EMISSION BEHAVIOUR OF EURO IV AND EURO V HDV - MEASUREMENT RESULTS AND AN UPDATED APPROACH FOR ASSESSMENT OF EMISSION FACTORS

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ABSTRACT

In the framework of the next HBEFA update at the TU Graz a method for a cost efficient and manufacturer independent in-use monitoring of Euro IV and Euro V HDV was elaborated. The in-use monitoring can be performed either by chassis dynamometer tests, on-board measurements or engine dynamometer testing. For the calculation of the resulting emission factors the emission model PHEM was revised and extended to be also capable for the depiction of the emission behaviour of current Euro IV and Euro V HDV. The paper presents first emission tests results and gives a description of the emission modelling approach for the calculation of the updated emission factors.

Keywords: *Heavy duty vehicle, emission legislation, Euro IV, Euro V, in-use testing, emission model.*

1. INTRODUCTION

In the first half of this decade the emission behaviour of heavy-duty vehicles (HDV) in real world conditions has been investigated in two large EU-projects: "ARTEMIS", an EU 5th Framework programme [1], and the COST 346 Action [2]. Both programmes have been initiated by an earlier project ordered by the Austrian BMLFUW within the D.A.CH.-NL.S. group in the year 1999 at the TU Graz for an update of the emission factors for HDV in the "Handbook on Emission Factors for Road Traffic" (HBEFA) [3]. The two above mentioned European projects on HDV emissions have also been coordinated by TU Graz. All projects have been finalised in the end of 2005, the last emission tests available for the analyses have been performed in the year 2004 including HDV emission standards up to Euro III. The main finding of the studies was, that since the mid of the 90ies nearly all heavy-duty engines had clearly increased NO_x-emissions in real world operation conditions compared to the homologation test, see e.g. [4], [5]. In contrast, the HDV emission output of particulate matter and CO_2 were observed to have decreased clearly over the HDV generations from 'Pre Euro' to Euro III.

Since the end of the above mention projects HDV certified according to the emission standards Euro IV and Euro V have entered the market. Euro IV is obligatory for new registered HDV since October 2006. Euro V will be compulsory for new registrations from October 2009 on, but this vehicle generation is already available on the market since mid of 2005 due to the high market demand (main reasons are a higher fuel economy and benefits in the road toll in Germany for Euro V). In 2008 in Central Europe the share of HDV certified to Euro IV and later on the total HDV mileage exceeds one third, in long distance transport this number already is in the range of two third. In actual emission inventories the emission behaviour of these vehicle generations from Euro IV on is based only on a prognosis, as no measurements of these modern engine concepts had been available at the time of the finalisation of the latest versions of the emission models elaborated in the above mentioned projects.

The implementation of the emission regulations for Euro IV and V caused a significant step in HDV vehicle technology. The emission limits for Euro III (European Stationary Cycle: NO_x: 5 g/kWh, PM: 0.1 g/kWh) have been met with engine internal measures only. As the regulations for Euro IV and V include a compulsory emission test in a transient type approval cycle (European Transient Cycle) with clearly more stringent emission limits (NO_x: Euro IV 3.5g/kWh, Euro V: 2g/kWh, PM: Euro IV&V: 0.03 g/kWh) the engine concepts are much more complex than previous engine generations. In general two approaches are used by the manufacturers in order to comply with the emission legislation, e.g. [6], [7]:

- The application of "Selective Catalytic Reduction" (SCR) - an exhaust aftertreatment using the reductant urea (which is carried on the vehicle in an aqueous solution, brand name: "AdBlue") for the reduction of NO_x emissions
- The application of Exhaust Gas Recirculation (EGR) and eventually a catalyst for the reduction of PM emissions

HDV certified to Euro IV are on the market based on both engine concepts. Until now (spring 2008) Euro V vehicles are only available with SCR exhaust aftertreatment, but it is announced that also Euro V engines based on EGR concept without any reductant for NO_x emissions will enter the market in 2008. However, due to the predominant application in long distance transport, Euro V HDV with SCR are the most common type within the above mentioned vehicle concepts. From the emission tests on former vehicle generations it was concluded that the real world emission behaviour is not necessarily always in line with the emission levels in the type approval. Due to the dramatically increased complexity of modern engine concepts and the variety of applied systems the assessment of actual real world emissions of Euro IV and Euro-V HDV hence have been an especially "hot" issue.

2. MEASUREMENT RESULTS

Background of the presented data is the work on the update of HDV emission factors for the next version of the "Handbook Emission Factors for Road Transport" (HBEFA) within the D.A.CH.-NL.S. group. The presented results are based on chassis dynamometer tests at the TU Graz (two Euro V vehicles with SCR; one Euro IV vehicle with EGR) and engine dynamometer tests at EMPA, Switzerland (two Euro IV engines: one with SCR, one with EGR). A detailed description of measurements performed at the TU Graz can be found in [8], a entire documentation on the emission test results will be available after the finalisation of the next HBEFA version in winter 2008/09.

