TRENDS IN REGULATED AND NON-REGULATED EMISSIONS OF CARS IN BOTH STATUTORY AND REAL-WORLD DRIVING CONDITIONS – DO THEY STILL FOLLOW REGULATIONS?

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ABSTRACT

As emission regulations for cars become more and more stringent for both gasoline and diesel technologies, it is of interest to see if both cold and hot emissions of vehicles from the fleet follow the trends outlined by regulations. Both regulated and non-regulated emission data was collected for groups of cars (8 – 30 vehicles each) for legislation levels Euro-2 to Euro-4, separately for diesel and gasoline engines. In considering regulated and non-regulated gasoline vehicles emissions it can be clearly seen that improvements in the statutory tests are significantly smaller from Euro-3 to Euro-4 than previously. Cold start emissions remaining almost equal in particular contribute to this finding. In addition the discrepancy between hot emissions in the legislative test and in real-world tests is increasing. Improvements from Euro-3 to Euro-4 (without diesel particle filters - DPF) for both important pollutants, NO_x and particle mass, are also small for diesel vehicles. This is paralleled by an increasing share of NO_2 in NO_x. In contrast the group of Euro-4 vehicles with DPF shows a dramatic drop in particles. Unfortunately this is combined with an increase in both NO_x and in the NO_2 share in NO_x (up to 65%). Consequently, emission estimates assuming real-world emissions improving in line with legislative limits need to be corrected.

Keywords: *Emission trends, emission development, legislative tests, real-world emissions, light vehicles.*

1. INTRODUCTION

As air quality is still not adequate in many locations in Europe (and the world) and traffic contributes greatly to air pollution, emission limits for motor vehicles are consistently tightened stepwise (Carslaw, 2004). Three-way catalysts have existed for more than 20 years and have reached a pollution reduction rate of more than 99%, even in transient driving. Their hardware and software have been optimised in many ways to minimize emissions. Many engineers assume that the actual emission levels are close to what is “technically feasible” and that adaptation to even more stringent legislative levels will become difficult with current exhaust system concepts. This is also true for diesels, although their exhaust aftertreatment systems such as particle traps and de-NO_x Systems or NO_x traps (NO_x: nitrogen oxides) do not have such a long history. It may be assumed, however, that emission quality is no longer decreasing in line with emission limits.

As the test cycle for homologation in Europe differs substantially from real-world driving, it may also be assumed that the increasingly sophisticated engine control units allow adaptation so that the difference between test-cycle emissions and real-world emissions may increase. The aim of this paper is to investigate if the real emissions of the newer vehicle classes are still decreasing in line with legislative limits as was the case in the last decade for Euro-1 and

Euro-2 vehicles. To do this, emission results from fleets of cars of Euro-2 to Euro-4 legislation levels in both regulated and real-world cycles are compared here for both diesel and gasoline vehicles. Such a comparison is important for fleet emission modellers as they have to decide on future emission quality development on the basis of present-day data in order to be able to make reliable emission forecasts for future years (e.g. de Haan 2000, Fischbeck 2007, Singh 2000).

In the following section the tests on which the comparison is based are described. The variation in emissions in legislative cycles is then presented, after which the trends in real world emissions are presented.

2. DESCRIPTION OF DATA SETS

2.1. Vehicles

Six groups of vehicles are used in this comparison: gasoline Euro-2 to Euro-4 and diesel Euro-2 to Euro-4. As shown in Table 1, each group of cars consists of 10 to 30 vehicles which, according to Joumard (2006) should be sufficient to achieve statistical relevance. As the Euro-3 and Euro-4 diesel groups were split into "non-particle filter (standard)" and "particle filter (PF)" subgroups, these subgroups are somewhat smaller. All groups of vehicles were chosen so that they represent an engine size and manufacturer distribution representative of the Swiss fleet. The individual vehicles were chosen so that each group has an average mileage of around 60,000 km (as the tests with gasoline Euro-3 took place early in 2001, the fleet was too new to have reached this mileage). They were recruited from private owners and tested without maintenance to obtain as realistic results as possible.

Table 1: Overview of vehicle characteristics

Category	No of vehicles	Empty mass [kg]	Average engine size [cm^3]	Power [kW]	Average mileage [km]
Gasoline Euro-2	30	1366	1960	87	54'119
Gasoline Euro-3	23	1285	1819	92	31'103
Gasoline Euro-4	20	1334	1962	99	57'609
Diesel Euro-2	8	1494	2146	82	65'761
Diesel Euro-3[1]	10	1570	2000	92	61'717
Diesel Euro-4	16	1537	2009	95	57'509
Diesel Euro-4 standard	10	1509	1873	85	63'822
Diesel Euro-4 with PF	6	1584	2236	112	46'988

To avoid disturbing this method of selection and to prevent additional laboratory effects no data was incorporated from other laboratories, despite the fact that this would have increased the statistical stability. For a detailed list of the various vehicles see Alvarez (2007a & b), Soltic (2001), Stettler (2004), Stilli (2006) and Vasic (2006) or contact the authors.

