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# Emission Factors from the Model PHEM for the HBEFA Version 3

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# Emission Factors from the Model PHEM for the HBEFA Version 3

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**CONTENT**

## DEFINITIONS

A 300 db ............................... Data base started in the FP 5 project Artemis, work package 300, including all available measurements on passenger cars and LCV from former projects, from ARTEMIS and also from the most recent national and international measurement campaigns

Driving Cycle ...................... Course of vehicle speed and road gradient over time.

Engine Control Unit ............ Controls various aspects of the operation of an internal combustion engine (e.g. fuel quantity, injection timing, boost pressure).

Emission factor..................... Specifies the average emission rate of a given emission source for a given pollutant relative to a specific activity. Emission factors for road traffic are usually given in “grams emissions per driven kilometre” or “grams emissions per gram fuel combusted” or “grams per engine start”.

Emission standard ................ Legal regulation, which defines certain test procedures and the limit values for emissions. Here “emission standard” refers to the stages of the European emission legislation commonly labelled as the “EURO”-stages.

Engine Map .......................... Dependency of engine related quantities like fuel consumption, emissions, temperatures or pressures on engine speed and engine power (or engine torque)

Exhaust gas after treatment .. Catalytic converters or diesel particulate filters

Gross Vehicle Weight .......... Weight including the vehicle itself, passengers, and cargo

Heavy Duty Vehicle ............ Vehicle for transportation of goods or persons with a gross vehicle weight > 3.5 tons

Light Commercial Vehicle ... Vehicles for transportation of goods or persons with a gross vehicle weight ≤ 3.5 tons excluding passenger cars

Light Duty Vehicle............... Vehicle for transportation of goods or persons with a gross vehicle weight of ≤ 3.5 tons including passenger cars

On-Board Diagnostics .......... System on board of the vehicle that monitors emission control components and alerts the driver (e.g. by a dashboard light) if a malfunction or emission deterioration occurs

Particulate Matter ................ According to the emission regulation Particulate Matter (“PM”) is defined as “any material collected on a specified filter medium after diluting the exhaust with clean filtered air so that the temperature does not exceed 325 K (52 ºC)”.

Particle number emissions.... If not otherwise mentioned in the report, all particle number emissions (PN) were detected by means of a CPC (Condensation Particle Counter) and followed the PMP protocol with hot dilution of the sample probe. The 50% cut off point of some CPC used was not in line with the PMP proposal and counted also smaller particles.

Tampering ........................... Manipulations on the vehicles hard- and/or software which lead to advantages for the vehicle owner but result in a massive deterioration of the emission behaviour (e.g. removing the particle filter or filling water instead of AdBlue in the SCR tank)

Traffic Situation .................. Categorisation of road traffic by the area type (urban or rural), street type, the speed limit and the "level of service" (measure of traffic density)

Vehicle Category.................. Passenger cars, Light Commercial Vehicles and Heavy Duty Vehicles (split into rigid trucks, truck & trailers articulated trucks, buses, coaches).

Vehicle Segments................. Each vehicle category is subdivided into groups of equal vehicle size and fuel type (e.g. the fleet segment "rigid truck with a gross vehicle weight from 12 to 14 tons, diesel engine"). These segments are further split into "sub-segment" according to different emission concepts (e.g. emission standard "Euro IV" with SCR exhaust after treatment)

**List of abbreviations**

A/F..................... Air to Fuel ratio

BS ...................... Brake Specific, i.e. [Unit]/kWh

CADC................ Common Artemis Driving Cycle

CI....................... Compression Ignition (i.e. diesel) engine

CO ..................... Carbon monoxide

$CO_2$ .................... Carbon dioxide

CPC ................... Condensation Particulate Counter

CVS ................... Constant volume sample

DOC .................. Diesel Oxidation Catalyst

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

EATS ................. Exhaust Aftertreatment System

ECU ................... Electronic Control Unit

EGR ................... Exhaust Gas Recirculation

ESC.................... European Stationary Cycle

ETC ................... European Transient Cycle

EUDC ................ Extra urban driving cycle

EURO ................ European Emission Regulation for Onroad vehicles

FC ...................... Fuel Consumption

GPS.................... Global Positioning System

GVW ................. Gross Vehicle Weight

HBEFA.............. Handbook on Emission Factors for Road Traffic

HC ..................... Hydro-Carbons

HD ..................... Heavy Duty

HDE................... Heavy Duty Engine

HDV .................. Heavy Duty Vehicle

IATS .................. Integrated Austrian Traffic Situations

LCV ................... Light Commercial Vehicle

LPG ................... Liquefied Petroleum Gas

MIL.................... Malfunction Indicator Light

NEDC................ New European Driving Cycle (UDC + EUDC)

NMHC............... Non-Methane Hydrocarbons

NO..................... Nitrogen monoxide (mass of NO is given as $NO_2$-äquivalent)

$NO_2$.................... Nitrogen dioxide

$NO_x$.................... Nitrogen oxides (NO and $NO_2$)

OBD .................. On-Board Diagnostics

OBM.................. On-Board Measurement

PASS ................ Photo-Acoustic Soot Sensor

PC...................... Passenger Car

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

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

PM..................... Particulate Matter (abbreviation used for Particulate mass value)

PN...................... Particulate Number emissions

SCR................... Selective Catalytic Reduction, catalytic reduction of $NO_x$ emissions in the exhaust by means of $NH_3$

SI....................... Spark Ignition (i.e. Otto) engine

SMPS................. Scanning Mobility Particle Sizer™

TA...................... Type Approval

TUG................... Graz University of Technology

UDC .................. Urban driving cycle

WSG.................. Wire Strain Gauge

WHTC............... World Harmonised Transient Cycle

# 1 Introduction

The basic emission factors[1] for the HBEFA V3 include emission measurements on recent vehicle technologies and are based on new methods for cars and LCV. All new measurements were collected in the data base systems of ARTEMIS and HBEFA V2 to make use of all existing data to a large extent. Improved model approaches to calculate emission factors for a set of driving cycles out of the data base of measured test cycles were elaborated and validated. The actual basic emission factors are now based on a common model approach for cars, LCV and HDV and also a more consistent set of traffic situations and related driving cycles has been established. The common model approach allows to add or to change driving cycles, traffic situations and vehicle classes in a very flexible way. All improvements can be seen as evolution in the knowledge and data quality for emission factors in the EU. Finally the future technologies and emission levels were assessed.

Following main improvements are included compared to HBEFA V2:

- Measurements up to EURO V for HDV and outlook for EURO VI
- Measurements up to EURO 4 for passenger cars and outlook for EURO 5 and 6 based on a few tested cars
- Measurements up to EURO 4 for LCV and outlook for EURO 5 and 6
- New traffic situations with different driving cycles compared to the HBEFA V2
- A new method to calculate emission factors for passenger cars and LCV
- An extended methodology to calculate emission factors for HDV equipped with SCR systems
- Emission factors for $NO_2$ and PN are now also provided

For emission factors for single traffic situations as delivered by the HBEFA a high accuracy is necessary. Otherwise the uncertainties of the emission factors would be higher than the differences between the traffic situations which would make the high resolution in terms of traffic situations useless. Therefore much effort was given to the calibration and validation of the model and the input data.

This report describes the model approach, the available data and shows results and uncertainties for the emission factors.

# 2 Methodology

A fundamental prerequisite in the elaboration of emission factors is to have a sufficient number of engines/vehicles measured for each fleet segment. According to results from ARTEMIS WP 300, e.g. [1], measurements on more than 10 vehicles per segment should be available to reach a reasonably accuracy of the average emission level. Figure 1 shows as example data on HC emissions from 211 different gasoline EURO 4 cars in different test cycles from

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[1] In the HBEFA the base emission factors from the model PHEM are used to calculate fleet average emission factors. For this task the base emission factors are corrected in the HBEFA for influences of the mileage and cold starts and then aggregated according to the shares of the vehicle segments on the total fleet mileage.

the A300 db. All cycles were started with hot engine. Some vehicle models are measured several times on different individual cars and not all cars were tested in all cycles. Measured values range from zero up to 0.92 g/km. As a consequence emission factors based on a small vehicle sample do have a high uncertainty due to the probability to have outliers in the sample. Therefore the emission factors in the HBEFA make use of almost all available data on measured vehicles. Since the actual method for simulating the emission factors is based on instantaneous emission measurements only a part of all test results could be used as model input (especially for cars and LCV many tests consist of bag data only). However, all available data was used for the model calibration to achieve robust emission levels. The methods for model calibration are described in the relevant chapters.

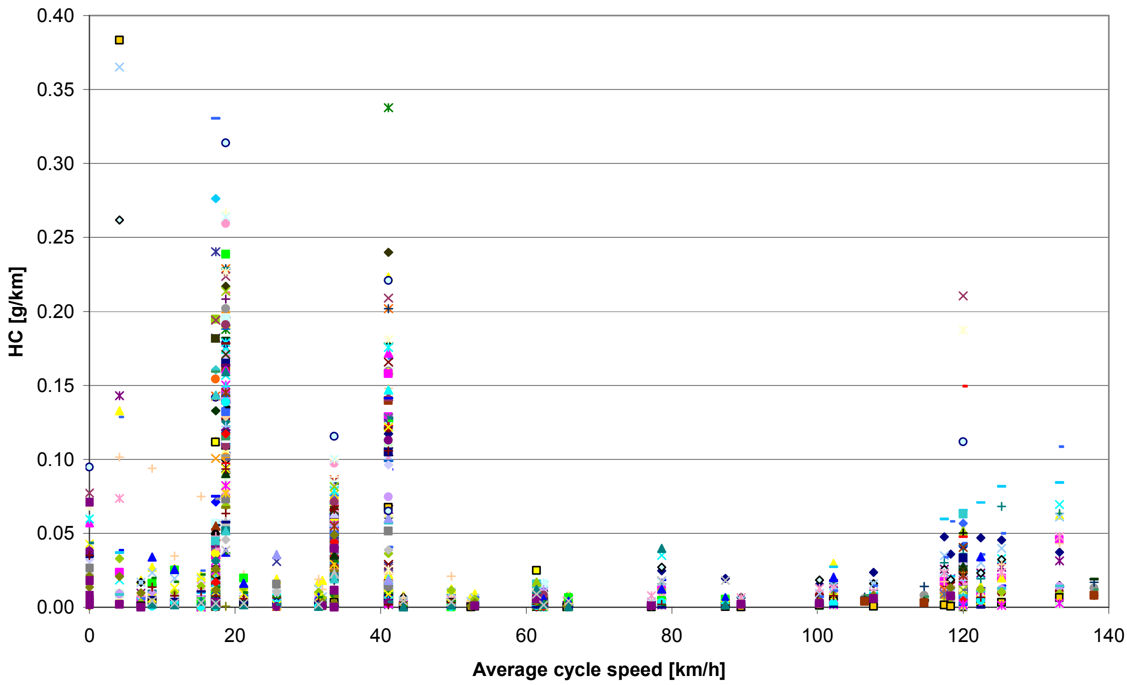


**Figure 1:** HC emissions from 211 gasoline EURO 4 cars in different test cycles (not all cars tested in all cycles)

Another problem is that different measurement campaigns often cover quite different test cycles. Not only the speed curves differ but also gear shift strategies and vehicle loadings. Vehicle preconditioning can also be different for real world cycles if not properly defined. The challenge of the project was to elaborate consistent emission factors for a completely new set of driving cycles out of this quite inhomogeneous data base.

To take all relevant influences into consideration in a systematic way and to allow automatic data processing to be capable of handling hundreds of measured vehicles the emission factors were simulated with the emission model PHEM.

PHEM was primarily developed to simulate the HDV emission factors in the HBEFA 2.1 and the ARTEMIS inventory model. In these applications emission factors for more than 600 000 combinations of HD vehicle segments (separated according to vehicle categories, vehicle weight classes and engine technologies) with different vehicle loadings based on representative driving cycles at different road gradients had to be simulated. From the beginning it was obvious, that it would be impossible to cover such an extensive number of HDV operation conditions directly with a representative number of experimental emission tests (e.g. by emission tests at a chassis dynamometer). Thus a suitable model had to be elaborated. It was decided to set the model on physical basis according to the longitudinal dynamics of vehicles to allow a reliable simulation of all relevant influences such as driving behaviour, road gradients, vehicle loading, etc. and to use engine emission maps as basis for the simulation of fuel consumption and emissions. This structure makes PHEM capable of including all sources of actual and past measurement campaigns to a large extent.

In the meantime the model PHEM was extended to be applicable for passenger cars and for LCV vehicles too. This task mainly required an extension to be able to obtain the PHEM engine maps not only from steady state engine tests but also from transient driving cycles of the entire vehicle. This new method is described e.g. in [32]. Due to the increasing number of emission measurements on HD vehicles with PEMS or on the chassis dyno, this method was successfully adapted for HDV too. As a result, PHEM can now set up engine maps from all sources of emission testing (engine test bed, chassis dynamometer and on-board tests with PEMS equipment).

Consequently in the HBEFA V3.1 the model PHEM was applied not only for HDV emission factors but also for the elaboration of emission factors from passenger cars and LCV. This was mainly due to the fact that test cycles in the measurement database on which the emission factors had to be based (A 300 db), include measurements in cycles with quite different gear shift strategies. Important real world cycles as sources of emission data are the CADC with rather high engine speed levels and the HBEFA cycles from the HBEFA-V1 with rather low engine speed levels. To take effects of the gear shift strategy on the emission level into consideration a model which has the engine speed explicitly as variable in the data set is necessary. Since no reliable information on the "representative European gear shift behaviour" is available, the model should be capable to adapt the underlying gear shift manoeuvres in the driving cycles in future easily if better data will be available. For this task a gear shift tool in the model is necessary.

For LCV also the loading of the vehicles was different in some measurement campaigns, leading to different engine power demands within the same test cycles. For such cases the engine power is an important variable in emission models. Simulating the engine power demand from the longitudinal dynamic of the vehicles finally allows also the simulation of any road gradients. In former models the effects of road gradients were depictured by "gradient factors", defining the ratio of emissions at a defined gradient compared to the emissions on a flat road. These gradient factors were measured on a very limited number of cars and cycles and included a high uncertainty.

Certainly the model has to be accurate and the model history has to allow a continuous work in future to build a stable basis for future updates of the emission factors.

The combination of all of these demands is fulfilled by the model PHEM in a reasonable way. However, this does not mean that PHEM is the best model for all single tasks.

<u>Advantages</u> are:

- Already available and validated
- Capable of simulating influences of
    - Different driving cycles
    - Different gear shift stretegies
    - Different vehicle loadings
    - Different road gradients

- o Different vehicle characteristics (mass, size, air resistance,…)

  in a consistent way based on engine emission maps

- ➢ High accuracy for fuel consumption, $CO_2$, $NO_x$, PM and PN
- ➢ Expandable for realistic emission factors for hybrid vehicles
- ➢ Also applicable for other related tasks (e.g. simulation of emission factors for scenarios on future technologies and vehicle characteristics due to the physical basis, interface to microscope traffic models,..)
- ➢ Includes already a cold start tool and thus allows the consistent simulation of all relevant exhaust components (except evaporation).

Disadvantages are

- ❖ Needs instantaneous emission data from the measurements with good time allocation of vehicle speed and emissions which is not standard at all many within the ERMES group yet. Thus not all measurements can be included at the moment[2]
- ❖ Needs detailed vehicle data as input from each measured vehicle
- ❖ Uncertainties for CO and HC emissions from modern cars[3]

To reduce disadvantages in future, it is suggested to develop a tool which allows the test bed engineers to convert the data from the measurements easily into the data necessary for instantaneous emission models. The tool should then also check consistency of the data and store it into a common data base format. This tool certainly would have to be adapted to the design of each test bed. However, the work on the HBEFA V3 showed that the data processing and data collection within the ERMES group should be heavily improved to make best use of the rather expensive measurements.

## 2.1 Emission model PHEM

PHEM calculates the engine power in 1 Hz based on the given courses of vehicle speed (the "driving cycle") and road gradient, the driving resistances and the losses in the transmission system. The 1 Hz course of engine speed is simulated based on the transmission ratios and a gear-shift model. Alternatively the course of engine load and/or engine speed can also directly be provided to the emission model. To take transient influences on the emission levels into consideration, the results from the emission maps are adjusted by means of transient correction functions. The model results then are the 1 Hz courses of engine power, engine speed, fuel consumption and emissions of CO, $CO_2$, HC, $NO_x$, NO, particle mass (PM) and particle number (PN).

The model also includes a cold start tool which is based on simplified heat balances and emission maps for cold start extra emissions. However, this tool was not used for the HBEFA V3.1 work.

For the simulation of $NO_x$ emissions of vehicles equipped with SCR exhaust aftertreatment it was found, that solely an engine based map based simulation approach would not reflect real

[2] Models using bag values from the measurements typically include much more measured vehicles (e.g. VERSIT+), reducing the uncertainty from the vehicle sample size in the model.

[3] the v*a model developed for the HBEFA-1 was more accurate for these components in the model comparison exercise in the course of the model selection for the HBEFA V3 update.

system behaviour. The temperature of the SCR system can drop in low load cycles below the operating temperature resulting in diminished $NO_x$ conversion rates. Thus SCR temperature is not only relevant for cold starts but also for all urban driving conditions. For the depiction of the resulting emission behaviour an additional SCR module was developed and integrated into the PHEM software.

A scheme of the PHEM model in the setup as used for the calculation of the emission factors for the HBEFA 3.1 is shown in Figure 2. The model elements “Hybrid vehicle tool” and “Cold start”, which are by default available in the current version of the PHEM software, have not been used in the context of HBEFA 3 emission factor calculations. Hybrid concepts have – so far – not been considered explicitly in the HBEFA3.1 fleet structure as a separate vehicle segment. However, with the foreseeable increasing market penetration of micro hybrids (start-stop function and brake energy recuperation) and maybe also from mild to full hybrids, their special emission behaviour should be depictured more precisely in future (e.g. zero emissions instead of idling emissions during stops).

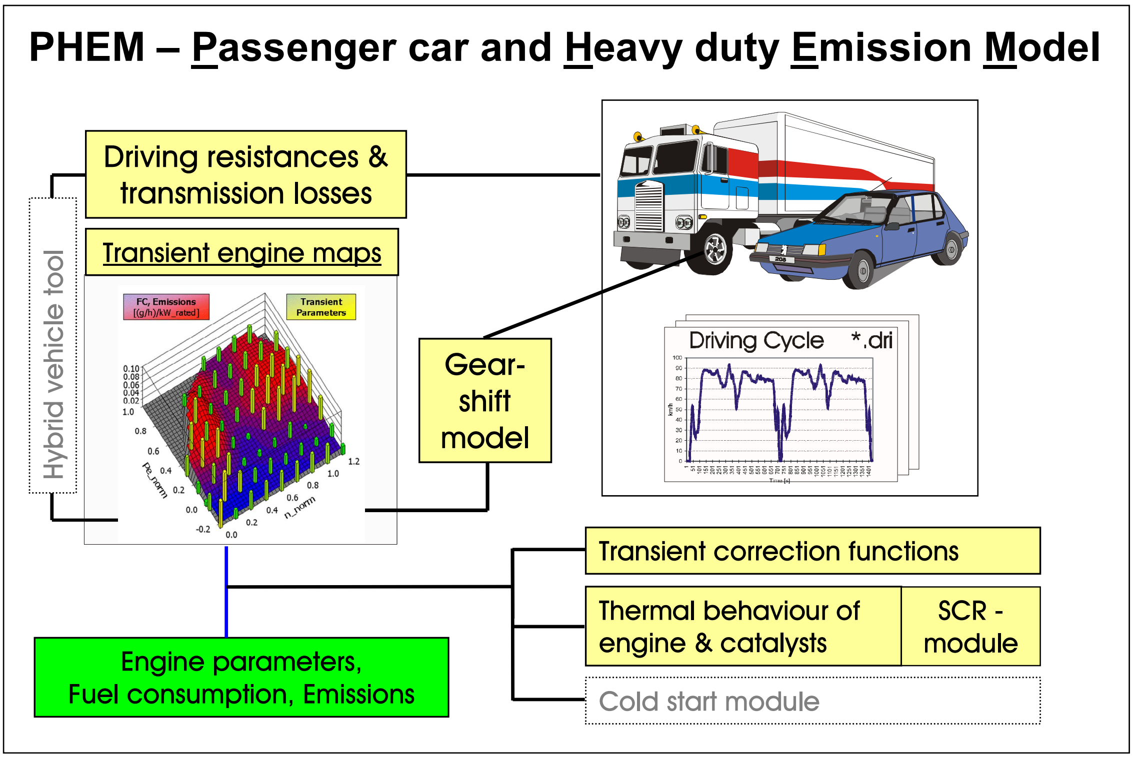


**Figure 2:** Scheme of the emission model PHEM for the simulation of HBEFA 3 emission factors

### 2.1.1 Simulation of engine power and engine speed

The engine power demand is calculated from the longitudinal dynamics for the vehicle in 1 Hz resolution from the input driving cycle and the input data on the vehicle. **Equation 1** shows the components considered for calculating the power demand.

**Equation 1**: Calculation of the engine power demand

$$P_e = P_R + P_L + P_A + P_S + P_{Transmission} + P_{Auxiliaries}$$

The calculation of the single components is described shortly in the following. A detailed description can be found in [10] and [18].

**Equation 2:** Power demand to overcome the rolling resistance [W]

$$P_R = (m_{Vehicle} + m_{Load}) \times g \times (\mathrm{Fr}_0 + \mathrm{Fr}_1 \times \mathrm{v} + \mathrm{Fr}_4 \times \mathrm{v}^4) \times \mathrm{v}$$

With $m_{vehicle}$............. mass of the empty vehicle in [kg]

$m_{Load}$................ mass of driver, passengers and/or payload in [kg]

$Fr_0$, $Fr_1$, $Fr_4$...... Rolling resistance coefficients [-], [s/m], [$s^4/m^4$]

v....................... velocity [m/s]

**Equation 3:** Power demand to overcome the air resistance [W]

$$P_L = C_d \times A_{Cs} \times \frac{\rho}{2} \times v^3$$

With $C_d$..................... air resistance coefficient [-]

$A_{Cs}$................... Cross sectional area [m²]

ρ ...................... density of the air [$kg/m^3$]

**Equation 4:** Power demand for acceleration [W]

$$P_A = (m_{Vehicle} + m_{Rot} + m_{Load}) \times \mathrm{a} \times \mathrm{v}$$

With a....................... acceleration of the vehicle [m/s²]

$m_{Rot}$................. equivalent mass for taking the inertia of rotational accelerated parts into consideration (in PHEM these parts are summarised in three groups (wheels, gear box parts, engine)

The equivalent mass can be calculated from the inertias and the transmission ratios.

**Equation 5:** Calculation of the equivalent mass for rotational accelerated parts

$$m_{rot} = \frac{I_{Wheels}}{r_{Wheel}^2} + I_{mot} \times \left( \frac{i_{Axle} \times i_{Gear}}{r_{Wheel}} \right)^2 + I_{transmission} \times \left( \frac{i_{Axle}}{r_{Wheel}} \right)^2$$

**Equation 6:** Power demand to overcome the road gradient [W]

$$P_S = (m_{Vehicle} + m_{Load}) \times g \times Gradient \times 0.01 \times \mathrm{v}$$

with: Gradient.......Road gradient in %

**Equation 7:** Power demand from auxiliaries [W]

$$P_{Auxiliaries} = P_0 \times P_{Rated}$$

Mit $P_0$..........Ratio of power demand from auxiliaries to rated engine power [-]

$P_{rated}$......Rated power of the engine [W]

**Equation 8:** Power losses in the transmission system [W]

$$\mathrm{P}_{transmission} = \mathrm{A}_0 \times (\mathrm{P}_{Differential} + \mathrm{P}_{Gear\,i})$$

with: $A_0$ .........Factor for adjusting the losses to single vehicles.

The power losses for the single gears are calculated as function of the transmission ratio, the actual rotational speeds and the power to be transmitted.

$$P_i = P_{rated} \times a \times \left( b + c \times \frac{n_{engine}}{I_{1.gear1}} + d \times ABS\left( P_{dr} + \frac{P_{Differential}}{P_{rated}} \right) \right)$$

$$P_{Differential} = P_{rated} \times e \times (f + g \times \frac{n_{wheel}}{n_{rated}} + h \times ABS \frac{P_{dr}}{P_{rated}}$$

with: $n_{wheel}$ ............rotational speed of the wheels [rpm]......... $n_{wheel} = \frac{60 \times v}{D_{wheel} \times \pi}$

$P_{dr}$ ................Normalised power demand from the engine to overcome the driving resistances (= total power demand without transmission losses)

a to h............factors from parameterisation

The actual engine speed depends on the vehicle speed, the wheel diameter and the transmission ratios of the axle and the gear box.

**Equation 9**: Calculation of the engine speed

$$n = v \times 60 \times i_{axle} \times i_{gear} \times \frac{1}{D_{wheel} \times \pi}$$

with: n................ engine speed [rpm]

v................ vehicle speed in [m/s]

$i_{axle}$ ............ transmission ratio of the axle [-]

$i_{gear}$ ............ transmission ratio of the actual gear [-]

$D_{wheel}$ ........ Wheel diameter [m]

For all cycles in the HBEFA the actual gear is calculated from a drivers gear shift model. This model defines the engine speed for shifting in a higher or lower gear as function of the power demand within the next seconds and of the actual normalised vehicle speed (ratio to maximum speed). As a result during accelerations and uphill driving higher engine speeds occur than at constant driving. The model also considers if the actual phase of the cycle is acceleration, deceleration or cruise. Some parameters of the equations are different for these phases and the numbers of gear changes per time unit is limited at cruise phases. Finally the model always checks if the actual power demand is higher than the full load power at the actual engine speed level. In this case a lower gear is selected. If no gear can deliver the necessary engine power to overcome the driving resistances in the given driving cycle PHEM reduces the speed for the next second and thus also the actual acceleration. This adaptation is an iterative process until the engine can deliver the calculated power demand. This option is used quite intensively when emission factors for high positive road gradients are simulated. Especially for HDV the engine power is then most often not sufficient to keep the target speeds as defined in the basic driving cycles for the traffic situations.

### 2.1.2 Engine map formats

The engine map format is normalised to be able to group engines with similar technology independent of their cylinder capacity and of their rated power. This fact is especially useful for heavy duty vehicles (HDV) where the engine power ranges from 80 kW to 400 kW. With normalisation of the map formats all measured HD engines of the same technology and EURO class can be grouped to an average engine map. The average maps then can be applied to all HDV size classes.

The normalised engine maps formats are defined as follows:

| | | |
|---|---|---|
| Engine speed: | idle = 0%, | rated speed = 100% |
| Engine power: | 0 kW = 0%, | rated power = 100% |
| Fuel consumption: | normalised to "(g/h) / kW_rated power" | |
| Emission values: | normalised either to | "(g/h) / kW_rated power" (HDV application) |
| | or | "(g/h)" (PC and LCV application) |

Since the evaluation of all measured data showed no significant dependency between the emission levels and the engine size, this methodology was found to be valid. An exception is the particle emission behaviour for HD engines with construction years 1990 and earlier ("pre EURO"), where an increasing particle emission level was visible with decreasing rated engine power (natural aspirated engines were used longer at smaller engine models). For this reason three average engine emission maps were installed for "pre EURO" engines. For HD engines certified to emission standards Euro I and newer the specific fuel consumption showed a dependency on the engine size, which is described in the model by correction functions applied on the calculation results based on the average engine maps, [17].

In order to handle emission data from test series, where only transient measurements are available (which is usually the case for chassis dynamometer tests and on-board tests with PEMS equipment), the PHEM formats of the emission maps include information on the "transient conditions" for each point of the map. The transient maps are generated by allocation of instantaneous measured emissions (e.g. in 1 Hz) to the corresponding normalised engine power and engine speed. To be able to take effects of cycle dynamics on the emission levels into consideration, for each point in the engine map additionally the relevant information of "how transient" the engine operation was in the test cycle at each load point is stored. This is done by means of "transient parameters", which are calculated from the course of normalised engine power and engine speed. In Figure 3 a scheme of the procedure of compilation of transient engine maps based on emission data for HDV is given. This method allows for a model parameterisation based on any kinds of emission tests, i.e. engine test bed, chassis dynamometer and also on-road tests with PEMS equipment.

