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Evolution of NO_x emissions in Europe with focus on road transport control measures

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Abstract. European emission trends of nitrogen oxides since 1880 and up to present are presented here and are linked to the evolution of road transport emissions. Road transport has been the dominating source of NO_x emissions since 1970, and contributes with 40% to the total emissions in 2005. Five trend regimes have been identified between 1880 and 2005. The first regime (1880–1950) is determined by a slow increase in fuel consumption all over Europe. The second regime (1950–1980) is characterized by a continued steep upward trend in liquid fuel use and by the introduction of the first regulations on road traffic emissions. Reduction in fuel consumption determines the emission trends in the third regime (1980–1990) that is also characterized by important differences between Eastern and Western Europe. Emissions from road traffic continue to grow in Western Europe in this period, and it is argued here that the reason for this continued NO_x emission increase is related to early inefficient regulations for NO_x in the transport sector. The fourth regime (1990–2000) involves a turning point for road traffic emissions, with a general decrease of emissions in Europe during that decade. It is in this period that we can identify the first emission reductions due to technological abatement in Western Europe. In the fifth regime (2000–2005), the economic recovery in Eastern Europe imposes increased emission from road traffic in this area. Western European emissions are on the other hand decoupled from the fuel consumption, and continue to decrease. The implementation of strict measures to control NO_x emissions is demonstrated here to be a main reason for the continued Western European emission reductions. The results indicate that even though the effectiveness of European standards is hampered by a slow vehicle turnover, loopholes in the type-approval testing, and an increase in diesel consumption, the effect of such technical abatement measures is traceable in the evolution of European road traffic emissions over the last 15 years.

1 Introduction

The historical trend in the anthropogenic emission levels of nitrogen oxides (NO_x=NO+NO_2) is increasingly important for our understanding, hence our ability, to optimize abatement of air pollution and reduce the adverse effects of these pollutants on ecosystems, human health and climate, on local, regional and global scales.

The anthropogenic NO_x emissions are dominated by combustion processes in road transport with a 40% share in 2005, followed by power plants (22%), industry (16%), off-road transport (15%) and the residential sector (7%) (Vestreng et al., 2007a). Anthropogenic emissions in Europe are at least four times larger than the natural emissions from lightning, soil emissions and forest fires (Simpson et al., 1999). European anthropogenic emissions of NO_x contribute to about 30% of global NO_x emissions in 1990, when excluding ships and biomass burning (Olivier et al., 1998; Cofala et al., 2007; Vestreng et al., 2006; Schultz et al., 2007). The evolution of emissions in Europe in the last 15 years (1990–2005) contrasts with the situation in Asia, Latin America, Middle East

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and Africa, where less policy regulations are in place and NO_x emissions are increasing (Naja et al., 2003; Cofala et al., 2007).

Much effort has already been invested in order to abate NO_x emissions in Europe, both at national and at European-wide level. The first UNECE regulations to control emissions from motor vehicles (ECE-R15) were already being discussed in the 1950s and came into force in 1970 (UNECE, 1958; Berg, 2003). They were designed to reduce the emissions of carbon monoxide (CO) and hydrocarbons (HC) due to incomplete combustion. The early European legislation can be viewed as a response to the US initiatives, which had at that time already introduced air pollution control policies to address the degradation of air-quality in Los Angeles, California. Much later, and within the framework of the Convention of Long-range Transboundry Air Pollution (LRTAP), two Protocols regulating NO_x entered into force; the 1988 Sofia Protocol sets a limit to national annual emissions or transboundary flux of nitrogen oxides at the 1987 level, while the effect-based 1999 Gothenburg Protocol sets fixed emission ceilings for the year 2010 (UNECE, 2004). The EU National Emission Ceilings (NEC) Directive (EC, 2001a) defines slightly more ambitious 2010 emission ceilings for some of the Member States than the Gothenburg Protocol. The reason for this is possibly that the NEC was designed to deliver slightly different environmental objectives compared to Gothenburg Protocol in terms of ecosystem protection. The European Commission has also issued a number of Directives and instruments aiming to control NO_x emissions from specific sectors. These are principally the Large Combustion Plant Directive (Directives 88/609/EEC and 2001/80/EC), emission limits for engines used in non-road mobile machinery (Directive 97/68/EC), the Waste Incineration Directive (Directive 2000/76/EC) and the ECE/Euro standards for road vehicles (Directive 70/220/EC and revisions).

Emissions from road transport have been determining NO_x emission levels for decades. Engine-out NO_x emissions consist mainly of NO (90–95%). NO is primarily formed by two mechanisms, namely the thermal (Zeldovich) and the prompt (Fenimore) mechanisms. The thermal mechanism is activated above 1600°C and is responsible for more than 90% of emissions from road transport. Reis et al. (2000) showed that road traffic may contribute substantially to exceedances of ozone indicators for both health and forests in Europe. Further, Carslaw et al. (2007) demonstrated the risk for the EU hourly limit of nitrogen dioxide ($200\,\mu g/m^3$) not to be met by 2010 in European cities due to the recent developments in road transport. Globally, road transport is responsible for substantial increase in the concentration of tropospheric ozone (5–15%) not only in the vicinity of the source but also in remote areas (Granier and Brasseur, 2003; Matthes, 2007).

This paper documents how European anthropogenic road traffic emissions have evolved since the 1880s and investigates to what extent the decrease in emissions after 1990 can be linked to policy regulations. Our analysis links NO_x emission trends in Europe to the evolution of fuel consumption as well as to the changes in vehicle technology. It further distinguishes between the Eastern and Western European regions, where differences in the level of penetration of policy measures have an impact on the evolution of the emissions. Although the analysis covers a 125 years time span, the main focus is on the last 15 years, when European NO_x emissions have begun to decrease. The methodology developed is presented in Sect. 2 which also documents the data sources used in the analysis. Data quality is discussed in Sect. 3. Results on European trends in NO_x emissions are presented in Sect. 4, and the discussion on the effectiveness of policy measures is given in Sect. 5. Finally, conclusions are summarized in Sect. 6. Emissions from international shipping at European waters are analyzed in a forthcoming paper (Jonson et al., 2009) and are thus not included here. With respect to the terminology adopted, NO_x emission figures correspond to NO_2-equivalents, except in cases where primary NO_2 emissions are explicitly discussed.

2 Methodology and data used

A European NO_x emission inventory that spans over 125 years has been compiled to provide further insight in the evolution of European air pollution. The inventory relies on available information on 1) activity data, 2) emission factors, 3) abatement level, and 4) the level of policy penetration. Such information is largely variable from period to period and for the different European countries and areas, and determines to a large extent the accuracy of the final results. Concise information on the information sources and an evaluation of the uncertainty associated with each source is included in the following.

2.1 1880–1985: EURONOX inventory

We have estimated anthropogenic fossil and biofuel combustion emission by European country and sector every 5 years since 1880. The underlying activity data corresponds to the European historical country borders in the time span considered, and we distinguish between three different periods: 1880–1915, 1920–1945 and 1950–1985. The emission estimation methodology differs only for the periods 1880–1945 and 1950–1985. An advantage of this study with respect to previous global estimates (e.g. van Aardenne et al., 2001; Schultz et al., 2007) is that we have applied emission factors which vary with time and by country.

Fuel consumption in the period 1880–1945 is calculated from energy and industry statistics collected by Mitchell (1981) and supplemented with information from the World Power Conferences (1948) and extrapolated OECD data (OECD, 2004). Detailed activity data and reliable emission factors are not available for this period, thus we derive the emissions by scaling 1950 emission sectors per country backwards in time, based on the solid and liquid fuel consumption. We underline that one main implication is that possible important changes in the average emission factor for coal combustion during this period are not considered in our emission estimates.

With regard to the period 1950–1985, we distinguished between the originally OECD and non-OECD countries, based on the availability of activity data. A detailed breakdown of activity data is published in the OECD Energy Statistics (OECD, 1966, 2004). We estimated NO_x emissions from about thirty different sub-sectors which were thereafter aggregated into SNAP sectors. For the non-OECD countries we used the production figures of electric power in thermal power plants from the UN Energy Statistics (UNECE, 1976, 1980 and 1981), to deduce the amounts of lignite and other fuels used in electric power plants. For most countries it has been assumed that mainly lignite was used in electric power plants. Consumption of hard coal was included in the energy budget of Poland and Hungary, and also natural gas was included in the case of the Former Soviet Union (USSR) and Romania.

Coke production figures were used to deduce the amount of coal used for coke. The remaining coal was distributed between the industrial and the residential sector. For the non-OECD countries, gasoline was assumed to be consumed only in cars, or in other internal combustion engines. It was also assumed that gas oils must have been too expensive to be used except in internal combustion engines of cars, trucks, off-road equipment and machinery, and in agriculture. In general, these uses are assumed to account for 80% of the gas oil consumption.

The emission factors used for this period are shown in Table 1 and are broadly based on the work by Pacyna et al. (1991), reviewing a large selection of country specific emission factors from national and international programmes, with a special attention on Eastern Europe. The emission factors from Pacyna (1991) are representative of 1985. We have altered these emission factors to reflect changes over time and between countries. Further improvements have been carried out for emissions in the transport sector which is the main focus in our study. These improved emission factors are mainly based on the work by Samaras and Zierock (1996).

