x and VOC emitters are further subdivided into sectors in order to account for sectoral emission controls that reduce either NO_x or VOC or a linear combination of them.

2.7.1.1 Decision Variables

The main decision variables are the annual emissions of the following four polutants from either sectors or countries:

n_{is}	annual emissions of NO_x in sector *s* of country *i*,
v_{is}	annual emissions of VOC in sector *s* of country *i*,,
a_i	annual total emissions of NH_3, and
s_i	annual total emissions of SO_2.

Additionally, optional variables are considered for limited violations of air quality targets. For such scenarios, variables corresponding to each type of the considered air quality targets are defined for each receptor:

yl_j	violation of ozone exposure targets (surplus if $y_{lj} < 0$);
ya_j	violation of the acidification targets (surplus if $ya_j < 0$).

Each variable represents a violation of a given environmental target. Violations of targets are balanced with surpluses at selected other receptors (within the same country).

2.7.1.2 Auxiliary Variables

Auxiliary variables are introduced for total national emissions of NO_x (n_i), total national emissions of VOC (v_i) (summing up all sectoral emission in a country) and the mean effective emissions of NO_x experienced at the *j-th* receptor (en_{ij}).

2.7.1.3 Outcome Variables

One outcome variable represents the sum of the costs of emission reductions. Annual costs related to the reduction of one or several pollutants to a certain level are described by piece-wise linear functions:

$cs_i(s_i)$	for SO_2,
$ca_i(a_i)$	for NH_3,
$cn_i(n_i)$	for stationary NO_x sources,
$cv_i(v_i)$	for stationary sources of VOC emissions, and
$c_i(n_i,v_i)$	for simultaneous NO_x and VOC control at mobile sources.

For each cost function the domain is specified through upper and lower bounds of the arguments, which implicitly defines lower and upper bounds for total national emissions. These bounds may be tightened by an optional specification of bounds on total national or sectoral emission, e.g., to reflect upper limits to the emissions related to the CRP scenario.

For each receptor, the following outcome variables correspond to the various environmental targets. For AOT60, the outcome variable $aot60_i$ is related to the decision variables by

$$AOT60_j = k60_j + \sum_{i=1}^{M}(a60_{ij}v_i + b60_{ij}n_i + c60_{ij}n_i^2) + \alpha 60_j \overline{en}_j^2 + \overline{en}_j \sum_{i=1}^{M} d60_{ij}v_i$$

with $k60_j$, $a60_{ij}$, $b60_{ij}$, $c60_{ij}$, $\alpha 60_{ij}$ and $d60_j$ as the receptor-specific coefficients of the reduced-form ozone model (see Section 2.5.4). A similar constraint is specified for the AOT40

$$AOT40_j = k40_j + \sum_{i=1}^{M}(a40_{ij}v_i + b40_{ij}n_i + c40_{ij}n_i^2) + \alpha 40_j \overline{en}_j^2 + \overline{en}_j \sum_{i=1}^{M} d40_{ij}v_i ,$$

where $k40_j$, $a40_{ij}$, $b40_{ij}$, $c40_{ij}$, $\alpha 40_{ij}$ and $d40_j$ are the coefficients of the reduced-form ozone model.

For acidification, the outcome variables the type *l* (relating to the *l*-th segment of the piece-wise linear approximation of the accumulated excess function of the receptor grid *j*) is related to the decision variables via:

$$ac_{lj} = tns_{lj}(\sum_i tn_{ij}n_i + \sum_i ta_{ij}a_i) + tss_{lj}\sum_i ts_{ij}s_i + kn_j + ks_j$$

with tn_{ij}, ta_{ij}, ts_{in} are the transfer coefficients for NO_x, NH_3 and SO_2, respectively, kn_j and ks_j *the* background depositions for sulfur and nitrogen and tns_j and tss_j scaling coefficients to convert sulfur and nitrogen deposition into units of acidity of the critical loads functions. The coefficients tn_{ij}, ta_{ij}, ts_{in} kn_j and ks_j are obtained from the EMEP model; tns_{lj} and tss_j, are extracted from the critical loads database.

The accumulated excess of acidification (aac_j) is calculated by a piece-wise linear function PWL_j

$$aac_j = PWL_j ac(ac_j)$$

For eutrophication, the outcome variable is linked to the decision variables

$$eu_j = \sum_i tn_{ij}n_i + \sum_i ta_{ij}a_i + ke_j$$

2.7.1.4 Constraints

Each of the decision variables is implicitly bounded by a corresponding definition of the domain of the cost function

$n_{is}^{min} \leq n_{is} \leq n_{is}^{max}$,
$v_{is}^{min} \leq v_{is} \leq v_s^{max}$,.
$a_i^{min} \leq a_i \leq a_i^{max}$,
$s_i^{min} \leq s_i \leq s_i^{max}$

The $AOT_{(l=60/40)}$ at each receptor is constrained by

$$AOT_{lj} - y_{lj} \leq AOT_{lj}^{max}$$

where AOT_{lj}^{max} is given by the user, and the accumulated excess acidity is constrained by

$$aac_j - ya_i \leq aac_j^{max}$$

with aac_j^{max} specified by the user.

Optionally, violations of targets can be balanced with surpluses of targets within restricted sets of receptors (J_m), where $m \in M$ is the index of a set of receptors. The balances are represented by the following constraints:

$$\sum_{j} wo_{lmj} y_{lj} \leq tbo_{lm} \text{ , l=0}$$

$$\sum_{l}\sum_{j} wo_{lmj} y_{lj} \leq \sum_{l} tbo_{lm}$$

$$\sum wa_{mj} ya_{j} \leq tba_{m}$$

where wol_{mj} and wa_{mj} are given weighting coefficients, J_m are set of receptors and tbo_{lm}, and tba_{lm} are target balances for the *m*-th set of receptors.

2.7.1.5 Goal function

A composite goal function is used for a single criterion optimization of th enon-linear ozone model in order to meet the following goals

- minimization of total costs of emission reductions,
- minimization of violations of environmental targets.

Therefore, the goal function is formulated as

$$goal\_function = \sum_{i} (ca_{i}(a_{i}) + cs_{i}(s_{i}) + cn_{i}(n_{i}) + cv_{i}(v_{i}) + c_{i}(n_{i}, v_{i}) + penalty$$

The penalty term is defined by

$$penalty = \rho \sum_{l}\sum_{j} y_{lj}^{\xi} + \rho_{a} \sum ya_{j}^{\xi}$$

where ρ and ρ_a are a large positive penalty coefficients. The penalty term exponent ξ is equal to 1, of the corresponding lower bound is equal to 0.

2.7.2 Sectoral Cost Curves as Input to the Optimization

Inputs to the optimization package include cost curves providing, for the various pollutants under consideration, the costs of reducing emissions at the different source regions for a selected year.

The current implementation of the RAINS model contains modules for estimating emission control costs for SO_2, NO_x, NH_3 and VOC. These estimates can be expressed in terms of cost curves, providing - for a given emission source (country) - the least costs for achieving increasingly stringent emission reductions. They are compiled by ranking the available abatement options according to their marginal costs. Consequently, this methodology produces piece-wise linear curves, consisting typically of about 20-80 segments, depending on the pollutant.

For each of the pollutants (SO_2, NO_x, VOC, NH_3) and the countries, such piece-wise linear curves can be used as input to the optimization. Although the solvers used for this exercise are capable of dealing with piece-wise linear curves, for reasons of increased numerical stability a smoothed approximation of the cost curves has been developed and used. For this the original piece-wise linear information was smoothed at corners.

The selected functional form guarantees that the curve is, within the selected interval, convex and monotonically decreasing, and shows asymptotic behavior at the maximum control level. For NO_x, the maximum deviation from the piece-wise linear curve is typically within a range of ± five percent.

The cost curves have been submitted to the Parties of the Convention on Long-range Transboundary Air Pollution for review (NO_x and NH_3: October 1998, VOC: December 1997, SO_2: June 1998). Comments received from the Parties have been fully incorporated into the cost curves. The full documentation of the cost curves is available on the internet (http://iiasa.ac.at/~rains).

3 Data Sources

3.1 Energy Projections

Input to the RAINS model are projections of future energy consumption on a national scale up to the year 2010. Part B of this report present analyses of emission control strategies for two alternative set of energy projections:

3.1.1 The ’Baseline’ Energy Scenario used for this Report

The ’baseline’ energy scenario reflects a kind of official ’business-as-usual’ view of the energy development, compiled from a variety of national and international sources. For the EU-15 countries, the default projection is the pre-Kyoto ‘Business as usual' (BAU) scenario of DG-XVII (Capros *et al*., 1997). In cases when countries officially reported alternative projections to the Commission, these national scenarios were used instead. For this Interim Report, the business-as-usual energy scenario has been replaced by national data for Austria, Belgium, Denmark, Finland, Germany, Greece, Ireland, Netherlands, Sweden and the UK. A national scenario has also been received from Italy on September 11, 1998. however, further clarification from national experts is required before the scenario can be implemented in the RAINS database.

