Vehicle Emission Deterioration Derived from Long-Term On-Road Measurements

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Introduction and state-of-knowledge

The effectiveness of vehicle exhaust after-treatment systems degrades with use, due to mechanical usage, wear of catalyst's coatings, poisoning of the catalyst and similar factors. Standard knowledge on the deterioration of emissions from gasoline cars in Europe is reflected in the respective chapter of the EMEP Guidebook for calculating emission inventories (1). A linear deterioration of unit emissions with vehicle mileage or age respectively is assumed. By lack of data, it is assumed that emissions do not further degrade above 120 000 km for Euro 1 and 2 vehicles and 160 000 km for Euro 3 and 4 vehicles, and remain constant thereafter. Due to lack of data the deterioration rates from gasoline cars are also assumed for gasoline light commercial vehicles. These values are based on a sample of about 30 records each for gasoline cars of emission control stages Euro 1 and Euro 2. However, very few Euro 2 cars had been driven more than 60'000 km at the time. All but two Euro 3 and all Euro 4 cars were driven less than 30'000 km at the time (2). Hence there is an urgent need to extend the sample for older and high-mileage cars, notably for Euro 3 and Euro 4 technologies.

Here we present deterioration factors that are based on a sample of about 113'000 records of gasoline passenger cars hot on-road emission over thirteen years of successive annual measurements in Switzerland. The large sample allows determining deterioration over vehicle age in so far unrivaled statistical accuracy, including high-mileages, and representative for the car fleet certified to Euro norms 1 to 4. These norms became mandatory in Europe in years 1992, 1996, 2000, 2005 respectively, setting emission limits for homologation tests, as well as in-use and durability standards. The time series for Euro 5 light duty vehicles (model years 2009ff.) is not long enough to allow a meaningful deterioration analysis. Our results suggest significant changes to established data, notably for older cars and vehicles with higher mileage.

Measurement site and data treatment

Vehicle emissions have been measured annually for more than 13 years now through on-road remote sensing at an extra-urban site just outside Zurich/Switzerland. The details of the measurement site and set-up have been reported elsewhere (12, 13). Here we only note that the road has an uphill gradient of 9.2°; to compare with measurements under flat driving we convert the gradient into an additional acceleration of approximately 1 m/s^2. The vehicles passing have a mean speed of 46 km/h and a mean acceleration rate of 1.1m/s^2; the 95th percentile speed and acceleration are 58 km/h and 2.8 m/s^2, respectively. Thus they indeed cover a wide range of engine conditions, which are even much wider than e.g. the legislative chassis dynamometer test cycle (13). Variation arises essentially from the emission rate of the individual vehicles and from the accuracy of the instrument. The measurements were performed with the same instrument (envirotest RS 3000) in years 2000 to 2010, with a envirotest RS 4600 for years 2011 and 2012, and with a different envirotest RS4600 in 2013. Routine calibrations were performed every hour and mean values are within 10% uncertainty between the two instruments. Data have been corrected for instrument drift on an hourly basis, thanks to Robert Gentala from envirotest. In parallel with the remote sensing measurements the number plate of each vehicle is recorded. This allows associating the emission measurement of any particular vehicles with its registration data, notably its emission control stage and year of first registration. Thus, the difference between the year of measurement and the year of first registration is used as vehicle age here. Age in turn is translated into mileage assuming average values from the latest Swiss survey (4).

