Impact of NOx vehicle emission standards failure on Air Quality in Europe

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Introduction

Vehicle exhaust emission standards have been tightened in the EU for several decades now, in order to protect health and the environment. This has led to a substantial decrease in total pollutant emissions, despite the growing volumes of passenger and freight transport. However, national emissions, particularly of NOx, exceed the ceilings accorded under the Gothenburg Protocol of the UNECE's Convention on Long-Range Transboundary Air Pollution (LRTAP) (EEA 2012) in twelve EU Member States. The main reasons for such exceedances are that more diesel cars have been sold than originally predicted when fixing the targets, and that diesel cars emit much more than expected under real-world driving conditions. The latter appears as a consequence of the effort to achieve high fuel efficiency. While this has largely helped to control CO_2 emissions, it was to the detriment of NOx.

In this study we estimate what the impact of the different vehicle emission standards has been so far and to predict what the impact of upcoming emission standards will be in the future, using the best current knowledge on road transport activity statistics and emission factors in Europe. We present several sensitivity calculations to reflect the considerable uncertainty about the real-driving NOx emissions of diesel light duty vehicles. The results of this work can be useful in designing both limits for upcoming standards but also in assessing the impact of deviating from such limits. This is necessary in both deciding on the next steps of emission control policy and to relevant air quality prediction models.

Methodology

The GAINS (Amann et al. 2011) framework has been used to compile the different scenarios in this study. In GAINS, transport emissions are estimated on a national level and include road vehicles split into 6 categories, 5 fuel types and 7 control levels. In terms of non-road mobile sources, GAINS covers building and construction machinery, (diesel) locomotives, agricultural tractors, ships, and airplane LTO emissions. Finally, tyre and brake wear, and road surface attrition are non-exhaust PM sources. Estimates cover all relevant air pollutants: NO_x, NMVOC, CO, PM (as PM_{10}, $PM_{2.5}$, BC and OC), SO_2 and CO_2. We only address NOx emissions in this paper though, as this appears one single pollutant responsible for significant contribution to air quality issues in Europe today. Total national emissions from transport over a given year are then calculated according to eq. (1).

$$Em_p = \sum_{fc} (FC_{fc} * EF_{fcp}) \quad (1)$$

with:

- Em_p total national emission of pollutant *p* [Unit: kt]
- FC_{fc} energy consumption of vehicle category *c,* powered by fuel *f* [unit: PJ]
- EF_{fcp} emission factor of pollutant *p* for vehicle category *c*, powered by fuel *f* [unit: g per MJ].

The total fuel consumption per fuel type and member state is obtained by the PRIMES model. This means that for historic years, fuel consumption per fuel type refers to the official value reported by each member state to Eurostat. For future years, fuel consumption per fuel is based on the PRIMES 2010 reference scenario (EC 2011) with extensions to 2050 from the reference case of the 2050 'Roadmap for moving to a competitive low carbon economy' of DG-CLIMA study (EC 2011). PRIMES projections take into account energy consumption and transport activity evolution in historic years, expected energy prices and activity projections, and policy targets decided on a European Union level.

For road transport in particular, the total fuel consumption per fuel delivered by PRIMES needs to be allocated to the different vehicle types and control levels (emission standards). This is done following an iterative process. First, results from the FLEETS project (Ntziachristos et al. 2008) are taken into account with regard to detailed stock of vehicles per fuel and control level. Annual mileage values are also contained in the database. The vehicle activity per control level which is estimated by multiplying number of vehicles by the age-discounted annual mileage is then combined with fuel consumption factors taken from COPERT 4 (Ntziachristos et al. 2009) to estimate total fuel consumption. This is compared to the PRIMES estimate per fuel type. In case of deviations, the vehicle mileage is adjusted so that the bottom up calculation matches the PRIMES one.

