A global ex-post analysis of European emission controls in the road transport sector: what have we gained since the implementation of the EURO standards?

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Introduction

Road transport is an important source for suspended fine particulate matter (PM2.5) and ozone (O_3) precursors. In most European urban areas, road transport is the principal source for NOx, CO, benzene and black carbon in ambient air (WHO, 2005). PM, O_3 and NO_2 are broadly considered to be Europe's most problematic atmospheric pollutants in terms of harm to human health. In particular, both high PM and O_3 pollution have been linked to reducing life expectancy and to cardiovascular and chronic respiratory effects (Krewski et al., 2009; Jerett et al., 2009). O_3 is further known to cause substantial damage to vegetation, leading to yield reduction and deteriorating crop quality (Krupa et al., 1998). Apart from the air quality impact, several studies have indicated the importance of road and other transport modes emissions for climate, not only through the well-known effect of emitted CO_2, but also through the short-term and more regional radiative forcing of PM and O_3 (Fuglestvedt et al., 2008; Unger et al., 2009; Shindell et al., 2011).

The implementation of emission standards during the past 40 years in and outside Europe has aimed at significantly reducing the emissions of NOx, NMVOCs and primary PM2.5. The introduction of reduced sulphur fuels and catalytic converters on vehicles (the latter driven by introduction of the successive EURO standards that regulate exhaust emissions of CO, NO_x, NMVOC and primary PM) have contributed substantially to overall reductions of PM emissions. For PM alone, the EURO4/IV emission factors (in force since 2005) are 69 % lower than the EURO2/II emission factors (from 1996) for light-duty (passenger) vehicles and 92 % lower for heavy-duty diesel vehicles (EEA, 2011a and 2011b). Figure 1 gives a graphical representation of the subsequent emission reductions of PM and NO_x for diesel passenger cars.

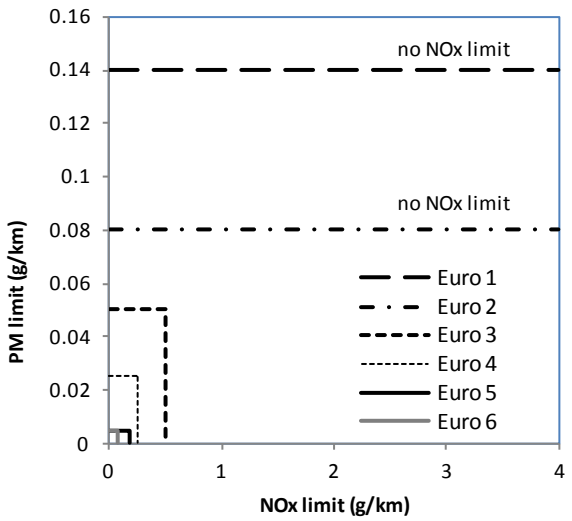

Figure 1: Schematic overview of PM2.5 and NO_x EURO emission standards for diesel passenger cars since EURO1. Compiled from http://dieselnet.com/standards/eu/ld.php#stds

In this study we use EDGAR v4.2 global historical global emission data from the transport sector, in combination with international fleet statistics, to evaluate the benefits that have resulted from the implementation of the EURO standards. Our approach is to evaluate how much the present day situation has improved compared to a fictitious present-day scenario in which the actual vehicle fleet emission controls would be limited to EURO1/I and EURO3/III standards respectively.

Previous studies have already evaluated the health impact of transport-related pollution (Heinrich et al., 2005; EEA, 2010). In this study we do not only consider impacts on air quality (in terms of health benefit and impact on crops), but we also consider the impact on climate through the change in radiative forcing from the short-lived climate pollutants (SLCP) such as O_3 and black carbon (BC), compared to limited-control-scenarios. Further, we also consider the impacts in countries outside Europe where legislation is being implemented based on the EURO standards.

Methods: emission scenarios

Today's road transport emissions are represented by the reference dataset, which is a subset of EDGARv4.2 historical data (EDGARv4.2, 2011). These emissions are compared with the fictitious scenarios of what current emissions would be if standards were not taken further than EURO1/I or EURO3/III. In what follows, the emission scenarios are denominated CFE1 (current fleet not beyond EURO1/I), CFE3 (current fleet not beyond EURO3/III) and REF2005 (current fleet), and we use EURO1 as a shortcut for the combined EURO1/I standards for both light and heavy duty vehicles, and similar for the other standard levels.

