EMISSIONS AND FUEL CONSUMPTION FROM HEAVY DUTY VEHICLES

COST 346 – Final Report

including Final Report of Working Group A

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**ACTION 346: ENERGY AND FUEL CONSUMPTION FROM HEAVY DUTY VEHICLES**

The primary objective of the Action was to develop an improved methodology for estimating pollutant emissions and fuel consumption from commercial road transport operated with Heavy Duty Vehicles (HDV’s) in Europe. The methods should make it possible to estimate the emissions [g/km] from single vehicles, as well as, from vehicle fleets. The activities were concentrated on improving the amount and quality of basic data on emissions and transport activity, as well as, on validating and enhancing existing models.


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ESF provides the COST Office through an EC contract
Management Committee
COST 346

Emissions and Fuel Consumption from Heavy Duty Vehicles

Working Group A: Vehicle Model
Final Report
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<thead>
<tr>
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<th>Contributors</th>
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We want to thank all partners for the excellent cooperation and engagement. We hope that the work of the team helps to improve the understanding of heavy duty vehicle emission behavior and modeling and to increase the quality of environmental assessments.

Martin Rexeis, Stefan Hausberger  
Graz 2005
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1. INTRODUCTION

In the projects COST 346 and ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems) emission factors for heavy duty vehicles were elaborated\(^1\). The projects COST 346 and ARTEMIS had also a close cooperation with the “Handbook on Emission Factors, HBEFA”.

The actual report describes the data, methods and results for heavy duty vehicles (HDV) elaborated within ARTEMIS and COST 346. Most of the text is similar to the final report of ARTEMIS WP 400 since both projects had the same task and worked in very close cooperation. ARTEMIS ended February in the year 2005, thus COST 346 does not provide different results but some additional information. All chapters which are different or additional compared to the final report of ARTEMIS WP 400 are listed in the following. Chapters which are not listed have the same content.

Scope of the work was to elaborate

- a model capable of simulating accurately emission factors for all types of HDV in any driving cycle for various vehicle loadings
- the necessary model input from the measurement program, a data collection campaign and literature review
- the emission factors for the overall inventory model using the model and data described before.

Due to the co-operation between ARTEMIS, COST 346 and HBEFA the measurement program covered 31 engines on the engine test bed and 6 HDV on the roller test bed, all tests following a common test protocol – the ARTEMIS protocol - to fit directly into the model structure. These measurements include a 54 steady state point engine emission map and the test of at least three different transient cycles.

Within the data collection campaign emission measurements from 71 engines were collected from other national and international programmes. Minimum demand on the measurement program to be included into the data collection was, that a steady state engine emission map exists which covers more than the type approval points. In total emission tests from 102 engines are used as model input data, representing the most extensive data base for HDV emission factors in Europe. Data from roller tests and from on board measurements on 50 HDV were collected and used for model validation purposes.

The resulting emission model PHEM (Passenger car and Heavy duty Emission model) is interpolating the fuel consumption and the emissions from the engine maps according to the course of engine power demand and engine speed in the driving cycles. The method is therefore capable of making use of the data from all engines from the data collection campaign.

For the elaboration of emission factors for the inventory model, PHEM was run with the data sets for average HDV according to certification level (EURO 0 to EURO 5), the size category (<7.5t up to 60t) and the vehicle loading.

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\(^1\) ARTEMIS dealt with all other modes of transport too. In this report only the results for heavy duty vehicles from ARTEMIS Work Package 400 are included. COST 346 covered different Working Groups (WG). WG A was responsible for the development of the emission factor model and the corresponding data collection and measurement program. In this report the work of WG A is included. Other working groups of COST 346 were AB (driving behavior), B (fleet model), C (dissemination), D (legislation).
Beside the vehicle and engine data also representative driving cycles have been developed as model input. These driving cycles were elaborated from COST 346 WG AB from an extensive analysis of all available on-board measurement data from driving behaviour studies for HDV. Details are given in the report from WG AB.

To obtain more accurate emission factors the influences of the fuel quality and of the level of maintenance of the HDV on their emission levels were investigated in detail. In COST 346 also the potential of retrofit exhaust gas after treatment systems were studied.

In total the model proved to be very flexible to provide emission factors for average HDV categories in any driving condition. Certainly all other national emission factor models can make use of the data sets produced. All tests are stored in detail in an electronic database. Different modal vehicle emission models were compared during the COST action using similar input data from the measurement campaign. A main result was that very different fleet emission factors were simulated by the models at the beginning of COST 346. Reason was that information on average emission levels of the heavy duty vehicle fleet in terms of engine emission maps was very limited and for each country different. These differences should be eliminated in future due to the common data base elaborated in COST 346 and ARTEMIS. Differences will still remain if different models are used for the calculation of the emission factors. Harmonizing not only the data but also the models could be a future task towards common European emission factors.

In this report, the following sections have been added compared to the final report of ARTEMIS WP400:

- Paragraph 9.4: Emission factors for PM number and PM active surface area

Appendices:

- III TRANSIENT EFFECTS ON THE ENGINE EMISSION LEVELS
- IV DEFINITION OF “ENGINE POWER”
- V TESTING DIFFERENCES IN ENVIRONMENTAL PERFORMANCE BY VARIOUS MANUFACTURERS AND BETWEEN GENERATIONS OF HDV ENGINES
- VI RETROFIT AFTERTREATMENT SYSTEMS FOR DIESEL ENGINES
- VII MODEL COMPARISON

All other chapters have been adopted only with minor modifications mainly concerning references to the information given in the added chapters.

2. APPROACH

The targeted results are emission factors for various categories of the HDV fleet (separated according to engine technology and vehicle weight classes) with different loadings of the HDV for different representative driving cycles at different road gradients (Figure 1). The results are emission factors for more than 100,000 combinations of vehicle categories, driving cycles, road gradients and vehicle loadings. These emission factors are then used as an input for the overall ARTEMIS inventory model, which is a databank that allows the user a user-friendly and simple simulation of aggregated emission factors for various traffic situations.
For the elaboration of the emission factors a methodology based on interpolations from steady state emission maps was chosen, since data on more than 100 measurements of engine maps were already available which should be used in the model. With a given driving cycle and road gradient the necessary engine power is calculated second per second from the driving resistances and losses in the transmission system. The actual engine speed is simulated by the transmission ratios and a drivers gear-shift model. To take transient influences on the emission level into consideration, the results from the steady state emission map are corrected by using transient correction functions. The method was implemented into a computer executable model with a user-friendly interface. The model is optimised for simulating fuel consumption and emissions from HDV fleets but can be used for simulations of single vehicles and passenger cars as well. Figure 1 gives a schematic picture of the model PHEM (Passenger car & Heavy duty Emission Model).

**Figure 1:** Emission factors to be modelled and diagram of the model PHEM from TU-Graz

Compared to direct measurement of the emission factors on the chassis dynamometer or – like done for LDV – to simulate the emissions using a vehicle speed times vehicle acceleration emission map (e.g. [22]) the PHEM approach has a disadvantage and many advantages when applied for HDV.

The main advantage of measuring emission factors directly on the chassis dynamometer is the higher accuracy and reliability of the factors for the tested vehicles since a model always has some simplifications and inaccuracies compared to the reality.

On the other hand, the model makes use of already existing data from the engine test bed to a maximum possible extent. From existing measurements data on more than 60 engines is already available (steady state emission maps), which has a quality high enough to be used for the simulation of emission factors whereas only a few measurements on the chassis dynamometer are available. Additionally, different HDV configurations often use the same engines. Thus measuring one engine on the engine test bed mostly covers a lot of different HDV.

To gain useful emission factors for HDV it is essential to take the influence of the vehicle loading and the road gradient into account. The road gradient heavily influences the driving behaviour and the emission level of HDV. Since more than 50% of the maximum allowed mass is allocated to the potential payload, the actual loading of the HDV also has a considerable effect on the emission levels, especially when combined with road gradients. To measure these influences an extensive and very expensive program for each HDV would be needed, while these effects can be simulated very accurately by the model.
The driving cycles that until now have been used for the Handbook on Emission Factors [67] have been updated in the project ARTEMIS. The simulation model can produce reliable results for any cycle, while measured emission factors cannot be changed to another set of driving cycles later on. Another effect of the modelling is a much better understanding of the emission behaviour of modern HDV.

In total, the modelling method is based on a much broader number of measured engines than a measurement campaign on the chassis dynamometer could ever produce within an acceptable budget. This clearly improves the reliability of the resulting fleet emission factors. The model is also capable of giving emission factors for an unlimited number of traffic situations.

3. DATA USED

The ARTEMIS-model makes to a large extent use of already existing measurements. For this purpose a coordinated data collection of all partners from D.A.CH.-NL and COST 346 was launched using standardised formats for data transfer (see Appendix I).

The measurement programme for the ARTEMIS-WP 400 and accordingly for the D.A.CH.-NL project was designed to fill open gaps and to develop a method capable of using all the data in a consistent way. Certainly the data gained from the new measurements are included into the data collection.

From the data collection campaign measurements on 102 engines are available. For 12 of the engines only emission maps from the 13-mode test (R 49) and the new ESC are available. For the others additional off-cycle points have been measured in the steady state tests. For 27 engines transient tests and complete steady state emission maps are available. 21 of these engines have already been measured according to the complete ARTEMIS measurement protocol. Most of the engines measured were derived from HDV in use for two months up to 2 years with regular service intervals. Table 1 to Table 4 show the engines used in the final version of the model.
Table 1: engines with construction year/certification level before EURO 1 used for the project (“80ies”)

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### Table 2: engines with certification level EURO 1 used for the project

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<td>RWTÜV</td>
</tr>
<tr>
<td>MAN D0824LF01</td>
<td>115 650 2400 x x --- 0</td>
<td></td>
<td>TNO Automotive</td>
</tr>
<tr>
<td>MAN D0826LF08</td>
<td>165 600 2400 x x --- 0</td>
<td></td>
<td>TNO Automotive</td>
</tr>
<tr>
<td>OM 366 LA</td>
<td>230 560 2100 x --- x 0</td>
<td></td>
<td>RWTÜV</td>
</tr>
<tr>
<td>OM 366 LA</td>
<td>177 600 2600 x --- x 2</td>
<td>TUG</td>
<td></td>
</tr>
<tr>
<td>MAN D0826 LF11</td>
<td>250 600 2400 --- --- --- ---</td>
<td>INRETS</td>
<td></td>
</tr>
<tr>
<td>MAN D0826 LF17</td>
<td>236 525 1900 x x x 0</td>
<td></td>
<td>TNO Automotive</td>
</tr>
<tr>
<td>MB OM 441 LA I/10</td>
<td>280 560 1900 x x x 3</td>
<td>EMPA</td>
<td></td>
</tr>
<tr>
<td>Mercedes OM 441 LA 6/1</td>
<td>230 550 2100 x --- x 0</td>
<td></td>
<td>RWTÜV</td>
</tr>
<tr>
<td>Mercedes OM 441 LA II/1</td>
<td>190 600 2300 x --- x 0</td>
<td></td>
<td>TNO Automotive</td>
</tr>
<tr>
<td>Mercedes OM 906 LA II/1</td>
<td>120 400 2000 x --- x 5</td>
<td>EMPA</td>
<td></td>
</tr>
<tr>
<td>RABA D10 UTSLL 190 E2</td>
<td>290 500 1892 x x x 3</td>
<td>TUG</td>
<td></td>
</tr>
<tr>
<td>SCANIA DSC 1201</td>
<td>294 590 1900 x x x 5</td>
<td>EMPA</td>
<td></td>
</tr>
<tr>
<td>SCANIA DSC 1201</td>
<td>279 530 1800 x x x 5</td>
<td>EMPA</td>
<td></td>
</tr>
<tr>
<td>Volvo D12A380</td>
<td>279 510 1800 x --- x 0</td>
<td>RWTÜV</td>
<td></td>
</tr>
<tr>
<td>Cummins N425 E20</td>
<td>349 750 1875 --- --- x 0</td>
<td>VTT</td>
<td></td>
</tr>
<tr>
<td>Cummins N475 E20</td>
<td>380 750 1850 --- --- x 0</td>
<td>VTT</td>
<td></td>
</tr>
<tr>
<td>Volvo DH10A - 285</td>
<td>210 630 2000 --- --- x 0</td>
<td>VTT</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3: engines with certification level EURO 2 used for the project

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>Specifications</th>
<th>Tests</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rated power [kW] rpm idle rpm rated ECE R49 ESC Off cycle points Nr. of transient tests</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D2866 LF20/ MAN 19.403 Semitrailer</td>
<td>297 600 2000 x x x 2</td>
<td></td>
<td>TUG</td>
</tr>
<tr>
<td>DAF XF 355; BM 347</td>
<td>355 525 2000 x x x 26</td>
<td></td>
<td>TNO Automotive</td>
</tr>
<tr>
<td>DAF XF280M</td>
<td>280 542 2000 x x x 12</td>
<td></td>
<td>TNO Automotive</td>
</tr>
<tr>
<td>FIAT 8060.45S/IVECO 120E18/FP</td>
<td>130 750 2700 x x x 2</td>
<td></td>
<td>TUG</td>
</tr>
<tr>
<td>IVECO 120E23(FLAT8060.45K)</td>
<td>167 750 2700 x x x 5</td>
<td>EMPA</td>
<td></td>
</tr>
<tr>
<td>IVECO 8060.45S</td>
<td>167 600 2700 x --- x 0</td>
<td></td>
<td>RWTÜV</td>
</tr>
<tr>
<td>MAN D0826 LF11</td>
<td>162 650 2400 x x x 4</td>
<td></td>
<td>RWTÜV</td>
</tr>
<tr>
<td>MAN D0826 LF17</td>
<td>191 600 2300 x --- x 0</td>
<td></td>
<td>RWTÜV</td>
</tr>
<tr>
<td>MAN D2865LF21</td>
<td>250 650 2000 x --- x 0</td>
<td></td>
<td>RWTÜV</td>
</tr>
<tr>
<td>MB OM 441 LA 1/10</td>
<td>247 513 1900 x x x 3</td>
<td>EMPA</td>
<td></td>
</tr>
<tr>
<td>MB OM 442 LA 6/1</td>
<td>280 560 1900 x x x 5</td>
<td>EMPA</td>
<td></td>
</tr>
<tr>
<td>Mercedes OM 441 LA II/1</td>
<td>230 550 2100 x --- x 0</td>
<td></td>
<td>RWTÜV</td>
</tr>
<tr>
<td>Mercedes OM 906 LA II/1</td>
<td>170 600 2300 x --- x 0</td>
<td></td>
<td>RWTÜV</td>
</tr>
<tr>
<td>RABA D10 UTSLL 190 E2</td>
<td>190 600 1900 x x x 0</td>
<td>KTI</td>
<td></td>
</tr>
<tr>
<td>SCANIA DSC 1201</td>
<td>290 500 1892 x x x 3</td>
<td>TUG</td>
<td></td>
</tr>
<tr>
<td>SCANIA DSC 1201</td>
<td>294 590 1900 x x x 5</td>
<td>EMPA</td>
<td></td>
</tr>
<tr>
<td>Volvo D12A380</td>
<td>279 530 1800 x x x 5</td>
<td>EMPA</td>
<td></td>
</tr>
<tr>
<td>Volvo D12A380EC97</td>
<td>279 510 1800 x --- x 0</td>
<td>RWTÜV</td>
<td></td>
</tr>
<tr>
<td>Cummins N425 E20</td>
<td>313 750 1900 --- --- x 0</td>
<td>VTT</td>
<td></td>
</tr>
<tr>
<td>Cummins N475 E20</td>
<td>349 750 1875 --- --- x 0</td>
<td>VTT</td>
<td></td>
</tr>
<tr>
<td>Cummins N525 E20</td>
<td>380 750 1850 --- --- x 0</td>
<td>VTT</td>
<td></td>
</tr>
<tr>
<td>Volvo DH10A - 285</td>
<td>210 630 2000 --- --- x 0</td>
<td>VTT</td>
<td></td>
</tr>
</tbody>
</table>
### Table 4: engines with certification level EURO 3 used for the project

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>Specifications</th>
<th>Tests</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rated power</td>
<td>rpm idle</td>
<td>rpm rated</td>
</tr>
<tr>
<td>DAF PE183C</td>
<td>183</td>
<td>600</td>
<td>2300</td>
</tr>
<tr>
<td>DAF XE 280 C1; BM 410</td>
<td>280</td>
<td>550</td>
<td>1900</td>
</tr>
<tr>
<td>DAF XE 315 C; BM 409</td>
<td>315</td>
<td>550</td>
<td>1900</td>
</tr>
<tr>
<td>IVECO Cursor</td>
<td>316</td>
<td>550</td>
<td>2100</td>
</tr>
<tr>
<td>MAN D0836 LF04</td>
<td>162</td>
<td>600</td>
<td>2400</td>
</tr>
<tr>
<td>RABA D10 TLL 225 E3</td>
<td>225</td>
<td>600</td>
<td>2100</td>
</tr>
<tr>
<td>RABA D10 UTSLL 190 E3</td>
<td>190</td>
<td>600</td>
<td>1800</td>
</tr>
<tr>
<td>Scania DC 1201 EU3</td>
<td>305</td>
<td>500</td>
<td>1914</td>
</tr>
<tr>
<td>Scania DC1201</td>
<td>309</td>
<td>500</td>
<td>1900</td>
</tr>
<tr>
<td>MB OM 501 LA III/3</td>
<td>260</td>
<td>560</td>
<td>1800</td>
</tr>
<tr>
<td>Volvo D12D 420 EC01</td>
<td>309</td>
<td>600</td>
<td>1800</td>
</tr>
<tr>
<td>Volvo D12C 420</td>
<td>309</td>
<td>600</td>
<td>1800</td>
</tr>
<tr>
<td>Volvo D12 D420 EC01</td>
<td>309</td>
<td>600</td>
<td>1800</td>
</tr>
<tr>
<td>Volvo D6B 220</td>
<td>162</td>
<td>700</td>
<td>2400</td>
</tr>
<tr>
<td>Scania DT 1202 470</td>
<td>345</td>
<td>500</td>
<td>1900</td>
</tr>
<tr>
<td>Caterpillar C-18 MDP00141</td>
<td>460</td>
<td>600</td>
<td>1900</td>
</tr>
<tr>
<td>Scania DC 11 03 340</td>
<td>250</td>
<td>500</td>
<td>1900</td>
</tr>
<tr>
<td>Volvo D6B 220</td>
<td>162</td>
<td>700</td>
<td>2400</td>
</tr>
<tr>
<td>DAF XE 315 C1</td>
<td>315</td>
<td>550</td>
<td>1900</td>
</tr>
<tr>
<td>Iveco F3AE0681B</td>
<td>294</td>
<td>550</td>
<td>2100</td>
</tr>
<tr>
<td>MAN D2866LF26</td>
<td>228</td>
<td>600</td>
<td>1900</td>
</tr>
<tr>
<td>Daimler Chrysler OM 501 LA III/5</td>
<td>290</td>
<td>560</td>
<td>1800</td>
</tr>
<tr>
<td>Scania DC 1203</td>
<td>309</td>
<td>520</td>
<td>1900</td>
</tr>
<tr>
<td>Volvo D12 D420</td>
<td>309</td>
<td>600</td>
<td>1800</td>
</tr>
<tr>
<td>Volvo D12 D460</td>
<td>338</td>
<td>600</td>
<td>1800</td>
</tr>
<tr>
<td>DAF IsBe 22 30 / CE 162 C</td>
<td>162</td>
<td>700</td>
<td>2500</td>
</tr>
</tbody>
</table>

From project related measurements on the HDV chassis dynamometer data for eight HDV are available. Five of these were measured according to the D.A.CH.-NL./ARTEMIS programme, which includes nine different driving cycles and an extensive recording of relevant parameters (e.g. engine speed, temperatures and pressures of inlet air and outlet air, etc.) and measurements of the engine from the HDV on the engine test bed. One HDV (IVECO 120E18/FP) was instrumented with on-board measurement systems and simultaneously measured on the chassis dynamometer. The engine was however not tested on the engine test bed.
Table 5: Data used from HDV chassis dynamometer tests and On-Board emission measurements

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Certification Level</th>
<th>Measurements available</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB O 45</td>
<td>Pre EU 1</td>
<td>X</td>
<td>2 cycles with 3 loadings, measured 1993</td>
</tr>
<tr>
<td>MB O 303</td>
<td>Pre EU 1</td>
<td>X</td>
<td>2 cycles with 3 loadings, measured 1993</td>
</tr>
<tr>
<td>MB 1324</td>
<td>EU 1</td>
<td>X</td>
<td>2 cycles with 3 loadings, measured 1993</td>
</tr>
<tr>
<td>D2866 LF20/ MAN 19.403</td>
<td>EU 2</td>
<td>X X X</td>
<td>9 cycles + steady state</td>
</tr>
<tr>
<td>IVECO 120E18/FP</td>
<td>EU 2</td>
<td>X X X</td>
<td>9 cycles + steady state + on-board</td>
</tr>
<tr>
<td>SCania 400 E2</td>
<td>EU 2</td>
<td>X X X</td>
<td>9 cycles + steady state</td>
</tr>
<tr>
<td>SCania DC 1201</td>
<td>EU 3</td>
<td>X X X</td>
<td>9 cycles + steady state</td>
</tr>
<tr>
<td>VOLVO FL6 220</td>
<td>EU 3</td>
<td>X X</td>
<td>9 cycles + steady state</td>
</tr>
<tr>
<td>MAN NL 202 F bus</td>
<td>EU 2</td>
<td>X</td>
<td>on-board measurements</td>
</tr>
<tr>
<td>Van Hool A600 bus</td>
<td>EU 2</td>
<td>X</td>
<td>on-board measurements</td>
</tr>
<tr>
<td>VOLVO FH12</td>
<td>EU 3</td>
<td>X X</td>
<td>On-Board emission measurement on two transalpine routes</td>
</tr>
</tbody>
</table>

Furthermore, a large number of chassis dynamometer tests and on-board emission measurements are available from the data collection campaign which can not be included directly into the emission model, because no corresponding measurements at the engine test bed are available and the information on the vehicle specifications is not complete. In order to still make use of these measurements for the ARTEMIS project, it was decided to pool these results for each emission component and emission standard (as a function of average speed of the driving cycle) and to compare the covered ranges with the results of the ARTEMIS emission model (see Appendix II).