The energy calibration is done both for historic and for future years. In the latter case, technological replacement as well as the improving vehicle efficiency with time need to be taken into account. For technological replacement we take into a number of different inputs. First, the total stock growth is also received by PRIMES. Second, intrinsic functions of scrappage rates in FLEETS estimate the number of vehicles per age group and vehicle type that leave the stock each year. The difference in the stock size from year to year plus the vehicles that are scrapped result to the total number of registrations that have to be introduced per vehicle type, country, and year. This demand for registrations is addressed by two sources. First, a distribution of second-hand registrations is estimated per age group, according to data from the relevant study of Mehlhart et al. (2011). Second-hand registrations are an important element for several countries in the eastern and southern Europe. The remaining demand for registrations is covered by new vehicle sales. This algorithm creates the age distribution of vehicles for each year of calculation. Using country-specific emission standard implementation matrices to account for national incentives on top of regular emission control intervals, the different age groups are then allocated to emission standards. Efficiency improvements are also considered for new registrations. These are generally following the EU commitments towards CO_2 reductions in the different vehicle categories.

Using this detailed algorithm, one estimates energy allocation per vehicle type, fuel, control level, country and year. By aggregating over the different control levels we obtain the FC_{fc} value, which is used in Eq.1. The next step in the process is to estimate representative emission factors. The average emission factor EF_{fcp} is calculated as the weighted sum of the emission factors per technology or emission concept *t* (i.e., identified by their EURO exhaust emission standard) for each combination of vehicle category *c* and fuel *f*, according to eq. (2).

$$EF_{fcp} = \sum_t (share_t * EF_{tp})_{fc} \qquad (2)$$

with:

EF average emission factor of pollutant p for vehicle category c, powered by fuel f [Unit: g per MJ];

share share of this technology t in total fuel consumption for vehicle category c, powered by fuel f [Unit: %], also called control share;

EFtpfc average emission factor of pollutant p for technology t, vehicle category c, powered by fuel f [Unit: g per MJ].

The emission factor per technology level is calculated using the COPERT 4 methodology. Emission factors per vehicle, fuel type, and technology level and unit of distance driven (g/km) are estimated taking into account local ambient conditions, share and mean travelling speeds of driving under urban, rural, and highway conditions, fuel effects on emissions, and the impact of vehicle age (degradation) on emission performance. For estimating the average emission factor per technology, we take as most representative the emission level corresponding to five years after the initial introduction of a vehicle technology. The distance-specific emission factor of COPERT 4 is then divided by efficiency to come up with the g per MJ emission expression used in GAINS. These values are then fed as EF_{tpfc} values into eq. (2).

Average emission factors

The standard average real-driving NOx emission factors derived by COPERT 4 (Ntziachristos et al. 2009) are shown in Table 1. Emission factors generally drop with control level, as expected. The only exception to this are diesel passenger cars where emission factors have not been dropping, while in cases they have been shown to increase with ‘improving’ control level under real-driving, though not over the homologation cycle. In fact, diesel Euro 5 appears as the technology with the highest emission factor historically even compared to the uncontrolled case. Expressed per unit of distance driven, the Euro 5 emission factor corresponds to a level of 0.85 g/km (emission limit = 0.18 g/km). This must be concluded from recent experimental data

(Carslaw et al. 2011; Hausberger 2010; Weiss et al. 2011) and there is currently little doubt that Euro 5 cars over real-world conditions exceed their NO_x emission limit several times. In our expression of emission factors per unit of energy consumed, the increase of Euro 5 over previous emission control levels appears actually higher, as vehicle efficiency improves with time. Emission factors for Euro 6 controls for diesel light duty vehicles are varied according to the scenarios defined below.

Table 1: Average NOx emission factor (g/MJ) per technology based on COPERT 4 (v10.0). Emission factors for Euro 6 diesel cars and light trucks are scenario assumptions.