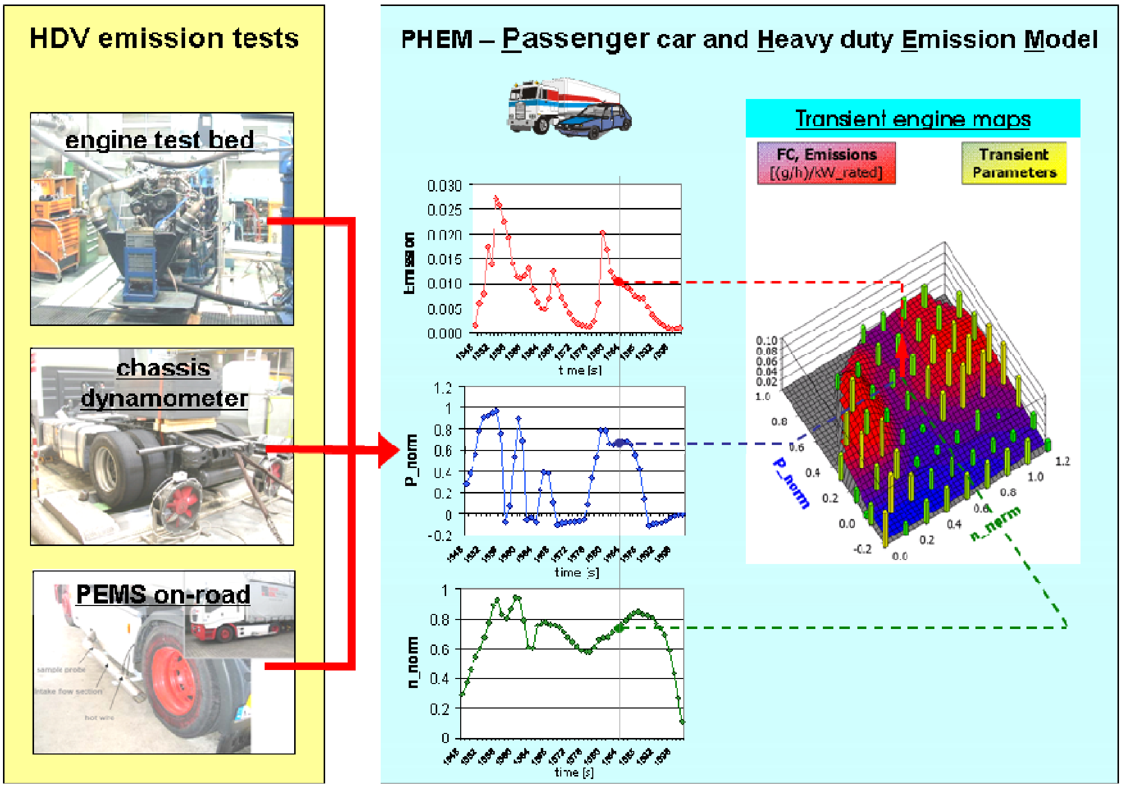


**Figure 3:** Compilation of "transient engine maps" based on transient emission tests

### 2.1.3 Transient emission correction functions

When simulating emissions for an unknown cycle, PHEM in a first step interpolates emissions from the transient map according to the actual engine power and engine speed. Effects of the cycle dynamics are considered in this step only implicitly due to the power demand to overcome translational and gyratory inertia. The consideration of effects of cycle dynamics on the emission levels is then done in a second step by applying the transient correction functions relative to the transient level of the points in the map. To make the function suitable for calculating average HDV with different engine sizes, the transient correction is – similar to the engine map formats - normalised by engine rated power. For the simulation of regulated emissions of PC and LCV no such normalisation by the engine power is applied, as this method proved to better reflect the detected emission behaviour of these vehicle categories. The mathematical formulation of the transient correction functions is given in Equation 10 and Equation 11. This formulation of the transient corrections function is also suitable to perform PHEM simulations based on steady state engine maps, as the transient parameters are zero in each point in the map.

**Equation 10:** Calculation of transient corrected emissions (applied for each second of a cycle)

$$\dot{m}_E = \dot{m}_{E,tm} + P_{rated} \cdot f_{trans}$$

with: $\dot{m}_E$ .............. emissions under transient conditions [g/h]

$\dot{m}_{E,tm}$ .......... emissions interpolated from the transient emission map [g/h]

$P_{rated}$ ............ rated engine power [kW]

$f_{trans}$ ............ transient correction function [(g/h) / kW_rated]

**Equation 11:** The transient correction function

$$f_{trans} = a \cdot (T_{1,i} - T_{1,tm}) + b \cdot (T_{2,i} - T_{2,tm}) + c \cdot (T_{3,i} - T_{3,tm})$$

with: a, b, c .................. empiric constants determined by statistical analysis of differences between measured transient emissions and emissions interpolated from the transient engine map [-]

$T_{1,i}$, $T_{2,i}$, $T_{3,i}$ .............. "transient parameters" in the second i of the simulated cycle calculated from the 1 Hz course of normalised engine power and engine speed [-]

$T_{1,tm}$, $T_{2,tm}$, $T_{3,tm}$ ...... "transient parameters" interpolated from the transient map for the engine operation point in the second I [-]

The definition of the transient parameters is given in Table 1. These quantities are calculated as function of the 1 Hz courses of normalised engine power and engine speed.

**Table 1:** Parameters for transient emission correction

| | |
|---|---|
| ABSdn2s | absolute change of the normalised engine speed within two seconds before the emission event |
| Ampl3P3s | average amplitude of the absolute values of the load changes from the engine power in the cycle over three seconds before an emission event |
| dP2s | Average difference of the normalised engine power over the last two seconds before an emission event |
| DynPneg3s | average negative engine power over three seconds before an emission event; set to zero if the negative engine power was not reached transiently |
| DynPpos3s | average positive engine power over three seconds before an emission event; set to zero if the positive engine power was not reached transiently |
| LW3P3s | number of load changes from the engine power in the cycle over three seconds before an emission event. Load changes are counted only if their absolute value is higher than 3% of the normalised engine power |
| P40sABS | difference of the normalised engine power at the emission event and the average normalised engine power over 40 seconds before the emission event |

The transient parameters represent physical influences by means of statistical analysis. The parameter dP2s for example shows a good correlation to the turbo charger performance (turbo lag) and thus explains variations in the air to fuel ratio in transient cycles compared to steady state operation. The air to fuel ratio is especially important for the particle emission level. P40sABS for example has a good correlation to the variation of the overall temperature level in transient loads compared to steady state tests. This level can influence HC, CO, PM and $NO_x$.

The transient correction functions are restricted to include at maximum three transient parameters in order to have stable and generally valid results.

### 2.1.4 Simulation of SCR exhaust after treatment

As already mentioned above, in the calculation of emission factors for vehicles equipped with SCR exhaust aftertreatment an engine map based approach alone proved to be not sufficient to depict the characteristics in $NO_x$ emission behaviour. Additional important influences on the tailpipe $NO_x$ emissions arise from the temperature level in the exhaust system, the applied

AdBlue dosing strategy and the physics of the chemical reactions inside the SCR-catalyst. For the depiction of these effects in the emission factor simulation a separate module for SCR $NO_x$ after treatment was developed and implemented in the PHEM software. The main challenge in this context was 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 in-use emission testing. Based on these boundary conditions a zero dimensional model approach has been developed. This PHEM SCR model substantially consists of two sub-parts:

I. Module for simulation of temperatures in the exhaust system

II. Module for simulation of $NO_x$ conversion

Figure 4 gives a scheme of the applied model approach for the simulation of temperatures in the SCR after treatment. In a first step the actual exhaust mass flow is calculated and a "quasi steady state" exhaust gas temperature at the inlet of the exhaust system is assessed from an engine map. This temperature map is compiled based on steady state temperature levels measured upstream of the SCR catalyst. Then the effects of the thermal inertias in the exhaust system upstream of the SCR system are modelled by calculation of heat transfer between exhaust gas and a heat capacity, which mainly represents the components of manifold and turbocharger. For a comparison of modelled temperatures with measurement from temperature sensors it turned out, that additionally the consideration of heat transfer effects and the thermal inertia of the temperature sensors are of crucial importance. The SCR catalyst is represented in the temperature model by a discrete thermal mass, which is affected by heat exchange mechanisms with the stream of exhaust gas and additionally heat losses to the environment.

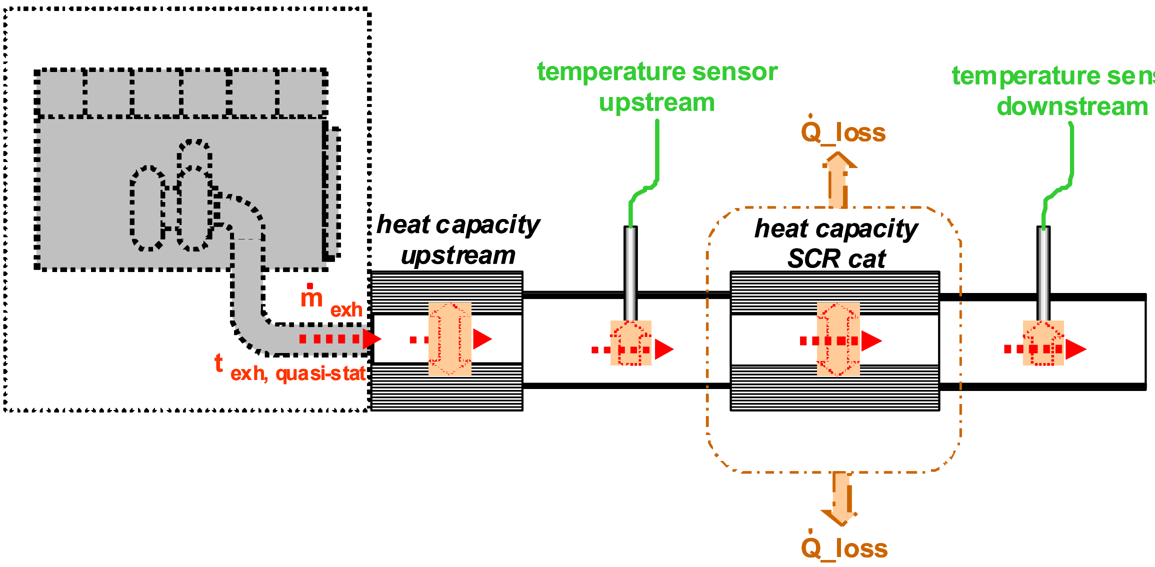


**Figure 4:** Scheme of the PHEM module for temperatures in the SCR exhaust after treatment

The tailpipe $NO_x$ emissions of a vehicle equipped with SCR aftertreatment result from the engine out $NO_x$ emission level ("raw" $NO_x$) and the $NO_x$ conversion rate in the SCR system ("De$NO_x$"). The engine out $NO_x$ emissions are simulated in PHEM based on the transient engine map approach. The De$NO_x$ rate in the SCR system is determined in PHEM from a set of characteristic curves. The basic De$NO_x$ value is taken from a characteristic curve as a function of the SCR temperature. Additionally within a certain temperature range a correction term is added to this basic $DeNO_x$ value. The basic idea of the correction function is to consider influences of additional parameters on the $DeNO_x$ rate by calculation of the difference of the parameter in the actual operation point to the value of the parameter in the basic characteristic $DeNO_x$ curve at the actual SCR temperature. Then a linear correction is applied as a function of this difference. Three parameters are considered in this $DeNO_x$ correction term representing the influences of the dosing strategy in combination with $NH_3$-storage in the catalyst, the space velocity and the temperature gradient inside the SCR catalyst. Figure 5 gives a scheme of the PHEM SCR $DeNO_x$ model approach.

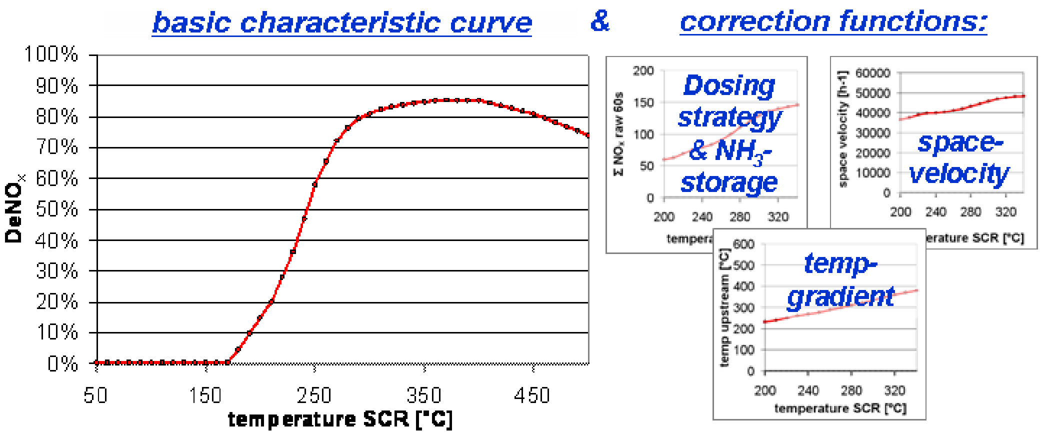


**Figure 5:** Scheme of the SCR $DeNO_x$ Model in PHEM

For the HBEFA V3.1 the SCR model was used for HDV only. Passenger cars and LCV with EURO 6 certification may also use SCR technology to a large extent. However, no measurements of such vehicles were available to parameterise the SCR model. Thus EURO 6 for cars and LCV is simply simulated by a constant reduction factor in the engine maps against the EURO 4 maps.

### 2.1.5 Set up of average emission maps and vehicle data

For the calculation of the HBEFA emission factors the emission model PHEM had to be parameterised to depict "technology-average" emission behaviour (e.g. "average Euro V HDV with SCR" or "average Euro 4 gasoline passenger car"). Hence the according "average transient maps" and the "average transient correction functions" had to be compiled. Due to practical reasons this process was performed in a different way for PC and LCV compared to HDV: For passenger cars and LCV in a first step PHEM was parameterised for each measured vehicle and then the averaging process for depiction of the "technology-average" emission behaviour was performed. For HDV the measured emissions of the different vehicles and/or engines within a technology class were first merged together to a compiled dataset including all emission records in 1 Hz and then the PHEM model setup was performed.

In the compilation process weighting factors were applied to the datasets for the different vehicles. Reasons were the consideration of the market shares of the manufacturers or to apply a lower weighting e.g. due to lower data quality.

For passenger cars and LCV additionally a calibration of the model parameters has been performed in order to adapt the model results to the emission level from all available emission tests (see section 4.2.2). As described before, PHEM needs instantaneous emission data with high quality time allocation of vehicle speed and emission values to set up engine maps. For passenger cars such instantaneous data was available only from EMPA and TUG. After calibration the model result are representative for the emission levels for each vehicle segment from all data sets in the A 300 db.

# 3 Emission factors for heavy duty vehicles (HDV)

In total 7.8 million HD emission factors have been calculated with PHEM and were provided to INFRAS, covering:

- 19 HD vehicle categories (see Table 3 on page 23)
- 3 vehicle loadings (empty, half loaded, fully loaded)
- 9 emission concepts (= 7 emission standards from "Pre Euro" to "Euro VI, thereof Euro IV and Euro V further split into "EGR-" and "SCR-vehicles")
- 272 "traffic situations"
- 7 road gradients (-6%, -4%, -2%, 0%, +2%, +4%, +6%)
- fuel consumption and seven exhaust gas components ($CO_2$, $NO_x$, $NO_2$, HC, CO, PM, PN)

This chapter gives an overview on the datasets for HD emission behaviour and HD vehicle specifications and presents an analysis of emission factors calculated for HDV certified from Euro III to Euro VI. A detailed documentation of the work performed in context of HBEFA3.1 HDV emission factors is given in [17]. A discussion of the emission behaviour of HD generations earlier than Euro III can be found in [18] and [19].

## 3.1 HD emission maps

Data on emission behaviour of HD generations certified to Euro III and earlier has been taken over unchanged from the ARTEMIS/COST 346 projects. However, new emission factors for the new set of driving cycles from HBEFA3.1 for HDV had to be calculated by PHEM.

For Euro IV HDV and newer in total in-use emission measurements on fifteen HD engines/vehicles have been processed and implemented into the PHEM emission model (Table 2). Regarding the emission concept Euro IV with EGR in-use tests on five HDV were available. However, these tests cover only one out of three manufacturers, which brought such vehicles on the market. HDV certified to Euro IV equipped with SCR aftertreatment were brought to the market by six (of in total seven) HD manufacturers. The available emission tests cover only two of these. The emission concept with the highest share on the actual HDV new registrations is Euro V based on SCR aftertreatment. All manufacturers provide HDV according to this technology. For this emission concept in-use tests on in total six HDV were available, covering four of the seven manufacturers. Euro V vehicles which apply EGR $NO_x$ emission control have been developed so far by only two manufacturers. As these vehicles have been introduced to the market quite recently, no in-use emission data on this HDV concept has been available within this study. Hence the emission factors for Euro V EGR have been assessed based on a prognosis.

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 a significant step in

HDV technology coming up in the mid of the next decade. For the HBEFA3.1 also a set of emission factors for this future HDV generation had to be elaborated. As the according technologies are still in the phase of development only emission data on a single prototype, which however does not fully reflect Euro VI boundary conditions, have been available. For the calculation of Euro VI emission factors the model parameterisation was hence mainly based on a technology assessment of a combination of EURO V EGR engines with an SCR after treatment system.

**Table 2:** Overview on the measured HDV for the HBEFA3.1 emission factors

| **Emission concept** | | **number of vehicles/engines measured** | | | **remarks** |
|---|---|---|---|---|---|
| | | **engine test bed (1)** | **chassis dynamometer** | **on-board (PEMS)** | |
| Pre Euro | | 40 *(2)* | --- | --- | |
| Euro I | | 13 *(2)* | --- | --- | |
| Euro II | | 21 *(10)* | 1 | --- | |
| Euro III | | 27 *(13)* | --- | --- | |
| Euro IV | EGR | 1 *(1)* | 1 | 3 | only in-use tests on one of three manufactures available |
| | SCR | 1 *(1)* | --- | 2 | |
| Euro V | EGR | --- | --- | --- | no in-use tests available - emission factors based on prognosis |
| | SCR | --- | 4 | 2 | |
| Euro VI | | 1 | --- | --- | Single tested engine not fully Euro VI compatible - emission factors based mainly on prognosis |

(1)….in brackets: number of engines measured also in transient tests

The average emission maps for each technology were set up from all available test data using the method described in chapter 2.1.5.

## 3.2 HD vehicle specifications

The HDV fleet segmentation has remained unchanged compared to the HBEFA V2 and ARTEMIS/COST 346, 2005. Table 3 gives an overview on the main vehicle specifications for all 19 HDV categories. The entire set of vehicle parameters from “pre Euro” to “Euro V” used in the emission factor simulation is discussed in detail in [18]. In this context it has again to be mentioned, that so far the amount of data available for fleet representative vehicle specifications (e.g. values for drag resistances, frontal areas, rolling resistances) is rather limited. This is especially the case for the vehicle category “rigid trucks”, where a huge bandwidth of vehicle body geometries, drive train configurations and tires exists.

Compared to the set of emission factors elaborated in previous projects in the work presented here additionally a prognosis for Euro VI HDV had to be calculated. Hence for all 19 vehicle categories additionally a set of Euro VI vehicle parameters have been estimated. This was done based on the Euro V vehicle data assuming that the same change in vehicle specifications from the Euro III to Euro V HD generation will again be achieved in the step from Euro V to Euro VI. In detail the modifications in the set of vehicle parameters for Euro VI HD compared to the Euro V specifications are:

- Reduction of drag coefficients by 2%

- Reduction of transmission losses by 1.3%
- Increase of engine rated power by 4%

All other vehicle specifications have been unchanged compared to Euro V.[4]

**Table 3:** Average values for gross vehicle weight rating, vehicle empty weight and rated power for the different vehicle categories (values shown are used for simulation of Euro III vehicles)

| vehicle class | | gross vehicle weight rating [tons] category | gross vehicle weight rating [tons] average | average vehicle empty weight [tons] | average rated power [kW] |
|---|---|---|---|---|---|
| rigid truck | | up to 7,5 | 5.8 | 3.5 | 85 |
| | | 7,5 to 12 | 11.0 | 6.0 | 140 |
| | | 12 to 14 | 13.5 | 7.3 | 160 |
| | | 14 to 20 | 17.2 | 8.8 | 230 |
| | | 20 to 26 | 25.5 | 11.8 | 275 |
| | | 26 to 28 | 27.0 | 12.2 | 275 |
| | | 28 to 32 | 32.0 | 13.6 | 290 |
| | | larger 32 | 35.5 | 14.3 | 305 |
| truck trailers and articulated trucks | | up to 28 | 18.0 | 9.2 | 210 |
| | | 28 (Switzerland) | 28.0 | 12.8 | 260 |
| | | 28 to 34 | 32.0 | 13.6 | 260 |
| | | 34 to 40 | 39.8 | 15.1 | 305 |
| | | 40 to 50 | 47.0 | 16.0 | 316 |
| | | 50 to 60 | 60.0 | 19.4 | 355 |
| Urban bus | midi | up to 15 | 11.5 | 6.7 | 165 |
| | standard | 15 to 18 | 17.8 | 10.4 | 210 |
| | articulated | larger 18 | 27.0 | 15.0 | 230 |
| coach | standard | up to 18 | 18.0 | 13.8 | 300 |
| | three axle | larger 18 | 24.0 | 15.6 | 330 |

The values shown are used for simulation of Euro III HDV. In the emission modelling, the vehicle empty weight and rated power varies within each vehicle category depending on the emission standard.

## 3.3 Driving cycles

The set of driving cycles for HDV was provided by TÜV® NORD Mobilität [26]. For the calculation of emission factors for road gradients different from flat conditions again the set of vehicle speed profiles for flat conditions has been used, as no comprehensive data on HDV driving behaviour for all combinations of traffic situations and road gradients was available. To overcome this problem, in the emission model the vehicle speed pattern is adapted, whenever the engine power of the HDV is not sufficient to follow the cycle for the given combination of road gradient and loading conditions. In such phases the HDV drives at full load in the gear/engine speed combination providing the highest power output. In previous studies, where on-board test with different vehicle loadings on highway sections with road gradients up to 7% have been performed, it was shown, that this method gives a reliable assessment for the basic influence of road gradients on the emission levels [24].

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[4] In the emission model the rolling resistance values are set similar for all HDV emission standards, because it is assumed that also older HDV generations are equipped with current tire designs. Concerning vehicle weight it is furthermore assumed, that the additional weight of the complex Euro VI engine concepts can be compensated by other lightweight measures in the vehicle and the trailer body.

As shown in [17], recorded vehicle speed patterns, which are affected with a strong noise caused by the measurement method (e.g. GPS or rotational speed sensors), cause errors in the simulation of emission levels. This matter of fact is especially valid for the simulation of HDV emissions, where the high vehicle masses even in connection with small magnitudes for acceleration cause a high power demand. Hence for the entire set of driving cycles provided by TÜV® NORD Mobilität a filter algorithm was applied. In tendency not applying the filter algorithm would lead to an overestimation of fuel consumption and emission levels.

## 3.4 Results

This section gives an overview of the HBEFA V3 HDV emission factors. The analysis performed focuses on a comparison on the emission levels of the HDV generations Euro III and newer including the forecast for Euro VI vehicles. A detailed comparison of the emission behaviour of older HDV emission concepts can be found in [18] and [19].

For the discussion of the emission results exemplarily driving cycles for four fundamental road types and four levels of service have been selected. Table 4 shows the selection of driving cycles and also gives the average speeds of the according driving cycles for trucks and urban busses. This dataset gives a quite good coverage of the whole range of vehicle speeds from highway to stop&go conditions.

**Table 4:** Selection of driving cycles for the discussion of HBEA 3 emission factor results

| **traffic situation** | | | | **trucks / truck & trailer combinations** | | **urban busses** | |
|---|---|---|---|---|---|---|---|
| **area type** | **road type** | **Speed limit** | **level of service** | **HBEFA 3 driving cycle ID** | **average speed** (km/h) | **HBEFA 3 driving cycle ID** | **average speed** (km/h) |
| rural | motorway-national | > 130 km/h | freeflow | 6 469 | 86.3 | 6 469 | 86.3 |
| | | | heavy | 6 472 | 81.0 | 6 472 | 81.0 |
| | | | saturated | 6 475 | 66.3 | 6 475 | 66.3 |
| | | | stop&go | 6 006 | 16.6 | 6 006 | 16.6 |
| | distributor / secondary road, sinuous | 100 km/h | freeflow | 6 257 | 66.0 | 6 519 | 47.2 |
| | | | heavy | 6 166 | 52.7 | 6 530 | 44.7 |
| | | | saturated | 6 086 | 41.6 | 6 558 | 36.7 |
| | | | stop&go | 6 003 | 13.5 | 6 003 | 13.5 |
| urban | trunk-toad / primary-city road | 70 km/h | freeflow | 6 240 | 59.1 | 6 539 | 53.7 |
| | | | heavy | 6 147 | 48.6 | 6 540 | 43.5 |
| | | | saturated | 6 107 | 38.6 | 6 553 | 38.7 |
| | | | stop&go | 6 003 | 13.5 | 6 003 | 13.5 |
| | distributor / secondary road | 50 km/h | freeflow | 6 074 | 39.8 | 6 535 | 25.8 |
| | | | heavy | 6 035 | 30.1 | 6 536 | 24.2 |
| | | | saturated | 6 026 | 28.7 | 6 565 | 20.5 |
| | | | stop&go | 6 422 | 11.8 | 6 422 | 11.8 |

For better comprehensibility of the emission results the distance specific engine work (unit: kWh per kilometres) for the selected set of cycles an flat road conditions is shown in Figure 6 for the truck & trailer combinations with 34-40t gross vehicle weight and 50% vehicle load. This HD configuration has the highest share of all vehicle segments on the overall HD mileage and is typically used in long distance transport. As a basic tendency a higher average cycle speed results in less energy consumption per driven distance. This can be explained by the fact that the higher air resistance at high speed cycles is overcompensated by less engine work, which is consumed in phases of acceleration and deceleration.

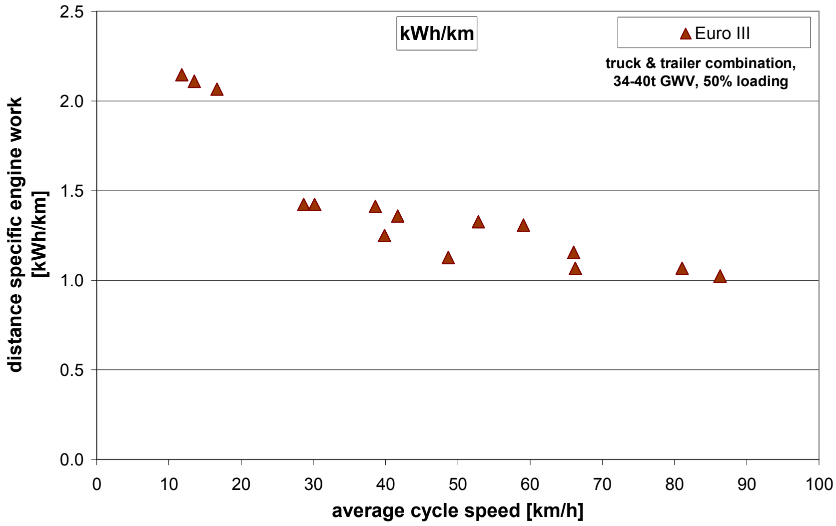



**Figure 6:** Distance specific engine work for selected set of cycles; flat road, truck & trailer combination 34-40t GVW, 50% loading

Figure 7 gives the comparison of the results for fuel consumption for the similar vehicle segment and the emission standards from Euro III to Euro VI. The right picture is a close-up view of the left picture. Basically the lowest fuel consumption is achieved by the SCR concepts for the emission standards Euro IV and Euro V. The considered half loaded long haul truck (with a total vehicle weight of 27.5t) can be operated at flat highway driving with 25 litres per 100 kilometres or even less. Compared to Euro III the reduction in fuel consumption is in a range of 5 to 7%. This result can be explained with the optimised combustion conditions with increased $NO_x$ engine out emissions, which are tolerable due to the application of an SCR aftertreatment system. Also for Euro IV and Euro V vehicles with EGR a slight improvement in distance specific fuel consumption compared to Euro III is calculated. The Euro IV results show approximately 3% less fuel consumption in the selected set of driving cycles. Euro V EGR HDV are forecasted to have slightly lower engine efficiencies than their Euro IV predecessors. Euro VI vehicles are predicted to show about 2% less fuel consumption compared to Euro V EGR vehicle. However, compared to Euro IV and Euro V SCR emission concepts, due to the tightening of the $NO_x$ limits, for Euro VI a slight increase of fuel consumption values has to be expected. However, for Euro VI HDV it is forecasted still to have lower fuel consumption than Euro III vehicles.

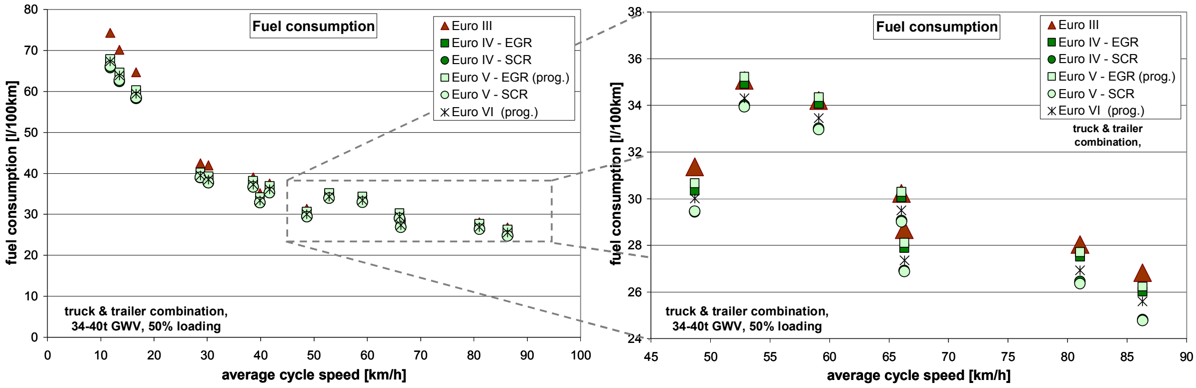



**Figure 7:** Examples HBEFA 3 emission factors for 0% road gradient; fuel consumption; truck & trailer combination 34-40t GVW, 50% loading

Figure 8 (left picture) shows the simulated $NO_x$ emission factors for flat road driving. Compared to Euro III vehicles the emission concept Euro IV EGR has approximately one third lower $NO_x$ emission levels nearly independent from the driving situation. This improvement in real world $NO_x$ emission performance reflects the tightening of the according type approval limits. In this context it has to be mentioned again, that only emission tests for one of three manufacturers, which provide such emission concepts have been tested. For EGR HDV certified to Euro V it is forecasted, that the decrease in type approval limits takes again fully effect on the real world emission levels. If this prognosis comes true Euro V EGR HDV would have $NO_x$ levels which are approx. 60% lower compared to Euro III.