2.2. Test procedure

All tests were run at Empa on the same two chassis dynamometers using the same measurement equipment. Certified exhaust gas analysers were used for the measurement of regulated emissions. Standard CLDs (chemiluminescence detectors) were used with and without converter to collect NO (nitrogen monoxide) and NO_2 (nitrogen dioxide). They were operated in the online mode (10 samples per second) to avoid chemical transformations occurring typically in exhaust gas collection bags (Weilenmann, 2005). The latter pollutants

[1] One vehicle in the Euro-3 Diesel group was equipped with a DPF.

were also recorded together with benzene, toluene, xylenes and ammonia using a CI-MS (Brühlmann 2006). This device was also connected by short lines to the tailpipe, collecting raw exhaust gas directly to minimize deposition. Exhaust particles were monitored as follows: for all diesel and some gasoline vehicles PM mass was recorded gravimetrically by a certified CVS system (constant volume sampling). For the newer diesel and gasoline cars PM number was also measured using a CPC (condensation particle counter). The CPCs were used with an evaporation tube (mainly in accordance with PMP 2007) and for some vehicles a cold CPC was also added. The latter is not discussed here.

A difficulty in this comparison is that both legislative and real-world cycles changed over generations. For Euro-2 vehicles the statutory NEDC test began with 40 s idling before the measurement and the driving cycle started. The data of the ECE cycle (first part) and of the whole NEDC of these vehicles therefore cannot be compared to Euro-3 and Euro-4 data for which the NEDC2000 without these 40 seconds is used.

Different cycles were used for the collection of (real-world) cold-start extra emissions in the past. To calculate cold-start extra emissions, that is the difference in emissions of the same test run once with cold and once with hot-stabilized drive trains, repetitive cycles of sufficient length are necessary as the duration of the warm-up phase is *a priori* unknown. The first part of the legislative NEDC cycle containing four repetitions of the ECE speed pattern is found to be too short for the last repetition to be used as completely hot. It is therefore not suitable for identifying cold-start extra emissions. The US FTP-75 shows equal driving patterns of sufficient length in the first and third (phase) bags. Unfortunately the third phase is run after a stoppage of 10 min and cannot be considered completely hot. Establishing the difference between bags 1 and 3 will therefore somewhat underestimate cold-start extra emissions. As this cycle is the only one driven with all vehicles, it will nevertheless be used here for comparison. In the ARTEMIS project a strongly repetitive cold-start cycle was established using 15 repetitions of IUFC (= INRETS urbain fluid court = short urban free flow cycle of INRETS, André 2004) to calculate cold-start extra emissions. The group of Euro-2 gasoline vehicles was not measured with this cycle.

Two different sets of cycles were used for the measurement of real-world emission of hot engines (more accurately drive trains). Firstly the R-cycles based on the Handbook (HBEFA 2004) datasets are used. These consist of 12 subcycles belonging to different traffic situations Secondly the CADC from the ARTEMIS project is used (André 2004). This consists of 14 subcycles. The results of both sets of cycles are pooled here to one hot real-world-emission factor according to the weighting of the Swiss traffic behaviour. The group of Euro-2 gasoline vehicles was not measured in the latter cycle. Both sets of cycles were derived from real-world data, but show substantial differences in dynamics.

3. EMISSION EVOLUTION IN STATUTORY TEST

It should be noted that ordinary commercial fuel was used for the statutory tests done in this project, not the special certification fuel that has to be used for homologation. As the vehicles were not maintained either, these results cannot be compared to homologation or in-use compliance data. They nevertheless present a realistic picture of real vehicle fleet behaviour.

In Figure 1 regulated emissions for gasoline vehicles are presented. As stated above for the Euro-2 group of cars the ECE part of the cycle was slightly different, so emissions cannot be compared directly.

It can clearly be seen that for all regulated pollutants the measured values decreased more sharply than the limit values for the step Euro-2 to Euro-3 and the opposite for the step Euro-3 to Euro-4. NO_x even rises. This is also reflected in the fact that the percentage of vehicles failing the test falls from 27% to 0% and rises again to 30% from Euro-2 to Euro-4. As the Euro-3 fleet had a lower mileage its emissions are possibly somewhat optimistic. However, the trends from Euro-2 to Euro 4 can be seen to be less clearly downward than the legislative limit values.