For this study we analyzed more than 170'000 records measured annually between years 2000 and 2013. They represent average on-road emissions from gasoline vehicles of up to 25 years old, and are hence uniquely suited for following mean unit emissions of a vehicle technology over time. In order to avoid irregular emission behavior at deceleration, high instantaneous acceleration, and top speeds we only use emission records for vehicle speed between 20 and 58 km/h (5% percentile to 95% percentile), and accelerations between 0 to 2.8 m/s^2. Furthermore, to ensure a sufficient statistical basis we require at least 100 records for gasoline cars for each mean value. In addition, means are only used if their 95th confidence interval is smaller than half the mean value. After these filters, we here use about 113'000 records for gasoline cars across Euro 1 to Euro 4 technologies, with about 20'000 to 30'000 records for each technology. In order to control for the variability of emission factors due to driving conditions and vehicles conditions, we have compared VSP, vehicle weight and vehicle engine power by vehicle accumulated mileage (Figure 1). The vehicle specific power (VSP) is a measure for engine load and useful for comparison between different measurement conditions (14). The mean VSP is about 18.5 kW/t and varies only by ±1 kW/t across the different vehicle ages. The ratio of engine power to vehicle mass is taken as indicator for the vehicle characteristics. More modern cars tend to have higher installed power, hence the mean increases from about 71 to 76 kW/t; but within each vehicle layer, the mean varies only by ±2 kW/t, with the notable exception of Euro 4 cars, where the power is consistently declining beyond 10 years of age. Given these largely stable relations, we can claim that driving conditions and vehicle characteristics are similar among different vehicle ages under each vehicle segment. Hence, changes in vehicle emissions can be mainly attributed to vehicle usage, i.e. deterioration.

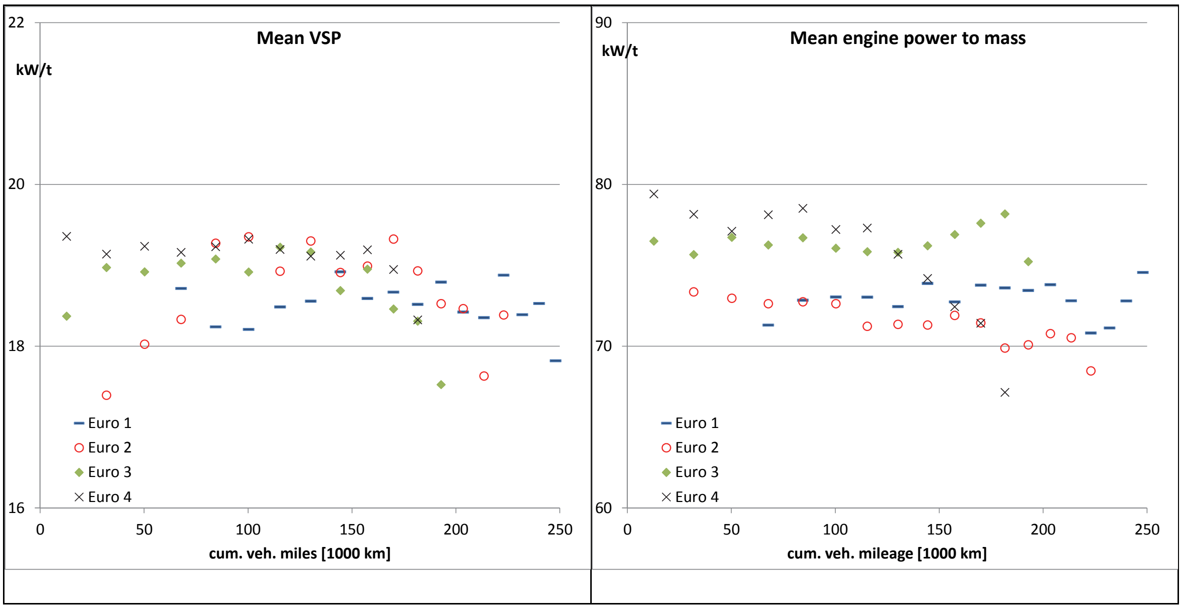

Figure 1: Mean VSP (left) and mean ratio of engine power to vehicle mass (right) as a function of cumulative mileage for each vehicle technology for gasoline passenger cars from remote sensing in Zurich/CH.

The measured concentration increments are converted to emission factors per unit fuel consumed assuming complete combustion (5). Measured NO concentrations are converted to NO_x assuming a certain share of NO2 emitted in primary form. According to the standard Handbook on Emission Factors (HBEFA) the primary share of NO2 emitted is independent of the exact driving conditions (6), hence the change rates derived in the following are independent of the exact pNO_2-share assumed. For gasoline powered vehicles the share is found constant at 7% across all technologies. No deterioration has been observed for the CO_2 emissions or the fuel consumption respectively from the different vehicles (7). Therefore we can assume that the denominator in our emission factor is stable, and hence that all measured changes are essentially a consequence of changes in the engine combustion or the exhaust after-treatment system.