3.1. Engine test bed, steady state measurements

The measurements from ARTEMIS WP 400 and the D.A.CH.-NL. project conducted on engine test beds provided the following information:

(1) Data on steady-state engine emission maps (emissions over engine speed and engine torque)

(2) Basic data for the development of functions for the “dynamic correction” (i.e. the different emission behaviour under steady-state and transient cycles).

For (1), the main task was to develop a methodology which is capable of including all emission maps from the data collection - where most often different maps have been measured - in a way, that real world engine loads can be interpolated accurately from one overall engine emission map (i.e. the whole engine map has to be covered). The main projects to be included from the data collection are given in Table 6.

To develop a method capable of making use of most of the data from national projects the D.A.CH.-NL./ARTEMIS measurement programme includes most of the points measured in the main national projects.
Table 6: Description of the main national measurement programmes on HDV engines

<table>
<thead>
<tr>
<th>Programme</th>
<th>No. of engines</th>
<th>Engine maps available</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dutch in-use-compliance tests</td>
<td>more than 100</td>
<td>ECE R49 13-mode test, some ESC additionally</td>
</tr>
<tr>
<td>German in-use-compliance tests</td>
<td>20</td>
<td>26 different points of engine speed and engine torque</td>
</tr>
<tr>
<td>Former German HDV-programme</td>
<td>30</td>
<td>35 different points of engine speed and engine torque (all engines older than year 1993)</td>
</tr>
<tr>
<td>Smaller national programmes</td>
<td>more than 10</td>
<td>13-mode-test, ESC, others</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td><strong>&gt;160</strong></td>
<td><strong>&gt; 4 different map-configurations</strong></td>
</tr>
</tbody>
</table>

The following steady-state measurements are included in the ARTEMIS programme:

- ECE R 49 13-mode test
- ESC 13-mode test (European Steady State Cycle)
- ARTEMIS-steady state test

The ECE R49 test and the ESC have to be performed as given in the corresponding EC documents. This also includes the recording of the full-load curve.

For the ARTEMIS steady state test interim points between the engine speeds A, B and C\(^2\) from the ESC-test were selected to check possible increases in the emissions in this area. Additionally, points in the engine speed range below speed “A” are measured. These points are fixed independently of the full load curve. Furthermore, 2 points between speed “C” and the rated speed were added. In total, 29 points are included in the ARTEMIS test, which are measured in addition to the ESC and ECE R49 tests. Figure 2 gives the measurement points for the ARTEMIS programme (example for a given full load curve).

Table 7 shows the calculation routine to determine the points. The normalised engine speed given is only an example for one engine. The measurement conditions are defined as in the ESC (duration of measuring each point) and the points have to be measured in a sequence according to increasing engine power.

\(^2\) The engine speeds A, B and C have to be calculated as given in the EC regulation ECE R 49 and 88/77/EWG for the European Stationary Cycle (ESC):

- Engine speed A = \(n_{lo} + 25\% \times (n_{hi}-n_{lo})\)
- Engine speed B = \(n_{lo} + 50\% \times (n_{hi}-n_{lo})\)
- Engine speed C = \(n_{lo} + 75\% \times (n_{hi}-n_{lo})\)

\(n_{lo}\)…engine speed where 50% from the rated power are reached
\(n_{hi}\)…engine speed (above rated rpm) where the power decreases to 70% of the rated power are reached
Figure 2: Steady-state points measured in the ARTEMIS programme (example)

Table 7: Test points for the ARTEMIS steady-state test

<table>
<thead>
<tr>
<th></th>
<th>norm. speed</th>
<th>normalised Torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>TUG-Interim</td>
<td>0.35nA 14.3%</td>
<td>10% 25% 50% 75% 100%</td>
</tr>
<tr>
<td>TUG-Interim</td>
<td>0.7nA 28.7%</td>
<td>-100% 10% 25% 50% 75% 100%</td>
</tr>
<tr>
<td>ESC-A</td>
<td>nA 0.25(nA - nB) 41.0%</td>
<td>10%</td>
</tr>
<tr>
<td>ESC-B</td>
<td>nA 0.50(nA - nB) 63.0%</td>
<td>10%</td>
</tr>
<tr>
<td>ESC-C</td>
<td>nA 0.75(nA - nB) 85.1%</td>
<td>-100% 10%</td>
</tr>
<tr>
<td>TUG-Interim</td>
<td>0.4nA+0.6nB 54.2%</td>
<td>-100% 10% 30% 60% 100%</td>
</tr>
<tr>
<td>TUG-Interim</td>
<td>0.6nB+0.4nC 71.9%</td>
<td>10% 30% 60% 100%</td>
</tr>
<tr>
<td>TUG-Interim</td>
<td>nC+(rated speed-nC)/2 92.5%</td>
<td>25% 75%</td>
</tr>
</tbody>
</table>

Explanations:
- 100% : motoring curve
- $n_{\text{norm}} = (n - n_{\text{idle}})/(n_{\text{rated}} - n_{\text{idle}})$
### Table 8: Sequence for the ARTEMIS steady-state test

<table>
<thead>
<tr>
<th>Point Nr.</th>
<th>Comment</th>
<th>normalised torque</th>
<th>Engine speed [%] &quot;example.&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>nlo + 0.75*(nhi - nlo)</td>
<td>-100%</td>
<td>72%</td>
</tr>
<tr>
<td>2</td>
<td>0.4<em>nA+0.6</em>nB</td>
<td>-100%</td>
<td>29%</td>
</tr>
<tr>
<td>3</td>
<td>0.7*nA</td>
<td>-100%</td>
<td>41%</td>
</tr>
<tr>
<td>4</td>
<td>0.35*nA</td>
<td>10%</td>
<td>14%</td>
</tr>
<tr>
<td>5</td>
<td>0.7*nA</td>
<td>10%</td>
<td>29%</td>
</tr>
<tr>
<td>6</td>
<td>nlo + 0.25*(nhi - nlo)</td>
<td>10%</td>
<td>41%</td>
</tr>
<tr>
<td>7</td>
<td>0.4<em>nA+0.6</em>nB</td>
<td>10%</td>
<td>54%</td>
</tr>
<tr>
<td>8</td>
<td>nlo + 0.50*(nhi - nlo)</td>
<td>10%</td>
<td>63%</td>
</tr>
<tr>
<td>9</td>
<td>0.6<em>nB+0.4</em>nC</td>
<td>10%</td>
<td>72%</td>
</tr>
<tr>
<td>10</td>
<td>nlo + 0.75*(nhi - nlo)</td>
<td>10%</td>
<td>85%</td>
</tr>
<tr>
<td>11</td>
<td>0.35*nA</td>
<td>25%</td>
<td>14%</td>
</tr>
<tr>
<td>12</td>
<td>0.7*nA</td>
<td>25%</td>
<td>29%</td>
</tr>
<tr>
<td>13</td>
<td>0.35*nA</td>
<td>50%</td>
<td>14%</td>
</tr>
<tr>
<td>14</td>
<td>0.4<em>nA+0.6</em>nB</td>
<td>30%</td>
<td>54%</td>
</tr>
<tr>
<td>15</td>
<td>interim C-rated speed</td>
<td>25%</td>
<td>93%</td>
</tr>
<tr>
<td>16</td>
<td>0.6<em>nB+0.4</em>nC</td>
<td>30%</td>
<td>72%</td>
</tr>
<tr>
<td>17</td>
<td>0.7*nA</td>
<td>50%</td>
<td>29%</td>
</tr>
<tr>
<td>18</td>
<td>0.35*nA</td>
<td>75%</td>
<td>14%</td>
</tr>
<tr>
<td>19</td>
<td>0.7*nA</td>
<td>75%</td>
<td>29%</td>
</tr>
<tr>
<td>20</td>
<td>0.35*nA</td>
<td>100%</td>
<td>14%</td>
</tr>
<tr>
<td>21</td>
<td>0.4<em>nA+0.6</em>nB</td>
<td>60%</td>
<td>54%</td>
</tr>
<tr>
<td>22</td>
<td>0.6<em>nB+0.4</em>nC</td>
<td>60%</td>
<td>72%</td>
</tr>
<tr>
<td>23</td>
<td>0.7*nA</td>
<td>100%</td>
<td>29%</td>
</tr>
<tr>
<td>24</td>
<td>nlo + 0.25*(nhi - nlo)</td>
<td>90%</td>
<td>41%</td>
</tr>
<tr>
<td>25</td>
<td>interim C-rated speed</td>
<td>75%</td>
<td>93%</td>
</tr>
<tr>
<td>26</td>
<td>nlo + 0.50*(nhi - nlo)</td>
<td>90%</td>
<td>63%</td>
</tr>
<tr>
<td>27</td>
<td>0.4<em>nA+0.6</em>nB</td>
<td>100%</td>
<td>54%</td>
</tr>
<tr>
<td>28</td>
<td>nlo + 0.75*(nhi - nlo)</td>
<td>90%</td>
<td>85%</td>
</tr>
<tr>
<td>29</td>
<td>0.6<em>nB+0.4</em>nC</td>
<td>100%</td>
<td>72%</td>
</tr>
</tbody>
</table>

**Measurements for the particulate steady state map**

Wherever possible, according to the schedule of each partner, a particulate emission map with all points (ESC, 13-mode test and ARTEMIS-test) is measured. Since each point has to be run for a rather long time to collect enough particulate mass (PM) on the filter, this is not possible for every engine.

Where the time schedule does not allow the measurement of particulate mass for each point in Table 7, particulates are measured at a reduced number of points (15), as defined in Table 9. The points are part of the ESC, ARTEMIS, and 13-mode tests and were selected to receive good coverage of the whole map (Figure 3).
Figure 3: Minimum number of points where particulate mass emissions are measured separately

Table 9 shows the calculation routine to determine particle measurement points. The normalised engine speed given again is only an example for one engine. The sample time that is necessary to achieve sufficient particulate mass on the filter for an accurate emission value has to be estimated, according to the type of engine and the load point. Just as for the total ARTEMIS test the points have to be measured in a sequence according to increasing engine power.

Table 9: Reduced ARTEMIS test for particulate emission measurements (normalised engine speeds given only as an example for one engine)

<table>
<thead>
<tr>
<th>(example)</th>
<th>norm. speed</th>
<th>normalised Torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>n_idle</td>
<td>0.0%</td>
<td>0%</td>
</tr>
<tr>
<td>TUG-Interim 0.35nA</td>
<td>14.3%</td>
<td>10%</td>
</tr>
<tr>
<td>TUG-Interim 0.77nA</td>
<td>28.7%</td>
<td>50%</td>
</tr>
<tr>
<td>A nlo + 0.25(nhi - nlo)</td>
<td>41.0%</td>
<td>10%</td>
</tr>
<tr>
<td>B nlo + 0.50(nhi - nlo)</td>
<td>63.0%</td>
<td>10%</td>
</tr>
<tr>
<td>C nlo + 0.75(nhi - nlo)</td>
<td>85.1%</td>
<td>25%</td>
</tr>
<tr>
<td>rated speed</td>
<td>100.0%</td>
<td>25%</td>
</tr>
<tr>
<td>TUG-Interim 0.4<em>nA+0.6</em>nB</td>
<td>54.2%</td>
<td></td>
</tr>
<tr>
<td>TUG-Interim 0.6<em>nB+0.4</em>nC</td>
<td>71.9%</td>
<td></td>
</tr>
<tr>
<td>TUG-Interim nC+(rated speed-nC)/2</td>
<td>92.5%</td>
<td></td>
</tr>
</tbody>
</table>

3.1.1 Setting of the sequence and duration of measurement

To run the ARTEMIS emission map on the engine test bed, an order of the modes and their duration had to be defined. Therefore, the influences of these two parameters on the emissions were investigated.

Since these investigations were time correlated with the measurements planned in Switzerland, EMPA took the task to come up with the inputs needed. The results of the following measurement programme lead to the decision on the final steady state measurement programme as defined in paragraph 3.1, see also [25].
**Measurement programme**

Three different versions of the ARTEMIS emission maps were performed. In the first one, engine power was increased from mode to mode, in the second one decreased. In both versions, the mode duration was set to 2 minutes like in ESC. In the third version, the mode duration was 5 minutes in order to provide sufficient sampling time for the particulates measurement. Again, engine power was increased from mode to mode.

In all versions, the change in engine power was a minimum from mode to mode in order to optimise the preconditioning time. The beginning of the modes was used for engine stabilisation and the emissions (excl. particulates) were measured during the last 35 seconds. Each version of the ARTEMIS emission map was measured three times in order to have a minimum statistical impression about the repeatability of these measurements. The measurements were performed with a 12 l EURO II engine, which was turbocharged and intercooled.

During all test modes, the emissions of CO₂, NOₓ, CO were within the repeatability for all versions of the ARTEMIS emission map. The repeatability of the measurements was very good, only in some measuring points, the CO emissions were very high and the repeatability was worse. All these points are at low engine speed with relatively high torque, where the combustion process is not stable.

During some test modes, the hydrocarbon emissions are different in the three versions of the emission map (Figure 7). Often, the higher emissions are measured in the version with the high mode duration. Since the standard deviation of the measurements is mostly at the same order of magnitude as the differences themselves, no significant conclusion can be drawn.

Based on the results of the measurements it was decided that the ARTEMIS emission map will be performed in an upward way, i.e. with increasing engine power from mode to mode and to use a test mode duration of 2 minutes for load points where no particulate measurements are performed (procedure according to 1999/96/EG for the ESC type approval test). If particulates are measured as well (multifilter test), the test mode duration has to be set to at least 5 minutes to have enough particle loading on the filter.

The ESC and the R49 13-mode test have been performed according to the corresponding EC regulations and the gaseous emissions have been recorded for each point separately to complete the engine emission maps.

The following figures contain the emission results obtained with the three versions of the ARTEMIS emission map. The bars represent the averages of three measurements and the lines show the standard deviation of the individual measurements.
Carbon dioxide ($CO_2$)

![Chart showing CO2 emissions at three different measurement modes of the ARTEMIS steady state test.]

**Figure 4:** $CO_2$ emissions at three different measurement modes of the ARTEMIS steady state test

Nitrogen oxides ($NO_x$)

![Chart showing NOx emissions at three different measurement modes of the ARTEMIS steady state test.]

**Figure 5:** NOx emissions at three different measurement modes of the ARTEMIS steady state test
3.1.2 Repeatability of the steady state measurements

At the TU-Graz some of the steady state ARTEMIS points were measured 4 times with mode durations between 2 to 15 minutes at a EURO 2 engine to assess the repeatability of the results for measurements are small with exception of points at low engine loads (Table 10).
Table 10: Deviation of measured emissions at steady state points in 4 repetitions (EURO 2, 300 kW)

<table>
<thead>
<tr>
<th>Measured point</th>
<th>Deviation to average measured value</th>
</tr>
</thead>
<tbody>
<tr>
<td>kW rpm NOx HC CO CO₂</td>
<td></td>
</tr>
<tr>
<td>-0.04 600</td>
<td>-0.2% 1.4% -6.9% -1.7%</td>
</tr>
<tr>
<td>0.15 600</td>
<td>3.3% 3.4% -4.8% 0.8%</td>
</tr>
<tr>
<td>-0.21 601</td>
<td>-4.0% 1.0% -7.3% -1.1%</td>
</tr>
<tr>
<td>0.10 601</td>
<td>0.8% -5.8% 19.0% 2.0%</td>
</tr>
<tr>
<td>3.1.2.1.1 Average deviation at idling</td>
<td>2.6% 3.4% 11.0% 1.5%</td>
</tr>
<tr>
<td>54.02 1174</td>
<td>1.6% -0.3% 1.2% 0.9%</td>
</tr>
<tr>
<td>54.09 1174</td>
<td>0.6% -2.1% -1.0% 0.5%</td>
</tr>
<tr>
<td>54.32 1174</td>
<td>-1.6% 3.3% 3.3% -0.7%</td>
</tr>
<tr>
<td>54.56 1174</td>
<td>-0.6% -0.8% -3.6% -0.7%</td>
</tr>
<tr>
<td>3.1.2.1.2 Average deviation at 54kW, 1174 rpm</td>
<td>1.2% 2.0% 2.6% 0.7%</td>
</tr>
<tr>
<td>108.27 1174</td>
<td>1.3% 1.1% 3.0% 0.3%</td>
</tr>
<tr>
<td>108.46 1174</td>
<td>-4.1% 0.8% 3.3% -0.9%</td>
</tr>
<tr>
<td>108.64 1174</td>
<td>1.6% -1.4% -4.2% 0.4%</td>
</tr>
<tr>
<td>108.73 1174</td>
<td>1.3% -0.4% -2.1% 0.2%</td>
</tr>
<tr>
<td>Average deviation at 109 kW, 1174 rpm</td>
<td>2.4% 1.0% 3.2% 0.5%</td>
</tr>
<tr>
<td>272.71 1482</td>
<td>-0.1% -4.9% 1.6% -0.2%</td>
</tr>
<tr>
<td>273.96 1483</td>
<td>0.9% 0.3% -0.5% 0.4%</td>
</tr>
<tr>
<td>274.31 1483</td>
<td>-0.2% 1.4% -1.4% 0.0%</td>
</tr>
<tr>
<td>274.41 1483</td>
<td>-0.6% 3.2% 0.4% -0.2%</td>
</tr>
<tr>
<td>3.1.2.1.3 Average deviation at 274 kW, 1483 rpm</td>
<td>0.6% 3.0% 1.1% 0.2%</td>
</tr>
<tr>
<td>220.46 1790</td>
<td>0.3% -1.9% -0.8% -0.3%</td>
</tr>
<tr>
<td>222.34 1791</td>
<td>-0.7% 2.3% 1.3% -0.6%</td>
</tr>
<tr>
<td>220.86 1791</td>
<td>-0.3% -1.2% 0.4% 0.5%</td>
</tr>
<tr>
<td>221.29 1791</td>
<td>0.7% 0.8% -1.0% 0.4%</td>
</tr>
<tr>
<td>3.1.2.1.4 Average deviation at 221 kW, 1791 rpm</td>
<td>0.5% 1.6% 1.0% 0.5%</td>
</tr>
</tbody>
</table>

3.1.3 Assessment of the steady state measurements

The assessment of the measured steady state engine maps shows that it is essential for the elaboration of real world emission factors for modern engines to use off-cycle measurements as well. Since electronic engine control systems – used from EURO 2 levels on - allow different injection timings over the engine map, optimisations in the specific fuel consumption can result in increased NOx emissions outside of the homologation test points. Actual common rail injection systems in EURO 3 engines give additional degrees of freedom e.g. from the rail-pressure and the possibility for pre-injection and post-injection what offers also possibilities for influencing the particle emissions differently within the engine map.

Figure 8 shows two typical NOx engine emission maps for EURO 1 engines with mechanical injection control. The emission maps are normalised for the engine speed (idling = 0%, rated speed = 100%) and the engine power (rated power = 100%). The emission values are given in (g/h)/kW_rated power. This unit is used in the vehicle emission model (see paragraph 4.4.2), and makes engines with different rated power directly comparable in these graphs.
The typical NO\textsubscript{x}-engine emission maps from EURO 1 and “Pre-EURO 1” engines are very smooth. Figure 9 gives the NO\textsubscript{x} emission maps for 6 different Euro 2 engines (different manufacturers). Compared to EURO 1 the NO\textsubscript{x} levels are lower at the 13-mode test points. Off-cycle the levels are higher than for Euro 1 engines. Obviously the injection time is later at the official test points, resulting in lower NO\textsubscript{x} but somewhat higher fuel consumption and particle emissions. Having the demand of the customers for low specific fuel consumption of HDV in mind, for many engine models an earlier injection time is chosen at off-cycle points.