Control Level	Motor-cycle	Gasoline PC	Gasoline LD Truck	Diesel PC	Diesel LD Truck	Diesel HD Truck
No control	0.109	0.841	0.77	0.269	0.425	1.012
Euro 1	0.278	0.171	0.127	0.289	0.372	0.791
Euro 2	0.254	0.101	0.055	0.290	0.372	0.856
Euro 3	0.111	0.042	0.032	0.335	0.309	0.657
Euro 4	n.a.	0.025	0.018	0.268	0.249	0.433
Euro 5	n.a.	0.025	0.016	0.376	0.346	0.248
Euro 6	n.a.	0.024	0.018	"Stepwise": 6a - 2014: 0.171 6b - 2017: 0.054	6a: 0.179 6b: 0.057	0.032
Euro 6 scenarios				"Legislation": 0.036 "Delayed": 6b only from 2020 "Proportional": 0.171 "Euro 6 = Euro 4": 0.268	0.038 0.179 0.249	

Scenario Definition

As there is major uncertainty about the future level of real-driving NOx emissions from light duty diesel vehicles, we design five scenarios by varying the Euro 6 emission factor. We do not intend to predict the future, but to analyse the impact of this technology on future emissions. The following assumptions on the real-driving NOx emission factor for Euro 6 light duty diesel vehicles are taken:

- "Legislation": The average real-driving NOx emission from Euro 6 diesel LDV is assumed equal to the emission limit value of 80 mg/km from 2015 onwards. With current knowledge, this seems a low emission scenario.

- "Stepwise lower": A stepwise reduction of real-driving emissions is assumed, such that a first generation of Euro 6 vehicles (Euro 6a) delivers a reduction over Euro 5 proportional to the reduction in emission limit values by 2014 (2015), i.e. about 380 mg/km. The second generation vehicles (Euro 6b) are assumed to emit on average 1.5 times the limit value under real-world driving from 2017 (2018) onwards, i.e. 120 mg/km. This reduction results from the introduction of real-drive emission controls e.g. by on-board PEMS. *We take this as reference scenario.*

- "Delayed steps": As above, but second generation vehicles (Euro 6b) only from 2020 onwards because of delayed introduction of real-drive emission controls.

- "Proportional": Euro 6 vehicles are introduced in 2015 but they only deliver emission reductions proportional to the ratio of the emission limits over Euro 5, i.e. about 380 mg/km. This is the 'default' approach used by COPERT 4.

- "Euro 6 = Euro 4": Assume, real-driving emissions from Euro 6 LDDV are only about 30% lower than the previous generation and hence at about the level of Euro 4 vehicles. This pessimist scenario would correspond to historic experience that new emission limit value did not result in reduced real-driving emissions.

Results

Figure 1 shows the energy consumption allocation aggregated for the most important vehicle categories (left panel) and for the light duty diesel vehicles (right panel), where this analysis focuses on. According to this scenario, total road fuel consumption in EU27 increases to about 13000 PJ in the years 2015 and 2020, after which it declines gradually to 12500 PJ in 2030, about the same level as in the year 2005. This means transport growth largely offsets improvements in vehicle fuel efficiency. Gasoline cars account for about one third of total road fuel consumption in the year 2010, heavy duty trucks, diesel cars and light commercial diesel vehicles for 25%, 23% and 11% respectively. These shares are projected to remain largely constant for the next decades.

New emission control technologies penetrate gradually the vehicle fleet (right panel of Figure 1). Uncontrolled passenger cars basically become extinct just before 2015. Conventional light duty trucks disappear some 5 years later. Already in 2020 Euro 6 cars are responsible for approximately 50% of total energy consumption. This is the combined effect of the replacement rate and the fact that new cars are generally driven more than older cars. Therefore, energy consumption should not be taken as directly equivalent to vehicle numbers in the stock. Euro 5 cars are responsible for some 25% of total energy consumption in 2020 and the remaining 25% is allocated to older technologies (as old as Euro 1). Technological replacement is somewhat slower in light trucks due to the later implementation dates and the longer useful lives, compared to passenger cars.