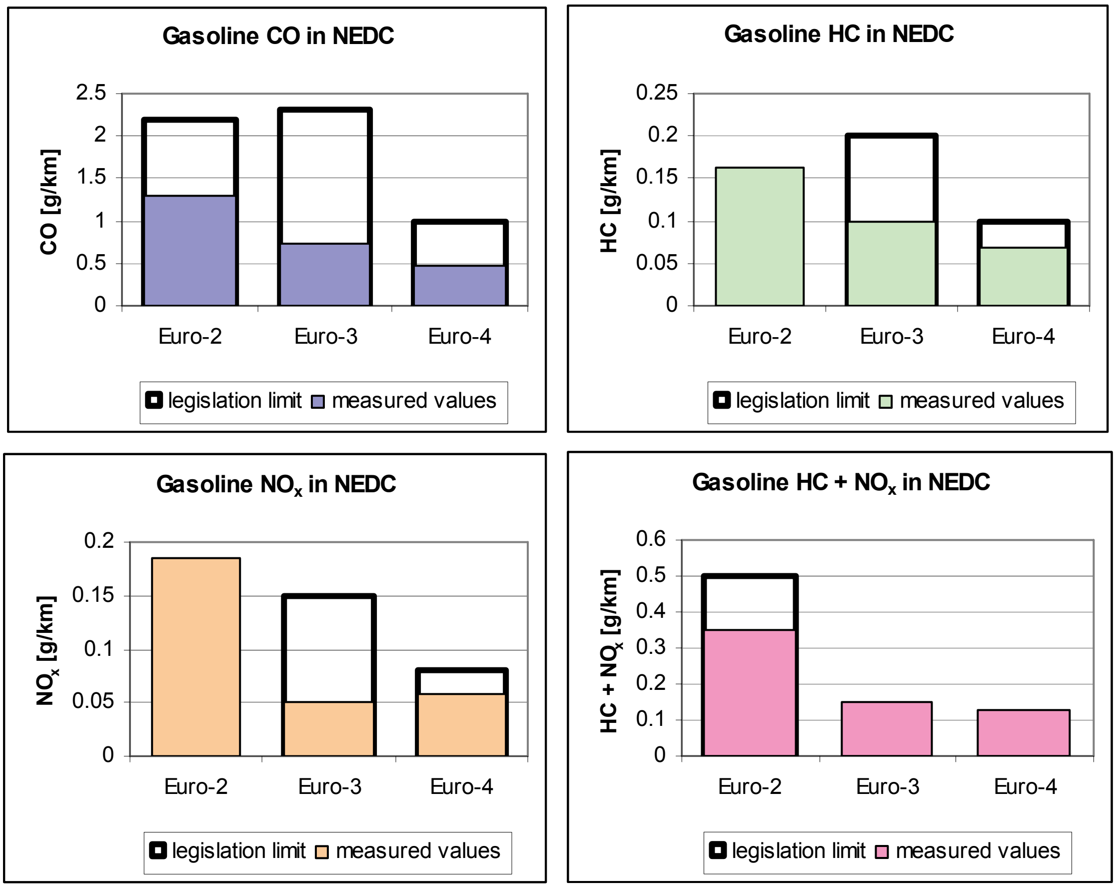


Figure 1: Regulated emissions of gasoline vehicles in legislative test (NEDC)

As Figure 2 shows, both the absolute values of benzene and the benzene to HC ratio decrease with the generations. It should be noted that the fuels for the three test series were not the same. Benzene content varied slightly between 0.7 and 0.8% and the content of aromatics was between 32 and 35%. As shown in Heeb (2003) two different effects cause the benzene/HC ratio to rise. In a rich air-to-fuel mixture the hot catalyst converts other aromatics to benzene. In lambda = 1 situations (stochiometry) no benzene is formed in the catalyst but the amount of benzene coming from the engine is not reduced as efficiently as other hydrocarbons. The results here indicate that for the older vehicles fuel enrichment was still active during warm-up when the catalyst was already converting, and benzene was thus reformed. With more and more vehicles having lean warm-up, this is reduced.

Figure 3 shows the emission trends over generations for diesel vehicles. The sole pollutant for which measured values fall faster than in legislation is CO (carbon monoxide). By analysing the online signals it was seen that this comes from earlier light-off of the oxidation catalysts possibly combined with more sophisticated fuel injection.