In ***Figure 1*** the measured brake specific NO_x emissions for the two tested Euro V vehicles based on SCR-concept are plotted over the average cycle speed and compared to the average Euro III emission levels elaborated in the ARTEMIS project. In driving cycles with high average speeds (rural and motorway driving conditions) the vehicles showed NO_x emission levels in the range of the Euro V emission limit (2g/kWh) or below due to medium and high engine loads connected with high temperatures in the SCR-system, which are needed for the reduction of engine-out NO_x emissions. If the vehicle was preconditioned with full-load in the rural and motorway driving cycles, the observed emission levels were even lower due to the high temperature of the SCR-system at the beginning of the emission tests. Compared to the average Euro III emission behaviour, the Euro V vehicles showed a reduction of NO_x emissions in rural and motorway driving conditions of approximately two third. However, in engine operation conditions, which cause temperatures of the SCR-catalyst below approx. 230°C, the exhaust aftertreatment systems were hardly able to reduce the NO_x emissions in the raw exhaust gas. In the tested configurations of vehicles, engines and SCR-systems, this was predominately the case for "vehicle 1" in driving cycles with average speeds below 20 km/h (which is common for urban centre driving or stop and go conditions), resulting in similar or even higher NO_x levels compared to Euro III vehicles. The second measured vehicle (“vehicle 3”) showed less sensitivity to low load conditions, but also in this case only small improvements have been observed compared to Euro III NO_x emission levels.

The share NO_2 on tailpipe NO_x emissions of the tested SCR vehicles was found to be in the range of 5 to 15%, which means no significant increase compared to former HDV generations without any catalytic exhaust aftertreatment.

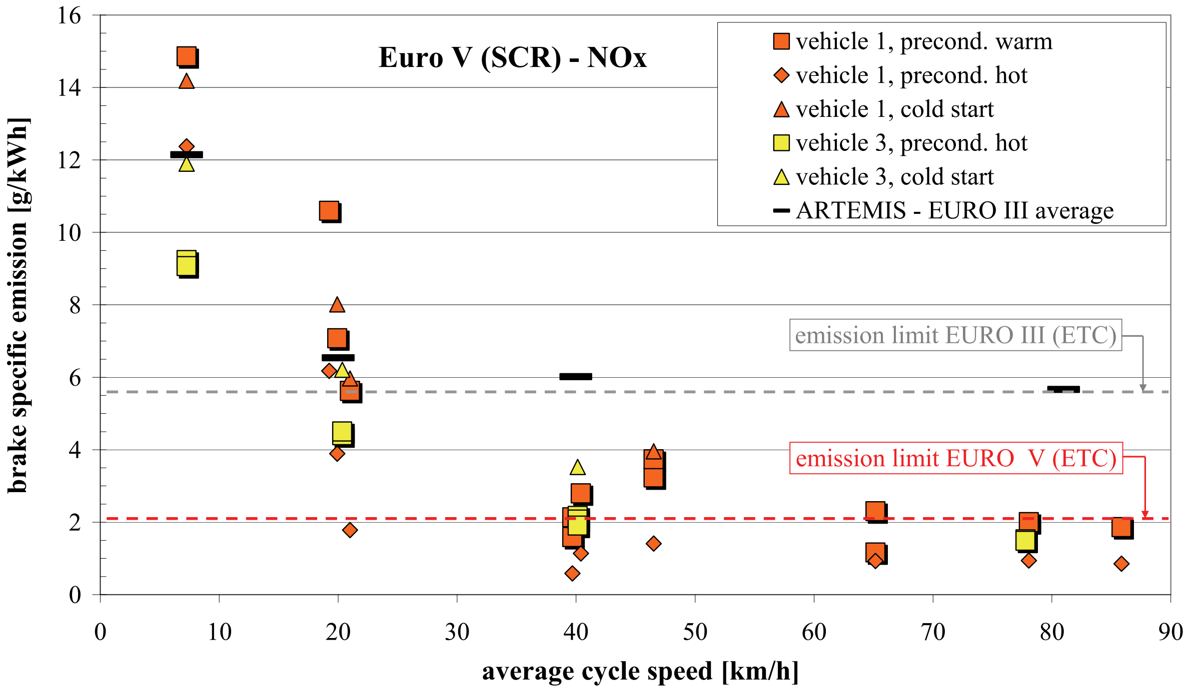

Figure 1: Brake specific NO_x emissions vs. average cycle speed; Euro V (SCR)

A sensible point which has to be addressed in connection with NO_x emissions of SCR vehicles is ‘tampering’. In order to save costs vehicle owners might not fill in AdBlue which is required for the NO_x reduction in the SCR aftertreatment. A rough assessment of yearly AdBlue costs for a Euro V truck operating in long distance transport comes up with up to 1000 €. Without any reductant, NO_x emissions of Euro V SCR vehicles would clearly exceed the NO_x output of any former vehicle generation. Facing this sensible issue the emission legislation demands a NO_x-sensor and an anti-tampering threshold value of 7 g/kWh for new HDV registrations after October 2007. However, so far there are no numbers for the tendency of the vehicle owners regarding NO_x tampering and the effectiveness of current on-vehicle anti tampering systems available. In any case, systematic frequent road side checks (performed by police or any kind of skilled officials with adequate diagnostic systems) in connection with the imposement of fines would prevent from widespread misuse.