One main point is that the emission factors for motor vehicles increase with time during the period 1950 to 1985. This is to reflect the fact that the development of new gasoline engines over this period led to less fuel-enriched mixtures, lower scavenging losses, and higher compression ratios to improve fuel efficiency and to control CO and HC emissions that were the focus at the time (UNECE, 1958). As a side-effect of improved combustion, (thermal) NO_x emissions to the atmosphere increased. According to Samaras and Zierock (1996), emission factors of 20.4 g/kg were applicable for gasoline cars without emission controls, i.e. vehicles produced before 1970 (Pre ECE R-15) but for vehicles with non-catalyst control (i.e. improved combustion) the emission factors increased to 36.7 g/kg (Table 1, footnote 3).

Table 1. Emission factors for nitrogen oxides related to fuels and sectors.

FUEL	ACTIVITY	EMISSION FACTOR ($g\,NO_2/kg$)
Hard coal (25 PJ/Tg)	Thermoelectric power plants	9
	Gas works	1
	Coke production[1]	1.5
	Industry sector	7
	Transport (railways)	2
	Other (residential)	2
Brown coal (11 PJ/Tg)	Thermoelectric power plants[2]	2–8
	Industry sector[3]	1.5–5
	Other (residential)	2
Residual fuel oil (40 PJ/Tg)	Thermoelectric power plants	10
	Industry sector	8
	Refineries	6
	Transport	6
	Other (residential)	8
Gas/diesel oil (43 PJ/Tg)	Thermoelectric power plants	6
	Industry sector	6
	Transport (heavy duty vehicles)[3]	30–50
	Agriculture (machinery)[3]	40–50
	Residential	2
	Other	5
Jet fuel (46 PJ/Tg)	Aviation	10
Kerosene (46 PJ/Tg)	Residential	1
Gasoline (46 PJ/Tg)	Transport (passenger cars)[3]	20–30
LPG (46 PJ/Tg)	Other (residential)	4
Natural gas (48 PJ/Tg)	Thermoelectric power plants	0.6
	Industry sector	0.4
	Other (residential)	0.3
Wood (19 PJ/Tg)	Residential fire places	1.9

[1] Including gas produced and burnt in association with the coke production (see text).

[2] Depending on fuel quality and combustion technology in the respective countries. The highest emission factor is assigned to Former Czechoslovakia (8 g/kg), followed by Albania, Bulgaria, Former USSR and Yugoslavia (7 g/kg), Poland (6 g/kg), Former East Germany, Hungary, Romania, Austria, Denmark and France (5 g/kg), Spain (4 g/kg), former West Germany Italy, Portugal and Turkey (3 g/kg) and Greece (2 g/kg).

[3] Depending on combustion concept and operation conditions (see text).

An increase in emission factors also occurred for diesel engines during this period, according to the US-AP42 (US EPA, 1991). The low emission factors for diesel engines are typical of engines with indirect injection. This design is not favoured for modern, large trucks, which have direct-injection engines and higher compression ratios. The effective compression ratio may be further increased by turbocharging, which further promotes the formation of NO_x. Emissions from for heavy duty vehicles (HDV) were not regulated until 1988 with the introduction of the ECE 49 Regulation. The lower limit of the emission factor range for HDVs in Table 1 (30 g/kg) is comparable to Conventional HDVs included in COPERT (http://lat.eng.auth.gr/copert), when these are converted per fuel mass used, and further, to the uncontrolled NO_x emission factors in the GAINS database (http://gains.iiasa.ac.at/gains) developed at IIASA. Measurement studies more often concern US and more recent vehicle fleets (e.g. Kirchstetter et al., 1999; Yanowitz et al., 2000; Kristensson et al., 2003; Schmid et al., 2000; Kohler et al., 2004), but Ekström et al. (2004) report on-road optical remote sensing measurements in Sweden per vehicle technology class which support the upper limits of the emission factor ranges both for gasoline passenger cars and heavy duty vehicles in Table 1.

The emission factors we have assigned to HDVs are lower in Eastern European (24–40 g/kg) than Western European countries (30–50 g/kg), to reflect the differences in vehicle technologies following the implementation of the ECE-R15 regulations in Western Europe. In addition, some Eastern European countries used to have a high proportion of 2-stroke engines which resulted in even lower average NO_x emission factors. In the extreme case of Former East Germany, more than 50% of the vehicles used to have 2-stroke engines, and the resulting emission factor for gasoline cars is consequently estimated at a much lower value (6–10 g/kg) than for the other countries included in this study (20–30 g/kg). While these simple considerations do not provide detailed and accurate inventories for each country, they may still give useful estimates of regional and temporal trends.

For stationary sources we do not include any variation of emission factors with time. We assign country specific emission factors for brown coal in thermoelectric power plants and in the industry according to fuel quality and combustion technology in the respective countries (UNECE, 1981; McInnes, 1996). This implies that emission factors for power plants are generally higher in Eastern Europe compared to Western Europe (Table 1, footnote 2). Due to lack of information about differences between countries in the industry sector, we have applied a uniform emission factor of 3 g/kg for the industry sector in all Eastern European countries. Emission factors for Western European industries are about 1 g/kg lower than those listed in Table 1, footnote 2 for power plants.

It is worth noting that we do not include the gas associated with the production of coke from coal, hence available for combustion (e.g. coke oven gas or blast furnace gas from the iron and steel industry) in separate sectors. It is instead included in the emission factor for coke production itself, and this is why we apply an emission factor for coke production orders of magnitude larger than Pacyna et al. (1991). Combustion in the residential sector is assumed to occur mainly in small domestic boilers, and the emission factor chosen for combustion in oil refineries is taken from Takacs et al. (2004).

Emissions from international shipping and aviation are not included in this study. Further we do not include emissions not directly related to fuel consumption like nitric acid and fertilizer production. According to Pacyna et al. (1991), these are minor sources (0.5% contribution around 1980), as is agricultural burning of straw and stubble (less than 1%). Emissions from waste, which, according to data reported to the LRTAP Convention contribute less than 1% to the national total in the 1980s, is not included. No attempt has been made to include NO from soils although some authors (e.g. Stohl et al., 1996) argue that the emissions are mainly from arable land and should therefore be considered as anthropogenic.

2.2 1980–2005: EMEP NO_x inventory

For data on NO_x emissions after 1980 this study relies mainly on data from the EMEP (Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe) programme. The EMEP inventory consists as far as possible of official data reported annually by 51 Parties to the Convention on Long-range Transboundary Air Pollution (LRTAP). The emission data is compiled at national level in accordance with the UNECE Emission Reporting Guidelines (UNECE, 2003) and the EMEP/CORINAIR Guidebook (http://reports.eea.europa.eu/EMEPCORINAIR4/en). The national emission estimates are accompanied by an Informative Inventory Report (IIR) documenting the uncertainties in the data included and possible deviations from the recommended methodologies in the Guidebook. These emissions are annually reviewed and evaluated, to check for errors and identify areas where improvements may be necessary (e.g. Vestreng et al., 2007a). In addition to emission data, national reporting includes activity data for the historical years 1990, 1995, 2000 and 2005. These official activity data reported by countries have been used for the study of emission trends in the period 1990–2005. In the absence of reported data, our analysis for the period 1990–2005 relies on trends in fuel consumption and implied emission factors from the GAINS database. Historic fuel consumption data in GAINS are extracted from national and international energy statistics. For the period 1980 to 1990, we include fuel consumption data from the sources outlined above for the EURONOX inventory.

Table 2 presents national NO_x emission trends and gives an overview of the completeness of official emissions in the EMEP inventory between 1980 and 2005. The relative share of emissions from road transport (in brackets) is also listed. Countries which passed the EMEP review are highlighted with grey background in Table 2; a total of nineteen countries. The table identifies also a second group of countries for which reported data had to be completed by interpolation and extrapolation in order to achieve full emission trends for the period. These twelve countries are marked in bold italics. For the remaining countries,

Table 2. Nitrogen oxides trends per European country 1980–2005 (Unit: Gg NO_2. Percentage contribution from road transport in brackets. Countries highlighted in – Grey: Officially reported data. Bold italics: Reported data completed by independent estimates. Stars: RAINS data, interpolation and extrapolation. Normal: EDGAR data, interpolation and extrapolation.