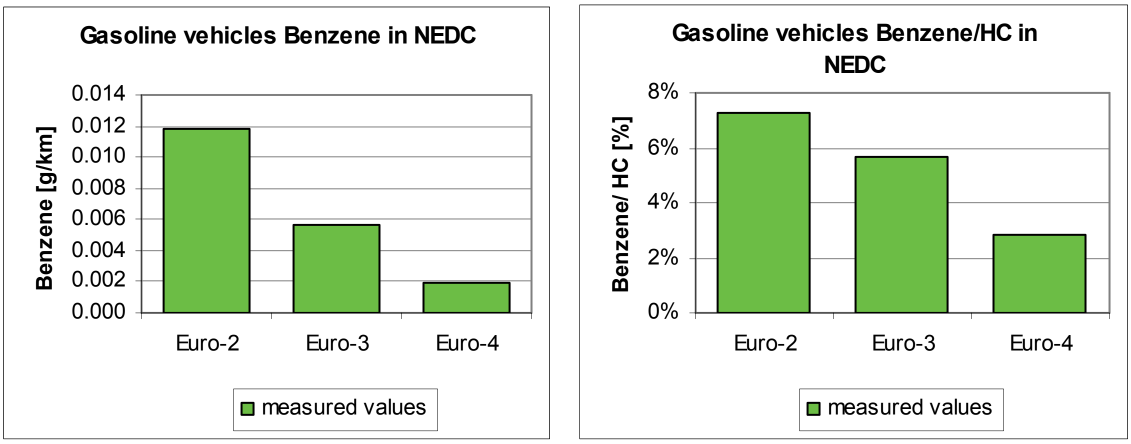


Figure 2: Regulated emission of gasoline vehicles relative to limit values

All other measured values (HC (hydrocarbons), PM_{mass} and NO_x) show decreasing trends over generations that are less pronounced than the legislation. The average NO_x and the average $HC+NO_x$ values of the Euro-4 group and the Euro-4 PF subgroup even exceed the limit values! This unsatisfactory trend is also reflected in the increasing number of individual vehicles failing the test, 37%, 40% and 62% for Euro-2 to Euro-4. When the Euro-4 group is split depending on the presence of a particle filter it is interesting to note that eight out of ten vehicles without a filter fail the PM_{mass} limit, while all vehicles with filters show PM_{mass} emissions below 10 % of the limit value. On the other hand, none of the vehicles with filters shows NO_x emissions below 80% of the legislative limit, with two out of six and the average even exceeding it.

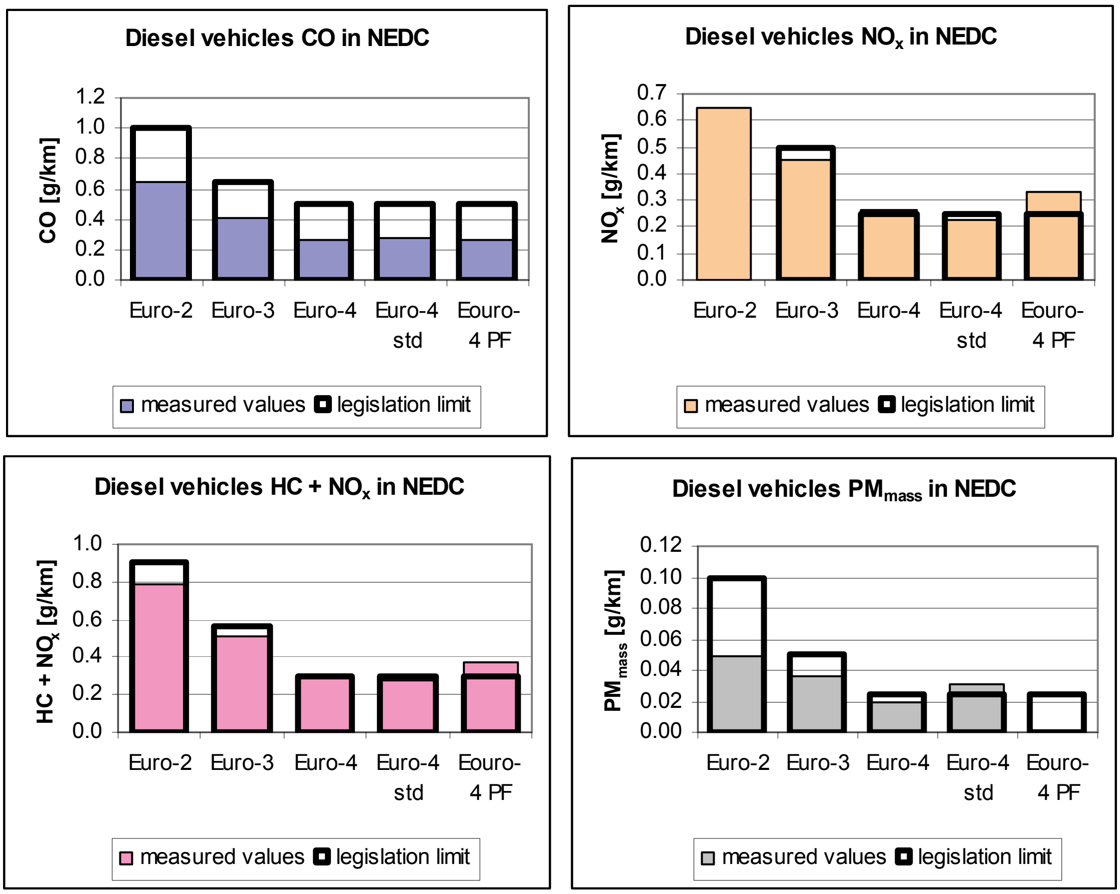
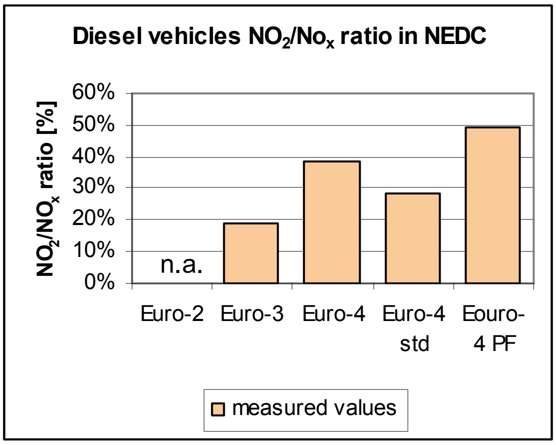