For the non-EU countries considered in RAINS, energy projections are based on data submitted by the governments to the UN/ECE and published in the UN/ECE Energy Data Base (UN/ECE, 1996). Where necessary, missing forecast data have been constructed by IIASA based on a simple energy projection model. For the Czech Republic, Norway, Poland and Slovakia the forecasts were modified based on comments obtained from national experts.

The energy scenario selected for this study projects for the 15 EU countries an increase of total energy consumption of 19 percent between 1990 and 2010. The demand for coal decreases by 30 percent. This decline is mainly compensated by a rapid increase in the demand for natural gas (72 percent by 2010) and for other fuels (nuclear, hydropower, renewable energy) by 24 percent (Table 3.2). The transport sector is expected to grow further, which - in spite of continuing improvement in fuel economy of new cars and trucks - results in an increase in the demand for transport fuels by 32 percent.

For the non-EU countries, the scenario projects a four percent drop in total primary energy consumption (Table 3.4). This is due to a sharp decrease in primary energy demand that occurred in the period 1990 - 1995 in the countries of the former Soviet Union and in other central and east European countries with economies in transition. Processes of economic restructuring in those countries will allow further economic development while keeping the total primary energy demand until 2010 below the 1990 level. Consumption of coal and oil by stationary sources is predicted to decrease by 22 and 33 percent, respectively. Consumption of natural gas will increase (by 12 percent). As in the EU countries, the demand for transport fuels will increase (by 11 percent over the period 1990 - 2010). In spite of a fast increase in car ownership, the growth in the demand for fuels is modest because of a rapid decrease in material- and transport intensities of the former so-called planned economies. Thus, until 2010 the demand for goods transport will also remain below the 1990 level.

It must be stressed that the selected energy scenario is an exogenous input to the RAINS model and does not specifically change due to constraints on emissions imposed by RAINS calculations.

Detailed data on fuel consumption for the RAINS categories is available on the Internet (http://www.iiasa.ac.at/~rains).

Table 3.1: Projections of total primary energy consumption for the countries of the EU-15 for the 'Baseline' scenario. Energy use for air transport is not included.

	Data source	1990 [PJ]	2010 [PJ]	*Change 1990-2010*	GDP growth [%/year]
Austria	National	1242	1421	14%	1.9%
Belgium	National	1907	2436	28%	2.1%
Denmark	National	731	783	7%	2.2%
Finland	National	1233	1604	30%	3.0%
France	BAU	9141	11143	22%	2.0%
Germany	National	14534	14179	-2%	2.3%
Greece	National	911	1785	96%	2.8%
Ireland	National	409	698	71%	4.6%
Italy	BAU	6676	8455	27%	1.9%
Luxembourg	BAU	122	129	6%	2.3%
Netherlands	National	2737	3715	36%	3.3%
Portugal	BAU	699	1113	59%	3.0%
Spain	BAU	3612	5227	45%	2.6%
Sweden	National	2430	2581	6%	n.a.
UK	National	8544	9875	16%	n.a.
EU-15		54927	65146	19%	n.a.

Table 3.2: Energy projections for the EU-15 by source category and fuel type for the 'Baseline' scenario. (Energy use for air transport not included)

Source category/fuel	1990 [PJ]	2010 [PJ]	*Change 1990-2010*
Stationary combustion sources:			
Total	44657	51625	16%
- Coal	11561	8147	-30%
- Liquid fuels	11917	12045	1%
- Gaseous fuels	10603	18277	72%
- Other	10576	13156	24%
Mobile sources - total	10271	13521	32%
TOTAL	54927	65146	19%

Table 3.3: Projections of total primary energy consumption for the non-EU countries used for this study Energy use for air transport is not included.

	1990 [PJ]	2010 [PJ]	*Change* *1990-2010*	GDP growth [%/year]
Albania	128	143	12%	1.5%
Belarus	1762	1553	-12%	0.5%
Bosnia-H.	311	297	-5%	-0.3%
Bulgaria	1310	1276	-3%	1.0%
Croatia	413	447	8%	1.4%
Czech Republic	1949	1764	-10%	1.6%
Estonia	423	366	-13%	0.5%
Hungary	1109	1350	22%	1.7%
Latvia	399	359	-10%	-1.1%
Lithuania	677	565	-17%	-0.7%
Norway	1426	1904	34%	2.0%
Poland	4250	5253	24%	3.0%
R. of Moldova	392	324	-17%	-2.2%
Romania	2425	2525	4%	1.2%
Russia	18237	16617	-9%	-0.4%
Slovakia	987	982	0%	1.4%
Slovenia	231	234	1%	3.6%
Switzerland	1119	1184	6%	1.3%
FYR Macedonia	151	138	-9%	0.5%
Ukraine	9970	8559	-14%	-1.0%
Yugoslavia	790	725	-8%	0.6%
Non-EU	48458	46567	-4%	0.6%

Table 3.4: Energy projections for the non-EU countries (Sources: UN/ECE, 1996a, RAINS estimates)

Source category/fuel	1990 [PJ]	2010 [PJ]	Change 1990-2010
Stationary combustion sources:			
Total	43837	41414	-6%
- Coal	11556	8981	-22%
- Liquid fuels	8434	5654	-33%
- Gaseous fuels	18241	20392	12%
- Other	5605	6388	14%
Mobile sources - total	4621	5152	11%
TOTAL	48458	46566	-4%

3.2 Forecast of Activity Levels used in the VOC Module for Stationary Sources

The future rate of VOC emitting activities, such as industrial production, fuel consumption or transport services, are derived in RAINS by modifying the present activity levels according to exogeneously provided projections, e.g., for the year 2010. Unfortunately, reliable and consistent projections of future activity rates at the process level are hardly available; most economic long-term forecasts restrict themselves to a rather aggregated level of economic activities and rarely specify even the development of the main economic sectors. Therefore, the temporal changes of the activity rates are derived on the following four concepts:

- The change of the activity rates for processing, distribution and combustion of fossil fuels is linked to changes in fuel consumption provided by the energy scenario input to RAINS. Internal consistency with the energy scenario used for calculation of SO_2 and NO_x emissions is maintained.
- Some other activity rates (dry cleaning, use of solvents in households, vehicle treatment, food and drink industry) are linked to the economic growth and population development.
- The temporal development of a number of industrial activities (e.g., degreasing, paint use, solvent use in chemical industry, printing, other industrial solvent use) is related to changes in the sectoral gross domestic product (supplied with the energy scenario). In many cases statistics suggest that these activities grow slower than the GDP. To reflect this trend, sector-specific elasticities derived from statistics have been applied. Furthermore, comments from national experts on the development of several sectors were taken into account.
- In the absence of more information the activity rates for less important emission sectors are kept constant. This was typically done
    i. for sectors where current emissions estimates are very uncertain (e.g., waste treatment),
    ii. where it is difficult to identify meaningful relations with other economic activities, and
    iii. for sectors where the increase in activity rates are expected to be offset by emission reductions induced by autonomous technical improvements.

3.3 Projections of Agricultural Livestock

3.3.1 The 'Baseline' Projection used for this Report

Agricultural activities are a major source of ammonia emissions, which in turn make a contribution to the acidification problem. Next to specific measures directed at limiting the emissions from livestock farming, the development of the animal stock is an important determinant of future emissions. IIASA has compiled a set of forecasts of European agricultural activities, based on national information (Marttila, 1995; Pippatti, 1996; Henriksson, 1996; Riseth, 1990; Menzi, 1995; Menzi *et al.*, 1997; Davidson, 1996), on studies performed for DG-VI of the Commission of the European Communities (EC DG-VI, 1995a-k) for Eastern Europe, and on Stolwijk (1996), Folmer *et al.* (1995) for EU countries. The forecast for the EU is based on the assumptions that

(i) until 2005 the Common Agricultural Policy will essentially consist of the type of the policies adopted under MacSharry, and

(ii) after 2005 the EU will gradually liberalize its agricultural policy (Stolwijk, 1996).

More detailed information on the ECAM (European Community Agricultural Model) model used to derive this forecast can be found in Folmer *et al.* (1995). Projections for the Republics of the Former Soviet Union were derived from an OECD study (OECD, 1995). The forecasts presented in this report are the result of the 1997 UN/ECE review, i.e., the original projections were modified as proposed by national experts.

Aggregated projections of livestock development as used for the further analysis in this report are presented in Table 3.5. In this table 'cattle' represents dairy cows and other cattle, 'pigs' include fattening pigs and sows, and poultry comprises laying hens, broilers and other poultry.

The forecast of fertilizer consumption for the EU-15, Switzerland and Norway is based on a study by the European Fertilizer Manufacturers Association (EFMA, 1996a,b). A "moderate grain price" scenario was used. The basic assumptions of this projection are

- that there will be no change in the Common Agricultural Policy (CAP) until the year 2000; thereafter a more market oriented, less regulated CAP is expected; and
- that by the year 2005/2006 the Central European Countries will have joined the EU.

Estimates on fertilizer consumption for the rest of Europe were derived from publications of the International Fertilizer Industry Association (Ginet, 1995). Since these forecasts do not always extend up to the year 2010, missing values were constructed based on a trend extrapolation.