	1980	1985	1990	1995	2000	2005
Albania*	25 (55)	29 (57)	23 (37)	16 (65)	22 (62)	25 (65)
Armenia	15 (44)	45 (49)	60 (41)	18 (20)	31 (59)	38 (61)
Austria	249 (45)	236 (46)	211 (47)	192 (49)	204 (54)	225 (58)
Azerbaijan	85 (45)	93 (41)	93 (21)	85 (8)	76 (4)	85 (4)
Belarus	***234 (43)***	***238 (42)***	***285 (33)***	***232 (28)***	***208 (41)***	***184 (30)***
Belgium	442***(46)***	325 (56)	382 (48)	372 (47)	330 (46)	293 (43)
Bosnia and Herzegovina*	66 (48)	73 (38)	73 (28)	51 (23)	53 (28)	52 (34)
Bulgaria	***357 (50)***	***375 (49)***	363 (38)	264 (33)	184 (31)	233 (39)
Croatia	60***(48)***	***73 (38)***	86 (38)	60 (45)	72 (43)	69 (40)
Cyprus	13 (56)	14 (58)	16 (42)	19 (44)	23 (43)	17 (39)
Czech Republic	***937 (21)***	***831 (22)***	***742 (19)***	***413 (43)***	***398 (42)***	***278 (35)***
Denmark	273 (26)	291 (32)	274 (38)	264 (37)	207 (39)	186 (37)
Estonia	***67 (43)***	***74 (41)***	74 (41)	38 (42)	35 (38)	32 (34)
Finland	295 (36)	275 (44)	299 (53)	258 (51)	235 (45)	177 (32)
France	1942 (43)	1726 (51)	1840(59)	1654 (60)	1405 (52)	1207 (45)
Georgia	121 (43)	140 (41)	64 (57)	13 (11)	30 (10)	32 (12)
Germany	3334 (35)	3276 (38)	2861 (47)	2170 (53)	1817 (55)	1443 (45)
Greece	***242 (40)***	306 (39)	299 (36)	320 (39)	328 (37)	317 (34)
Hungary	273 (41)	263 (42)	276 (42)	193 (45)	194 (52)	203 (62)
Iceland	21 (21)	21 (20)	26 (21)	27 (21)	28 (22)	29 (27)
Ireland	73 ***(36)***	91 ***(40)***	121 (36)	123 (38)	130 (40)	116 (37)
Italy	1606 (40)	1661 (41)	1943 (46)	1808 (51)	1373 (51)	1173 (46)
Kazakhstan	164 (21)	179 (19)	179 (18)	162 (8)	119 (8)	151 (8)
Latvia	***61 (43)***	***67 (41)***	67 (30)	40 (37)	38 (42)	41 (43)
Lithuania	152 ***(36)***	166 ***(34)***	158 (34)	65 (36)	49 (51)	58 (58)
Luxembourg*	23 (40)	21 (40)	20 (44)	32 (75)	33 (80)	29 (80)
Malta	***12 (39)***	***15 (38)***	***14 (20)***	***13 (22)***	***12 (27)***	***12 (24)***
Netherlands	583 ***(40)***	589 (44)	558 (47)	468 (45)	394 (45)	344 (42)
Norway	181 (32)	213 (31)	213 (35)	212 (30)	212 (21)	197 (18)
Poland	***1229 (38)***	***1500 (26)***	***1581 (25)***	***1121 (28)***	***838 (27)***	***811 (28)***
Portugal	166 (33)	166 (37)	246 (32)	278 (32)	287 (39)	281 (36)
Republic of Moldova	***58 (43)***	***66 (42)***	***131 (26)***	***79 (26)***	***27 (30)***	***31 (28)***
Romania*	523 (27)	542 (24)	527 (23)	400 (22)	331 (25)	346 (34)
Russian Federation	***3280 (37)***	***3600 (33)***	***3600 (31)***	***2563 (36)***	***2357 (40)***	***2795 (43)***
Serbia and Montenegro*	118 (48)	145 (38)	165 (32)	133 (30)	137 (36)	149 (36)
Slovakia	***226 (28)***	***201 (29)***	***215 (21)***	***174 (23)***	***109 (31)***	***97 (38)***
Slovenia	51 (52)	53 (50)	63 (58)	66 (65)	60 (61)	58 (59)
Spain	1045 (33)	954 (37)	1178 (41)	1254 (39)	1349 (39)	1405 (34)
Sweden	404 (44)	426 ***(41)***	314 (55)	280 (54)	231 (49)	205 (41)
Switzerland	170 ***(61)***	179 ***(71)***	158 (59)	122 (53)	104 (53)	86 (49)
TFYR of Macedonia*	37 (48)	47 (38)	46 (23)	35 (30)	39 (34)	30 (33)
Turkey*	364 (43)	483 (39)	691 (42)	789 (44)	942 (36)	932 (42)
Ukraine*	1598 (15)	1754 (13)	1753 (12)	1245 (15)	861 (22)	960 (26)
United Kingdom	2772 (36)	2728 (40)	2966 (45)	2384 (46)	1897 (43)	1627 (34)
Total	23944 (36)	24550 (36)	25256 (38)	20507 (41)	17809 (42)	17059 (39)

emissions were derived from other sources. The main source for non-offical emission estimates in the EMEP inventory is data from the GAINS model (http://gains.iiasa.ac.at/gains) developed at IIASA. These emissions are not completely independent from those officially reported in that IIASA, through bi-lateral consultations, may include data provided by the countries themselves. The GAINS model is now capable of reproducing national emissions of NO_x for almost all Parties with an uncertainty margin of less than 5% (UNECE, 2007). Because there are a few countries for which neither official nor GAINS data are available, EDGAR emission data (http://www.mnp.nl/edgar) are also included. The EDGAR inventory is a global inventory but it does not have the same level of detailed vehicle classification as the GAINS model. There are eight countries for which RAINS data have been used and these are marked with a star in Table 2. The emission estimates for the remaining five countries rely on EDGAR emission data. The coverage of reported emissions is about 40% in the 1980s, increasing to nearly 60% after 1990. The level of confidence is considered to be higher for the reported and reviewed emission data, due to country specific insight and the detailed input to the calculations.

3 Data quality

As indicated from the discussion above, the level of accuracy of the data used all through the NO_x inventory from 1880 to 2005 increases as we approach recent times. In this section we document the uncertainties in the EMEP and EURONOX inventories, and justify the merging of these two inventories.

3.1 Uncertainties in the EMEP inventory

There are recognised uncertainties in the selection of emission factors and even though national statistics of activity data as compiled from e.g. data reported by individual facilities, registration offices and different surveys are in most cases reliable, there is also an element of uncertainty in this basic input to the national emission calculations. Discrepancies between actual and apparent national emission estimates are also introduced when emission data are reported, in line with the UNECE reporting Guidelines, based on fuel sold rather on fuel used. This is because the amount of fuel sold in a country may be strongly influenced by "fuel tourism". This is a term used for retail purchase of fuel in one country for consumption abroad, mainly due to fuel price differences. The effect of fuel tourism is shown to have opposite and equally large effect for countries with high "green taxes" as discussed in Sect. 5 in the case of Germany. The implication is that while the European emission trend for NO_x may be correctly reflected, the national (road transport) emission trends for several European countries may be affected by the tax and transit levels.

The uncertainty level for national emissions included in the EMEP inventory is based on information given in the Informative Inventory Reports (IIR). Based on a review of this information from a limited number of countries, the uncertainty in national emissions is considered to be between 8% and 23% for Western Europe and around 25% for Eastern Europe. The EMEP inventory contains in addition emission estimates from the GAINS model, and according to Schöpp et al. (2005), the uncertainty in these emissions are comparable to those reported by the countries. Uncertainty estimates for individual sectors are not reported by the Parties, but Schöpp et al. (2005) indicate that the sector uncertainty is higher, and might be nearly three times larger for emissions from gasoline passenger cars and diesel heavy duty trucks. Kuhlwein and Friedrich (2000) estimate the statistical error in transport NO_x emissions in West Germany to be 16–22%, comparable to the results for United Kingdom estimated by Schöpp et al. (2005). The above uncertainty ranges are applicable from 1990 onwards (Vestreng et al., 2006). Quantitative uncertainty estimates for the 1980s are not available, but they are likely to be higher, due to the lower coverage of reported emissions and absence of published non-official estimates. In addition, recalculation of emission data by many Parties are only performed from 1990 onwards, hence the accuracy in the 1980s emissions may not benefit from methodological improvements in emission estimation.

A complementary way to assess the validity of emission data is to combine model and observation data. The general downward trend in EMEP emission data from 1990 onwards have been confirmed by a recent model study by Jonson et al. (2006). The study concludes that even though the EMEP model tends to overpredict winter concentrations and underpredict summer concentrations compared to measurements, NO_2 levels and seasonal patterns are well captured. Further, Fagerli and Aas (2008) show that the reduction in EMEP NO_x emissions between 1990 and 2003 is comparable to the downward trend observed in measurements of nitrate in precipitation.

A trend study by Konovalov et al. (2008) applying inversion techniques with GOME and SCIAMACY measurements between 1996 and 2004, broadly confirms that the NO_x emission trends in Europe have been decreasing, and further indicates that the quality of the EMEP inventory has increased over the last few years. Our evaluation of regional differences in inventory uncertainties is in agreement with the above study, where particularly large differences between the EMEP and satellite data are found in Balkan countries, Georgia, Russia and Turkey.

3.2 Uncertainties in the EURONOX inventory

The comparability between the EURONOX and EMEP inventories has been assessed for the two common years, 1980 and 1985. Table 3 shows differences in national total and road transport emissions per country in both inventories. The agreement on the national total levels is generally good, with an underestimation of less than 10% on the European level in EURONOX relative to EMEP. The better agreement in 1985 is probably because the emission factors applied are more representative for 1985 than for 1980.

The comparability deteriorates when individual sectors are considered, but the differences are still mostly within the uncertainty range indicated by Schöpp et al. (2005). In contrast to the national total emissions, road transport is

Table 3. Comparison between EMEP and EURONOX 1980 and 1985 national total and road transport emission data (Unit: Gg NO_2)[1].