As such, the CFE1 scenario describes the situation with the total number of vehicles and their distribution as of today, but replacing the emission standards of EURO2 to EURO6 and of the Enhanced Environmental Vehicles (EEV) by those of EURO1. Similarly, in the CFE3 scenario, vehicles in today's fleet with emission standards EURO4 – 5 – 6 are substituted by EURO3, while all other vehicle emission are left unchanged. In particular no changes in US emission standards for on-road vehicles, wherever they occur, were applied, so that the effect of the EURO-standard development could be evaluated on world-scale, including non-European countries which are implementing EURO standards.

For the OECD and large non-OECD countries (~112 countries), activity data on the consumption of fuel (diesel, petrol, LPG, natural gas, biodiesel and bio-gasoline, other liquid biofuels, kerosene and residual fuel oil) in road transport were taken from the IEA-statistics on the energy balance of OECD countries 1960-2005 and large non-OECD countries 1970-2005 (IEA/OECD, 2007). For the calculation of the country-specific fleet distribution and their respective technologies international statistics from the International Road Federation (IRF,1990, 2005, 2007) were analysed in the framework of the EU funded project 'Quantify' and coupled with the respective fuel type. A realistic annual vehicle mileage, multiplied with average fuel consumption was triangulated with the national total fuel. National distributions were considered for USA and Canada, Germany, Japan, Thailand, Taiwan, India and Singapore. The allocation of the technologies to common fuel types is mainly based on EEA (2009) and updated to account for the increasing diesel share for passenger cars (ACEA, 2009, First registration of diesel cars in Europe) from 2005 until 2008.

For the end-of-pipe measures, the introduction of specific emission regulations was considered and the main information was obtained from the CONCAWE project (CONCAWE, 1997, 2001). Also the information of the EU27 emissions standards of the RAINS model (IIASA, 2007) was taken into account and the emission reduction percentage was implemented for the respective technology and substance. In Western Europe and in Japan, the EURO standards 1 to 6 were considered for passenger cars, light and heavy duty vehicles, while the EURO standards 1 to 3 and the EEV standard were considered for busses driving with natural gas. For North America, standards for US Tier 1 to 3 were considered for passenger cars and light duty vehicles whereas US Phase Tier 1 to 2 for heavy duty vehicles.

In general, default emission factors were calculated for 12 specific regions based on the chapter 'Road Transport' of the EMEP/EEA air pollutant emission inventory guidebook (2009). These emission factors were converted from g/vkm into kg/TJ considering the amount of fuel type and per technology based on the information of the Quantify project (Borken et al., 2007). The discussion of the NO_x emission factor reduction for EURO5 and EURO6 is followed via the Task Force on Emission Inventories and Projections (TFEIP) under the UNECE Convention on Long-range Transboundary Air Pollution. However, the NO_x emission factors have shown in recent real world emission measurements with EURO4 and EURO5 light-duty vehicles to be up to three times higher than the standard value of the EMEP/EEA Guidebook (Kousoulidou et al., 2010; Weiss et al., 2010). Therefore the emission inventories presented in this study may underestimate the real pollution from the transport sector.

Methods: the TM5-FASST tool

The pollutant levels and associated impacts resulting from the constructed emission scenarios are evaluated with the source-receptor model TM5-FASST on a global scale. TM5-FASST was developed as a spin-off of the full TM5 Chemical Transport Model (TM5-CTM) to bypass computationally expensive runs with the latter. This was done by using TM5-CTM to create an extensive library of [Δ emission/ Δ concentration] coefficients, so-called source-receptor (SR) coefficients, between 56 source regions and the global grid as a receptor at 1°x1° resolution,

from a reference scenario on which a 20% emission perturbation is applied for the precursors SO_2, NO_x, CO, BC, OC, NMVOC and NH_3 and resulting pollutants ozone (O_3), fine particulate matter $PM_{2.5}$ (as a sum of SO_4, NO_3, NH_4, BC, OC and H_2O) and specific O_3 metrics for crop damage (Van Dingenen *et al*., 2009) and health, as well as for instantaneous radiative forcing per Tg of emitted component.