The real world $NO_x$ emission behaviour of SCR vehicles certified to Euro IV and Euro V has found to be more complex. Due to the sensitivity of the SCR system to exhaust temperatures and - as a consequence - to the engine load levels, tailpipe $NO_x$ are extra sensitive to different combinations of driving cycle, vehicle loads and road gradient. In the vehicle configuration considered in the left picture in Figure 8 (truck & trailer combination, 34-40t gross vehicle weight, 50% vehicle load) the SCR system reaches full operation temperature in motorway and rural driving conditions in combination with low traffic densities. This results in $NO_x$ emission levels which are in the range of one half to two thirds lower compared to Euro III emission behaviour. For urban driving situations with low and medium traffic densities the average $NO_x$ levels of Euro IV and Euro V SCR HDV are calculated to be approximately at Euro III level. In stop and go conditions the $NO_x$ output of this recent HDV generations have been found to exceed the Euro III $NO_x$ level, as the SCR aftertreatment is totally inactive at these vehicle operation conditions due to the low exhaust gas temperatures. Figure 8 gives a similar picture for the $NO_x$ emission factors for the HDV segment urban bus, 15-18t GVW, 50% loading. For this vehicle category the SCR vehicles certified to Euro IV have lower $NO_x$-emissions than Euro III in any driving conditions. However, this $NO_x$ emission benefit is assumed to be small in inner urban driving and in high traffic situations - vehicle operation conditions, which are the normal case for this vehicle category.

Euro VI $NO_x$ emissions levels are forecasted to be significantly lower than those for Euro V, independent from the vehicle category or driving situation. Due to the proposed change in type approval procedures the transition from Euro V to Euro VI in real world emissions is assumed to be more effective than in the nominal decrease in type approval limits (-80%). However, due to the complexity of the future emission regulation in combination of the potential applied technological solutions this forecast has to be assessed as rather uncertain.

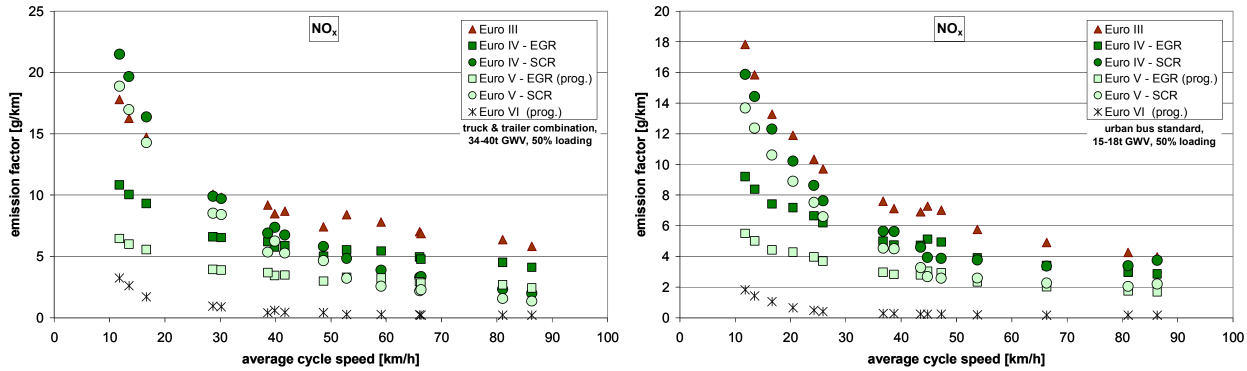



**Figure 8:** Examples HBEFA 3 NOx emission factors for 0% road gradient; truck & trailer combination 34-40t GVW, 50% loading (left picture), urban bus standard 15-18t GVW, 50% loading (right picture)

Figure 9 exemplarily gives calculated emission factors for the emissions of PM (left picture) and PN (right picture) again for the vehicle segment truck & trailer combinations with 34-40t gross vehicle weight and 50% vehicle load. Independent from the kind of HDV vehicle operation the introduction of the emission standards Euro IV and V (both emission standards have similar PM limits) resulted in a reduction of real world PM emission levels of about 80%, which correlates with the decrease of the homologation limits. For both Euro IV and Euro V, the EGR and SCR concepts show approximately similar emission levels. However, it again has to be mentioned, that so far no emission tests on one of the two main EGR HDV manufacturers have been available. For Euro VI vehicles it is forecasted, that due to comprehensive introduction of DPFs the PM emission levels will further be significantly reduced by about 90%. For PN emissions the emission reductions from Euro III to Euro IV and V are assessed to be slightly less significant than for PM. But with the introduction of Euro VI due to the expected DPF application also PN levels will drop to very low absolute levels. If these announced technological solutions for PM reduction will prove high filtration efficiencies over the entire vehicle life (and first experiences from the US market, where DPFs have been introduced by all HD manufacturers with the emission standard US 2007, indicate this fact), the issue of particle emissions originated from the HD diesel combustion process can be regarded as solved in the near future.

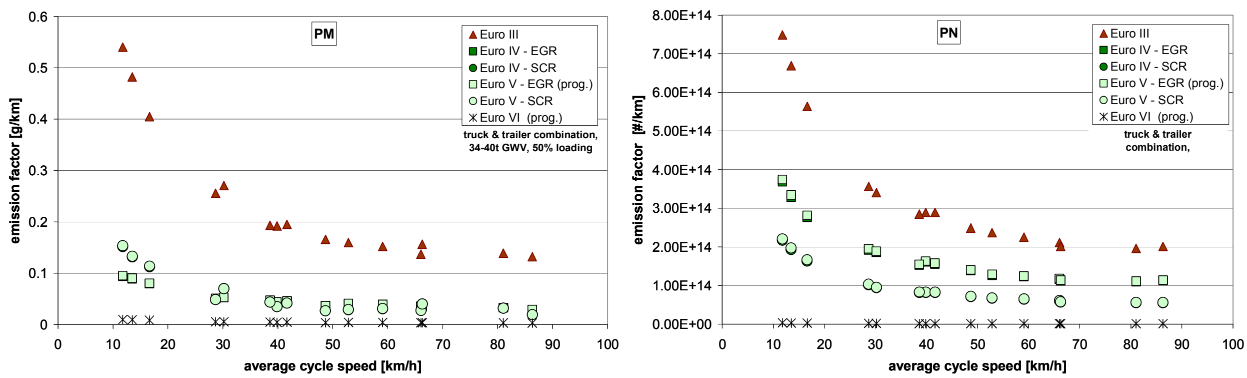



**Figure 9:** Examples HBEFA 3 emission factors for 0% road gradient; PM (left picture), PN (right picture); truck & trailer combination 34-40t GVW, 50% loading

Figure 10 gives examples for the calculated emission factors of HC (left picture) and CO (right picture). Due to the comprehensive introduction of exhaust aftertreatment in HDV certified from Euro IV on, the emission levels for HC dropped by about 90% compared to Euro III vehicles. However, already for of Euro III vehicles the absolute HC levels were at low absolute numbers. The latter statement is also valid for the emission component CO. This emission component is quite hard to oxidise in the diesel exhaust aftertreatment, so the further improvement for HDV emission standards Euro IV and later are comparable small compared to HC. For CO emissions, it also has to be mentioned, that the emission levels of the tested vehicles showed a much larger scattering than compared to all other emission components, so the assessment of the average CO levels of the different emission concepts is affected with higher uncertainties. However, in any case the real world emission levels for CO are much lower than demanded in the type approval procedure for all HDV emission standards.

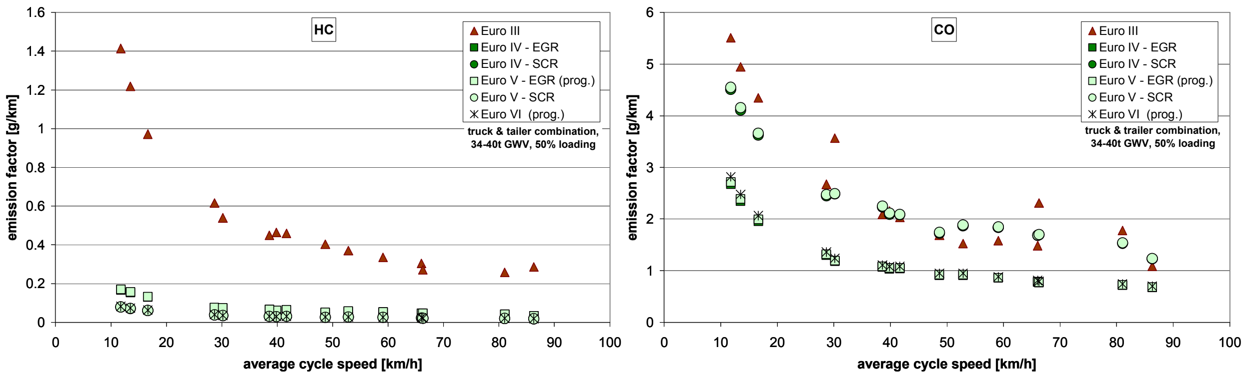



**Figure 10:** Examples HBEFA 3 emission factors for 0% road gradient; HC (left picture), CO (right picture); truck & trailer combination 34-40t GVW, 50% loading

# 4 Emission factors for passenger cars

With the emission model PHEM the set of passenger cars (PC) emission factors for the HBEFA3.1 has been calculated. In total 142 800 PC emission factors have been provided to INFRAS, covering:

- 2 PC vehicle categories (gasoline and diesel)
- 8 emission concepts (= 7 emission standards from “Pre Euro” to “Euro 6, thereof Euro 4 diesel further split into “with DPF“ and “without DPF”)
- 272 “traffic situations”
- 7 road gradients (-6%, -4%, -2%, 0%, +2%, +4%, +6%)
- fuel consumption and seven exhaust gas components ($CO_2$, $NO_x$, $NO_2$, HC, CO, PM, PN)

This chapter gives an overview on the datasets for PC emission behaviour and PC vehicle specifications and presents an analysis of emission factors calculated for PC. A detailed documentation of the basic work performed with the model PHEM on PC emission factors is given in [29].

## 4.1 Vehicle data

The model PHEM needs the vehicle data relevant to calculate the driving resistances as input data. The setting of this data influences the simulated engine power demand over the driving cycles and consequently also influences the simulated fuel consumption and emission values. Beside the engine power also the engine speed course is relevant for the emissions, thus the wheel diameter, the transmission ratios of the drive axle and of the single gears as well as the number of gears are necessary model input data.

This input data had to be elaborated for the average segments of PC. When simulating the emission factors for passenger cars the question aroused which vehicle fleet shall be depictured. Several options exist:

a) Vehicle sample as selected in the data base on measurements. Advantage is that quite detailed information is available on the driving resistances for many of the measured cars and the calibration of the simulated emissions on the average measured values per vehicle segment is straight forward[5]. Disadvantage is that the vehicle data from the single segments (e.g. gasoline EURO 4 and diesel EURO 4) are not representative for the new registered cars in Europe since the vehicles were not selected in a coordinated way within the ERMES group (the samples were selected rather for special purposes within the measurement programmes of each country). This is especially the case for PC segments with small sample sizes.

b) EU fleet average (=applied version). Advantage is that this data is a good compromise for the definition of the "average" car fleet in the HBEFA. Disadvantage is that the vehicle data is different compared to the data in the measured sample and differences in simulated emissions and measured emissions can not exactly be differentiated to model uncertainties and to differences in the vehicle data. This is especially true for the CADC cycles where the power to mass ratio of the vehicles also influences the gear shift strategy to be used for the measurements. Furthermore no data on average driving resistance values is available for the EU new car fleet.

For the HBEFA the version b) of the vehicle data set was selected for vehicle mass and average rated engine power of the new registrations. These data is available on an EU level (Figure 11).

[5] Within each vehicle segment different vehicle sub-samples have been measured in the different driving cycles. Thus the vehicle data for the "average measured car" is not representative for the emissions measured in the single cycles. Simulating each cycle with the data from the measured sub-sample is the correct approach for model validation but would not lead to a common data set for the simulation of fleet average emission factors. Furthermore not for all vehicles measured the driving resistance values are documented.

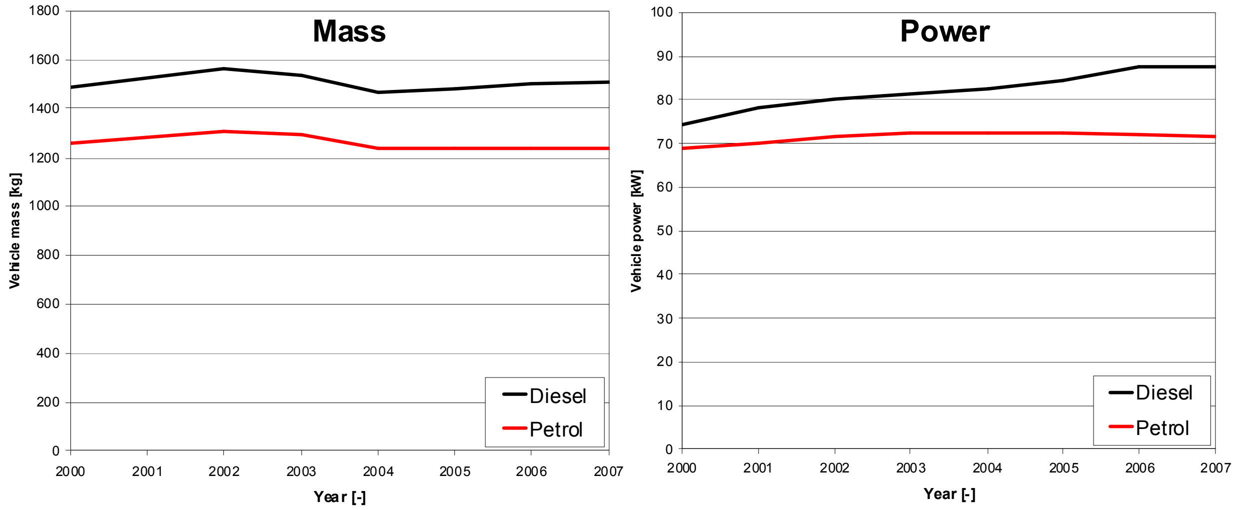



**Figure 11:** Development of average vehicle mass and engine rated power of new registered cars in Europe from [35]

To obtain the average vehicle mass for the different EURO classes the average of the new registrations of those years was taken in which the according EURO emission level was prescribed for new registrations. Since the real world emission levels shall depicture real world loading of the vehicles on average 1.25 persons per car have been assumed with some luggage resulting in total 95 kg/car. Data for the new vehicle registrations before the year 2000 was not available on an EU level. Thus the trends had to be assessed from data available from Austria and Switzerland. The resulting data used as model input is shown in Figure 12.

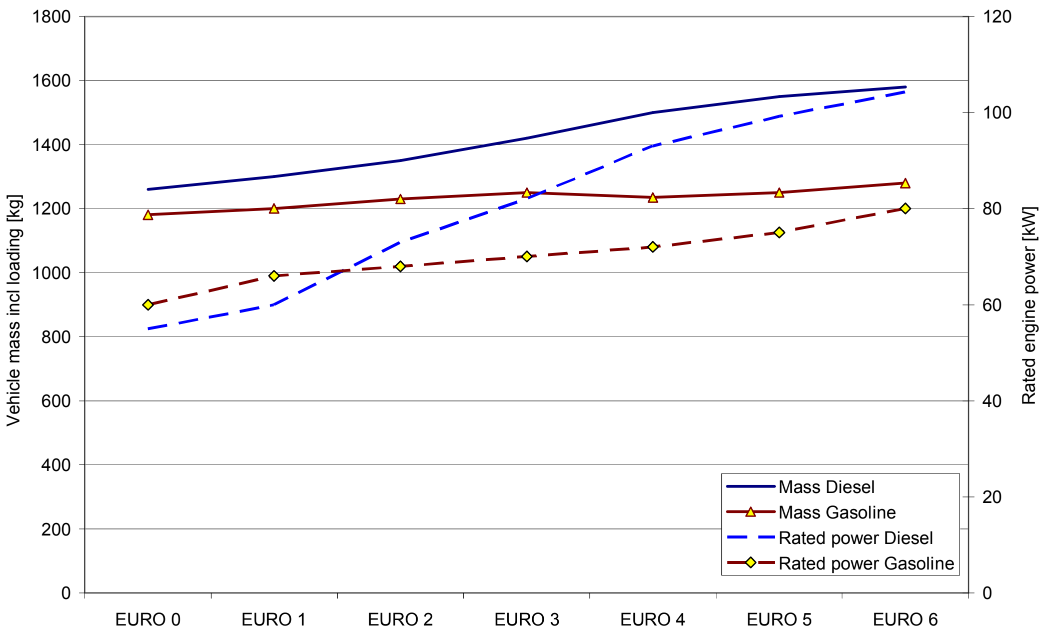



**Figure 12:** Development of average vehicle mass and engine rated power of new registered cars in Europe applied in PHEM

The other relevant model input data for the vehicle specifications was taken from the measured vehicles and was adapted by linear regression to fit to the values for the vehicle mass and engine power (e.g. moments of inertia as function of the rated engine power, frontal area of the vehicle as function of the vehicle mass). Table 5 and Table 6 show the data set used for the HBEFA.

**Table 5:** Vehicle data used as model input for **diesel** cars

| | EURO 0 | EURO 1 | EURO 2 | EURO 3 | EURO 4 | EURO 5 | EURO 6 |
|---|---|---|---|---|---|---|---|
| Mass [kg] | 1260 | 1300 | 1350 | 1420 | 1500 | 1550 | 1500 |
| Rated power [kW] | 55 | 60 | 73 | 82 | 93 | 93 | 93 |
| Cd-Value [-] | 0.3328 | 0.3253 | 0.3203 | 0.3163 | 0.3113 | 0.305 | 0.299 |
| $A_{Cs}$ [m²] | 2 | 2.05 | 2.1 | 2.16 | 2.16 | 2.16 | 2.16 |
| I_engine [kg m$^2$] | 0.3727 | 0.3894 | 0.4525 | 0.4803 | 0.5234 | 0.5234 | 0.5234 |
| Wheel Diameter [m] | 0.6136 | 0.6136 | 0.6136 | 0.6264 | 0.6264 | 0.6264 | 0.6264 |
| $m_{rot}$-Wheels [kg] | 40 | 40 | 40 | 41 | 41 | 41 | 41 |
| I-Gearbox [kg m$^2$] | 0.0521 | 0.0532 | 0.0561 | 0.0580 | 0.0605 | 0.0605 | 0.0605 |
| FR0 [-] | 0.00961 | 0.00943 | 0.00935 | 0.00912 | 0.00890 | 0.00881 | 0.00872 |
| FR1 [s/m] | 0.00011 | 0.00011 | 0.00011 | 0.000105 | 0.000103 | 0.000102 | 0.000101 |
| FR4 [s$^4$/m$^4$] | -1.270E-10 | -1.297E-10 | -1.311E-10 | -1.325E-10 | -1.380E-10 | -1.380E-10 | -1.380E-10 |
| Transmission: | | | | | | | |
| Axle Ratio [-] | 3.791 | 3.791 | 3.791 | 3.655 | 3.728 | 3.720 | 3.720 |
| Gear 1 [-] | 3.587 | 3.587 | 3.587 | 3.602 | 3.708 | 3.708 | 3.708 |
| Gear 2 [-] | 1.981 | 1.981 | 1.981 | 1.972 | 2.024 | 2.024 | 2.024 |
| Gear 3 [-] | 1.229 | 1.229 | 1.229 | 1.233 | 1.278 | 1.278 | 1.278 |
| Gear 4 [-] | 0.862 | 0.862 | 0.862 | 0.875 | 0.936 | 0.936 | 0.936 |
| Gear 5 [-] | 0.678 | 0.678 | 0.678 | 0.679 | 0.741 | 0.741 | 0.741 |
| Gear 6 [-] | | | | | 0.616 | 0.616 | 0.616 |

**Table 6:** Vehicle data used as model input for **gasoline** cars

| | EURO 0 | EURO 1 | EURO 2 | EURO 3 | EURO 4 | EURO 5 | EURO 6 |
|---|---|---|---|---|---|---|---|
| Mass [kg] | 1180 | 1200 | 1230 | 1250 | 1235 | 1250 | 1280 |
| Rated power [kW] | 60 | 66 | 68 | 70 | 72 | 75 | 80 |
| Cd-Value [-] | 0.3328 | 0.3253 | 0.3203 | 0.3163 | 0.3113 | 0.305 | 0.299 |
| $A_{Cs}$ [m²] | 2 | 2.05 | 2.1 | 2.118 | 2.118 | 2.160 | 2.16 |
| I_engine [kg m$^2$] | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 | 0.5000 |
| Wheel Diameter [m] | 0.5491 | 0.5989 | 0.5989 | 0.5989 | 0.6064 | 0.6264 | 0.6264 |
| $m_{rot}$-Wheels [kg] | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| I-Gearbox [kg m$^2$] | 0.0600 | 0.0600 | 0.0600 | 0.0600 | 0.0600 | 0.0600 | 0.0600 |
| FR0 [-] | 0.01065 | 0.01005 | 0.00948 | 0.00903 | 0.00890 | 0.00881 | 0.00872 |
| FR1 [s/m] | 0.00014 | 0.00013 | 0.00012 | 0.000117 | 0.000103 | 0.00010 | 0.00010 |
| FR4 [s$^4$/m$^4$] | 2.171E-10 | 2.310E-10 | 2.457E-10 | 2.340E-10 | -1.380E-10 | -1.394E-10 | -1.408E-10 |
| Transmission: | | | | | | | |
| Axle Ratio [-] | 3.925 | 3.944 | 3.944 | 3.944 | 4.083 | 4.0000 | 3.8000 |
| Gear 1 [-] | 3.500 | 3.586 | 3.586 | 3.586 | 3.630 | 3.630 | 3.630 |
| Gear 2 [-] | 1.950 | 1.990 | 1.990 | 1.990 | 2.052 | 2.052 | 2.052 |
| Gear 3 [-] | 1.295 | 1.369 | 1.369 | 1.369 | 1.380 | 1.380 | 1.380 |
| Gear 4 [-] | 0.900 | 1.045 | 1.045 | 1.045 | 1.048 | 1.048 | 1.048 |
| Gear 5 [-] | 0.730 | 0.847 | 0.847 | 0.847 | 0.842 | 0.842 | 0.842 |
| Gear 6 [-] | | | | | | | |

Since the fuel consumption simulated with this data was already quite close to the measured fuel consumption values in all measured driving cycles it can be assumed that the influence of the driving resistance values from the vehicle sample on the pollutant emission levels is rather small.

For future measurement campaigns it is recommended to include also the settings for the driving resistance values from the chassis dynamometer into the data base. In this context it has to be considered if the driving resistance values for the measurements are taken from manufacturer definitions or from coast down tests with “average tyre/road conditions”. The actual experience shows that the driving resistance data used for type approval of a car represents rather the optimum situation which hardly can be found in real life where vehicles are driven on not perfect road surfaces sometimes with insufficient tyre pressure and also with luggage racks.

The application of the model PHEM certainly raises questions on the quality of the rather detailed input data for an emission factor model. Such data is not necessary for simpler models like average speed models or vehicle emission maps based on vehicle speed and acceleration. However, the other models do have the same uncertainties in terms of driving resistance values used in the measurements and representativenes of the tested vehicle sample. Having the uncertain parameters explicit in the model input data helps learning to understand there effects on the resulting emission factors and can help to improve the design of future measurement and data collection campaigns.

## 4.2 Available emission data

For PC the model PHEM already had vehicle data and engine emission maps available. For the work on the HBEFA 3.1 following updates were done:

1) Adding of all instantaneous emission data from EMPA and TUG into the average engine maps
2) Adaptation of the vehicle specifications according to the available fleet statistics
3) Calibration of the model parameters with the bag values for all real world cycles in the A 300 db.

### 4.2.1 Instantaneous measurements

As mentioned before, to set up the engine maps with the model PHEM needs instantaneous emission measurements with $\leq$1Hz resolution. The time allocation between actual emission value and actual vehicle operation (speed curve or engine power and engine speed) has to have a high quality, i.e. less than one second deviation.

When using instantaneous emission measurements several influences need to be considered:

- The exhaust gas volume flow is variable in transient test cycles. This leads to variable velocities of the exhaust gas through the exhaust gas system of the vehicle and within the undiluted part of the emission measurement system. Thus the time delay between engine out and arrival at the analysers is not constant.
- The turbulent mixing at parts of the exhaust gas system of the vehicle (especially silencer and catalyst inlet) and within the emission measurement system (especially inlet of CVS tunnel) leads to a smoothening of emission peaks since gas with higher and lower concentrations is mixed there during transport from the engine out to the analyser
- The analysers also lead to time delays and to smoothening of the signals.

These influences shall be known for the test beds where instantaneous emission measurements are used to fill engine emission maps. If necessary, correction functions for the inaccuracies mentioned before have to be applied, e.g. [34].

This level of data was supplied only from EMPA and TUG at the time being. The number of vehicles available to set up the engine maps is shown in Table 7.

**Table 7:** Instantaneous emission measurements available for setting up the engine emission maps for the PC segments

| | SI | CI |
|---|---|---|
| EURO 0 | 2 | (1) |
| EURO 1 | 3 (1) | (1) |
| EURO 2 | 4 (1) | 4 |
| EURO 3 | 9 | 8 |
| EURO 4 | 23 | 24 |
| EURO 5 | (2) | 1 (2) |
| EURO 6 | (2) | (2) |

(1) Maps from small samples which proved not to result in representative trends over engine load and engine speed compared to the bag data for model calibration (A 300 db). Thus the engine map from the closest EURO class was used and calibrated according to all available bag data for the segment.

### 4.2.2 Bag data for calibration

Since the high number of bag data from tests on passenger cars has a high value and the data proved to be very important to gain representative emission levels, each vehicle included in the A 300 db was used for model calibration if the single vehicle were tested in one or more of the test cycles shown in Table 8.

**Table 8:** Test cycles used for model calibration

| Cycle group | Sub cycles | comments |
|---|---|---|
| EMPA -hot | C1, C2, C3, D1, D2, D3, E1, E2, E3 | cycles used mainly by EMPA for HBEFA V2 |
| HBEFA | R1_I (AE1), R1_II (AE2), R1_III (A3), R2_I (A4), R2_II (LE1), R2_III (LE2s), R3_I (LE2u), R3_II (LE3), R3_III (LE5), R4_I (LE6), R4_II (StGoHW), R4_III (StGoUrb)- | cycles used mainly by EMPA for HBEFA V2 |
| EMPA BAB | L2_III, BAB437, BAB736, BAB1000 | |
| CADC | Urban, Road, Motorway with all sub-cycles | Used in the project ARTEMIS and in many following measurement campaigns |
| TUG HBEFA | Urban, Road Motorway with all sub-cycles | Includes actual traffic situations in the HBEFA |
| Legislative NEDC (1) | Cold, hot, ECE, EUDC | In versions for EURO 2 and for EURO 3ff |
| Legislative US_FTP (1) | Cold, hot, FTP 72, FTP 1, 2 | |

(1) not used for determination of calibration factors only to check validity of the measured data

For the calibration each of the cycles was simulated for all segments of the passenger cars (i.e. all combinations of Euro classes and propulsion systems). Then the model results were compared to the average emission values measured for the corresponding vehicle segment.

For the calibration always the weighted absolute deviation between measurement and simulation was tuned towards a minimum. The weighting factor takes into consideration, that different numbers of vehicles have been measured in the different test cycles shown in Table 8. If for example only one car of the sample in A300db was measured in the CADC but 19 cars were measured in HBEFA cycles, then the weighting factor of the emission level of CADC was 1/20 and the one of HBEFA cycles 19/20.

**Equation 12:** Calculation of the relative deviation between simulation and bag data from the A 300 db

$$Dev = \frac{\sum_{i=1}^{n}(E_{PHEM} \times m_i)}{\sum_{i=1}^{n}(E_{Measured} \times m_i)}$$

With Dev .................. relative deviation between measurement and simulation

i ........................ Index for the test cycles with measurements available for a vehicle segment (CADC, HBEFA,…)

$E_{PHEM}$ .............. Emission value simulated with the model PHEM for an exhaust gas component for the test cycle i

$E_{Measured}$ ........... Measured average emission value for an exhaust gas component in the test cycle i

$m_i$ ..................... Number of vehicles within the vehicle segment measured in cycle i

The model calibration was then performed for each vehicle segment and for each exhaust gas component according to the following system:

1. If the modelled fuel consumption showed deviations larger than 5% and the deviations were different at different average speed levels, the vehicle specifications were slightly adapted within logical boundaries (frontal area, air resistance coefficient, rolling resistance values[6]). Remaining deviations were allocated to the differences in the measured vehicle sample compared to the average real world fleet. Then all emissions were recalculated with the adapted vehicle data. $CO_2$ emissions are calculated from the fuel consumption and thus are not further calibrated.
2. The relative deviation (Dev according to Equation 12) between simulated emissions and measured emissions was then calculated. The absolute level of the emissions stored in the engine maps from PHEM were then calibrated by multiplication with (1/Dev). This leads to zero deviation after the calibration.
3. The emission levels simulated and measured were plotted over average cycle power and average cycle speed (each calculated with PHEM) and a weighted polynomial trend line was drawn for measured and simulated emissions. Weighting was again done by the numbers of vehicles tested per cycle. If the two trend lines showed a pronounced difference, the emissions in the engine map were adapted simply by the ratio of the two trend lines. This proved to be necessary for some of those segments were less than 10 vehicles were available for setting up the engine maps (see Table 7).

