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Update of Emission Factors for EURO 4, EURO 5 and EURO 6 Diesel Passenger Cars for the HBEFA Version 3.3

Final Report

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Content

Abbreviations

ADAC..........Allgemeiner Deutscher Automobil-Club

CADC..........Common ARTEMIS Driving Cycle (Urban, Rural, MW = Motorway)

CF ....Conformity factor

DB..............Database

DPF............Diesel Particulate Filter

EGR ....Exhaust Gas Recirculation

EMPA..........Swiss Federal Laboratories for Materials Science and Technology

ERMES ....European Research group on Mobile Emission Sources

EU..............European Union

FC ....Fuel consumption

HBEFA........Handbook Emission Factors for Road Transport

HDV ....Heavy Duty Vehicles

LDV............Light Duty Vehicles

RDE ....Real Drive Emissions

RS..............Remote Sensing

RWC ....Real world cycle

PEMS..........Portable Emission Measurement System

PHEM..........Passenger car and Heavy duty Emission Model

SCR ....Selective Catalytic Reduction

TAP............International Transport und Air Pollution Conference

TNO ....Netherlands Organisation for Applied Scientific Research

TUG ....Graz University of Technology

UBA............Umweltbundesamt (Federal Environmental Protection Agency)

WLTC..........Worldwide harmonized Light-duty vehicles Test Cycle

1. Scope of work

The last HBEFA update (Handbook Emission Factors for Road Transport) was published in July 2014. This update included already the EURO 6 emission classes for diesel and petrol cars based on measurements at 5 passenger cars, which were available at that time. It was noted, that especially NOx emissions from the measured sample may not be representative for EURO 6 diesel car fleet. To check and to update the EURO 6 emission factors with all vehicle emission tests at EURO 6 diesel cars collected around Europe since HBEFA 3.2, the HEBFA 3.3 has been produced. In course of the work a first assessment of temperature dependency of the hot NOx emission factors was made. A similar dependency was also found for EURO 4 and EURO 5 diesel cars which lead to an update of emission data for these categories in the HBEFA 3.3 as well.

HBEFA 3.3 is a so-called "quick update", because only the NOx emission factors for diesel passenger cars have been revised. An update for all exhaust gas components is planned for HBEFA 4.1. Following adaptations from HEBFA 3.2 to 3.3 have been performed

- New emission factors of EURO 6, EURO 6d-Temp and EURO 6d replace the previous emission factors of EURO 6 and EURO 6c in HBEFA 3.2.
- New NOx emissions factors of EURO 4 diesel cars replace the old ones in HBEFA 3.2.
- A correction function for the influence of ambient temperature on NOx emissions for EURO 4, EURO 5 and EURO 6 diesel cars has been introduced.

The update is based on RDE (Real Drive Emissions) and dynamometer measurements. For the effect of ambient temperature on NOx emissions, also remote sensing measurement data have been used.

2. Methodology

The emission factors are based on the simulation of a huge number of driving situations and vehicle categories. The simulations have been done using the simulation tool PHEM (Passenger car and Heavy duty vehicle Emission Model). The simulation tool was already described in the HBEFA 3.2 final report (Rexeis M. et. al. 2013). The basic methods are unchanged but the software PHEM was updated in the meantime (improved interpolation routines, gear shift logics and other details). In addition, PHEM was extended to handle On-Board emission test data as input for engine emission maps (chapter 3.2).

A short description about PHEM is given in the following. PHEM is an emission map based instantaneous emission model, which has been developed by TUG (Graz University of Technology) since the late 1990's. It calculates fuel consumption and emissions of road vehicles in 1 Hz time resolution for a given driving cycle based on the vehicle longitudinal dynamics and emission maps. The model has already been presented in several publications, e.g. (Hausberger S. et al. 2009), (Zallinger M., 2010), (Rexeis M. et. al. 2009). PHEM simulates the engine power necessary to overcome the driving resistances, losses in the drive train and to run basic auxiliaries in 1 Hz over any driving cycle. The engine speed is simulated by the transmission ratios and a driver gear shift model. Then basic emissions are interpolated from the engine emission maps. Depending on the vehicle technology, the status of the exhaust gas after treatment systems and dynamic effects are considered in addition. With this approach, realistic and consistent emission factors can be simulated for any driving condition since the main physical relations are taken into consideration. E.g. variations in road gradients and in vehicle loading influence the engine power demand and the gear shift behaviour and thus lead to different engine loads over the cycle. Figure 1 shows the scheme of the model PHEM.

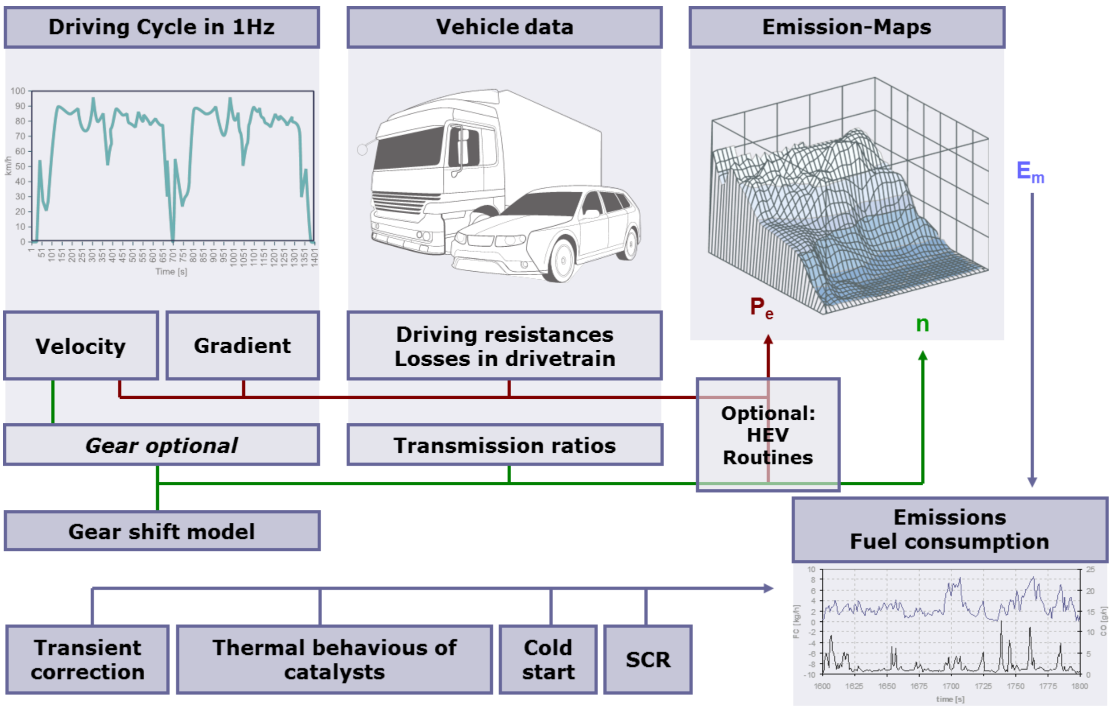

Figure 1: Scheme of the PHEM model

To simulate representative fleet average emissions per vehicle class, representative engine maps are necessary. PHEM produces emission maps by sorting the instantaneously measured emissions into standardised maps according to the actual engine speed and power.

To produce representative engine maps from vehicle tests, many vehicles should be included and realistic driving situations should be considered. Consequently, the inclusion of PEMS (Portable Emission Measurement System) data by the newly developed methodology in addition to the dynamometer data was very beneficial for a broader vehicle sample for the PHEM simulation.

The new method resolves the typical issue from PEMS tests, where most often no reliable torque signal is available. PHEM offers now the new option to calculate the engine power from the measured CO2 mass flow (or fuel flow) and engine speed based on generic engine efficiency maps (Figure 2). Thus, only the measured engine speed and the emissions are necessary to compile engine emission maps. This method, also called “CO2 interpolation method”, was already presented at the International Transport und Air Pollution Conference in Lyon 2016 (Matzer C. et al. 2016).

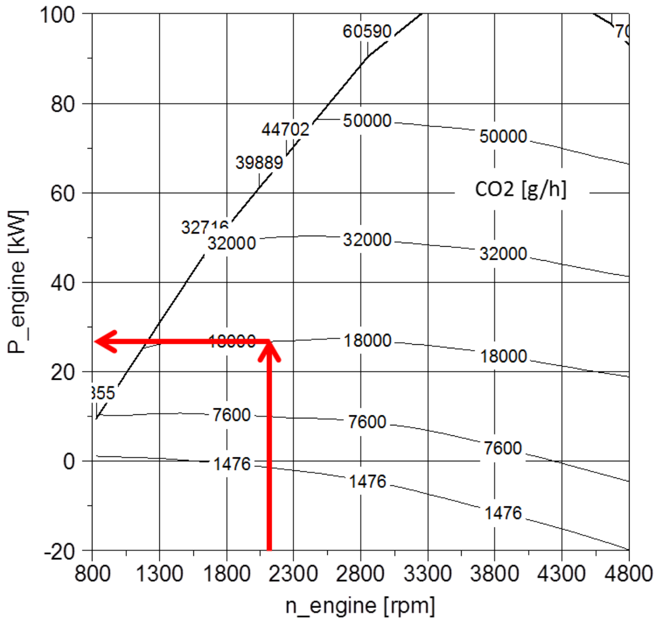

Figure 2: Example for interpolation of engine power from a generic CO2 map

The accuracy of the method can be tested by comparing measurement results for cycles driven on the dynamometer with simulation results based on the generic fuel maps for these cycles. When the test mass and road load values from the dynamometer setting are used as input for the PHEM simulation, the difference to the measured fuel consumption results from:

- Deviations of the vehicle specific fuel map to the generic map.
- Differences in the generic model for losses in the gear box and the axle.
- Differences in the real auxiliary power demand to the generic data used in PHEM.