The tested EURO 3 engines show a different setting according to the new ESC (European Steady State Cycle). The EURO 3 regulation also limits the NO\textsubscript{x} emissions between the 3 engine speeds of the homologation test. Corresponding to this regulation the EURO 3 NO\textsubscript{x} emission maps have a low level between the highest and lowest engine speed from the ESC. Outside of this range also for EURO 3 engines an optimisation for the specific fuel consumption can be observed, resulting in increased NO\textsubscript{x} emissions (Figure 10).
Figure 9: Steady-state NO\textsubscript{x}-engine emission map for six different EURO 2 engines

Figure 10: Steady-state NO\textsubscript{x}-engine emission map for six different EURO 3 engines
Looking at the emissions in the 13-mode test (R49) – where for almost all engines from the data collection emission values are available – it is found that even in this type approval test only small reductions in the emission level have been achieved from EURO 1 to EURO 2 since EURO 2 engines on average were much closer at the limit values than the EURO 1 engines. For the EURO 3 engines the ESC test was used for the following graphs. To give an impression of the emission level over the complete engine map, the following figures show also the emissions in a weighted 29-point map, which is drawn from the standardised engine map (see 4.4.2). The difference to the emission values given for the ECE R49 and the ESC is that the weighted 29 point value covers the measured off-cycle points too. The emission values of the single points are weighted according to an “average” engine load pattern in real world driving (see 4.4.2). Figure 11 shows, that the fuel consumption values correspond quite well in the ECE R49 test and the 29-point map.

Figure 11: Fuel consumption in the type approval tests (above) and in the weighted 29-point map (below) for different engines.
The average emission levels of NO\textsubscript{x} decreased clearly from pre EURO 1 engines to EURO 1 (Figure 12). Three of the EURO 2 engines available exceed the limits in the ECE R49 test where the engine with the highest NO\textsubscript{x}-level was not implemented into the databank for the emission factors because it obviously had malfunctions in the engine control unit (ECU). While the NO\textsubscript{x}-emissions in the ECE R49 decreased from EURO 1 to EURO 2, the NO\textsubscript{x} values in the weighted 29-point map have on average the same emission level for EURO 2 than for EURO 1. This indicates, that EURO 2 engines on average have higher emissions in points not covered by the R49 test. This was already visible from the engine maps given before.

The measured EURO 3 engines show lower NO\textsubscript{x} emissions than EURO 2 engines in the type approval test (ECE R49 or ESC respectively), over the total engine map the NO\textsubscript{x} values for EURO 3 are also clearly below the EURO 2 average. This results from the broader range covered by the new ESC test. The different engine control strategy at the type approval points and in the other range of the engine map leads to the fact that the emission levels of EURO 2 and EURO 3 engines in real world driving exceed the corresponding ECE limits emission limits.

![Figure 12: NO\textsubscript{x}-emissions in the type approval tests (above) and in the weighted 29-point map (below) for different engines.](image-url)
CO emissions dropped clearly from pre-EURO 1 to EURO 1, but the levels of EURO 1, 2 and EURO 3 engines look rather similar at the 29 point engine map (Figure 13). But CO is not a critical emission for HDV and all engines are clearly below the limits.

Figure 13: CO-emissions in the type approval tests (above) and in the weighted 29-point map (below) for different engines.

Like for CO and NOₓ the HC-emissions dropped from the construction years before 1990 to EURO 1 and only small changes occurred from EURO 1 to EURO 3 (Figure 14).
For particle emissions no data for the ECE R49 13-mode tests for engines older than EURO 1 are available. Anyhow, particle engine maps are available for all of these engines, but not measured at the points according to the 13-mode test. The data on the ECE R49 tests show a significant drop from EURO 1 to EURO 2 (Figure 15). The tested EURO 3 engines have lower particulate emissions in the corresponding type approval tests than the tested EURO 2 engines. Looking at the complete engine map (29-point values) the clear decrease in the particle emissions from engines built in the 80ies to EURO 1 is visible. An even more significant drop of the particle emission levels was reached from EURO 1 to EURO 3. On the other hand, the average particle emissions from the tested EURO 3 engines are only 14% lower than the average EURO 2 values over the complete engine map, although the emission limits have been reduced by one third.
Figure 15: Particle-emissions in the type approval tests (above) and in the weighted 29-point map (below).

The analysis performed shows clearly that the decision to take a sufficient number of off-cycle test points into the ARTEMIS steady state programme was fundamental for assessing real world emission behaviour of HDV. Emission maps obtained from the R 49 13-mode test or the ESC would underestimate the emission level especially for NOx significantly for many engines.

In the following a comparison between the emission behaviour of engines from Western and Eastern European manufacturers is made. For this analysis measurements of the following Eastern European engines are available:

- 1 “pre EURO 1” engine
- 1 EURO 2 engine
- 2 EURO 3 engines
Table 11 gives a comparison of the emission levels of the average Western European engine certified according emission standards before EURO 1 and the comparable Eastern European engines. Both the average Western European engine and the tested Eastern European engine fulfilled the emission limits (“EURO 0” 1990, last emission tier before the introduction of “EURO 1”), for NOx, CO and HC in the type approval test as well as in real world engine load patterns. Also the levels of the PM emissions the are in a comparable order of magnitude, although no PM emission limit value was defined until EURO 1 came into force.

Table 11: Comparison emissions Eastern and Western European engines, Pre EURO 1

<table>
<thead>
<tr>
<th></th>
<th>FC</th>
<th>NOx</th>
<th>CO</th>
<th>HC</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Western Europe engines average</strong></td>
<td>246.4</td>
<td>10.7</td>
<td>4.3</td>
<td>1.2</td>
<td>---</td>
</tr>
<tr>
<td><strong>Eastern Europe engine 1</strong></td>
<td>244.5</td>
<td>12.0</td>
<td>3.7</td>
<td>1.1</td>
<td>0.37</td>
</tr>
<tr>
<td><strong>Western Europe engine average</strong></td>
<td>242.8</td>
<td>12.1</td>
<td>2.7</td>
<td>0.7</td>
<td>0.43</td>
</tr>
<tr>
<td><strong>Eastern Europe engine 1</strong></td>
<td>239.4</td>
<td>13.1</td>
<td>3.8</td>
<td>1.1</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Table 12 shows the comparison between Western an Eastern European engines for the emission standard EURO 2. As discussed above the EURO 2 Western European engines fulfilled the limit value for NOx emissions in the type approval test (6.6 g/kWh), but are optimised for fuel consumption in real world engine load pattern what results in remarkable higher NOx emissions outside the ECE R49 test (7.2 g/kWh, using the weighted 29 points map). The tested Eastern European engine shows a slightly lower NOx emission level in real world driving (5.7 g/kWh) compared to the type approval test (5.9 g/kWh). As a consequence of this, the specific fuel consumption of the Eastern European EURO 2 engine is more than 10g/kWh worse compared to the average Western European EURO 2 engine. The PM emission level of the average Western European engine and the Eastern European engine are approximately equal.

Table 12: Comparison emissions Eastern and Western European engines, EURO 2

<table>
<thead>
<tr>
<th></th>
<th>FC</th>
<th>NOx</th>
<th>CO</th>
<th>HC</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Western Europe engines average</strong></td>
<td>210.6</td>
<td>6.6</td>
<td>0.9</td>
<td>0.2</td>
<td>0.12</td>
</tr>
<tr>
<td><strong>Eastern Europe engine 2</strong></td>
<td>221.6</td>
<td>5.9</td>
<td>1.6</td>
<td>0.3</td>
<td>0.12</td>
</tr>
<tr>
<td><strong>Western Europe engine average</strong></td>
<td>206.8</td>
<td>7.2</td>
<td>0.8</td>
<td>0.2</td>
<td>0.11</td>
</tr>
<tr>
<td><strong>Eastern Europe engine 2</strong></td>
<td>220.0</td>
<td>5.7</td>
<td>1.1</td>
<td>0.3</td>
<td>0.14</td>
</tr>
</tbody>
</table>

A comparison between the average Western European engine and the two tested Eastern European engines for the emission standard EURO 3 is given in Table 13. Again the Eastern European engines obviously were less optimised for fuel consumption, what results in slightly lower NOx emissions in real world load patterns and a slightly higher fuel consumption. The differences are however much lower than for the emission standard EURO 2.

---

3 About 50% of the 10g/kWh difference in the specific fuel consumption can be attributed to the fact, that the tested Eastern European engine has a lower rated engine power compared to the average Western European engine (the specific fuel consumption decreases with increasing engine size, see page 60)
### Table 13: Comparison emissions Eastern and Western European engines, EURO 3

<table>
<thead>
<tr>
<th>Type approval test (ESC)</th>
<th>Limit EURO 3</th>
<th>Western Europe engines average</th>
<th>Eastern Europe engine 3</th>
<th>Eastern Europe engine 4</th>
<th>Western Europe engine average</th>
<th>Eastern Europe engine 3</th>
<th>Eastern Europe engine 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>---</td>
<td>5.0</td>
<td>2.1</td>
<td>0.7</td>
<td>0.10</td>
<td>212.1</td>
<td>4.9</td>
</tr>
</tbody>
</table>

[ g/kWh]

Summarising it can be stated that the three tested Eastern European engines for EURO 2 and EURO 3 have not been that optimised for fuel consumption outside the type approval tests like the Western European engines, and therefore show a lower emission level for NO\textsubscript{x} compared to real world driving. Since the Eastern European Engines are not very frequent on the European roads they have not been included in the model for the simulation of the emission factors. In general there is no indication that Eastern European engines have a higher emissions level compared to their Western European counterparts.

#### 3.2. Engine test bed, transient measurements

The ARTEMIS measurement programme consists of the following cycles:

- ETC (European Transient Cycle, Figure 16)
- ELR (European Load Response test)
- TNO-real world cycles (for 7 kW per ton total vehicle weight and 12.5 kW per ton total vehicle weight; Figure 17, Figure 18)
- DACH-Handbook-test cycle (designed to cover different transient engine load patterns for model validation rather than to reflect real world engine loads; Figure 19)

A detailed description of the test programme is given in [25].

23 engines with useful results for transient tests are available. Most of them followed exactly the ARTEMIS programme. A detailed analysis of this data for the development of transient correction functions is given in chapter 4.5.2.
Figure 16: European Transient test Cycle (ETC)
Figure 17: TNO real world test Cycle (12.5 kW/ton)
Figure 18: TNO real world test Cycle (7 kW/ton)
3.2.1 Assessment of the transient engine tests

To assess the changes in emissions from EURO 2 to EURO 3 technology, for three measured EURO 3 engines also the corresponding predecessor EURO 2 engine was measured in transient tests. Figure 20 shows the measured fuel consumption [g/kWh] of the EURO 3 engines and of the EURO 2 engines. The EURO 3 engines have about 3% higher fuel consumption compared to the EURO 2 engines. The engines of manufacturer 3 show the smallest increase from EURO 2 to EURO 3. For the EURO 3 engine of manufacturer 3 it is assumed, that the engine control strategy is different under transient load compared to steady state conditions (chapter 4.6.2).
Figure 20: Measured fuel consumption for three EURO 3 engines and for the predecessor EURO 2 engines from different manufacturers in two different transient cycles.

Figure 21 gives the measured NOx-emissions [g/kWh] for the EURO 3 engines and the EURO 2 predecessor engines. The EURO 3 engines show reductions from –15% up to even little increased emissions compared to the corresponding EURO 2 engines, depending on the test cycle.

In agreement with the measured fuel consumption values, the EURO 3 engine from manufacturer 3 shows the smallest NOx reduction rates compared to the EURO 2 predecessor. The EURO 2 engines of manufacturer 1 and manufacturer 3 have very low NOx emission levels compared to all EURO 2 engines measured. This may be an explanation for the rather small NOx reduction rates from EURO 3 to EURO 2. The simulated emission factors (chapter 9) – which are based on a much broader number of tested engines - give clearly higher reductions from EURO 3 to EURO 2. For the 6 engines shown here, the NOx emissions measured in the ETC and TUG cycles are on average 10% lower for the EURO 3 engines than for the EURO 2 engines on average, what is rather below the expected reduction rate. In comparison, the NOx limit was reduced by 29% from EURO 2 to EURO 3 (see Table 24 on page 77).
The ratio of the particle emissions from EURO 3 to EURO 2 showed a strong dependency on the manufacturer (Figure 22). On average, the particle emissions measured in the ETC and TUG cycles are on the same level for the EURO 3 engines than for the EURO 2 engines. In comparison the emission limits for particulate emissions were reduced by 33% from EURO 2 to EURO 3. As for NOx, the EURO 2 engines from manufacturer 1 and manufacturer 3 showed the lowest particulate emission levels in the ETC of all EURO 2 engines measured.

Figure 21: Measured NOx-emissions for three EURO 3 engines and for the predecessor Euro 2 engines from different manufacturers in two different transient cycles

Figure 22: Measured particle emissions for three EURO 3 engines and for the predecessor Euro 2 engines from different manufacturers in two different transient cycles
For CO emissions the EURO 3 engines have on average over the ETC and TUG cycle 37% higher emissions than the EURO 2 engines (Figure 23). The EURO 3 engine from manufacturer 2 exceeds the CO levels from the EURO 2 engine clearly but the EURO 2 version had very low CO levels already.

![Graph of CO emissions for different manufacturers and engine versions](image)

**Figure 23:** Measured CO-emissions for three EURO 3 engines and for the predecessor Euro 2 engines from different manufacturers in two different transient cycles

For hydrocarbons the evaluation gave –20% from EURO 2 to EURO 3 but again with a high dependency on the test cycle used (Figure 24).

![Graph of HC emissions for different manufacturers and engine versions](image)

**Figure 24:** Measured HC-emissions for three EURO 3 engines and for the predecessor Euro 2 engines from different manufacturers in two different transient cycles

Later on in the report a detailed comparison of steady state measurements and the transient tests is given (paragraph 4.5).
3.3. **Chassis dynamometer measurements**

The tests on the HDV-chassis dynamometer were mainly performed for model development and model evaluation (paragraph 4.6). The engines are tested on the engine test bed according to the ARTEMIS/D.A.CH.-NL. programme, then the engine is fitted into the HDV again and the tests on the chassis dynamometer are performed. This gives the whole chain for model development from steady state emission maps and transient engine tests to the simulation of HDV driving cycles.

To cover a broad range of relevant driving situations for the model validation, the following driving cycles have been measured:

- 2 urban cycles: medium dynamic, high dynamic
- 3 rural cycles: low dynamic, medium dynamic, high dynamic
- 3 highway cycles: low dynamic, medium dynamic, high dynamic

The cycles are taken from the Handbook on Emission Factors [67] and were selected after model runs with PHEM (chapter 4), according to the calculated engine load, changes of the engine load (dynamics) and the vehicle speed respectively to cover low-speed to high-speed cycles and low-dynamic to high-dynamic cycles. Figure 25 shows the speed curve of these cycles which are measured with 0% road gradient simulation.

Additionally, emissions at constant speeds are measured, whereby the vehicle speed and the driving resistances are adapted to measured steady-state points on the engine test bed. This allowed an assessment of the potential inaccuracy related to different measurement systems and different boundary conditions compared to the tests on the engine test bed (paragraph 4.6.3).

![Figure 25: Driving cycles for the measurements on the chassis dynamometer.](image-url)
Three HDV were tested according to the complete D.A.CH.-NL programme. As an example Figure 26 gives the measured NO$_x$- and PM emissions for a EURO 2 HDV for the cycles measured as a function of average cycle speed.

![Graph showing NO$_x$ and PM emissions for a EURO 2 HDV on the chassis dynamometer for different real-life driving cycles as a function of average cycle speed.](image)

**Figure 26:** NO$_x$ and PM -emissions measured for a EURO 2 HDV on the chassis dynamometer for different real-life driving cycles as a function of average cycle speed

3.4. **On-board emission measurements**

On-board measurements have been performed in real traffic situations and on an isolated test track. The used measurement systems are VOEM (Vito’s On-the road Emission & energy Measurement system, [40]) and VOEMLow (Vito’s On-the road Emission & energy Measurement system for Low emitting vehicles, [42]). Both are dedicated systems for on-board measurements of (ultra low) gaseous emissions and fuel consumption of vehicles and enable to analyse the dynamic emission behaviour under real life driving. VOEM and VOEMLow consist of an on-line sampling system for the exhaust gas, laboratory grade analysers, measuring equipment of fuel consumption, vehicle speed, engine speed and lambda value, the power supply and a data-acquisition system. The major differences in the methodology between the two systems are the absence of dilution in the VOEMLow system resulting in a higher sensitivity for low concentrations. The measurement of particulate matter emission is realised over an on-board real time PM mass measurement system as a module of VOEM and VOEMLow. It consists of a R&P TEOM 1105 weighing device coupled with a Horiba MDT-905 sampling system, both controlled by a rugged PC [41].

Three heavy duty vehicles were tested by VITO using VOEM(Low), one small rigid truck (EURO2) and two buses (EURO1 and EURO2). On one vehicle simultaneous on-board and transient chassis dynamometer measurements have been performed to establish the possible differences between the two systems.
3.4.1 Vehicle 1

The main objective of the measurement campaign on vehicle 1 (rigid truck, emission standard EURO2) was a comparison of the on-the-road measurement systems with the standard CVS system on chassis dynamometer (Figure 27). For this purpose the vehicle was measured on the roller test bed of TU Graz with on-board measurement devices and CVS system running in parallel. VOEMLow is compared to CVS for only part of the tests (tests on November 16th). For VOEMLow all average differences are well below 10%. This is confirmed by over 150 comparative tests executed on 2 LD diesel fuelled vehicles and one ultra low emitting LD petrol one (as part of the EC funded Decade project and realised on CVS systems of IDIADA and MIRA). The on-board measurement of PM emissions with the TEOM show an average underestimation of 30% compared to the gravimetric measurements with the CVS system.

![Figure 27: Difference of the results from the onboard measurement systems to the standard CVS system](image)

3.4.2 Vehicle 2

Vehicle 2 (city bus, emission standard EURO 1) was measured using the VOEMLow system both on a test track performing HBEFA cycles and on real bus lines in Barcelona. Emissions and fuel consumption measured on a bus line with no road gradient and with an average road gradient of 2% (positive in one and negative in the other direction) were compared.

3.4.3 Vehicle 3

Emission measurements on vehicle 3 (city bus, emission standard EURO 1) were performed in Belgium around Mol and the city of Turnhout. All measurements have been executed with two different vehicle loadings (1 ton, 5.6 tons).

More details on the used measurement systems and the on-board measurement program are given in the report on ARTEMIS WP434 [76]. The measured emission results are compared with model results in paragraph 4.6.3 and in Appendix II.
4. THE HDV EMISSION MODEL

The methodology chosen for the model PHEM (Passenger Car and Heavy duty Emission Model) is based on an extensive literature review and on a previous feasibility study [28]. The following gives a short summary on how it was decided to use this approach.

With the exception of the “Tieber” model all vehicle models reviewed employ the same methodology to simulate engine torque and engine speed. Driving resistance and transmission losses are used to calculate the actual engine power, and transmission ratios and a gear-shift model are combined to calculate the actual engine speed. All the models use emission maps for the calculation of fuel consumption and emissions as function of torque/power and engine speed. Two models offer use fixed driving cycles, the other models require speed-time cycles as an input.

The influence of transient engine load (compared with steady-state load) on emission behaviour is taken into consideration in two of the models (TNO, TUG). The methods used by TNO and TUG for analysing and taking into account the effects of transient operation on emissions are similar; both approaches are based on the differences between the emissions calculated using steady-state emission maps and the emissions measured during transient cycles. Both models use functions to describe these differences using parameters describing driving cycle dynamics. The TNO approach is based on a parameter relating to vehicle speed (RPA, relative positive acceleration), the TUG approach is based on parameters relating to engine power and engine speed. Table 14 gives a summary of the features of the models reviewed.

Table 14: Main features of the models reviewed

<table>
<thead>
<tr>
<th>Model</th>
<th>Driving cycles</th>
<th>Torque/Power</th>
<th>Engine Speed</th>
<th>Fuel Cons.</th>
<th>Emisions</th>
<th>Transient correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHEM, TU-Graz</td>
<td>Speed curve as input, gears can be computed</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>ADVISOR 2000</td>
<td>Speed curve as input</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Tieber, TU-Graz</td>
<td>Speed curve as input</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Implicit</td>
</tr>
<tr>
<td>Vehicle Motion Simulator, Finland</td>
<td>Speed and gears can be computed</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>SIMULULCO, INRETS</td>
<td>Speed and gears can be computed</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>TÜV-Rheinland</td>
<td>Speed curve as input</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>TNO van de Weijer</td>
<td>Speed curve as input</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>TNO-ADVANCE</td>
<td>Speed-curve as input</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Possible</td>
</tr>
<tr>
<td>TNO HD Testcycles</td>
<td>Cycle and vehicle parameters as input</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Implicit</td>
</tr>
<tr>
<td>VETO (VTI)</td>
<td>Speed and gears can be computed</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>SEEK (Danish Technological Institute)</td>
<td>Speed curve as input, gears computed</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>NO</td>
</tr>
</tbody>
</table>

Following boundary conditions were given for the project:

- the emission factors have to be calculated for given driving cycles, so it was decided to use these cycles as model input. The model should perform only checks on the driveability of the cycles with the given vehicle and engine characteristics.
most of the available measurements are steady state engine emission maps, so it was decided to use these maps as basic input. This leads to the demand of simulating engine power and engine speed from the given driving cycles.

The accuracy of the emission simulation should be high, so the development of transient correction functions for the emissions gained from the steady state maps was necessary.