Emission deterioration of gasoline passenger cars

The long-term remote sensing measurements of gasoline powered passenger cars can confirm a number of key assumptions of the EMEP/EEA deterioration rates (15). There is a gradual increase of unit emissions with vehicle age (mileage); the deterioration rates need to be differentiated for each pollutant; deterioration rates are high for Euro 1 and Euro 2 technologies, and significantly lower for Euro 3 and Euro 4 technologies. However, various other important assumptions cannot be confirmed and should better be corrected as follows (Figure 2):

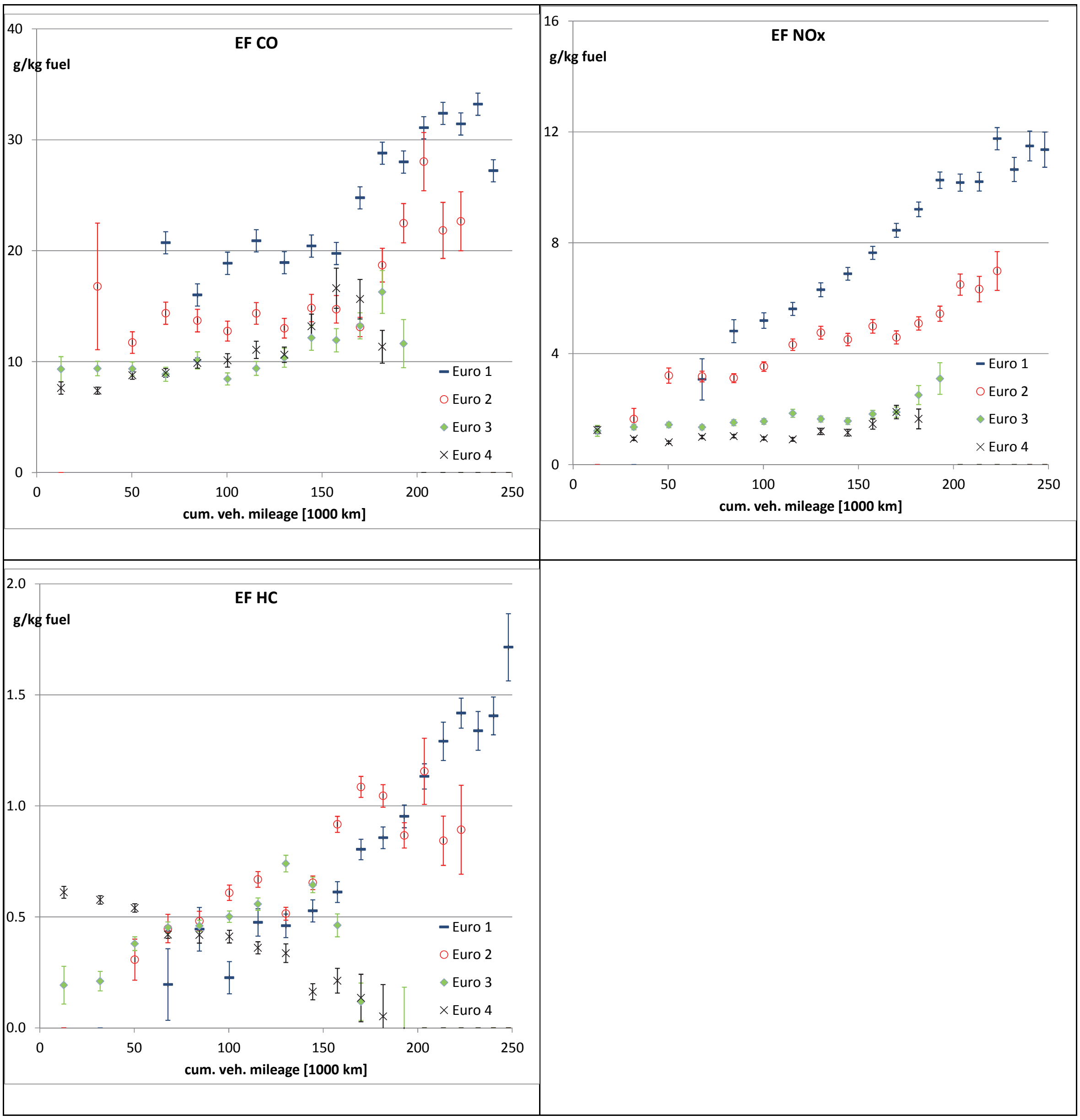

Figure. 2: Unit emissions of CO (upper left), NO_x (upper right) and HC (lower left) of gasoline passenger cars as a function of vehicle mileage for Euro 1 to Euro 4 technologies. Each dot represents the mean value over at least 100 individual measurements; the whiskers represent the standard deviation of the mean.