The share of these generic values in the total uncertainty is open yet.

By calibrating the PHEM model data to meet the measured fuel consumption values, a more representative generic data set can be established in future.

For the quick update HBEFA 3.3 only a few results from dynamometer tests were analysed as outlined above. These showed an uncertainty of the generic diesel EURO 6 data between approximately 5 % and 20 %. A detailed analysis is planned for HBEFA 4.1.

3. Emission factors for diesel passenger cars

The following subchapters give a documentation about the work for the HBEFA 3.3 quick update.

3.1. Available emission data for EURO 6 diesel passenger cars

3.1.1. Test cycles

In principle, every cycle from dynamometer or RDE-trips with instantaneously measured emissions and engine speed can be used for engine emission map creation by the CO2 interpolation method in PHEM. For representative engine maps, the coverage of all relevant engine load and engine speed situations is necessary. Therefore, measurement data with included high-load operating points are suitable. Cycles with such operating points for example are the CADC or the ERMES cycle.

To avoid mixing effects of emissions behaviour due to cold and hot starts, only measurement data with hot starts have been used to create the hot emission maps. Hot start means, that the engine is already in the operating temperature range at cycle start. The additional emissions due to cold start are considered by a separate calculation step in the HBEFA. For the quick update measurement data of following cycles from the dynamometer have been used:

- CADC:
  CADC stands for Common Artemis Driving Cycle and consists of the 3 phases urban, road and motorway. By averaging the emissions from the subcycles a representative emission level for real world driving can be calculated (described as CADC 1/3 Mix in this report). The motorway part is available with 130 km/h and 150 km/h maximum velocity.
- ERMES:
  This cycle from the European Research group on Mobile Emission Sources is similar to the CADC but shorter.
- WLTC:
  The WLTC stands for Worldwide harmonized Light-duty vehicles Test Cycle and is from 1st of September 2017 on the new test cycle for homologation.
- RWC:
  RWC means Real World Cycle and is an extract of a real world trip with road gradients and activated auxiliaries for the dynamometer. The RWC is a vehicle specific cycle.

Additional to the dynamometer measurements also RDE-trips have been used for the HBEFA 3.3 update. RDE-trips cover high-load operating points even better than measurements on the dynamometer. The real drive emissions are measured with a PEMS. In past it was difficult to work with data from RDE measurements, because on the one hand such data were rare and on the other hand a power signal was not available or was too inaccurate for the engine map creation. With the new CO2 interpolation method, also data from RDE-trips without power signal can be successful considered for the map creation.

The measurements on the dynamometer are performed with constant ambient temperature between 20 °C and 30 °C. The ambient temperature of RDE-trips can fluctuate more than the mentioned range and influence the emission behaviour. Due to this problem and to be consistent with the dynamometer data of EURO 0 to EURO 5 only measured data between 15 °C and 30 °C ambient temperature have been used for map creation[1]. The limit of 15 °C for including measurements into the data for the base engine emission maps was selected, since several PEMS tests were in a range of 15 °C to 20 °C. The temperature effect in this range was assumed to be small so the advantage of the larger vehicle sample seemed to be more important than to have the data separation exactly at 20 °C as it is standard on dynamometer tests. More detailed analysis and further measurements on temperature effects are suggested for HBEFA 4.1. The influence of the mentioned ambient temperature on NOx emissions are considered by a post-processing work based on the simulated data.

3.1.2. Overview on the sample of measured vehicles

As mentioned, only instantaneously measured data from real world cycles and RDE-trips as described in 3.1.1 are used as representative data source for the emission model PHEM. The following table gives an overview on the number of the available measurements on EURO 6 diesel cars, which fulfil these demands. In total, the measurement data of 25 vehicles have been used provided by the emission labs all-over Europe. ADAC (Germany) provided data of 2, EMPA (Switzerland) of 12, TNO (Netherlands) of 2 and TUG (Austria) of 9 vehicles. Table 1 shows also the number of vehicles measured on the different cycles. For example, EMPA measured the CADC with 12 vehicles, the ERMES cycle with 5 vehicles.

Table 1: Available EURO 6 diesel cars

Lab	# vehicles tested in					# total measured vehicles
	CADC hot	ERMES hot	WLTC hot	RWC hot	RDE hot	
ADAC	1	2	-	-	-	2
EMPA	12	5	-	-	-	12
TNO	-	-	-	-	2	2
TUG	6	6	3	2	2	9
Total	**19**	**13**	**3**	**2**	**4**	**25**

Table 2: Available cycles measured with EURO 6 diesel cars

Lab/ cycle	# CADC hot	# ERMES hot	# WLTC hot	# RWC hot	# RDE hot	Total
ADAC	1	2	-	-	-	3
EMPA	12	5	-	-	-	17
TNO	-	-	-	-	3	3
TUG	12	10	4	3	9	38
Total	**25**	**17**	**4**	**3**	**12**	**61**

[1] The data available for EURO 0 to EURO 5 emission factors so far are results from dynamometer tests between 20 °C and 30 °C. The analysis for temperature effects on the hot emission factors (chapter 3.6) suggests testing in future also at lower temperature levels to cover European temperature levels.

3.1.3. Details of measured vehicles

Following table gives an overview on the main specifications of the vehicles used and the source where the measured data are from. The registration number refers to the number of new registrations of the particular vehicle from 2013 to 2015 according to the EU-28 CO2 monitoring database. This is the timeframe where mainly the EURO 6 cars have been introduced. Registrations in 2016 were not considered since no data during the work on the update of the PHEM model was available. For double tests of the same vehicle models the corresponding registration number was split up (unweighted). The registration number is the basis for the weighting of the engine maps for the average engine emission maps for PHEM. The sample of measured vehicle covers 18 % of the passenger car diesel models registered 2013 to 2015.

Table 3: Specifications of EURO 6 diesel cars used in the engine emission map for PHEM and new registrations of the vehicles in EU-28

Lab	Make	Model	P_{rated} [kW]	n_{rated} [U/min]	New registrations [#]
TUG	BMW	X5	180	4000	79756
TUG	BMW	530d	180	4000	11851
TUG	Audi	A4 Allroad	180	4000	306698
TUG	Mazda	CX-5	110	4500	49514
TUG	BMW	320d	120	4000	103691
TUG	Kia	Carens	104	4000	40461
TUG	Audi	Q7	160	4000	37221
TUG	VW	Sharan	110	3500	88353
TUG	Peugeot	508 SW	88	3500	122878
EMPA	VW	Golf VII	81	3200	855277
EMPA	Mazda	CX-5	110	4500	49514
EMPA	BMW	530d	190	4000	11851
EMPA	Mercedes-Benz	GLK 220	125	3200	48060
EMPA	VW	Passat	103	4200	459372
EMPA	Renault	Senic	96	4000	278320
EMPA	Mini	Cooper	85	4000	18994
EMPA	Mercedes-Benz	A220	125	3400	17357
EMPA	BMW	X3	140	4000	95544
EMPA	Mercedes-Benz	ML 350	190	3600	34730
EMPA	Porsche	Macan	190	4000	25615
EMPA	Peugeot	208 SW	110	3750	340831
ADAC	BMW	118d	110	4000	103691

Lab	Make	Model	P_{rated} [kW]	n_{rated} [U/min]	New registrations [#]
ADAC	BMW	320d	140	4000	103691
TNO	Ford	Focus	70	3600	326974
TNO	Mercedes-Benz	C220	125	3000	57407

3.2. Elaboration of the PHEM engine emission maps for EURO 6

To produce the engine emission maps with PHEM the measured emissions – typically in 1 Hz resolution – are processed to be correctly time aligned to the engine speed signal in a first step. Then the emissions are sorted by PHEM into the engine map according to the actual engine speed and power values. Then average values per node in the map are calculated. Finally from the single normalised engine maps per vehicle the average normalised engine map is calculated as weighted average. The single steps are described blow.

Step 1: Preparation of the available modal measurement data

As described in chapter 3.1.2 in total 61 measurement data sets from 25 vehicles are available for the engine map creation. These data sets from dynamometer and RDE-tests had to be processed to be applicable for PHEM. The pre-processing of the data ensures that:

- The correct time shift between emissions and load signal is given. To date only a constant time shift has been used for most data sets (exception: RDE-trips from TUG are variable time shifted). Variable time shift means, that the instantaneous emission signals are time shifted for the transport time based on the exhaust gas mass flow rates. That improves the emission signal especially for dynamometer measurements (Weller K. et. al. 2016).
- Cold start is excluded from the measurement data. According to the RDE legislation for RDE-trips with cold start the first 5 minutes from the recorded data have been removed.
- Only cycles and trips have been processed for the base emission maps, where the average ambient temperature was between 15 °C and 30 °C. Test data at lower temperatures was used to analyse the influences of ambient temperature.

Due to no information on possible DPF regenerations especially on RDE-trips, the measurement data is not corrected regarding the different emissions during regeneration. As a consequence no correction factor for considering the DPF regeneration in simulation data has been used since the regenerations are already included in the measurement data.

Step 2: Engine map creation with measurement data of each vehicle

The described CO2 interpolation method for map creation requires the measured emission and engine speed in an appropriate temporal resolution, the FC or CO2 engine map (FC correlates with CO2) and full load plus drag curve of each vehicle. In most of the cases, no engine specific engine fuel flow map is available. Therefore a so-called generic CO2 map is used.