The models PHEM, Vehicle Motion Simulator, TNO HD Testcycles, VETO, ADVISOR and SEEK have been included in a common procedure of model comparison and model improvement in the project COST 346. The model comparison was based on HDVs which have been measured on the chassis dynamometer and whose engines were tested on the engine test bed as well. All tested models showed a good performance in the comparison (see Appendix VII for more details). Since a basic version of the model PHEM was available from the HBEFA work already as complete source code and PHEM included already important features like a gear shift model, standardisation of emission maps and a transient correction function, it was decided at first within ARTEMIS to do further improvements based on the model PHEM. Consequently the data structure for the simulation of emission factors from the engine tests was designed in formats necessary as input for the model Phem. As a result, from the reviewed models only Phem has at present all relevant input data available to simulate emission factors for average HDV from Euro 0 to Euro 3 in all vehicle size categories. Thus the simulation results provided in this report are gained by the model Phem. However, we assume that all other model approaches can make use of the newly available data also if they are based on engine test data.

4.1. Basic methodology

The model interpolates the fuel consumption and the emissions from steady state engine emission maps for every second of given driving cycles. For interpolating the emissions from the engine map the actual power demand from the engine and the engine speed are simulated according to the vehicle data given as model input. The simulation of the actual power demand of the engine is based on the driving resistances and the transmission losses. The engine speed is calculated using the transmission ratios and a gear-shift model.

The different emission behaviour over transient cycles is taken into consideration by “transient correction functions” which adjust the second-by-second emission values according to parameters describing the dynamics of the driving cycle.

The results of the model are the engine power, the engine speed, the fuel consumption, and emissions of CO, CO₂, HC, NOₓ and particles every second, as well as average values for the entire driving cycle. Figure 28 gives the scheme of the model.
While this method is common for most models compared (with exception of the transient correction function), the model PHEM has some special features developed straightforward to enable easy simulations of average HDV classes.

The input data is modular, i.e. different files for:
- The vehicle characterisation
- The driving cycle
- The engine emission map
- The full load curve

This enables a quick simulation of a whole variety of vehicle / driving cycle combinations.

A main problem in the elaboration of emission factors for average HDV is to have a sufficient number of engines measured for each HDV fleet segment because overall more than 100 segments of the fleet have to be covered. A “fleet segment” is defined here as the combination of a vehicle type (e.g. single truck or truck trailer) with a EURO category (e.g. EURO 3) and a size class (e.g. 34-40 tons maximum allowed payload). Since each size class has its typical values for the rated engine power, each measured engine basically can be applied to one fleet segment only.

To avoid a separation of the measured engines according to the rated engine power, the engine maps are normalized and brought into a standard format (see par. 4.4.2). This enables the development of average engine maps independent of the engine size. Without this method of averaging emission maps, even the high number of measured engine maps available for this project would leave some “HDV-layers” covered by one engine only (or even without an appropriate engine at all). The method of size independent averaging guarantees that the single HDV fleet segments are covered by a proper number of measurements of different engines.

In the input file for the driving cycle the measured engine speed or the gear position can be given as optional model input. If neither the engine speed nor the gear position is given in the input file, PHEM uses the gear-shift model to simulate the engine speed. When recalculating
driving cycles measured at the chassis dynamometer, differences between simulated and measured emissions related to differences in the gear-shift strategy can be addressed exactly. This is a helpful tool for model development and model validation.

For the development of the transient correction functions and the normalisation of the engine emission maps PHEM offers an “engine only” and an “engine analysis” option. With these options engine power and engine speed cycles can be recalculated according to the measurements on the engine test bed instead of modelling the total vehicle. In the following each step of the simulation is described in detail.

4.2. Simulation of the engine power

For a proper simulation of the actual engine power all relevant driving resistances occurring in real world cycles have to be taken into consideration. Limit for the details to be covered is mainly the availability of data necessary for the simulation of the forces caused by single parts of a vehicle.

PHEM is developed to make mainly use of the data available from the data collection of the project. More detailed approaches have been tested too for single vehicles, as to whether they could bring better results for the emission simulation. The experience was that more detailed data is very hard to get from manufacturers on the one hand and that on the other hand a more detailed input shows only very little influence on the simulated results. Thus, the drive train system is not simulated in detail but as a unit block. This shall guarantee that all necessary model input data is covered by an adequate number of measurements.

The actual engine power is calculated according to:

\[ P = P_{\text{rolling resistance}} + P_{\text{air resistance}} + P_{\text{acceleration}} + P_{\text{road gradient}} + P_{\text{transmission losses}} + P_{\text{auxiliaries}} \]

The single parts of the total power demand from the engine are calculated as follows.

4.2.1 Power for overcoming the rolling resistance

The power for overcoming the rolling resistance is simulated in PHEM using the well known approach:

\[ P_R = m \times g \times (f_{r0} + f_{r1} \times v + f_{r2} \times v^2 + f_{r3} \times v^3 + f_{r4} \times v^4) \times v \]

where:
- \( P_R \) ..........power in [W]
- \( m \) ..........mass of vehicle + loading [kg]
- \( g \) ..........gravitational acceleration [m/s²]
- \( f_{r0} \) to \( f_{r4} \) ......rolling resistance coefficients
- \( v \) ..........vehicle speed in [m/s], the vehicle speed is computed as average speed of second \( i \) and second \( (i+1) \) from the given driving cycle. The corresponding acceleration is \( (v_{i+1} - v_i) \).

The determination of the rolling resistance coefficients for the different vehicle categories is described in chapter 6.
4.2.2 Power for overcoming the air resistance

The power for overcoming the air resistance is simulated as

\[ P_{\text{air}} = C_d \times A_{\text{frontal}} \times \frac{\rho}{2} \times \nu^3 \]

with:
- \( P_{\text{air}} \) ...........power in [W]
- \( C_d \) ..............drag coefficient [-]
- \( A_{\text{frontal}} \) .........frontal area of the HDV in [m²]
- \( \rho \) .................density of the air [on average 1.2 kg/m³]

The values for \( C_d \) and \( A_{\text{frontal}} \) are taken from the specifications given by the manufacturer. If no manufacturer specifications for the \( C_d \) value were available the \( C_d \) was set according to those of a similar HDV in a data bank of the TUG Institute (see chapter 6).

4.2.3 Power for acceleration

The model offers two options for the simulation of the power demand for vehicle acceleration. The more detailed option simulates the rotating masses as three blocks: wheels, gearbox, other rotating masses:

**Option 1:**

For the calculation the power for the acceleration of the rotating masses is converted to the vehicle acceleration. This gives the following equation:

\[ P_a = (m_{\text{vehicle}} + m_{\text{rot}} + m_{\text{loading}}) \times a \times \nu \]

with:
- \( m_{\text{rot}} \)....... to the wheel reduced mass for rotational accelerated parts

\[ m_{\text{rot}} = \frac{I_{\text{wheels}}}{r_{\text{wheel}}^2} + I_{\text{mot}} \times \left( \frac{i_{\text{axle}} \times i_{\text{gear}}}{r_{\text{wheel}}^2} \right)^2 + I_{\text{transmission}} \times \left( \frac{i_{\text{axle}}}{r_{\text{wheel}}} \right)^2 \]

- \( I \) ........... moment of inertia from the rotating masses [kg m²]
- \( a \) ........... acceleration of the vehicle [m/s²]
- \( \nu \) ........... vehicle speed [m/s]

The part of the wheels can be simplified assuming the wheels to be cylinders (\( I = m \times r^2 / 2 \))

\[ \frac{I_{\text{wheels}}}{r_{\text{wheel}}^2} = 0.5 \times m_{\text{wheels}} \]

with:
- \( m_{\text{wheels}} \)..... mass of the vehicles wheels (including rims)

If the moments of inertia are not known, a simplified method is used:

**Option 2:**

\( m_{\text{rot}} \) from the formula above is assessed by a “rotating-mass-factor” \( \Lambda \):

\[ \Lambda(\nu) = \frac{m_{\text{veh}} + m_{\text{rot}}}{m_{\text{veh}}} \]

With this simplification the power for acceleration is:

\[ P_a = (m_{\text{veh}} \times \Lambda(\nu) + m_{\text{loading}}) \times a \times \nu \]
\( \Lambda \) is expressed as function of the vehicle speed in this option to take the influence of the differing transmission ratios and the resulting decreasing influence of angular acceleration of the engine and the gear box block with increasing vehicle speed into consideration.

with:  
\[ \Lambda(v) = \Lambda_0 \times 0.833 \times [1 - 0.4 \times \log(v \times 0.0667)] \]  
for \( 1 \text{m/s} < v < 12 \text{m/s} \)

below \( 1 \text{m/s} \) \( v \) is set equal 1, above \( 12 \text{m/s} \) \( v \) is set to constant 12.0

\( a \)..........................acceleration of the vehicle \([\text{m/s}^2]\)
\( m_{\text{vehicle}} \).............mass of the vehicle (ready for driving) in \([\text{kg}]\)
\( m_{\text{loading}} \)..............mass of the payload or the passengers and luggage in \([\text{kg}]\)
\( \Lambda_0 \).................rotating mass factor, to be given as model input (ca. 1.05 to 1.2)

The formula for option 2 is derived from the more detailed simulation according to the model for option 1.

For the first assessment of the actual power demand always the simplified equation is used since the gear choice of the driver is modelled as a function of the actual power demand. Thus the gear and the transmission ratios are not known at the first step of iteration.

### 4.2.4 Power for overcoming road gradients

The power for overcoming road gradients is calculated as:\(^4\):

\[ P_g = m \times g \times \text{Gradient} \times 0.01 \times v \]

with:  
\( P_g \)..........................power in \([\text{W}]\)
\( \text{Gradient} \)........road gradient in \%
\( m \)..........................mass of the vehicle + loading in \([\text{kg}]\)

The road gradient has to be given as model input value in the file containing the driving cycle on second per second basis.

### 4.2.5 Power demand of auxiliaries

The assessment of the HDV measurements on the chassis dynamometer suggested a rather constant power demand of auxiliaries from the tested vehicles (compare paragraph 4.6.3). The power demand is therefore calculated in a simplified way:

\[ P_{\text{auxiliaries}} = P_0 \times P_{\text{rated}} \]

with:  
\( P_{\text{auxiliaries}} \).............power in \([\text{kW}]\)^5
\( P_0 \)..........................power demand of the auxiliaries as ratio to the rated power [-]

For average HDV this equation is sufficient from today’s point of view. For special HDVs (e.g. garbage trucks) a more detailed approach may improve the model accuracy.

---

\(^4\) This formula is based on the assumption that \( \sin \alpha = \tan \alpha = \text{Gradient} \), which is valid for the range of road gradients, which are common for driving on paved roads (e.g. error of less than 2\% for a road gradient of 20\%)

\(^5\) Only the power demand of auxiliary equipment which is necessary for the operation of the vehicle but not for engine operation has to be considered in this context. For details see Appendix IV.
4.2.6 Power demand of the transmission system

The power losses between the engine and the wheels are simulated as a function of the actual power, the engine speed and the transmission ratio. A simplified equation according to [70] – based on transmission efficiencies - is used for a first iteration since the gear choice of the driver is modelled as a function of the actual power demand. Thus the gear and the transmission ratios are not known at the first step of iteration.

The transmission efficiency is defined here as:

\[
\eta_{\text{transmission}} = \frac{P_{\text{dr}}}{P_e} = \frac{P_e - P_{\text{transmission}}}{P_e}
\]

and \( P_{\text{transmission}} = P_e - P_{\text{dr}} \)

Simplified equation for the first assessment:

\[
\eta_{\text{transmission}} = \begin{cases} 
-0.57 \times \left( \frac{P_{\text{dr}}}{P_{\text{rated}}} \right)^2 + 2.7 \times \left( \frac{P_{\text{dr}}}{P_{\text{rated}}} \right) + 0.57 & \text{where } P_{\text{dr}}/P_{\text{rated}} < 0.2 \\
-0.0561 \times \left( \frac{P_{\text{dr}}}{P_{\text{rated}}} \right)^2 + 0.1182 \times \left( \frac{P_{\text{dr}}}{P_{\text{rated}}} \right) + 0.8507 & \text{where } P_{\text{dr}}/P_{\text{rated}} > 0.2 
\end{cases}
\]

The power losses in the transmission system are:

\[
P_{\text{transmission}} = \frac{P_{\text{dr}}}{\eta_{\text{transmission}}} - P_{\text{dr}}
\]

with \( P_{\text{dr}} \) ........... Power to overcome the driving resistances (without transmission losses)

After the first rough assessment of the power losses in the transmission system (and after the first iteration of the power necessary for the acceleration of rotating masses) the next subroutine of PHEM is executed which selects the actual gear by a driver gear-shift model (paragraph 4.3).

After the actual gear is determined, the losses in the transmission system are simulated according to the following method.

(a) Manual Gear box

The losses in the transmission system are directly calculated as power loss. The use of transmission efficiencies is avoided since the transmission efficiency is near to zero for low power transmission conditions. This would lead to a not well defined value since a low value for the engine power has to be divided by an efficiency near to zero.

Following the basic method of PHEM, the formulas used are normalised to the rated power of the engine.
Power losses in the Differential [kW]:

\[ P_{\text{Differential}} = P_{\text{rated}} \times 0,0025 \times (-0,47 + 8,34 \times \frac{n_{\text{wheel}}}{n_{\text{rated}}} + 9,53 \times \text{ABS} \frac{P_{\text{dr}}}{P_{\text{rated}}}) \]

with: 
- \( P_{\text{rated}} \): rated power of the engine 
- \( n_{\text{wheel}} \): rotational speed of the wheels [rpm] 
- \( n_{\text{rated}} \): 
- \( P_{\text{dr}} \): power demand from the engine to overcome the driving resistances (= total power demand without transmission losses)

Power losses in the gear box [kW]:

These losses are simulated for four transmission ratios. The losses for gears between these ratios are interpolated linearly. This method takes the characteristics from splitter-gear shifts – which are most common in HDV – into consideration and was gained from measured data of a gear box.

\[
\begin{align*}
P_{1,\text{gear}} &= P_{\text{rated}} \times 0,0025 \times \left( -0,45 + 36,03 \times \frac{n_{\text{engine}}}{I_{1,\text{gear}}} + 14,97 \times \text{ABS} \left( P_{\text{dr}} + \frac{P_{\text{Differential}}}{P_{\text{rated}}} \right) \right) \\
P_{8,\text{gear}} &= P_{\text{rated}} \times 0,0025 \times \left( -0,66 + 16,98 \times \frac{n_{\text{engine}}}{I_{8,\text{gear}}} + 5,33 \times \text{ABS} \left( P_{\text{dr}} + \frac{P_{\text{Differential}}}{P_{\text{rated}}} \right) \right) \\
P_{9,\text{gear}} &= P_{\text{rated}} \times 0,0025 \times \left( -0,47 + 8,34 \times \frac{n_{\text{engine}}}{I_{9,\text{gear}}} + 9,53 \times \text{ABS} \left( P_{\text{dr}} + \frac{P_{\text{Differential}}}{P_{\text{rated}}} \right) \right) \\
P_{16,\text{gear}} &= P_{\text{rated}} \times 0,0025 \times \left( -0,66 + 4,07 \times \frac{n_{\text{engine}}}{I_{16,\text{gear}}} + 0,000867 \times \text{ABS} \left( P_{\text{dr}} + \frac{P_{\text{Differential}}}{P_{\text{rated}}} \right) \right)
\end{align*}
\]

The total power losses in the transmission system are the sum of the losses in the differential and in the gear box. For the calibration of the absolute values a factor \( A_0 \) is introduced which can be set by the model user.

\[ P_{\text{transmission}} = A_0 \times (P_{\text{Differential}} + P_{\text{gear i}}) \]

with: 
- \( A_0 \): factor for adjusting the losses (to be defined in the model input data, usually set to 1).

When setting the factor \( A_0 \) to 1 the transmission losses are in the range given in Figure 29 for real world driving cycles.
(b) Automatic gear box:
The power losses are simulated as a function of the vehicle speed according to [70]. Data for the elaboration of a more detailed approach is not available yet.

$$\eta_{\text{transmission}} = 0.16 + 0.87 \times \left\{ \frac{(0.0001 \times v \times 3.6)^3}{(0.00213 \times (v \times 3.6)^2 + 0.084 \times v \times 3.6)} \right\} \text{ at } v<5.56 \text{ m/s}$$

$$\eta_{\text{transmission}} = 0.88 \text{ at } v>5.56 \text{ m/s}$$

The power losses in the transmission system are then:

$$P_{\text{transmission}} = \frac{P_{\text{dr}}}{\eta_{\text{transmission}}} - P_{\text{dr}}$$

With \( P_{\text{dr}} \) ........... Power to overcome the driving resistances (without transmission losses)

With the equations given in this chapter the power demand from the engine can be simulated for any vehicle / loading / driving cycle combination.

4.3. Simulation of the engine speed

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

Calculation of the engine speed:

$$n = v \times 60 \times i_{\text{axle}} \times i_{\text{gear}} \times \frac{1}{D_{\text{wheel}}} \times \pi$$
The main problem for the simulation is the assessment of the actual gear since a given vehicle speed can be driven with different gears and the choice which gear to take is depending on a subjective assessment of the driver.

The gear shift behaviour is modelled in PHEM for different types of drivers:

a) Fast driver,

b) Economic driver,

c) Average driver.

The basic assumption is that the „fast driver“ style is located in an rpm range where high engine torque and high engine power are available and that the „economic driver“ style is located in an rpm range where the specific fuel consumption is the lowest for the given engine power demand. For these driving styles limits of the engine speed are defined where the gear has to be changed upwards or downwards.

The “average driver” is a mixture of style a) and style b) depending on the engine power needed within the next seconds. If the virtual “average driver” realises that he will need a high engine power within the next seconds (e.g. for acceleration or a road gradient) he will take a gear rather according to style a), if the coming power demand is rather low he will behave like style b). The share of style a) and b) are calculated automatically for style c).

The simulation routines for the different driving styles are given below.

**The „fast driver“ model**

Gear shift up:

An engine speed in the actual gear is fixed (n\textsubscript{up}) where the next higher gear is selected as soon as the actual engine speed exceeds n\textsubscript{up}.

Gear shift down:

An engine speed in the actual gear is fixed (n\textsubscript{down}) where the next lower gear is selected as soon as the engine speed is lower than n\textsubscript{down}.

**The „economic driver“ model**

Gear shift up:

An engine speed is fixed (n\textsubscript{up\_e}) where the next higher gear is selected as soon as the engine speed in the next higher gear is above n\textsubscript{up\_e} (shifts over two gears are also possible)

Gear shift down:

An engine speed is fixed (n\textsubscript{down\_e}) where the next lower gear is selected as soon as the actual engine speed is lower than n\textsubscript{down\_e}.

The engine speeds n\textsubscript{up\_e} and n\textsubscript{down\_e} are set in a way that the virtual driver stays in the engine speed range with the best fuel efficiency of the engine.
The “average driver” model

As expected none of these simple models gives satisfying explanations for the gear shift behaviour for longer real world cycles. By analysing the cycles, the gear-shift behaviour was found to be between the styles a) and b). Therefore, the “average” driver model is a mixture of the style a) and b). As criterion for the shares of the styles a) and b) the maximum power demand within the next 6 seconds is used.

Equations for the gear shifts of the “average driver”

\[
P_{6,\text{max}} = \text{highest } \frac{P_e}{\text{highest }} \quad \text{(in second } i \text{ to second } (i + 5))
\]

with: \( P_e(i) \) — actual engine power at second \( i \) of the cycle divided by the rated engine power

\( i \) — second in the driving cycle

The shares of style a) and b) are defined as follows:

\[
\% \text{"fast driver"} = 100 \times (3.3333 \times P_{6,\text{max}} - 1.6667)
\]

If the calculated share is higher than 100% it is set to 100%, if the calculated share is lower than 0% it is set to 0% (Figure 30).

The share of the „economic driver“ is 100% minus the share of the „fast driver“.
The gear for the „average driver“ model is then:

\[
\text{Gear} = \text{gear}_{\text{fast driver}} \times (\% \text{ fast driver}) + \text{gear}_{\text{economic driver}} \times (\% \text{ economic driver})
\]

The computed value for the gear is then rounded to the most nearby integer value.

Beside the model mix of fast driver and economic driver, the model offers also a manual mixture of fast driver and economic driver from 0% to 100% of each style. For the simulations done for the ARTEMIS emission factors only the model mix was used.