Table 3.5: Projection of livestock up to the year 2010 (million animals)

	Cattle			Pigs			Poultry		
	1990	2010		1990	2010		1990	2010	
Austria	2.6	2.2	-15%	3.7	3.4	-7%	13.8	12.0	-13%
Belgium	3.1	2.8	-11%	6.4	7.2	12%	23.6	40.3	71%
Denmark	2.2	1.7	-23%	9.3	11.7	26%	16.2	17.4	7%
Finland	1.4	0.9	-33%	1.4	1.4	-2%	9.5	8.1	-14%
France	21.4	20.9	-3%	12.3	17.4	42%	271.7	317.3	17%
Germany	19.5	15.7	-19%	30.8	21.2	-31%	113.9	78.6	-31%
Greece	0.7	0.6	-20%	1.0	1.2	21%	27.7	33.0	19%
Ireland	7.0	7.4	6%	1.0	2.2	110%	9.0	13.2	46%
Italy	7.8	7.0	-11%	6.9	6.5	-7%	173.3	184.0	6%
Luxembourg	0.2	0.4	78%	0.1	0.1	-33%	0.1	0.1	-28%
Netherlands	4.9	4.8	-2%	13.9	11.2	-20%	93.8	79.5	-15%
Portugal	1.3	1.3	-2%	2.7	2.2	-17%	31.2	33.6	8%
Spain	5.1	6.0	17%	16.0	20.3	27%	44.9	83.1	85%
Sweden	1.7	1.8	5%	2.3	2.4	4%	12.6	12.6	0%
UK	12.1	10.4	-14%	7.5	7.8	5%	136.4	141.0	3%
EU-15	91.2	83.9	-8%	115.2	116.0	1%	978	1054	8%
Albania	0.6	0.8	21%	0.2	0.3	17%	5.0	8.4	68%
Belarus	7.2	4.3	-40%	5.2	4.0	-23%	49.8	43.3	-13%
Bosnia -H	0.9	0.7	-22%	0.6	0.6	-10%	9.0	8.0	-11%
Bulgaria	1.6	0.9	-41%	4.4	4.3	-2%	36.3	43.6	20%
Croatia	0.8	0.6	-27%	1.6	1.3	-17%	15.0	8.4	-44%
Czech Rep.	3.4	3.4	3%	4.6	5.8	26%	33.3	49.1	48%
Estonia	0.8	0.6	-28%	1.1	1.2	9%	7.0	7.8	11%
Hungary	1.6	1.6	-3%	9.7	7.9	-19%	58.6	63.5	8%
Latvia	1.5	0.7	-52%	1.6	1.5	-7%	11.0	7.6	-31%
Lithuania	2.4	2.2	-7%	2.7	2.8	2%	18.0	19.2	7%
Norway	1.0	0.7	-25%	0.7	0.8	10%	5.4	5.3	-2%
Poland	10.0	12.9	28%	19.5	23.8	22%	70.0	97.8	40%
R. Moldova	1.1	1.0	-13%	2.0	1.5	-27%	25.0	19.0	-24%
Romania	6.3	6.2	-2%	11.7	10.3	-12%	119.3	146.8	23%
Russia	42.2	27.3	-35%	30.5	30.5	0%	474.3	326.5	-31%
Slovakia	1.5	0.8	-44%	2.5	2.6	2%	16.5	22.0	34%
Slovenia	0.5	0.4	-22%	0.6	0.7	18%	13.5	12.9	-4%
Switzerland	1.9	1.7	-8%	1.8	1.4	-22%	6.5	6.5	0%
FYR Maced.	0.3	0.3	-1%	0.2	0.2	7%	22.0	22.0	0%
Ukraine	25.2	20.5	-19%	19.9	23.0	15%	255.1	260.0	2%
Yugoslavia	2.2	2.0	-8%	4.3	4.1	-5%	28.0	21.0	-25%
Non-EU	113.0	89.6	-21%	125.4	128.3	2%	1279	1199	-6%
Total	204.2	173.5	-15%	240.6	244.3	2%	2256	2253	-0%

Table 3.6: Projections of nitrogen fertilizer use (in 1000 tons N/year)

	Nitrogen fertilizer use		
	1990	2010	*Change*
Austria	137	109	*-20%*
Belgium	166	137	*-17%*
Denmark	395	261	*-34%*
Finland	228	180	*-21%*
France	2493	2457	*-1%*
Germany	2200	1801	*-18%*
Greece	428	294	*-31%*
Ireland	370	357	*-4%*
Italy	879	919	*5%*
Luxembourg	20	16	*-20%*
Netherlands	404	291	*-28%*
Portugal	150	144	*-4%*
Spain	1064	1052	*-1%*
Sweden	212	199	*-6%*
UK	1516	1298	*-14%*
EU-15	10662	9515	*-11 %*
Albania	73	60	*-18%*
Belarus	780	676	*-13%*
Bosnia -H	19	10	*-47%*
Bulgaria	453	530	*17%*
Croatia	114	190	*67%*
Czech Rep.	370	350	*-5%*
Estonia	110	151	*37%*
Hungary	359	639	*78%*
Latvia	143	221	*55%*
Lithuania	256	309	*21%*
Norway	111	92	*-17%*
Poland	671	855	*27%*
Moldova	123	228	*85%*
Romania	765	780	*2%*
Russia	3418	1994	*-42%*
Slovakia	217	180	*-17%*
Slovenia	88	103	*17%*
Switzerland	63	30	*-52%*
FYR Macedonia	6	3	*-50%*
Ukraine	1885	1599	*-15%*
Yugoslavia	146	145	*-1%*
Non-EU	10170	9145	*-10 %*
Total	20832	18660	*-10%*

3.4 Changes in the Database since the Fifth Interim Report

Since the Fifth Interim Report to the Commission a number of changes have been made to the database of the RAINS model. In addition to changes in the 1990 emission database used in RAINS (see 2.7.1.) the most important updates are as follows:

- Belgium, Germany, Greece and Ireland submitted officially national energy projections to the replace the 'Business as usual' scenario. Denmark and Netherlands decided to change their national scenarios, and Sweden proposed modifications to the previously submitted projection. All these changes were incorporated into the baseline energy scenario. Due to late submission and still unresolved issues, it was not possible to include the Italian projection in the analysis of this report.
- Austria, Belgium, Finland, France, Germany, Greece, Italy and the UK provided new country-specific parameters for the emission- and cost calculations and detailed information on the 'Current Legislation' scenario.
- The latest information on Current Reduction Plans provided by the UN/ECE secretariat (UN/ECE, 1998) was implemented in the database. As a consequence, the REF scenario was slightly changed.
- IIASA received comments on the SO_2, NO_x and VOC modules from Norway, the Czech Republic and Poland. These comments have been incorporated into the database for this report. However, some issues (e.g., unabated emission factors for mobile sources in the Czech Republic) remain unresolved.
- Based on Finnish data, the sulfur content of fuel wood has been revised for all countries where no specific information is available. For 1990, this modification reduced total European (including non-EU countries) SO_2 emissions by 60 kt, i.e., by 0.2 percent.
- Cost estimates for low sulfur heavy fuel oil were revised to reflect the information provided by CONCAWE (CONCAWE 1998).
- The RAINS abatement technology database for ammonia was extended to include the substitution of urea by ammonium nitrate fertilizers.
- Based on the comments provided by UK and French experts (AEA Technology, CITEPA), several parameters in the VOC module have been adjusted. This includes the introduction of additional sectors (e.g., splitting printing into four sub-categories). Further extensions and modifications of the control technology database (e.g., adjustment of abatement options for printing, paint use, vehicle refinishing, refineries; introduction of options for leather tanning, agrochemicals production and road paving with asphalt).
- A detailed inventory of consumer products (domestic solvent use) and emission abatement possibilities provided by AEA Technology (Passant and Vincent, 1998) improved the description of this sector in RAINS and helped to determine the reduction potential.
- Following Swedish comments, control options (new boilers and catalysts) for residential combustion boilers (VOC) were introduced.
- Information provided by CONCAWE on average throughput of gasoline stations in several European countries was taken into account to derive country-specific abatement costs.
- Detailed information on the present penetration of Stage II vapor recovery installations and current legislation on further introduction of these systems provided by CONCAWE improved RAINS databases.

- The RAINS databases were updated to incorporate the final reports of the UN/ECE Task Forces on Control Technologies for Stationary Sources (VOC, NO_x) (IFARE 1998a,b). This resulted in modifications of several parameters (reduction efficiencies, investment and operating costs) for various sectors (e.g., refineries, degreasing operations, printing, etc.).
- Emission factors and control strategies for Slovakia were updated to reflect latest national information.