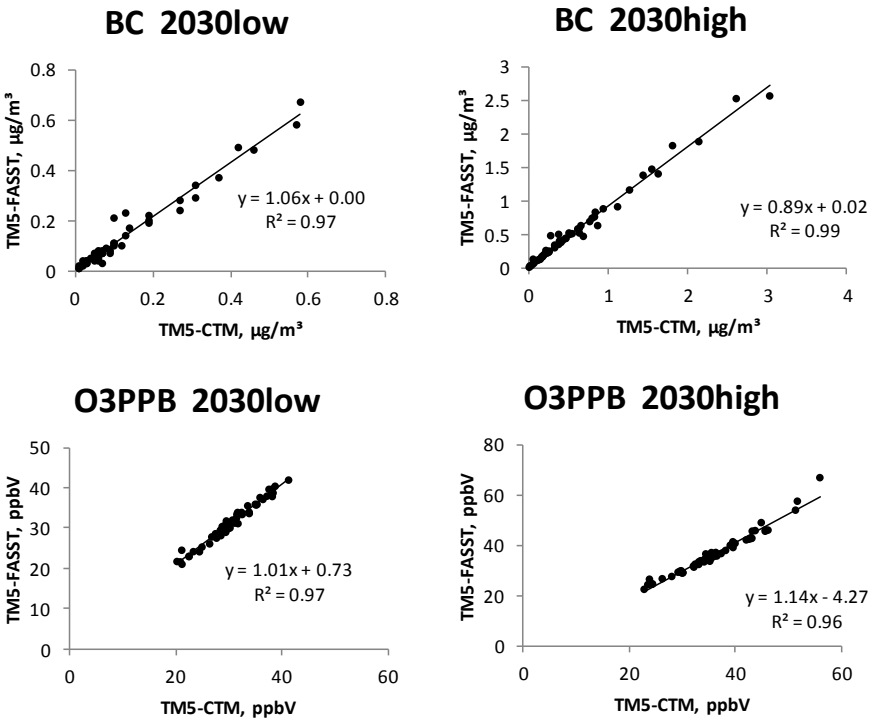

Figure 2: comparison between TM5-FASST and TM5-CTM region-integrated concentration of O_3 and PM2.5, illustrating the performance of the simplified TM5-FASST source-receptor model

Most European countries are defined as individual source regions, except for the smallest countries which have been grouped (e.g. Belgium, the Netherlands and Luxemburg). In the current version, the US, China and India are treated as a single emission regions each, i.e. without break-down in states or provinces. Although some Integrated Assessment models cover Africa as a single socio-economic entity, it was decided to divide the vast-continent of Africa in 6 regions (Egypt, Northern without Egypt, Western, Eastern, Southern without South Africa, and South Africa) to be able to simulate large differences in transport characteristics in this continent.

After having calculated the SR coefficients for all source regions and for all precursors they are applied to estimate the resulting concentrations and impacts from arbitrary emission strength by linear scaling. In order to simplify the interpretation of the results, the concentrations and impact SR coefficients on the 1°x1° receptor grid are aggregated to the level of the 56 source regions, resulting in a 56x56 SR matrix for each precursor and each relevant endpoint. SR coefficients are derived both as population-weighted averages (human health impacts) and area-weighted averages (crop yield impacts) over the respective regions, in order to realistically represent the exposure to the damaging pollutants.

TM5-FASST includes as well source-receptor relations between emitted compounds and the resulting global instantaneous forcing. Radiative forcing efficiency by aerosols is calculated with the off-line radiative transfer model OTM (Marmer *et al*., 2007). The normalized forcings from a reference scenario calculated with TM5-CTM are stored and are subsequently scaled with aerosol columns from actual scenarios. Radiative forcing for ozone was approximated by using the forcings obtained for the scenario results by Dentener *et al.* (2005), based on Edwards and Slingo (1996), and scaling them with ozone columns resulting from actual scenarios. The emission-based forcings of ozone precursors (NO_x, NMVOC, CO) include feedbacks on OH, CH_4 lifetime and resulting hemispheric background O_3 (Naik *et al*., 2005; Shindell *et al*., 2009).