**Figure 30:** share of the “fast driver model” in the “average driver model” as a function of the highest engine power demand within the next 6 seconds

**Additional checks for the computed gear shift strategy**

Many checks and additional gear shift rules are necessary to avoid hectic gear shift behaviour from the model with much to frequent gear shift manoeuvres. The main additional checks are listed below:
• Gear shifts are allowed not more than every 3 seconds
• The engine speed must not exceed the rated engine speed. In this case a higher gear is used.
• The driving cycle is subdivided into phases of cruise (\(|a|<0.125\ \text{m/s}^2\)), acceleration (\(a>0.125\ \text{m/s}^2\)) and deceleration (\(a<-0.125\ \text{m/s}^2\)), where “a” represents the average acceleration value for the seconds (t-2) to t in the cycle in \([\text{m/s}^2]\).
• During deceleration phases gear shifts upwards are suppressed
• During acceleration phases gear shifts downwards are suppressed
• During cruise phases gear shifts are suppressed if the velocity and the actual power demand have not changed by more than 6% since the last gear shift manoeuvre.
• If the initial gear is reached after a gear shift again within 5 seconds this gear shift manoeuvre is suppressed
• If within 6 seconds a higher and a lower gear compared to the initial gear is used, this gear shift manoeuvre is suppressed
• During deceleration phases the driver does only shift back into the 1st gear if an acceleration from velocities below 1.5 m/s follows.
• If the actual engine power demand is higher than the full load power available in the chosen gear, the next lower gear is used if none of the rules before is violated, otherwise the acceleration of the vehicle is reduced.

The gear shift model meets the available measured gear shifts quite well and leads to engine load distributions similar to the ones found in real world traffic.

Certainly also this model approach can not simulate all gear changes – especially for single drivers – exactly. But the calculated engine load (rpm and kW combinations) do match the real world driving very well. This is the most relevant criterion when interpolating emission factors from an engine map. As an alternative for the simulation of the engine speed the model allows also to set the measured engine speed or the measured gear positions as input variables. In this case the measured values are used instead of the simulated ones. This option is helpful for validation work with measurements from the chassis dynamometer.

4.4. Interpolation from the engine emission map

With the equations given in chapter 4.2 and 4.3 the actual engine speed and the actual engine power are calculated for every second of the driving cycle. With this data the emission values are interpolated from the engine emission maps for every second of the cycle.

The resulting emission values are defined here as “quasi stationary emissions” since they are calculated for a transient cycle from an emission map which has been measured under steady state conditions. The total “quasi stationary emissions” over the driving cycle are the integral of the second per second values over the cycle.

The model PHEM is able to handle almost any formats of engine maps, both concerning the number and position of the points in the map, as well as concerning the content of the maps (emission values, voltages, etc.). The only requirement is that units are adapted to the model standards (see paragraph 4.4.2). This flexibility can be used e.g. for the simulation of temperature levels etc.

The routine for the interpolation is described in the next paragraph.
4.4.1 The interpolation routine

To find the best interpolation routine, multiple options were tested on their accuracy and stability for the given task. The method according to Shepard proved to be the most stable routine for differing layouts of the engine map. With some small adaptations, this method proved to be one of the most accurate interpolation routines for the given task, with the additional advantage of being very simple to programme.

The adapted Shepard method:

**Step 1:** the distances between the point to be interpolated and the given points from the engine map in the engine power / engine speed plane are calculated as \( R^2 \).

\[
R^2(i) = \left( P_e - P_{\text{map}}(i) \right)^2 + \left( n - n_{\text{map}}(i) \right)^2
\]

with:

- \( P_e \) .............. actual engine power of the point to be interpolated subdivided by the rated power
- \( n \) .............. actual normalised engine speed of the point to be interpolated
- \( P_{\text{map}}(i) \) ...... engine power of point \( i \) in the engine map subdivided by the rated power
- \( n_{\text{map}}(i) \) ...... normalised engine speed of point \( i \) in the engine map

\( R^2 \) is used as a selection criterion and as a weighting factor for interpolating points with a normalised engine power \( >0.05 \).

**Step 2:** Selection of the points to be used for the interpolation:

Points with \( R^2 < 0.07 \) are used.

If less than 3 points from the map are within this criterion the radius is doubled until three or more points are within the given radius \( R^2 \). \(^6\)

**Step 3:** Modified interpolation according to Shepard:

The emission value for the point to be interpolated is simply gained by the weighted average of the points selected in step 2. The weighting is done according to \( R^2 \) from step 1.

\[
E_o(P_e,n) = \frac{1}{\sum R_{(i)}^2} \times \sum \left( \frac{1}{R_{(i)}^2} \times E_{\text{map}(i)} \right)
\]

\( E_o(P_e,n) \) .............. basic interpolated value (emission, fuel consumption, etc.)

\( E_{\text{map}(i)} \) .............. value for point \( i \) given in the engine map (only for selected points in step 2)

Since the basic Shepard routine is not capable of making extrapolations, the basic interpolated value from the equation above is adjusted assuming a constant emission value [g/kWh] for this small adjustment.

\[
E(P_e,n) = E_o(P_e,n) + E_o(P_e,n) \times (P_e - P_{\text{Sh}})
\]

only if \( P_e \) greater 0.05

with:

\( E(P_e,n) \) .............. interpolated value (emission, fuel consumption, etc.)

\(^6\) This is not relevant when using the standard formats for the engine maps according to paragraph 4.4.2 since the format ensures a sufficient number of points to be located within \( R^2 \) in any case.
P_{Sh}........... basic interpolated normalised engine power like for E_0(P_e,n)

This method gives very accurate results for most parts of the engine map, especially when the standardised formats are used (paragraph 4.4.2). Inaccuracies arise in the range of low or zero engine loads with engine speeds above idle speed. In this range the influence of the engine speed on the emission level proved to be lower than at higher loads. Therefore, the weighting factor for the distance in engine speed direction is decreased. Additionally, the weight of all available measured points near to zero engine power is increased.

The formula is as follows:

**Equation 1:** Weighting factor for interpolating points with an engine power between \(-0.05\) and 0.05 from rated power

\[
\hat{R}^2(i) = \left(\left(P_e - P_{map}(i)\right)^2 + \left(n - n_{map}(i)\right)^2 \times 888.9 \times \left|P_e\right|^3 + 0.001 \times \left|P_e\right| + \left|P_{map}\right| + 0.005\right) \times 9.52
\]

The next modification to the Shepard routine is a lower weighting of points in the map which have a different sign of the engine power compared to the power of the point to be interpolated. This separates the map into the range with positive and negative power output of the engine since the emission behaviour between these ranges is rather different.

In combination with the modified Shepard method a standard engine map with 32 points was found to be the best compromise between accuracy and expenditures for measuring the engine emission map. The ARTEMIS steady state measurement programme is in line with these 32 points found and all standard emission maps for model input into PHEM are using these points (thirteen virtual points are added to the 32 point standard, see paragraph 4.4.2). However, theoretically the method works for all maps containing three or more points. Figure 31 gives the results for the interpolation of 68 points measured at a EURO 2 engine from the standard 32 point engine map. With exception of the fuel consumption, the engine emission maps are not a flat surface. Still, most points are interpolated with an error in the range of the measurement accuracy.
4.4.2 Standard formats for the emission maps

As described in paragraph 4.4.1 a standard format for the engine emission maps was elaborated as a compromise between accuracy and the expenditure necessary for measuring the points on the engine test bed\(^7\). All formats from other projects (such as e.g. the German in-use-compliance programme) can be converted easily into the standard format.

Beside the fact that the combination of the normalised emission maps and the modified Shepard routine give reliable and well validated results for the interpolation from the engine maps, the main reason for the elaboration of normalised engine maps was to provide a possibility for creating average engine maps out of the single engine maps. The advantages of average engine emission maps are explained below:

- A main problem of the elaboration of emission factors for average HDV is to have a sufficient number of engines measured for each HDV fleet segment, because in total more than 100 segments of the fleet have to be covered (“pre-EURO 1 <7.5 ton” up to “EURO 5 60 ton”). Since each size class has its typical values for the rated engine power, each measured engine can basically be applied on only a few fleet segments. A method for averaging engine maps independent of the rated engine power would increase the number of engines applicable per fleet segment approximately by a factor of 10.

---

\(^7\) In general the accuracy of the simulation of steady state emissions increases with the number of points measured in the engine map. Since the data collection includes between 29 and 80 measured points per engine a compromise had to be found, which can also handle a smaller number of measured points.
The elaboration of “transient correction functions” is based on a comparison of the measured emissions in a transient engine cycle and the emissions interpolated from the engine emission map for the same cycle (quasi-stationary emissions). Since the format of the engine map (number and location of the points) has an influence on the results of the interpolation, standard formats for the engine maps are necessary for this task to gain general valid functions. General valid functions for the transient correction are a prerequisite for making use of the broad data base existing of measurements where only steady state tests were performed.

For these reasons a standard map format for all engines was defined where the number and location of the points in the engine map are identical and the values in the map are normalised to be independent of the engine size. The average map can then be calculated simply as the average value for the single points in the map over all engine maps.

The engine maps are normalised in the following way to make them independent of the engine size:

- Engine speed: idle = 0%, rated speed = 100%
- Engine power: 0 kW = 0%, rated power = 100%
- Emission values: (g/h)/kW_rated power

The points measured in the engine map are different for each engine (depending on the full load curve and the measurement programme itself) while in a “standard map” the points have to be fixed (Figure 32). The model PHEM offers a routine to convert the measured points into the standard format by interpolation from all measured values. For this task the routine “create norm map” from PHEM can be used. This routine interpolates the 32 points from the standard map out of all points measured, according to the modified Shepard routine (paragraph 4.4.1).

The method described in paragraph 4.4.1 showed that the accuracy of the interpolation is not optimal in the range of very low engine loads if no measured points are given in the engine map for this range. In this region of the map the accuracy of the measurements is also rather low and shows a poor repeatability.

Since only a few engines have measured steady-state map points in this region, this area was assessed from the transient tests. From the available measurements the ratio of fuel consumption and emissions at points with zero power but engine speeds above idling has been calculated. These data were used to add three points at zero load to all engines where no measurements in this range had been done. A similar approach was applied for the engine map area with engine speeds near to idling, where five points have been added.

Five additional points at the motoring curve (with -25% of the rated power) and different engine speeds are also added in the normalised map, too. For these points fuel consumption and emissions are set to zero (trailing throttle fuel cutoff). This avoids unstable extrapolations in the motoring range (Figure 32).
In Figure 33 to Figure 36 the weighted average emissions in the standard emission map for all EURO 2 and EURO 3 engines available are plotted as a function of the rated engine power. The average emission level for each engine has been calculated by averaging the single emission values according to an average engine load pattern in real world driving (here referred to as “weighting”). For all emission components no trend of the emission level over the rated engine power is visible; for CO and HC emissions of EURO 3 engines the trends differ depending on the manufacturer.

---

8 The real world driving pattern consists of the following time shares: 50% highway, 29% rural and 21% urban driving.
**Figure 34:** Weighted average PM-emission values [g/kWh] in the standard engine maps over the rated engine power for EURO 2 and EURO 3 engines.

**Figure 35:** Weighted average CO-emission values [g/kWh] in the standard engine maps over the rated engine power for EURO 2 and EURO 3 engines.

**Figure 36:** Weighted average HC-emission values [g/kWh] in the standard engine maps over the rated engine power for EURO 2 and EURO 3 engines.
Since the evaluation of all measured engine maps showed no significant dependency between the emission levels (g/kWh) and the rated engine power, it is allowed to create average engine emission maps of engines with different rated engine power. Exceptions are the engines with construction years 1990 and earlier ("pre EURO 1"). In these cases a clearly increasing particle emission level is visible with decreasing rated engine power. In the absence of type approval limits, smaller engines on average had cheaper and/or older technology. Especially the naturally aspirated engines have rather high particle levels. For this reason three average engine emission maps were installed for “pre EURO 1” engines (Figure 37).

As a result of the considerations described above, the measured engine maps are averaged over the following categories:

- EURO 3
- EURO 2
- EURO 1
- pre EURO 1: 
  - * <140 kW
  - * 140-240 kW
  - * > 240 kW

![Pre-EURO 1 engines PM](image)

**Figure 37:** Average particle emissions in the standard engine maps [(g/h)/kW_rated power], “pre EURO 1” engines

Figure 38 to Figure 40 show the average weighted values for fuel consumption for all available engines of the emission standards EURO 1, EURO 2 and EURO 3 as a function of the rated engine power. A clear decrease of the specific fuel consumption with increasing engine size can be observed for all engine generations.
**Figure 38:** Weighted average specific fuel consumption in the standard steady state engine map, EURO 1 engines

**Figure 39:** Weighted average specific fuel consumption in the standard steady state engine map, EURO 2 engines
In order to avoid a further separation of the measured engine maps dependent on engine size, the engine size dependency on the specific fuel consumption is described in the model by correction functions:

\[
FC_{QS} = FC_{QS, \text{average map}} \times \frac{f_{FC}(P_{\text{rated}})}{f_{FC, \text{average map}}}
\]

where:  
- \( FC_{QS} \) ..........quasi stationary simulation result for fuel consumption in [g/h]  
- \( FC_{QS, \text{average map}} \) quasi stationary simulation result for fuel consumption in [g/h] interpolated from the average engine map  
- \( f_{FC}(P_{\text{rated}}) \) ..........engine size dependent weighted specific fuel consumption [g/kWh] as a function of the rated engine power  
- \( f_{FC, \text{average map}} \) ........weighted specific fuel consumption [g/kWh] of the average engine map

The functions for \( f_{FC} \) have been determined by linear regression based on the average weighted fuel consumption of the single measured engine maps and the according values for rated engine power. Single outliers in the measurements that do not follow the general observed trend have been excluded in this analysis to get a comparable decrease in the specific fuel consumption with increasing rated engine power for all engine emission standards. Table 15 gives the correction functions for the emission standards EURO 1 to EURO 3 and the according values of the weighted specific fuel consumption of the average engine maps. For the engine generation “pre EURO 1” no size dependent correction of the fuel consumption is necessary as the engine maps are already split into three size classes. For the correction of the fuel consumption values for the emission standards EURO 4 and EURO 5 (basic assumptions and assessment of the engine maps see paragraph 5.2) the decrease of specific fuel consumption with increasing engine size is assumed similar to EURO 3.
### Table 15: weighted specific fuel consumption, values for the average map and correction function according to rated engine power

<table>
<thead>
<tr>
<th>Emission standard</th>
<th>engine size dependent weighted specific fuel consumption [g/kWh]</th>
<th>average rated power of engine sample [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$f_{FC} (P_{rated})$</td>
<td>$f_{FC} \text{ min}$</td>
</tr>
<tr>
<td>EURO 1</td>
<td>230.6 - 0.0798*P_{rated}</td>
<td>206.2</td>
</tr>
<tr>
<td>EURO 2</td>
<td>222.6 - 0.0575*P_{rated}</td>
<td>202.2</td>
</tr>
<tr>
<td>EURO 3</td>
<td>237.9 - 0.0841*P_{rated}</td>
<td>208.9</td>
</tr>
<tr>
<td>EURO 4 (SCR)</td>
<td>220.4 - 0.0841*P_{rated}</td>
<td>191.9</td>
</tr>
<tr>
<td>EURO 5 (SCR)</td>
<td>223.5 - 0.0841*P_{rated}</td>
<td>195.0</td>
</tr>
</tbody>
</table>

With this method the number of engines measured per segment and consequently the reliability of the resulting emission factors is increased approximately by ten times compared to previous methods where a segmentation of the engines measured according to the engine power was necessary. When the standardised maps are used by the model, the absolute values for the engine speed at idling and the rated engine speed as well as the rated engine power are given as model input (e.g. average values for a HDV segment). The absolute emission values in the map are then gained simply by multiplication of the map values with the rated engine power.

Figure 41 gives as an example the shape of the PM-engine emission map of an EURO 2 engine using all measured points (R 49, ESC, 30 off cycle points) in comparison to the shape of the standardised PM map of this engine. Some of the ‘dents’ at the type approval engine speeds, which can be seen in the map containing all measured points (left picture), are not reproduced in the standardised engine map since these engine speeds are not included in the standardised map. Due to the fact that the engine speeds of the type approval tests are located according to the individual full load curves, and thus are different for each engine, it is not possible to include type approval points into standardised maps in a general valid way.

Anyhow, when calculating emissions for a complete transient cycle the results usually differ not more than 3% when using all measured points compared to the usage of the standardised 40 point maps since the points of the standardised engine map are averaged values from the nearest measured points. Relevant differences may occur if transient cycles covering only small rpm ranges located at or near the type approval rpm are simulated. For the simulation of HDV emission factors the averaging effect of the standardised maps is rather advantageous. Using the original maps it happens for some engines that small differences in the vehicle speed result in very different emission factors.

For other purposes than calculating emission factors, such as assessing emissions in the ETC or WHDC cycle for a specific engine, the use of the originally measured engine map can be more advantageous.

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9 Only relevant if the off-cycle emissions of the engine under consideration are clearly different to the emissions at the type approval points.
Figure 41: Comparison of the PM-engine emission map from all measured values (52 points) and the standardized emission map (32 points) for an EURO 2 engine

Influences of the manufacturer

Since many countries do have very specific fleet compositions with respect to the manufacturer it was of interest to find out if the share of each manufacturer in the average engine emission map has a significant influence. A detailed analysis of this task is given in Appendix V.

Two different tests were carried out to check the possible influence of the country of manufacturer on the emissions. Here to the weighted average map emissions from the standard engine map format (paragraph 4.4.2) were available for 71 engines from different technology generations (pre-EURO 1 to EURO 3) and trademarks (countries of manufacturer).

The two-population test of hypothesis for means, carried out on EURO1, -2 and -3 engines, revealed that in some cases significant differences were observed between German and non-German engines:

EURO 1 German engines show a lower NOx emission,
EURO 2 German engines show a higher NOx and a lower PM emission, compared to other engines.

Within the dataset, a significant difference was found between the fuel consumption of Dutch and non-Dutch EURO 3 engines. In the other cases, the variance on the measured fuel consumption was too high to find a significant difference.

Some of the subgroups of EURO 1, -2 or -3 engines emit statistically more CO or HC than engines of another subgroup.

The cluster analysis was carried out on all the engines of the dataset. Any of the generated clusters of engines coincide with one or another group of engines where engines of the same generation and country of manufacture were put together. Hence, the cluster analysis does not confirm the country of manufacturer to be a determining factor to make distinction between the environmental performance of HDV engines. Therefore, the conclusion is drawn, that for emission estimation no difference needs to be made between trademarks of engines. In the report he stressed that the statistical tests were carried out on a sample of limited size (two-
population test of hypothesis for means: 42 engines – cluster analysis: 71 engines). One should therefore be careful with taking above findings representative for all the engines running in Europe, especially the findings concerning the eventual difference in fuel consumption between different manufacturers of HDV engines.

Comparison of using average engine maps and single engine maps

As expected the use of the average engine emission map for one technology class gives the same results of PHEM as calculating each engine separately and making the average emission factor afterwards. Figure 42 and Figure 43 show the results of model runs where all available engine emission maps for EURO 2 engines were implemented into the same truck, to simulate the emissions for three different real world driving cycles. These are compared to the results with the average EURO 2 engine map for the same truck configuration. The results with the average EURO 2 map are identical to the average of all single simulations. This makes the method well suited for the simulation of average HDV emission factors.

![Figure 42: Simulated fuel consumption of a truck-configuration using the single engine maps available for EURO 2 compared to the simulation with the average EURO 2 engine map.](image-url)
Figure 43: Simulated particulate emissions for a truck-configuration using all single engine emission maps available for EURO 2 compared to the simulation with the average EURO 2 engine map.

For the emission standards EURO 1 to EURO 3 the averaging of the single measured engine maps has been performed in such a way, that all commercial vehicle manufacturers, which are available in the engine measurement database, have the same share on the “average engine map”.

4.5. Simulation of transient cycles

Since the engine emission maps are measured under steady state conditions while the real world driving behaviour results almost always in transient engine loads, it is of high interest how accurate transient test cycles from the engine test bed can be recalculated by using the engine maps. For this analysis all engines where transient tests have been performed have been taken into consideration.

4.5.1 Comparison of measured emissions and interpolation results from engine maps

When steady state engine emission maps are used to calculate quasi-stationary emissions for transient cycles, rather high differences occur between calculated and measured emissions. This is mainly valid for particle, HC and CO emissions. The difference is especially assumed to be an effect of different combustion conditions compared to the steady state measurements (e.g. inlet pressure and temperature for turbocharged engines with intercooler). Other known potential inaccuracies like the interpolation routine and the repeatability of the measurements show relatively lower effects. Figure 44 shows as an example the particle emissions measured for 12 engines (EURO 1 to EURO 3) in different transient cycles according to the ARTEMIS measurement programme. It is obvious that the interpolation from the steady state engine maps underestimates the particle emissions in transient cycles by up to 50%. In general EURO 3 engines (on the right side of the graph) show less influence from transient conditions than EURO 1 and EURO 2 engines. This suggests a better application of these engines to changing conditions under transient load.
Figure 44: Deviation between the result of the quasi-stationary recalculation of the particulate emissions (“PM-sta.”) and the measured emission values for the transient tests of 12 different engines. The numbers give the engine number code (1-ETC means “engine one in the ETC”)

Using a statistical analysis to assess transient influences requires a lot of measured emission values. To increase the number of measured transient cycles the existing cycles are subdivided into “sub-cycles” of 20 seconds, by using the modal measurements. Beside increasing the number of measured values this method has also the advantage that a broader range of transient conditions is covered. While the average for many potential transient parameters (e.g. the change of the engine power) is zero or near to zero for longer cycles like the ETC, this is not the case in the short sub-cycles.