A number of changes were introduced in the database since the Sixth Interim Report to the European Commission:

- A more precise technical interpretation of the outcome of the conciliation process of the Auto/Oil Programme between the European Parliament and the Council led to modifications in the CLE scenario for the EU-15 countries. As a consequence, the CLE scenario shows generally lower NO_x and VOC emissions and higher costs compared to the calculations presented in the Sixth Interim Report.
- For the non-EU countries, the REF scenario was changed to reflect the decisions taken at the UN/ECE Working Group on Strategies at their August 1998 session. Thereby, for non-EU countries, the CLE estimates are used as the starting point for the optimization.
- For Denmark, the assumptions about the applicability of NO_x control for gas fired power stations were modified to incorporate additional information on size distribution, boiler types, etc. provided by national experts.
- For Belgium, the applicability of some SO_2 and NO_x control technologies were modified to reflect findings of the recent assessments performed by Belgium experts.
- For Germany, the national energy scenario was updated with the latest projections on power capacity expansion.
- For Ireland, certain sectors omitted in the Irish CORINAIR'90 database were estimated in the RAINS emission inventory and subsequently included into the VOC cost curves.
- The VOC module for UK has been updated to account for the information provided by AEA Technology on manufacture, use and costs for paints.

4 The Current Legislation on Emission Controls in the European Countries

4.1 *Emission Control Measures Adopted by Current Legislation*

The Current Legislation (CLE) scenario explores the impacts of adopted national and international legislation for emission control, based on projections of future energy consumption.

For SO_2 and NO_x, the starting point for the analysis is a detailed inventory of regulations on emission controls, taking into account the legislation in the individual European countries, the relevant Directives of the European Union (in particular the Large Combustion Plant Directive - LCPD (OJ, 1988) and the directives on sulfur content of liquid fuels (gas oil - Johnson & Corcelle (1995), heavy fuel oil - COM(97)88, 1997)), as well as the obligatory clauses regarding emission standards from the protocols under the Convention on Long-range Transboundary Air Pollution. For instance, the Second Sulfur Protocol (UN/ECE, 1994b) requires emission control according to 'Best Available Technology' (BAT) for new plants. It also requires the reduction of the sulfur content in gas oil for stationary sources to 0.2 percent and to 0.05 percent if used as diesel fuel for road vehicles.

An inventory of national and international emission standards in Europe can be found in Bouscaren & Boucherau (1996). In addition, information on power plant emission standards has been taken from the survey of the IEA Coal Research (McConville, 1997). For countries of Central and Eastern Europe the environmental standards database developed by the Central European University (CEU, 1996) has also been used.

For the control of NO_x emissions from mobile sources, the scenario considers the implementation of the current UN/ECE legislation as well as country-specific standards if stricter. For the Member States of the European Union the current EU standards for new cars, light commercial vehicles and heavy duty vehicles (HDV) have been taken into account: the Directives 70/220/EEC as amended by 96/69/EC, and 88/77/EEC as amended by 96/1/EC; see McArragher (1994). Additionally, the scenario assumes for all EU countries after the year 2000 the implementation of the measures outlined in the Communication COM(96) 248 presenting the results and consequences from the Auto/Oil 1 programme. The agreement resulting from conciliation between Council and European Parliament on the envisaged legislation referred to by this Communication and the Commission's proposal on emissions from HDV (COM(97) 627) is also taken into account. This includes vehicle-related measures like improved catalytic converters, engine modifications and on-board diagnostic systems. Furthermore, the impacts of the envisaged improved inspection and maintenance practices and the changes in fuel quality are incorporated. The pace of the implementation of the vehicle-related measures depends on the turnover of vehicle stock and has been based on modeling work performed for the Auto/Oil 1 study.

SO_2 and NO_x control measures assumed in the 'Current Legislation' scenario in individual countries or groups of countries are specified in Table 4.1. to Table 4.6.

For VOC, the CLE scenario assumes for the EU countries the implementation of the Solvent Directive of the EU (COM(96)538) as proposed by the Commission. Furthermore, the obligations of the VOC Protocol of the Convention on Long-range Transboundary Air Pollution (UN/ECE, 1994d) were incorporated. For mobile sources, the measures pertaining to the regulations on carbon canisters of Directive 91/441/EEC complemented by the proposed amendment of Dir. 70/220 in the Auto/Oil 1 package are assumed to be fully implemented in the EU countries. Emissions from non-road mobile machinery engines are subject to Directive 97/68/EC. It was further assumed that VOC emissions from gasoline distribution will be controlled through the Stage-I measures in all the EU countries (reflecting the Directive 94/63/EC). Additionally, Stage-II controls were assumed for several countries (Table 4.6).

Table 4.1: Measures assumed for the 'Current Legislation' (CLE) scenario for SO_2 emissions in EU countries

Stationary and mobile sources:

- Emission standards for new plant from the Large Combustion Plant Directive - LCPD (OJ, 1988) and from the Second Sulfur Protocol (UN/ECE, 1994a) also taking into account a proposal for a revision of the LCPD adopted by the Commission on 8.7.98 (COM(98) 415 final.
- Limits on sulfur content of gas oil for stationary and mobile sources and for heavy fuel oil as in the appropriate directives (Johnson & Corcelle, 1995, COM(97)88, 1997)
- National emission standards on stationary sources if stricter than the international standards..

Table 4.2: Measures assumed for the 'Current Legislation' (CLE) scenario for SO_2 emissions in the non-EU countries

Stationary and mobile sources:

Signatories of the Second Sulfur Protocol (Bulgaria, Croatia, Czech Republic, Hungary, Norway, Poland, Russian Federation, Slovak Republic, Slovenia, Switzerland, Ukraine) - New plant emission standards and limits on the sulfur content of gas oil for stationary and mobile sources as in the Protocol.

Czech Republic, Croatia, Norway, Poland, Slovak Republic, Slovenia, Switzerland, Romania, F. Yugoslavia - national emission standards on existing and new plant

Other countries in Central and Eastern Europe – no control

Table 4.3: Measures assumed for the 'Current Legislation' (CLE) scenario for NO_x emissions in the countries of the European Union

Stationary sources:

- Emission standards for new plant and emission ceilings for existing plant from the Large Combustion Plant Directive - LCPD (OJ, 1988). These standards require implementation of primary emission measures (combustion modification) on large boilers in the power plant sector and in industry.) A proposal for a revision of the LCPD adopted by the Commission on 8.7.98 (COM(98) 415 final is also taken into account.
- National emission standards on stationary sources – if stricter than in the LCPD.

Mobile sources:

- EU standards for cars and light commercial vehicles (LCV) (Directive 70/220/EC du Conseil, du 20 mars 1970, concernant le rapprochement des législations des États membres relatives au mesures à prendre contre la pollution de l'air par les gaz provenant des moteurs à allumage commandé équipant les véhicules à moteur, OJ 76, 6.4.70, p. 1, as amended by 96/69/EC, OJ L 282, 1.11.96, p. 1)
- EU standards for heavy duty vehicles (HDV) according to Council Directive 88/77/EC of 3 December 1987 on the approximation of the laws of the Member States relating to the measures to be taken against the emission of gaseous pollutants from diesel engines for use in vehicles, OJ L 36, 9.2.88, p. 33, as amended by 96/1/EC, OJ L 40, 17.2.96
- EU standards for non-road machinery engines (Directive 97/68/EC of the European Parliament and the Council of 16 December 1997 on the approximation of laws of the Member States relating to measures against the emissions of gaseous and particulate pollutants from internal combustion engines to be installed in non-road mobile machinery, OJ L 59, 27.2.98, p. 1-85, as well as for mopeds and motorcycles (Directive 97/24/EC of the European Parliament and the Council of 17 June 1997 on certain components and characteristics of tow or three-wheel motor vehicles, OJ L 226, 18.8.97, p. 1)
- From 2000 - fuel quality and emission standards (for LDV, LCV, HDV) and improved inspection/maintenance, as resulting from the Auto/Oil Programme (Communication from the Commission to the European Parliament and the Council on a future strategy for the control of atmospheric emissions from road transport taking into account the results from the Auto/Oil Programme (COM(96) 248, 18.6.1996), amended by the agreement resulting from conciliation between Council and European Parliament related to LDV, LCV, fuels (PE-CONS 3619/98, PE-CONS 3620/98) and by COM(97) 627, 3.12.97, on HDV-emissions.

Table 4.4: Measures assumed for the 'Current Legislation' (CLE) scenario for the control of NO_x emissions in the non-EU countries

Stationary sources:

- Czech Republic, Croatia, Hungary, Norway, Poland, Slovak Republic, Slovenia, Switzerland, Romania, Yugoslavia – controls according to national emission standards on new and existing sources
- Other countries in Central and Eastern Europe – no control[21]

Mobile sources:

- Czech Republic, Hungary, Poland, Slovak Republic, Slovenia - National mobile source standards comparable with 1992 and 1996 standards for the EU (requirement for catalytic converters for gasoline engines and combustion modifications on diesel engines)
- Other CEE countries - pre-1990 UN/ECE standards on mobile sources (no requirement for catalytic converters for gasoline engines and for combustion modifications on diesel engines)
- Norway and Switzerland - standards identical with those for the EU countries (see previous table)

Table 4.5: Measures assumed for the 'Current Legislation' (CLE) scenario for VOC emissions for EU countries

Stationary sources:

- Emission ceilings and standards from the Solvent Directive (Proposal for a Council Directive on limitation of emissions of volatile organic compounds due to the use of organic solvents in certain industrial activities (COM(96) 538, 6.11.96)
- Stage I controls on gasoline storage and distribution - European Parliament and Council Directive 94/63/EC of 20 December 1994 on the control of volatile organic compound (VOC) emissions resulting from the storage of petrol and its distribution from terminals to service stations, OJ L 365, 31.12.94, p. 24 (EC, 1994)
- Stage II according to existing legislation in Austria, Belgium, Denmark, Germany, Italy, Luxembourg, Netherlands and Sweden.