TM5-FASST was validated against the full TM5-CTM model for pollutant and forcing fields. In general, the TM5-FASST model reproduces well the region-averaged concentrations of $PM_{2.5}$ and O_3 modelled by the TM5-CTM model for a wide range of emission scenarios. This is illustrated in figure 2 which shows an inter-comparison between the CTM and FASST versions of TM5 of receptor-region-averaged BC and O_3 concentrations for a low and high emission scenario respectively. More details on the TM5-FASST model and its validation can be found in UNEP (2011).

Methods: Impacts

From the calculated change in PM2.5 and O_3 between the REF2005 and both limited-control-scenarios (CFE1, CFE3), we derive the amount of avoided premature mortalities for the population older than 30 years. We adopt the methodology described by Anenberg et al. (2010). Cause-specific mortalities from cardio-pulmonary (CP) disease and lung cancer (LC) are calculated as PM2.5 impacts, and long-term mortalities from respiratory disease (RESP) as O_3 impacts. The relative risk (RR) values are 13% and 14% for a 10µg/m³ increase in PM2.5 for CP and LC respectively (Krewski et al., 2009). The RR for death from respiratory disease from O_3 is 4% for a 10ppbV increase in the seasonal (April-September) average daily 1-hr maximum O_3 concentration (Jerett et al., 2009). Cause-specific base mortalities for the year 2005 are taken from the most recent WHO ICD-10 update (WHO, 2012) for individual countries where available, or back-calculated from 14 WHO regional average mortalities when not available. Population numbers and the fraction of population older than 30 years are obtained from the UN Population Division (UN, 2011).

Impacts on 4 crops (wheat, maize, rice and soy bean) are calculated following the methodology by Van Dingenen et al. (2009). In brief, the SR-relations for various metrics for crop exposure to ozone (AOT40 and mean seasonal daytime ozone concentration) were pre-calculated based on stored hourly ozone concentrations from the full TM5 model runs. The metrics are averaged or accumulated over the appropriate crop growing season, which varies with geographical location and with crop type, and overlaid with crop suitability maps from Fischer et al. (2000) in order to obtain a country or region-averaged value for the O_3 metric. The relative yield loss for each crop is then obtained by applying appropriate exposure-response functions from literature (see Van Dingenen et al., 2009 for more details) to the region-averaged exposure metric.

As climate-relevant metric we calculate equivalent CO_2 emissions (CO_{2e}) from emitted short-lived pollutants following Fuglestvedt et al. (2010) by integrating the instantaneous forcing of a 1 year pulse emission for each emitted component over a time horizon of 100 years, and finding the 1 year CO_2 emission strength that would yield the same integrated forcing. The integrated forcing is calculated for primary $PM_{2.5}$ emissions (BC, OC), for secondary aerosol precursors (SO_2, NO_x, NH_3) and for O_3 precursors (NO_x, CO, NMVOC, CH_4). Only direct radiative forcing was considered, indirect effects on cloud formation and lifetime were not included.

Results and discussion

Emissions:

Table 1 shows the relative decrease in emissions between CFE1 (emissions controls limited to EURO1) and the actual year 2005 emissions for EU27 and other regions where vehicle standards have been applied, and similar for the CFE3 scenario. The figures for EU27, Africa and the World have been aggregated from the FASST countries or regions making up the respective regions. The effect of EURO standards on emissions is not only observed in Europe. Outside Europe, the highest impacts of the implementation of beyond-EURO1 standards are observed in Japan and China which are major producers for the European market and in other regions which have implemented European emission standards (e.g. the Middle East, Australia and New Zealand, Brazil,…).

Most of the emission reductions since EURO1 (and their associated benefits, see below) have been achieved by EURO2/II and 3/III controls. At the evaluation year 2005, beyond-EURO3 controls have only been implemented to a significant degree in Europe and Japan and consequently hardly affect other regions. The small difference between the reference scenario and the CFE3 scenario stems from the fact that the year 2005 penetration of EURO4/IV and 5/V vehicles is relatively small: they represent only 14% (by energy consumption) of the global

EURO-controlled vehicle fleet (EDGAR v4.2). For the year 2008, the share has already increased to 33%.