Comparing the modal measurements with the results of the interpolation out of the engine map shows that the differences between measurement and simulation increases clearly with shorter sub-cycles. Since transient influences can increase the quasi-stationary emission level as well as they can lower it, the positive and negative errors in the simulation will to a great extent be averaged over long cycles. Figure 45 shows as example the situation for the NOx-emissions which are recalculated rather accurately for all engines and all test cycles if the total cycles are taken into consideration. For the 20 second sub-cycles the deviation between the interpolation and the measured emissions is up to 5 times higher, especially at low emission levels. For CO and HC the situation is even worse.

---

10 1Hz recorded emission values
Figure 45: Deviation between the result of the quasi-stationary recalculation of the NOx-emissions for transient cycles and the measured emission values for the total test cycles for 15 engines (left) and for 20 second sub-cycles for one EURO 2 engine.

The drawback of the method is that the modal (second-by-second) values have to be treated carefully. Errors in the allocation of the emission value to the actual engine load and engine speed occur due to the fact that the time between emissions leaving the engine and reaching the analysers depends on the length of the sampling line and the response times of the analysers and varies under changing engine load and engine speeds. Using 20 seconds length for the sub-cycles keeps these errors low; shorter time periods should not be used when standard equipment is used for the emission measurements.

For particulates no emission values can be gained for the sub-cycles since only one filter value for the total cycle exists. The transient correction functions for particulate emissions were therefore analysed by pooling all engines measured within one technology class.

4.5.2 The transient correction functions

As a consequence of paragraph 4.5.1 the quasi-stationary emission results have to be corrected according to the dynamics of the cycle to improve the accuracy of the model. Although transient engine tests are only available for about 25% of all engines in the database, the method has to be generally valid for all engines, at least for all engines with the same technology.

Boundary conditions for performing such a correction are:

- All engines where transient tests have been performed have to be analysed to gain functions which are generally valid.
- The typical time resolution of the HDV simulation models is 1 second. This is also the typical resolution of driving behaviour measurements.
- Engines in use must not be damaged during the measurements at the engine test beds. Therefore there is no possibility for measurements of combustion parameters (e.g. pressure in the cylinder).
These boundary conditions suggest to use statistical methods, because from many existing engine tests insufficient data is available to use detailed analytical approaches\(^\text{11}\). Simplified analytical methods still would need extensive work to allow the simulation of average transient effects for the engines from Euro 0 to Euro 5. Such a method is described in Annex VII, where the model parameterisation for two of the measured engines was elaborated during COST 346. Such an approach may be integrated in future projects or could be added later to the existing models.

The statistical approach is based on the following procedure:

- transient cycles of the engine test bed are recalculated using the steady-state engine emission maps in the standardised format, resulting in “quasi-stationary” emissions
- the difference between the measured emissions and the quasi-stationary calculation (referred to as “transient emission” is associated with transient influences
- parameters are searched by statistical means which can explain these differences.

The basic problem of developing dynamic correction functions is finding relevant parameters expressing the dynamic aspects of a cycle which provide good correlations with the difference between measured emissions and the “quasi-stationary” emissions calculated for the transient test.

For this task extensive assessments of the measured data and the results of the interpolations from the engine maps were performed. From these investigations “transient parameters” were extracted which show high correlations with the transient emissions. For each single engine equations were then set up via multiple regression analysis which describe the differences between the measured emissions in the transient cycles and the emissions calculated for these cycles from the standardised steady state engine maps. For the analysis the 20-second sub-cycles have been used. Finally those “transient parameters” giving similar equations for all engines were filtered out to obtain equations generally valid for all engines.

The analysis showed that using the difference between quasi-stationary model results and the measured emissions proved to result in much better functions than the ratio of stationary model results to the measured emissions. This resulted in the following methodology for transient corrections.

\[
E_{\text{trans}} = E_{\text{QS}} + P_{\text{Rated}} \times F_{\text{trans}}
\]

with

- \(E_{\text{trans}}\) .......emission value under transient condition [g/h]
- \(E_{\text{QS}}\) ........quasi stationary emission value interpolated from the steady-state emission map [g/h]
- \(P_{\text{rated}}\) ......rated engine power [kW] (since emission values are normalised to the rated power)
- \(F_{\text{trans}}\)........dynamic correction function [(g/h)/kW\text{rated power}]

\[
F_{\text{trans}} = A \times T_1 + B \times T_2 + C \times T_3
\]

with \(A,B,C\) .......coefficients (different according to the exhaust gas component but constant for one engine technology)

\(^{11}\) A detailed analytical approach for simulation of the emission behavior of an engine under transient conditions requires a large number of engine specific data (geometry, thermal capacities, mass inertia of the turbocharger, ECU application data etc.) and most likely needs measurements at a higher sampling rate than 1 Hz for calibration.
T₁, T₂, T₃,... transient parameters (calculated by the model PHEM from the engine speed and engine power course).

More than 3 parameters are not included into the functions to have stable and generally valid results, although for single engines equations using more parameters gives much better results. To make the function suitable for calculating average HDV with different engine sizes it is – as the emission maps - normalised with a division by the rated engine power.

The transient parameters that showed the best correlation with transient emissions are the following:

- LW₃P₃s ........... number of load changes of 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 0.03*(Pₑ/P_rated)
- 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
- P₄₀sABS ........ difference of the normalised engine power at the emission event and the average normalised engine power over 40 seconds before the emission event
- Dyn_Pneg₃s..... average negative engine power over three seconds before an emission event; set to zero if the negative engine power was not reached transiently.
- Dyn_Ppos₃s..... average positive engine power over three seconds before an emission event; set to zero if the positive engine power was not reached transiently.
- ABS_dn2s........ absolute change of the normalised engine speed within 2 seconds before the emission event in second i (0.5*(n_norm(i)-n_norm(i-2))

The transient correction functions are implemented in the model PHEM and can be switched on or off. The user simply has to select the emission level (“pre EURO 1” to “EURO 5”).

Table 16 shows the transient coefficients and the transient parameters for the correction of fuel consumption and NOₓ.

<table>
<thead>
<tr>
<th>Emission standard</th>
<th>Fuel Consumption</th>
<th>NOₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ampl₃P₃s</td>
<td>LW₃P₃s</td>
</tr>
<tr>
<td>EURO 0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>EURO 1</td>
<td>22.973</td>
<td>0</td>
</tr>
<tr>
<td>EURO 2</td>
<td>22.973</td>
<td>0</td>
</tr>
<tr>
<td>EURO 3</td>
<td>26.238</td>
<td>-1.099</td>
</tr>
</tbody>
</table>

According to these values, the correction function for the NOₓ emissions of EURO 2 engines is given as example.

12 The criterion for a “transient” load is: \(((Pₑ(i) - Pₑ(i-2))*0.5)^2 \geq 10^{-7}\)
**Equation 2:** transient correction function (NOx emissions) for EURO 2 engines

\[ F_{\text{trans-NOx}} = (-1.7 \times \text{Ampl3P3s} - 0.389 \times \text{P40sABS} + 0.203 \times \text{Dyn_Ppos3s}) \quad [(\text{g/h})/\text{kW rated power}] \]

HC and CO are corrected in an analogous way. The corresponding transient coefficients are shown in Table 17.

**Table 17:** Transient coefficients for the CO and HC correction

<table>
<thead>
<tr>
<th>Emission standard</th>
<th>CO</th>
<th>HC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ampl3P3s</td>
<td>P40sABS</td>
</tr>
<tr>
<td>EURO 0</td>
<td>3.311</td>
<td>0.322</td>
</tr>
<tr>
<td>EURO 1</td>
<td>3.311</td>
<td>0.322</td>
</tr>
<tr>
<td>EURO 2</td>
<td>3.311</td>
<td>0.322</td>
</tr>
<tr>
<td>EURO 3</td>
<td>3.3</td>
<td>0.387</td>
</tr>
</tbody>
</table>

Because of the limited number of particulate emission measurements (no sub-cycle approach was possible) it was not possible to elaborate separate functions for the “pre EURO 1” engines, especially for the three engine-power-sub-categories in this class (paragraph 4.4.2). The few available transient tests for those engines showed a similar general tendency as the EURO 1 and EURO 2 engines. Therefore the same functions are applied (Table 18). EURO 3 engines generally show less increase of the particle emission level under transient conditions compared to steady state tests. This results from a better engine application using inter alia the features provided by modern fuel injection systems and optimised turbo charge systems with variable turbine geometries.

**Table 18:** Transient coefficients for the particulate emission correction

<table>
<thead>
<tr>
<th>Emission standard</th>
<th>Particulate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ampl3P3s</td>
</tr>
<tr>
<td>EURO 0</td>
<td>0.381</td>
</tr>
<tr>
<td>EURO 1</td>
<td>0.381</td>
</tr>
<tr>
<td>EURO 2</td>
<td>0.381</td>
</tr>
<tr>
<td>EURO 3</td>
<td>0.144</td>
</tr>
</tbody>
</table>

With this set of equations the accuracy of the simulation is improved for all engines in nearly all cycles.

As the influence of transient effects on the overall emission level for the emission standards from EURO 4 on is assumed to be small, the according transient correction functions are set to zero. Especially for PM emissions the low particle emission limits will not allow a significant increase under transient conditions compared to steady state conditions. Even if the transient PM emissions in the raw exhaust gas increases, the rise will probably be reduced by the exhaust gas aftertreatment (also valid for the CO and HC emissions).

### 4.6. HDV Emission Model Accuracy

In this paragraph the method described to calculate emissions is analysed to assess the accuracy of the model and the resulting emission factors. The accuracies analysed are those related to

1. The engine sample (relevant for the average engine maps and the average transient correction function)
(2) The accuracy of simulating emissions for given engine speed and engine power cycles (recalculation of transient engine tests)

(3) the accuracy of simulating emissions for given vehicle speed cycles (recalculation of chassis dynamometer tests of HDVs).

Whereas (1) takes into consideration that the engine sample included into the model database has to be seen as a random sample of all engines on the road, (2) shows the accuracy reached when the cycles for the engine power and the engine speed measured during the tests are given as model input. This is theoretically the maximum accuracy the model can reach for the simulation of a single HDV since for (3) the engine power and the engine speed cycles have to be simulated from the vehicle speed cycle.

4.6.1 Influence of the engine sample
Since the emission levels of the different engines within the categories “pre EURO 1” to EURO 3 show a scattering, the accuracy of predicting the average emission level within an engine category depends on the number of engines tested. Although the data base is the largest available within Europe, the sample size is small compared to the number of engines on the road. Thus uncertainties arise from the limited number of engines tested.

To assess this uncertainty for each EURO category the average emission value, the standard deviation of the emission values and the 95% confidence interval, were calculated, assuming that the engines in the database are a random sample. The emission values used here for each engine are the weighted averages of the 32 point standard engine maps, since these values are the only emission levels available for all engines (paragraph 3.1.3 and 4.4.2).

Table 19 gives the results of this assessment. Obviously the samples of tested engines give reliable levels for the fuel consumption. Only the category “pre EURO 1 > 240 kW” has a rather large confidence interval with +/- 7% of the average value. The confidence intervals for NOx of EURO 1 to EURO 3 engines are also small, but for the “pre EURO 1” categories the high scattering of the NOx-emission levels leads to rather broad confidence intervals.

For CO, HC and PM the emission levels of the single engines differ much more than for the fuel consumption and NOx. As a result the confidence intervals are much larger.

Table 19: Average values of fuel consumption and emissions for the EURO classes and their 95% confidence interval resulting from the random engine sample

<table>
<thead>
<tr>
<th>Emission standard</th>
<th>Nr. of engines</th>
<th>FC average (g/kWh)</th>
<th>95% confidence +/-</th>
<th>NOx average (g/kWh)</th>
<th>95% confidence +/-</th>
<th>CO average (g/kWh)</th>
<th>95% confidence +/-</th>
<th>HC average (g/kWh)</th>
<th>95% confidence +/-</th>
<th>PM.average (g/kWh)</th>
<th>95% confidence +/-</th>
</tr>
</thead>
<tbody>
<tr>
<td>pre EURO 1 &lt; 140 kW</td>
<td>8</td>
<td>256.1</td>
<td>3.8%</td>
<td>9.9</td>
<td>20%</td>
<td>3.55</td>
<td>13%</td>
<td>1.67</td>
<td>27%</td>
<td>0.625</td>
<td>18%</td>
</tr>
<tr>
<td>pre EURO 1 140 - 240 kW</td>
<td>13</td>
<td>242.8</td>
<td>4.0%</td>
<td>12.1</td>
<td>11%</td>
<td>2.71</td>
<td>30%</td>
<td>0.73</td>
<td>18%</td>
<td>0.425</td>
<td>21%</td>
</tr>
<tr>
<td>pre EURO 1 &gt; 240 kW</td>
<td>6</td>
<td>236.4</td>
<td>7.0%</td>
<td>10.7</td>
<td>21%</td>
<td>1.19</td>
<td>23%</td>
<td>0.36</td>
<td>29%</td>
<td>0.315</td>
<td>24%</td>
</tr>
<tr>
<td>EURO 1</td>
<td>11</td>
<td>213.9</td>
<td>3.0%</td>
<td>7.3</td>
<td>7%</td>
<td>1.23</td>
<td>28%</td>
<td>0.37</td>
<td>22%</td>
<td>0.247</td>
<td>14%</td>
</tr>
<tr>
<td>EURO 2</td>
<td>17</td>
<td>206.8</td>
<td>1.8%</td>
<td>7.2</td>
<td>7%</td>
<td>0.77</td>
<td>16%</td>
<td>0.22</td>
<td>12%</td>
<td>0.106</td>
<td>11%</td>
</tr>
<tr>
<td>EURO 3</td>
<td>24</td>
<td>214.9</td>
<td>1.6%</td>
<td>5.5</td>
<td>3%</td>
<td>0.65</td>
<td>13%</td>
<td>0.19</td>
<td>20%</td>
<td>0.091</td>
<td>10%</td>
</tr>
</tbody>
</table>

4.6.2 Accuracy of simulating transient engine tests
Since the emission factors are not derived from measuring the corresponding cycles directly but from simulation tools, this certainly adds inaccuracies to the results. To assess the magnitude of errors, the results of the simulation of transient engine tests are compared to the measured values.

\[\text{13 For averaging the different areas in the engine map have been weighted according to an “average” engine load pattern in real world driving} \]
When elaborating the transient correction factors it proved rather soon that no functions can be derived explaining the differences between the quasi-stationary and the measured emissions in transient cycles that are absolutely satisfying for all engines. The reason is that the engines are constructed and calibrated to transient loads very differently, and consequently depend on the make and the model. Different adjustments in the engine application (especially the fuel injection timing) are visible rather clearly by the quality of the simulated fuel consumption and NOx emission values. Other parameters, such as the construction of the turbo charger, the fuel injection pressure and – if available – also multiple fuel injection are visible mainly in the quality of the simulation for particle emissions and CO.

Looking at the simulation results for single engines it can be stated that the simulation has a good accuracy for most of the tested engines when using the average transient correction function. But for one specific EURO 3 engine the model showed a clear underestimation of NOx emissions in combination with a significant overestimation for the fuel consumption values in all transient cycles. It may be assumed that this engine changes the engine control mechanism under transient load compared to the steady state tests (for details see [27]). Using transient correction functions developed especially for this single engine makes the model accuracy very good again for the engine under consideration, but these functions are not applicable to the other makes and models.

Since the main task of the study is the elaboration of emission functions for average HDVs it will not be of major importance for the model accuracy if some engines are not simulated with a satisfying accuracy. As described in paragraph 4.5.2 it was essential to elaborate transient correction functions valid for all tested engines on average, and to be able to apply the functions also to the average engine maps for which no transient tests are available. Therefore, the inaccuracies for some engines are acceptable as long the overall prediction quality is satisfactory. As shown in Table 20, the absolute deviation between simulation and measurement for fuel consumption and NOx emissions over all engines and test cycles are on average very small. HC and PM emissions are predicted with lower quality, with an average absolute deviation of approximately 20%, CO emissions have the lowest prediction quality with an average absolute deviation of approximately 35%.

Table 20: Average absolute difference between simulated emissions and measured emissions for all engines in all transient tests

<table>
<thead>
<tr>
<th></th>
<th>FC</th>
<th>NOx</th>
<th>CO</th>
<th>HC</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>EURO 2</td>
<td>% absolute deviation</td>
<td>1.2%</td>
<td>9%</td>
<td>36%</td>
<td>16%</td>
</tr>
<tr>
<td>engines</td>
<td>standard deviation</td>
<td>1.4%</td>
<td>10%</td>
<td>46%</td>
<td>23%</td>
</tr>
<tr>
<td>EURO 3</td>
<td>% absolute deviation</td>
<td>2.4%</td>
<td>8%</td>
<td>33%</td>
<td>20%</td>
</tr>
<tr>
<td>engines</td>
<td>standard deviation</td>
<td>3.3%</td>
<td>10%</td>
<td>40%</td>
<td>23%</td>
</tr>
</tbody>
</table>

The deviations given in Table 20 show the accuracy for simulating single engines. This is not really relevant for the task of simulating average fleet emissions since overestimations for one engine can be compensated by underestimations for another engine in the same category. For this reason a comparison of the average measured values of all engines compared to the average simulated results of all engines gives a better picture of the model accuracy.
Figure 46 to Figure 50 show the results for all EURO 2 and EURO 3 engines measured. Except for maybe for CO and HC the emission components in all cycles are matched very well by the simulation, with similar prediction quality for the five different transient tests.

### Figure 46: Average measured fuel consumption vs. simulation results for all EURO 2 engines and all EURO 3 engines

### Figure 47: Average NOx-emissions vs. simulation results for all EURO 2 engines and all EURO 3 engines

### Figure 48: Average CO emissions vs. simulation results for all EURO 2 engines and all EURO 3 engines

The differences between the average values [g/h] for fuel consumption and emissions of EURO 2 and EURO 3 engines are both related to differences in the engine behaviour as well as differences in the engine size (measured EURO 3 engines on average larger than measured EURO 2 engines).
Figure 49: Average HC emissions vs. simulation results for all EURO 2 engines and all EURO 3 engines

Figure 50: Average PM emissions vs. simulation results for all EURO 2 engines and all EURO 3 engines

Table 21 summarises the model accuracy for the simulation of the average EURO 2 and EURO 3 emission behaviour in the transient test cycles. The results show that the errors are below 1.5% for the fuel consumption, below 3.5% for NOx and below 14% for HC and PM. Since these deviations are in the order of magnitude of the repeatability of measurements, the achieved model accuracy can be seen as very good. Only for CO higher deviations to the measured values occur. However, CO is a rather uncritical exhaust component for HDV. Due to the relatively low absolute emission values of HC and CO, a somewhat higher inaccuracy is still regarded acceptable.

Table 21: Percent difference between the average of the measured fuel consumption and emissions and the average simulation results for all EURO 2 and all EURO 3 engines

<table>
<thead>
<tr>
<th>Test cycle</th>
<th>EURO 2 engines</th>
<th>EURO 3 engines</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FC</td>
<td>NOx</td>
</tr>
<tr>
<td>ETC</td>
<td>-0.4%</td>
<td>1.8%</td>
</tr>
<tr>
<td>UST</td>
<td>0.3%</td>
<td>-2.6%</td>
</tr>
<tr>
<td>TUG</td>
<td>0.1%</td>
<td>1.3%</td>
</tr>
<tr>
<td>TNO7</td>
<td>1.1%</td>
<td>3.1%</td>
</tr>
<tr>
<td>TNO12.5</td>
<td>0.9%</td>
<td>3.1%</td>
</tr>
</tbody>
</table>
The accuracy of simulating the different transient tests suggests that differences in the emission values can be predicted very well with the model. Beside the need of meeting the average emission levels of the HDVs this is the second important task of the model, since a huge number of different driving cycles, vehicle loadings and road gradients have to be simulated.

Since the methodology developed allows to pool the engines measured independent of their rated power, the model increases the number of measured engines per HDV category approximately by a factor of ten (the HDV size classes from<7.5t to 60t have a rated engine power range from approx. 85 kW to 355 kW. Without the normalized engine map formats this would lead to about ten engine-power classes). The sample per category being ten times higher due to the pooling decreases the 95% confidence intervals from the limited number of measured engines (Table 19) for the single HDV size classes by approximately a factor of four. In total, the modelling adds some inaccuracy to the resulting emission factors but decreases the errors due to the limited engine sample.

4.6.3 Accuracy of simulating HDV driving cycles

Beside providing data necessary for model development and model improvement, the measurements of HDV on the chassis dynamometer can also be used to indicate the accuracy of the model when simulating total HDV in different driving cycles. Compared to the simulation of transient engine tests the following potential sources of errors are added:

1. Simulation of the engine power instead of using the measured engine power of the engine test bed
2. Simulation of the engine speed instead of using measured engine speed of the engine test bed

The conclusion of the detailed analysis of all measurements on the engine tests was that some engines showed an emission behaviour very far away from the average of the tested engines and could therefore not be simulated very accurately by using the average transient correction functions. Having these results in mind, the four HDV tested on the chassis dynamometer are a very small number for the assessment of the model quality.