Figure 1 shows as example the final result from the calibration of the $NO_x$ emissions from EURO 0 diesel cars. For this segment 34 cars in BAB and 2 cars in the CADC sub cycles have been measured. Thus the BAB has a high weighting factor. For EURO 0 diesel cars no instantaneous emission data with sufficient quality was available to set up the engine emission

[6] The adaptations were made only within the boundaries given by the next car segments. E.g. the air resistance coefficient was assumed to drop from EURO 0 to EURO 6, therefore e.g. the adaptation for EURO 1 can be done only between the values of EURO 0 and EURO 2.

maps with PHEM. Thus the EURO 2 map was used as starting point and the calibration of the absolute $NO_x$ level and the adaptation of the engine map shape over the engine power and over engine speed was performed as described above. The result shows a very good correlation with the measured data.

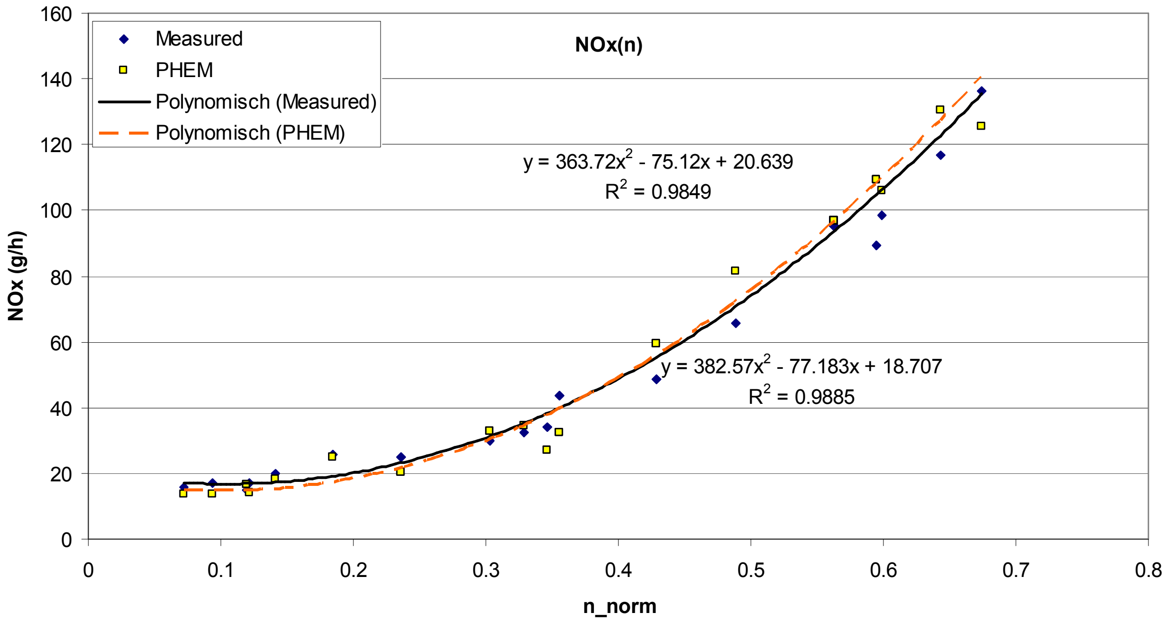



**Figure 13:** Final result from calibration of the $NO_x$ emissions from EURO 0 diesel cars (measured 34 cars in BAB and 2 cars in the CADC sub cycles)

In total more than 3000 vehicles were available from the A300 db (Table 9). In total approx. 1000 of these vehicles were tested in cycles useful for the determination of calibration factors. This is a sufficient number to assess the average emission levels. Especially for vehicle segments older than EURO 3 a high number of vehicles was measured quite often in one or two cycles only (e.g. EURO 0 diesel in Figure 13). The model calibration for the trends over engine power and engine speed thus is not very reliable for these old vehicle segments. However, the approach seemed to be the best option to transfer old measured data into emission factors for a new set of driving cycles in a consistent way.

**Table 9:** Number of vehicles in the A 300 db measured in at least one cycle

| fueltype | Total | pre-EURO | EURO-1 | EURO-2 | EURO-3 | EURO-4 |
|---|---|---|---|---|---|---|
| | [number of vehicles measured in ≥1 cycle] | | | | | |
| diesel | 543 | 207 | 48 | 54 | 135 | 99 |
| gasoline | 2597 | 878 | 1191 | 164 | 156 | 208 |

With this calibrated data set all hot emission factors for passenger cars were calculated with the model PHEM.

## 4.3 Results

This section shows the results for HBEFA 3 passenger car emission factors. The analysis performed focuses on a comparison of the emission levels of the different EURO classes. A detailed comparison of the emission behaviour of older HDV emission concepts can be found in [29].

For the discussion of the emission results the same traffic situations have been selected as for HDV (see Table 4). These traffic situations cover four fundamental road types and four levels of service and give a quite good coverage of the whole range of vehicle speeds from highway to stop&go conditions. The driving cycles for cars are different than those for HDV[7].

As for HDV the distance specific engine work (unit: kWh per kilometres) for the selected set of cycles on flat road conditions is shown in Figure 14. Compared to the truck & trailer combination with 34-40t GVW shown in chapter 3.4 the passenger cars need approximately 1/10 of the specific energy.

For the diesel cars the effect of increasing masses from EURO 1 to EURO 6 can be seen especially in the slower cycles where acceleration and deceleration play an important role for the work to be provided by the engine. Here the EURO 5 and EURO 6 vehicles have the highest specific energy demand. With increasing average cycle speed the improvements in the drag resistance coefficient get more important and the modern vehicle concepts show a better performance. For gasoline the differences in the specific engine work are smaller due to the rather constant average vehicle mass.

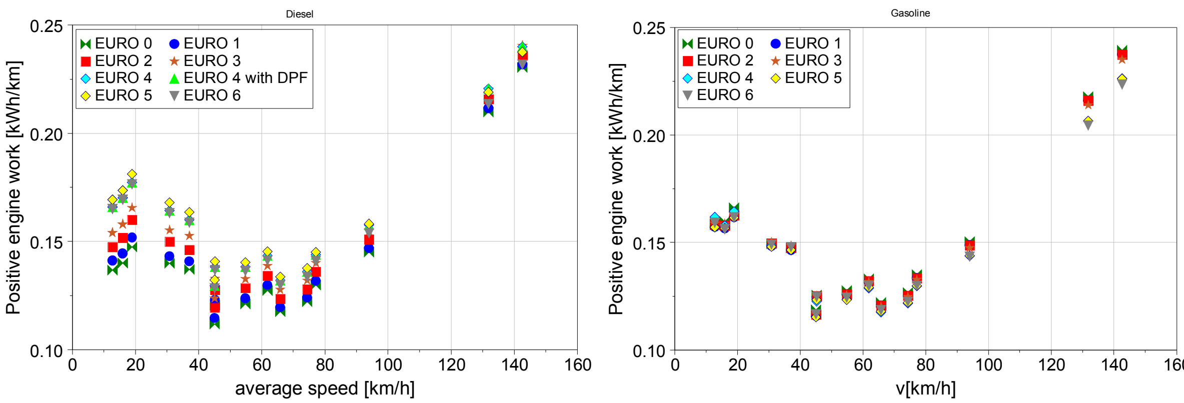



**Figure 14:** Distance specific engine work for selected set of cycles for passenger cars (left picture = Diesel, right picture = gasoline)

The absolute values as well as the trends in vehicle masses and also in the other relevant vehicle parameters like the air resistance most likely are different for each country. Thus the fuel consumption values of the new car fleet can be quite different in each state. Since a quite accurate statistic is available from the $CO_2$ monitoring for all new registered passenger cars in the EU, the specific fuel consumption values [g/km] are calibrated in the HBEFA for each country separately to meet the national statistics. However, the specific engine work also influences the results for all exhaust gas components[8]. Figure 15 shows the results for fuel consumption as simulated by PHEM for the average cars.

The improved engine technology as well as the better transmission and more gears available in the modern cars compensate for the higher engine work demanded in slow cycles for diesel cars. For gasoline cars we see the effects of an increased rated engine power from EURO 0 to EURO 6. As a result the same driving cycles are run in relatively lower engine power demand

[7] The traffic situations and the driving cycles in HBEFA V3 are described in an extra report from Heinz Steven which is not available yet

[8] For models which are based on vehicle speed (and acceleration) only, this influence is implicitly in the model due to the vehicle sample from the measurements.

for the newer cars. Due to the rather high gradient of the engine efficiency map at low loads for gasoline cars the newer models do not necessarily show lower fuel consumption values than the old vehicles.

In general the steep increase of engine work demand at higher cycle speeds is partially compensated by a better fuel efficiency at the higher engine loads. Thus the increase of the fuel consumption is less pronounced than the increase of the engine work.

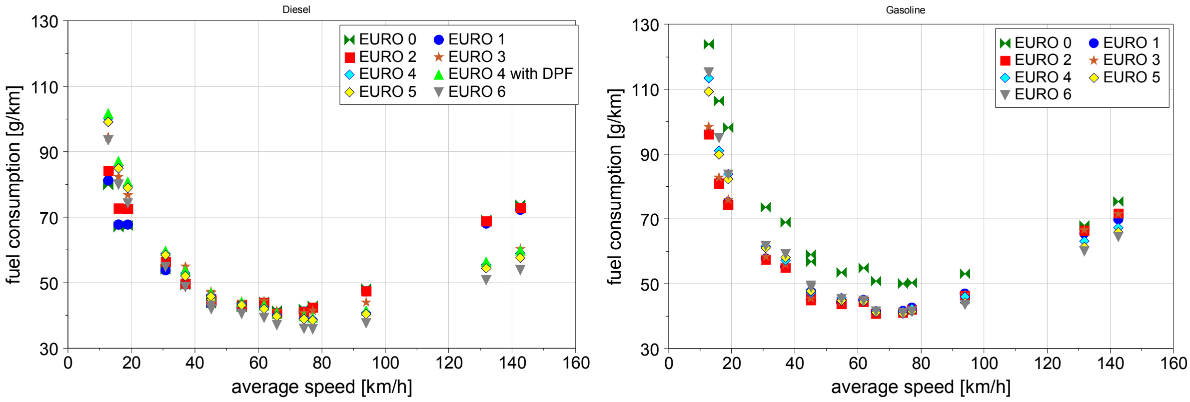



**Figure 15:** Specific fuel consumption for selected set of cycles for passenger cars

Figure 16 shows the development of the specific $NO_x$ emissions for diesel and gasoline cars. From EURO 3 until EURO 5 the gasoline vehicles have much lower $NO_x$ levels than diesel vehicles. For EURO 6 diesel may reach a similar $NO_x$ behaviour like the gasoline vehicles. However, no EURO 6 diesel cars have been measured within the ERMES group and the technologies for $NO_x$ reduction (high EGR, SCR, NOx trap, etc.) will have to prove that they are applied for similar efficiencies in real world traffic than in the type approval cycle. This is questionable if the NEDC remains the only type approval cycle for EURO 6. If EURO 5 diesel cars will have a lower NOx level than the EURO 4 cars is open yet and should be validated by more measurements in future. The one EURO 5 car measured in the CADC yet did not show $NO_x$ reductions compared to the EURO 4 predecessor.

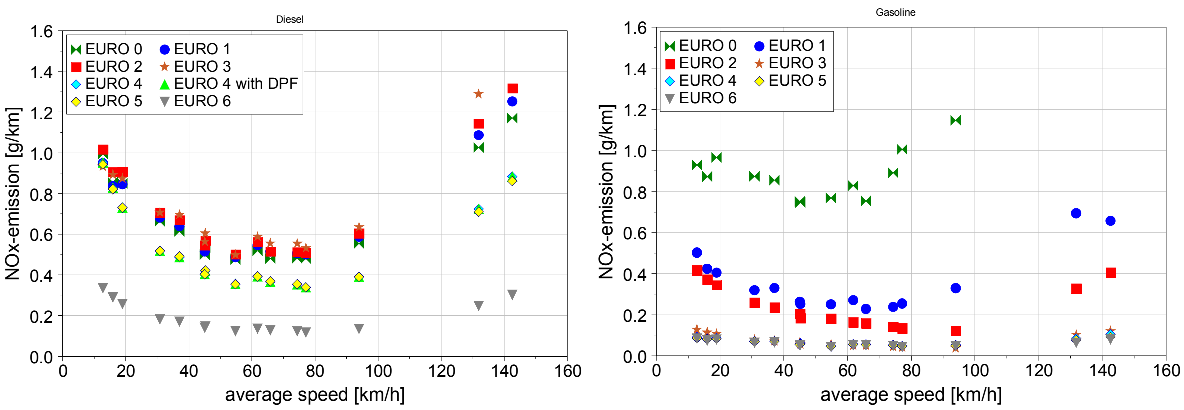



**Figure 16:** Specific NOx emissions for a selected set of cycles for passenger cars

Figure 17 shows the results for PM emissions. Here a clear reduction from EURO 0 to EURO 4 can be seen. The vehicles with DPF (part of EURO 4 and all from EURO 5 on) show lower PM levels than the gasoline vehicles.

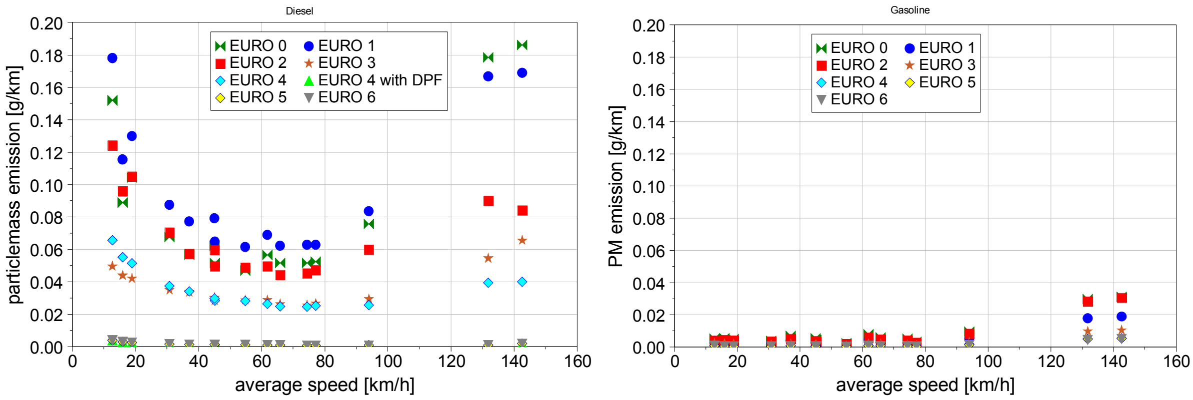



**Figure 17:** Specific PM emissions for selected set of cycles for passenger cars

The HC emissions simulated are shown in Figure 18. The diesel vehicles generally have low HC emission levels. Gasoline cars reduced HC consequently from EURO 0 to EURO 4.

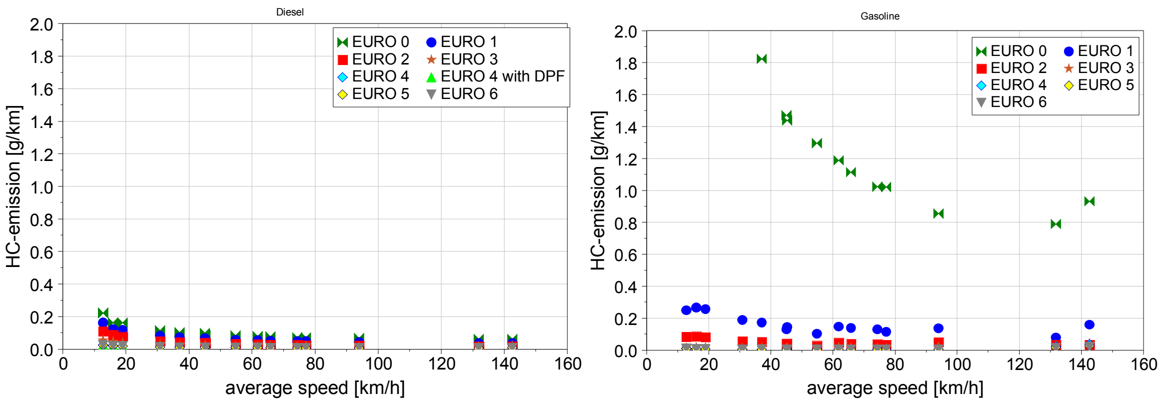



**Figure 18:** Specific HC emissions for selected set of cycles for passenger cars

CO emissions are low for diesel cars and for modern gasoline cars in urban and rural driving (Figure 19). For gasoline cars increased CO emissions were found at high cycle speeds. This may be attributed to a more rich A/F ratio which protects the catalyst from overheating at high relative engine loads for several of the tested vehicles. The available oxygen and $NO_x$ in the exhaust gas in such operation conditions converts then HC more efficiently than CO in the catalyst.

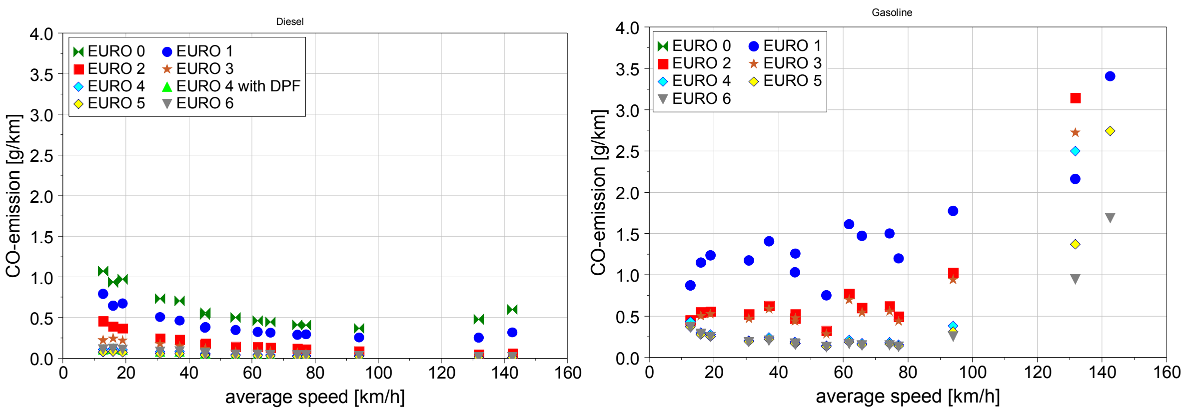



**Figure 19:** Specific CO emissions for selected set of cycles for passenger cars

Figure 20 shows the results for the PN emissions. For PN the DPF reduces the emission level by nearly two orders of magnitude, resulting in even lower PN emissions than gasoline cars. For diesel cars without DPF the trend shows decreasing emissions from EURO 0 to EURO 4. This reflects the result from measurement campaigns, where the frequently found thesis that new engines have more and smaller particle emissions was not approved at all, e.g. [27].

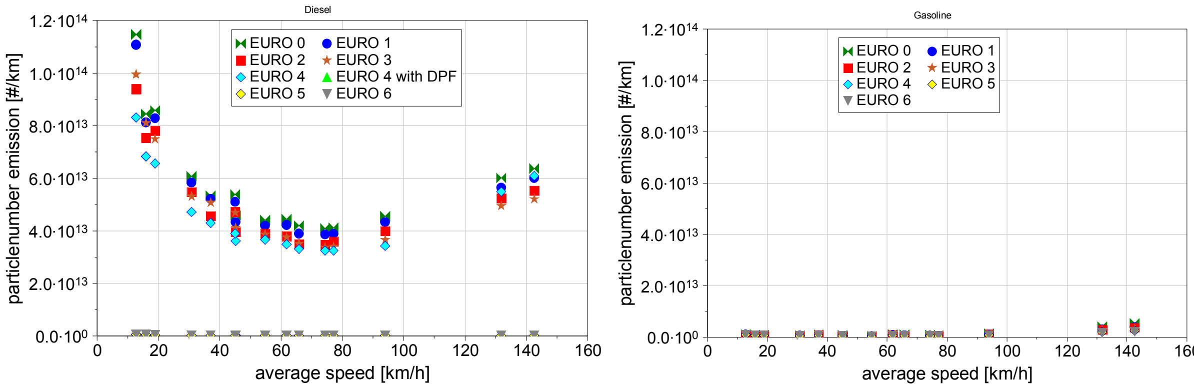



**Figure 20:** Specific PN emissions for selected set of cycles for passenger cars

# 5 Emission factors for light commercial vehicles

In principle following differentiations have to be made for the segmentation of LCV:

- Engine type (gasoline or diesel)
- Euro class
- Reference mass (N1-I, N1-II, N1-III)
- Loading

Only a few of these segments are covered with measurements available from ARTEMIS and all following activities of the ERMES group. Additionally the available measurements used partly different loadings and as for passenger cars the driving cycles used in the different measurement campaigns varied over the years. Thus the results of the different measurements can not be compared directly.

Thus it was agreed in the ERMES group to use engine emissions maps from passenger cars (or where more appropriate from HDV), define the vehicle specifications according to statistical data for LCV and simulate the emissions of all LCV segments with the model PHEM. The available measurements on LCV have been used to calibrate the model PHEM.

The following chapters describe the methodology and the data used for model parameterization and for model calibration.

## 5.1 Vehicle data

Data on LCV properties was available for Austria and Switzerland. This included average vehicle mass, maximum loading capacity and rated engine power values according to the years of new registration and subdivided into diesel and gasoline vehicles. Additionally the values for the LCV measured in the A 300 data base were available.

In total this gave a rather consistent picture of the time series of LCV vehicle data. Figure 21 shows the data used for the vehicle mass and for the rated engine power for the average LCVs in the model PHEM. Table 10 and Table 11 show more detailed values for the vehicle specifications. For other model input data, such as moments of inertia from engines, wheels and gear boxes, the transmission ratios etc., data available from the measurements in the A 300 data base was transformed to the average vehicle data (e.g. the moment of inertia of the engine and gear box as function of the rated engine power and of the Euro class, rolling resistance coefficients as function of the vehicle mass[9]).

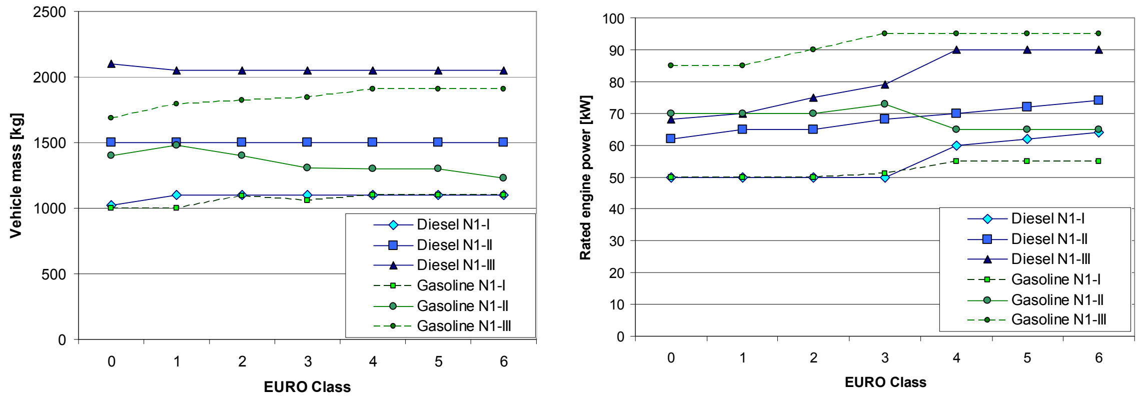



**Figure 21:** Development of vehicle mass and of rated engine power for the "average" LCV in the model PHEM

Main trends and uncertainties found are:

- The power to mass ratios are increasing from EURO 0 to EURO 4
- The vehicle empty mass is rather constant, only for gasoline the N1-I show an increasing mass while the N1-II show decreasing mass.
- No reliable data on the cross sectional area of the vehicles was found. This value certainly depends very much on the type of LCV (minibus, pickup, box waggon). However, the development of the share of these LCV types over time for N1-I to N1-III for gasoline and diesel was not found in any data sets.
- Air resistance coefficients seem to drop from EURO 0 to EURO 4 but depend also on the type of LCV and thus also include uncertainties.

[9] The basic formulas for Fr0 were taken from [18]. In addition an increase of +8% from EURO 4 to EURO 0 was assumed for rolling resistance coefficients which is related to losses from the wheel rim to the gear box. The tyres are assumed to be on a similar level for all vehicles on the road at a given year since the tyres are changed more frequently than the vehicles.

**Table 10:** Vehicle data used as input for the model PHEM to simulate emission factors for average **diesel LCV** (not all parameters listed)

| N1_I | EURO 0 | EURO 1 | EURO 2 | EURO 3 | EURO 4 | EURO 5 | EURO 6 |
|---|---|---|---|---|---|---|---|
| vehicle mass [kg] | 1025 | 1100 | 1100 | 1100 | 1100 | 1100 | 1100 |
| Loading [kg] | 275 | 275 | 275 | 275 | 275 | 275 | 275 |
| Cd-value [-] | 0.35 | 0.34 | 0.33 | 0.32 | 0.31 | 0.31 | 0.30 |
| $A_{Cs}$ [m²] | 2.40 | 2.40 | 2.40 | 2.40 | 2.40 | 2.40 | 2.40 |
| Rated power [kW] | 50 | 50 | 50 | 50 | 60 | 62 | 64 |
| Fr0 [N] | 1.147E-02 | 1.126E-02 | 1.115E-02 | 1.073E-02 | 1.062E-02 | 1.051E-02 | 1.041E-02 |
| Fr1 [Ns/m] | 9.218E-05 | 9.037E-05 | 8.860E-05 | 8.686E-05 | 8.600E-05 | 8.514E-05 | 8.429E-05 |

| N1_II | EURO 0 | EURO 1 | EURO 2 | EURO 3 | EURO 4 | EURO 5 | EURO 6 |
|---|---|---|---|---|---|---|---|
| vehicle mass [kg] | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 | 1500 |
| Loading [kg] | 285 | 285 | 285 | 285 | 285 | 285 | 285 |
| Cd-value [-] | 0.35 | 0.34 | 0.33 | 0.32 | 0.31 | 0.31 | 0.30 |
| $A_{Cs}$ [m²] | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| Rated power [kW] | 62 | 65 | 65 | 68 | 70 | 72 | 74 |
| Fr0 [N] | 1.147E-02 | 1.126E-02 | 1.115E-02 | 1.073E-02 | 1.062E-02 | 1.051E-02 | 1.041E-02 |
| Fr1 [Ns/m] | 9.218E-05 | 9.037E-05 | 8.860E-05 | 8.686E-05 | 8.600E-05 | 8.514E-05 | 8.429E-05 |

| N1_III | EURO 0 | EURO 1 | EURO 2 | EURO 3 | EURO 4 | EURO 5 | EURO 6 |
|---|---|---|---|---|---|---|---|
| vehicle mass [kg] | 2100 | 2050 | 2050 | 2050 | 2050 | 2050 | 2050 |
| Loading [kg] | 360 | 360 | 360 | 360 | 360 | 360 | 360 |
| Cd-value [-] | 0.35 | 0.34 | 0.33 | 0.32 | 0.31 | 0.31 | 0.30 |
| $A_{Cs}$ [m²] | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 | 5.00 |
| Rated power [kW] | 68 | 70 | 75 | 79 | 90 | 90 | 90 |
| Fr0 [N] | 1.129E-02 | 1.109E-02 | 1.099E-02 | 1.057E-02 | 1.047E-02 | 1.036E-02 | 1.026E-02 |
| Fr1 [Ns/m] | 9.218E-05 | 9.037E-05 | 8.860E-05 | 8.686E-05 | 8.600E-05 | 8.514E-05 | 8.429E-05 |

**Table 11:** Vehicle data used as input for the model PHEM to simulate emission factors for average **gasoline LCV** (not all parameters listed)

| N1_I | EURO 0 | EURO 1 | EURO 2 | EURO 3 | EURO 4 | EURO 5 | EURO 6 |
|---|---|---|---|---|---|---|---|
| vehicle mass [kg] | 1000 | 1000 | 1090 | 1060 | 1100 | 1100 | 1100 |
| Loading [kg] | 228 | 228 | 228 | 228 | 228 | 228 | 228 |
| Cd-value [-] | 0.35 | 0.34 | 0.33 | 0.32 | 0.31 | 0.31 | 0.30 |
| $A_{Cs}$ [m²] | 1.97 | 1.97 | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |
| Rated power [kW] | 50 | 50 | 50 | 51 | 55 | 55 | 55 |
| Fr0 [N] | 1.151E-02 | 1.128E-02 | 1.119E-02 | 1.079E-02 | 1.068E-02 | 1.058E-02 | 1.047E-02 |
| Fr1 [Ns/m] | 9.218E-05 | 9.037E-05 | 8.860E-05 | 8.686E-05 | 8.600E-05 | 8.514E-05 | 8.429E-05 |

| N1_II | EURO 0 | EURO 1 | EURO 2 | EURO 3 | EURO 4 | EURO 5 | EURO 6 |
|---|---|---|---|---|---|---|---|
| vehicle mass [kg] | 1400 | 1475 | 1400 | 1310 | 1300 | 1300 | 1225 |
| Loading [kg] | 229 | 229 | 229 | 229 | 229 | 229 | 229 |
| Cd-value [-] | 0.35 | 0.34 | 0.33 | 0.32 | 0.31 | 0.31 | 0.30 |
| $A_{Cs}$ [m²] | 2.25 | 2.25 | 2.20 | 2.10 | 2.10 | 2.10 | 2.10 |
| Rated power [kW] | 70 | 70 | 70 | 73 | 65 | 65 | 65 |
| Fr0 [N] | 1.151E-02 | 1.128E-02 | 1.119E-02 | 1.079E-02 | 1.068E-02 | 1.058E-02 | 1.047E-02 |
| Fr1 [Ns/m] | 9.218E-05 | 9.037E-05 | 8.860E-05 | 8.686E-05 | 8.600E-05 | 8.514E-05 | 8.429E-05 |

| N1_III | EURO 0 | EURO 1 | EURO 2 | EURO 3 | EURO 4 | EURO 5 | EURO 6 |
|---|---|---|---|---|---|---|---|
| vehicle mass [kg] | 1685 | 1790 | 1820 | 1840 | 1910 | 1910 | 1910 |
| Loading [kg] | 340 | 340 | 340 | 340 | 340 | 340 | 340 |
| Cd-value [-] | 0.35 | 0.34 | 0.33 | 0.32 | 0.31 | 0.31 | 0.30 |
| $A_{Cs}$ [m²] | 3.30 | 3.30 | 3.30 | 3.35 | 3.40 | 3.40 | 3.40 |
| Rated power [kW] | 85 | 85 | 90 | 95 | 95 | 95 | 95 |
| Fr0 [N] | 1.140E-02 | 1.117E-02 | 1.105E-02 | 1.063E-02 | 1.050E-02 | 1.040E-02 | 1.029E-02 |
| Fr1 [Ns/m] | 9.218E-05 | 9.037E-05 | 8.860E-05 | 8.686E-05 | 8.600E-05 | 8.514E-05 | 8.429E-05 |

After finalising the emission factors for all LCV segments, data on the specific $CO_2$-emissions from the fleet of new registered LCV in the EU was made available in [37]. Furthermore a proposal for a $CO_2$-limit value is given in [37] for the average of new sold LCV from each manufacturer as follows:

Limit value function: $E_{CO2} = 175+0.093*(M-M_0)$ [g/km]

with: M............ Vehicle reference mass [kg]

$M_0$ .......... 1706 kg until October 2016; from Oct.2016 calculated from the average mass of the new registrations in the EU within the last 3 calendar years.