Mobile sources:

- All directives and legislation acts aimed at a reduction of emissions from mobile sources mentioned for NO_x also apply to NMVOC
- Passenger cars - small canister according to the Council Directive 91/441/EEC of 26 June 1991 amending directive 70/220/CEE on the approximation of the laws of the Member States relating to measures to be taken against air pollution by emissions from motor vehicles, OJ L 242, 30.8.91, p. 1 - 6 (EC, 1991)

---

[21] Because measures depending on implementation of primary NO_x reduction measures on new power plants are state-of-the-art technology, such controls were assumed by default in all countries.

Table 4.6: Measures assumed for the 'Current Legislation' (CLE) scenario for VOC emissions for non-EU countries

Stationary sources:

- National legislation for solvent use and gasoline storage and distribution (Stage I and Stage II) in Norway and Switzerland.

Mobile sources:

- All directives and legislation acts aimed at a reduction of emissions from mobile sources mentioned for NO_x also apply to NMVOC (see Table 4.4).
- Introduction of small carbon canisters in Norway and Switzerland consistent with the Council Directive 91/441/EEC.
- For Czech Republic, Hungary, Poland, Slovakia and Slovenia it is assumed that in the year 2010 part of the fleet will be equipped with small carbon canisters following the EU Council Directive 91/441/EEC.

4.2 Emissions Projected for the 'Current Legislation' (CLE) Scenario

For constructing the CLE scenario, the emission control measures listed above were combined with the level of energy consumption as projected by the 'Baseline' energy scenario for the year 2010. Table 4.7 and Table 4.8 compare the emission estimates for the year 1990 with the CLE scenarios. For all of Europe, total SO_2 emissions are 61 percent below 1990 level (-69 percent for the EU countries). NO_x is projected to decline by 34 percent (-43 percent in the EU), and VOC emissions by 35 percent. Ammonia would be 24 percent below the 1990 levels (see Table 4.7 and Table 4.8).

Table 4.7: NO$_x$ and VOC emissions of the Current Legislation (CLE) scenario for the year 2010 compared with the values for 1990 (RAINS estimates) and Current Reduction Plans (CRP), in kilotons.

	NO$_x$ (kt)			VOC (kt)		
	1990	CRP	CLE	1990	CRP	CLE
Austria	192	154	110	352	266	206
Belgium	351	309	199	374	256	195
Denmark	274	192	131	182	136	86
Finland	276	224	159	213	150	111
France	1867	1276	1017	2423	1683	1256
Germany	2662	1256	1256	3100	1100	1123
Greece	345	344	426	336	293	268
Ireland	113	105	73	110	138	55
Italy	2037	2060	1166	2055	1749	1166
Luxembourg	22	19	10	19	13	7
Netherlands	542	327	304	490	247	237
Portugal	208	221	181	212	144	164
Spain	1162	892	866	1008	669	699
Sweden	338	200	195	492	290	283
United Kingdom	2839	1186	1385	2667	1351	1638
EU-15	13226	8766	7478	14032	8484	7494
Albania	24		36	31		41
Belarus	402		316	371		309
Bosnia-H.	80		60	51		48
Bulgaria	355		297	195		190
Croatia	82		91	103		111
Czech Rep.	546		296	442		367
Estonia	84		73	45		49
Hungary	219		198	204		174
Latvia	117		118	63		56
Lithuania	153		138	111		105
Norway	220		183	297		302
Poland	1217		879	797		807
Moldova	87		66	50		42
Romania	518		458	503		504
Russia	3486		2798	3542		2787
Slovakia	219		132	151		140
Slovenia	60		36	55		40
Switzerland	163		85	278		145
FYR Macedonia	39		29	19		19
Ukraine	1888		1433	1161		851
Yugoslavia	211		152	142		139
Non-EU	10170		7873	8609		7226
Total	23396		15351	22641		14719

Table 4.8: SO_2 and NH_3 emissions of the Current Legislation (CLE) scenario for the year 2010 compared with the values for 1990 (RAINS estimates) and Current Reduction Plans (CRP), in kilotons.

	SO_2 (kt)			NH_3 (kt)		
	1990	CRP	CLE	1990	CRP	CLE
Austria	93	60	42	77	77	67
Belgium	336	215	208	97	104	96
Denmark	182	90	97	77	103	72
Finland	232	116	124	40	34	31
France	1250	737	489	805	807	798
Germany	5280	661	661	757	306	571
Greece	504	570	562	80	78	74
Ireland	178	155	70	127	126	130
Italy	1679	1042	593	462	416	432
Luxembourg	14	4	9	7	6	9
Netherlands	201	98	74	233	136	196
Portugal	284	294	146	71	93	67
Spain	2189	2143	793	352	353	383
Sweden	119	67	69	61	48	61
United Kingdom	3805	980	1099	329	333	297
EU-15	16345	7232	5035	3576	3020	3283
Albania	72		55	32		35
Belarus	843		494	219		163
Bosnia-H.	487		415	31		23
Bulgaria	1842		846	141		126
Croatia	180		70	40		37
Czech Rep.	1873		366	107		108
Estonia	275		175	29		29
Hungary	913		546	120		137
Latvia	121		104	43		35
Lithuania	213		107	80		81
Norway	52		33	23		21
Poland	3001		1525	505		541
Moldova	197		117	47		48
Romania	1331		594	292		304
Russia	5012		2344	1282		894
Slovakia	548		137	60		47
Slovenia	200		76	23		21
Switzerland	43		36	72		66
FYR Macedonia	107		81	17		16
Ukraine	3706		1488	729		649
Yugoslavia	585		269	90		82
Non-EU	21599		9877	3980		3462
Total	37944		14912	7556		6745

5 References

Alcamo J. (1987*) Uncertainty of Forecasted Sulfur Deposition Due to Uncertain Spatial Distribution of SO_2 Emissions.* Preprints of the 16th NATO/CCMS International Technical Meeting on Air Pollution Modelling and Its Application, Lindau, FRG.

Alcamo J., Shaw R., and Hordijk L. (eds.) (1990) *The RAINS Model of Acidification.* Science and Strategies in Europe. Kluwer Academic Publishers,. Dordrecht, The Netherlands

Allemand, N., R. Bouscaren, D. Heslinga, I. Marlowe, C.J. Potter, M. Woodfield, K. H. Zierock (1990) *A Costed Evaluation of Options for the Reduction of Photochemical Oxidant Precursors, Volume 2. - Abatement Technology and Associated Costs*. Report No. EUR 12537/II EN, Commission of the European Communities, Brussels - Luxembourg.

Amann M, Klaassen G. (1995). *Cost-effective Strategies for Reducing Nitrogen Deposition in Europe*. *Journal of Environmental Management* (1995) **43**, 289-311

Amann M. (1990) *Energy Use, Emissions and Abatement Costs.* [in:] Alcamo J., Shaw R., and Hordijk L. (eds.) (1990) *The RAINS Model of Acidification.* Science and Strategies in Europe. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Amann M., Bertok I., Cofala J., Gyarfas F., Heyes C., Klimont Z., Makowski M., Shibayev S., Schöpp W., Syri S. (1998) *Cost-effective Control of Acidification and Ground-level Ozone*. Fourth Interim Report to the Commission DG-XI. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

ApSimon, H.M. [ed] (1994) *The Potential for Abatement of Ammonia Emissions from Agriculture and the Associated Costs.* Workshop at Culham Laboratory, 31 October - 2 November 1994

Barret K., Sandnes H. (1996) *Transboundary Acidifying Air Pollution calculated transport and exchange across Europe, 1985-1995.* In: Barret K., Berge E. (eds.) Transboundary Air Pollution in Europe. MSC-W Status Report 1996, Meteorological Sythesizing Centre - West, Norwegian Meteorological Institute, Oslo, Norway.

Barrett M. (1996) *Characteristics of Technological Emission Control Options from the Auto/Oil Program in the RAINS Format*. Pollen, Colchester, UK.

Bertok I., Cofala J., Klimont Z., Schöpp W., Amann M. (1993) Structure of the RAINS 7.0 Energy and Emissions Database. WP-93-67, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Bouscaren R., Bouchereau, J.M., 1996, Review of Strategies and Policies Developed in European Union and East and Central Europe to Prevent Acidification and Tropospheric Ozone Formation. Report CITEPA/IIASA – 348. Centre Interprofessionnel Technique d'Etudes de la Pollution Atmospherique, Paris, France.