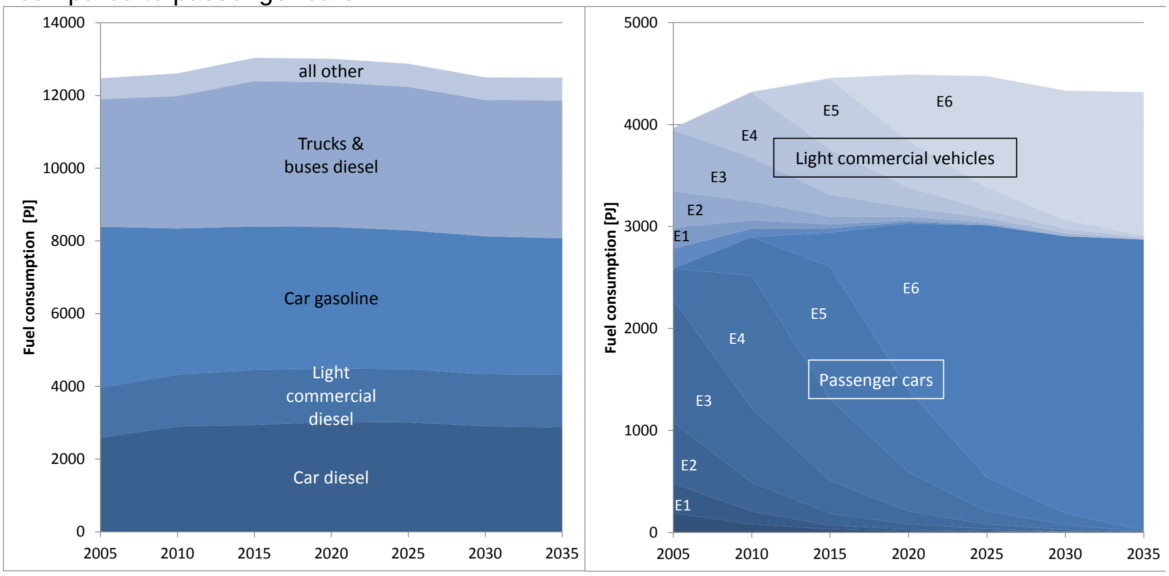

Figure 1: Evolution of road fuel consumption in EU27 from 2005 to 2035 according to the PRIMES 2010 Reference scenario. Left: All road vehicles, right: Close-up on light duty diesel vehicles, showing the gradual penetration of Euro control standards (abbreviated E1 to E6).

In the Reference scenario total NOx emissions from road vehicles in EU27 are expected to decrease from 5000 kt in the year 2005 to 3100 kt in 2020 and further to 530 kt in 2035 (Figure 2, left panel), despite largely constant fuel consumption. Until 2020 this decrease is largely due to reductions in unit emissions from heavy duty vehicles (-75%) and from gasoline cars (-86%). Emissions from light duty diesel vehicles actually increase until 2015 (Figure 2, right panel). That is because the average emission factor increased, because of an increasing share of diesel cars in the fleet, and the overall increase in passenger transport activity in the period. In fact, had the financial crisis not hit in this period, NOx increases from LDVs would have been even higher.

Emissions from light duty diesel vehicles are projected to decrease only when Euro 6 vehicles enter the fleet from 2015 onwards (in the Reference scenario). Their unit emissions are effectively a factor seven lower than from Euro 5 vehicles. By 2035, when effectively all light duty diesel vehicles are certified to Euro 6, emissions are expected to have decreased by 80% compared to the year 2005.

As a result, the contribution from road transport to total NOx emissions in EU27 decreases from 44% in 2005 to 33% in 2020 and eventually 15% in 2035, provided the Euro 6 emission standards will be effective in real-driving.