- Deterioration rates differ for all Euro norms; the rates are not identical for Euro 1 and 2 technologies nor for Euro 3 and 4 technologies, as suggested by the EMEP/EEA formula.
- Deterioration continues for all pollutants and all technologies beyond the limits of 120'000 and 160'000 km assumed by EMEP/EEA for Euro 1/2 and Euro 3/4 technologies. In particular, long-term deterioration for Euro 3 and Euro 4 vehicles is significantly higher, thus these vehicles contribute more to the total emissions.
- For Euro 1 and Euro 2 cars, observed deterioration rates of CO and NO_x emissions are significantly lower compared to the rates suggested by EMEP/EEA, while in the same order of HC emissions up to 120'000 km, much lower.
- For Euro 3 cars, observed deterioration rates of NO_x emissions are significantly higher compared to the rates suggested by EMEP/EEA, while CO and HC deterioration rates can be confirmed (except for mileages higher than 160'000 km).
- For Euro 4 cars, observed deterioration rates of NO_x and CO emissions are about twice as high as the rates suggested by EMEP/EEA, while HC emissions actually decrease with mileage. This has also been observed in the original ARTEMIS data (8). It is therefore not evident that the assumption of constant unit emissions is well founded.

In order to understand the relationship between vehicles' cumulative mileage and its unit emissions, we fitted the data with three statistical models, i.e. linear regression model, logarithmic model (nature log transformation on accumulated mileage) and exponential model (nature log transformation on emission factors). The best-fitted statistical model for each pollutant / vehicle technology is selected using the Akaike information criterion (AIC_p). AIC_p is a measure of the relative goodness of fit of statistical models for a given set of data (9). Based on the AIC_p selection criteria, the exponential model (i.e. nature log transformation on emission factors) performs better than the other two regression models for majority segments except for HC of Euro 2 and Euro 4 where a linear regression provides the best fit. In addition, the aging effect is not statistically significant on emission factor of HC for Euro 3.

Comparison of deterioration rates

We define the deterioration rate as the percentage change rate of the emission factor at mileage x over the emission factor of a new car: EF(x km)/EF(0 km) – 1. This relative measure allows comparing the deterioration rates given in g/km with the change rates from our observational data in g/kg fuel. We assume for our data the best fitting regression curves as determined above, i.e. exponential increase, except for linear functions for HC Euro 2 and Euro 4 technologies. Table 1 summarizes deterioration rates at 50'000, 100'000 and 200'000 km for gasoline passenger cars, comparing with deterioration rates according to the EMEP/EEA guidebook at the average speed of 45 km/h at the measurement site.

Table 1: Illustrative deterioration rates for gasoline passenger cars at 50'000, 100'000, 200'000 km according to EMEP/EEA and as derived from remote sensing measurements in Zurich (RS-ZH).
EMEP/EEA*: Calculated for the average speed of 45 km/h at the measurement site; arithmetic average over size classes (<1.4l, 1.4-2.0l, >2.0l); deterioration rate relative to EF @ 0 km.
a: Deterioration rate at 120'000 km – thereafter constant; b: deterioration rate at 160'000 km – thereafter constant.
RS-ZH: Exponential regression curve for all technologies and pollutants, except for HC Euro 2 and Euro 4.