Air quality benefits:

The reduction of NO_x and NMVOC emissions in general leads to a reduction in PM2.5 and O_3 levels compared to the limited-control-scenarios, with obvious benefits for health and crop yields. The REF2005 scenario has a population-weighted PM2.5 concentration which is 6 µg/m³ lower than under CFE1 in EU7 and 8 µg/m³ lower in Japan. The benefit for the 6 month mean daily maximal O_3 concentration, compared to CFE1, is less pronounced: 4 ppbV in EU27 and 0.30 ppbV in Japan. For the highly urbanized regions (Belgium, The Netherlands, UK, Germany), the model even predicts lower O_3 levels under the CFE1 and CFE3 scenarios, because of high NO emissions which locally scavenge O_3, leading to the formation of NO_2. It is encouraging that the simplified TM5-model reproduces these features of O_3 chemistry, in agreement with the high-resolution regional chemical transport model used in a similar study (EEA, 2010).

Table 2 summarizes the major health impacts for selected regions. The first column shows the number of total PM2.5 and O_3 road transport-related premature mortalities (CP + LC + RESP) for REF2005. The second column shows the number of additional mortalities under scenario CFE1, split up in the share by EURO2+3 (difference between CFE1 and CFE3 scenario) and EURO>3 (CFE3 scenario) policies respectively. On a global scale, the implementation of EURO standards has more than halved the number of premature deaths from road transport related air pollution. 55% of the global health benefit has taken place in Europe (EU27).

Avoided crop yield losses are shown in the rightmost column of Table 2, with absolute crop yield numbers split up as described above, along with the total avoided relative yield loss compared to CFE1. The highest relative yield benefit is observed in EU27 (+1.5% compared to the CFE1 scenario), however large differences occur between individual countries: in particular Mediterranean countries (Spain, Italy, Greece) have a 3% to 5% higher crop yield than it would be the case under the CFE1 scenario. Note that the negative effect on Japan's crop production from beyond-EURO3 controls is real and is a consequence of the same O_3 quenching process by NO. The small benefit (+9 Tonnes/yr) from EURO2-3 is the net result of a local negative impact (titration effect) and a regional-scale transported positive impact from China.

Climate benefits:

The abatement of PM2.5 and NO_x has also a net beneficial effect for climate. PM2.5 emission controls have particularly decreased the diesel-related emissions of black carbon particles, whereas NO_x and NMVOC emission reductions in general contribute to a decrease in tropospheric O_3 levels, with some exceptions as discussed above. Table 3 summarizes the net CO_2-equivalent emission reduction from all components considered from limited-control-scenarios, compared to the current situation. This takes into account the reduced emission of cooling components (OC, SO_2), leading to a warming effect which however is largely compensated by the cooling effect from reduced BC and O_3. As a reference, we also include the actually achieved CO_2 emission reductions, although not part of the EURO standards, but realized through enhanced fuel efficiency. In Europe, with a high share of diesel vehicles, the CO_{2e} emission reduction from pollutant precursors corresponds to 15% of the actual CO_2 reduction in EURO2-6 controlled vehicles. In Japan, the CO_{2e} emission reduction corresponds to 10% of real CO_2 emission reductions for the same set of vehicles.

Conclusions

The implementation of EURO standards has dramatically improved air quality in Europe and Japan compared to a scenario where the year 2005 vehicle fleet emission control would be limited to EURO1 or EURO3. On a global scale, road transport pollutant emissions are roughly 50% and 15% lower than under the CFE1 and CFE3 scenarios respectively. Associated benefits for health and crops are obvious and are observed in the regions where the abatement takes place, although the O_3-related benefits are transported over a larger regional scale because of the longer lifetime of O_3.

The benefits extend beyond classical air-quality impacts: the achieved reduction in BC and O_3 has also contributed to a lower warming of the atmosphere than would have been the case

under the CFE1 scenario, and adds 5-10% to the avoided warming by reduced CO_2 emissions as a consequence of improved fuel efficiency.