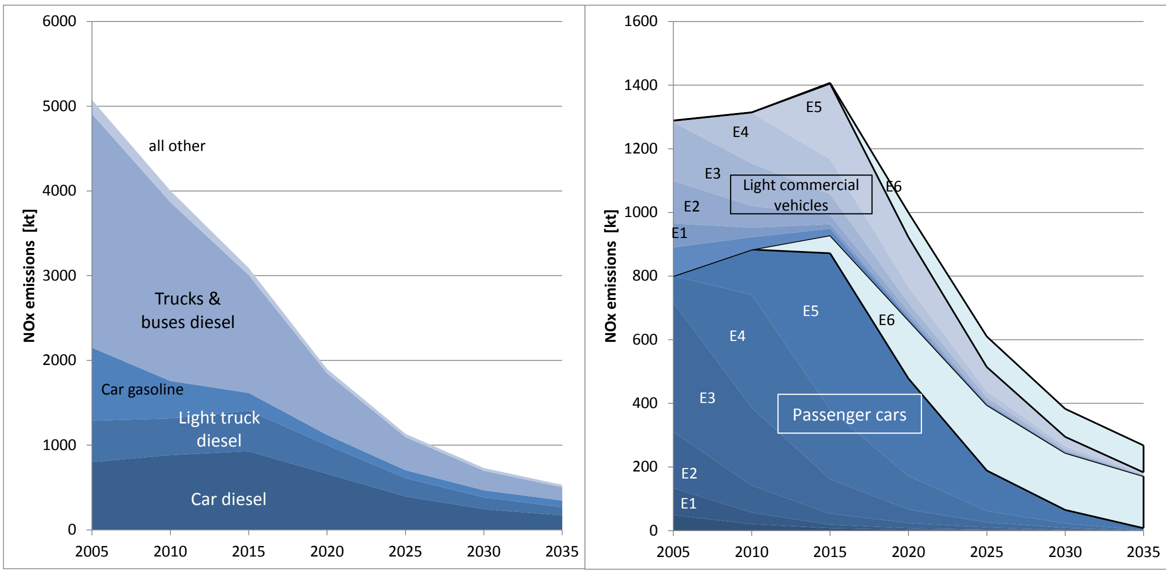

Figure 2: Evolution of NOx emissions from road transport in EU27 from 2005 to 2035 according to Reference Scenario. Left: All road vehicles, right: Close-up on light duty diesel vehicles, highlighting that only with an effective Euro 6 emission control emissions are expected to decrease. The calculation is made in 5 year steps; therefore the turning point from 2018 onwards is not visible.

Figure 3 shows a range of possible developments of total NOx emissions from road transport in EU27 depending on the timing and level of real-driving NOx emissions from Euro 6 light duty diesel vehicles.

- Because of the big emission reductions from heavy duty vehicles and gasoline cars there is little doubt that total NOx emissions are going to decline significantly. Further, all scenarios assume that Euro 6a and 6b unit emissions will be lower than Euro 5, hence total emissions are expected to continue decreasing beyond 2015.
- A potential delay in timing of the Euro 6.2 emission standard with an assumed 120 mg NOx/km on real-driving would result in 120 kt and 95 kt more NOx emissions in 2020 and 2030 or 6% and 13% more than in the Reference scenario, respectively.
- If Euro 6 vehicles would only deliver a proportional reduction on real-driving, then NOx emissions from light duty diesel vehicles would be twice as high as in the Reference scenario in 2030; in consequence, NOx emission from all road vehicles would be higher by 60% in that year, though at a much reduced level.
- If Euro 6 vehicles would bring only a small reduction and emit e.g. as Euro 4 vehicles, then emissions from light duty diesel vehicles would only slightly decline to about 1200 kt. In that case emissions from all road vehicles would be more than twice as high as in the Reference scenario in the year 2030 and almost three times higher in 2035, still down by 70% compared to the year 2005.