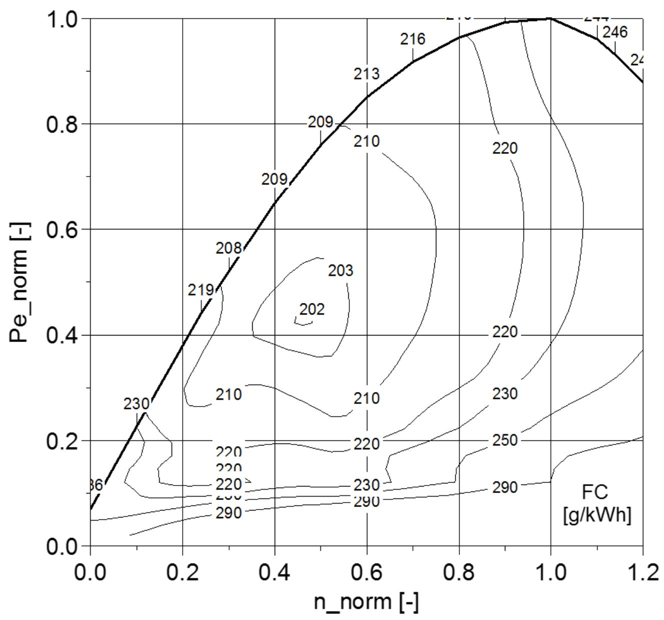

Figure 3: Generic CO2 map for 2013 engine technology

Figure 3 shows one example for a generic CO2 map. This map is derived from a steady state engine map for a 2002 engine considering the CO2 savings of different engine technologies introduced from 2002 up to now. The CO2 savings depending on engine technologies have been acquired in a project together with Ricardo-AEA for the European Commission (Hill N. et. al. 2015). With the introduction of different technology levels based on the generic base fuel map different technology levels are covered in a systematic way. For the HBEFA update 2 generic maps for model years 2012-2014 and 2015-2016 have been generated.

As mentioned before, also individual full load and drag curves are necessary as input for PHEM. For cases where the literature review was not successful, default data has been used. PHEM calculates with the given engine speed and CO2 the engine power in each time step, P = f (n, CO2) and creates the emission map by sorting the instantaneous emissions like NOx, CO, etc. in the generic engine map. In order to get consistent maps the CO2 interpolation method was also used for map creation with measurement data of dynamometer tests where a wheel power signal is in most of the cases available[2].

An average emission map from all tests is obtained by averaging the single maps in normalised formats. The normalisation procedure in PHEM is basis for averaging single engine maps of engines with different rated power and speed ranges and reads as follows:

$P_{e\_norm} = P_{engine} / P_{rated}$

$n_{norm} = (n_{engine} - n_{idle}) / (n_{rated} - n_{idle})$

$FC_{norm} = FC / P_{rated}$ (similar for CO_2)

[2] In the past the engine power was calculated from the dynamometer tests based on the road load and test mass settings of the vehicle on the dynamometer with assumptions on transmission losses and auxiliary power demand. Due to inaccurate time alignment between power signals and emission signals, the resulting fuel maps had various qualities depending on the data sources. This issue should be eliminated by calculating the power signal from the CO2 value. The time alignment to the engine speed signal is still relevant for the CO2 based method.

P_{e_norm}… ... normalised engine power in [-]

P_{engine}… .... actual effective engine power in [kW]

P_{rated}…...... rated engine power in [kW]

n_{norm}… ...... normalised engine speed in [-]

n_{engine}…..... actual engine speed in [rpm]

n_{idle}…........ idling speed in [rpm]

n_{rated}… ...... speed at rated power in [rpm]

FC_{norm}… ... normalised fuel consumption in [g/kWh]

FC…......... fuel consumption in [g/h]

3.2.1. Calculation of the average base EURO 6 emission map

The base NOx emission map for the EURO 6 diesel cars was produced by building the weighted average from all single engine maps from the vehicles listed in Table 3. As weighting factor the shares of the single models in the total registration number of all vehicles in Table 3 was used. The average map consists of the weighted average of each node point in the normalised map format.

3.2.2. Calibration of the average EURO 6 emission map

The calibration shall align the simulated emission levels with the measured levels. For the creation of the final EURO 6 engine map several calibration steps were performed. The calibration has the target to calibrate the PHEM model which is based on a limited sample of vehicle tests to the broader sample of bag results stored in the ERMES DB (ERMES database). In the past the instantaneous data available for PHEM engine emission maps was a subset of the ERMES DB, thus the calibration routine was one single step, (Rexeis M. et. al. 2013).

In the actual calibration for HBEFA 3.3 many tests in the vehicle sample with instantaneous data for PHEM had no suitable bag data from chassis tests in the ERMES DB (e.g. the vehicles with PEMS tests only). Vice versa also bag data without suitable instantaneous data from chassis tests are available in the ERMES DB (e.g. cycles without measurement of engine speed).

Consequently a more sophisticated method for the calibration was elaborated which is described below.

As basis for the calibration the CADC test results available in the ERMES DB have been recalculated with PHEM. Since in the basis EURO 6 map several vehicles are included for which no CADC test result is available, a direct calibration of the base map to the ERMES DB CADC results seemed not to be appropriate. Such a calibration would have eliminated the broader data from PEMS tests in the base engine map.

Consequently an extra EURO 6 engine map was produced, which consisted only of those vehicles, for which both, instantaneous emission data and CADC test results in the ERMES DB were available. In the PHEM simulation with this sub-sample engine map also the vehicle data from these vehicles were used as input (weighted according to the shares listed in Table 4). The known values from the tested vehicles were the rated power, idling speed, rated engine speed and the test mass. All other values used the generic values of EURO 6 diesel cars as already elaborated for HBEFA 3.2 (air and rolling resistance coefficients, transmission losses and auxiliary power demand). Thus the calibration adjusts these generic data to meet the measured emissions of the sub-sample.

Table 4 shows the sub-sample of vehicles used for the calibration. A weighted average map has been calculated with the 17 engine maps. The weighting factors are based on the number of vehicle registrations listed in Table 4.

Table 4: Vehicles for model validation and calibration with the ERMES DB (vehicles where instantaneous emission data and CADC test results are available)

Lab	Make	Model	P_{rated} [kW]	n_{rated} [U/min]	Weighting Factor
TUG	BMW	530d	180	4000	0.5%
TUG	Audi	A4 Allroad	180	4000	12.4%
TUG	Mazda	CX-5	110	4500	0.8%
TUG	VW	Sharan	110	3500	3.6%
EMPA	VW	Golf VII	81	3200	34.6%
EMPA	Mazda	CX-5	110	4500	0.8%
EMPA	BMW	530d	190	4000	0.5%
EMPA	Mercedes-Benz	GLK 220	125	3200	1.9%
EMPA	VW	Passat	103	4200	9.3%
EMPA	Renault	Senic	96	4000	11.3%
EMPA	Mini	Cooper	85	4000	0.8%
EMPA	Mercedes-Benz	A220	125	3400	0.7%
EMPA	BMW	X3	140	4000	3.9%
EMPA	Mercedes-Benz	ML 350	190	3600	1.4%
EMPA	Porsche	Macan	190	4000	1.0%
EMPA	Peugeot	208 SW	110	3750	13.8%
ADAC	BMW	320d	140	4000	2.8%

For the validation run the CADC has been chosen as reference cycle since this cycle represents roughly real world driving and since the CADC had the highest number of available tests. The simulation run showed that the simulated NOx were approximately 10 % higher than the bag data from the ERMES DB. Hence, the NOx in the average map were corrected by division with a factor of 1.1. Figure 4 shows the results of the second simulation run for the CADC urban, road, motorway and the 1/3 Mix. The grey bars (simulated) fit to the orange bars (measured, values also weighted). The blue bars are the unweighted measured values. The motorway part is weighted with the appropriate shares of measured cycles with 130 km/h and 150 km/h maximum velocity.

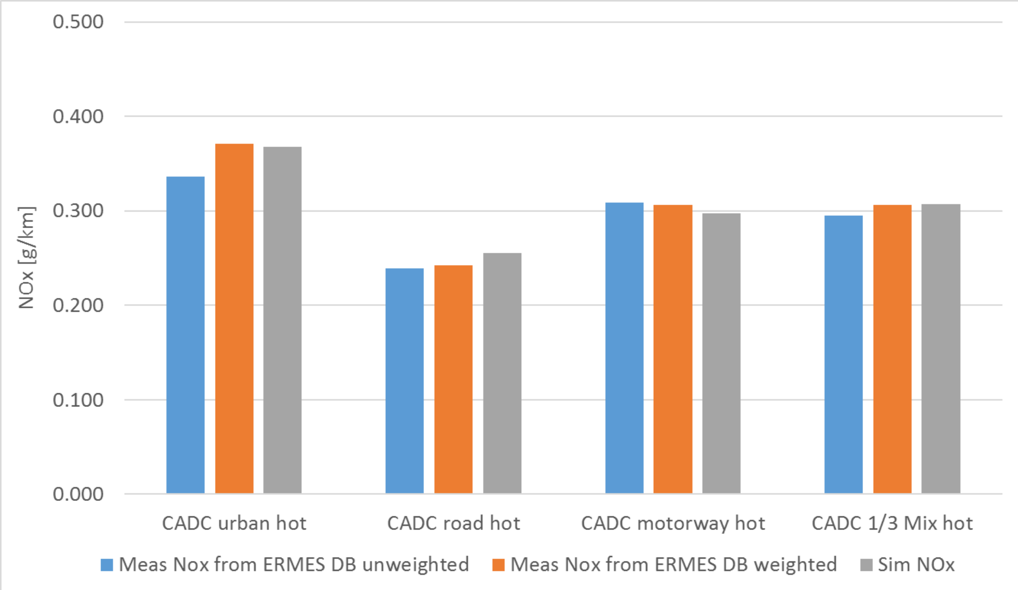

Figure 4: Simulation results for EURO 6 diesel cars sub-sample after model calibration

In a second step, the weighted base average emission map described in chapter 3.2.1 from all vehicles was adjusted with the calibration factor described before (i.e. division by 1.1). The NOx map in [g/kWh] created in this step is shown in Figure 5.