Figure 2 shows the measured brake specific NO_x emissions of the Euro IV vehicle (EGR-concept) tested on the chassis dynamometer. The observed NO_x emission levels at operating temperature are clearly below the average Euro III values. But, as already observed for Euro II and Euro III HDV, the brake specific emissions clearly exceed the according type approval limits in the ETC in all real world operation conditions. Even in motorway driving, which comes quite close to the load pattern tested in the ETC, the observed NO_x emissions have been in a range of 4g/kWh compared to 3.5g/kWh specified in the ETC for Euro IV. This finding can be explained by the well known “trade-off” between engine-out NO_x emissions and fuel consumption. As the ETC does not sufficiently cover all real world operation conditions, the high customer demand for low fuel consumption results in NO_x levels higher than the emission limits in all engine operations outside the ETC. ***Figure 3*** (left picture) shows the NO_x emission map of a Euro IV EGR engine in steady state conditions. As found in former analyses [4] below the engine speed range controlled by ESC and ETC, the optimisation for specific fuel consumption with clearly increased NO_x emissions is obvious. Due to the more stringent NO_x emission limits for Euro IV the observed 'gradients' in the NO_x map turn out to be steeper compared to Euro III engines.

Contrary to the findings for the Euro V SCR vehicles, the NO_x emission level of the tested Euro IV EGR concept is much less sensitive to low load operation conditions typical for urban driving and stop and go conditions. In these driving situations the NO_x emissions of the EGR Euro IV vehicle are clearly lower than the NO_x emissions of the two tested Euro V HDV. During cold start conditions, the Euro IV vehicle deactivates the EGR system which causes a significant increase of the NO_x emission level. This effect has more effect in emission test cycles with low average speeds, because the warm up of the engine takes more time and therefore covers a higher share of the total cycle duration. Hence, as found for Euro V SCR vehicles, the NO_x emission levels of Euro IV EGR HDV are quite sensitive to cold start conditions, which was not the case for HDV generations of Euro III and earlier. However, the importance of extra emissions caused by starting the engine from ambient conditions is still assumed to be low. Different to the situation for passenger cars, HDV have a much higher operation time during the day with a smaller number of starts and shorter periods with engine shut-off.

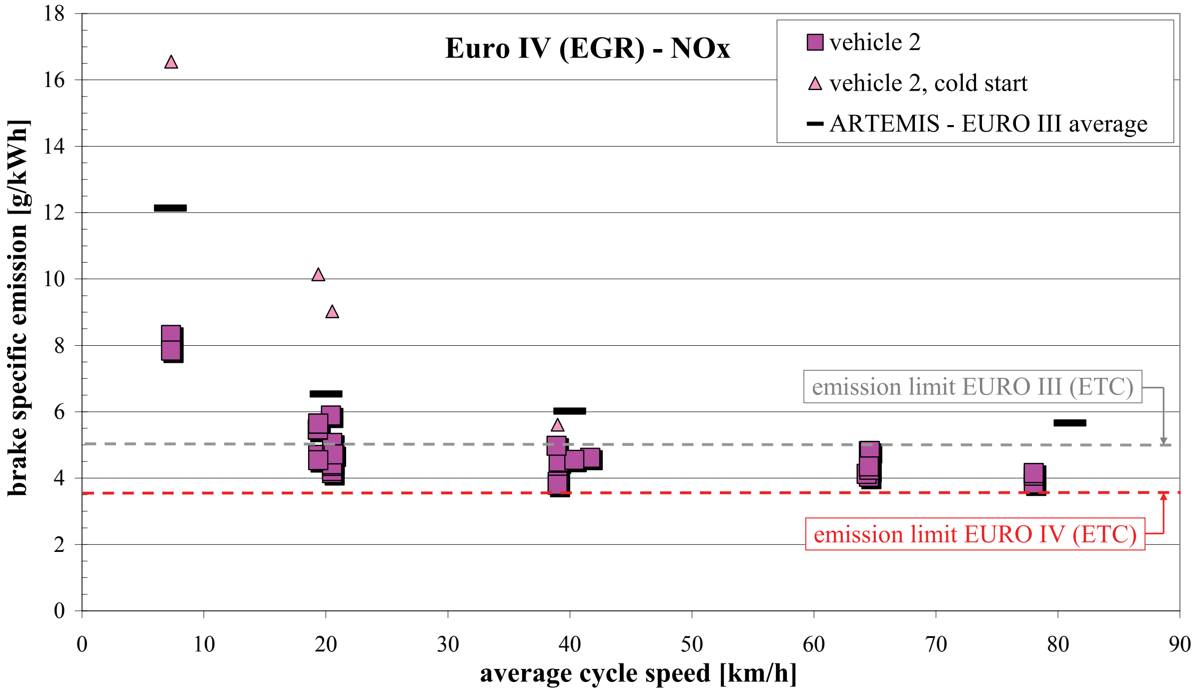

Figure 2: Brake specific NO_x emissions vs. average cycle speed; Euro IV (EGR)

The share of NO_2 on the tailpipe NO_x emissions of the tested Euro IV EGR HDV (both equipped with a catalytic PM aftertreatment) were in the range of 25 to 50%.