Figure 3: Regulated emissions of diesel vehicles in legislative test (NEDC)

As discussed in detail in Alvarez (2008), the NO_2 share in NO_x rises substantially with the introduction of oxidation catalysts and rises even faster with PF (Figure 4 left). Note that for legislation the NO_x values are calculated from concentration measurements by assuming all to be NO_2 (molar mass = 46 g MOL^{-1}). However, the true values of NO_x, the sum of NO and NO_2, are used to discuss NO_2 share in NO_x. As discussed in many papers (e.g. Carslaw 2004, Weilenmann 2005), this results in a new and unexpected situation for both NO_2 and ozone air quality policies. As the legislative test also contains cold-engine phases, the shares of NO_2 in NO_x are even smaller than in pure hot driving.

The number of particles follows a similar pattern to the particle mass (Figure 4 right). A continuous drop is observed over generations. However, Euro-4 vehicles without filters show emissions like Euro-3 vehicles. The subset of Euro-4 vehicles with PF, with emissions 1000 times smaller, makes the average Euro-4 level smaller than the Euro-3 value.



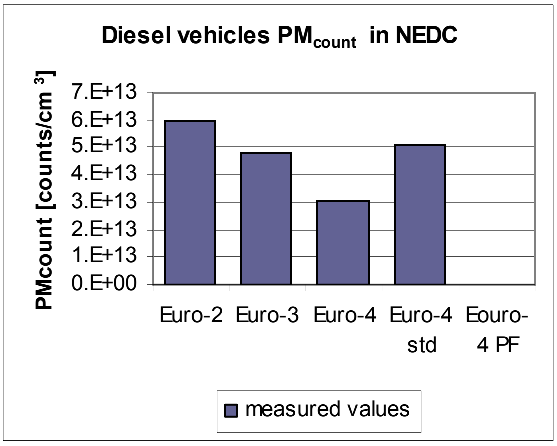


Figure 4: NO_2/NO_x ratio and particle count data of diesel vehicles in legislative test (NEDC)

4. EMISSION EVOLUTION IN REAL-WORLD TESTS

4.1. Cold start emissions

For many fleet models, real-world emission data is split into cold-start extra emissions (CSEE) and hot emissions. Cold-start extra emissions for the regulated pollutants of gasoline cars for both FTP and IUFC15 cycles are shown in Figure 5. Note that all the cold-start data shown here comes from tests at 23° C. A detailed analysis of cold-start emissions as a function of ambient temperature is presented in Favez (2007).

For the CSEE of CO and HC it can be clearly seen that the FTP-75 cycles give lower results than the IUFC15 cycle. For the step from Euro-3 to Euro-4 the drop in CSEE is considerably smaller than for the legislative limits and comparable to the reduced drop in NEDC emissions.

CSEE of diesel vehicles are omitted due to lack of space.

4.2. Hot real-world emissions

The difficulty in discussing hot emissions of real-world cycles is that they cannot be compared directly to emissions of the statutory test, as the latter is run with a cold engine. So the emissions of the hot part of the statutory test (EUDC = extra-urban driving cycle) are used for comparison. As that part of the test is a mixture of rural and motorway driving its emissions cannot be compared directly to general real-world driving containing urban, rural and motorway elements. The comparison of the emission trends over generations of EUDC and real world cycles can nevertheless give some idea as to whether real-world emissions follow legislation.

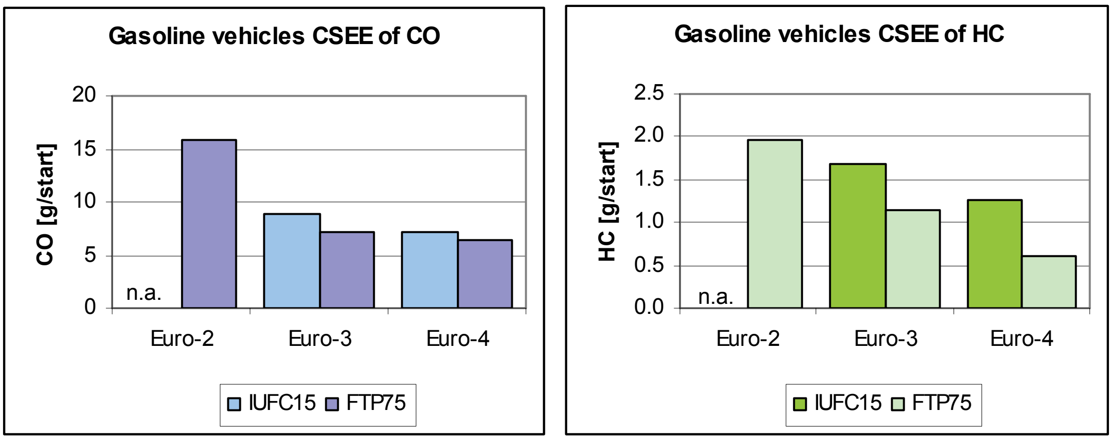


Figure 5: Cold start extra emissions of gasoline vehicles

Figure 6 illustrates the well-known fact that real-world emissions are higher than EUDC emissions. In addition it can be clearly seen that the trends in real-world CO emissions do not fall as sharply as EUDC emissions do. For NO_x it is interesting to note that the emissions of the Euro-3 sample are even lower than those of the Euro-4 sample for all cycles. It is assumed that this is due to the low mileage of the Euro-3 sample (Table 1). Nevertheless, the improvement from Euro-2 to Euro-4 is only half as great as is required by legislation.