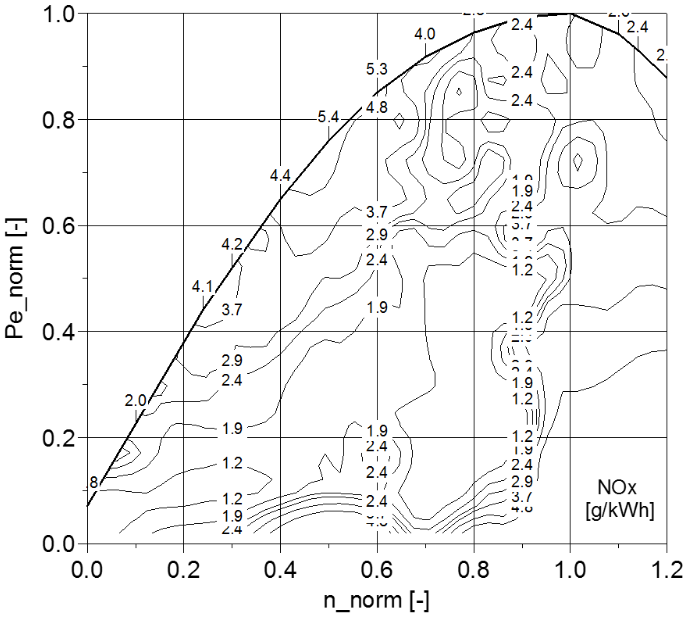

Figure 5: Calibrated EURO 6 NOx map for diesel cars

3.2.3. Validation of the EURO 6 diesel car NOx simulation results

Figure 6 shows the validation of the EURO 6 diesel car for the CADC. The blue bars are the weighted measured CADC values from all vehicles in the ERMES DB. The yellow bars describe the simulation result with the calibrated engine map from the full sample and the weighted vehicle data from the full sample as listed in Table 3. The higher NOx values compared to the simulation results with the sub-sample (Figure 4) result from the additional data in the map (broader sample of vehicles) and from different vehicle properties.

The final EURO 6 diesel car for the HBEFA shall be representative for the average European EURO 6 diesel car. Consequently the vehicle data for PHEM simulation was adjusted to power and mass from the vehicles registered from 2013 to 2015 according to the EU-28 CO2 monitoring database. The green bars present the corresponding simulation results. The EU average EURO 6 car shows even higher NOx due to a lower rated engine power of the EU average vehicle compared to the average vehicle in the engine emission map. This leads to more time shares in engine map areas with higher specific NOx emissions.

As mentioned before, the ERMES DB data on CADC results and the tests used for engine emission map creation are samples from the total fleet where it is unknown, which sample is more representative for the total fleet. Since the engine map sample includes additional PEMS tests, it was decided to trust more in the engine map data and not to calibrate the PHEM simulation results to the ERMES DB CADC values[3].

The last settings (green bars) are thus the settings used for the simulation of the HBEFA driving cycles.

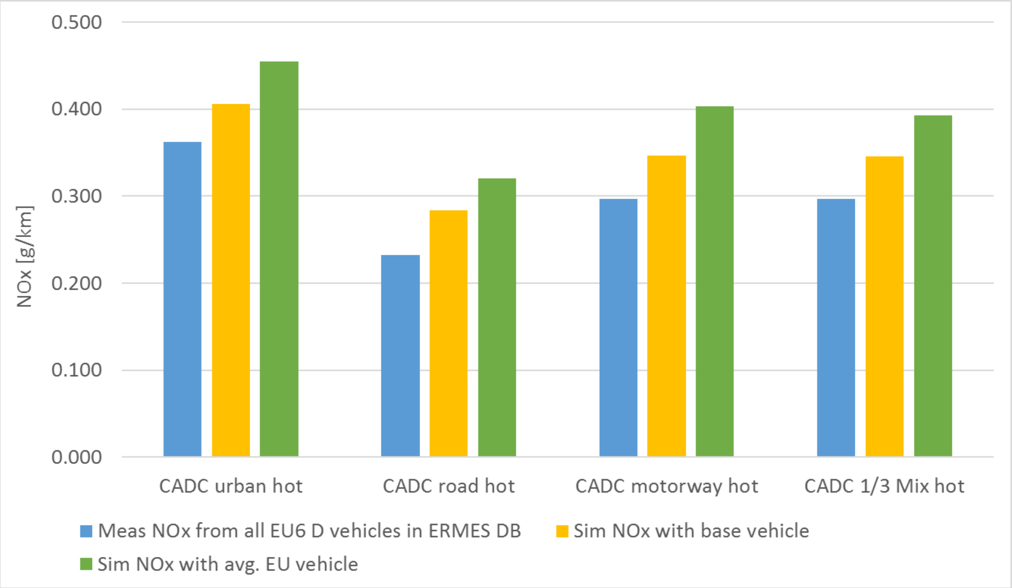

Figure 6: Simulation results for EURO 6 diesel in the CADC using different vehicle settings

Table 5 shows the main specifications for the average EURO 6 diesel car used for the HBEFA update.

Table 5: Specifications for average EURO 6 diesel car

Total vehicle mass [kg]	P_{rated} [kW]	n_{rated} [U/min]
1651	99	3672

[3] The step from yellow to green bars due to the lower rated engine power on EU average results from more time shares near to full load where the specific NOx emissions [g/kWh] usually are increasing. This effect seems to be reasonable for the fleet average and thus was considered in the average EURO 6 diesel car in PHEM by simply using the EU average rated power for EURO 6 diesel cars.

3.3. Assessment of the EURO 6d-Temp and EURO 6d diesel vehicles

The implementation of EURO 6d-Temp and EURO 6d is planned in future, hence no vehicles with such certification are available. Due to these conditions an estimation based on the RDE legislation was made. The RDE legislation introduces CFs (conformity factors) for the new EURO classes to describe the emission limits for RDE-trips based on the emission limits for the dynamometer test cycle. E.g. the CF for NOx EURO 6d-Temp is 2.1, for NOx EURO 6d 1.5. Thus, the NOx limit for RDE-trips is 168 mg/km for EURO 6d-Temp and 120 mg/km for EURO 6d. The EURO 6d map has been created by selecting engine maps of those vehicles listed in Table 3, which already fulfil the EURO 6d legislation according to the measured NOx emissions. The criterion was to reach the RDE limit with the simulated NOx on CADC considering a correction factor for different dynamic driving style between RDE-trip and CADC.

The trip dynamics are defined in the RDE legislation with the parameters vehicle velocity and positive vehicle acceleration (> 0.1 m/s²), also known as $v{*}a_{pos0.1}$. According to the RDE legislation, the $v{*}a_{pos0.1}$ calculation is done for each second of a trip and the 95 % percentile of $v{*}a_{pos0.1}$ is calculated[4]. The 95 % percentile ($v{*}a_{pos0.1}$) is one relevant kinematic RDE-trip parameter and is used as criterion whether a RDE-trip is valid or invalid. Figure 7 shows the average 95 % percentile ($v{*}a_{pos0.1}$) of 11 vehicles in 32 RDE-trips for urban, road and motorway parts of the trips. In addition the maximal allowed 95 % percentile ($v{*}a_{pos0.1}$) for valid trips and the 95 % percentile ($v{*}a_{pos0.1}$) of the CADCs with maximum speed of 130 km/h and 150 km/h are plotted. From the figure it can be derived that the dynamics of the CADC are on average approximately 50 % lower than the maximum 95 % percentile of the $v{*}a_{pos0.1}$ value. The NOx emissions of actual vehicles on average increase by 30 % to 60 % between trips with average 95 % percentile ($v{*}a_{pos0.1}$) compared to trips with maximum allowed 95 % percentile ($v{*}a_{pos0.1}$). For future EURO 6d compliant vehicles less sensitivity against dynamic load changes is assumed or a better adjustment to the actual NOx level (e.g. control function to remain in any driving situation with a safety margin below the CF limit). It was assumed that the CADC should give 20 % lower NOx emissions than a worst case RDE test. Since measurement data for these selected vehicles are not available for the CADC, the CADC NOx emissions are based on simulations.

Therefore, a vehicle should have NOx values below 100 mg/km to be capable of meeting the 120 mg/km maximum allowed 95 % percentile ($v{*}a_{pos0.1}$) to fulfil EURO 6d provisions. Consequently, only these vehicles were selected to compute the EURO 6d engine maps for PHEM.

[4] The 95 % percentile is the value where 95 % of the total $v{*}a_{pos0.1}$ values are below.