Regarding fuel consumption, engine concepts with SCR NO_x aftertreatment system showed a significantly lower fuel consumption (reductions of 5% and more) than the Euro III engine generation. The fuel consumption of the tested EGR engines (Euro IV) was in the range of the most efficient Euro III engines. Improvements in HDV fuel consumption due to innovations in vehicle technology is not assessed here.

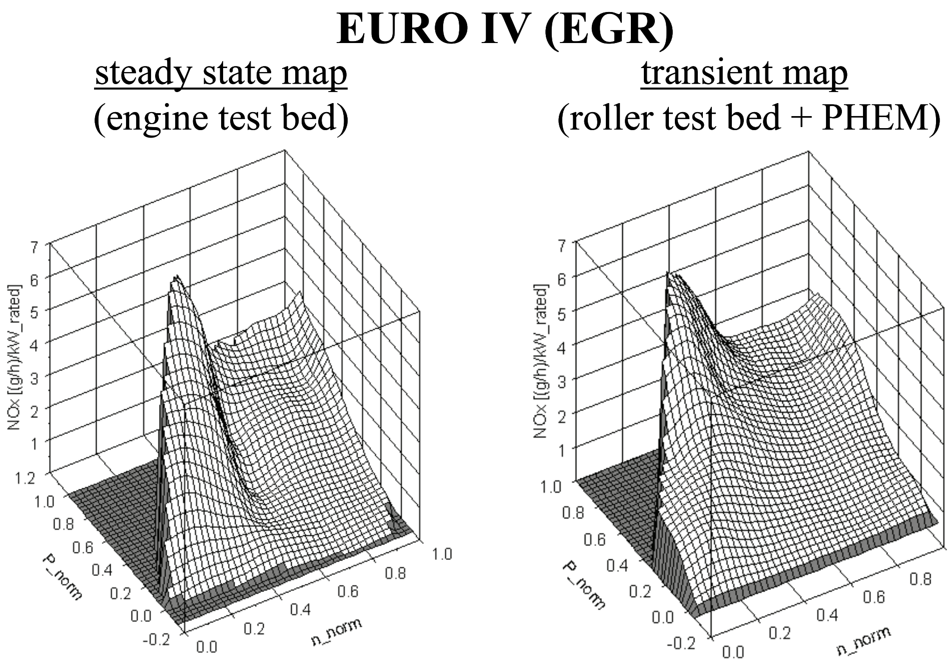

Figure 3: Euro IV EGR NO_x emission map. Left: Steady state map (engine test bed, *source EMPA*); Right: 'transient' map (measured on the chassis dynamometer and generated with PHEM, similar engine make but different model compared to left picture)

In ***Figure 4*** the measured brake specific emissions for mass of particulate matter (PM) are shown. The picture includes both results for Euro IV and Euro V vehicles, as similar PM emission limits apply for both emission standards. In general for PM emissions in the exhaust gas a decrease of the emission levels by approximately a factor of three to four compared to the average EURO III values was found. This reduction is inline with the decrease of the corresponding emission limits in the type approval cycle.