	1980				1985			
	National total		Road transport		National total		Road transport	
Country/Inventory	EMEP	EURONOX	EMEP	EURONOX	EMEP	EURONOX	EMEP	EURONOX
Albania	25	25	14	14	29	29	16	16
Austria	249	231	112	130	236	229	109	148
Belgium	442	371	202	144	325	325	182	157
Bulgaria	357	357	177	177	375	375	182	182
Cyprus	13	–	7	–	14	–	8	–
Denmark	273	290	70	95	291	291	92	115
Finland	295	228	105	96	275	222	120	119
Former Czechoslovakia	1163	616	264	168	1033	597	239	165
Former USSR	5835	5720	1807	2483	6421	6143	1818	2529
Former Yugoslavia	332	371	162	177	391	464	155	175
France	1942	1931	827	986	1726	1793	879	1113
Germany	3334	3390	1163	1381	3276	3509	1231	1595
Greece	242	242	98	98	306	307	120	128
Hungary	273	297	111	174	263	287	111	175
Iceland	21	12	4	10	21	15	4	13
Ireland	73	89	26	49	91	77	36	55
Italy	1606	1429	646	763	1661	1576	678	958
Luxembourg	23	21	9	14	21	24	8	19
Malta	12	–	5	–	15	–	6	–
Netherlands	583	508	234	234	589	494	262	252
Norway	181	143	58	107	213	151	66	107
Poland	1229	1147	466	294	1500	1192	385	274
Portugal	166	135	55	77	166	149	56	88
Romania	523	568	141	203	542	565	130	172
Spain	1045	866	341	405	954	995	351	515
Sweden	404	286	177	169	426	278	176	190
Switzerland	170	138	104	104	179	170	127	127
Turkey	364	356	157	164	483	513	189	255
United Kingdom	2772	2266	989	884	2728	2261	1099	1018
Total	23944	22033	8530	9598	24550	23030	8834	10658

[1] Former USSR includes emissions from Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Latvia, Lithuania, Republic of Moldova, Russian Federation and Ukraine. Former Czechoslovakia includes Czech Republic and Slovakia. Former Yugoslavia includes Bosnia and Herzegovina, Croatia, Serbia and Montenegro, Slovenia and The former Yugoslav Republic (TFYR) of Macedonia.

generally increasingly overestimated by the EURONOX inventory, indicating that the emission factors applied might have been too high for some countries. Particularly for some of the Eastern European countries, the discrepancies in sector emissions could also be attributed to the lack of detailed activity data. While it is clear that much more detailed information about the conditions in each country would have been desirable when developing the EURONOX inventory, the agreement with the EMEP data is considered sufficient to merge the two inventories in 1980, by scaling the EURONOX inventory to the relevant EMEP sectors. In order to account for the sources not included in the EURONOX inventory, we scaled the residential sector also together with the EMEP agricultural and waste emissions.

3.3 Comparison with other estimates

The combined EURONOX and EMEP inventory is compared to independent anthropogenic inventories both at national total and at road-transport levels. Schöpp et al. (2003) has compiled a NO_x inventory between 1880 and 1960 based on a study by Dignon and Hameed (1989). The Dignon and Hameed (1989) inventory is merged with estimates from an old version of the RAINS model from 1960 onwards. The European NO_x trend presented in Schöpp et al. (2003) differs considerably from our work in that emissions are consistently higher in Schöpp et al. (2003) over the whole 1880–2005. The difference between the inventories is particularly large in the 1950s, and amount to nearly 40% in 1960 at the European

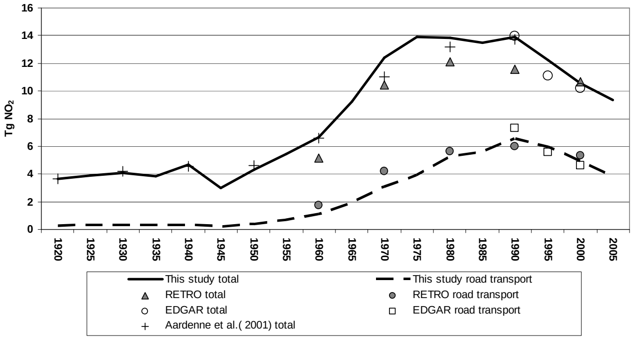

Fig. 1. Comparison between this study and the van Aardenne et al. (2001), RETRO and EDGAR inventories for OECD Europe as defined in EDGAR.

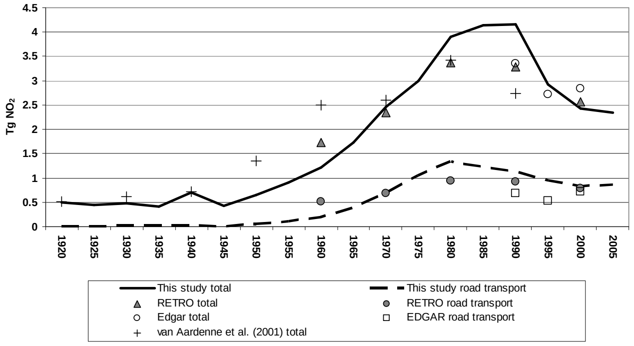

Fig. 2. Comparison between this study and the van Aardenne et al. (2001), RETRO and EDGAR inventories for East Europe as defined in EDGAR.

level. Dignon and Hameed (1989) derive emissions by regression analysis from total fuel consumption. It is likely that the more refined approach we have followed, with application of representative emission factors in distinct fuel consumption sectors, is the main reason for the large discrepancy between these two inventories.

A global inventory published by van Aardenne et al. (2001) is available for the years 1890 to 1990 in ten-year intervals. The road-transport emissions are not separately documented but are included in the fossil fuel combustion sector. National and road-transport data per decade between 1960 and 2000 were made available to us on a regional level for the more recent RETRO inventory (Schultz et al., 2007). EDGAR data (http://www.mnp.nl/edgar) are available per country and sector in five-year intervals between 1990 and 2000. Comparison with these three inventories has been made on the regional "OECD Europe" and "East Europe" level, as defined by EDGAR (http://www.mnp.nl/edgar). The comparison is made from 1920 onwards as such regional comparisons are hampered by differences in country borders, particularly before 1920.

The OECD emissions presented in Fig. 1 represent between 97% (1920) and 55% (2005) of the total European emissions according to our inventory. Our work and the van Aardenne et al. (2001) study compare well both in terms of trend and national emissions level over the whole hundred year time span (Fig. 1). The RETRO inventory defines the peak in total emissions in 1980, contrasting both our work and the work by van Aardenne et al. (2001). The RETRO national total estimates are lower than this study, the van Aardenne et al. (2001) and the EDGAR inventories for all years but 2000, where the inventories coincide. The underestimation in the RETRO inventory compared to EMEP can only be partly explained by the incompleteness of the RETRO inventory with respect to national navigation, railway, waste treatment and disposal, and cement manufacturing. The difference in trend between the RETRO and the other inventories between 1980 and 2000 seems to be due to application of more efficient abatement in stationary sources, as the trend in road transport compares fairly well between our work and the EDGAR inventory.

The much larger relative differences in emission level (more than 100% in some years) and trends for both total and road transport emissions in "East Europe" support that the uncertainties are larger in this area (Fig. 2). Road transport emissions increase in the EDGAR inventory between 1995 and 2000, contrasting the EMEP emissions. This increase is reflected in the totals, and results in an overestimation of the EDGAR emissions in year 2000 compared both to our study and to the RETRO emissions. The increase in transport emissions in EDGAR follows the trend in fuel consumption in this area, and does not take into account that emissions have decreased in line with the implementation of Euro standards in countries like Poland and the Czech Republic as discussed below, that took place in this period. The RETRO road transport trend is much weaker than in our work, indicating that emission factors vary less with time.

4 Results on European emission trends 1880–2005

4.1 European total trends

Figure 3 shows the trends in solid and liquid fuel consumption from 1880 to 2005 as compiled for this study. The total fuel consumption increased by more than a factor of ten over a period of a hundred years (1880–1980). Before 1950, solid fuel was the main energy carrier in Europe, and the consumption increased steadily from 1880 onwards; the increase only interrupted by the economic depressions in the 1930s and later during the Second World War. Liquid fuel consumption showed a dramatic increase after 1950, among other reasons due to the availability of oil imported from the Middle East. The results presented here trace the relative importance of liquid fuel consumption in comparison with solid fuel use. Between 1950 and 1970 the consumption of liquid fuel increased by a factor 18, and has exceeded the solid fuel consumption in all years since 1970. While European solid fuel consumption continued to increase until to the end of the 1980s, the increase in liquid fuel consumption ceased between 1970 and 1980, decreased thereafter until about 2000, and then increased again. The stabilisation and decrease in liquid fuel consumption after the 1970s is a result of the high oil prices following the oil crises (e.g. Glover and Behrens, 2006) and is also due to decreased consumption in Eastern European countries. Solid fuel consumption drops sharply between 1990 and 2000 and increases thereafter. The decline in solid fuel is mainly due to decrease in hard coal consumption all over Europe. In addition the consumption of brown coal went down in the EU area.

The trends in European NO_x emission related to these fuel consumption results are presented in Fig. 3, where also trends per sector are included. The sectors included in this analysis broadly follow the SNAP categorization.