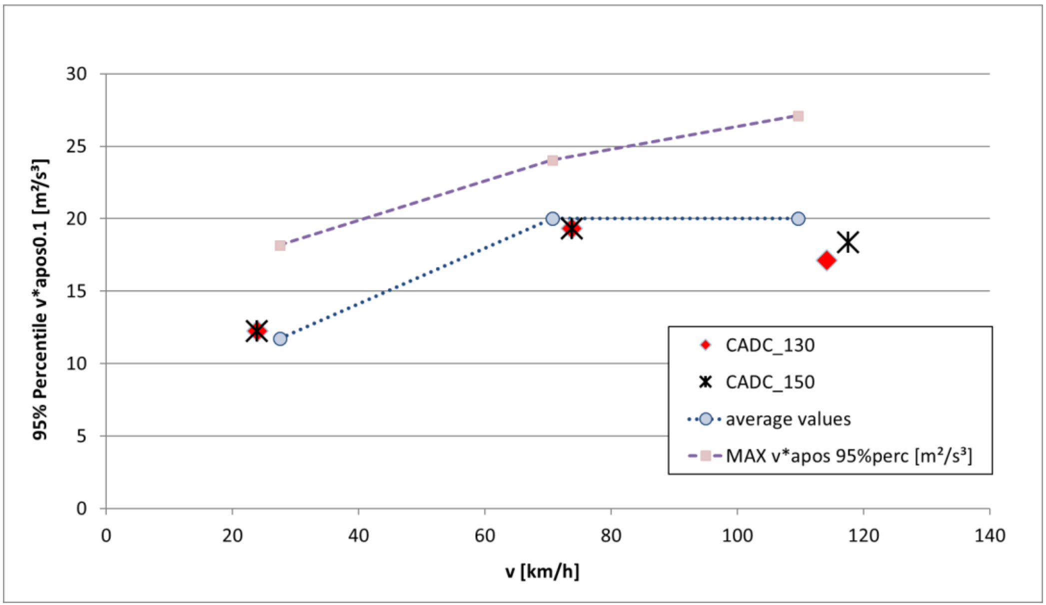

Figure 7: Trip dynamics of RDE-trips and CADCs

Table 6 shows the selected vehicle from Table 3.

Table 6: Vehicles for EURO 6d map creation

Lab	Marke	Modell	P_rated [kW]	n_idle [U/min]	n_rated [U/min]
TUG	VW	Sharan	110	830	3500
EMPA	BMW	530d	190	700	4000
EMPA	Mercedes-Benz	GLK220	125	750	3200
EMPA	Mini	Cooper	85	900	4000
ADAC	BMW	118d	110	750	4000
TNO	Mercedes-Benz	C220	125	750	3000

Due to missing information about future registrations the average EURO 6d map has been created without weighting. Since the driving styles and ambient conditions for RDE compliant testing are not covering 100 % of the real world conditions, real world average emissions may be slightly higher in future than average emissions from RDE testing. To consider this effect a factor of 1.2 for NOx has been applied for the EURO 6d map for PHEM. This factor is an assumption based on actual experiences at TUG with RDE testing. Certainly the emission values produced for EURO 6d are a technology assessment and need to be validated with measurements of future EURO 6d compliant cars. Figure 8 shows the EURO 6d NOx map.

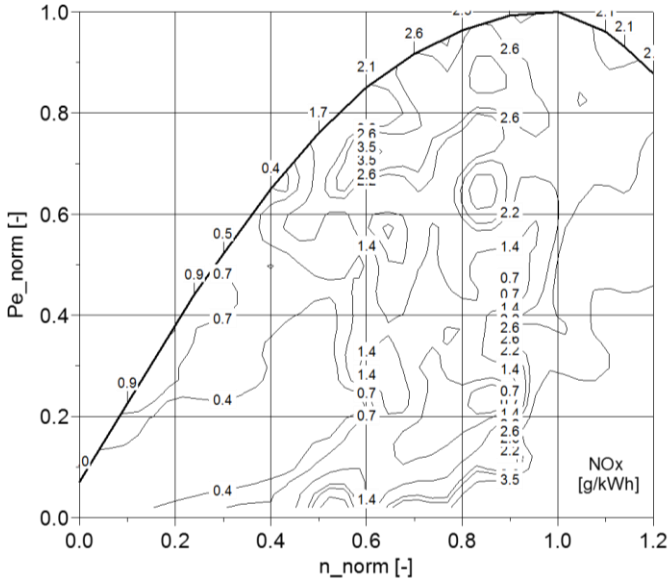

Figure 8: EURO 6d NOx map for diesel cars

The vehicle characteristics for EURO 6d simulation is similar to the EURO 6 one, only the rolling resistances have been reduced by 15 %. Furthermore, the aerodynamic resistance has been reduced by 10 %. These assumptions are based on the project with Ricardo-AEA (Hill N. et. al. 2015).

The map for EURO 6d-Temp (Figure 9) has been derived from the EURO 6 and EURO 6d map. As reference cycle also the CADC was used. Considering correction methods like mentioned before the EURO 6 map was weighted with 19 % and the EURO 6d map with 81 %. The same weighting factors have been used for the vehicle characteristics.

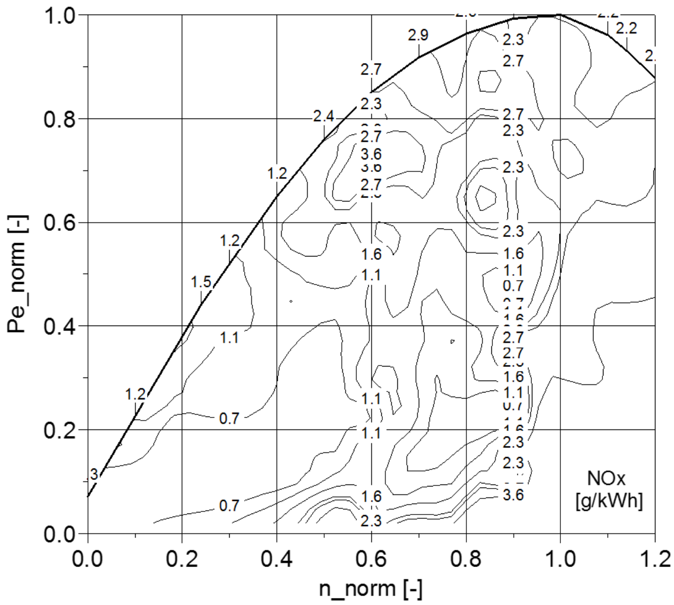

Figure 9: EURO 6d-Temp NOx map for diesel cars

Figure 10 and Figure 11 show the simulation results for EURO 6, EURO 6d-Temp and EURO 6d average diesel car in the CADC with 130 km/h and 150 km/h maximum velocity. In addition the NOx emissions of EURO 5 average diesel car in the CADC are shown for comparison between the different EURO classes. The values of the EURO 5 car are unchanged between HBEFA 3.2 and 3.3.

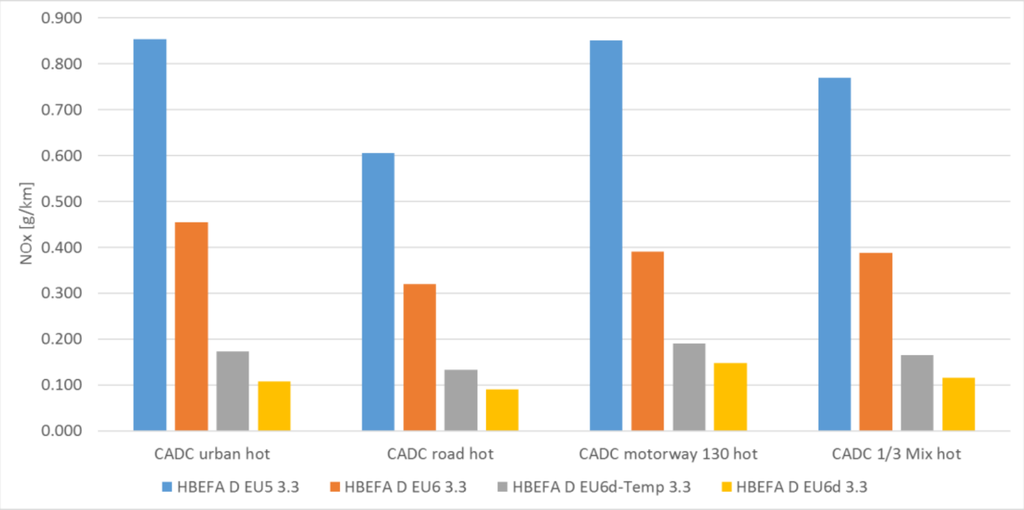

Figure 10: Simulation results for EURO 5, EURO 6, EURO 6d-Temp and EURO 6d diesel cars in the CADC with 130 km/h maximum velocity

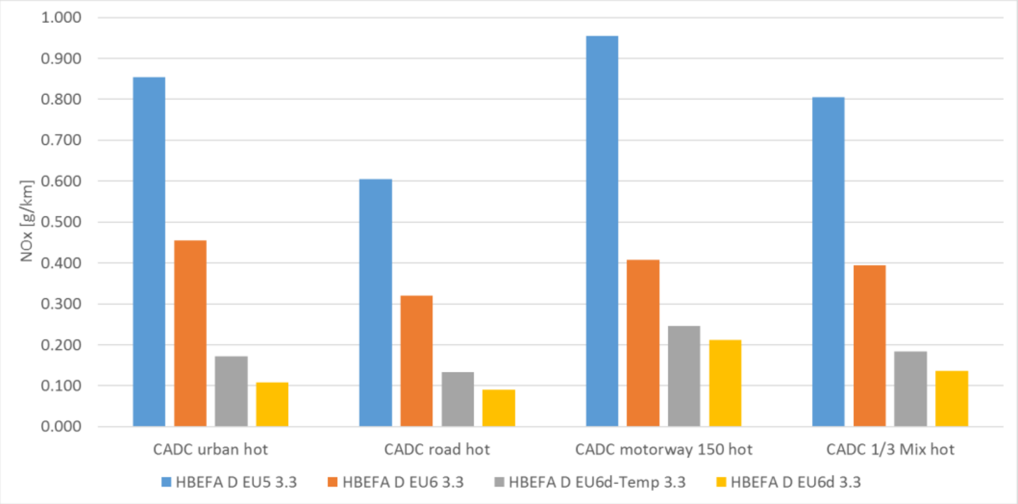

Figure 11: Simulation results for EURO 5, EURO 6, EURO 6d-Temp and EURO 6d diesel cars in the CADC with 150 km/h maximum velocity

3.4. Readjustment of the PHEM engine emission maps for EURO 4

Due to the availability of new measurement data of EURO 4 diesel vehicles in the ERMES DB a readjustment of the EURO 4 emission map has been performed.