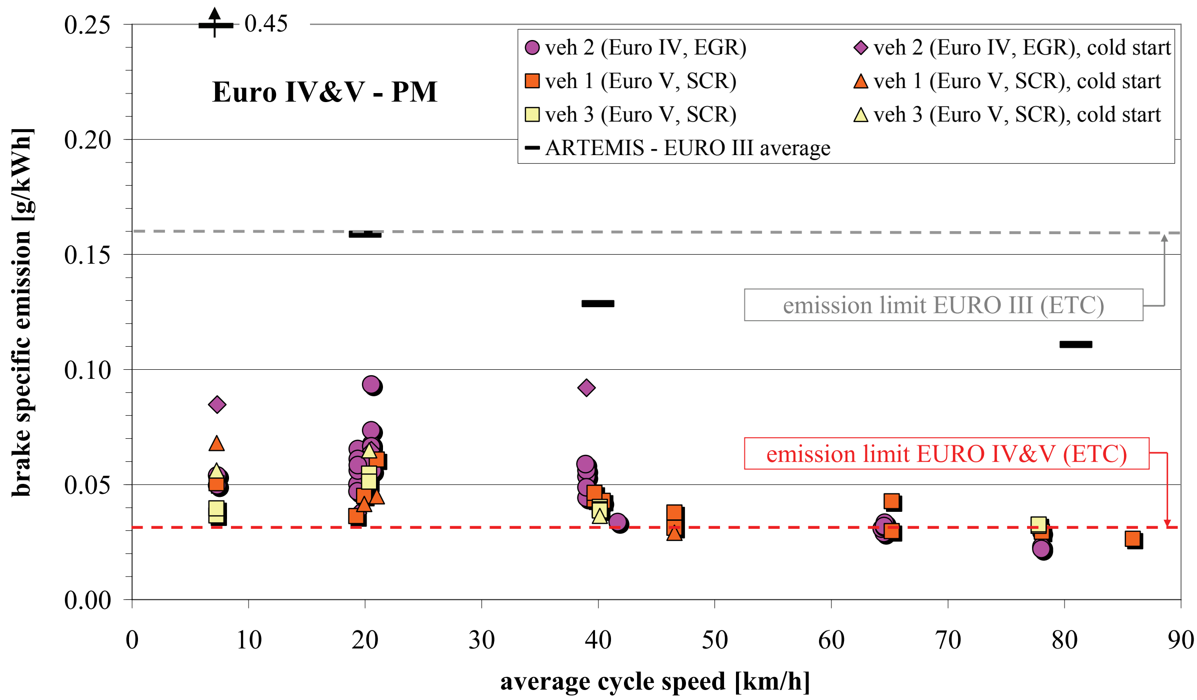

Figure 4: Brake specific PM emissions vs. average cycle speed; Euro IV & V HDV

For emissions of hydrocarbons (HC) and carbon monoxide (CO) due to the introduction of catalytic exhaust aftertreatment in all modern HDV concepts the already low emission levels of Euro III diesel HDV are clearly underrun in all emission tests by all tested Euro IV and Euro V HDV.

3. EMISSION FACTOR MODELLING

The method for the ascertainment of the real world emission behaviour of HDV up to the emission standard Euro III elaborated in the beginning of this decade in the above mentioned projects was based on steady state and transient engine test bed measurements and is well established within Europe in the meantime. For the calculation of the resulting emission factors for all combinations of engine emission standards, HDV vehicle classes and the loading and driving conditions the instantaneous emission model "PHEM" (Passenger car and Heavy duty Emission Model) has been developed at TU Graz. PHEM interpolates fuel consumption and emissions from engine maps according to the 1 Hz course of engine power demand and engine speed in the driving cycles under consideration. To obtain a higher model quality the effects of transient engine operation on the emission levels were investigated in detail and implemented into the emission model. In total the method proved to be very flexible to provide emission factors for average HDV categories in any driving condition [9].

For the evaluation of the in-use emissions of post-Euro III HDV a revision of the test protocol and the method of emission modelling was obvious. The first reason was that for engines from Euro IV on engine test bed tests can hardly be performed without support from the manufacturer, because a special test bed version of the ECU is required to run the engine on the test bed. This would be a very unfavourable option for an in-use test programme, because the independency of such a HDV monitoring would not be guaranteed. A further argument for an update of the HDV in-use test protocol were the rapidly increasing costs of engine test bed tests for modern HDV engine concepts, as not only the engine but also the exhaust aftertreatment system have to be dismantled from the vehicle and put on the test bed. Additionally in the last years the availability of Portable Emission Measurement Systems (PEMS) introduced the option to perform real world emission measurements by in-use on-road tests also. These reasons call for an in-use test protocol and an emission model structure which is capable to make use of emission test on entire vehicles also.

Hence in 2005 a project for the elaboration of an updated test protocol and emission modelling approach for Euro IV and Euro V HDV was launched at the TU Graz. During this study PHEM was extended to be able to set up 'transient engine maps' from transient tests on complete vehicles also. A similar method was already applied in the emission model for the simulation of emissions of passenger cars [10]. In this kind of PHEM application the engine emission maps are in general gained from transient emission tests on the chassis dynamometer. The transient maps are generated by allocation of 1 Hz instantaneous measured emissions to the corresponding engine operation point specified by engine power and engine speed. To be able to take transient effects on the emission levels into consideration, for each point in the engine map also the information "how transient" the engine operation was in the emission test is stored. This is done by 'transient parameters', e.g. the derivation of torque and engine speed or the number of load changes in the previous seconds. When an unknown cycle is simulated by the model, the 1 Hz emissions are interpolated from the transient map according to the actual engine power and engine speed as in the former 'steady state map' approach. But the effects of transient loads on the emission level are now calculated relative to the transient level of the points in the transient map. The updated version of PHEM still is able to make use of the emission data gained with the 'old' test procedures for HDE up to Euro III in order to provide a consistent set of emission factors for future calculations of HDV fleet emissions.

Concerning modelling of PM emissions where no 1Hz recording of emission values is possible the 1Hz data either of particulate number (PN) emissions or of mass soot are used together with PM filter results for the parameterisation of the transient maps. Additionally, the simulation of emission factors for PN has been included into the modelling approach.