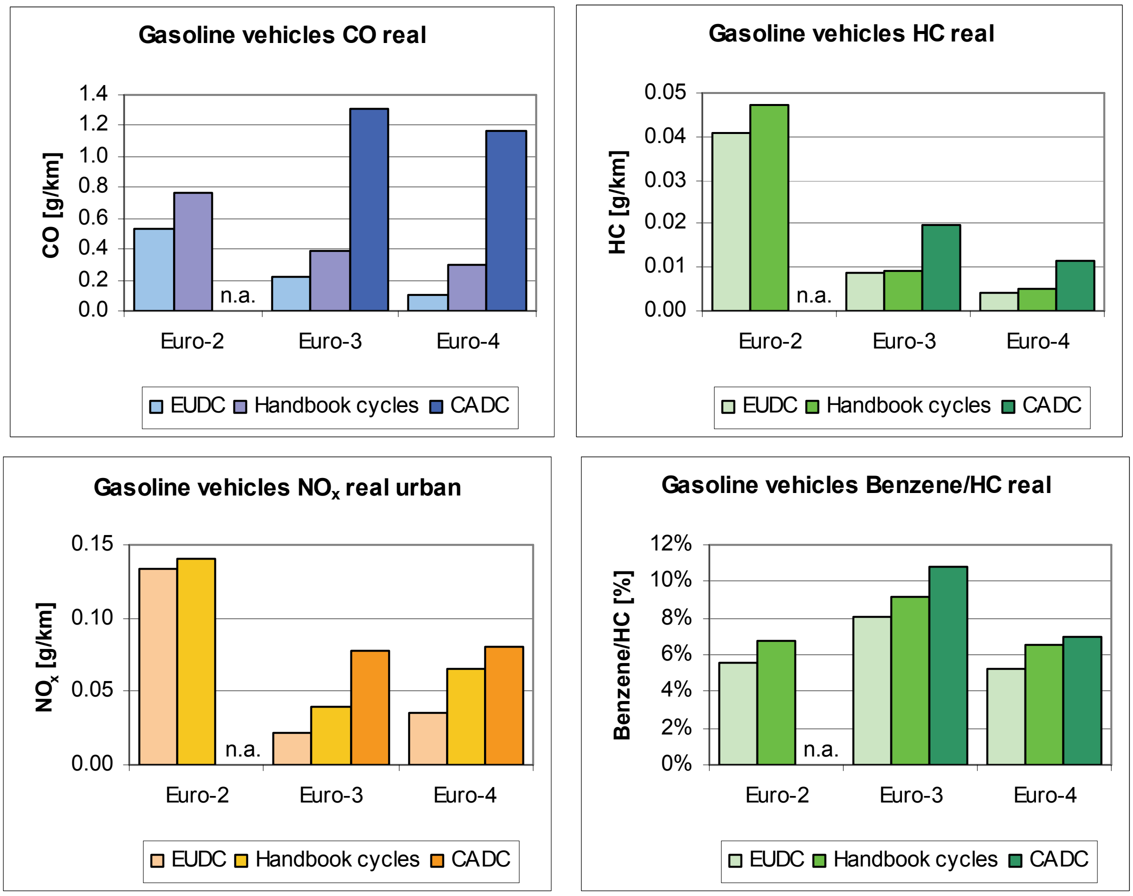


Figure 6: Real world hot emissions of gasoline vehicles

While hot hydrocarbons fall substantially, the share of benzene/HC is roughly constant (the variations are assumed to be caused by the different fuels used), confirming that the catalyst conversion efficiency for benzene is considerably lower than for other hydrocarbons. Values of 5 to 11% are significantly higher than the concentration in the fuels.

Figure 7 shows the hot real-world emissions of the relevant pollutants of diesel cars. The good news for diesel car emissions is that particle mass, as well as particle number, falls at least by a factor of two, while legislation requires a fourfold drop. However, if a larger part of the diesel fleet than the 37% assumed here is sold with OEM particle filters, the particle load will fall by at least two orders of magnitude.