To compare the data set and model results from PHEM with the data and proposals from [37] PHEM was used to simulate the NEDC type approval cycle for the three LCV categories defined in Table 10. To depicture type approval conditions the vehicle loading was set to 100 kg as defined in the TA procedure. Cold start was simulated for 23° start temperature resulting in 7% increase in $CO_2$-emissions compared to the hot running conditions. The comparison in Figure 22 shows that the PHEM results for EURO 4 LCV with CI engine are approximately 15% higher than given as trend line for the 2007 new registrations in [37]. Since PHEM simulates real world vehicles on average real world road conditions the higher results for PHEM are plausible due to higher driving resistances (no ideal tyres and tyre pressure, rain, snow, grit on the road, crosswind, etc.).

The distance from $CO_2$-emissions calculated with PHEM for EURO 6 to the limit function in Figure 22 is again approx. 15% for the N1-III category of the HBEFA V3[10]. For smaller EURO 6 LCV the relative distance to the limit curve is higher. An explanation may be, that in the PHEM data set mainly vehicles are depictured which can be clearly identified as LCV. Thus no "passenger car like" LCV are in the vehicle data from PHEM. If this is the correct approach for the users of the HBEFA needs to be discussed in future.

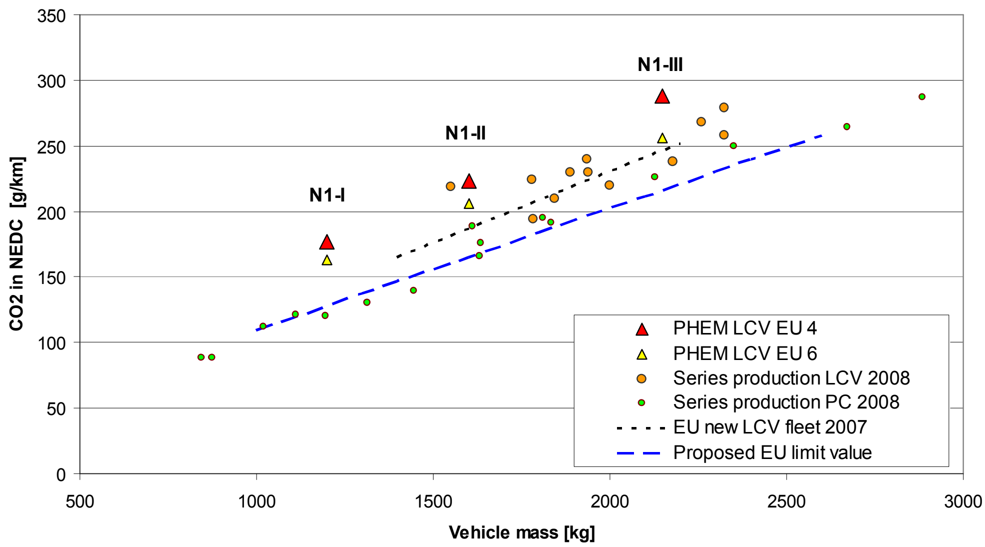



**Figure 22:** Specific $CO_2$-emissions from LCV simulated with PHEM for HBEFA V3, stated for single new models in 2008 and stated as EU-Fleet average according to [37] compared to the discussed future $CO_2$-limit function for LCV, [37]

1) [10] When the limit value proposal was announced the vehicle data for LCV in PHEM was adapted with a longer drive axle transmission ratio in a six-gear box to achieve lower fuel consumption values for EURO 5 and EURO 6

Adaptations of the LCV data set could be done easily in future if necessary. For the actual version of the HBEFA the comparison with the new statistics shows at least reasonable agreements so no urgent need for adaptations seems to be necessary.

## 5.2 Available emission data

For LCV the model PHEM had no sounded data available before start of the work for the HBEFA V3[11]. For the HBEFA 3 following work has been done:

1) Set up of engine emission maps from the instantaneous emission data available for LCV from TUG. Simulation of all measured cycles using the vehicle data for the average LCVs as shown before and comparison with all bag data available in the A 300 data base.
2) Applying the engine emission maps from the passenger cars instead of the maps from the few LCVs. Then rerun the simulation of all measured cycles as performed in 1).
3) Applying the engine emission maps from the HDV instead of the maps from the few LCVs. Then rerun the simulation of all measured cycles as performed in 1). This step was done only for the N1-III diesel vehicles of EURO 2 since for this LCV category the highest number of measurements was available (i.e. 7 LCV).
4) Comparison of the quality of the results from 1), 2) and 3). The engine maps from passenger cars showed the best fitting with the available measurements on LCV and thus were used for the next steps.
5) Calibration of the model parameters with the bag values for all real world cycles in the A 300 db. A calibration was performed for the cycle / LCV-segment combination where at least 7 vehicles have been measured. For the other categories conclusions by analogy had to be drawn to treat all emission maps in a comparable way. It was not possible to create a mathematical formulation for these adaptations since both, the different exhaust gas limits for N1-I to N1-III as well as the available measured data had to be balanced and the available measurements are very inhomogeneous for the LCV segments.

### 5.2.1 Instantaneous data

The methods for using instantaneous data for elaborating engine emission maps for PHEM is described already in chapter 2.1.2. The available instantaneous data for LCV is described already in chapter 6.3.2 since this data was used for model validation mainly.

The engine emission maps for the simulation of LCV with the model PHEM are based on the engine maps from passenger cars and are calibrated with bag data from the available LCV tests (see 5.2.2).

### 5.2.2 Bag data for calibration

For most LCV categories between zero and three vehicles have been measured (Table 12). These samples are rather unlikely to be representative for the LCV fleet. However, the simulation results show reasonable agreements with most of the measured data. Several of the measurements seem to be outliers which e.g. show higher fuel consumption levels for N1-I vehicles than for N1-III vehicles.

2) 11 PHEM used also data from cars with an increased mass and cross sectional area but without calibration.

**Table 12:** Number of LCVs with available bag data results from real world test cycles in the A 300 data base

| LCV category | Diesel | Gasoline |
|---|---|---|
| | No. Of vehicles measured | |
| EURO 4 N1-III without DPF | 6 | - |
| EURO 4 N1-II without DPF | 1 | - |
| EURO 4 N1-I without DPF | - | - |
| EURO 4 N1-III with DPF | 6 | - |
| EURO 4 N1-II with DPF | - | - |
| EURO 4 N1-I with DPF | - | - |
| EURO 3 N1-III | 2 | - |
| EURO 3 N1-II | - | - |
| EURO 3 N1-I | - | - |
| EURO 2 N1-III | 7 | 2 |
| EURO 2 N1-II | 1 | 3 |
| EURO 2 N1-I | 1 | - |
| EURO 1 N1-III | 2 | 3 |
| EURO 1 N1-II | 5 | 11 |
| EURO 1 N1-I | - | - |
| EURO 0 N1-III | 2 | - |
| EURO 0 N1-II | 5 | 9 |
| EURO 0 N1-I | - | 10 |

In the following some pictures are shown describing the results of the calibration work. In these pictures the bars for the measurements with less than 3 vehicles[12] are marked in white colour to show the related high uncertainty of this value.

Figure 23 shows the results for the fuel consumption of the diesel LCV in the CADC 1/3 mix. The CADC 1/3 mix here is defined as the average of the specific emissions in urban, road and motorway from the CADC.

It can be seen, that the simulation based on vehicle data for LCV together with the engine maps from passenger cars resulted in a good agreement of the simulated and measured values. Beside the CADC a lot of bag data was available for the BAB cycle and for the FTP 72 for LCV between EURO 0 and EURO 2. This data was also taken for model calibration but is not shown here. For LCV segments with only few vehicles measured also the average vehicle masses from the vehicle sample in the tests differed sometimes substantially from the "average" vehicle specifications used in PHEM for the simulation. This effect can be seen for example in the results for EURO 1 and EURO 0 LCV. The model results are assumed to better represent the real ratios from EURO 0o to EURO 4[13].

[12] Also LCV segments, where only other cycles than the CADC was measured and thus the CADC-emission value was only assessed by ratios (e.g. CADC/BAB, CADC/FTP,…) are marked white

[13] The measurements would e.g. suggest that EURO 1 had higher fuel consumption than EURO 0 and EURO 2, what is very unlikely.

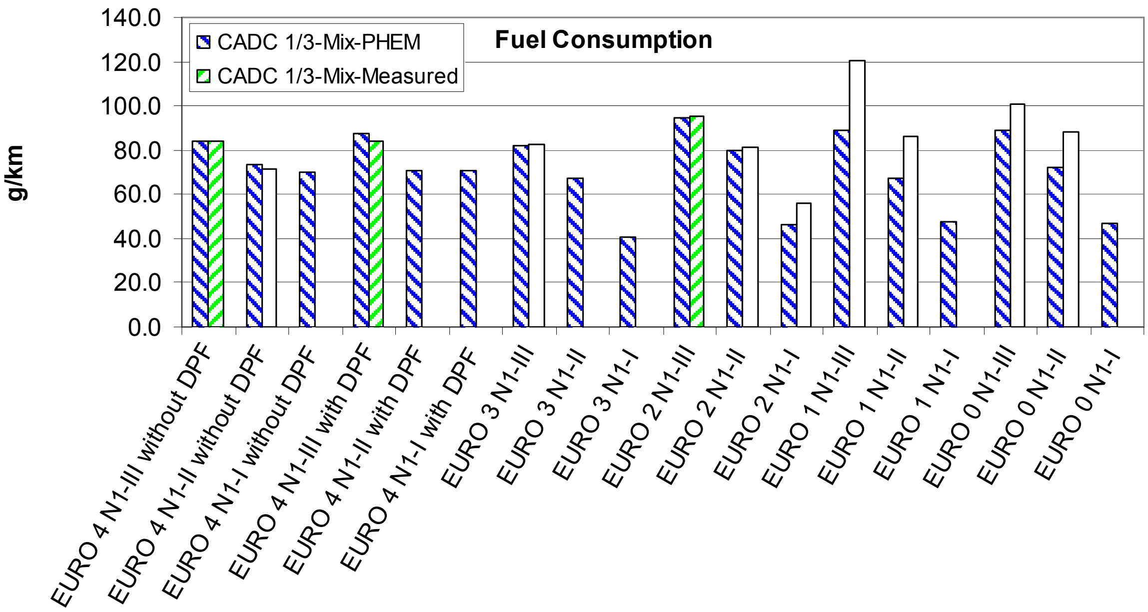



**Figure 23:** Comparison of simulation and measurement for the fuel consumption of diesel LCV in the CADC 1/3 Mix (white bars represent segments where less than 3 LCV were measured)

Figure 24 compares the results for EURO 4 diesel N1-III LCV for the single cycles since not only the average emission level is relevant for the HBEFA but also the accuracy for each traffic situation. Although the vehicle data applied in PHEM ("Fleet average") is not exactly the average from the 6 measured LCV the trends between measured and simulated emissions are very similar.

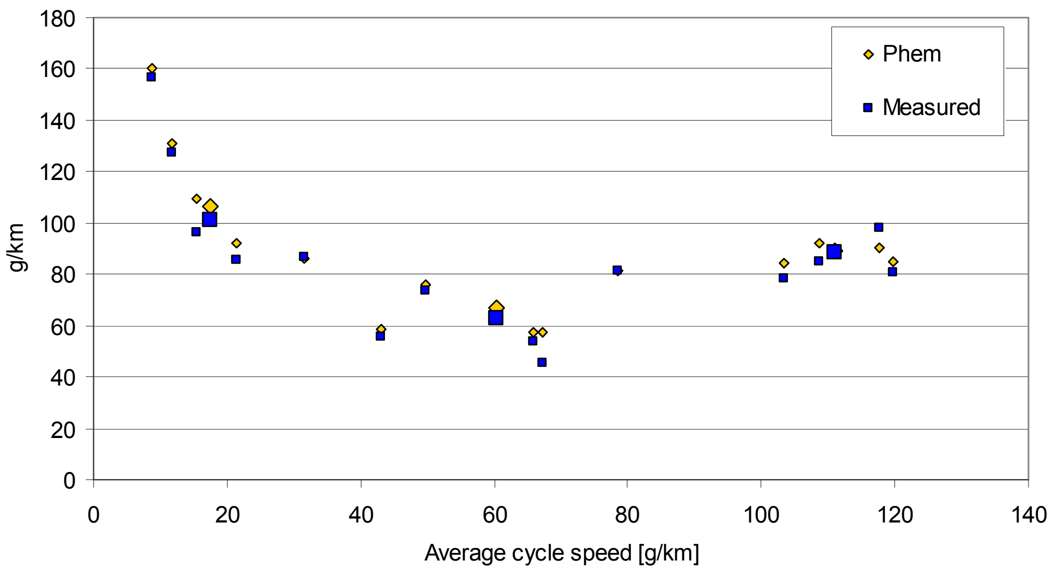



**Figure 24:** Comparison of simulation and measurement for the fuel consumption of EURO 4 diesel N1-III LCV (large dots are the 3 bag values of the CADC)

For pollutant emissions the uncertainties resulting from the small vehicle samples in the measurements are higher than for fuel consumption since the technology and application of the single vehicles influence the pollutant emissions much more than the fuel consumption (which is determined by the engine efficiency which does not show big spreads between makes and models). Figure 25 shows that after calibration the $NO_x$ levels are met very well for all LCV segments with a sufficient number of vehicles measured. The LCV segments where only a few vehicles are measured have not been calibrated to this test results but the basic engine emission maps[14] have just been calibrated with the same correction factors than the LCV categories around.

The resulting $NO_x$ emission values show reasonable trends over the EURO classes and over the size classes. The simulated $NO_x$ emissions from EURO 2 N1-I show an astonishing level since it is higher then for the larger N1-II and N1-III vehicles. However, for the N1-I category, which is quite similar to cars, the emission map from the average EURO 2 car was used unchanged. The calibration of the EURO 2 N1-III to the measured $NO_x$ values of the N1-III leads to a reduction of the $NO_x$ against the passenger car map by 20% to reach the measured LCV N1-III $NO_x$ levels. To adapt the engine emission maps for the small N1-I class to the calibration factor of the large N1-III class seemed to be not representative for the fleet average.

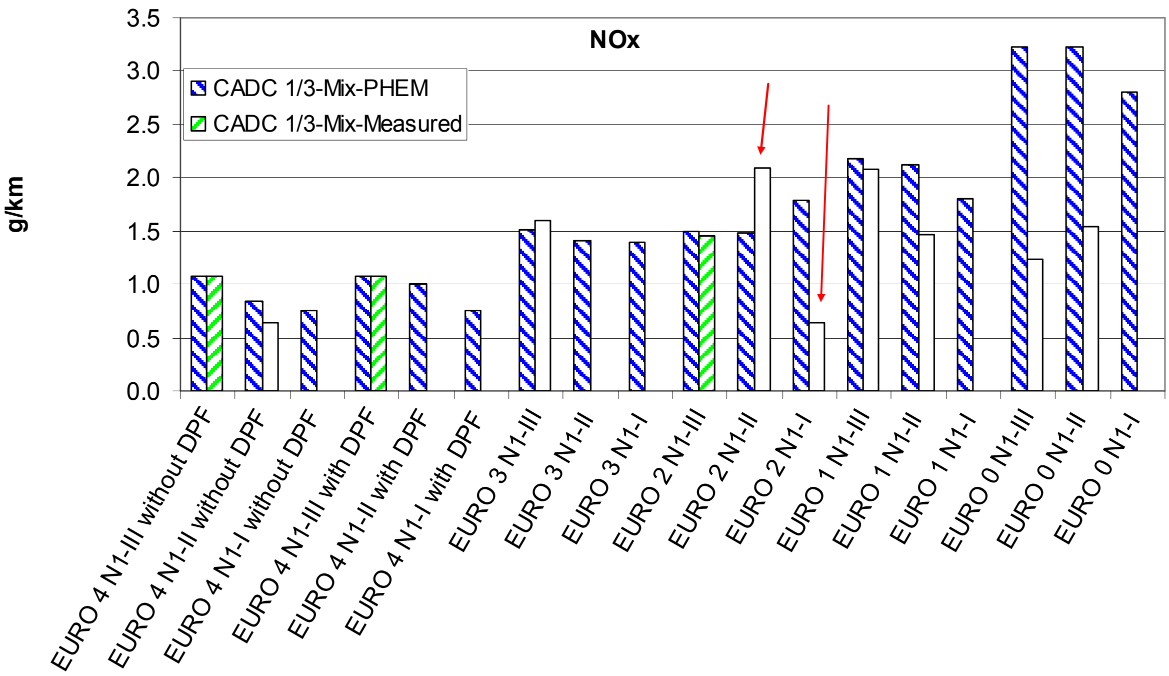



**Figure 25:** Comparison of simulation and measurement for $NO_x$ emissions of diesel LCV in the CADC 1/3 Mix (white bars represent segments where less than 3 LCV were measured)

Figure 26 shows the detailed results for EURO 4 N1-III for $NO_x$. As for the fuel consumption the single cycles are depictured with a reasonable quality (differences are partly related to different vehicle specifications).

[14] Which are the passenger car maps from the compareable engine technology which shall give more reliable values for the trends from EURO 0 to EURO 4 than the few LCV tested.

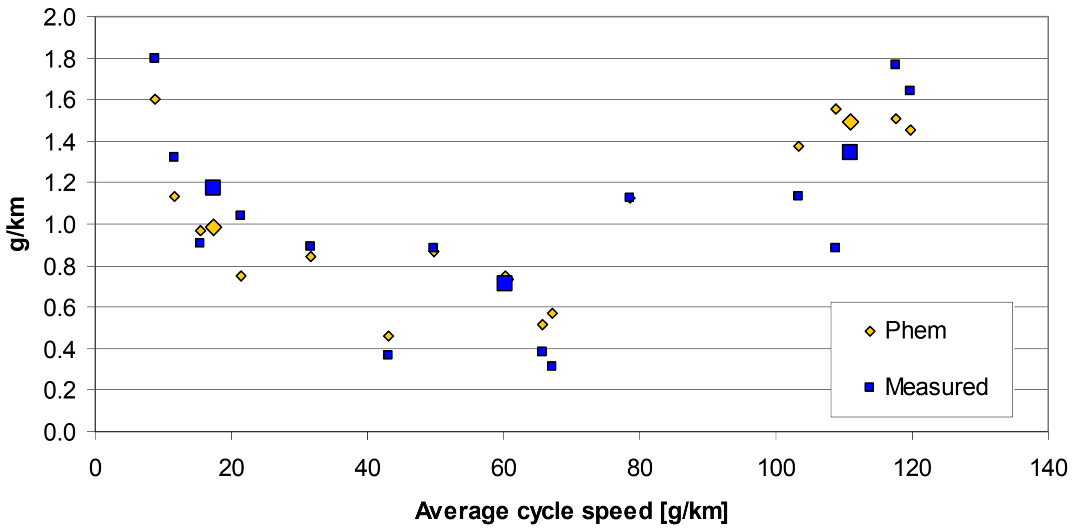



**Figure 26:** Comparison of simulation and measurement for the $NO_x$ emissions of EURO 4 diesel N1-III LCV (large dots are the 3 bag values of the CADC)

For PM, HC and CO similar qualities in the calibration were reached as for NOx. Figure 27 shows as example the comparison for PM. Also the ratios simulated with PHEM between the EURO classes and size classes show reasonable trends.

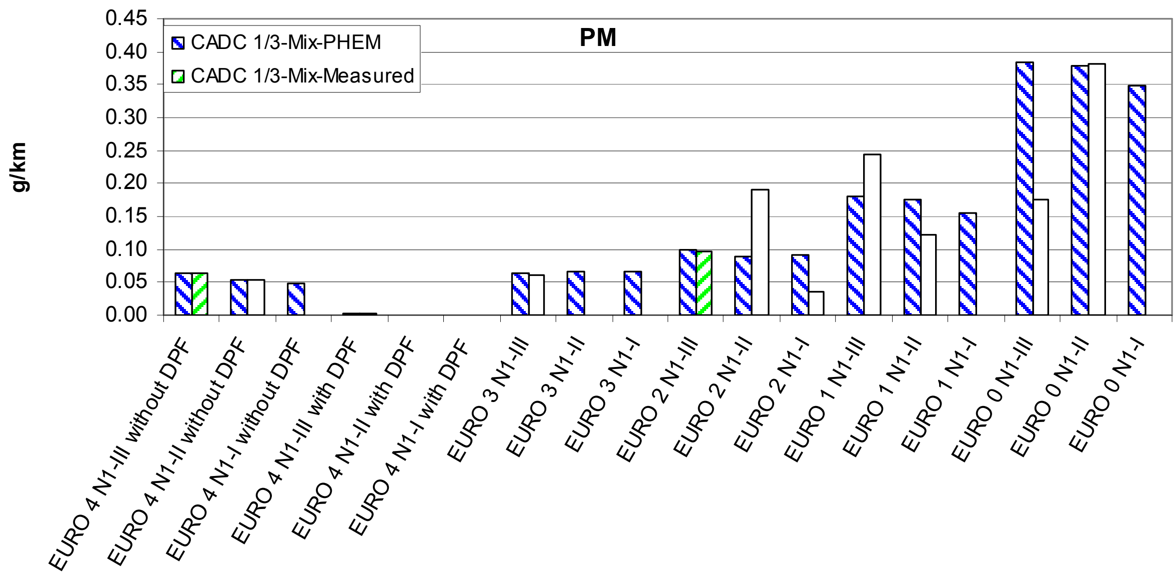



**Figure 27:** Comparison of simulation and measurement for PM emissions of diesel LCV in the CADC 1/3 Mix (white bars represent segments where less than 3 LCV were measured)

For the LCV with gasoline engines a reasonable number of measured LCV is available only for the EURO 1 and EURO 0 for the N1-II class. There 11 LCV have been measured in the HBEFA cycles, in FTP and in the BAB. The comparison of the simulation results with PHEM using the engine emission maps from the passenger cars proved to meet the measured values already quite well without different calibration for the size classes from N1_I to N1-III. Thus it was decided to use the corresponding engine emission maps from the passenger cars for all EURO classes and for all size classes without calibration to keep the consistency between old EURO classes and the LCV from EURO 2 on, where no measurements on gasoline LCV are available.

It may be concluded that the LCV diesel emission factors are now on a reasonable level. However, the uncertainties in LCV emission factors can not be assessed from the small numbers of LCV measured. It certainly is higher than for passenger cars.

It is thus recommended to include also measurements of LCV in the national LDV measurement campaigns (e.g. 5% to 10% of the tested vehicles being LCV) to establish a consistent data base at least from EURO 5 on.

## 5.3 Results

This section shows the results for HBEFA 3 LCV emission factors. The analysis performed focuses on a comparison of the emission levels of the different EURO classes and diesel versus gasoline. The results are shown for the same set of traffic situations with the same driving cycles as for passenger cars (chapter 4.3). If the driving cycles for passenger cars are representative for LCV also is not known yet.

The cycles selected cover four fundamental road types and four levels of service and give a quite good coverage of the whole range of vehicle speeds from highway to stop&go conditions. All results are given for flat road and for the example of the large LCV (N1-III). Since all emission factors are included in the HBEFA the user can perform further analysis on N1-I and N1-II vehicles as well as for different road gradients on demand. The following pictures shall just explain basic trends.

Figure 14 shows the distance specific engine work (unit: kWh per kilometres) for the selected set of cycles. Compared to the truck & trailer combination with 34-40t GVW shown in chapter 3.4 the passenger cars need approximately 1/5 of the specific energy, compared to the passenger cars the LCV has approximately the double energy demand per km. Since a main difference to passenger cars is the larger cross sectional area with higher $C_d$ values, the difference to passenger cars increases at high vehicle speeds. In the fast highway cycles the old LCV diesel do not reach the cycle-target speeds due to the rather low rated engine power. Only from EURO 4 on the LCV can follow the cycles from passenger cars. In slower cycles the higher vehicle mass of the N1-III LCV compared to passenger cars is the main reason for the higher energy demand. From these results we can conclude, that the drivability of the average LCV is like a passenger car with quite low power to mass ratio. Since PHEM reduces the actual vehicle speed automatically to the maximum possible speed at full load, the LCV are driven in the model at much higher relative engine loads than passenger cars and reach quite often full load. This may be a realistic picture of LCV driving but some measurements on LCV in parallel to passenger cars in future driving behaviour programs would be very helpful to improve the knowledge. Due to improvements in air resistance design and a more efficient drive train the energy demand drops from EURO 0 to EURO 6.

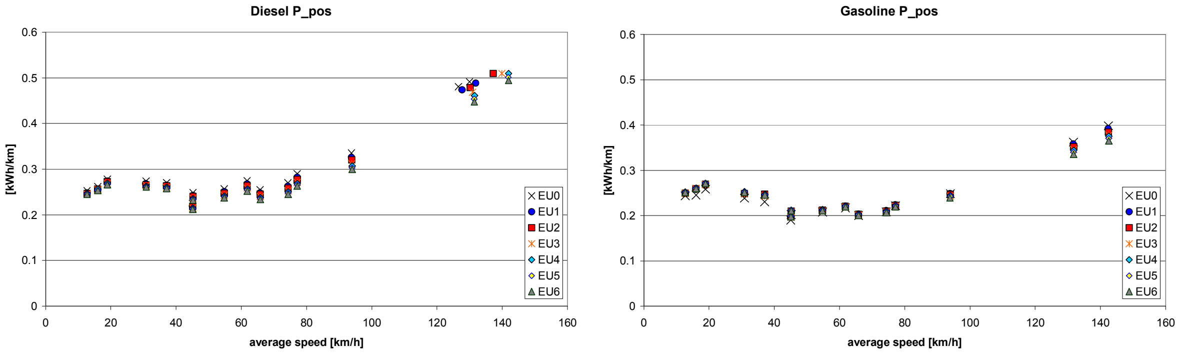



**Figure 28:** Distance specific engine work for a selected set of cycles for LCV N1-III (left picture = Diesel, right picture = gasoline)

The high shares of driving at high loads add uncertainties to the results for fuel consumption and emissions compared to passenger cars. Since the basic shape of the engine maps are taken from the instantaneous passenger car measurements which typically are not driven at full load in the chassis dynamometer test cycles, the emission maps include high shares of extrapolated points near the full load curve. In general each engine emission map was checked for consistency in these extrapolated areas. Thus the resulting emission factors should have a higher quality than the former values gained from regression analysis of the bag data from the inhomogeneous measurements. However, the user should have in mind the uncertainties at high engine loads (i.e. high vehicle speeds and also at high road gradients). These uncertainties can not even be estimated with the data available today.

As expected, the fuel consumption values from EURO 0 to EURO 6 show decreasing trends (Figure 29). For the diesel LCV a drop from EURO 2 to EURO 3 is obvious. Such a drop was also be found for passenger cars. The technological explanation should be the improvement of the engines fuel efficiencies due to the introduction of direct injection diesel engines at most makes and models around 2000. For EURO 6 a further decreasing trend is assumed, however, the actual proposal for $CO_2$-Limit of 175 g/km in the NEDC most likely won't be met with the reduction rates calculated here. Gasoline LCV in the HBEFA V3 have lower average masses and lower cross sectional areas than the diesel LCV. Nevertheless gasoline LCV have higher fuel consumption in slow cycles due to the worse fuel efficiency of SI engines at low engine loads compared to CI engines. At higher engine loads this disadvantage of the SI engine is smaller. Thus the fuel consumption value for the gasoline LCV is lower than for the diesel LCV at higher speeds due to the smaller vehicle and the resulting lower engine power demand.