During the project also the test protocol for the HDV in-use monitoring programme has been revised and extended for Euro IV and V vehicles compared to the former protocol. The main focus was set in the selection of suitable driving cycles for chassis dynamometer tests and a proper definition of boundary conditions for on-board tests for a representative assessment of the emission behaviour and PHEM data compatibility. But also the test protocol for engine dynamometer tests was revised. The full documentation of the work is given in [8].

The following section gives a comparison of measured emission factors and PHEM results for the Euro IV and V HDV tested at the chassis dynamometer. As defined in the updated test protocol, the TNO 12.5 kW/t HD cycle and a full-load test were used for setup of the transient engine maps. This set of cycles proved to provide a good drivability on the chassis dynamometer, a high representativeness for real world emission behaviour and a good coverage of the engine map for PHEM parameterisation. ***Figure 3*** (right picture) shows the shape of the transient NO_x map for the Euro IV EGR vehicle generated by PHEM. Compared to the steady state map of a comparable engine measured at the engine test bed (similar make and engine generation, but slightly different engine size; ***Figure 3***, left picture), the sharp border between high and low brake specific NO_x emissions determined by the ESC is blurred. Reasons can be found in different EGR rates in transient engine operation (potential optimisation for the ETC, which focuses on a smaller engine speed range than the ESC) and some inaccuracies in the allocation of measured 1Hz NO_x emissions and the corresponding engine operation point in the setup of the transient map.

Figure 5 compares measured and simulated NO_x emission factors for the Euro IV EGR vehicle. For model validation a selection of HD cycles from the HBEFA and ARTEMIS driven with 50% vehicle loading have been used. One particular cycle was also driven with empty, half and fully loaded HDV. The model slightly overestimates the average NO_x level in the validation cycles by 6%, the regression coefficient between measured and simulated values is 97%. Also the nonlinear effect of increased vehicle loading on the NO_x levels is predicted by PHEM very well. The maximum model deviation for a particular cycle is 25%.

The model approach for the simulation of NO_x emissions of SCR vehicles is not finalised yet. As expected the thermal conditions in the exhaust system turned out to be the crucial parameter. Hence for this kind of model application PHEM is currently extended by a thermal model for the simulation of temperatures in the exhaust system. The main challenge in this context is to formulate a model structure, which provides a depiction of all important physical effects but also allows for a quick model parameterisation based on a small amount of data, which can simply be recorded during the HDV in-use tests.

Figure 6 gives a comparison of measurement and PHEM results for CO_2 and PM emission factors comprising both a Euro IV and a Euro V vehicle. The average CO_2 level in the validation cycles is met by the model by 5% deviation, providing a regression coefficient (R^2) between measurement and simulation of 99.7%. The average PM emissions are predicted by the model by 2% deviation with a $R^2$of 94%. The shown results for PM emission factors are based on the setup of the PHEM transient maps by means of the AVL Micro Soot Sensor, which proved to be a very valuable device for the 1 Hz detection of soot also at low emission levels.