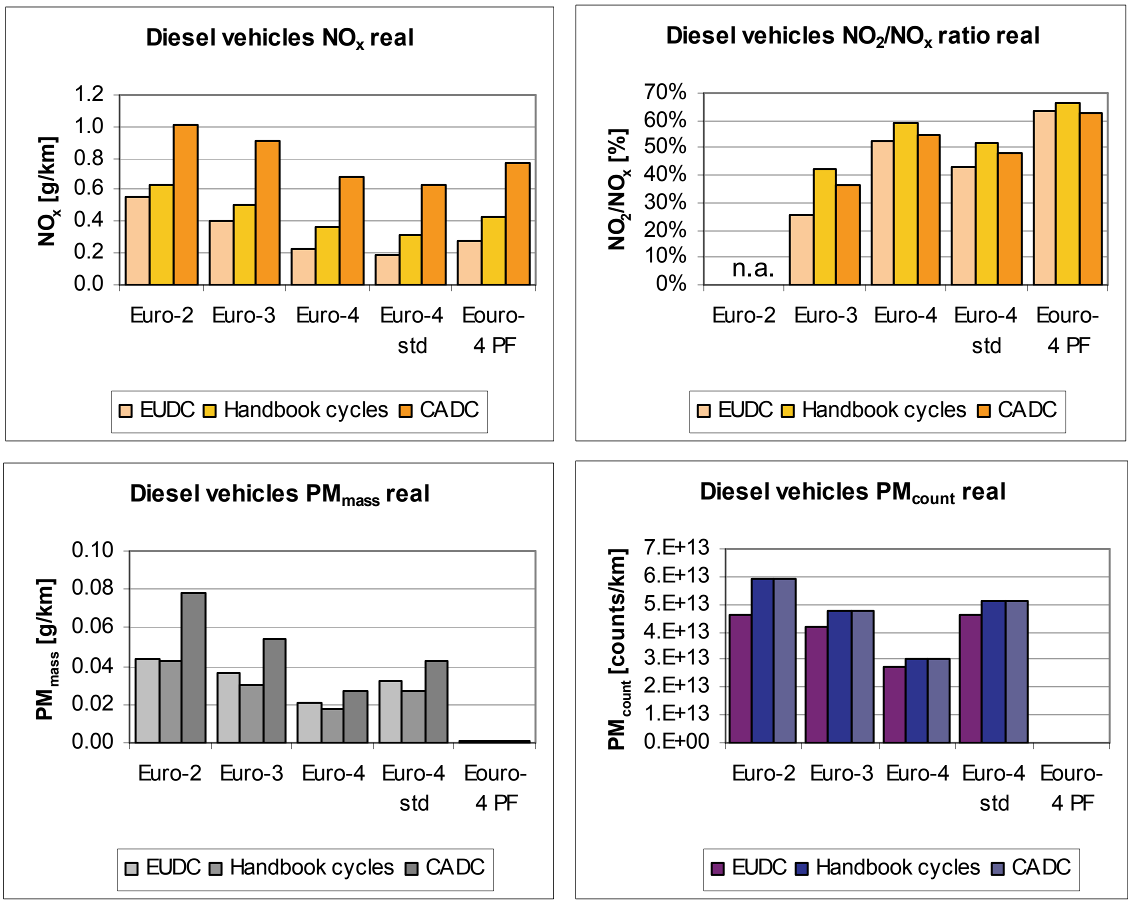


Figure 7: Real world hot emissions of diesel vehicles

On the other hand real-world NO_x is falling by substantially less than a factor of two over these generations even though it should fall four times, and in addition the NO_2 share in NO_x rises sharply and reaches roughly 55% for the mixed Euro-4 group and more than 60% for the vehicles equipped with PF. These figures are clearly higher than in the homologation tests, where the oxidation catalysts and the filters with catalytic coating are partly inactive during warm-up.

5. CONCLUSIONS

The following findings can be extracted from this data:

- The reduction in measured pollutants in the legislative tests is less pronounced than the reduction in legislative limits. For diesel vehicles this is in line with a rising number of individuals failing the test and with fleet average emissions of NO_x and particle mass being above limits.
- The reduction in pollutants in the real-world cycles is even smaller than in the legislative test. This indicates that the difference in behaviour between legislative test and real cycles is increasing and supports the call for more realistic driving cycles for certification.

- For gasoline vehicles it can be seen that the cold-start benzene share in the emitted HC falls over the generations as more and more lean warm-up is applied. On the other hand the benzene/HC ratio remains constant for hot emissions up to 11%, and benzene thus remains a problem.
- Diesel particle number (as well as its mass) falls continuously over the generations. However, the group of Euro-4 vehicles without filters have higher emissions than the Euro-3 group. The vehicles that are equipped with such filters emit two orders of magnitude less.
- The share of NO_2 in NO_x is constantly below 2% for gasoline vehicles, but rises to a maximum of more than 60% for Euro-4 PF cars. This ratio is clearly larger in hot driving than the values from the legislative test containing a cold start indicate.

For gasoline vehicles these observations indicate that further improvement will require a significantly greater technical effort, which will also increase the risk of malfunction and thus increase the need for in-use compliance tests.