In addition to this small sample size:

- One engine had increased NOx emissions and decreased fuel consumption in transient tests compared to steady state conditions (already mentioned in paragraph 4.6.2).
- For one HDV the engine map had to be measured on the chassis dynamometer since the owner did not allow to dismounting of the engine. This HDV was equipped with on-board measurement systems from VITO. The HDV was tested on the chassis dynamometer in the ARTEMIS project to get information on potential differences between the on-board results and the results gained with the CVS system of the chassis dynamometer.

Apart from the complex modelling of total HDV, the measurements on the HDV chassis dynamometer are not trivial either. Compared to the real world driving the following influences have to be considered when measuring emissions on the chassis dynamometer:

1. Potential different engine behaviour when running in the HDV on the chassis dynamometer instead of running on the engine test bed (on the engine test bed several boundary conditions, like cooling and exhaust gas back pressure, are simulated by the test bed)
2. Potential different slip compared to driving on the road
3. Potential instable rolling resistances resulting from the high thermal load of the tyres at longer periods of high engine power

With the knowledge of these effects, HDV measurements can be performed more accurately on the chassis dynamometer. This will be explained in the following.

**Influences of temperature and pressure of the intake air**

Different conditions of the intake air to the engine and the exhaust gas backpressure on the engine test bed, the chassis dynamometer and on the road may result in significantly different emission behaviour. These values are controlled on the engine test bed by the setting of the test stand according to the values given by the manufacturers; on the chassis dynamometer this is mainly controlled by the fan for simulating the air stream and thus may be different compared to real driving on the road.

To check whether the temperature and the pressure of the engine intake air to the engine are on the same level on the road and at the time when the engine is tested on the engine test bed or on the chassis dynamometer, one HDV was equipped with several sensors during the chassis dynamometer tests and during real world driving.

To compare the temperature and pressure levels between engine test bed, chassis dynamometer and road, the temperatures and pressures measured in the steady state points on the engine test bed were taken as input values for the engine map in the model PHEM. With this temperature and pressure map the driving cycles on the road and on the chassis dynamometer were simulated.

The pressure values showed comparable levels on the road and on the test beds, while the intake air temperatures after the charge air cooling were in the city cycle on average higher on the chassis dynamometer than on the engine test bed (+13°C in the city cycle and +7°C in the highway cycle). The values measured on the road were between the chassis dynamometer measurements and the engine test bed measurements (Figure 51).

![Figure 51: Intake air temperatures in a slow city cycle and a fast highway cycle (HDV=measured on chassis dynamometer; engine = interpolated from engine test bed measurement)](image-url)
This result indicates that the cooling on the chassis dynamometer has been somewhat less efficient than on the road. But this effect also strongly depends on the actual ambient temperature, which is constant 25°C on the chassis dynamometer but certainly very variable on the road. The temperature levels from the engine tests rather give an optimum value for ambient temperatures in the range of 15°C to 20°C.

To clarify the potential influences on the emission levels a slow urban cycle and a fast highway cycle were tested on the chassis dynamometer with different settings of the fan for simulating the air stream and thus a changed cooling of the charge air (Figure 52, Figure 53).

The findings are that the speed of the air stream had little influence for this HDV when varied in a sensible range. The particle emissions at high speeds showed a clear increase when the fan speed was reduced to 25% of the original wind speed.

The measured trend that NOx emissions increase with higher speed of the cooling air (= more cooling) while particulate emissions decrease with more cooling is rather contradictory to the expected effect. A possible explanation is a temperature dependent engine control strategy e.g. to protect the engine from overheating.\textsuperscript{15}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{emissions.png}
\caption{Emissions measured for a EURO 2 HDV with different settings of the fan speed in a highway cycle (km/h = fan speed)}
\end{figure}

\textsuperscript{15} The measurements of cold starts for all four HDV also showed clearly increased NOx emissions compared to the same cycles started with a hot engine. This is most likely due to a different engine control strategy for cold engine conditions compared to hot engine conditions.
Figure 53: Emissions measured for a EURO 2 HDV with different settings of the fan speed in a city cycle (km/h = fan speed)

In general these measurements suggest that emissions measured on the chassis dynamometer shall not differ significantly compared to engine test bed measurements as long as the fan speed is set correctly. Anyhow, this uncertainty in the measurement overlaps the influence of the model accuracy when using engine maps measured on the engine test bed to simulate measurements on the chassis dynamometer.

Since the ambient temperature and air pressure show high differences over a year in real world driving, a potential significant influence of the ambient conditions on the emission levels has to be expected. The assessment of this effect was not task of this study and may be examined in the future.

Influence of the tyre temperatures

Especially at highway cycles the tires have a high thermal stress on the chassis dynamometer. In tests of long cycles at high speeds and high loads the tyres can even catch fire. To check the influence of changing tyre temperatures on the driving resistances at the chassis dynamometer, coast down tests with different preconditioning of the vehicle were performed. One coast down test was run immediately after driving a highway cycle (hot tyres), another coast down was performed after one hour standstill (cold tyres but still with the power train at operating temperature); see Figure 54. The setting and preconditioning of the test bed was identical for all tests, so differences in the speed curve of the coast down can be allocated to differences in temperature levels of tires and bearings of the HDV. For each of these coast down tests the resistance forces were calculated (polynomic approximation, Figure 55). Although this test reflects a worst case scenario, the driving resistances do not differ by more than 2% for hot tyres compared to cool tyres.

Since before each emission measurement the HDV is preconditioned by driving on the test bed in a similar way, the influence of changing temperature levels of the tires obviously can be neglected.
The tyres are rested between two rollers on the test bed whereas one of them is connected with the generator, the other is rolling free (Figure 56). As mentioned before, this causes a higher thermal stress to the tires compared to driving on the road. The thermal stress increases with a higher weight on the driven axle, so from that point of view this weight shall be kept low. On the other hand the forces which can be transmitted from the tyres to the rollers decrease with lower weight on the axle. To avoid high slip the weight on the driven axis should be high\(^\text{16}\). The weight loaded thus is a compromise to keep the slip low as well as to be able to drive all cycles without damaging the tires by overheating.

\(^{16}\) The influence of the vehicle weight on the driving resistances is simulated by the generator via the control unit
Measurements of the rotational speed of the driven tyres and the rollers of the chassis dynamometer show a slip of up to 15% for high loads and poor tyre-roller combinations. The slip on the chassis dynamometer obviously is higher than on average on the road. Until now, no measurements are known to assess the influence of a different slip on to the measured emissions. However, the influence is assumed to be small.

**Figure 56:** Schematic pictures of the rollers from the dynamometer

**Model validation with chassis dynamometer tests**

The procedure for simulating the fuel consumption and emissions of the single HDV measured on the chassis dynamometer was the following:

1) Setting all relevant parameters in the PHEM input data file according to the manufacturers’ specifications or measured values (see Table 22)

2) Calculate the rolling resistance coefficients and the drag coefficient from the coast down test on the road

3) Set the value for $P_0$ (power demand from auxiliaries) to the standard value (2.5% from the rated power$^{17}$).

4) Recalculate the measured driving cycles using the following input files:
   - the 40-point standardised engine emission map from the actual HDV (paragraph 4.4.2)
   - the full load curve from the actual HDV
   - the average transient correction function for the relevant EURO-category (paragraph 4.5.2)
   - the gear-shift model settings according to paragraph 4.3
   - the measured vehicle speed curve from the chassis dynamometer

of the test bed (rolling resistance forces and acceleration forces) in a way, that the same resistances as measured on the street are reached in the coast down test on the chassis dynamometer. Therefore, the driving resistances are generally independent of the weight loaded on the vehicle on the chassis dynamometer as long as no significant slip occurs and the temperatures of the tires keep at a comparable level as during the coast down test on the chassis dynamometer.

$^{17}$ Since neither in literature nor from manufacturers any detailed data on the power demand from auxiliaries was available, the value for $P_0$ had to be found by comparing the simulated fuel consumption with the measured one.
Overall, the only variable parameter for the simulation was P0, which was determined at 2\% to 3.5\% of the rated power for all simulated HDV by comparing the fuel consumption of the model with the measurement. Since these sensitivity tests for the setting of P0 showed close agreement for all HDV the average value of P0 from these HDVs, was set to 2.5\% in the final simulation.

**Table 22: Example for a PHEM vehicle data input file**

<table>
<thead>
<tr>
<th>Source</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAN 19.403</td>
<td>with manual gearbox; standard diesel</td>
</tr>
<tr>
<td>P0</td>
<td>ratio of power demand for auxiliaries to rated engine power (value for 50 km/h)</td>
</tr>
<tr>
<td>Gear box</td>
<td>0 for manual; 1 for automatic</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Driving resistances:</th>
</tr>
</thead>
<tbody>
<tr>
<td>vehicle mass [kg]: 15000</td>
</tr>
<tr>
<td>Loading [kg]: 15500</td>
</tr>
<tr>
<td>Cw-value [-]: 0.5</td>
</tr>
<tr>
<td>cross sectional area [m**2]: 9.5</td>
</tr>
<tr>
<td>Engine</td>
</tr>
<tr>
<td>Wheels</td>
</tr>
<tr>
<td>Gearbox</td>
</tr>
<tr>
<td>--P0 [% from rated power]: 0.035</td>
</tr>
<tr>
<td>--Rated power [kW]: 297.3</td>
</tr>
<tr>
<td>--rated engine speed [rpm]: 2000</td>
</tr>
<tr>
<td>Engine speed at idling [rpm]: 600</td>
</tr>
<tr>
<td>Gear box type (0=man; 1=auto): 0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rolling Resistance Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fr0: 0.0076</td>
</tr>
<tr>
<td>Fr1: 0.00018</td>
</tr>
<tr>
<td>Fr2: -0.00001</td>
</tr>
<tr>
<td>Fr3: 0</td>
</tr>
<tr>
<td>Fr4: 0</td>
</tr>
<tr>
<td>Factor transmission losses (1.0 = standard): 1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transmission:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achsle ratio [-]: 3.7</td>
</tr>
<tr>
<td>Wheel diameter [m]: 1.035</td>
</tr>
<tr>
<td>Transmission 1. gear [-]: 13.8</td>
</tr>
<tr>
<td>Transmission 2. gear [-]: 11.55</td>
</tr>
<tr>
<td>Transmission 3. gear [-]: 9.59</td>
</tr>
<tr>
<td>Transmission 4. gear [-]: 8.02</td>
</tr>
<tr>
<td>Transmission 5. gear [-]: 6.81</td>
</tr>
<tr>
<td>Transmission 6. gear [-]: 5.7</td>
</tr>
<tr>
<td>Transmission 7. gear [-]: 4.58</td>
</tr>
<tr>
<td>Transmission 8. gear [-]: 3.84</td>
</tr>
<tr>
<td>Transmission 9. gear [-]: 3.01</td>
</tr>
<tr>
<td>Transmission 10. gear [-]: 2.52</td>
</tr>
<tr>
<td>Transmission 11. gear [-]: 2.09</td>
</tr>
<tr>
<td>Transmission 12. gear [-]: 1.75</td>
</tr>
<tr>
<td>Transmission 13. gear [-]: 1.49</td>
</tr>
<tr>
<td>Transmission 14. gear [-]: 1.24</td>
</tr>
<tr>
<td>Transmission 15. gear [-]: 1</td>
</tr>
<tr>
<td>Transmission 16. gear [-]: 0.84</td>
</tr>
</tbody>
</table>

The results for the single HDVs are shown below. The fuel consumption values are simulated quite accurately, the highest deviation was +13\% (vehicle 4) but as mentioned before, the engine of this HDV obviously used a more economical engine control strategy under transient cycles than at the steady state tests. For vehicle 4 NO\textsubscript{x}-emissions are underestimated by up to 30\% (Figure 59). This is also in line with the findings from the engine tests.
The fuel consumption simulated for the other HDVs are within -10% to +14% agreement to the measured values. In general, the deviations between measurement and simulation are approximately double the deviations reached for the simulation of the engine tests.

The NO\textsubscript{x}-emissions are simulated within +/-25% agreement to the measured values. For comparison, the engine tests were simulated within +/- 15% for NO\textsubscript{x}.

**Figure 57:** Comparison of fuel consumption and NO\textsubscript{x}-emissions measured on the chassis dynamometer versus the simulated values

The deviations for simulating the HC- and CO emissions of the HDV are in the same order of magnitude as found for the simulation of engine tests. The deviation for HC is between –30% and +50%. Again the simulation of the CO-emissions of a single HDV is very inaccurate (-40% to +100% deviation). The accuracy of the simulation of the particulate emissions of a single HDV is at the same level as for HC (Figure 61).

**Figure 58:** Comparison of HC- and CO-emissions measured on the chassis dynamometer versus the simulated values

In general, the results are very well in line with all findings of the simulation runs of the engine test cycles. The accuracy for the simulation of the total HDV is somewhat lower than for the simulation of just the engine. But this is in accordance with what was expected due to the fact that the engine power demand and the engine speed have to be simulated for the calculation of HDV driving cycles.

As already mentioned before, the main task of the “average transient correction function” is to correct the emissions of the “average” HDV in an optimum way since the output of the study are emission factors for “average” HDVs in different categories.
Just as for the assessment of the engine simulation, the comparison between measurement and simulation shall be based on the average of the measured HDV within the different categories. As only three EURO 2 HDV and one EURO 3 HDV were measured, the results of all four vehicles are averaged for the following comparison, to get a (more or less) representative sample.

Although only four HDVs are in the sample, the average emissions of these vehicles are simulated quite accurately. The error for the fuel consumption is below 7% for all cycles (Figure 59). For NOx an accuracy of −6% to +18% is reached. The underestimation of the highly transient cycles at low speed are also related to the NOx-emission behaviour of the EURO 3 HDV, where a different engine control strategy may be used for transient and steady state loads.

![Figure 59: Comparison of the fuel consumption and the NOx-emissions measured on the chassis dynamometer versus the simulated values for the average of all measured HDV](image1)

Also HC and CO are simulated very accurately for the average of the tested vehicles, where for the HC-emissions the error is below 22%, and for CO the error is below 40%. The high relative deviations occur at the cycles with very low specific emissions (Figure 60).

![Figure 60: Comparison of the HC- and the CO-emissions measured on the chassis dynamometer versus the simulated values for the average of all measured HDV](image2)

For particulate emissions the deviations between the measurement and the simulation of the single vehicles are between +/-50%, which is worse than those on the engine test bed. For the average of the vehicles the differences between measurement and simulation are between +/-15% (Figure 61). This accuracy for the PM emissions of the “average” HDV is similar to the results found on the engine test bed.
Table 23 summarises the results for the average of the four tested HDV. Although a direct comparison with the findings of the engine test simulation is not possible, due to the limited number of HDV tested on the chassis dynamometer, the results suggest that the accuracy drops by 2.5% for the fuel consumption and by 5% to 10% for the emissions when simulating the total HDV instead of simulating engine tests. However, the model accuracy reached is still very acceptable.

Table 23: Deviation between measurements on the chassis dynamometer and the simulation for the average of all HDV [(simulated-measured)/measured]

<table>
<thead>
<tr>
<th>Average velocity [km/h]</th>
<th>13023</th>
<th>14022</th>
<th>7130_70</th>
<th>3020</th>
<th>2020</th>
<th>7130_85</th>
<th>1020</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel [% dev.]</td>
<td>-2%</td>
<td>-5%</td>
<td>6%</td>
<td>6%</td>
<td>7%</td>
<td>2%</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>NOx [% dev.]</td>
<td>-13%</td>
<td>-9%</td>
<td>6%</td>
<td>2%</td>
<td>-6%</td>
<td>-4%</td>
<td>-18%</td>
<td>-8%</td>
</tr>
<tr>
<td>HC [% dev.]</td>
<td>3%</td>
<td>-3%</td>
<td>17%</td>
<td>20%</td>
<td>17%</td>
<td>21%</td>
<td>24%</td>
<td>6%</td>
</tr>
<tr>
<td>CO [% dev.]</td>
<td>7%</td>
<td>10%</td>
<td>-5%</td>
<td>-10%</td>
<td>35%</td>
<td>4%</td>
<td>48%</td>
<td>8%</td>
</tr>
<tr>
<td>PM [% dev.]</td>
<td>-5%</td>
<td>11%</td>
<td>-11%</td>
<td>-17%</td>
<td>16%</td>
<td>1%</td>
<td>-4%</td>
<td>-1%</td>
</tr>
</tbody>
</table>

5. EMISSION MAPS FOR EURO 4 AND EURO 5

The assessment of the emission behaviour of engines fulfilling EURO 4 and EURO 5 is highly uncertain. EURO 4 will be introduced from October 2005 for type approval of new models, respectively from October 2006 for first registration of new vehicles; for EURO 5 the introduction dates are October 2008 respectively October 2009. What can be learned from the measurement programme on EURO 2 and EURO 3 engines is that simply extrapolating emission factors from older engine technologies to future standards according to the future emission limits is not a suitable approach.

Table 24 contains a summary of the emission standards and their implementation dates. Compared to the EURO 3 limits engines have to reduce especially the particulate matter emissions to fulfil the EURO 4 limits. But also a 30% reduction of NO\textsubscript{x} without an unacceptable fuel penalty will be a challenging task. For EURO 5 limits, NO\textsubscript{x} emissions have to be reduced by a further 43% compared to EURO 4. This is very unlikely to be possible at acceptable engine efficiencies for conventional combustion technologies without applying exhaust gas after treatment.
### Table 24: Emission limits in steady-state engine tests for HD Diesel Engines in the EU

<table>
<thead>
<tr>
<th>Tier</th>
<th>Date &amp; Category</th>
<th>Test Cycle</th>
<th>CO [g/kWh]</th>
<th>HC</th>
<th>NOx</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euro 1</td>
<td>July 1992 &lt;85 kW</td>
<td>ECE R49</td>
<td>4.5</td>
<td>1.1</td>
<td>8.0</td>
<td>0.612</td>
</tr>
<tr>
<td></td>
<td>July 1992 &gt;85 kW</td>
<td></td>
<td>4.5</td>
<td>1.1</td>
<td>8.0</td>
<td>0.36</td>
</tr>
<tr>
<td>Euro 2</td>
<td>Oct. 1996</td>
<td></td>
<td>4.0</td>
<td>1.1</td>
<td>7.0</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>Oct. 1998</td>
<td></td>
<td>4.0</td>
<td>1.1</td>
<td>7.0</td>
<td>0.15</td>
</tr>
<tr>
<td>Euro 3</td>
<td>Oct. 2000</td>
<td>ESC</td>
<td>2.1</td>
<td>0.66</td>
<td>5.0</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.13*</td>
</tr>
<tr>
<td>Euro 4</td>
<td>Oct. 2005</td>
<td>ESC resp. ELR</td>
<td>1.5</td>
<td>0.46</td>
<td><strong>3.5</strong></td>
<td>0.02</td>
</tr>
<tr>
<td>Euro 5</td>
<td>Oct. 2008</td>
<td>ESC resp. ELR</td>
<td>1.5</td>
<td>0.46</td>
<td><strong>2.0</strong></td>
<td>0.02</td>
</tr>
</tbody>
</table>

* for engines of less than 0.75 dm³ swept volume per cylinder and a rated power speed of more than 3000 min⁻¹

Compared to EURO 3 diesel engines EURO 4 and EURO 5 engines have to fulfil the emission limits also in a transient engine test (“ETC”- European Transient Cycle; engine speed and engine load profile shown in Figure 62, emission limits given in Table 25). So optimisations on the single test points of the ESC will not suffice to reach the emission levels at type approval. With this regulation it can be assumed that the emission levels in real world driving conditions may decrease more compared to EURO 3 than the emission limit tightening suggests.

### Table 25: Emission limits in transient engine tests for HD diesel engines in the EU

<table>
<thead>
<tr>
<th>Tier</th>
<th>Date &amp; Category</th>
<th>Test Cycle</th>
<th>CO [g/kWh]</th>
<th>HC</th>
<th>NOx [m⁻³]</th>
<th>PM [m⁻³]</th>
<th>Smoke [m⁻³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euro 3</td>
<td>Oct. 2000</td>
<td>ETC resp. ELR</td>
<td>(5.45)</td>
<td>(0.78)</td>
<td>(5.0)</td>
<td>(0.16 0.21)</td>
<td>0.8</td>
</tr>
<tr>
<td>Euro 4</td>
<td>Oct. 2005</td>
<td>ETC resp. ELR</td>
<td>4.0</td>
<td>0.55</td>
<td><strong>3.5</strong></td>
<td><strong>0.03</strong></td>
<td>0.5</td>
</tr>
<tr>
<td>Euro 5</td>
<td>Oct. 2008</td>
<td>ETC resp. ELR</td>
<td>4.0</td>
<td>0.55</td>
<td><strong>2.0</strong></td>
<td><strong>0.03</strong></td>
<td>0.5</td>
</tr>
</tbody>
</table>

*a measured in the ETC (European Transient Cycle)
*b measured in the ELR (European Load Response test)
*c the measurement of the ETC is not mandatory for EURO 3 engines [it is mandatory for natural gas engines, engines with aftertreatment, and as a NOx screening test to review the control strategy (see Directive 2001/27/EC)]
*d for engines of less than 0.75 dm³ swept volume per cylinder and a rated power speed of more than 3000 min⁻¹
Figure 62: European Transient Cycle (ETC), example for an EURO 3 engine

However, most of the ETC is located in the same region of the engine map as is covered by the ESC (Figure 63), thus it still will not be absolutely necessary for a manufacturer to optimise the emission levels over the complete engine map to reach the emission limits. Especially low engine speeds are driven rather seldom. In total, only 13% of the ETC time have engine speeds below 40% ($n_{\text{norm}}$).