National shipping and domestic aviation is included in the off-road sector. Agriculture and waste, being in general minor NO_x sources, have been merged with the residential sector. This distinction of sectors clearly shows the dominant effect of road transport emissions over the last 35 years. Based on the developments in road transport, we have distinguished five emission trend regimes between 1880 and 2005. In the first regime, 1880–1950, the historical total NO_x emission trend follows the moderately growing fuel consumption. Between 1950 and 1980 (the second regime), NO_x emissions grew steeply by a factor of 4.4, i.e. almost twice as fast as the sulphur emission increase during this same period (Vestreng et al., 2007b). The NO_x emission trend was strongly related to the increase in road transport emissions during this period, as indicated in Fig. 3. Already in 1970 the road transport emissions became the single most important source of NO_x with a share of nearly 30% of total emissions. The growth in the second and third largest sources (power plants and industry) was considerably less. The large change in the residential and off-road sectors between 1970 and 1975 shown in Fig. 3 was due to a reduction in the domestic consumption of residual fuel oil and an increase in diesel consumption in the agricultural sector. While we find the decrease in residual oil for heating plausible, we suspect that the detailed statistics we have used on diesel consumption in the off-road sector prior to 1970 might be defective.

In the third regime, 1980–1990, the share of NO_x emissions from road transport is large (about 40%), and has remained relatively constant at the European level for the last 25 years (Table 2 and Fig. 3). Total NO_x emissions peaked in 1990, partly due to continued increase in road transportation activity up to this point in time, and partly to the fact that emissions from stationary sources remained relatively stable between 1980 and 1990. The fourth regime, 1990–2000, is characterized by a steep decline in NO_x emissions. The highest share of road transport to the total emissions (42%) is found around year 2000, and does not coincide with the peak in total NO_x emissions. This is due to the slower reduction rate of road-transport emissions (22%) relative to emissions from power plants (42%) and the industry (33%), between 1990 and 2000. As a result of the combined reductions, the total NO_x emissions monotonically decreased by 32% between 1990 and 2005. The largest reductions took place in the first half of the 1990s. The reasons of this decline are different in different parts of Europe and will be explained in the next section. Finally, in the fifth emission trend regime, 2000–2005, the downward emission trend has flattened out.

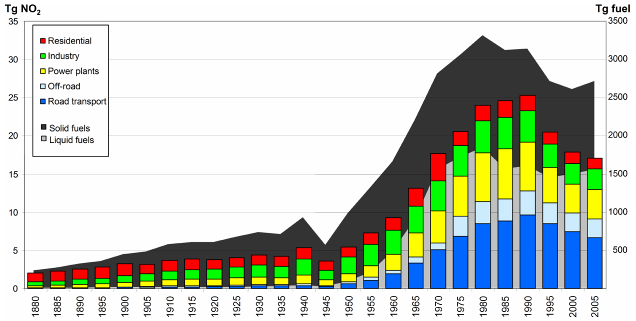

Fig. 3. European solid and liquid fossil fuel consumption 1880–2005. Data from the GAINS model 1990–2005 (Tg fuel/year, right axis). Sector trends in European NO_2 emissions 1880–2005 (Unit TgNO_2, left axis).

4.2 Trend differences between European countries in the last twenty-five years

We focus our analysis on the last three emission trend regimes, i.e. 1980–2005 for two main reasons. First, large changes in the emission trends can at least partly be associated to the technological development and policy regulations in this period. Second, the emission data uncertainty is anticipated to be lower than in the period before 1980, as indicated in Sect. 3, and this should lead to more solid conclusions. The analysis particularly addresses road-transport, which is the most significant sector and a number of policy regulations have been developed to abate NO_x emissions from vehicles. The effectiveness of these regulations in Eastern and Western European countries is separately assessed.

The country specific details in NO_x emission trends after 1980 for both national and road transport emissions (percentage contribution in brackets) are highlighted in Table 2. The largest contributors are the Russian Federation, United Kingdom and Germany. The total NO_x emissions in Europe increased by 5% from 1980 to 1990 due to increased emissions in most countries but a few notable exceptions like Germany and France where emissions from power plants and the industry were reduced.

NO_x emissions decreased in most countries between 1990 and 2005, but there are substantial differences in the emission trends depending on the socio-economic and political situation in each country. A large reduction appears in this

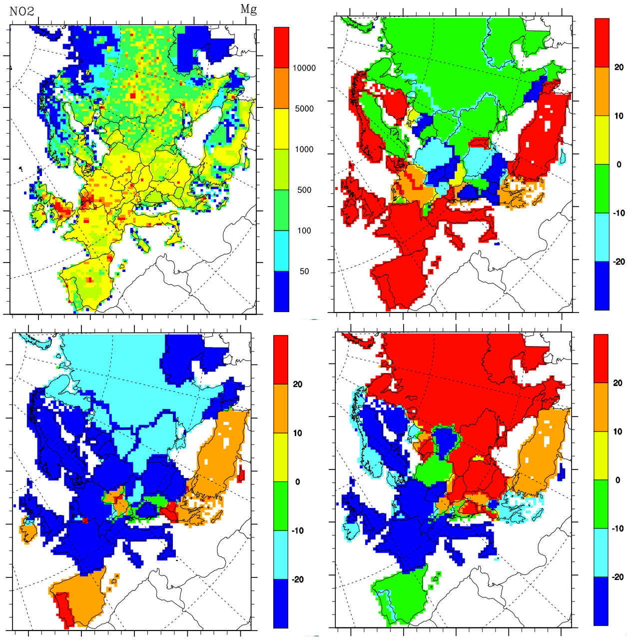

Fig. 4. Road transport emissions of NO_2 in 2005 (top left). Unit Mg. Difference in road transport emissions between 1980 and 1990 (top right), 1990 and 2000 (bottom left), 2000 and 2005 (bottom right). A negative number indicates a reduction. Unit: Percent.

period between 1990 and 1995 (Fig. 3) due to the disintegration of the Soviet Union in 1991. As a result of the economic recession, the reduction in NO_x emissions from the power plants and the industry was twice as large in the east as in the west, despite the introduction of specific abatement measures in the latter.

Except for the effect of this outstanding political situation, the NO_x emission trend over the period 1990 to 2005 has been dominated by changes in road transport. However, there are large differences between the east and the west. In Western Europe, road transport has been the dominant NO_x emission source over the whole period 1980 to 2005, while power plants were the most important NO_x source in Eastern Europe until 1995. For example, the road transport contribution in 1990 varied from less than 20% of total NO_x in Ukraine and Kazakhstan to about 60% in France and Switzerland. As a result, 70% of the total European road transport NO_x emissions in 1990 came from Western Europe. In 2005, this share dropped to 63% mainly due to reductions in Western European emissions, but also due to increase in emissions in the recovering economies in Eastern Europe.

Figure 4 presents the trends in road transport NO_x emission, separately for the periods 1980–1990, 1990–2000 and 2000–2005 together with a reference map of emissions in 2005. The legend accompanying the difference maps (-20% to $+20\%$) has been chosen to highlight the main differences, but the percentage differences might in certain cases exceed ±50% in any of the three periods considered.

a) 1980–1990

Road transport emissions in Europe increased by 13% in the period 1980–1990 despite a 10% reduction in Eastern Europe (cold colours in the upper right map of Fig. 4). The reduction in the east is linked to decreased fuel consumption due to income deterioration, as a consequence of the inefficiency in resource allocation (investments) (Gros and Steinherr, 1991). Exceptions to this general picture, where emissions increased, are Armenia, the Republic of Moldova, Hungary, Slovenia, Croatia and Estonia. While the explanation for the increased emissions in Hungary can readily be linked to the increase in gasoline consumption, the situation is not clear for the Former Yugoslav and USSR Republics. Fuel consumption data for individual Former Yugoslav and USSR Republics have not been available to us for the period 1980–1990, thus firm conclusions regarding the reasons behind the apparent increase in emissions cannot be drawn. Based on the rather stable fuel consumption trend in both the Former USSR and Yugoslavia between 1980 and 1990, it is not unlikely that fuel consumption increased in some areas and decreased in other parts of this region.