Bouscaren, R., N. Allemand, W. F. J. M. Engelhard, S. C. Wallin, K.-H. Zierock (1988) *Volatile Organic Compounds and Nitrogen Oxides - Cost Effectiveness of Measures Designed to Reduce the Emissions of Precursors of Photochemical Oxidants, Phase 1 - Final Report*. Commission of the European Communities, Report No. EUR 11856 EN, May 1988.

Capros P. and Kokkolakis K. (1996) *CO_2-10% Target Scenario 1990-2010 for the European Union: Results from the Midas Model.* Report to the European Commission DG-XI, National Technical University Athens, Greece.

Capros *et al.*, 1997, Business as Usual Energy Scenario for EU-15. National Technical University of Athens (NTUA), Athens, Greece.

Cofala J., Kurz R., Amann M. (1997) *Application of the Current EU Air Emissions Standards to the Central and Eastern European Countries - An Integrated Assessment of the Environmental Effects*. Draft Final Report to the European Environmental Agency (EEA). IIASA, Laxenburg, Austria, July 1997

Cofala J., Syri S. (1998b). *Sulfur emissions abatement technologies and related costs for Europe in the RAINS model database.* IR-98-35, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

Cofala J., Syri S. (1998b). *Nitrogen oxides emissions abatement technologies and related costs for Europe in the RAINS model database.* IR-98-88, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

COM(97) 88. , 1997. Council Conclusions on a Community Strategy to Combat Acidification. The Council of the European Union.

CONCAWE (1988) *The control of vehicle evaporative and refuelling emissions - the "on-board" system.* Report no. 88/62. The Hague, November 1988.

CONCAWE (1990) *Closing the Gasoline System - Control of Gasoline Emissions from the Distribution System and Vehicles*. Report No. 3/90, CONCAWE, Brussels.

CONCAWE (1993) *The European Environmental and Refining Implications of Reducing the sulphur Content of Marine Bunker Fuels.* Report No. 1/93, CONCAWE, Brussels.

CONCAWE (1998) COCAWE's view on the Additional Costs for Producing HFO at 0.6%. File Note, July 2, 1998, Brussels

Davidson, I. (1996). Personal communication. UK Ministry of Agriculture, Food and Forestry , London. November 1996.

de Leeuw F., van Zantvoort E. (1997) Exceedance of Ozone Threshold Values in the European Community in 1996. XI/581/87 Report to the Commission by the European Environment Agency, National Institute for Public Health and the Environment, Bilthoven, The Netherlands.

de Smet P.A.M., Slootweg J., Posch M. (1997) The European Background Database for Critical loads. In: Posch, M., J.-P. Hettelingh , P.A.M. de Smet, and R.J. Downing (eds.) (1997) *Calculation and mapping of critical thresholds in Europe*. Status Report 1997, Coordination Center for Effects, RIVM, Bilthoven, The Netherlands.

DG XVII (1996) *Energy in Europe: European Energy to 2020 - A Scenario Approach*. Directorate General for Energy (DG-XVII), European Commission, Brussels, Belgium

EC DG VI (European Commission Directorate-General for Agriculture) (1995a). Agricultural Situation and Prospects in the Central and Eastern European Countries - Summary Report. EC DG VI Working Document. Brussels.

EC DG VI (European Commission Directorate-General for Agriculture) (1995b). Agricultural Situation and Prospects in the Central and Eastern European Countries - Bulgaria. vol. I and II (Annexes), EC DG VI Working Document. Brussels.

EC DG VI (European Commission Directorate-General for Agriculture) (1995c). Agricultural Situation and Prospects in the Central and Eastern European Countries - Czech Republic. EC DG VI Working Document. Brussels.

EC DG VI (European Commission Directorate-General for Agriculture) (1995d). Agricultural Situation and Prospects in the Central and Eastern European Countries - Hungary. EC DG VI Working Document. Brussels.

EC DG VI (European Commission Directorate-General for Agriculture) (1995e). Agricultural Situation and Prospects in the Central and Eastern European Countries - Poland. EC DG VI Working Document. Brussels.

EC DG VI (European Commission Directorate-General for Agriculture) (1995f). Agricultural Situation and Prospects in the Central and Eastern European Countries -Romania. EC DG VI Working Document. Brussels.

EC DG VI (European Commission Directorate-General for Agriculture) (1995g). Agricultural Situation and Prospects in the Central and Eastern European Countries - Slovak Republic. EC DG VI Working Document. Brussels.

EC DG VI (European Commission Directorate-General for Agriculture) (1995h). Agricultural Situation and Prospects in the Central and Eastern European Countries - Slovenia. EC DG VI Working Document. Brussels.

EC DG VI (European Commission Directorate-General for Agriculture) (1995i). Agricultural Situation and Prospects in the Central and Eastern European Countries - Estonia. EC DG VI Working Document. Brussels.

EC DG VI (European Commission Directorate-General for Agriculture) (1995j). Agricultural Situation and Prospects in the Central and Eastern European Countries - Latvia. EC DG VI Working Document. Brussels.

EC DG VI (European Commission Directorate-General for Agriculture) (1995k). Agricultural Situation and Prospects in the Central and Eastern European Countries - Lithuania. EC DG VI Working Document. Brussels

EC, 1991, Council Directive of 26 June 1991 amending the Directive 70/220/EEC on the Approximation of the Laws of the Member States relating to Measures to be Taken Against Air Pollution by Emissions from Motor Vehicles (91/441/EC) Official Journal of the European Communities. OJ No. L242/1.

EC, 1994, European Parliament and Council Directive 94/63/EC of 20 December 1994 on the Control of Volatile Organic Compound (VOC) Emissions Resulting from the Storage of Petrol and its Distribution from Terminals to Service Stations. Official Journal of the European Communities. OJ No. L365/24.

EC (European Commission) (1996a) The European Auto Oil Programme. A report by the Directorate Generals for: Industry;Energy; and Environment, Civil Protection & Nuclear Sfety of the European Commission. XI 361/96. Brussels, Belgium.

EC (1996b) *Communication to the Council and to the Parliament on a Future Strategy for the Control of Atmospheric Emissions from Road Transport Taking into Account the Results from the Auto Oil Program*. COM(96) 248, 1996. Brussels, Belgium.

ECETOC (European Centre for Ecotoxicology and Toxicology of Chemicals) (1994) *Ammonia Emissions to Air in Western Europe*. Technical Report No. 62. Brussels, July 1994.

EEA (European Environmental Agency) (1996). *Joint EMEP/CORINAIR'90 Atmospheric Emission Inventory Guidebook, First Edition*. Vol.1-2. Copenhagen, Denmark.

EEC (Economic Commission for Europe VOC Task Force) (1990) *Emissions of Volatile Organic Compounds (VOC) from Stationary Sources and Possibilities of their Control.* Karlsruhe, July 1990.

EFMA (European Fertilizer Manufacturers Association) (1996a). Forecast for the Development of Mineral Fertilizer Consumption in Western Europe until the Year 2005/06. EFMA Agro-Economic Task-Force, September 1996.

EFMA (European Fertilizer Manufacturers Association) (1996b). Agriculture and Fertilizer Consumption in EFMA Countries (moderate grain price scenario). Zurich, July 16, 1996.

EMEP, 1997, Transboundary Air Pollution in Europe, Part 1. EMEP MSC-W report 1/97, Oslo, Norway.

EPA (U.S. Environmental Protection Agency) (1994) *Control Techniques for Volatile Organic Compound Emissions from Stationary Sources.*

ERM Economics (1996) *Costs and Benefits of the Reduction of VOC Emissions from Industry*. ERM Economics, CHEM Systems, London, May 1996

Folmer, C., Keyzer, M.A, Merbis, M.D., Stolwijk, H.J.J., and Veenendaal, P.J.J. (1995). The Common Agricultural Policy beyond the MacSharry Reform. North-Holland, Contributions to Economic Analysis: 230. Amsterdam, Elsevier Science.

Foster, F. O., R. H. Lilie, W. G. Roberts, G. A. van Ophem (1987) *Cost-Effectiveness of Hydrocarbon Emission Controls in Refineries from Crude Oil Receipt to Product Dispatch.* Report No. 87/52, CONCAWE, Den Haag, January 1987.

Ginet, H. (1995). Personal communication. International Fertilizer Industry Association, Paris. December 1995.

Gorißen N. (1992) *Entwicklung der Kfz-Schadstoffemissionen - Erfordernisse und Möglichkeiten zur Minderung.* Paper presented at the Colloquium "Environmental Protection in Cities", Dresden, 20-22. 05. 1992.

Haan de, M.H.A, Ogink, N.W.M. (1994) *Naar veehouderij en milieu in balans. 10 jaar FOMA onderzoek. Onderzoek inzake de mest- en ammoniakproblematik in de veehouderij. Rundvee.* Report, Financierings Overleg Mest- en Ammoniakonderzoek (FOMA), Ede, 4 October, 1994, The Netherlands. [in Dutch]

Hartog den, L.A., Voermans, J.A.M. (1994) *Naar veehouderij en milieu in balans. 10 jaar FOMA onderzoek. Onderzoek inzake de mest- en ammoniakproblematik in de veehouderij. Varkens.* Report, Financierings Overleg Mest- en Ammoniakonderzoek (FOMA), Ede, The Netherlands. [in Dutch]

Hein, J., Kippeln, C, Schultmannn, F., Rentz, O. (1994) *Assessment of the cost involved with the Commission's draft proposal for a Directive on the limitation of the organic solvent emissions from the industrial sectors.* Final Report: Appendix. Karlsruhe, August 1994.