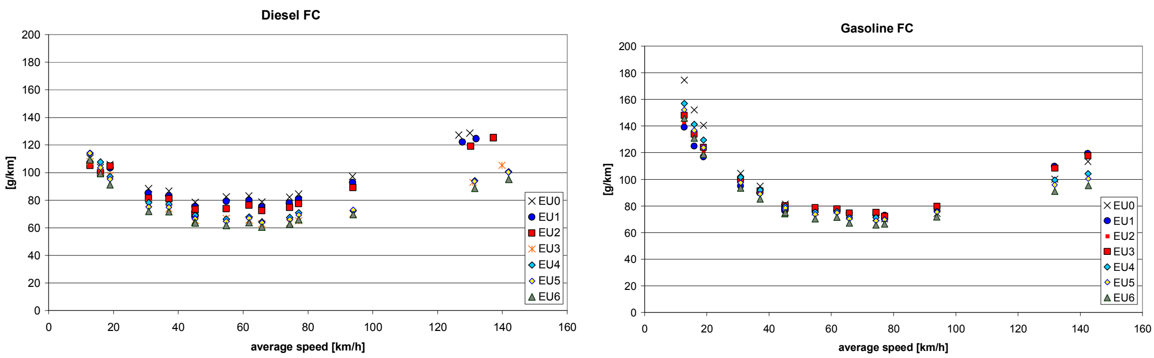



**Figure 29:** Specific fuel consumption for a selected set of cycles for LCV N1-III

Figure 30 shows the trend for the specific $NO_x$ emissions for diesel and gasoline cars. From EURO 3 on the gasoline LCV have much lower $NO_x$ levels than diesel. Main drops in the specific $NO_x$ emissions from the diesel cars can be seen from EURO 3 to EURO 4 and then from EURO 5 to EURO 6. However, the emission levels for EURO 6 LCV are just an assessment based on the engine technologies discussed already for passenger cars.

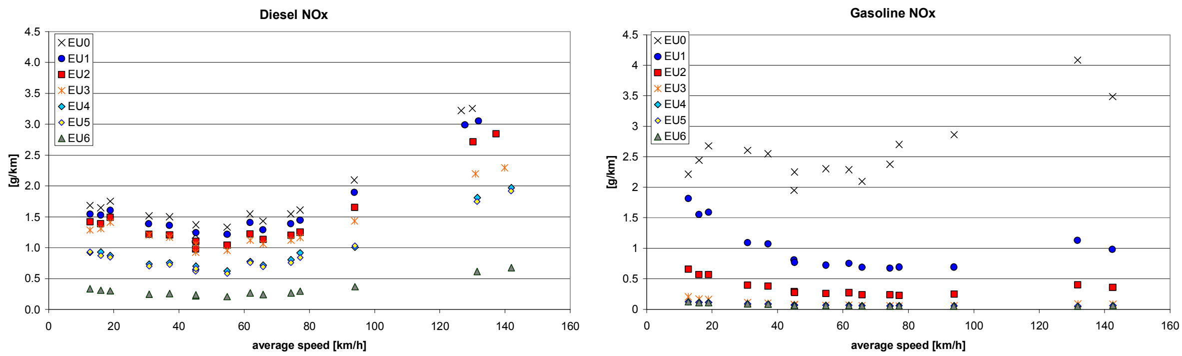



**Figure 30:** Specific NOx emissions for a selected set of cycles for LCV N1-III

Figure 31 shows the results for PM emissions. Here a clear reduction from EURO 0 to EURO 4 can be seen. The vehicles with DPF (part of EURO 4 and all from EURO 5 on) show lower PM levels than the gasoline vehicles. The continuous reduction of the PM emissions with each EURO class is more pronounced than for the passenger cars. However, this trend is based on the calibration of the model data by a few measured LCV only (chapter 5.2.2).

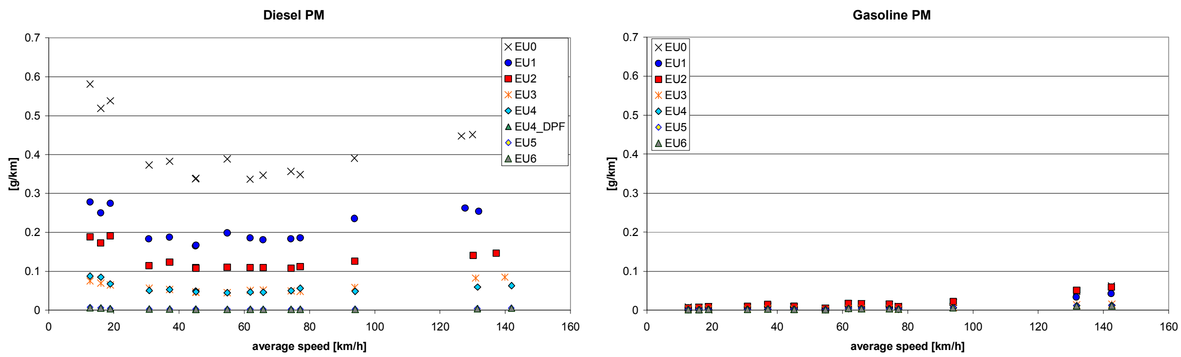



**Figure 31:** Specific PM emissions for a selected set of cycles for LCV N1-III

Figure 32 shows the HC emissions simulated for the LCV N1-III. The diesel vehicles generally have low HC emission levels. Gasoline cars reduced HC consequently from EURO 0 to EURO 4. A main drop happened with EURO 1 due to the introduction of the 3-way catalyst.

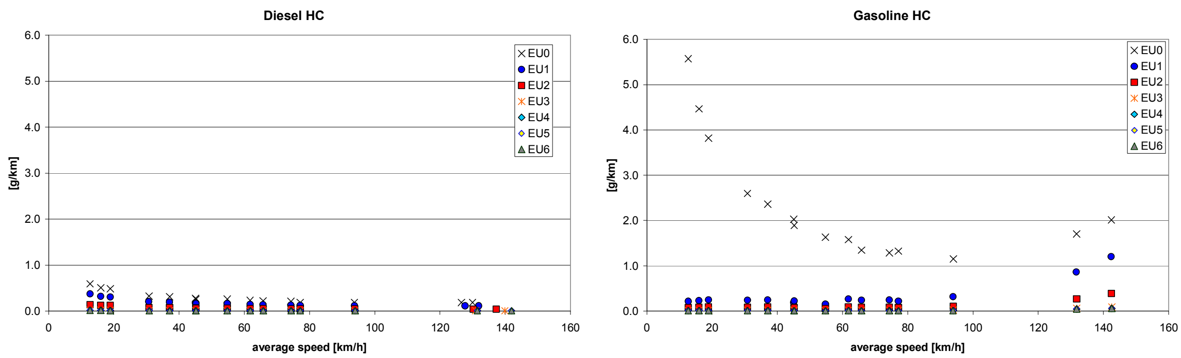



**Figure 32:** Specific HC emissions for a selected set of cycles for LCV N1-III

Figure 33 shows the CO emissions, which are low for diesel LCV and for modern gasoline LCV in urban and rural driving. For gasoline LCV the model results in increased CO emissions at high cycle speeds. As for passenger cars this can be attributed to a more rich A/F ratio which protects the catalyst from overheating at high relative engine loads. The available oxygen and $NO_x$ in the exhaust gas in such operation conditions converts then HC more efficiently than CO in the catalyst.

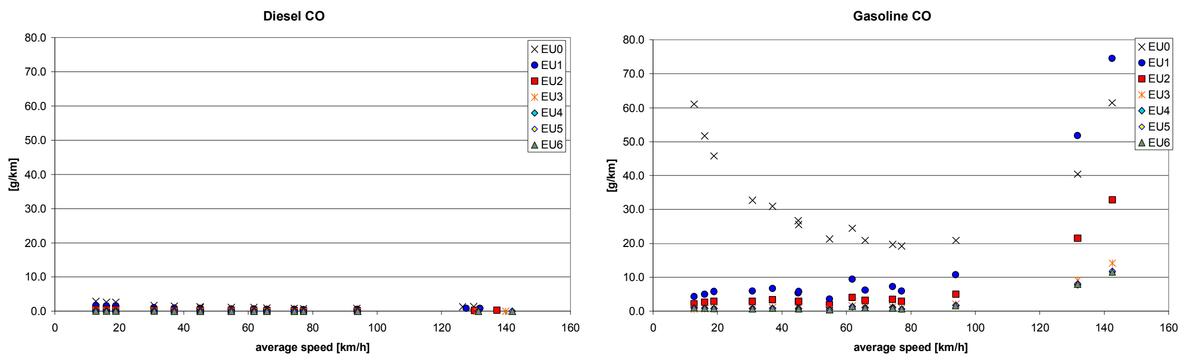



**Figure 33:** Specific CO emissions for a selected set of cycles for LCV N1-III

Figure 34 shows the results for LCV N1-III for PN emissions. Here the DPF reduces the emission level by two orders of magnitude, resulting in even lower PN emissions than gasoline LCV. For the diesel LCV without DPF the trend shows decreasing emissions from EURO 0 to EURO 4. This trend is based on result from measurement campaigns on passenger cars only (chapter 4.2) since no PN measurements are available for older LCV.

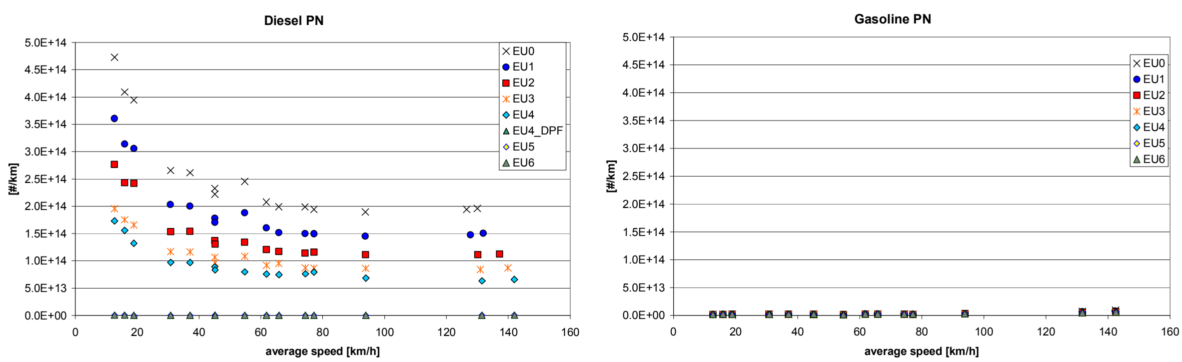



**Figure 34:** Specific PN emissions for a selected set of cycles for LCV N1-III

# 6 Uncertainties and model validation

This chapter gives a short discussion of potential sources of uncertainties, which have to be taken into consideration when the resulting emission factors are applied for an assessment of real world emissions. Following main sources of uncertainties are addressed:

**(A) Uncertainties related to the sample of tested vehicles/engines**

In this context the uncertainty is addressed which arises from the fact that not the entire fleet can be monitored in the in-use tests but only a small sample. The related uncertainty in the emission factors increases with a lower number of measured vehicles/engines and with a larger scattering of the observed emission behaviour in the available datasets. A statistical quantification of this range of uncertainty in the assessed emission behaviour for the different fleet segments is in detail given in the chapters 3 to 5 for the different vehicle categories.

**(B) Uncertainties related to the model**

The uncertainties, which are in a simplified way labelled as "model uncertainties", refer to imperfections of the applied emission model in the depiction of the emission behaviour of the different vehicle segments. This issue has been in detail investigated in the process of PHEM model validation. Most recent analysis can be found in [17] and [29]. In short, the according inaccuracies originate from:

1. Model simplifications compared to complex conditions in reality
2. Inaccuracies or errors in the measurement data which have been used for model parameterisation or for validation purposes.

**(C) Other Uncertainties**

For the influencing factors listed below a quantification of the according uncertainties is not feasible with the data available.

- Driving cycles including gear shift behaviour
- Cold start conditions
- Effects of malfunctions, deterioration and maintenance conditions
- Tampering (e.g. chip tuning or SCR vehicles operated without AdBlue)
- Loading conditions
- Operation of air condition and other auxiliaries
- Fuel influence (e.g. use of alternative fuels or low fuel quality)
- Vehicle specifications
- Fleet composition

In the following some uncertainties are quantified and details relevant to assess the actual quality of the emission factors are described.

## 6.1 Repeatability of the measurements

Exhaust gas components with low emission levels can have a rather worse repeatability in emission measurements. This mainly affects:

- CO, HC from all modern vehicles
- PM and PN from diesel cars with DPF and from gasoline cars
- $NO_x$ from gasoline vehicles.

The effect of the repeatability of measurement results can be high in a model validation based on single vehicles with a few measurements only. Figure 35 shows a typical result from the test series for diesel cars. Using the CADC number 1 for model parameterisation leads to an overestimation of CO emissions in most other cycles, since this CADC had two times the CO emissions than the CADC number 2 in all parts (urban, road, motorway). Figure 36 shows the results for the HC emissions of a Euro 4 gasoline car with exceptional bad reproducibility. It showed, that the differences of up to -99% (or >+ 200 00%) in the emission levels from single cycles can not at all be explained by differences in the course of engine load and engine speed and have to be attributed to some effects not covered by the model (e.g. changes in λ-control for OBD tests or some malfunctions).

Since only one or two tests per cycle and vehicle are available for the majority of the vehicles, the influences of the repeatability of the measurements is not tackled in a reasonable statistical way for single vehicles. In the standard procedure for LDV the engine maps were produced by the model PHEM from the CADC only (other available cycles were used for model validation and calibration). Especially for vehicles where only one measured CADC was available such a parameterisation can result in large deviations from the average emission behaviour of the vehicle. As a result in such cases large deviations to measured emissions occur when the validation cycles are simulated. The other way round it also can happen, that the CADC used for model parameterisation meets the average emission behaviour but some of the validation cycles recalculated are outliers. Certainly this effect also leads to rather high deviations between model results and measurements.

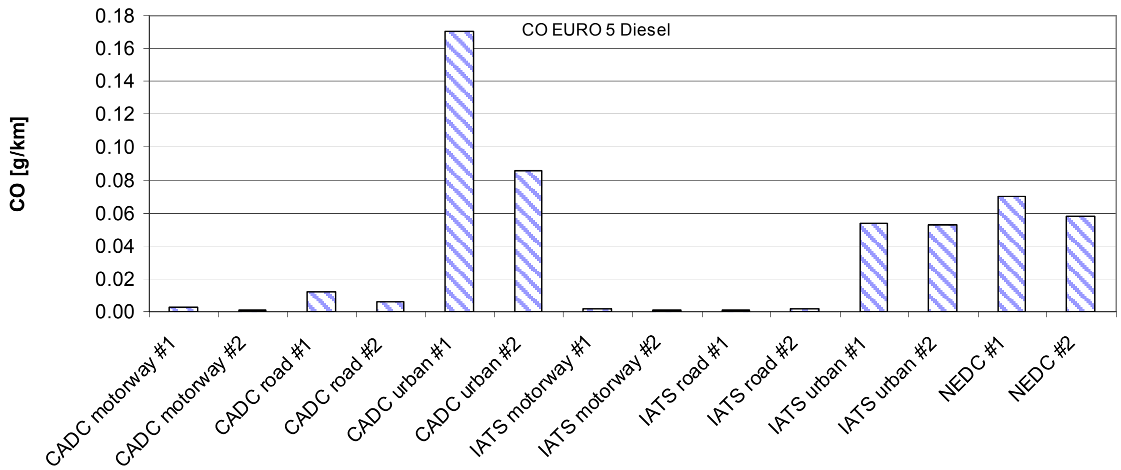



**Figure 35:** CO emissions measured on a Euro 5 diesel car in CADC, NEDC and IATS in two repetitions each

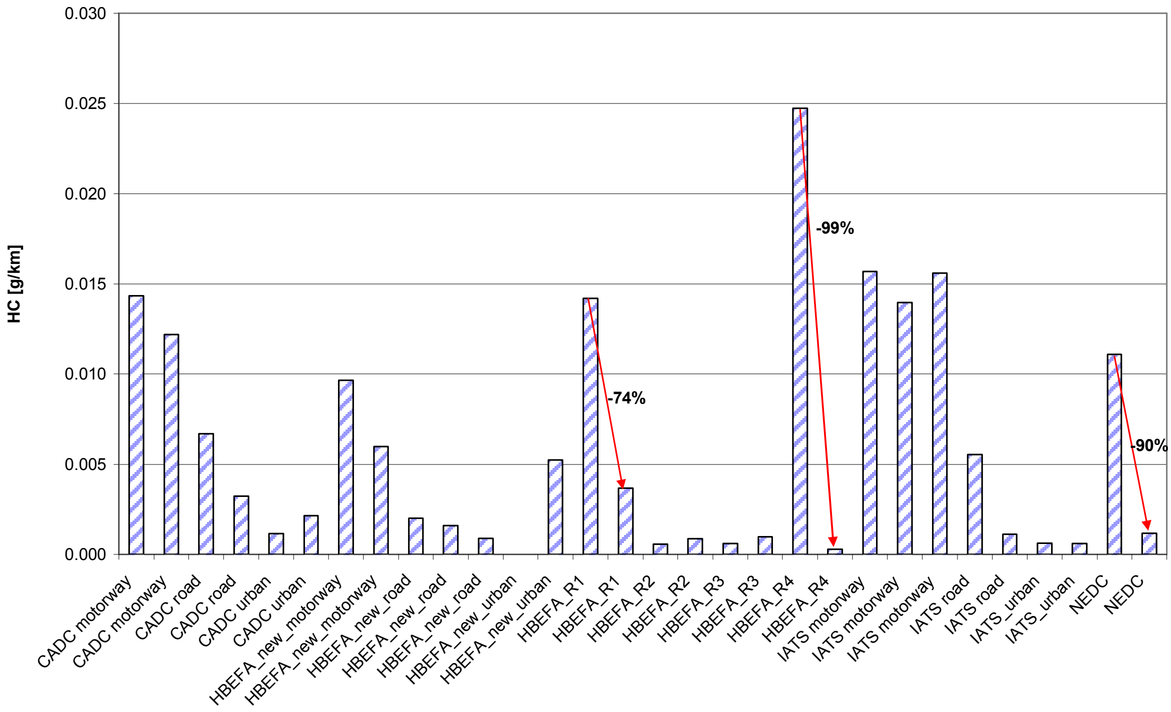



**Figure 36:** HC Emissions in hot running conditions measured on a Euro 4 gasoline car in CADC, NEDC, HBEFA new, HBEFA old and IATS in two or three repetitions each (some cycles with very high deviations are marked)

Certainly the different emission levels in test repetitions have physical backgrounds, but these can not be depictured by "rather simple" engine map based vehicle emission models (e.g. effects of a not continuous regeneration of the DPF, some OBD test sequences, etc.). Thus we either have to accept that the emission models do have high deviations from (some) single test results or we need to extend the models to depicture also non continuous effects.

Basically we assume that those effects leading to outliers in the measured emission level are mainly caused by the vehicle and not by the measurement equipment. Thus these effects also occur in real world driving with a certain probability and are relevant for the emission level of the vehicle fleet. Therefore the number of tests for filling the engine emission maps has to be high enough to ensure that the real world probability is reflected also in the engine emission maps used for the emission factors. For this demand not necessarily each vehicle has to be tested many times in the same cycle but also a sufficient number of vehicles tested one or two times per cycle is acceptable. In this case the uncertainties in the emissions simulated for the single vehicles are rather high but the entire fleet average emission factors shall have a (much) lower uncertainty. This effect is valid only, if all vehicles have similar physical effects leading to similar outliers in the emission levels.

The problem of how to detect "outliers" in the emission measurements and a method to include or exclude this data in a correct way evolved during the work on the HBEFA V3 and is not finally solved yet. We suggest adding this as a topic for the design of future measurement campaigns on EURO 5 and EURO 6 vehicles. For such low emitting technologies the "outliers" may become more important than for the older technologies.

However, also when looking on the following figures for model comparison and model validation the effects of possible outliers in the data has to be kept in mind.

## 6.2 Inter model comparison

The model PHEM was validated in several studies and with various vehicle samples, e.g. [10], [11], [17], [18], [28], [29], [31], [33]. In the validation runs the results from the model PHEM are compared to the data measured in the same driving cycles at the chassis dynamometer, at the engine test bed or on board of single vehicles or for vehicle samples. Typically the driving cycles used for model validation are not used for the parameterisation of the model. Actual results for the model accuracy in the emission factors for HBEFA V3 are described in the following.

Since the HBEFA V3 is based on a new set of traffic situations and corresponding driving cycles it was clear, that emission factors have to be transformed:

- Measurements -> Emission factors for new traffic situations
- Emission factors for old traffic situations -> Emission factors for new traffic situations

For this exercise an adequate model is necessary, otherwise the new traffic situations may improve the structure of the HBEFA but would reduce the accuracy.

To select proper models for the emission factors for the HBEFA 3 a model comparison was performed at the ERMES group. In this study the partners received measured data of 10 EURO 4 diesel vehicles and 20 EURO 4 gasoline vehicles from EMPA. The engine maps for the single vehicles were calculated from the CADC cycle only, since this is the standard application of PHEM[15].

From the single engine maps and the vehicle data the average vehicles were produced by simply averaging of all input files. With the average gasoline car and with the average diesel car the measured cycles were simulated. The measured emissions for three of all cycles were not delivered by EMPA to the modellers but where used for the final model comparison. The methods as well as the results for PHEM are described in [36].

Figure 37 shows as example the results for the fuel consumption of the "average" diesel vehicle. Main sources of uncertainties proved to be the fact, that some vehicles were equipped with five gears while others used 6 gears and some had automatic gear boxes. Averaging the transmission ratios would not lead to an integer value for the number of gears. However, depicting the average EURO 4 diesel car as 6 gear version proved to result in a sufficient accuracy for most exhaust gas components.

[15] Due to the set up of instantaneous engine maps by PHEM a few cycles are sufficient to fill the maps. Here the CADC proved to be the best cycle within the typical real world cycles from the past measurement programs. However, even the CADC leaves high engine loads open which are necessary especially to simulate uphill driving. Thus future tests should adapt the CADC to better fulfil the actual needs for model parameterisation. The accuracy in the model comparison most likely would have been higher, if also the HBEFA cycles were used for the set up of the engine maps, however, this data is not available for the majority of vehicles and thus the results would not be representative for the actual application in the HBEFA.

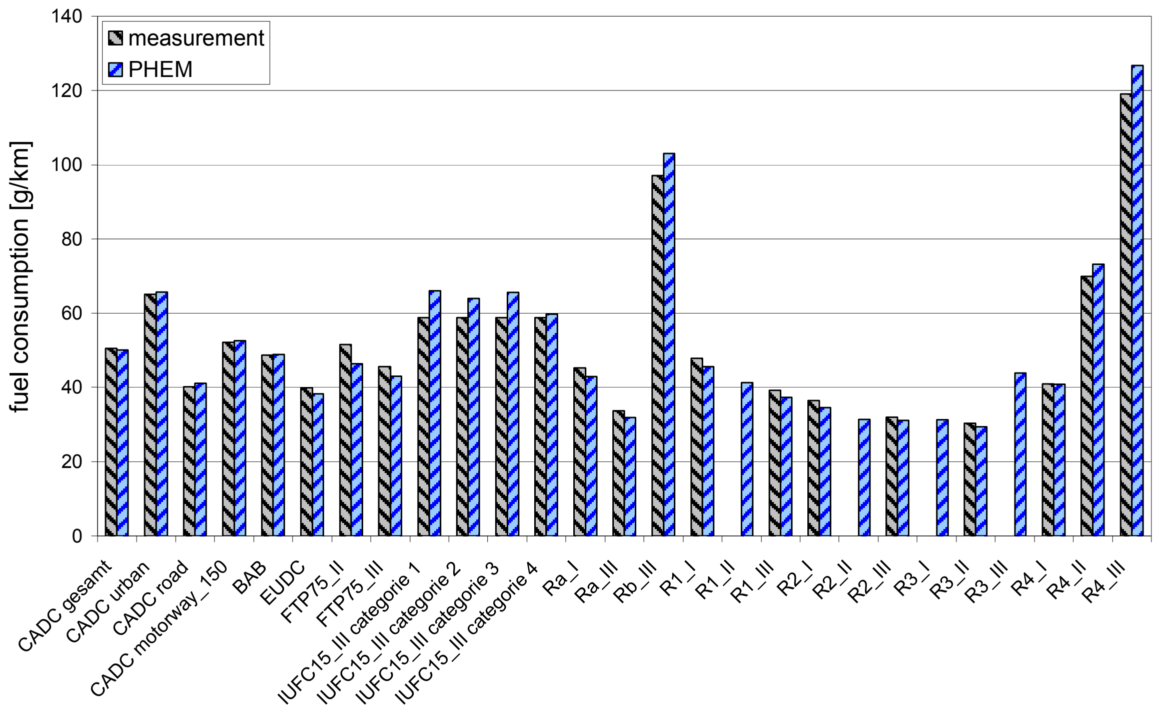



**Figure 37:** Fuel consumption for the average EURO 4 diesel vehicle in the validation according to **[36]**

While the results for fuel consumption, $NO_x$ and PM were found to be quite accurate, the accuracy for CO was rather poor, both from diesel and gasoline cars, e.g. Figure 38. After the inter model comparison some efforts were taken to improve the model quality for CO but still CO has the highest uncertainties within the simulated exhaust gas components.

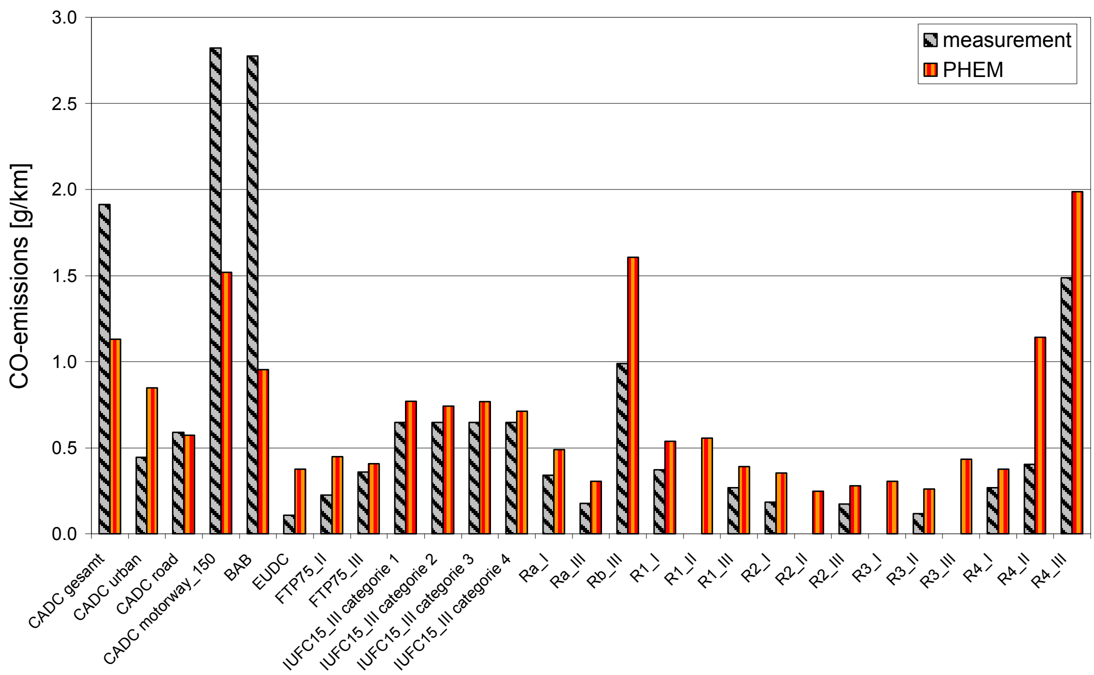



**Figure 38:** CO emissions for the average EURO 4 gasoline vehicle in the validation according to **[36]**

The result for CO, HC, NOx, PM and $CO_2$ were compared for the models available within the group. Based on the necessary data for model parameterisation and on the accuracies found in the study PHEM and the v/a*v map model from Infras and TÜV-Rheinland, [6], have been selected. Results of the inter model comparison will not be described to avoid misinterpretations for some of the models.

PHEM as well as the v/a*v map model were applied to calculate emission factors for passenger cars while for LCV and HDV only PHEM was used from the beginning on to save resources. The results for cars from both models were compared to detect potential uncertainties in the emission levels. This comparison showed that both models resulted in rather similar emission factors. Thus it was decided to apply PHEM for the emission factors of cars too. This leads to a consistent data set for all vehicles on one hand and also to consistent emissions at different road gradients since PHEM can simulate emissions at all road gradient levels while the v/a*v map model basically can simulate flat roads only.

## 6.3 Model validation for the new HBEFA V 3 cycles

Due to the new driving situations with different driving cycles and different gear shift rules for the new version of the HBEFA V3 a validation of the simulated emission factors for passenger cars and light commercial vehicles was necessary.

Main questions in this specific validation were:

- Can the emission factors in selected cycles of the new HBEFA V3 be simulated with any other measured cycles as model input data?
- Can influences of different gear shift rules in the CADC and in the new and in the old HBEFA cycles depictured by the model PHEM?
- Can emission maps from passenger cars be used to fill gaps in the simulation of LCV?