The first step was the simulation of the CADC with the EURO 4 emission map and EURO 4 vehicle from HBEFA 3.2. The simulation run with the “old” engine map is shown in Figure 12 and Figure 13 (grey bar). In the motorway phase the simulation underestimates the average measured value from the ERMES DB.

Due to the underestimation especially in the motorway part, the readjustment of the emission map has been done only for data points in the high load and speed area of the engine map. The NOx correction in the data points of the map starts at engine speed = 0.42 and engine power = 0.44 (both values normalised). Iteration processes determined the level and correction area of the factor. The blue bar in Figure 12 and Figure 13 shows the simulation result with the adapted NOx emission map. The CADC 1/3 Mix comparison between simulation and measurement shows a smaller deviation after the re-calibration.

The average NOx emissions according to the ERMES DB however, are still underestimated for the highway part of the CADC by the model PHEM. A calibration for a better agreement for the highway 130 km/h parts lead to a worse agreement in the urban, road and highway 150 km/h parts and was thus not used for HBEFA 3.3.

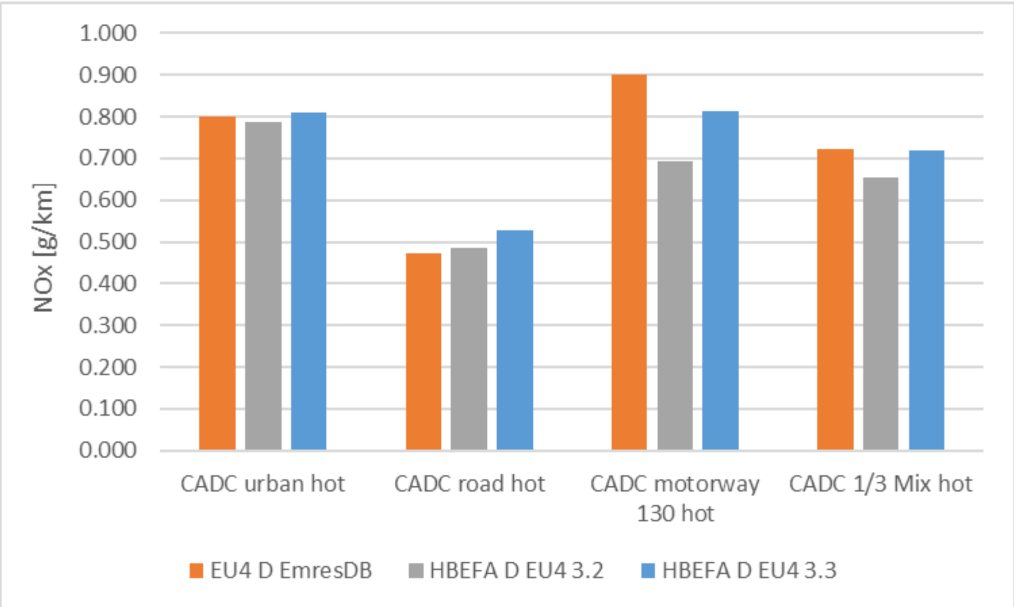

Figure 12: Simulation results for EURO 4 diesel cars after readjustment (CADC 130 km/h)

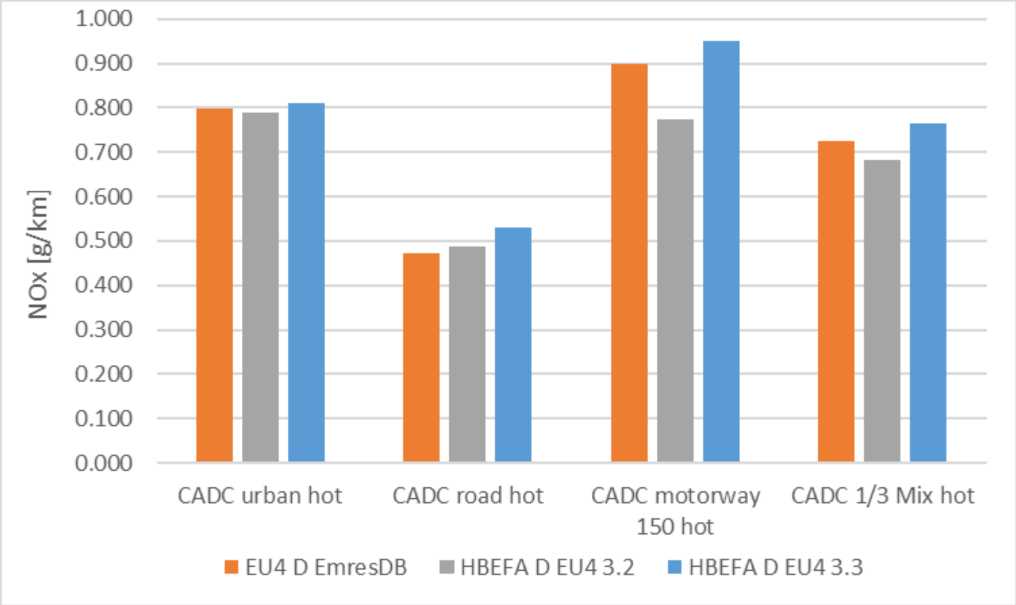

Figure 13: Simulation results for EURO 4 diesel cars after readjustment (CADC 150 km/h)

3.5. Calculation of HBEFA 3.3 emission factors

With the PHEM parameterisation for emission behaviour of EURO 4, EURO 6, EURO 6d-Temp and EURO 6d diesel vehicles as described in the previous chapters, emission factors for the full set of HBEFA driving cycles in combination with all road gradients (-6 %, -4 %, -2 %, +/-0 %, +2 %, +4 %, +6 %) have been calculated.

Figure 14 and Figure 15 show the new NOx emissions results as function of the vehicle velocity for the mentioned EURO classes for 0 % road gradient. In Figure 14 the old NOx emission results of EURO 6 and EURO 6c from HBEFA 3.2 are also plotted. Figure 15 shows the old and new NOx emission factors of EURO 4. In both charts the NOx emissions of EURO 5 for comparisons between the different EURO classes are plotted. As mentioned, for this segment the values are unchanged between HBEFA 3.2 and 3.3.

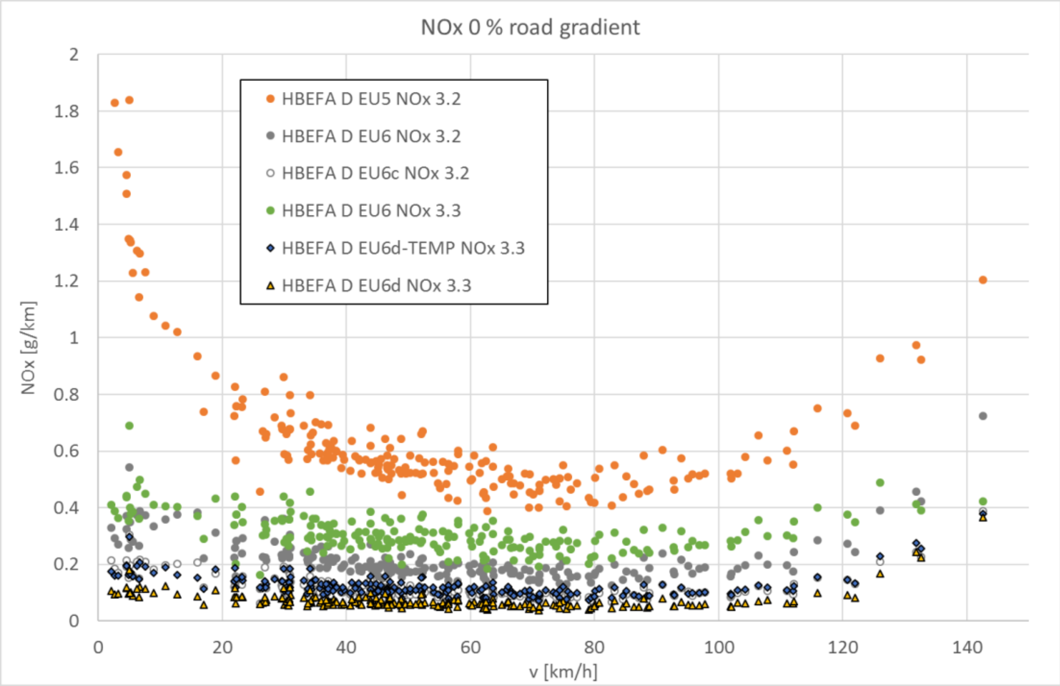

Figure 14: Old (HBEFA 3.2) and new (HBEFA 3.3) NOx emission factors for EURO 5 and EURO 6 diesel cars