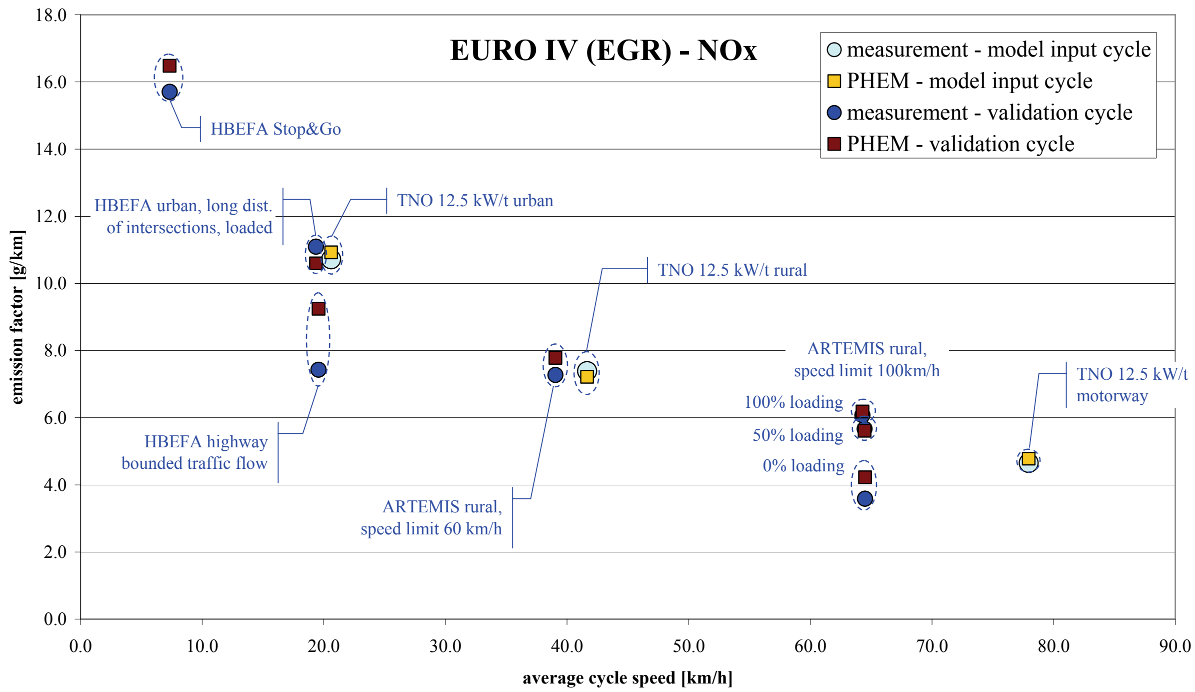

Figure 5: Comparison measured and simulated NO_x emission factors; Euro IV (EGR)

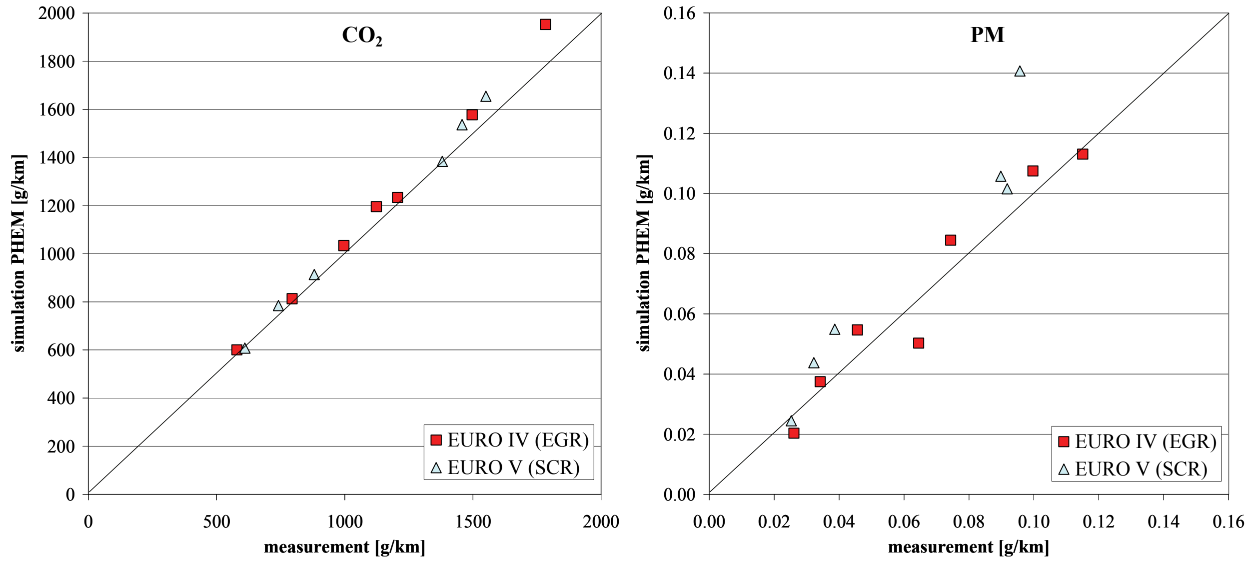

Figure 6: Comparison measured and simulated emission factors for CO_2 and PM in the validation cycles

Compared to the validation results for the method of HDV emission factor modelling used up to Euro III, the new approach (comprising both test protocol for the entire vehicle and the simulation approach) provides an at least equal model quality for all exhaust gas components. Especially regarding the calculation of PM emissions factors the inclusion of a 1Hz measurement signal has lead to a clear improvement of prediction quality, even more if the lower absolute emission levels of Euro IV and Euro V are taken into consideration. The model accuracy of the prediction of NO_x emission factors for SCR vehicles is still open, as the required additional model tools are still in development.

Furthermore, in the appraisal of the prediction quality of the emission modelling for the calculation of fleet average emission factors, it additionally has to be kept in mind, that only the availability of a sufficient number of vehicle tests guarantees for a representative depiction of the fleet average emission behaviour. As far as it became apparent until now, for the update of the HBEFA (planned for end of 2008) a more coordinated approach between European countries for a larger amount and more systematic emission tests on Euro IV and Euro V HDV would be preferable.

4. SUMMARY

In the framework of the next HBEFA update at the TU Graz a method for a cost efficient and manufacturer independent in-use monitoring of Euro IV and Euro V HDV was elaborated. The in-use monitoring can be performed either by chassis dynamometer tests, on-board measurements or engine dynamometer testing. For the calculation of the resulting emission factors the emission model PHEM was revised and extended to be also capable for the depiction of the emission behaviour of current Euro IV and Euro V HDV. The work on the HDV emission factors for the next HBEFA version will be finalised until the end of 2008.