In total four EURO 4 passenger cars, two diesel and two gasoline, and two EURO 4 light commercial vehicles were measured on the chassis dynamometer for the validation. The test vehicles were measured in fourteen different driving cycles on the chassis dynamometer of the Institute of Internal Combustion Engines and Thermodynamics of the Graz University of Technology.

### 6.3.1 Test cycles

The emission factors of former projects were most often calculated for different cycles than the cycles measured on the chassis dynamometer since the test cycles did not represent exactly those traffic situations demanded by the users. For passenger cars many measurements in the old Handbook cycles R1 – R4, in the CADC and in the Modem-Hyzem cycles are available in the A 300 db. From these cycles the following have been selected for the validation tests:

- NEDC according to the homologation procedure
- HBEFA cycles R1, R2, R3 and R4
- CADC (urban, road and motorway)
- Nine new cycles from HBEFA V 3
- IATS (Integrated Austrian Traffic Situations)

For the CADC tests the corresponding gear shift strategy was chosen according to the ARTEMIS selection criterion. Each test cycle was repeated twice, if the deviation of the two repetitions was too high a third measurement of the cycle was performed.

On the chassis dynamometer the emissions of CO, $CO_2$, HC, $NO_x$ (split up in NO and $NO_2$), particulate mass, and particulate number, as well as the vehicle velocity and the braking force of the test bed was measured. The fuel consumption was calculated by the C-balance method.

#### 6.3.1.1 HBEFA R1, R2, R3 and R4

These cycles are part of the old HBEFA cycles which have been used regularly at EMPA for passenger car and light-commercial vehicle being tested within the framework of the national emission factor study. The cycles were gained from extensive driving behaviour studies and selected on-road recordings. The speed signals were smoothed with a running-mean smoother in order to obtain driving cycles suitable for test bench measurements. Gear changes are defined as for the NEDC.

The 12 most important (with respect to vehicle performance, i.e., annual mileage) driving patterns have been selected to be represented in the set of real-world testbench driving cycles directly. Each driving cycle consists of three driving patterns. The related speed time series (also called speed curves) are depicted in Figure 6-39.

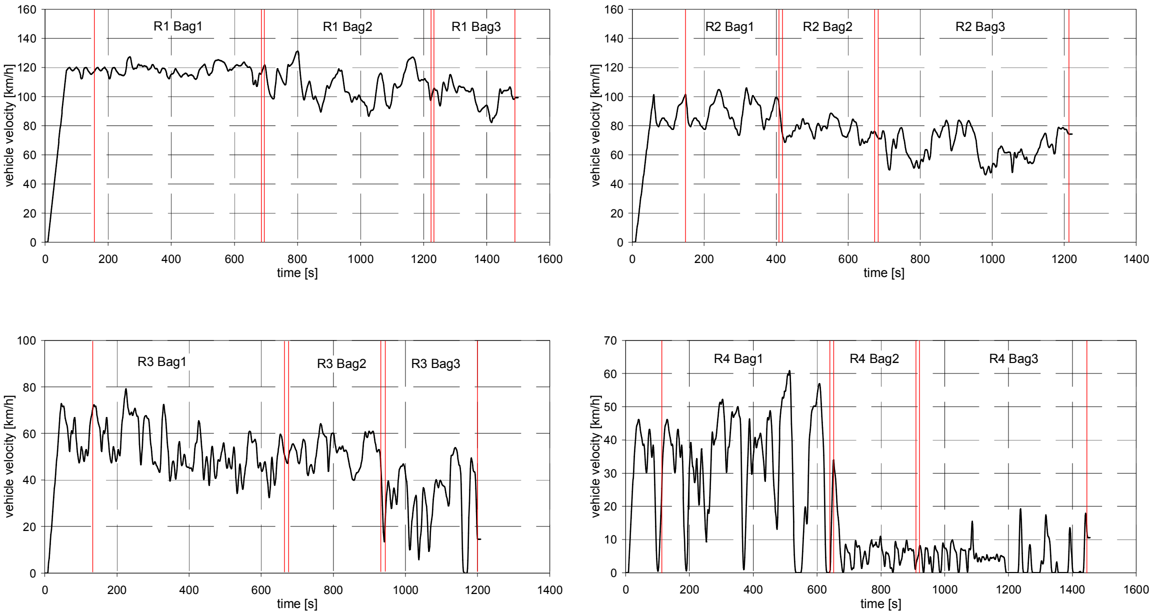



**Figure 6-39:** speed profile of the HBEFA cycles R1, R2, R3 and R4

#### 6.3.1.2 CADC

Within the framework of the European research program ARTEMIS, the Common ARTEMIS Driving Cycle (CADC) was developed [1]. The CADC is based on three large data sets of on-road recordings of driving behaviour: the multi-national Modem/Hyzem data, the Swiss data, and the German data. The final real-world CADC driving cycle consists of "kinematic segments" from the Modem/Hyzem data set. The CADC consists of three parts, urban, road and motorway. The three parts can be used independently, and therefore all parts start and end with zero speed. Each of the three parts is subdivided in different sub-cycles (Figure 40). The sub-cycles are designed to cover a broad range of real world driving behaviours and were obtained from a cluster analysis of the Modem/Hyzem data. The length of the sub-cycles does not necessarily represent the share of the driving situation in average real world traffic but is defined by minimum sub-cycle length to obtain meaningful results from the emission tests.

Gear shift manoeuvres are defined according to the power to weight ratio and the "maximum speed" in the 3rd gear of the vehicle in 4 different vehicle classes. The CADC highway part exists in two versions which are similar, except in their second phase. In this second phase, the standard cycle reaches 150 km/h while the alternative one remains below 130 km/h (for use at those test benches or at those vehicles not suitable for driving speeds above 130 km/h). In the validation the 130 km/h version was used.

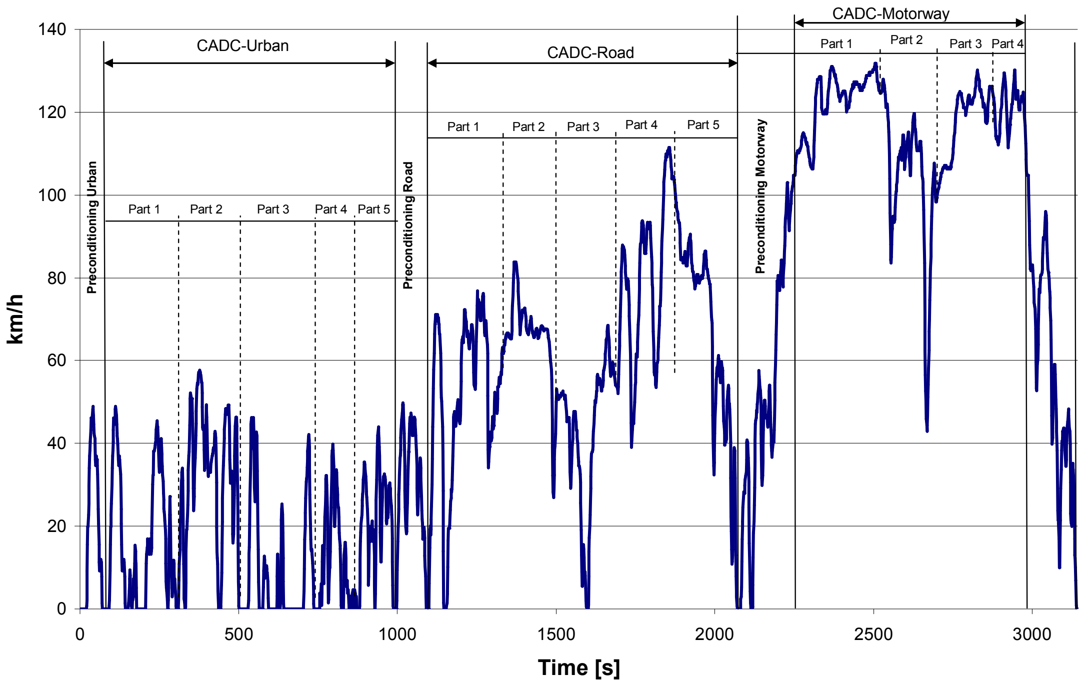
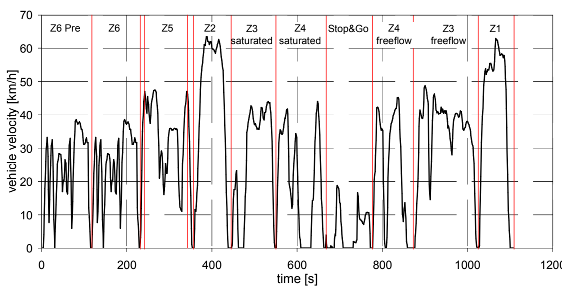


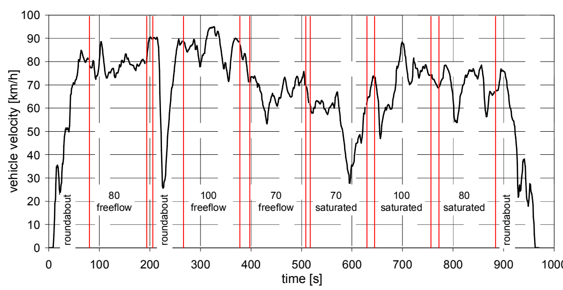

**Figure 40:** speed profile of the CADC

### 6.3.1.3 IATS cycles

The IATS-cycle (Integrated Austrian Traffic Situations) was gained from driving behaviour studies in Austria in the area of the city of Graz, [29]. There roads with defined traffic situations have been selected for the measurements and for each traffic situation a sub-cycle representative in terms of kinematic parameters and resulting emissions was selected. The sub-cycles of the IATS thus can be allocated to defined traffic situations and measured emissions can be used directly as emission factors.

Similar to the CADC for the IATS-cycle also 4 vehicle classes with different gear shift strategy were defined (further differentiated into 5 and 6 gear boxes). The selection of the gear shift strategy for a vehicle uses the same criteria as the CADC.



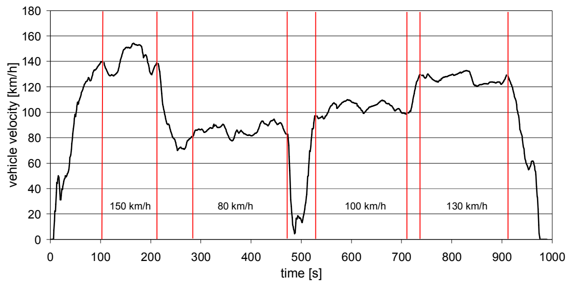



**Figure 41:** Speed profile of the IATS cycles

#### 6.3.1.4 New HBEFA test cycle

With the driving cycles available from the first draft set of new driving cycles for the HBEFA V3 in the year 2007 three new test cycles were created which are representing the urban, road and motorway driving situations. The gear shift strategy was calculated for every single vehicle with the PHEM model before the tests were performed on the chassis dynamometer. Figure 42 shows the three parts (urban, road and motorway) of the new HBEFA cycle. Each bag consists of three different traffic situations. Some of the sub-cycles were slightly adapted in the course of the development of HBEFA V3. Thus the “new HBEFA test cycle” would have to be adapted if used in future projects. After adaptation and adding some full load parts to cover the entire engine load map, the cycle may be used as basis to set up a common cycle for future test programmes which consequently uses the knowledge gained with the CADC cycle.

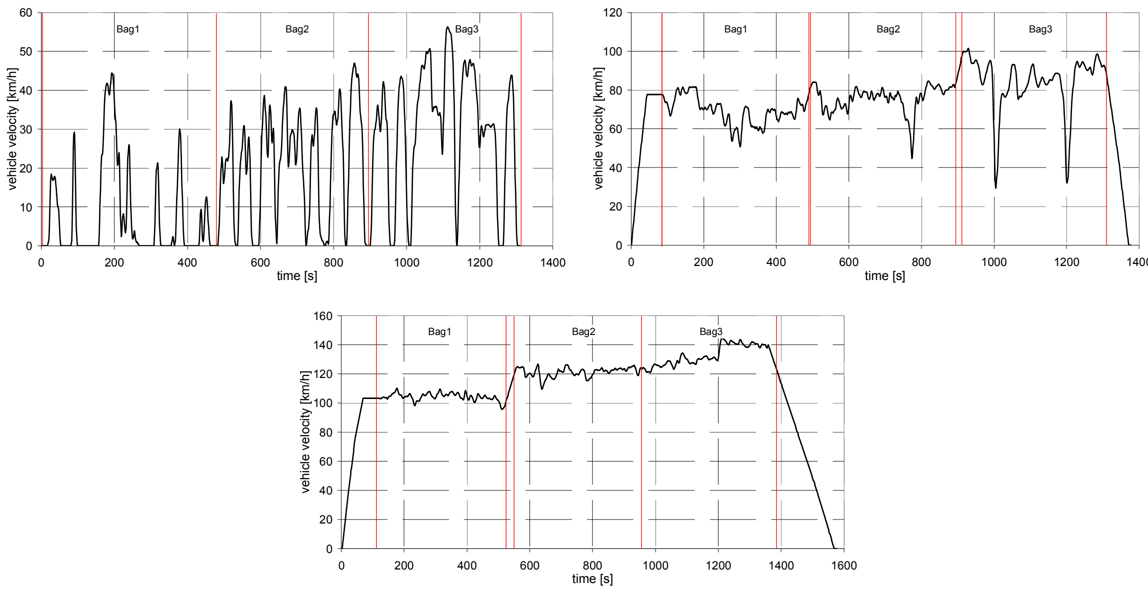



**Figure 42:** Speed profile of the new HBEFA cycles (urban, road, motorway with sub-cycles)

### 6.3.2 Test vehicles

For the tests four different passenger cars (two diesel and two gasoline) and two different light commercial vehicles were measured, see Table 13 and Table 14. All vehicles were measured in all cycles described before. The results were used as input for the A 300 db as well as for the validation of the PHEM application for the HBEFA cycles.

**Table 13:** Tested passenger cars

| vehicle | Opel Zafira 1.9 CDTI | VW Golf V GT 2.0 TDI | VW Golf V 1.4 FSI | Chevrolet Nubira 1.6 |
|---|---|---|---|---|
| engine | Diesel | Diesel | Otto | Otto |
| | turbocharging | turbocharging | fuel stratified injection | multi point injection |
| displacement [cm³] | 1910 | 1996 | 1390 | 1598 |
| rated power [kW] | 110 | 125 | 59 | 80 |
| gearbox | manual | manual | manual | manual |
| | 6 gear | 6 gear | 5 gear | 5 gear |
| exhaust aftertreatment | oxidation catalyst | oxidation catalyst | 3-way catalytst | 3-way catalytst |
| | diesel particulate filter | diesel particulate filter | | |
| year of manufacture | 2007 | 2006 | 2008 | 2008 |
| mileage [km] | 66600 | 111000 | 2441 | 300 |
| vehicle weight [kg] | 1628 | 1438 | 1153 | 1350 |
| EURO class | EURO 4 | EURO 4 | EURO 4 | EURO 4 |

**Table 14:** Tested light commercial vehicles

| vehicle | VW Crafter 2.5 TDI | VW Multivan T5 1.9 TDI |
|---|---|---|
| engine | diesel | diesel |
| | turbocharging | turbocharging |
| displacement [cm³] | 2459 | 1986 |
| rated power [kW] | 120 | 77 |
| gearbox | manual | manual |
| | 6 gear | 5 gear |
| exhaust aftertreatment | oxidation catalyst | oxidation catalyst |
| | diesel particulate filter | |
| year of manufacture | 2008 | 2006 |
| mileage [km] | 4972 | 108500 |
| vehicle weight [kg] | 2087 | 2180 |
| EURO class | EURO 4 | EURO 3 |

The driving resistance of three vehicles (VW Crafter, VW Multivan T5 and Opel Zafira) was determined with a coast down test according to the regulation 70/220/EWG and for the other three cars the values of the manufacturer were available. The results of the coast down test are assumed to be higher than the values of the manufacturer because the tires and the road pavement were not selected for low rolling resistance values.

### 6.3.3 Set up of engine emission maps

To check potential systematic errors when using different test cycles for model parameterisation, the engine emission maps of PHEM were set up one time with the CADC and one time with the IATS. Figure 43 and Figure 44 compare the occupancy of the engine maps when filled with different test cycles.

Due to the variable time, the exhaust gas needs from engine out to the analysers and the following delay time in the analyser's response, the emission signal and the vehicle speed have time shifts between approx. 2 and 20 seconds depending on the design of the test bed and on the analysers used. This time delay can be compensated to a large extent. However, to reduce the remaining risk of an inaccurate time allocation between measured emissions and the vehicle speed and the according engine power and engine speed the model PHEM takes in the standard set up three seconds running averages for all measured signals (after correction of the time shifts). This averaging process reduces the number of seconds with emissions measured at full load remarkable since most cycles show only short phases of full load driving, if at all. As a result the old HBEFA cycles, which are rather smooth, do not cover high loads very well. The situation for the NEDC is even worse. The old HBEFA cycles and the NEDC consequently have not been used for setting up the engine emission maps.

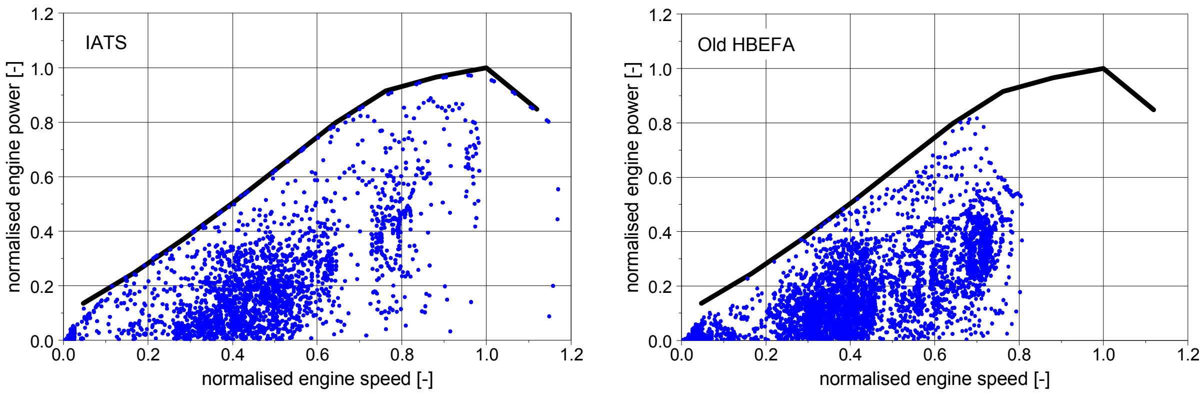



**Figure 43:** Typical occupancy of the engine maps from the IATS (left) and from all twelve old HBEFA cycles (each dot is one value in the map).

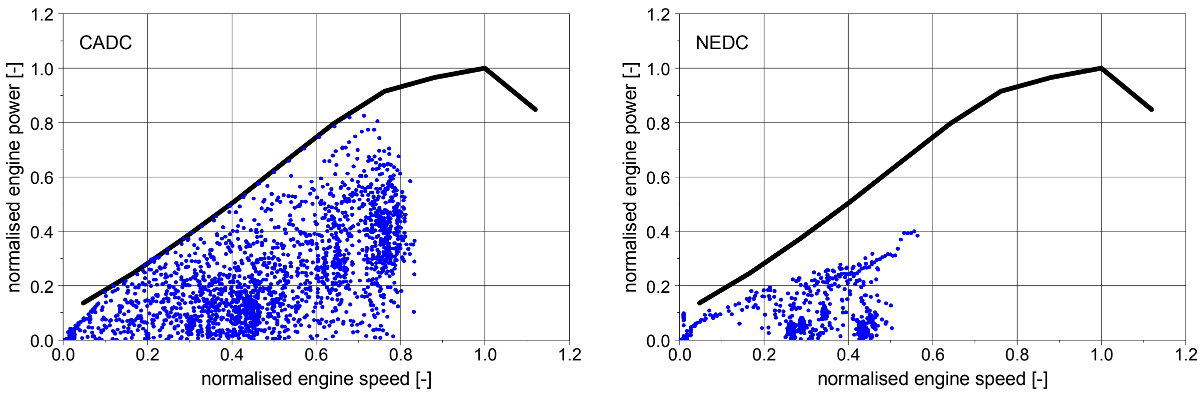



**Figure 44:** Typical occupancy of the engine maps from the CADC (left) and from the NEDC (each dot is one value in the map).

All measured cycles have then been simulated with PHEM using one time the engine maps from the CADC, the other time the engine maps from the IATS cycles. The results showed similar uncertainties for both versions of engine map origin tested. Figure 45 and Figure 46 compare the results for a Euro 5 diesel car.

For PM and CO the differences for some cycles are more likely to be a result of outliers in the measured emissions (see chapter 6.1) than to be an effect of systematic differences between the two versions of engine emission maps. Especially the high CO emissions of two cycles were not found in any other tests of this car. For a final statement much more repetitions per cycle would have been necessary in the measurement program.

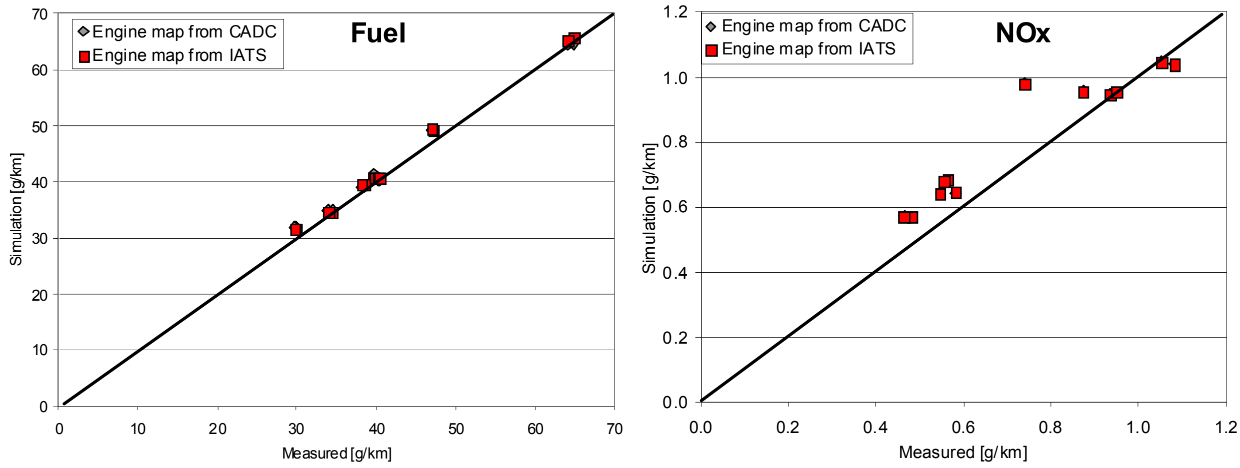



**Figure 45:** Fuel consumption and $NO_x$ emissions measured and simulated for a EURO 5 diesel car with DPF with two different origins of the engine emission map.

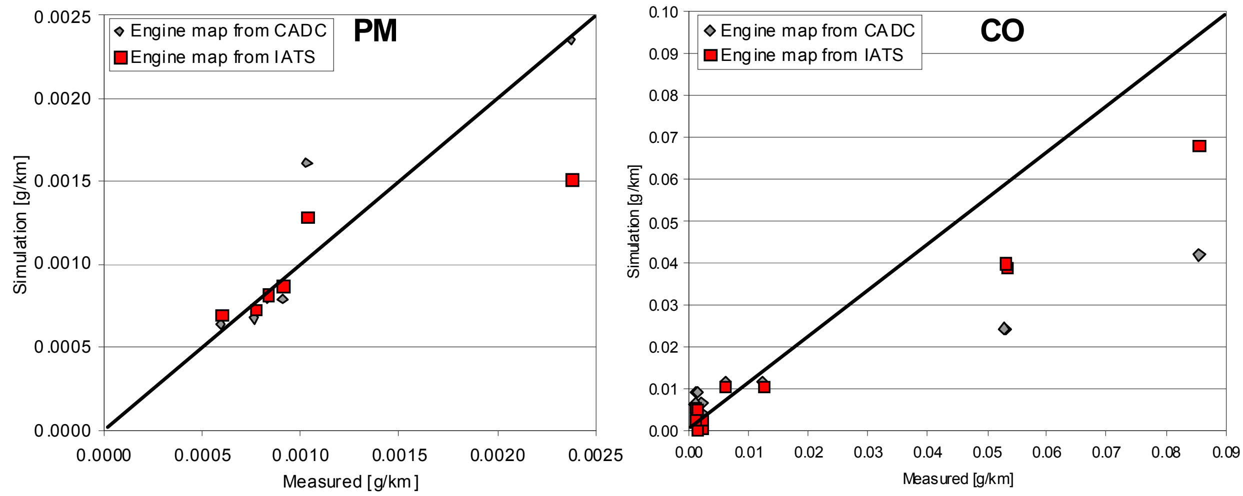



**Figure 46:** PM and CO emissions measured and simulated for a EURO 5 diesel car with DPF with two different origins of the engine emission map.

### 6.3.4 Simulation of different cycle groups

The CADC is the most common real world test cycle in the A300 data base and was used as standard cycle for the set up o the engine maps for PHEM. Thus it was also checked if engine maps gained from the CADC can depicture the emission levels from other test cycle groups without systematic errors. For this validation exercise the NEDC-hot, the old HBEFA, the new HBEFA, the IATS and the CADC itself have been simulated with the model PHEM using the engine maps gained from the CADC test. The following pictures show some examples.

Figure 47 shows $NO_x$ emissions measured and simulated for the VW Golf GT for the different cycle groups. The average deviation between measured and simulated $NO_x$ for the single cycle-groups is between -2% (CADC) and +5% (NEDC-hot). Thus we can conclude that the influences of different gear shift strategies and different cycle dynamics -which heavily influence the EGR rates and thus also $NO_x$-Emissions of modern diesel cars - is depictured well by the model PHEM for this vehicle. The influence of the gear shift rules and of the cycle dynamics can be seen in Figure 47 in the right picture, where the CADC cycles lead to much higher $NO_x$ values compared to the other cycle groups, both in the measurement and in the simulation.

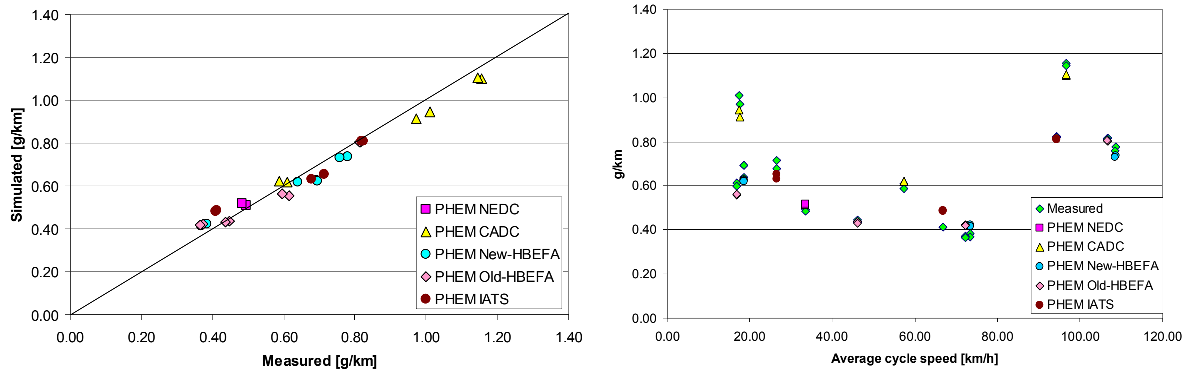



**Figure 47:** $NO_x$ emissions measured and simulated (PHEM with CADC as input data) for the VW Golf GT for the different cycle groups.

Figure 48 shows the fuel consumption as example for a good agreement between measurement and simulation on the left side and the PM emissions as example for a worse agreement.

PM and PN as well as HC and CO are very low for this car due to a good combustion and due to the DPF. Furthermore these exhaust gas components seemed to be quite sensitive for this car on the pre-conditioning of the vehicle. The CADC used here for the set up of the engine map obviously had no active regeneration process of the DPF while some other cycles indicated such a filter regeneration resulting in higher levels of CO, PM, PN and also HC. We can conclude from this picture that the PM and PN emissions from this vehicle can not be simulated in single cycles without applying a more sophisticated DPF model. Only the average emission level, which is very low compared to cars without DPF, can be simulated here. This is true for several vehicles with a DPF. If a more detailed simulation for cars with DPF shall be applied has to be decided for the next version of the HBEFA.

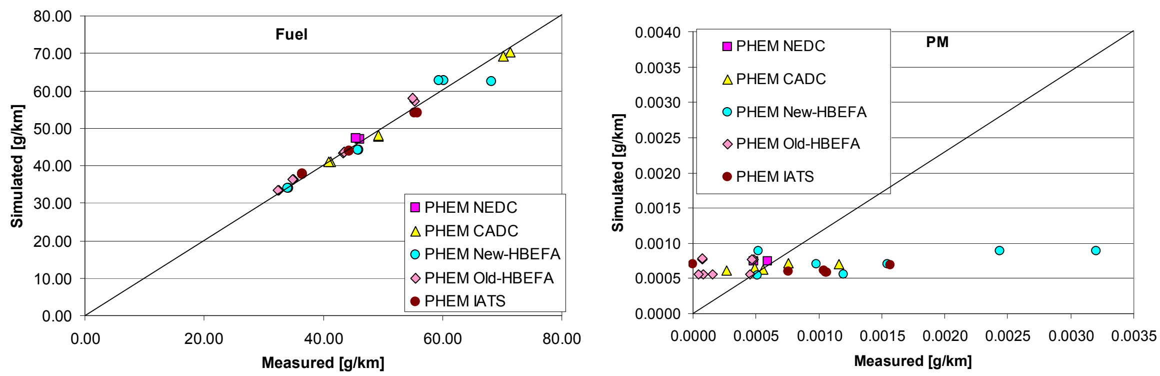



**Figure 48:** Fuel consumption (left) and PM emissions (right) measured and simulated (PHEM with CADC as input data) for the VW Golf GT with DPF for the different cycle groups.