In most of Western Europe and Turkey, road transport emissions increased between 1980 and 1990 (by warm colours in the upper right map of Fig. 4). The overall increase was 27% in Western Europe. Fuel consumption went down or stabilized also in this region due to the high oil prices following the oil crisis in the 1970s. At the same time, early non-catalyst controls introduced with the different steps of UNECE Regulation No. 15 (1970–1983) were associated with an increase in NO_x emissions from vehicles (Berg, 2003). Due to relatively slow fleet turnover, as further discussed in the next section, the introduction of the ECE-R15 regulation may be responsible for the overall increase between 1980 and 1990. In some Western European countries though, road transport emissions decreased between 1980 and 1990. These are Sweden, Belgium, Luxembourg, Austria, Switzerland, Cyprus and Malta. The fuel consumption went down also in these countries. A possible explanation for the emission decrease could be the early introduction of diesel passenger cars. In the case of Turkey, the increased emissions are due to a substantial (80%) increase in gasoline consumption.

b) 1990–2000

In the period 1990–2000, road transport emissions decreased by 23% in Europe, and reductions were evident (about 20%) both in the east and the west (Fig. 4, lower left map). In Eastern Europe, the decrease in emissions is associated with a decrease in fuel consumption in former Soviet republics, Romania and Bulgaria. A country's transport volume is closely linked to its GDP, and the overall decrease in road transport is an effect of the restructuring of the economies after the disruption of the Soviet Union in 1991. Russia is an important trade partner, so the depression also affected countries outside the Union. Further, the infrastructure in this region which was already rather poor further decayed during this period (EEA, 2007). Decreased emissions in other Eastern European countries are linked to decreased emission factors, rather than decreased fuel consumption. The share of the high-polluting car fleet built in Eastern Europe decreased in these areas between 1990 and 2000 as the increase in the stock of vehicles is due to imports of cleaner cars from Western Europe. This development took place also in the Czech Republic, but here the increased share of lower NO_x emitting cars only damped the increase in emissions. Albania and the Former Yugoslav Republic of Macedonia increase their emissions due to increased fuel consumption, without an accompanying decrease in emission factors. The 7% decrease in road transport emissions reported by Croatia cannot be explained without assuming a decrease in emission factors, as both GAINS and IEA report increased fuel consumption in the transportation sector in Croatia between 1990 and 2000.

In Western Europe, the introduction of improved vehicle technologies and stringent inspection systems related to the Euro standards has been the primary force in reducing NO_x road traffic emissions in the period 1990–2000, despite economic growth and increases in fuel consumption. All countries but Portugal, Spain, Greece, Turkey, Cyprus, Malta, Austria, Ireland and Luxembourg reduced their emissions (Fig. 4 lower left map). These nine countries which increased emissions between 1990 and 2000 can be divided in three groups based on the possible causes for the emission growth. The high age of the vehicle fleet combined with increasing number of vehicles may explain the lack of reductions in the first group, containing Portugal, Spain and Greece. In the second group with Turkey, Cyprus and Malta the main reason for emission increase is that the Euro standards were not applied at the same time as in the rest of Europe. Increase in emissions reported from Austria, Ireland and Luxembourg are caused by fuel tourism as defined in the previous sections. Austria and Ireland provide road transport emissions both according to fuel sold and fuel used. Their estimates for NO_x emissions calculated on the basis of fuel used show a decreasing trend between 1990 and 2000, opposing the data reported as requested by the UNECE Guidelines according to fuel sold. The reason for the increased emission in Austria is a large increase in emissions from heavy duty vehicles (Anderl et al., 2007). In Ireland, the reason is that fuel is less expensive in Ireland than in the United Kingdom during this period. UK fuel prices apply to Northern Ireland, thus drivers tank in Ireland (DEHLG, 2006).

c) 2000–2005

In the period 2000–2005, road transport emissions in Europe continue to decrease. The total European emission reduction in this five years period is 11% comparable to the preceding regime, but with important differences in Eastern and Western Europe. Fuel consumption in the traffic sector increased in all European countries except in Germany. In Germany high tax on fuel combined with improvements in vehicle technology, result in a considerable decline in diesel consumption as further discussed in Sect. 5. The situation from the 1980s (Fig. 4 upper right map) with decreasing emissions in the east and increased emissions in west is reversed in this period (Fig. 4 lower right map).

Increase in emissions from Eastern Europe follows the increase in fuel consumption (Fig. 4 lower right map). The recovering of the economy is responsible for the emission growth, and it is illustrative that loans for transport from the European Bank for Reconstruction and Development to the EECCA countries have mostly financed roads after year 2000. This contrasts with the previous periods when rail and port projects dominated (EEA, 2007). The EECCA countries have their own car industry, so new western technologies will not necessarily become standard. Another reason why emissions in EECCA countries increase may be related to use of lead as an additive to the fuel. Lead additives poison the catalysts, and are not completely abandoned both due to lack of regulations and due to a claimed black market for leaded gasoline. In addition to this, the price of fuel is low and even subsidised in some countries (EEA, 2007). In Belarus, emission decreased between 2000 and 2005. There is no essential production of cars except for heavy duty vehicles here. Produced lorries comply with Euro 2 and later standards and passenger cars are imported. Import of cars which not comply with certain Euro standards are not directly prohibited, but the older cars are imposed higher tax. The situation with respect to how the introduction of Euro standards has influenced the emission trend is mixed for the EU-10 countries. While Hungary, Latvia, Lithuania and Slovakia report an increase in emissions between 2000 and 2005, due to less effective implementation of the Euro Standards, decrease in emissions are seen in Poland, Czech Republic, Estonia and Slovenia. In addition, Croatia which according to the Belgrade report (EEA, 2007) implemented the Euro standards from year 2000 decreased their emissions.

Contrasting the general increase in Eastern European emissions, the decrease in emission continues in Western Europe between 2000 and 2005. The only countries where emissions increased were Turkey and Austria. In Turkey emissions increased because of lack of abatement measures and Austria due to fuel tourism.

5 Effectiveness of policy regulations in the transport sector

As indicated in Fig. 3, the European road transport emissions have been decoupled from the liquid fuel consumption since 1995. This section investigates to what extent the decrease in NO_x transport emissions can be associated to the introduction of the Euro standards for both passenger cars and heavy duty vehicles. Table 4 shows the NO_x relevant emission

Table 4. Emission standards for road transport in Europe post-1992.

Emission Standard	Regulation	Impl. Year[1]	NO_x (g/km) or (g/kWh)	NO_x (Gg/PJ) [Converted]	Main technology improvements over preceding step
Gasoline PCs and LDVs (g/km)					
Euro 1	91/441/EC	1992	0.62[2]	0.25	Closed-loop TWC[3]
Euro 2	94/12/EC	1996	0.35[2]	0.14	Faster light-off
Euro 3	98/69/EC	2000	0.15	0.06	Faster light-off and twin lambda control
Euro 4	98/69/EC	2005	0.08	0.03	Faster light-off and improved lambda control
Euro 5 and 6	EC 715/2007	2010–2015	0.06	0.02	Improved aftertreatment materials, deNOx for direct injection vehicles
Diesel PCs and LDVs (g/km)					
Euro 1	91/441/EC	1992	0.90[2]	0.44	Improved combustion
Euro 2	94/12/EC	1996	0.67[2]	0.32	Oxidation catalyst
Euro 3	98/69/EC	2000	0.50	0.24	Two oxidation catalysts, high pressure injection
Euro 4	98/69/EC	2005	0.25	0.12	Precise injection and pressure control
Euro 5	EC 715/2007	2010	0.18	0.09	Diesel particle filters
Euro 6	EC 715/2007	2010	0.08	0.04	deNOx, presumably SCR[3]
HDVs (g/kWh)					
Euro I	91/542/EEC	1992	8.0	0.84	Improved combustion
Euro II	91/542/EEC	1996	7.0	0.74	Electronic engine control
Euro III	1999/96/EC	2000	5.0	0.56	High pressure injection
Euro IV	1999/96/EC	2005	3.5	0.40	EGR, precise injection control
Euro V	1999/96/EC	2008	2.0	0.25	Cooled EGR[3] or SCR
Euro VI	Only draft proposal	2014	0.4	0.05	Presumably SCR+DPF[3]

[1] For LDVs and HDVs. For LDVs, the implementation date is roughly one year later than PCs to allow for calibration of new technology.
[2] Regulations set a standard for the sum of HC and NO_x emissions. The value quoted in the table is an inferred value based on typical HC/NO_x split for the particular vehicle technology.
[3] TWC: Three-way catalytic converter; SCR: Selective catalytic reduction; DPF: Diesel particle filter.

standards per vehicle category and the associated emission control technology in the European Union after 1992.

We analyse here to what extent emission factors calculated on the basis of officially reported road transport emissions and activity data (implied emission factors) comply with the Euro standards. This information is only available from 1990 to 2005 for ten Western European countries (Austria, Denmark, France, Germany, Netherlands, Norway, Portugal, Spain, Switzerland and United Kingdom) and can be retrieved from the EMEP database (http://www.ceip.at/emission-data-webdab). These ten countries represent more than 50% of total European emission from road transport in 1990, and they are considered to represent the situation in Western Europe. For Eastern Europe, relevant data are available for 2005 for seven countries (Estonia, Lithuania, Macedonia, Poland, Romania, Slovakia and Slovenia). Therefore, a separate analysis has also been undertaken for this particular year.

5.1 Trends in emissions and fuel consumption by country and vehicle class

The fuel types considered here are gasoline and diesel. The reported consumption of hydrogen is negligible and also the reported consumptions of compressed natural gas (CNG) and liquefied petroleum gas (LPG) are very low to affect the trends. In addition, the fuel consumption in mopeds and motorcycles is small compared to other vehicles categories and therefore these have not been considered in the following analysis. It is a limitation to our analysis that the reported emissions do not distinguish between gasoline and diesel use in vehicles. The implied emission factors are thus calculated based on total emissions and fuel consumption for each vehicle class.