Henriksson, M. (1996). Personal communication. Swedish Environmental Protection Agency, Stockholm, Sweden.

Hettelingh J.-P., Posch M., de Smet P., Downing R.J. (1995) *The use of critical loads for emission reduction agreements in Europe.* Water, Air and Soil Pollution **85**:2381-2388

HMSO (1994) Royal Commission on Transport and Environmental Pollution. *Eighteenth Report: Transport and the Environment*. HMSO, London, UK.

Holwerda, D., F. Ingelaat, G. Kolkman, L. Westerlaken (1995) *Kwantitatieve informatie veehouderij 1995-1996.* Informatie en Kennis Centrum Landbouw, Ede, Juli 1995, The Netherlands. [in Dutch]

IFARE (1998a,b) Task Force on the Assessment of Abatement Options/Techniques for Volatile Organic Compounds from Stationary Sources (Version April 1998). French-German Institute for Environmental Research, University of Karlruhe, Germany.

ILO (International Labor Organization) (1995) YearBook of Labor Statistics 1995. Geneva, Switzerland.

IMF (International Monetary Fund) (1995) International Financial Statistics Yearbook 1995. Washington D.C. USA.

Johnson S. and Corcelle G. (1995) *The Environmental Policy of the European Communities*. 2nd Edition. Kluwer Law International, London - The Hague.

Jourdan, M., Rentz, O. (1991) *Reduction of Volatile Organic Compounds from Dry Cleaning Facilities*. Reprt to the CEC, DG XI. Final Report, Karlsruhe, November 1991.

Kärenlampi L., Skarby L., (eds), 1996. Critical levels for Ozone in Europe: Testing and Finalizing the Concepts. UN-ECE Workshop Report. University of Kuopio, Dept. of Ecology and Environmental Science.

Klaassen, G. (1991a) Past and Future Emissions of Ammonia in Europe. Report SR-91-01, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, March 1991.

Klaassen, G. (1991b) Costs of Controlling Ammonia Emissions in Europe. Report SR-91-02, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, April 1991.

Klaassen, G. (1995) Personal communication. IIASA, Laxenburg, Austria

Klimont Z., Amann M., Cofala J. (1998) Estimating Costs for Controlling Emissions of Volatile Organic Compounds (VOC) from Stationary Sources in Europe. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

Klokk, N., S. (1995) *Measures for Reducing NO_x Emissions from Ships*. In: Proceedings of the Workshop on 'Control technology for Emissions from Off-road Mobile Sources'. Oslo, 8 –9 June 1995, Oslo, Norway.

KWS 2000 (1989) *Control Strategy for Emissions of Volatile Organic Compounds.* Project Group Hydrocarbons 2000. Ministry of Housing, Physical Planning and Environment. The Hague, February 1989

KWS 2000 (1993) *Strategie 1992-2000.* Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer. [in Dutch]

KWS 2000 (1997) *Annual Report 1995*. InfoMil, Den Haag, March 1997

Mackowski J.M. (1998) Personal communication.

Martilla, J. (1995). Personal communication. Agricultural Economics Research Institute (MTTL), Helsinki, Finland.

McArragher *et al.* (1994) *Motor Vehicle Emission Regulations and Fuel Specifications.* 1994 Update. CONCAWE, Report No. 4/94, Brussels, Belgium.

McArragher, J. S. *et. al* (1987) *An Investigation Into Evaporative Hydrocarbon Emissions from European Vehicles*. Report No. 87/60, CONCAWE, The Hague.

McConville, A., 1997. *Emission standards handbook* 1996: Air Pollutant Standards for Coal-Fired Plants. IEA Coal Research, London., UK.

Menzi, H. (1995). Personal communication. Swiss Federal Research Station for Agricultural Chemistry and Hygiene of Environment. Liebefeld-Bern, Switzerland. October 1995.

Menzi, H., Frick, R, Kaufmann, R. (1997) *Ammoniak-Emissionen in der Schweiz: Ausmass und technische Beurteilung des Reduktionspotentials.* Schiftenreihe der FAL 26.

Eidgenössiche Forschungsanstalt für Agragökologie und Landbau, Zürich-Reckenholz, Institut für Umwelschutz und Landwirtschaft, Liebefeld-Bern. [in German]

Münch, J., Axenfeld, F. (1995) *Ergänzende Berechnung der Ammoniak-Emissionen aus der Tierhaltung in Baden-Württemberg für 1991 und 1994 nach Vorgaben des MLR.* Dornier GmbH, Umwelt-und Reigionalplanung, Fredrichshafen. December, 1995. [in German]

OECD (1993) *Advanced Emission Controls for Power Plants*. OECD Documents, OECD, Paris, France.

OECD (Organization for Economic Co-operation and Development) (1990) *Emissions of Volatile Organic Compounds from Solvents Usage Operations.* Environment monographs No. 23. Paris, August 1990

OECD (Organization for Economic Co-operation and Development) (1992) *Emission Control for Nitrogen Oxides and Volatile Organic Compounds - Technology and Costs Compendium.* Environment monographs No. 22. Paris, January, 1992

OECD (Organisation for Economic Co-operation and Development) (1995). Agricultural Policies, Markets and Trade in the Central and Eastern European Countries, Selected New Independent States, Mongolia and China - Monitoring and Outlook 1995. OECD, Paris.

OJ (1988) *Council Directive of November 1988 on Limitation of Emissions of Certain Pollutants in the Air from Large Combustion Plants*. Official Journal of the European Communities, L336, Volume 31, 7 December 1988, pp.1-13.

OJ 97/C 351/01 (1997a) Common Position (EC) No 39/97 adopted by the council on 7 October 1997 with a view to adopting Directive 97/…/EC of the European Parliament and of the Council relating to the quality of petrol and diesel fuels and amending Council Directive 93/12/EEC. Official Journal of the European Communities, Brussels, Belgium.

OJ 97/C 351/02 (1997b) Common Position (EC) No 40/97 adopted by the council on 7 October 1997 with a view to adopting Directive 97/…/EC of the European Parliament and of the Council relating to measures to be taken against air pollution by emissions from motor vehicles and amending Council Directive 70/220/EEC. Official Journal of the European Communities, Brussels, Belgium.

Oudart B., Bouscaren R., Allemand N. (1998) Review of Input Date of the RAINS Model Cost Module. CITEPA/398, CITEPA, Paris, France.

Passant, N. R. (1993) Emissions of Volatile Organic Compounds from Stationary Sources in the UK. Warren Spring Laboratory LR990. Stevenage, December 1993

Passant N., Vincent K. (1998) Review of the Efficiency and Cost of Control Measures for Sulphur Dioxide and Volatile Organic Compounds, AEAT-3851, AEA Technology Culham, UK

Passant N et al. (1998) Review of IIASA Cost Curves for the Reduction of Emissions of Nitrogen Oxides, Sulfur Dioxide, Ammonia and Volatile Organic Compounds. AEAT-2941, AEA Technology Culham, UK

Pipatti, R. (1996). Personal communication. VTT Energy, Energy and Power Systems, Espoo, Finland.

Posch, M., J.-P. Hettelingh , P.A.M. de Smet, and R.J. Downing (eds.) (1997) *Calculation and mapping of critical thresholds in Europe*. Status Report 1997, Coordination Center for Effects, RIVM, Bilthoven, The Netherlands.

Posch, M., P.A.M. de Smet, J.-P. Hettelingh and R.J. Downing (eds.) (1995) *Calculation and mapping of critical thresholds in Europe.* Status Report 1995, Coordination Center for Effects, RIVM, Bilthoven, The Netherlands, 198 pp.

Rentz O., Remmers J., Plinke E. (eds.) (1987*): Proceedings of the Workshop on Emission Control costs*, 28.09-01.10. 1987, Esslingen am Neckar, Germany. Executive Body for the Convention on Long-range Transboundary Air Pollution, Institute for Industrial Production (IIP) University of Karlsruhe, Karlsruhe, Germany.

Rentz O., Haasis H.-D., Jattke A., Russ P., Wietschel M., Amann M. (1994) *Influence of Energy Supply Structure on Emission Reduction Costs*. Energy **19**(6), pp. 641-651

Rentz O., Röll C., Oertel D., Holtman T., Hein J., Karl U. (1993) *Minderung der VOC-Emissionen in der Bundesrepublik Deutschland.* UBA-FB 104 04 167, May 1993. [in German]

Rentz O., Schleef, H-J., Dorn R., Sasse H., Karl U. (1996) Emission Control at Stationary Sources in the Federal Republic of Germany. Vol. I: Sulphur Oxide and Nitrogen Oxide Emission Control. French – German Institute for Environmental Resaearch University of Karlsruhe (TH). Karlsruhe, Germany.