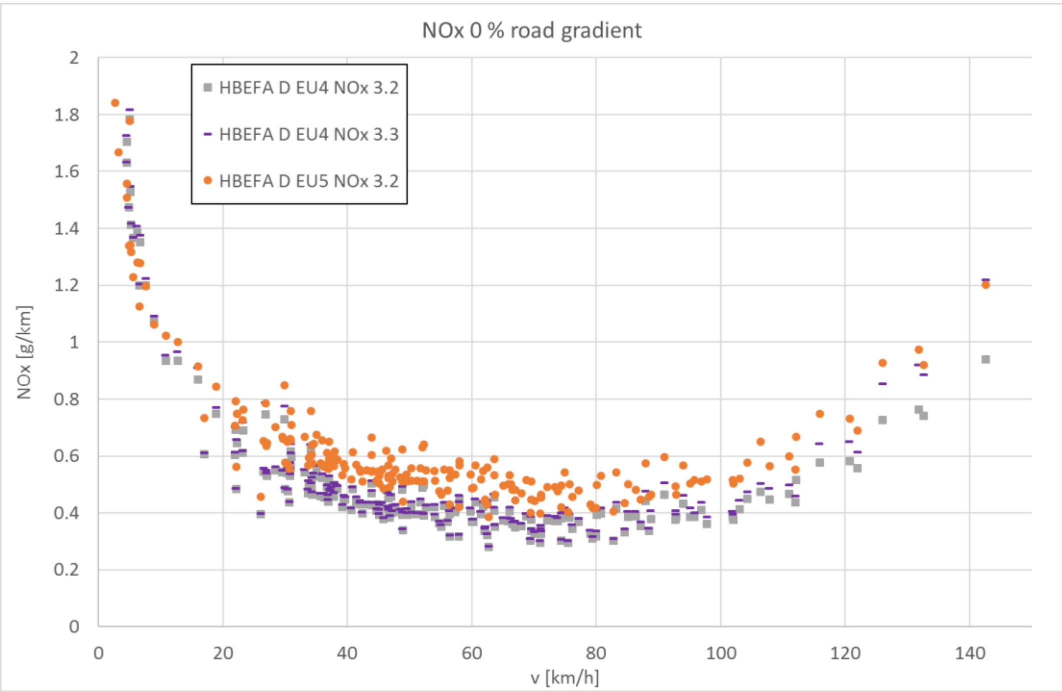

Figure 15: Old (HBEFA 3.2) and new (HBEFA 3.3) NOx emission factors for EURO 4 and EURO 5 diesel cars

3.6. Effects of ambient temperature on NOx emissions

The NOx formation can be described with the Zeldovich mechanism, e.g. (Hausberger S., Sams T. 2016) and depends on the temperature and the oxygen concentration at the flame front in the combustion chamber. Higher temperature and sufficient oxygen concentration result in higher NOx emissions if all other conditions are unchanged. Both parameters can be influenced by different NOx reduction technologies, e.g. the EGR (exhaust gas recirculation). The EGR uses the properties of inert gas to reduce temperature and oxygen with the recirculation of (cooled) exhaust gas.

For conservative technologies lower ambient temperatures result in lower temperature at the flame front and as a consequence in a lower NOx formation.

Due to the recirculation of combustion products, the water vapour concentration in the exhaust gas is increasing with the EGR rate. Consequently, lower ambient temperatures are more critical in terms of condensation effects in the EGR path at higher EGR rates. Condensation of water with particles and hydrocarbons in the distillate can cause severe problems, such as interlocking of the cooler or the intake system due to coking. Therefore, the EGR can be reduced or deactivated to save components in the EGR path. If the EGR rate is reduced at lower ambient temperatures, this results in more NOx at lower ambient temperature. The EGR is in most of the cases optimised for an ambient temperature range of 20 °C to 30 °C. The effect of higher NOx at lower temperatures was not considered in the emission factors in HBEFA 3.2 or older since almost all vehicle tests were conducted at standard conditions around 25 °C at the dynamometer. In the meantime a method to evaluate remote sensing data on temperature effects was elaborated as outlined in the HBEFA report (Keller M. et. al. 2017) and the PEMS test data provided measurements at different temperature levels for validation. HBEFA 3.3 now considers temperature effects.

For the investigations based on vehicle testing, measurement data of RDE and dynamometer tests from 7 different diesel EURO 6 vehicles driven at different ambient temperatures have been used to produce vehicle and ambient temperature specific engine maps by PHEM. To compare only the effect of the ambient temperature a simulation run for all vehicles on a common cycle was necessary. The vehicles with the appropriate engine maps have been simulated on the CADC, the simulation results for diesel cars are shown in Figure 16. The NOx are plotted as function of the ambient temperature. The trend with higher NOx at lower ambient temperatures could be verified.

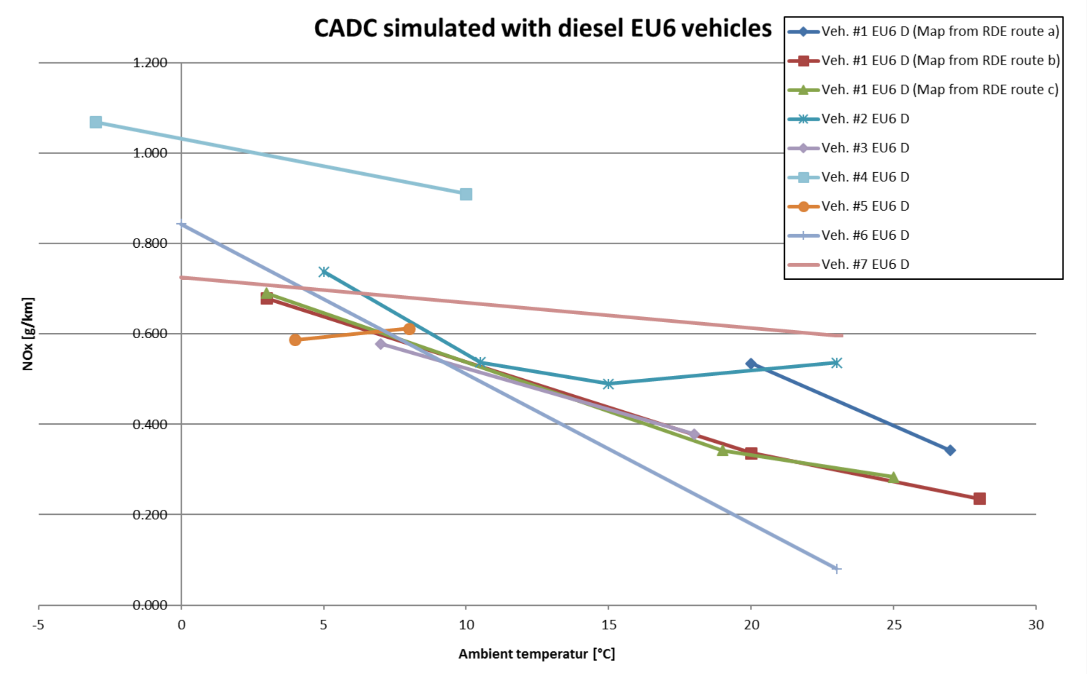

Figure 16: Effects of ambient temperature on NOx emissions for EURO 6 diesel cars

The simulated data can also provide a generic correction function, shown in Figure 17 (same simulated data as in Figure 16).

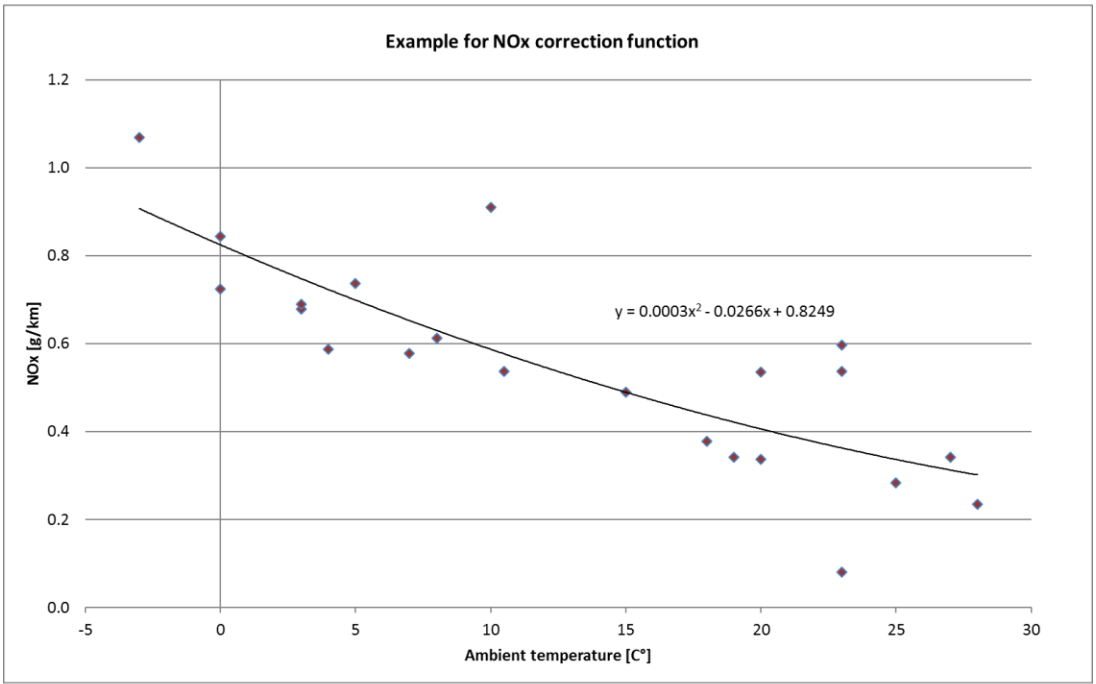

Figure 17: Example for NOx correction function for EURO 6 diesel cars

To check the NOx temperature behaviour also remote sensing measurement data from Sweden have been analysed. The following chart shows effects for EURO 4, EURO 5 and EURO 6 diesel cars. In addition the TUG data are plotted (red rhombi with blue edging), which fit the remote sensing data very well. As mentioned before, the EGR is optimised for a temperature range > 20 °C, therefore only data points are plotted below this threshold. Furthermore, all trend lines are described by linear equations.