As example for the results for the cars with SI engine Figure 49 shows the fuel consumption and HC emissions measured and simulated with PHEM using CADC as input data for the Chevrolet Nubria for the different cycle groups. Fuel consumption shows average deviations between -6% (NEDC) and +4% (old HBEFA cycles). Since the fuel consumption levels from

SI engines reacts quite sensitive on the gear shift manoeuvres we can conclude that this difference between the cycle groups is covered by PHEM quite well.

For HC deviations of up to several 1000% between the repetitions of the single cycles occurred for this vehicle. The repeatability of the HC emissions of this car is shown also in Figure 36 in chapter 6.1. The problem of such worse repeatability has been discussed there already.

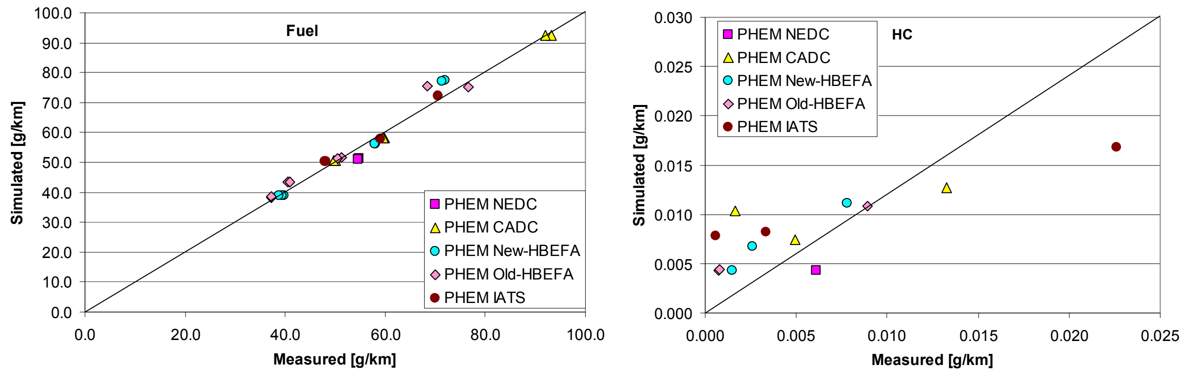



**Figure 49:** Fuel consumption (left) and HC emissions (right) measured and simulated (PHEM with CADC as input data) for the Chevrolet Nubria for the different cycle groups.

The two LCV measured and simulated for the validation showed similar model qualities than the diesel cars. Figure 50 and Figure 51 show results for the VW Multivan T5. The accuracy is limited for HC but the HC emissions of the vehicle are on a low level.

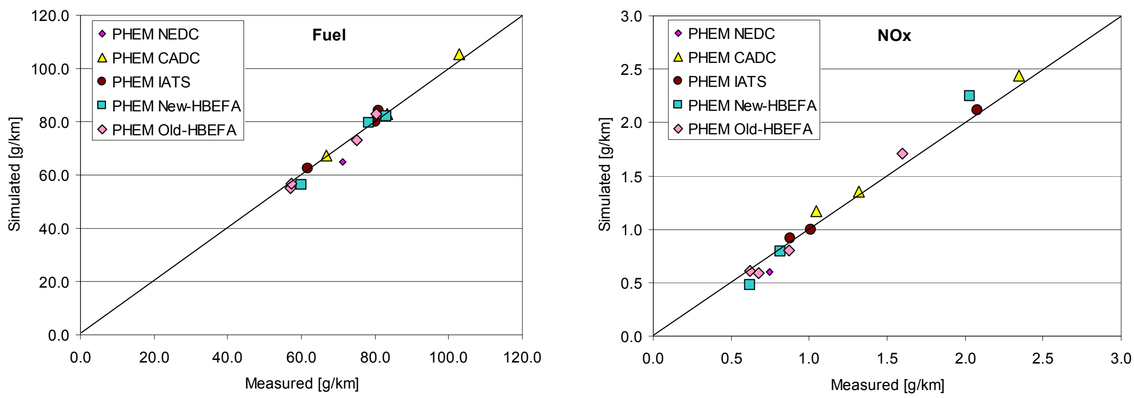



**Figure 50**: Fuel consumption and $NO_x$ emissions measured and simulated (PHEM with CADC as input data) for the VW Multivan T5 for the different cycle groups

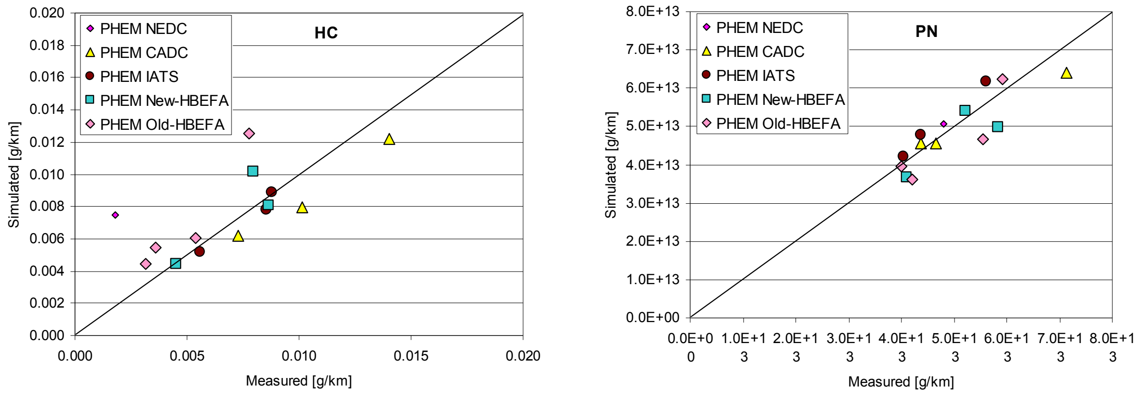



**Figure 51**: HC and PN emissions measured and simulated (PHEM with CADC as input data) for the VW Multivan T5 for the different cycle groups

Results for the VW Crafter are shown in Figure 52. The simulation of $NO_x$ emissions showed a rather bad quality for this specific vehicle with deviations between measurement and simulation up to 30%. The reasons are not known but may be seen in a quite sensitive EGR strategy which is not fully depictured by the transient correction functions of the model PHEM.

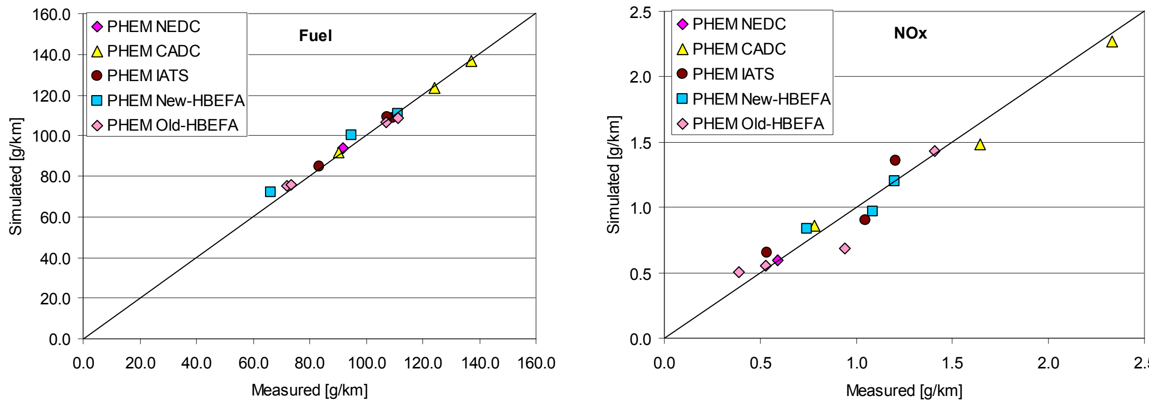



**Figure 52**: Fuel consumption and $NO_x$ emissions measured and simulated (PHEM with CADC as input data) for the VW Crafter for the different cycle groups

The uncertainties in the simulated emission factors are described in chapter 6.5, thus not all results for the single vehicles are shown here.

## 6.4 Quantification of uncertainties in HDV emission factors

The uncertainties arising from the limited sample size do influence the general level of the emission factors and may also influence the difference of the emission factors between the different traffic situations. The uncertainties from the sample have been calculated for a 5% probability of error from all measured vehicles.

The uncertainties from the model should have very low influence on the general level of the emission factors if no systematic errors are included but influence the difference of the emission factors between the different traffic situations. To calculate fleet average model uncertainties from the rather inhomogeneous test data for all measured vehicles and cycles the emissions have been calculated with PHEM for all measured vehicles in all test cycles. Then the calculated as well as the measured emissions have been aggregated for the vehicle segments. From the aggregated absolute values the relative deviation between simulation and measurements and consequently the uncertainties have been calculated again for a 5% probability of error.

Table 15 summarises the findings for the uncertainties from the sample and from the model. For the emission concepts Euro IV and Euro V HDV with SCR after treatment the uncertainties from the tested sample is +/-25 to 30% for $NO_x$ and +/- 17% for PM. Brake specific fuel consumption and the associated $CO_2$ emissions are quite well verified within a range of +/- 2%. The highest range of (relative) uncertainties arises for emissions of CO (+/-59%), however on basis of low absolute emission levels. For the emission concept Euro IV with EGR $NO_x$ control only one of three manufacturers has been tested, thus no uncertainty arising from the sample can be calculated since the sample may have systematic errors. Since a very extensive collection of in-use data was available for Euro III, the uncertainty from sample is significantly lower than for Euro IV ff.

The uncertainties from the model are approx. +/-10% for the $NO_x$ emissions from Euro IV EGR concepts while NOx emissions calculated for SCR vehicles show an uncertainty of about +/-20 to 25% due to the more complex SCR behaviour. Emission factors for PM and PN of Euro IV and Euro V vehicles can be assessed by the emission model within a range of uncertainty of about +/- 30 to 40%. For fuel consumption and $CO_2$ emissions the best model quality is achieved (+/- 4%). For emissions of HC and CO, the highest range of (relative) uncertainties is calculated with about +/- 40 to +/- 60%. These large ranges of uncertainties are to a great extend attributed to the low absolute HC and CO emission levels.

For the assessment of the range of uncertainties for local conditions the uncertainties from the tested sample and from the model have been combined by means of the error propagation law.

**Table 15:** Overview ranges of uncertainties from measured sample and from emission model

| emission concept | emission component | Range of uncertainty (1) | | | remarks |
|---|---|---|---|---|---|
| | | average emission level (2) | local conditions | | |
| | | | model uncertainty | Local total (3) | |
| **Euro III** | **$NO_x$** | 2.6% | 6.2% | **6.8%** | different model approach compared to Euro IV ff; numbers for range of uncertainties hence not fully comparable to Euro IV ff |
| | **CO** | 13% | 40% | **42%** | |
| | **HC** | 17% | 25% | **31%** | |
| | **PM** | 11% | 12% | **16%** | |
| | **FC** | 1.6% | 3.3% | **3.6%** | |
| | **PN** | n.q. | n.q. | **n.q.** | only very few data available |
| **Euro IV - EGR** | **$NO_x$** | n.q. | 11% | **n.q.** | only one of three manufacturers measured |
| | **CO** | | 62% | | |
| | **HC** | | 40% | | |
| | **PM** | | 31% | | |
| | **FC** | | 4% | | |
| | **PN** | | 29% | | |
| **Euro V - EGR** | **all emission components** | n.q. | n.q. | **n.q.** | no emission tests available - emission factors based on (optimistic) prognosis |
| **Euro IV - SCR** | **$NO_x$** | 26% | 24% | **36%** | --- |
| **Euro V - SCR** | **$NO_x$** | 30% | 22% | **37%** | --- |
| **Euro IV & V - SCR** | **CO** | 59% | 47% | **76%** | --- |
| | **HC** | 21% | 47% | **51%** | very low absolute emission levels |
| | **PM** | 17% | 42% | **45%** | --- |
| | **PN** | 41% | 32% | **52%** | --- |
| | **FC** | 2% | 4% | **4%** | --- |
| **Euro VI** | **all emission components** | n.q. | n.q. | **n.q.** | no emission tests available - emission factors based on (optimistic) prognosis |

(1).. All uncertainties given for 5% probability of error. Additional uncertainties from the HDV vehicle operation (driving cycles, gear shift behaviour, vehicle specifications and loading conditions) can not be quantified here.
(2).. Uncertainty from sample
(3)... Combined uncertainties from Sample & model

## 6.5 Quantification of uncertainties for LDV emission factors

The uncertainties of the sample for passenger cars have been calculated for the measurements out of the A 300 db for a 5% probability of error for three different traffic situations (based on the bag values for the CADC cycles urban, rural and motorway). Table 16 shows the uncertainties of the sample for the three traffic situations and the emissions for all vehicle categories and also the number of measured cars.

**Table 16:** Overview ranges of uncertainties from measured sample in the A 300 db

| | | | Uncertainties of the sample | | | | Number of measured vehicles | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Urban | Rural | Highway 150 [km/h] | Highway 130 [km/h] | Urban | Rural | Highway 150 [km/h] | Highway 130 [km/h] |
| CO2 | Diesel | EURO 0 | 24% | 27% | 31% | NA | 2 | 2 | 2 | 0 |
| | | EURO 1 | 17% | 16% | 16% | NA | 3 | 3 | 3 | 0 |
| | | EURO 2 | 7% | 7% | 12% | 8% | 28 | 28 | 21 | 3 |
| | | EURO 3 | 5% | 4% | 7% | 9% | 46 | 54 | 32 | 8 |
| | | EURO 4 | 6.1% | 4% | 5% | 16% | 73 | 80 | 61 | 13 |
| | Gasoline | EURO 0 | 27% | 21% | 21% | NA | 7 | 7 | 6 | 0 |
| | | EURO 1 | 12% | 10% | 6% | 34% | 7 | 8 | 5 | 3 |
| | | EURO 2 | 7% | 5% | 6% | 8% | 31 | 29 | 11 | 10 |
| | | EURO 3 | 4% | 3% | 3% | 7% | 77 | 84 | 35 | 24 |
| | | EURO 4 | 4% | 3% | 2% | 11% | 157 | 163 | 129 | 12 |
| CO | Diesel | EURO 0 | 10% | 3% | 35% | NA | 2 | 2 | 2 | 0 |
| | | EURO 1 | 62% | 37% | 68% | NA | 4 | 4 | 3 | 0 |
| | | EURO 2 | 38% | 51% | 77% | 44% | 28 | 28 | 21 | 3 |
| | | EURO 3 | 42% | 56% | 46% | 35% | 42 | 49 | 31 | 7 |
| | | EURO 4 | 41% | 35% | 30% | 55% | 66 | 65 | 52 | 13 |
| | Gasoline | EURO 0 | 112% | 113% | 68% | NA | 7 | 7 | 6 | 0 |
| | | EURO 1 | 104% | 90% | 46% | 65% | 7 | 8 | 5 | 3 |
| | | EURO 2 | 47% | 77% | 74% | 139% | 31 | 29 | 11 | 10 |
| | | EURO 3 | 39% | 26% | 37% | 72% | 77 | 84 | 35 | 23 |
| | | EURO 4 | 26% | 18% | 25% | 48% | 142 | 160 | 127 | 12 |
| HC | Diesel | EURO 0 | 20% | 33% | 23% | NA | 2 | 2 | 2 | 0 |
| | | EURO 1 | 37% | 44% | 42% | NA | 4 | 4 | 3 | 0 |
| | | EURO 2 | 32% | 35% | 45% | 75% | 28 | 28 | 21 | 3 |
| | | EURO 3 | 62% | 27% | 31% | 40% | 46 | 53 | 31 | 8 |
| | | EURO 4 | 27% | 21% | 31% | 49% | 65 | 70 | 44 | 13 |
| | Gasoline | EURO 0 | 105% | 96% | 32% | 0% | 7 | 7 | 6 | 0 |
| | | EURO 1 | 125% | 145% | 127% | 95% | 7 | 8 | 5 | 3 |
| | | EURO 2 | 33% | 30% | 55% | 45% | 30 | 28 | 11 | 10 |
| | | EURO 3 | 40% | 35% | 19% | 80% | 76 | 83 | 35 | 24 |
| | | EURO 4 | 30% | 17% | 30% | 36% | 125 | 128 | 116 | 12 |
| NOx | Diesel | EURO 0 | 48% | 31% | 14% | NA | 2 | 2 | 2 | 0 |
| | | EURO 1 | 14% | 4% | 11% | NA | 4 | 4 | 3 | 0 |
| | | EURO 2 | 10% | 11% | 13% | 28% | 28 | 28 | 21 | 3 |
| | | EURO 3 | 8% | 6% | 12% | 25% | 46 | 54 | 32 | 8 |
| | | EURO 4 | 9% | 8% | 9% | 18% | 73 | 80 | 61 | 13 |
| | Gasoline | EURO 0 | 38% | 40% | 34% | 0% | 7 | 7 | 6 | 0 |
| | | EURO 1 | 81% | 100% | 119% | 137% | 7 | 8 | 5 | 3 |
| | | EURO 2 | 55% | 61% | 62% | 79% | 31 | 29 | 11 | 10 |
| | | EURO 3 | 25% | 24% | 34% | 47% | 77 | 84 | 35 | 24 |
| | | EURO 4 | 25% | 21% | 83% | 87% | 150 | 160 | 126 | 12 |
| PM | Diesel | EURO 0 | 56% | 90% | NA | NA | 2 | 2 | 0 | 0 |
| | | EURO 1 | 7% | 55% | NA | NA | 2 | 2 | 0 | 0 |
| | | EURO 2 | 40% | 46% | 33% | 39% | 23 | 24 | 17 | 3 |
| | | EURO 3 | 18% | 18% | 42% | 34% | 43 | 49 | 28 | 6 |
| | | EURO 4 | 34% | 32% | 34% | 89% | 55 | 62 | 53 | 2 |
| | Gasoline | EURO 0 | NA | NA | NA | NA | 0 | 0 | 0 | 0 |
| | | EURO 1 | NA | NA | NA | NA | 0 | 0 | 0 | 0 |
| | | EURO 2 | 83% | 123% | NA | 148% | 4 | 4 | 0 | 3 |
| | | EURO 3 | 54% | 36% | 107% | 84% | 11 | 11 | 2 | 6 |
| | | EURO 4 | 26% | 26% | 19% | 47% | 110 | 109 | 106 | 4 |

The model uncertainties were calculated based on a dataset of 19 gasoline vehicles and 7 diesel vehicles measured at EMPA. Average PHEM input data sets were established for the EURO 4 gasoline sample and for the EURO 4 diesel sample by averaging the engine maps and the vehicle data from the single vehicles of each category.

The model uncertainties were calculated from the deviation between the simulated HBEFA cycles and the bag data from the EMPA measurements for the average of the diesel and gasoline sample. Since the CADC was used for the set up of the engine emission maps the results should give a good estimation of the uncertainties from the model for the simulation of different driving cycles. The uncertainties of the emission measurement (see chapter 6.1) are included in the model uncertainties since no calibration of the measured CADC data was made. Table 17 and Table 18 show the result of the model uncertainties of the average EURO 4 gasoline and diesel vehicle.

**Table 17:** Uncertainties from the emission model for EURO 4 gasoline vehicles (for the EMPA vehicle sub-sample)

| **SI** | **FC** | **$NO_x$** | **HC** | **CO** |
|---|---|---|---|---|
| | Model uncertainty [%] (1) | | | |
| Urban | 6.1% | 51% | 101% | 232% |
| Road | 4.7% | N/A | 70% | 64% |
| Motorway | 3.4% | 29% | 28% | 38% |

(1) simulated values differ from the measured values within the given range with a 5% probability of error

**Table 18:** Uncertainties from the emission model for EURO 4 diesel vehicles (for the EMPA vehicle sub-sample)

| **CI** | **FC** | **$NO_x$** | **HC** | **CO** | **PM** |
|---|---|---|---|---|---|
| | Model uncertainty [%] (1) | | | | |
| Urban | 0.9% | 13% | 16% | 202% | 23% |
| Road | 1.9% | 17% | 33% | 449% | 9% |
| Motorway | 1.9% | 10% | 17% | N/A | 9% |

(1) simulated values differ from the measured values within the given range with a 5% probability of error

The reason for the high uncertainties for the CO-emissions of EURO 4 diesel vehicles is that there are some quite high CO-peaks (factor 1000 higher then the normal level) in many CADC urban measurements. These measurements were used for the engine map creation and therefore the level of the engine map is too high.

For the assessment of the range of uncertainties for the absolute emission level at local conditions the uncertainties from the tested sample and from the model have been combined by means of the error propagation law for the EURO 4 vehicles. Table 19 and Table 20 show the result of the uncertainties for the local conditions for the EURO 4 gasoline as well as the EURO 4 diesel vehicle.

**Table 19:** Uncertainties of vehicle sample and model for EURO 4 gasoline vehicles (for the EMPA vehicle sub-sample)

| SI | FC | NOx | HC | CO |
|---|---|---|---|---|
| | Total uncertainty [%] (1) | | | |
| Urban | 7.1% | 57% | 105% | 234% |
| Road | 5.4% | N/A | 72% | 66% |
| Motorway | 4.0% | 88% | 41% | 45% |

(1) simulated values differ from the real values within the given range with a 5% probability of error

**Table 20:** Uncertainties of vehicle sample and model for EURO 4 diesel vehicles (for the EMPA vehicle sub-sample)

| CI | FC | NOx | HC | CO | PM |
|---|---|---|---|---|---|
| | Total uncertainty [%] (1) | | | | |
| Urban | 6.1% | 16% | 31% | 206% | 41% |
| Road | 4.8% | 19% | 40% | 450% | 33% |
| Motorway | 4.9% | 14% | 36% | N/A | 35% |

(1) simulated values differ from the real values within the given range with a 5% probability of error

The overall uncertainty for the emission factors in the HBEFA V3 should be lower due to following differences:

1) The vehicle sample is larger, thus the uncertainty of the limited sample is lower but also the uncertainty due to the repeatability of the measurements – which is included in the model uncertainties – should be lower due to a higher number of total repetitions
2) The engine emission maps were calibrated with a very large number of bag measurements

The improvements due to these effects can not be quantified. However, it can be concluded that the fuel consumption and thus also $CO_2$ emissions can be simulated quite accurately, $NO_x$ and PM from diesel cars reach also good model accuracy, while CO can not be predicted with a reasonable accuracy for different driving cycles. For CO the model uncertainty is rather higher than the typical difference between cycles. CO emissions show also a low repeatability in the measurements and a high scattering between vehicles. Fortunately CO is not a critical exhaust gas component for modern vehicles.

For the vehicle segments with high emission levels according to the former emission standards the accuracy is assumed to be better than for the modern cars since electronic control systems do not influence the combustion and no exhaust gas after treatment systems are applied. Thus the overall uncertainties for the entire fleet of vehicle cars will be rather lower than shown for the EURO 4 vehicles before.

For LCV the available data does not allow a reasonable assessment of the uncertainties due to the very limited number of tested vehicles. The model uncertainties per vehicle are found to be quite similar than for passenger cars (chapter 6.3). But the fact, that the emissions of the LCV fleet had to be calculated with engine emission maps from passenger cars calibrated for the LCV emission levels certainly adds uncertainty in the absolute emission levels as ell as in the calculated differences between the traffic situations.

# 7 Summary

The basic emission factors for all vehicle segments in the HBEFA V3 have been calculated with the model PHEM for all combinations of traffic situations, vehicle loadings and road gradients. PHEM calculates the actual engine power demand based on the vehicle longitudinal dynamics and the actual engine speed based on a drivers gear shift model and the transmission ratios in 1Hz resolution for any cycle/vehicle combination. The fuel consumption and emissions are then interpolated from engine maps. Influences of transient load changes are corrected by so called transient correction functions and the effects of the thermal behaviour of the exhaust gas after treatment systems are simulated based on the calculation of heat transfer and heat balances.

For HDV this work was a continuation of the HBEFA V2 and the ARTEMIS model. For passenger cars and also for light commercial vehicles the application of the model PHEM was a novelty in the actual HBEFA. Main advantages of the application of PHEM for all vehicle categories are the consistency of the resulting emission factors, the possibility to calculate emission factors for different road gradients, different vehicle loadings and – if necessary - also different gear shift behaviours of drivers in a physical adequate and thus consistent way. The model PHEM has been extended for this task and can now set up engine emission maps from all sources of measurements (engine tests, roller test bed, PEMS) as long as high quality instantaneous test results are available. This allowed establishing a consistent data base from the very inhomogeneous set of test cycles and driving conditions. In the analysis of the instantaneous data the measurements on the engine test bed gave the most accurate results, directly followed by tests on the chassis dynamometer. The accuracy of engine maps gained from on board measurements with PEMS equipment mainly suffered from the difficulty to obtain accurate engine power signals. Since testing a modern engine on the engine test bed needs much more effort than PEMS tests or chassis dynamometer tests, only one modern engine was available from engine test bed measurements.

The engine maps and vehicle data for the single vehicles were aggregated to average data sets for the vehicle segments. For passenger cars and for light commercial vehicles the model input data was finally calibrated with all available bag data in the A 300 db. For HDV this step was not necessary since all relevant measurements were available as instantaneous data and are thus included in the model already.

From the work for the HBEFA V3 the engine maps and the vehicle data for the average vehicle segments up to EURO 6 are now available.

The emission factors for HDV are based in total on 117 measured HD vehicles and HD engines. 102 of the engines fulfilled emission limits up to EURO III while only a small sample of 15 was certified according to EURO IV or EURO V. For EURO IV engines with EGR systems measurements for only one of total three manufacturers were available. For EURO V engines with EGR no vehicle was measured yet. As a result from the rather small sample of tested vehicles the uncertainty of the emission factors for EURO IV and EURO V is rather high. It is recommended to add some tests to the data base in future and to coordinate the vehicle selection in the ERMES group.

The emission factors calculated for HDV are well in line with the results for the HBEFA V2 up to EURO III vehicles. EURO IV and EURO V were based on assessments only in the

HBEFA V2. Thus the actual emission factors based on measurements show somewhat different results. The $NO_x$ emissions from EURO IV HDV with EGR dropped similar to the type approval limits compared to EURO III. $NO_x$ from SCR equipped vehicles (EURO IV and V) showed more reduction than the type approval limit in high engine load cycles but comparable small reductions in low engine loads (e.g. city cycles). This is due to the thermal behaviour of the SCR-systems which cool down at low engine loads with low exhaust gas temperatures. In stop&go conditions such vehicles have similar $NO_x$ emission levels as the EURO III trucks. PM and PN emissions show clear reductions from EURO III on. This is due to the improved engine technology and also due to applied exhaust gas after treatment systems (partial flow filters). HC and CO are on a quite low level for all HDV segments. In the HBEFA V3 also a split of $NO_x$ into $NO_2$ and NO is provided. The $NO_2$ emissions are based on a quite large number of measurements and show clearly increasing trends due to catalytic active exhaust gas after treatment systems. With EURO VI this trend is assumed to be broken.

For LDV all emissions are reduced from EURO 0 to EURO 5 but the reductions achieved between the EURO classes are not evenly distributed. Especially NOx from diesel cars did not show much reduction from EURO 0 to EURO 3. From EURO 3 to EURO 4 a rather significant $NO_x$-reduction was found. EURO 5 is assumed to have quite similar emission levels as EURO 4 since the emission limits for $NO_x$ were not reduced very much. Unfortunately for the HBEFA V3 only tests on one diesel EIRO 5 car were available. The big step for $NO_x$ from diesel cars is expected for EURO 6. However, if the NEDC remains the only test cycle in type approval it may show in future that the reduction rates applied from EURO 5 to EURO 6 were too optimistic. It is strongly recommended to test EURO 5 diesel cars rather soon to be able to react in time with eventually necessary adaptations of the EURO 6 type approval regulations. Certainly also EURO 6 cars should be tested as soon as available for measurements in the ERMES group. The PM and PN emissions proved to be significantly reduced by the introduction of diesel particle filters. All of the tested vehicles with DPF showed very low particle emission levels. This may shift the focus to PN emissions from direct injecting gasoline engines in the next future. However, the morphology of the particles from such engines is quite different than from diesel cars without filter. Thus it is not clear if the health effects are comparable. HC and CO emissions are on low levels for the modern LDV.

The uncertainty analysis showed a high accuracy for fuel consumption and thus also $CO_2$ emissions. $NO_x$ and PM from diesel cars do reach also good model accuracy, while CO can be predicted only with a very limited accuracy

The data set of the model PHEM allows in principle a simple calculation of new sets of emission factors for different driving cycles and/or different vehicle specifications if demanded in future, e.g. for emission factors for specific local conditions or for a next update of the HBEFA. PHEM also offers an interface to micro scale traffic models. In this version the vehicles are driving on a virtual network according to the results of the traffic model and PHEM selects automatically the vehicle segments to meet a prescribed fleet composition. Thus the models PHEM and HBEFA can be used for a broad range of tasks in a consistent way in future. The tools hopefully assist to develop and to test intelligent measures to reduce negative impacts of the road transport sector.

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