With EURO4 and EURO5 vehicles making up only 14% of the global EURO-controlled vehicle fleet in the REF2005 scenario, there is still ample margin for air quality and climate benefits through replacement incentives. However, we recall that the assumed diesel NO_x emission factors for EURO4-5 are probably strongly underestimated. For the year 2005, the impact of this underestimation is relatively low because of the small share of EURO4 and EURO5 controlled vehicles. However, the share of beyond-EURO3 vehicles has increased in Europe and Japan since 2005, and the discrepancy between expected and real benefits will be growing accordingly.

Table 1: Emission changes between limited-control-scenarios (CFE1 and CFE3) and current situation (REF2005)

	EU27	USA	China	Japan	India	Brazil	Russ.Fed.	Africa	World
Relative change in emission from CFE1 scenario to current situation (year 2005)									
SO_2	-75%	+0%	-57%	-81%	-34%	-34%	-43%	-35%	-40%
NO_X	-77%	-1%	-49%	-84%	-26%	-31%	-27%	-21%	-46%
BC	-81%	-0%	-48%	-95%	-20%	-18%	-32%	-20%	-64%
POM	-78%	-4%	-44%	-92%	-17%	-24%	-26%	-14%	-54%
$PM_{2.5}$	-80%	-2%	-47%	-78%	-20%	-24%	-30%	-19%	-61%
NMVOC	-66%	-1%	-48%	-86%	-17%	-28%	-9%	-7%	-31%
CO	-72%	-2%	-48%	-66%	-16%	-38%	-17%	-8%	-32%
Relative change in emission from CFE3 scenario to current situation (year 2005)									
SO_2	-44%	+0%	-0%	-65%	-1%	+0%	-0%	-1%	-5%
NO_X	-43%	+0%	-1%	-65%	+0%	+0%	-0%	+0%	-13%
BC	-34%	+0%	+0%	-74%	-1%	+0%	-0%	-1%	-17%
POM	-37%	+0%	-0%	-68%	-1%	+0%	-0%	-1%	-20%
$PM_{2.5}$	-30%	+0%	+0%	-41%	+0%	+0%	-0%	-0%	-13%
NMVOC	-35%	+0%	-0%	-56%	+0%	+0%	-1%	-1%	-17%
CO	-13%	+0%	+0%	-18%	+0%	+0%	-0%	+1%	-2%

Table 2: Estimated benefits for human health and crops in the current REF2005 scenario, relative to fictitious limited-control-scenarios.

	Current premature mortalities from transport emissions x1000/year	Avoided mortalities from (Eur2-3) + (Eur>3) controls x1000/year	Avoided crop production loss from (Eur2-3) + (Eur>3) controls (total relative yield gain) Metric Tonnes/yr
EU27	56	151+34	2754+541 (+1.5%)
USA	17	1+0	642+83 (+0.2%)
China	55	47+1	1733+104 (+0.4%)
India	56	19+0	614+22 (+0.2%)
Brazil	2	1+0	304+0 (+0.2%)
Russ. Fed.	7	4+0	449+76 (+0.7%)
Africa	11	6+1	361+65 (+0.4%)
Japan	9	41+12	9-14 (-0.04%)
World	263	289+50	8995-1122 (+0.42%)

Table 3 Actual CO_2 and CO_2-equivalent emissions of short-lived pollutants for the year 2005 (REF2005) and avoided emissions relative to limited-control-scenarios. Unit: Tg CO_2/year

Climate impacts	CO_2 (REF2005)	CO_{2e} (REF2005)	Avoided CO_2 emissions from (EURO2-3) + (EUR>3) controls	Avoided CO_{2e} from (EURO2-3) + (EUR>3) controls
EU27	867	118	2149+805	389+46
USA	1500	163	20+0	2.8+0
China	228	32	309+1	29+0
India	95	22	46+1	2+0
Brazil	138	8	74+0	2+0
Russ. Fed.	74	16	56+0	1+0
Africa	28	9	7+0	-3+0
Japan	217	22	454+469	72+18
World	4575	469	4013+1326	460+63

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