Clearly the future level of NOx emissions, and consequently of NO2 ambient concentrations, depends on the effectiveness of Euro emission controls under real-driving conditions. Emissions for light duty diesel vehicles will only decrease in about the same rate as e.g. from trucks if the Euro 6 norm is really effective. At the moment this is not guaranteed given preliminary measurements, that the emission test cycle has not yet been modified, and that the real-driving controls have not yet been defined. Therefore, efforts should be concentrated on introducing an effective RDE policy package for the Euro 6 standard.

The impact different NOx emissions on the exceedance of annual NO2 concentration limit values will be analysed in follow-up work.

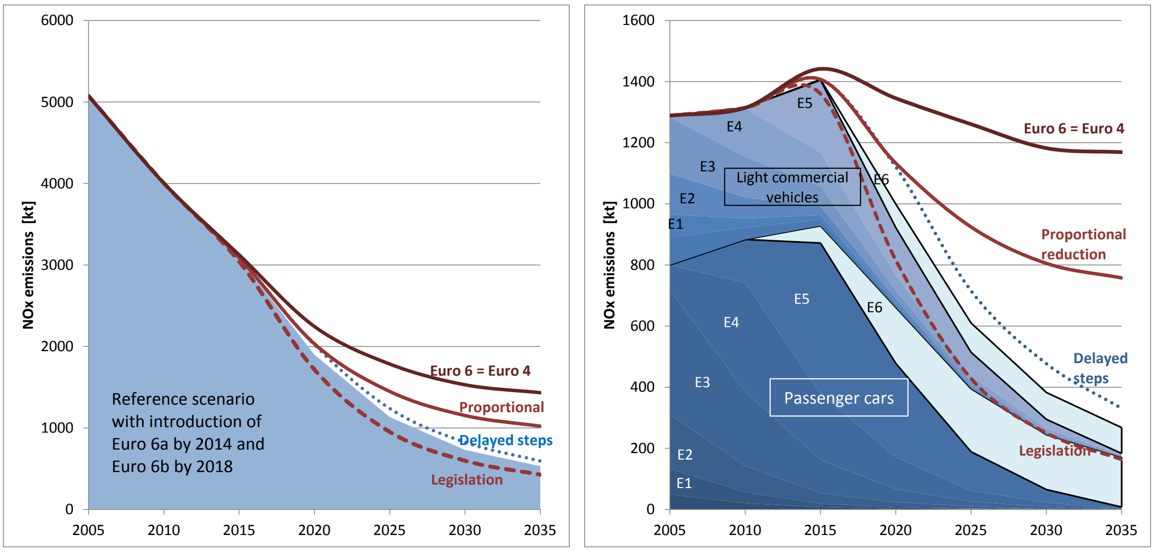

Figure 3: Evolution of NOx emissions in EU27 from 2005 to 2035according to different scenarios on timing and level of real-driving NOx emissions from Euro 6 light duty diesel vehicles. Left: Emissions from all road vehicles. Right: Emissions from light duty diesel vehicles only.

Conclusions

A range of possible scenarios about future evolution of NOx emissions has been presented in this study, with the aim to assess the necessity and the potential of additional measures towards improving air quality in Europe. The following conclusions can be drawn based on the analysis:

- Total NO_x emissions from road transport are expected to decrease, mostly as a result of efficient heavy duty emission control, although the emission control of diesel light duty vehicles has historically been below expectations.

- Current and foreseen measures decrease the contribution of transport to total manmade NOx from 44% in 2005 to 15% in 2035.

- The effectiveness of the upcoming Euro 6 regulation for diesel light duty vehicles is of paramount importance for improving air quality in Europe. No firm provisions are yet in place and initial measurements show a wide range of possible emissions. Failure could almost double NOx emissions from road vehicles in 2035, an extra of 14% on the total manmade emissions. Effective control of *real-drive emissions* is crucial.

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