In Western Europe, the overall trend in fuel consumption shows that petrol consumption decreased (20%), while diesel consumption increased (90%) between 1990 and 2005. The shift to diesel is the impact of the European Automobile Manufacturers Association's commitment on the reduction of CO_2 emissions from passenger cars (Commission Recommendation 1999/125/EC) (ACEA, 2007). This agreement promoted the use of diesel passenger cars because they have up to 30% higher fuel efficiency than gasoline cars of similar size. The net fuel consumption in road transport increased about 23% from 1990 to 2005. Passenger cars consumed by far the largest share of fuel (60%), followed by heavy duty vehicles (28%) and LDVs (12%). The promotion of diesel cars via the ACEA Commitment greatly benefited the curtailment of greenhouse gases. At the same time, it should not be forgotten that diesel passenger cars emit as much as three times higher NO_x emissions per kilometre than gasoline cars of the same emission standard. Just to put it into perspective, assuming that the increase in fuel consumption would have originated from increase in petrol rather than diesel consumption (thus diesel consumption remaining at the 1990 levels), this would have led to some 1/3 lower NO_x emissions in 2005.

With respect to road transport emissions of NO_x, these decreased by 44% between 1990 and 2005 in Western Europe, despite the increase in fuel consumption. The emission reductions were largest for PC (63%) followed by HDV (21%) and LDV (2%). Figure 5 compares the trends in total fuel consumption from 1990 to 2005 with individual trends for gasoline and diesel consumption and with the total NO_x emissions for passenger cars in selected Western European countries. NO_x PC emissions decrease monotonically while diesel consumption substantially increases (by nearly 200%) and gasoline consumption moderately decreases (by 19%). There is a clear decoupling of emission and fuel consumption of passenger cars already since 1990, as result of the developments in vehicle emission control technologies.

For HDV the situation is more complex. Fuel consumption increased in all countries between 1990 and 2005, except in Germany, where HDV consumption decreased by 30% between 2000 and 2005. This substantial decrease in diesel sold is not likely due to technological developments alone, but also due to the high tax on diesel in Germany. The high fuel prices in Germany prevent transit traffic refuelling, and promote fuel tourism to other neighbouring countries. Emissions from HDV between 1990 and 2005 decreased in all countries, except in Spain and Portugal and Austria, where emissions increased, by more than 200% in the case of Austria. Austria is a counter case to Germany, in that some 30% of the diesel sold is consumed outside the country. The onset of emission reduction from HDV comes almost ten years later than the corresponding turning point of passenger cars emission. The main reason for the delay in HDV emission reduction is the inefficiency of Euro II standards in addressing NO_x. With regard to LDVs, their fuel consumption increased in all countries. Their emission levels have remained relatively stable compared to the emission trends in PC and HDV, with slight increases or decreases in equally many countries. The above results show that the implementation of Euro standards has contributed to a decoupling of emissions and fuel consumption of all vehicle classes in Western Europe since 1990.

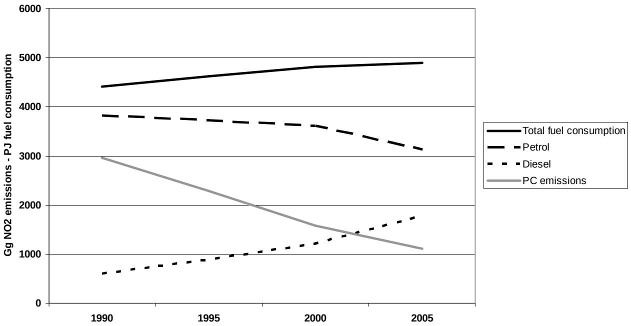

Fig. 5. Trends in Western European fuel consumption and emissions from Passenger Cars (Austria, Denmark, France, Germany, Netherlands, Norway, Portugal, Spain, Switzerland and United Kingdom).

5.2 Trends in implied emission factors

We have derived implied emission factors (IEF) between 1990 and 2005 based directly on reviewed officially reported emissions and total (gasoline plus diesel) fuel consumption. In this way we can compare the average emission level of the whole fleet in each country, with the emission levels expected when developing the Euro standards. The results for Western Europe are presented in Fig. 6, which shows that the implied emission factors decrease for all vehicle classes from 1990 to 2005. The average IEF reductions for all countries examined in this period are 67%, 42% and 35% for PC, LDV, and HDV respectively. The periods with largest IEF reductions vary with vehicle class and country. For PC, the largest IEF reductions (35%) occurred between 1995 and 2000 while max reductions for HDVs (20%) appeared five years later (2000 to 2005). On average, the IEF reductions from LDVs remained relatively constant, at 17%, in all five-year periods. We know today that the introduction of electronic controls in Euro II (1997), and less so in Euro III (2001) heavy duty engines led to excessive NO_x emissions over operation modes that were not included in the type-approval test (Hausberger and Rexeis, 2004). As a result, countries with a fast turnover of their HDV fleet were delayed in meeting the stringent emission standards expected. This is the reason why the mean HDV-fleet emission factors in several countries (UK, Netherlands, Austria, Denmark, Switzerland) in 2000 still appears higher than the Euro I emission standard introduced eight years before (1992). The situation improves in 2005 with only Austria and Denmark appearing to have HDV emission levels clearly beyond the emission standards 8 years ago (Euro II).

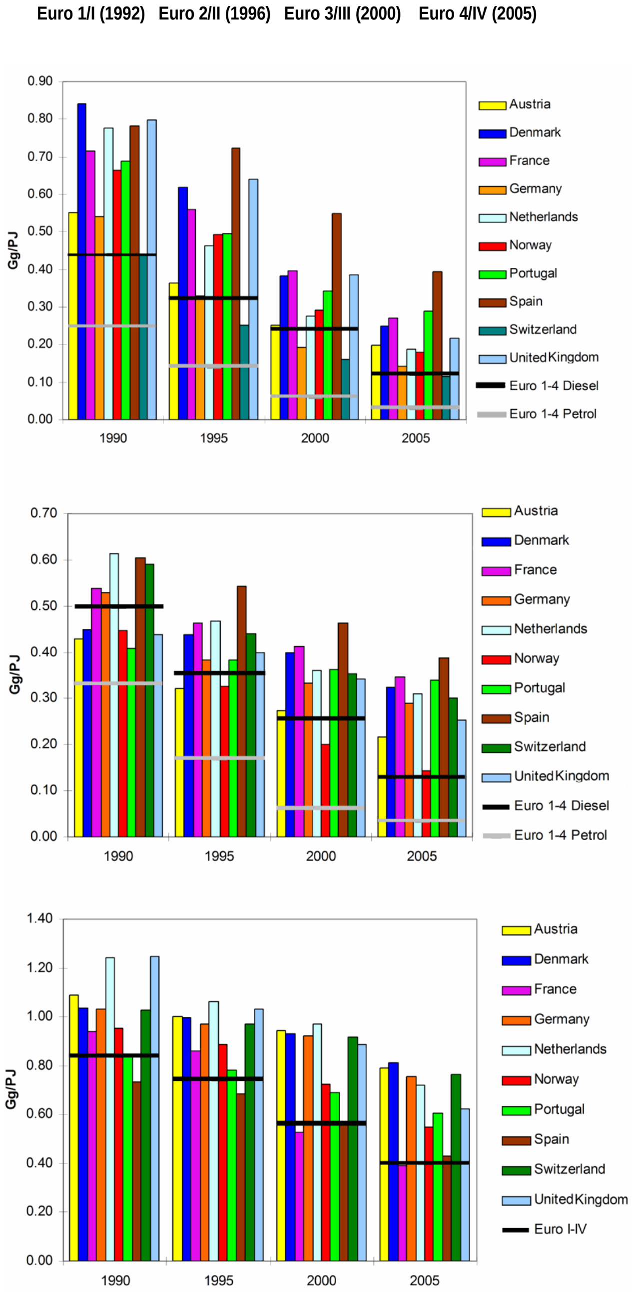

Fig. 6. Implied emission factors 1990–2005 for Passenger Cars (top), Light Duty Vehicles (middle) and Heavy Duty Vehicles (bottom) compared to the Euro standards.

Table 5. Implied emission factor for 2005 (Unit: Gg NO_2/PJ)

	PC	LDV	HDV
Austria	0.20	0.22	0.79
Denmark	0.25	0.32	0.81
Estonia	0.30	0.32	0.47
France	0.27	0.35	0.39
Germany	0.14	0.29	0.76
Lithuania	1.04	0.45	0.60
Macedonia	0.75	0.37	0.98
Netherlands	0.19	0.31	0.72
Norway	0.18	0.14	0.55
Poland	0.43	0.44	0.81
Portugal	0.29	0.34	0.61
Romania	0.76	0.53	0.65
Slovakia	0.31	0.34	0.60
Slovenia	0.31		
Spain	0.39	0.39	0.43
Switzerland	0.11	0.30	0.76
United Kingdom	0.22	0.25	0.62

The conclusions related to the effectiveness of the Euro emission standards for passenger cars are less straightforward, since the IEF is a composite value of gasoline and diesel vehicle emission levels, while separate emission standards have been in place, depending on the fuel used. In general, Fig. 6 shows that the average fleet emission level in 2000 in several European countries corresponded to a level between the gasoline and diesel Euro 1 levels, eight years ago. Spain, with a rather old vehicle fleet including a fair share of gasoline cars, fails to meet even the (high) diesel Euro 1 emission standard level even eight years after the introduction of the standard. Even in 2005, the average emissions of the Spanish PC fleet are only marginally below the diesel 1992 levels. On the other hand, average PC fleet emissions in Germany and Switzerland seem quickly (e.g. within five years) to attain the emission standards, despite the large fleet of diesel passenger cars. A similar decadal delay in effective implementation of the Euro standards is also seen for LDVs.