The introduction of diesel PF was a major step in reducing particle emissions. However, the problem of increased NO_2 emissions needs to be solved in near future.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

Alvarez R., Favez J. Y., Weilenmann M., (2007a) Tracing of road traffic emissions, Gasoline passenger cars Euro-4, Standard program. Empa report 203270g, ISSN 1424-2532, Dübendorf, Switzerland.

Alvarez R., Favez J. Y., Weilenmann M., (2007b) Tracing of road traffic emissions. Diesel Passenger Cars Euro-4, Standard program. Empa report 203270h, ISSN 1424-2532, Dübendorf, Switzerland.

Alvarez R., Weilenmann M., Favez J.-Y., (2008) Evidence of Increased Real-World NO_2 Emissions within the Total NO_x Discharge of Modern Light Vehicles - Derived from a Reliable Online Measuring Method. Atmospheric Environment, accepted 25.1.08

Andre M., (2004) The ARTEMIS European driving cycles for measuring car pollutant emissions. SCIENCE OF THE TOTAL ENVIRONMENT 334-35, pp 73 – 84.

Bruehlmann S.,Novak P., Lienemann P., Trottmann M., Gfeller U., Zwicky CN., Bommer B., Huber H., Wolfensberger M., Heeb NV., (2006) Three-way-catalyst induced benzene formation: A precursor study. APPLIED CATALYSIS B-ENVIRONMENTAL 70, pp 276 – 283.

Carslaw D. C., Beevers S. D., (2004). Investigating the potential importance of primary NO_2 emissions in a street canyon. Atmospheric Environment 38, 3585-3594.

de Haan P., Keller M., (2000) Emission factors for passenger cars: application of instantaneous emission modelling. ATMOSPHERIC ENVIRONMENT 34, pp 4629 – 4638.

Favez J.-Y., Weilenmann M., (2007) Cold start emissions of passenger cars at different low ambient temperatures, 6th international conference on Urban Air Quality, 27-29 March 2007, Limassol, Cyprus, Editors: Ranjeet S. Sokhi and Marina Neophytou, University of Hertfordshire College Lane, Hatfield AL10 9AB, United Kingdom, ISBN: 978-1-905313-46-4.

Fischbeck PS, Gerard D, Rice D, (2007) Interactive forecasting tool for impact of new engine technologies on fuel consumption and emissions. TRANSPORTATION RESEARCH RECORD 2011, pp 78 – 86.

HBEFA, (2004) Handbook Emission Factors for Road Transport. Infras, Mühlemattstrasse 45 3007 Bern, Switzerland.

Heeb N.V., Forss A.M., Saxer Ch., Wilhelm P., (2003) Methane, benzene and alkyl benzene cold start emission data of gasoline-driven passenger cars representing the vehicle technology of the last two decades. ATMOSPHERIC ENVIRONMENT 37, pp 5185 – 5195.

Joumard R. et al.,(2006) Accuracy of exhaust emissions measurements on vehicles bench. ARTEMIS deliverable 2, report LTE 0522, INRETS case 24, 69675 Bron cedex, France, tel.: +33 (0)472 14 23 00, fax: +33 (0)472 37 68 37.

PMP Working Group (2007): Amendments to the UNECE Regulations, Regulation No. 83, Proposal for Draft Supplement 7 to the 05 series of amendments to Regulation No. 83, 10/07.

Singh RB, Colls JJ, (2000) Development and preliminary evaluation of a particulate matter emission factor model for European motor vehicles. JOURNAL OF THE AIR & WASTE MANAGEMENT ASSOCIATION 50, pp 1805 – 1817.

Soltic P., Weilenmann M., (2001) Nachführung der Emissionsgrundlagen Strassenverkehr, Ergänzungen der Messdaten auf das Bezugsjahr 2000, Empa-Report 201209, ISSN 1424-2532, Dübendorf, Switzerland.

Stettler P., Weilenmann M., Forss A.-M., Mohr M., Mattrel P., Saxer Ch., Heeb V., (2004) Nachführung der Emissionsgrundlagen Strassenverkehr: Messungen 01 – 02 Benzinpersonenwagen Euro-0 und Euro-3 sowie Dieselpersonenwagen Euro-2, Empa Report. 202 114, ISSN 1424-2532, Dübendorf, Switzerland.

Stilli J., Weilenmann M., (2006), Ergänzung derMessdaten auf das Bezugsjahr 2005 – Diesel Personenwagen Euro-3 Standardprogramm, Empa report No. 203 270f, ISSN 1424-2532, Dübendorf, Switzerland.

Vasic A.-M., Weilenmann M., Heeb N., Saxer Ch., (2006) Measurement Data Completion on Reference Year 2005 Gasoline Passenger Cars Euro-3, Empa report No. 203 270c, ISSN 1424-2532, Dübendorf, Switzerland.

Weilenmann M., Saxer CH., Forss A.-M., Heeb N., Stilli J., Novak Ph., (2005) *Time-resolved raw gas measurements of NO and NO_x for Diesel and gasoline vehicles*, presentation at the 14th international symposium Transport and Air Pollution 1. – 4. June 2005, Graz.