			Euro 1			Euro 2		
	Pollutant	engine size	**50k**	**100k**	**200k**	**50k**	**100k**	**200k**
EMEP/EEA*	CO	<1.4l	154%	309%	370%[a]	154%	309%	370%[a]
		1.4l-2.0l	89%	178%	214%[a]	89%	178%	214%[a]
		>2.0l	43%	85%	102%[a]	43%	85%	102%[a]
RS-ZH	**CO**	**avg.**	**25%**	**55%**	**94%**	**16%**	**35%**	**57%**
EMEP/EEA*	NOx	all	201%	402%	483%[a]	201%	402%	483%[a]
RS-ZH	**NOx**	**avg.**	**35%**	**84%**	**149%**	**33%**	**76%**	**133%**
EMEP/EEA*	HC	<1.4l	62%	125%	150%[a]	62%	125%	150%[a]
		1.4l-2.0l	97%	195%	234%[a]	97%	195%	234%[a]
		>2.0l	83%	166%	199%[a]	83%	166%	199%[a]
RS-ZH	**HC**	**avg.**	**76%**	**210%**	**446%**	**122%**	**243%**	**365%**

			Euro 3			Euro 4		
			50k	**100k**	**200k**	**50k**	**100k**	**200k**
EMEP/EEA*	CO	<1.4l	24%	47%	76%[b]	24%	47%	76%[b]
		>1.4l	6%	11%	18%[b]	6%	11%	18%[b]
RS-ZH	**CO**	**avg.**	**13%**	**28%**	**13%**	**28%**	**13%**	**28%**
EMEP/EEA*	NOx	<1.4l	0%	0%	0%[b]	0%	0%	0%[b]
		>1.4l	9%	18%	28%[b]	9%	18%	28%[b]
RS-ZH	**NOx**	**avg.**	**21%**	**47%**	**21%**	**47%**	**21%**	**47%**
EMEP/EEA*	HC	<1.4l	8%	16%	25%[b]	8%	16%	25%[b]
		>1.4l	0%	0%	0%[b]	0%	0%	0%[b]
RS-ZH	**HC**	**avg.**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**

The biggest discrepancies are found generally at mileages above the assumed EMEP/EEA limit, and for CO and NO_x emissions of Euro 1 and 2 cars, where deterioration is overestimated by several factors. Deterioration rates of HC seem to be estimated quite well for Euro 1 and 2 cars, given the uncertainties around this measurement. The observed data suggest a negative deterioration effect on HC unit emission for Euro 4 passenger car, i.e. as vehicle mileage getting higher, HC unit emission is getting lower. On the other hand, observed deterioration rates for European gasoline cars of Euro 3 and Euro 4 technologies (MY 2000ff and 2005ff) of CO and NO_x are higher than previously assumed, and the differences increase the higher the mileage due to the assumed exponential deterioration.

Discussion

Our results are derived for the fleet and maintenance conditions of vehicles measured in Zurich. It is known that different manufacturers use exhaust emission controls with varying characteristics (10, 11). Hence countries' fleets the emission levels might be different, but change rates are expected to be similar.

There is anecdotal evidence that the oldest vehicles are actually those that are either particularly well maintained or have actually a much lower mileage. Therefore it is possible that the apparent deterioration for the oldest age group slows down as a consequence of this sampling bias. But if this phenomenon is present in our data, it is not the same for all pollutants. Nonetheless it might be worth to experiment with deterioration functions that are piecewise defined, to reflect the changed behaviour better. In other words one regression line may not the best fit for all data ranges. Certain vehicles like taxis will be driven much more annually than the average private car. Hence, their apparent deterioration with age would be higher. However, given that the cars were measured at an extra-urban rural community we can rule out a significant influence of taxis over the thirteen years of observation.

With new understanding of the long-term deterioration it would be good to re-calculate the impact on the resulting totals compared to previous calculations. We can expect lower absolute contributions of CO and NO_x from older Euro 1 and Euro 2 cars. On the other hand, we can also expect higher absolute contributions of CO and NO_x from Euro 3 and Euro 4 vehicles. Their impact on total emissions depends on the mileage share of these vehicles in the fleet at any given point in time. Given that Euro 3 and Euro 4 account for a significant amount of vehicles in the current on-road fleet in Europe, it is worth to reassess the impacts of higher Euro 3 and Euro 4 deterioration factors on the total road emissions. Given this revision, the air pollution benefits of scrappage programs targeting the oldest vehicles Euro 1 and Euro 2 may have been overestimated, while durability of later technologies may not be as persistent as assumed.

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