Due to lack of reported data, changes over time in IEF cannot be determined for Eastern European countries. The analysis for Eastern Europe is restricted to year 2005. Table 5 compares implied emission factors for PC, HDV and LDV in Eastern and Western European countries. IEFs in Eastern European countries are a factor of 2.3 and 1.4 higher than in Western European countries for PC and LDV, respectively. This is because the Euro standards did not fully apply to Eastern European countries before their accession to the European Union in 2004. The result further implies that the implementation of technological measures to abate road transport emissions has been less effective in Eastern Europe, due to a slower turnover of vehicles towards more modern, less polluting technologies. The results for HDVs in Table 5, show that countries with slow turnover of the fleet have lower IEFs. This is most likely due to loopholes in the type approval testing of HDVs as pointed out above.

The conclusion from this analysis is that Euro standards have clearly facilitated a substantial reduction in the road transport emissions in Western Europe. There has however taken some eight to ten years for policy regulations to come fully in effect in several European countries. This is the effect of the slow turnover of the vehicle fleet in many countries but also due to the deviations between the emissions in real-world conditions, compared to the type-approval driving cycle. Life cycle assessments of car fabrication might shed light to whether or not the policy should increase the incitement to a faster vehicle turn-over.

6 Conclusions

The significant increase of liquid fuel consumption in Europe between 1950 and 1980 led to an unparalleled historic increase of NO_x emissions from road transport by a factor 14 (Fig. 3). Road transport emissions have been the main source of NO_x in Europe already since the 1970s and are currently responsible for about 40% of total anthropogenic emissions. Technological and policy developments to abate European emissions have clearly facilitated a substantial reduction in the NO_x levels. Between 1990 and 2005 emissions decreased by more than 30% (Fig. 3, Table 2), but have now started to increase in many Eastern European recovering economies.

Based on the development in road transport emissions, we determined five NO_x emission trend regimes in Europe. While the emission trends in the first two of these (1880–1950 and 1950–1980) are mainly determined by the development in fuel consumption, the last three regimes are driven more by policy developments. In the third regime (1980–1990) road transport emissions decreased in Eastern Europe and increased in Western Europe (Fig. 4 upper right map). These regional trends resulted in an overall increase in NO_x emissions. The emission decrease in Eastern Europe was linked to deterioration in incomes, followed by a decrease in fuel consumption. In Western Europe, fuel consumption increased despite historical high oil prices in the beginning of the period. In addition, the ECE-R15 regulations introduced in the 1970s to improve combustion in motor vehicles, increased NO_x emission factors and NO_x emissions peaked in 1990. In the fourth regime (1990–2000), large reductions in transport emissions took place all over Europe (Fig. 4 lower left map). In Eastern Europe, decrease in emissions is linked both to decline in fuel consumption in Former Soviet Republics, and to a reduced share of high NO_x emitting vehicles in other Eastern European countries. The energy consumption increased in Western Europe, but policy regulations fostered technological development and implementation of measures, which resulted in large decreases in road transport emissions. In the fifth regime (2000–2005), the emissions pattern from the 1980s was reversed (Fig. 4 lower right map). Emissions continued to decrease in Western Europe due to the implementation of stricter control measures. On the other hand, emissions increased in line with the GDP in large parts of Eastern Europe. Historically, the most striking difference in NO_x emission distribution between Eastern and Western Europe is the much higher contribution from road transport in Western Europe. However, as a result of the recent development in road transport emissions, the emission levels in Eastern and Western Europe are now rapidly approaching each other.

Environmental and political concerns drove the decision to abate NO_x emissions, resulting in the NO_x Protocol under the Convention on Long Range Transboundary Air pollution (UNECE, 2004) in 1988 and were then followed by the Multi-effect Protocol in 1999. In addition, European Commission regulations specifically targeting the transport sector (Euro 1–4) were introduced between 1992 and 2005. The UN Protocol obligations may have led to substantial reductions, but we found that it was a lot easier to trace the effectiveness of the sector specific regulations. The emission limits for vehicle exhaust introduced by the Euro standards (Table 4) led to a substantial decrease in emission factors for all vehicle types in the EU region (Fig. 6). Despite a significant increase in the fuel consumption over the whole period 1990–2005, emissions monotonically decreased in the case of passenger cars (Fig. 5). There is clear evidence that the policy approach taken to reduce NO_x emissions has been effective in bringing NO_x levels down. On the other hand, our study shows broadly in line with Zachariadis et al. (2001) that it takes roughly ten years or more after the introduction of an emission standard to reach an equal level of average fleet emissions. This delay shows one of the inherent limitations with regard to the effectiveness of road transport policy. Although each new emission standard may introduce significant NO_x reductions over the one it replaces, it takes several years before a substantial portion of the fleet complies with the new emission standard. This leads to a rather gradual reduction in emissions from road transport. In order to fully account for the delay in compliance, it is important to note that introduction of new technologies was in some cases accompanied by HDVs and passenger cars emitting much higher in real-world operation than the emission standard level (Hausberger and Rexeis, 2004; Ntziachristos and Samaras, 2000), due to loopholes in the type- approval procedure.

This analysis shows that diesel consumption in vehicles increased substantially between 1990 and 2005. For the purpose of abating CO_2 emissions, this development is very welcomed, but from the air quality perspective, the dieselization hampered a more rapid NO_x abatement. If the increase in fuel consumption since 1990 in passenger cars had been met by an increase in gasoline rather than diesel, this would have resulted in around 30% lower NO_x emissions today (2005). The above considerations led us to conclude that the policy aimed at reducing NO_x from the transport sector has not been as effective as the ambition level.

Large Combustion Plants (LCP), albeit not the main focus of our study, is the second largest emission source in Europe (Fig. 3). Emissions from LCPs amount to about 20% of total EU-25 emissions. Sector specific regulations have been enforced in this sector through the Integrated Pollution Prevention and Control (IPPC) Directive 96/61/EC (EC, 1996) and the LCP Directive 2001/80/EC (EC, 2001b). Emissions within the EU-25 have by 2004 been reduced by

44% compared to 1990. The main emissions control systems are Selective Catalytic Reduction (SCR), and Selective Non-Catalytic Reduction (SNCR). The SCR process uses ammonia to reduce NOx by injecting it into flue gases while passing over a catalyst. Extremely high levels of NO_x reduction, typically around 90 percent are accomplished in this manner. The SNCR process relies on ammonia injection into hot flue gas streams to react with the NO_x at high temperatures. The NOx reduction varies with technologies and fuels that are burned, but typically a 50–70 percent reduction rate is achieved. Technology to reduce emissions from LCPs are available, and it has been shown that emissions would have been 60% to 90% lower if all plants had performed according to the lower and upper end of best available technology respectively (EEA, 2008).

Some issues for future consideration are addressed. Due to the increase in diesel consumption, primary NO_2 emissions may be increasing in Europe, despite the overall reduction in NO_x. In diesel exhausts, excess oxygen may lead to much higher NO_2/NO_x ratios (50%) in vehicles equipped with oxidation aftertreatment (diesel oxidation catalyst or catalyzed filter) for PM control (AQEG, 2006) than for gasoline three-way catalytic converter cars (less than 5%). Current evidence shows that ambient concentrations of NO_2 do not decrease at the same rate as NO_x in various European hotspots (Lambrecht, 2007; Carslaw et al., 2007), mainly due to the increasing NO_2 ratio in late diesel technology vehicles. Hourly NO_2 concentration limit values become mandatory in Europe starting from 2010 (EC Daughter Directive 99/30/EC). The proportion of primary NO_2 in vehicle exhausts may need to be addressed in future NO_x inventories. Another effect of the increase in diesel consumption in road transport is that less non-methane volatile organic pollutants (NMVOC) are emitted from this sector. The average NO_x/VOC emission ratio for PC and LDV has increased by a factor 2 between 1990 and 2005 according data officially reported to the UNECE. The impact on tropospheric ozone production of the above EU wide changes in emission ratios from road transport should be further assessed by air quality modelling.

It has been demonstrated here that implied emissions factors for NO_x in 2005 are sometimes even higher than the emission standard requested 15 years before. Although the slow vehicle replacement rate is responsible for a large part of this deviation, an equally significant part originates from the discrepancy of real-world operation emissions and emission standards. The next stage of emission standards expected in Europe by 2009–2010 (Euro 5) will further reduce NO_x emissions from both gasoline and diesel vehicles. This will be achieved with both in-cylinder measures and aftertreatment devices, such as selective catalytic reduction (SCR) systems and lean-NO_x catalysts. It needs to be made sure that these devices will be effective over the complete or, at least, a large portion of the engine operation range, to avoid excessive off-cycle emissions. Emission control regulations in the future should therefore more effectively address off-cycle emissions, e.g. by introducing a type-approval test covering a wider range of engine operation modes.

This paper does not analyse the implications for NO_x emissions from the transport sector by introducing larger proportion of biofuels in accordance with the EC biofuel directive (Directive 2003/30/EC), nor the contribution from international shipping on European NO_x emission levels, but these are nevertheless important subjects for future studies.

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