Riseth, O. (1990) Personal communication. Norsk Institutt for Landbruksøkonomisk Forskning (NILF), Oslo, Norway. October 1990.

Rodt S. *et al.* (1995) *Passenger Cars 2000. Requirements, Technical Feasibility and Costs of Exhaust Emission Standards for the Year 2000 in the European Community*. Federal Environmental Agency (UBA), Berlin, Germany.

Rodt *et al*. (1996) *HDV 2000. Requirements, Technical Feasibility and Costs of Exhaust Emission Standards for Heavy Duty Vehicle Engines For the Year 2000 in the European Community.* Federal Environmental Agency (UBA), Berlin, Germany.

Ryboshapko A.G. et al. (1996) Anthropogenic Emissions of Oxidized Sulfur and Nitrogen into the Atmosphere of the Former Soviet Union in 1985 and 1990. Report No. CM-89. Department of Meteorology, Stockholm University, International Meteorological Institute in Stockholm, Stockholm, Sweden.

Schärer B. (1993) *Technologies to Clean up Power Plants. Experience with a 21 billion DM FGD and SCR Retrofit Program in Germany*. Part 1 and 2. *Staub - Reinhaltung der Luft* 53 (1993) 87-92 , 157-160.

Schürmann (1994) *Study on the Detailed Methodology of the Determination of VOC-Emissions in Gasoline Distribution (DRAFT).* Weyer Verfahrenstechnik, Basel, Switzerland. December 19, 1994. Study on request of Federal Office of Environment, Forests and Landscape, Section Air Pollution Control, Bern, Switzerland.

Shah R.W., Amann M. (1990) *Effect of Uncertainty on Source-Receptor Relationships on Transboundary Air Pollution Control Strategies*. In: J. Fenhann *et al*. (eds.) Environmental Models, Emissions and Consequences, Elsevier Science Publishers, Amsterdam, The Netherlands

Selvig E., (1997) Comments to preliminary results for Norway from the RAINS model and ship abating measures for nitrogen oxides emissions. Norwegian Pollution Control Authority, Oslo, Norway (unpublished)

Simpson, D. (1992) *Long period modelling of photochemical oxidants in Europe : A) hydrocarbon reactivity and ozone formation in Europe. B) On the linearity of country-to-country ozone calculations in Europe*. EMEP MSC-W Note 1/92, Norwegian Meteorological Institute, Oslo, Norway.

Simpson, D. (1993) Photochemical model calculations over Europe for two extended summer periods : 1985 and 1989. Model calculations and comparison with observations. *Atmos. Environ*., **27A**, No. 6, pp. 921-943.

Sluyter R., van Zantvoort E. (1997) *Overview of the Situation in the European Union during the 1997 Summer Season.* XI/593/87 Report to the Commission by the European Environment Agency, National Institute for Public Health and the Environment, Bilthoven, The Netherlands.

Stolwijk, H. (1996) Personal communication. Centraal Planbureau, Den Haag, The Netherlands.

Tajthy T., Tar M. (1997) *Formation of ammonia emissions in Hungary*. Report 717-08-1441/96. Environmental Protection Institute, Budapest, Dec. 1997 (in Hungarian).

Takeshita, M. (1995) *Air Pollution Control Costs for Coal-Fired Power Stations*, IEAPER/17, IEA Coal Research, London, UK.

Tangena, B. (1985) *Optimalisatie bestrijding verzurende emissies,* [Optimization of abating acidifying emissions, in Dutch], Ministerie van Volkshuisvesting, Ruimtelijke ordening en Milieubeheer, Leidschendam, The Netherlands.

Technica (1984) *Optimization of abatement of acidyfying emissions.* Technica consulting scientist and engineers, London, UK.

Touche Ross & Co. (1995) *A Cost-Effectiveness Study of the Various Measures Likely to Reduce Pollutant Emissions from Road Vehicles for the Year 2010*. Final Report. Edinburgh, UK.

UBA (Umweltbundesamt) (1993). Ammoniak - Emissionen in Österreich 1990. Berechnung und Abschätzung sowie Regionalisierung auf Basis politischer Bezirke. UBA-92-068. Bindesministerium für Umwelt, Jugend und Familie, Wien, January 1993. [in German]

UBA (1996) *Manual on Methodologies for Mapping Critical Loads/Levels and Geographical Areas where they are exceeded* (final draft). Umweltbundesamt, Berlin, Germany.

UN/ECE (1988) *Protocol to the 1979 Convention on Long-Range Transboundary Air Pollution Concerning the Control of Emissions of Nitrogen Oxides or their Transboundary Fluxes.* Depositary Notification C.N.252.1988. Treaties-1 of 6 December 1988.United Nations, Economic Commission for Europe, Geneva., Switzerland.

UN/ECE (1994a) *Protocol to the 1979 Convention on Long-Range Transboundary Air Pollution on Further Reduction of Sulphur Emissions*. Document ECE/EB.AIR/40, United Nations, Economic Commission for Europe, New York and Geneva, 106 pp.

UN/ECE (1994b) *Nitrogen Oxide Emissions from On-Road Heavy-Duty Vehicles (HDV): Options for Further Reduction.* EB.AIR/WG.6/R.16/Rev.1. United Nations Economic Commission for Europe, Geneva, Switzerland.

UN/ECE (1994c) *Control Options and Technologies for Emissions from Mobile Sources.* EB.AIR/WG.6/R.15/Add.1. United Nations Economic Commission for Europe, Geneva, Switzerland.

UN/ECE (1994d) *Protocol to the 1979 Convention on Long-range Transboundary Air Pollution on the Control of Volatile Organic Compounds or Their Transboundary Fluxes done at Geneva on 18 November 1991.* GE.94-30788, United Nations Economic Commission for Europe, Geneva, Switzerland.

UN/ECE (1995a) *Annual Bulletin of Electric Energy Statistics for Europe 1995.* United Nations Economic Commission for Europe, Geneva, Switzerland.

UN/ECE (1995b) *Strategies and Policies for Air Pollution Abatement. 1994 Major Review.* United Nations Economic Commission for Europe, Convention on Long-Range Transboundary Air Pollution, Geneva Switzerland.

UN/ECE (1996a) *Energy Balances for Europe and North America 1992, 1993-2010.* United Nations Economic Commission for Europe, Geneva, Switzerland.

UN/ECE (1996b). Report on Abatement Techniques to Reduce Ammonia Emissions from Agricultural Livestock. Report of the UNECE Working Group on Technology prepared by The Netherlands (lead country). Ministry of Housing, Spatial planning and Environment, The Hague, January 1996.

UN/ECE (1996c) *Report of the Sixth Seminar on Control Technologies for Emissions from Stationary Sources,* Budapest, 14-17 October 1996. EB.AIR/SEM3.3, UN/ECE, Geneva, Switzerland

UN/ECE (1997) Task Force on the Assessment of Abatement Options/Techniques for Nitrogen Oxides from Stationary Sources, Draft BAT document. French-German Institute for Environmental Research, University of Karlsruhe, Germany.

UN/ECE (1997) Anthropogenic Emissions of Air Pollutants (1980 – 2010) in the ECE Region. EB.AIR/GE.1/1997.3. United Nations Economic Commission for Europe, Geneva, Switzerland.

UN/ECE (1998) Anthropogenic Emissions of Air Pollutants (1980 – 2010) in the ECE Region. EB.AIR/GE.1/1998.4. United Nations Economic Commission for Europe, Geneva, Switzerland.

VROM (Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer) (1995a) *Emission Reduction by Internal Floating Roofs.* Projectbureau KWS 2000. May 1995

VROM/DGM (Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer - Directoraat-General Milieubeheer) (1995b) *Kosteneffectiviteit van milieumaatregelen in de industrie - beschrijving van de methodiek, deel A.* No. 119. VROM, Den Haag, December 1995. [in Dutch]

VROM/DGM (Ministerie van Volkshuisvesting, Ruimtelijke Ordening en Milieubeheer - Directoraat-General Milieubeheer) (1997) *Vervolgonderzoek Kosteneffectiviteit van Milieumaatregelen in de Industrie - Eindrapportage*. VROM, Den Haag, March 1997. [in Dutch]

WHO 1997 *Air Quality Guidelines for Europe*. Second edition, Copenhagen, (in press)

Williams, L. J., D. Beardshall, P. G. Edgington, F.O. Foster, R.H. Lilie, H.D. Richards (1986): *Hydrocarbon Emissions from Gasoline Storage and Distribution Systems*. Report No. 85/54, CONCAWE, DenHaag, September 1986.

Zimmermann, A., Hausheer J., Pfefferli, S. (1997) *Ammoniak: Kosten der Emissionsminderung - Betriebswirtschaftliche Beurteilung der Möglichkeiten zur Reduktion der Ammoniak-Emissionen in der Schweiz.* Schriftenreihe der Eidg. Forschungsanstalt für Agrarwirtschaft und Landtechnik (FAT) Nr. 44, Tänikon.

Ziros G. (1998) Energy balances and Emissions of SO_2 and NO_x in Greece. Letter from the Greek Ministry of Environment, 15.04. 1998. Athens, Greece (in French).