The Euro IV and Euro V HDV measured and analysed so far provide a clear decrease of PM and NO_x emissions compared to former HDV generations, especially in rural and motorway driving conditions. Also the great efforts of the manufacturers towards lower fuel consumption and lower CO_2 emissions are obvious. However, it again turned out that emission limits in the homologation cycle can not directly be transferred into real world emission factors. Especially the NO_x emission levels of current SCR vehicle generations have found to be quite sensitive to the engine operation conditions, resulting in emission levels even lower than the type approval limit in motorway driving but clearly increased NO_x output in driving conditions with high idle shares. In this context also the issue of potential increased NO_x levels caused by vehicle owners which might not fill in the reductant required for NO_x reduction in the SCR aftertreatment in order to save costs (‘tampering’) has to be mentioned.

5. CONCLUSIONS AND OUTLOOK

The new approach to elaborate the necessary input data for the model PHEM from transient tests on the complete vehicle proved to be a reliable and cost efficient method for the elaboration for the update of HDV emission factors. The new approach includes an update of the HDV in-use test procedures.

The main challenge of a HDV monitoring programme is to point out sensible issues in the area of conflict between emission regulation and technological and economical boundary conditions which HDV manufacturers are subject to. From the experiences gained on Euro IV and Euro V HDV so far, already some crucial points for an effective future emission regulation became apparent. The need for a type approval cycle, which covers also urban and low load driving, is obvious. A second important issue is the consideration of the performance of the total system of engine and exhaust aftertreatment system installed in the entire vehicle. This can most effectively be ensured by an additional ‘Off Cycle Emission’-test (OCE) on the complete vehicle within the type approval procedures. A further essential point is inclusion of a cold start test in the homologation procedure.

The next step of the European HDV emission regulation ‘Euro VI’ is announced to come into force in 2013/14. The proposed legislation details (NO_x limit: 0.4 g/kWh = -80% compared to Euro V; PM limit: 0.01 g/kWh = -66% compared to Euro V) indicate an even more significant step in HDV technology coming up in the mid of the next decade. In principle the current Euro VI proposal addresses the issues of all above mentioned crucial points for an effective emission legislation: The ETC is planned to be replaced by the ‘WHTC’ (World Harmonised Transient Cycle), which has a higher coverage at low engine speeds and engine loads and which has to be tested also in cold start conditions. Also a separate OCE- test is announced to be introduced, however not on the entire vehicle but on the engine test bed. A very important point, which is still not covered in the current version of the Euro VI legislation, is how tampering incidents will be avoided or at least tried to be complicated.

However, a remarkable contribution of Euro VI HDV on the improvement of the air quality will take place not before the mid of next decade. Until then the HDV fleet emission output will be predominately determined by the emission behaviour of Euro V vehicles.

6. ACKNOWLEDGMENTS

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7. REFERENCES

[1] http://www.trl.co.uk/artemis/introduction.htm

[2] http://www.cordis.lu/cost-transport/src/cost-346.htm

[3] Handbook Emission Factors for Road Transport (HBEFA) Version 2.1 (28. Feb. 2004); http://www.hbefa.net/

[4] Hausberger S., Rexeis M.: Emissions from Heavy Duty Vehicles; Transport&Airpollution Conference; ISBN: 3-902465-16-6, Graz 2005

[5] Steven H.: On-Road NOx Emissions; Comparison of In-Use Operating Conditions with Exhaust Emissions Test Condition; European Conference of Ministers of Transport. CEMT/CS/ENV(2005)2/REV2.

[6] Müller W.: Strategies for commercial vehicle engines to fulfil the worldwide exhaust emission legislation. 4th International Exhaust Gas and Particulate Emissions Forum, 14/15 March 2006, Ludwigsburg

[7] Lämmermann R. Held W.: Commercial-vehicle engines and exhaust-gas aftertreatment in the confict between customer benefits and emission legislation. 4th International Exhaust Gas and Particulate Emissions Forum, 14/15 March 2006, Ludwigsburg

[8] Rexeis M., Hausberger S., Vuckovic T., Kofler T., Stadlhofer W.; Development of In-Use Tests for Heavy Duty Vehicles; Elaborated by order of Federal Ministry of Agriculture, Forestry, Environment and Water Management; Federal Ministry of Transport, Innovation and Technology and Federal Environment Agency - Austria; Report Nr. FVT-61/07/Rex Em 19/04/6790; Graz, 30.11.2007

[9] Rexeis M, .Hausberger S, Riemersma I., et.al.: Heavy duty vehicle emissions; Final Report of WP 400 in ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems); DGTREN Contract 1999-RD.10429; University of Technology, Graz; report no. : I 02/2005/Hb 20/2000 I680; 2005

[10] Zallinger M., Le Anh T., Hausberger S.: Improving an instantaneous emission model for passenger cars; Transport&Airpollution Conference; ISBN: 3-902465-16-6, Graz 2005

[11] Zallinger M., Tate J., Hausberger S.: An Instantaneous Emission Model for the Passenger Car Fleet. 17th International Conference "Transport and Air Pollution" 15/16 June 2008, Graz