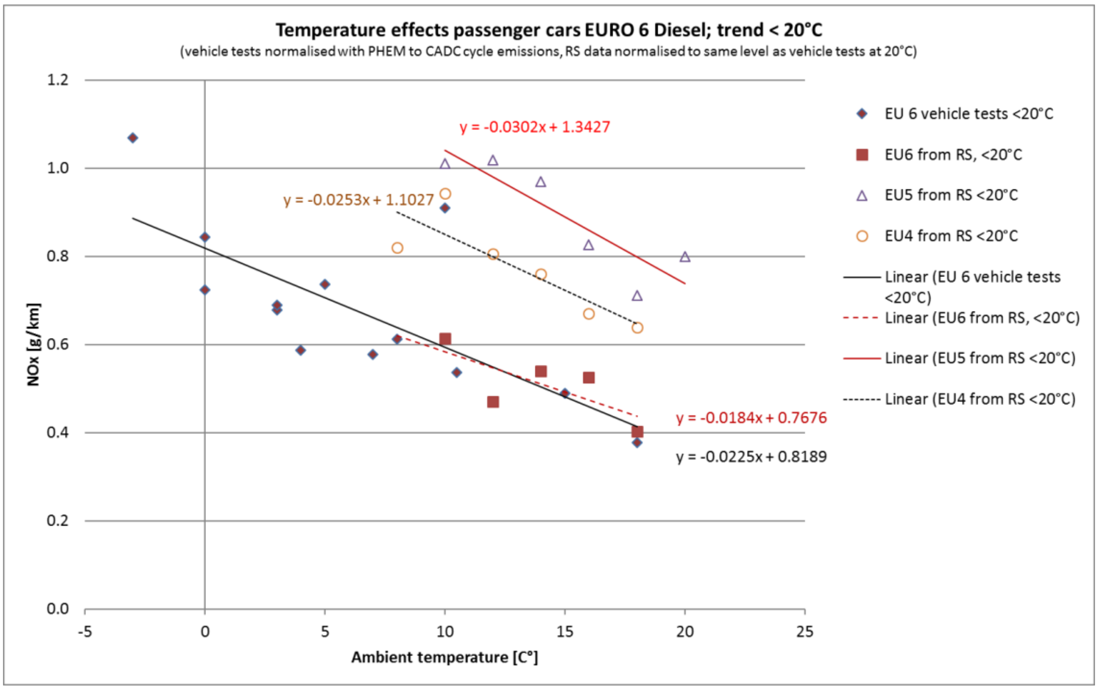

Figure 18: Preliminary NOx correction functions for EURO 4, EURO 5 and EURO 6 diesel cars based on vehicle tests and on Remote Sensing data from Sweden

These linear equations from remote sensing measurement data were used as basis for the correction in the HBEFA but have been further adjusted to remote sensing data provided from tests in Switzerland. The final correction functions were elaborated for the following boundary conditions:

- Ambient temperature effect on NOx emissions occurs only below 20 °C for EURO 4, EURO 5 and EURO 6.
- Ambient temperature effect on NOx emissions for EURO 6d-Temp and for EURO 6d are limited by the boundary conditions defined in the RDE regulation (limits have to be met down to 3 °C for EURO 6d-Temp and down to -3 °C for EURO 6d). Temperature effects are relevant only below these temperature thresholds for future vehicles.
- NOx does not further increase below 0 °C. The available data do not cover lower temperatures, thus no statement on the real behaviour is possible at the moment. It is assumed, that EGR is on fleet average already reduced down to almost zero percent at 0 °C, so that no further effect on NOx occurs.

With the additional remote sensing data from Switzerland the NOx correction functions shown in Figure 19 were elaborated. To produce the average correction functions the NOx emissions at temperatures below 20 °C were divided by the average NOx emissions between 20 °C and 30 °C for all single sources and from the relative NOx changes the regression lines were calculated.

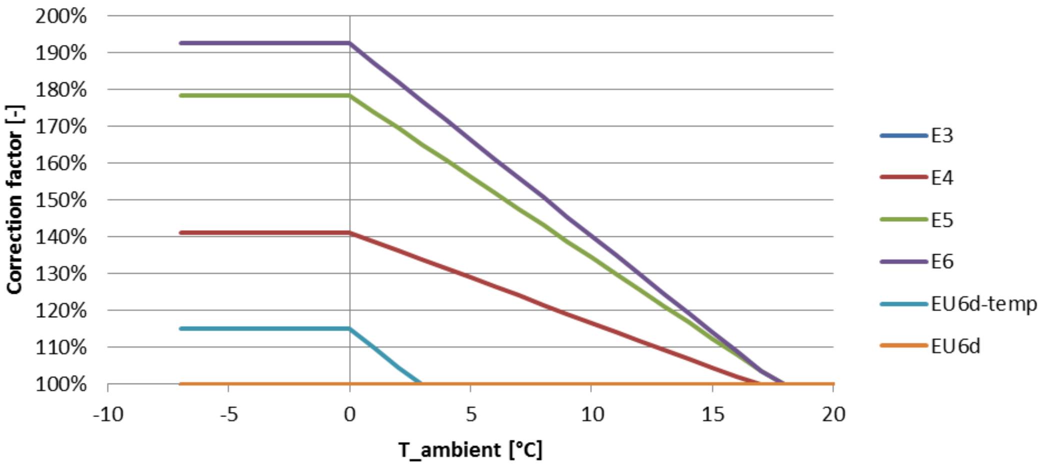

Figure 19: NOx correction functions for EURO 4, EURO 5 and EURO 6 diesel cars based on all available data and implemented in HBEFA 3.3

More details about the implementation of the temperature function are described in the final report for the HBEFA 3.3 (Keller M. et. al. 2017).

4. Conclusions and Outlook

The HBEFA 3.3 is a so-called quick update, because only the NOx emission factors for EURO 4 to EURO 6 diesel passenger cars have been revised. EURO 6c diesel was replaced by EURO 6d-Temp und EURO 6d to reflect the actual RDE legislation which was not known at the time when HBEFA 3.2 was elaborated.

In total measurements on 25 vehicles with 61 emission tests have been used for the EURO 6 NOx emission factors calculation. 12 of the 61 emission tests were RDE-measurements of 4 different vehicles.

For each map creation in HEBFA 3.3, the CO2 interpolation method has been used. The method calculates the engine power based on a generic map from the measured CO2 flow and the engine speed. This is especially necessary for RDE-trips, because in most of the cases the power signal is not known or too inaccurate for the engine map creation. Thus – apart from NOx, PN, HC, CO etc. – also engine speed and CO2 are essential for map creation. The CO2 interpolation method is already implemented in the simulation tool PHEM.

The emission maps created by the CO2 interpolation method have been used for the average EURO 6 diesel vehicle model creation. The weighting of the vehicle specific maps for the average emission map is based on the European vehicle registration numbers. The maps for EURO 6d and EURO 6d-Temp have been derived from the measurement data under estimation of the NOx conformity factor for RDE legislation.

Due to new measurement data in the ERMES DB, also the EURO 4 diesel map for cars has been readjusted. The modifications for EURO 4 are minimal, only the NOx emissions are a little bit higher for higher velocities.

For the diesel vehicles, an effect of ambient temperatures on NOx emissions was observed and is now considered in the HBEFA 3.3 by post-processing. The appropriate correction functions for EURO 4, EURO 5 and EURO 6 diesel vehicles have been derived from remote sensing data.

The analysis of the temperature effects showed an unexpected high effect on the NOx emissions. Having typical European temperature levels in mind, which are mainly between -5 °C to 25 °C, the temperature sensitivity of the NOx emissions leads to NOx increases compared to test conditions between 20 °C and 30 °C of more than 30 %. Since the data used for the elaboration of the temperature correction factors is limited, a more comprehensive study on the temperature effects is suggested. The study should investigate on more vehicles and should also analyse if the simple relative adjustment of base emission factors is a correct approach for all traffic situations. Such a study could also consider possibilities to reduce the temperature sensitivities by retrofitting control software of EURO 6 vehicles.

The next HBEFA update is planned for 2018/2019 and should include:

- A complete update of passenger cars emission data (including also other exhaust gas components and further test data which are expected to be produced in 2017 and 2018)
- Update for emission factors for 2-wheelers
- Update of the LDV and HDV emissions factors based on new RDE and dynamometer measurement data

5. Acknowledgements

The HBEFA 3.3 quick update would not have been possible without the support from vehicle emission labs: EMPA (Switzerland), TNO (Netherlands) and ADAC (Germany) provided important dynamometer and RDE measurement data. Sweden and Switzerland also provided remote sensing data to consider the ambient temperature effects on NOx emissions. The authors would like to thank Mario Keller (INFRAS / MK Consulting, Switzerland) for the ERMES DB management and for processing of the simulated emission factors.

Finally the work would not have been possible without the funding from UBA Germany and UBA Austria, who set up well organised projects as basis for the HBEFA quick update.

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