Today (February 2005), still no decision has been made on what will be controlled exactly by OBD for EURO 4 and EURO 5. Most likely in the first step (“OBD 1”) only the major functions are controlled. A “OBD 1b” is discussed, to be introduced in 2007, which shall already control the emissions by means of emission sensors. Not to exceed values for NOx are discussed in this context.

Figure 63: European Stationary Cycle (ESC) and European Transient Cycle (ETC) in the engine map, example for an EURO 3 engine
The main question for the assessment of the emission maps for EURO 4 and EURO 5 engines is whether technologies will be used that may have a varying efficiency over the engine map. Potential technologies for EURO 4 and EURO 5 engines are discussed below but at the moment it can not be foreseen which of them will be the dominant system to be applied in the future.

5.1. Technologies under consideration

In general three possibilities for reaching EURO 4 and EURO 5 type approval levels are possible in the near future:

- Improved engine technology
- Exhaust gas after treatment
- Alternative combustion concepts

While EURO 4 could be achieved with conventional but improved engine technologies (fuel injection, exhaust gas recirculation, variable turbine geometry at the turbo charger,...) this is rather unlikely for EURO 5 emission limits. At least, the engine efficiency would be unacceptable for reaching the 2 g/kWh NOx.

Using exhaust gas after treatment systems could reduce NOx and particles to the targeted levels. The problem of these systems is especially their unproven durability and the additional investment costs. In the following a general overview on the technological options for exhaust gas after treatment systems is given. The special issue of retrofit aftertreatment systems for the reduction of particle emissions is discussed in detail in Appendix VI.

5.1.1 Diesel Particulate Filter (DPF)

Today, different after treatment systems to reduce particulate matter (PM) emissions are under development for HDV application. For all systems the main technological tasks are

- a controlled regeneration of the filter where the collected particle load has to be burned below temperatures critical for damaging the filter material,
- a durability of several 100.000 kilometres, where especially the minimisation of the backpressure increase due to cumulated ash stored in the diesel particulate filter (DPF) is a challenge.

Without or with delayed regeneration the filter becomes blocked, which rapidly increases the exhaust gas back pressure. To start the filter regeneration process for current filter technology using catalytic coating or fuel borne regeneration, temperatures above 300°C are necessary which do not occur under all load conditions for HDV engines (see e.g. Figure 64). An overloading by only 3-4 grams per litre filter volume causes a rise in regeneration temperature in the order of 300-400°C. Such temperatures can damage the filter.

Accumulated ashes from lubricating oil additives will melt at high temperatures (>1100°C) during regeneration and can react with the filter substrate and clog the filter permanently (glazing effect). Therefore, the loading rate and temperature of the filter have to be monitored accurately to prevent overheating and damage to the filter. Of course, low ash lubricants have to be available for engines with DPF.
Figure 64: Measured exhaust gas temperatures at an EURO 3 engine in a real world test cycle (TNO 7.5 kW/ton cycle) and resulting engine temperature map.

These difficulties will most likely need the interaction (or the integration) of a control system with the engine control unit. Following systems are given as example for today’s development:

- Continuously Regenerated Trap (CRT™, Johnson Matthey)
- Fuel-Borne Catalysed Filter

**Continuously Regenerated Filter (CRT™, Johnson Matthey)**

This technology (Figure 65) uses the NO\textsubscript{x} in the exhaust gas to maintain a continuous regeneration of the trap. An oxidation catalyst is placed upstream of the filter to convert NO into NO\textsubscript{2}. The following reactions are relevant for the CRT operation:

\[
\begin{align*}
\text{Chemical reactions in the Oxidation Catalyst:} \\
2\text{NO} + \text{O}_2 &= 2\text{NO}_2 \\
\text{Chemical reactions in the Filter:} \\
\text{C} + \text{NO}_2 &= \text{CO}_2 + 2\text{NO} \\
\text{C} + \text{O}_2 &= \text{CO}_2
\end{align*}
\]

This regeneration requires temperatures above 230\degree C to start the filter regeneration process, and 350\degree C to achieve an equilibrium. For any category of HDV driving situations can occur where this temperature is not reached over a longer period. This leads to an accumulation of particles in the filter which are then burned at high temperatures once the needed temperature for regeneration is reached again. Such situations can damage the filter. Thus, additional systems for active regeneration may be needed such as electrical or fuel burner heaters, potentially supported by a fuel additive. These regeneration aids can be used at other particle filters as well (e.g. fuel burner regenerated trap).
In this system (Figure 66) an additive is used to reduce the soot ignition temperature. The additive is introduced into the fuel tank after refuelling (in proportion to the fuel on-board the vehicle). Additives currently used are cerium, iron and strontium. A comparable system has already been introduced in the passenger car market in series production (PSA, ©FAP). Main disadvantage is the need of an additional tank on board.

Malfunctions that are specific to this system are most likely to occur in the additive supply system, e.g. too little dosing could lead to delayed regeneration and overheating during the regeneration process, like for the CRT system.

Beside the technological tasks to be solved, particulate traps cause additional investment costs and result in a slight penalty in fuel efficiency (1-3%). Therefore, research on improving engine technologies in the future to reach the particle limit values without filters is under progress.

Due to the technological disadvantages described, the application of DPFs in EURO 4 and EURO 5 in large series production is not assumed for the elaboration of the basic emission maps. In the ARTEMIS model the option of “DPF-technology” can be chosen, which takes a
reduction in particulate mass of approximately 90% and an increase in fuel consumption of 3% compared to the relevant basic engine emission map into account. This option may be helpful for assessing options for e.g. urban bus fleets.

5.1.2 Diesel Particulate Catalysts

Beside the DPF, where the exhaust gas is flowing through a porous medium, recently open systems have been developed. These systems are often called particulate catalysts or PM-cat. Figure 67 shows the principle of such a PM-cat. Due to the special shaping of the catalyst, the exhaust gas is flowing into a storage medium where particles are deposited. If the storage medium is full, the exhaust is flowing through the open channels of the catalyst without further separation of the particles. As soon as the PM-cat reaches regeneration temperatures again, the particles are burnt and the PM-cat can work at the original efficiency levels again. The risk of damages to the engine or to the PM-cat is obviously much smaller than for a DPF without closed loop control.

PM-cats have efficiencies in the range of approximately 50% and at least one HDV manufacturer will apply this technology in the smaller EURO 4 vehicles.

![Figure 67: Schematic picture of a particulate catalyst (Source Twin-Tec)](image)

5.1.3 NO\textsubscript{x} reduction technology

Today there are two different after-treatment systems available to reduce NO\textsubscript{x} emissions.

- Selective Catalytic Reduction (SCR)
- NO\textsubscript{x} Adsorber catalyst

Since the DeNO\textsubscript{x} Catalyst needs phases of engine running with a rich air to fuel ratio – which increases the fuel consumption - SCR is clearly favourable for HDV application. No manufacturer plans at the moment to introduce NO\textsubscript{x} Adsorber technology in the European HDV market.
Selective Catalytic Reduction (SCR)

In the SCR system urea is dissolved in water and is injected in the exhaust gas stream where a hydrolysis process converts it into CO₂ and NH₃. Alternatively the NH₃ can be gained from Ammonia carbonate. The ammonia is then used as a NOₓ reducing agent, producing N₂ and water over the SCR catalyst. The SCR catalyst is a honeycomb structure made of ceramic material. To prevent ammonia from passing through to atmosphere (ammonia slip) an oxidation catalyst downstream the SCR catalyst is usually applied. Figure 68 shows the principle scheme of the SCR Catalyst.

![Figure 68: Principle of the SCR Catalyst (Source: PUREM)](image)

At proper exhaust gas temperatures the SCR is capable of reducing the NOₓ emissions by more than 65%. One of the drawbacks from today’s systems is that the SCR catalyst does not work at temperatures below approximately 150°C. So the urea injection starts only at a defined exhaust temperature, and is controlled by a temperature sensor. Engines running a considerable time at idle speed, e.g. in city busses, may have problems reaching the required temperature, especially in winter. Additionally, after a cold start the system will not be active until the operating temperature is reached.

A main concern is an empty urea tank. Since there are in principle no vehicle performance penalties when the reactant tank is empty, there is no incentive to the driver to replenish the tank while the urea is not free of charge. Monitoring of the reactant level in the tank (as well as the chemical composition to avoid replenishing it with water) therefore is crucial for compliance, but can only be managed by adequate control systems. Currently a European framework for such requirements is discussed in the MVEG forum (Brussels).

5.1.4 Exhaust Gas Recirculation (EGR)

EGR is used to reduce NOₓ emissions by recirculating a portion of the exhaust gas back into the combustion chamber. This reduces the oxygen available in the cylinder for combustion, and leads to lower peak temperatures that inhibit the formation of NOₓ.

There are different principles of exhaust gas recirculation.

- External High Pressure EGR
- External Low Pressure EGR
- Internal EGR

All of these options may be used at EURO 4 and/or EURO 5 HDV engines.

In a high pressure EGR system the exhaust gas is forced back into the intake air manifold by the pressure in the exhaust manifold. For cooling the exhaust gas an EGR cooler is used.
A problem of this system is the potential pollution of the intake valves by the exhaust gas.

![Figure 69: High pressure EGR (Source: AVL)](image1.png)

As alternative, the low pressure EGR system re-routes the exhaust gas after the turbocharger and (if mounted) the particulate filter into the fresh airflow before the turbocharger.

Apart from these external EGR systems, also an overlapping opening of the exhaust and the intake valves can be used to obtain a mixture of fresh air and exhaust gas in the cylinder (Figure 70). Different systems for a variable valve control are on the market today.

![Figure 70: Internal EGR (Source: Hino Motors Limited)](image2.png)

### 5.2. Estimation of EURO 4 and EURO 5 emission maps

The experience of the assessment of the measurements on EURO 2 and EURO 3 engines was that a high fuel efficiency is the main target for HDV engines and a crucial point for the competitiveness of a HDV on the market. It certainly has to be assumed that also for EURO 4 and EURO 5 the manufacturers will focus on finding solutions with a high fuel efficiency at low investment and running costs.

The following boundary conditions for EURO 4 and EURO 5 engines are assumed:
• All EURO 5 HDVs will use SCR technology (latest announcements indicate that some manufacturers, e.g. Scania, may use high EGR with high pressure injection and particulate catalysts to reach also EURO 5 at least for the smaller engines)

• The basic technology for reaching EURO 4 will also be SCR. EGR with VTG or two stage chargers and PM-cat will be applied mainly for some smaller EURO 4 vehicles. This slightly increases the fuel consumption factors for this fleet. Potentially different pollutant emission behaviour (NO\textsubscript{x}, PM, HC, CO) from HDV with SCR and EGR can not be properly assessed today

• Emission reduction strategies will be followed to such an extent that the type approval levels in the ETC and in the ESC test cycles are achieved

• Emission reduction strategies will most likely not be followed in regions of the engine map where this is not urgently necessary (certainly not if this would imply penalties to the fuel consumption and costs)

• The application of the SCR will be optimised in the regions of the engine map covered by the type approval tests (ETC and ESC)

• In regions of the engine map that are not covered by the ETC or ESC, a limited urea dosing will be used to reduce the urea consumption. In addition, the EGR may be operated with lower EGR rates

• An OBD system is assumed to be installed, which limits the NO\textsubscript{x} emissions everywhere in the engine map to 5 g/kWh for EURO 4 and to 3.5 g/kWh for EURO 5\textsuperscript{18}. Without such a control system, especially at low engine speeds much higher NO\textsubscript{x} levels than presented in the emission factors could emerge. This could drastically increase emission factors for urban and road traffic. For this reason, in-use control of the future technologies seems to be necessary.

• The application of the SCR system allows for higher raw exhaust NO\textsubscript{x} emissions. This enables to further optimise the fuel consumption (earlier injection timing). Compared to EURO 3 engines reductions of approx. 7% (for EURO 4 engines) and 5% (EURO 5 engines) are predicted.

• The reduction of particle emissions will be realised by an optimised fuel injection and combustion process, in combination with an oxidation catalyst (or PM-cat) but without application of a diesel particulate filter. Available measurements of a EURO 5 SCR test engine\textsuperscript{19} showed PM emissions 40% lower than the EURO 5 limit value both in the ESC and ETC cycle.

• HC and CO emission levels are rigorously reduced by the catalyst, even if they are already below the type approval limits.

Based on these assumptions, the emission levels of the two EURO 3 engines with the most advanced technology (in the standardised format) were reduced until emissions were reached at a level of at least 5% below the type approval limits for EURO 4 and EURO 5. For this task the ETC and the ESC were simulated for each of the virtual EURO 4 and EURO 5 engines with the model PHEM. The two basic EURO 3 engines had different full load curves. For one of the engines the ESC speed C was above the rated engine speed for the other below

\textsuperscript{18} Only in the low load engine map area this limitation will likely not be practicable, because very low absolute NO\textsubscript{x} emissions have to be detected by the OBD system

\textsuperscript{19} Measurements of a EURO 5 test engine with SCR technology and the according EURO 3 basic engine have been available from the PARTICULATE project
the rated engine speed. The exercise was made at the single engines to take the different shapes of the full load curves into consideration. For EURO 4 and EURO 5 no change in the full load curves has been assumed compared to EURO 3.

The resulting reductions of NO$_x$ and particulate emission necessary to reach EURO 4 and EURO 5 are impressive. Particulate emissions will have to be reduced by approximately 70% to 90% compared to EURO 3 (depending on the basic EURO 3 engine). The reduction rates for the NO$_x$ emissions to reach EURO 5 are in the range of 50% to nearly 70%.

Figure 71 gives as example the reduction rates applied to a EURO 3 engine to reach EURO 5 emission levels. The technologies necessary will undoubtly make the system much more complex. From the environmental point of view a main question for the future is the durability of the technologies used. While today’s HDV diesel engines show a rather constant emission level over their technical life time, this fact may change with the introduction of much more complex systems.

![Figure 71: Reduction rates for a EURO 3 engine to reach EURO 5 emission levels for NO$_x$ (left) and particulates (right). Reduction rate = (EURO 5/EURO 3) -1](image)

The resulting engine emission maps for EURO 4 and EURO 5 are shown in the next chapter.

### 5.3. Average Emission Maps for Pre EURO to EURO 5

This chapter documents the engine emission maps used for the EURO categories. The graphs of the maps were drawn up with the software UNIPLOT using the standardised engine emission map formats as input\(^\text{20}\).

\[^{20}\text{Very uneven values in a map cause problems for interpolation routines, also for those of commercial graphical software programs. As a result, the pictures shown include some artifacts from the software used and are not necessarily representing exactly the values of the standardised engine emission maps.}\]
Figure 72: Fuel consumption maps for the average technology classes (standardised map formats, values in (g/h)/kW$_{\text{Rated Power}}$)
Figure 73: NOx-emission maps for the average technology classes (standardised map formats, values in (g/h)/kW Rated Power)
Figure 74: Particulate matter-emission maps for the average technology classes (standardised map formats, values in (g/h)/kW_{Rated Power})
Figure 75: CO-emission maps for the average technology classes
(standardised map formats, values in (g/h)/kW Rated Power)
Figure 76: HC-emission maps for the average technology classes
(standardised map formats, values in (g/h)/kW Rated Power)
6. VEHICLE DATA

For the elaboration of the emission factors the HDV fleet has been split in 19 vehicle categories (Table 26)\textsuperscript{21}. Each vehicle category consists of 18 different vehicles: 6 emission standards (from “pre EURO 1 to EURO 5) each with 3 vehicle loadings (empty, half-loaded, fully loaded). This results in total in 342 different vehicles, which had to be simulated by the emission model.

**Table 26: HDV vehicle categories in the ARTEMIS emission model**

<table>
<thead>
<tr>
<th>vehicle class</th>
<th>gross vehicle weight rating [tons]</th>
</tr>
</thead>
<tbody>
<tr>
<td>category</td>
<td></td>
</tr>
<tr>
<td>rigid truck</td>
<td>up to 7.5</td>
</tr>
<tr>
<td></td>
<td>7.5 to 12</td>
</tr>
<tr>
<td></td>
<td>12 to 14</td>
</tr>
<tr>
<td></td>
<td>14 to 20</td>
</tr>
<tr>
<td></td>
<td>20 to 26</td>
</tr>
<tr>
<td></td>
<td>26 to 28</td>
</tr>
<tr>
<td></td>
<td>28 to 32</td>
</tr>
<tr>
<td></td>
<td>larger 32</td>
</tr>
<tr>
<td>truck trailers and articulated trucks</td>
<td>up to 28</td>
</tr>
<tr>
<td></td>
<td>28 (Switzerland)</td>
</tr>
<tr>
<td></td>
<td>28 to 34</td>
</tr>
<tr>
<td></td>
<td>34 to 40</td>
</tr>
<tr>
<td></td>
<td>40 to 50</td>
</tr>
<tr>
<td></td>
<td>50 to 60</td>
</tr>
<tr>
<td>Urban bus</td>
<td>midi up to 15</td>
</tr>
<tr>
<td></td>
<td>standard 15 to 18</td>
</tr>
<tr>
<td></td>
<td>articulated larger 18</td>
</tr>
<tr>
<td>coach</td>
<td>standard up to 18</td>
</tr>
<tr>
<td></td>
<td>three axle larger 18</td>
</tr>
</tbody>
</table>

The objective was to get plausible average vehicle specifications for each single vehicle category. As a first step, the different vehicle specifications needed for the model input (e.g. masses, driving resistances, losses) have been investigated by analysis of statistical data, literature review and vehicle measurements (e.g. coast down tests). In a second step a “calibration” of the assembled sets of vehicle data for the different vehicle categories was performed by a comparison of the fuel consumption predicted by the model PHEM with data from on-road measurements, test reports in technical journals, information from transport business and the data bank of the Institute.

6.1. Specifications for the vehicle generation EURO 3

To harmonise the model input data on the vehicles, first the data for the vehicle generation EURO 3 was fixed. For all other “EURO-classes” the model input data was then established by factors relating to the EURO 3 vehicle specifications (discussed in paragraph 6.2).

---

\textsuperscript{21} The classification has been made according to the structure of different national registration data
6.1.1 Gross vehicle weight rating, vehicle empty weight

The values for the average gross vehicle weight rating and the average vehicle empty weight within the vehicle categories are shown in Table 27. For all HDVs below 32 tons maximum allowed gross weight, the information is drawn out of national registration data in Switzerland. For trucks, truck trailers and semi trailers above 32 tons up to 40 tons maximum allowed gross weight data was elaborated from “Lastauto & Omnibus Journal” (different yearbooks) and specifications of the manufacturers. The average specifications for truck trailers and semitrailers above 40 tons were provided by the Ministry of Transport and Communications of Finland.

Table 27: Average values for gross vehicle weight rating, vehicle empty weight and rated power for the different vehicle categories (EURO 3 vehicles)

<table>
<thead>
<tr>
<th>Vehicle class</th>
<th>Gross vehicle weight rating [tons]</th>
<th>Average</th>
<th>Gross vehicle weight rating [tons]</th>
<th>Average</th>
<th>Average vehicle empty weight [tons]</th>
<th>Average rated power [kW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>rigid truck</td>
<td>up to 7,5</td>
<td>5.8</td>
<td>up to 7,5</td>
<td>5.5</td>
<td>3.5</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>7,5 to 12</td>
<td>11.0</td>
<td>7,5 to 12</td>
<td>11.0</td>
<td>6.0</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>12 to 14</td>
<td>13.5</td>
<td>12 to 14</td>
<td>13.5</td>
<td>7.3</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>14 to 20</td>
<td>17.2</td>
<td>14 to 20</td>
<td>17.2</td>
<td>8.8</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>20 to 26</td>
<td>25.5</td>
<td>20 to 26</td>
<td>25.5</td>
<td>11.8</td>
<td>275</td>
</tr>
<tr>
<td></td>
<td>26 to 28</td>
<td>27.0</td>
<td>26 to 28</td>
<td>27.0</td>
<td>12.2</td>
<td>275</td>
</tr>
<tr>
<td></td>
<td>28 to 32</td>
<td>32.0</td>
<td>28 to 32</td>
<td>32.0</td>
<td>13.6</td>
<td>290</td>
</tr>
<tr>
<td></td>
<td>larger 32</td>
<td>35.5</td>
<td>larger 32</td>
<td>35.5</td>
<td>14.3</td>
<td>305</td>
</tr>
<tr>
<td>truck trailers and articulated trucks</td>
<td>up to 28</td>
<td>18.0</td>
<td>up to 28</td>
<td>18.0</td>
<td>9.2</td>
<td>210</td>
</tr>
<tr>
<td></td>
<td>28 (Switzerland)</td>
<td>28.0</td>
<td>28 (Switzerland)</td>
<td>28.0</td>
<td>12.8</td>
<td>260</td>
</tr>
<tr>
<td></td>
<td>28 to 34</td>
<td>32.0</td>
<td>28 to 34</td>
<td>32.0</td>
<td>13.6</td>
<td>260</td>
</tr>
<tr>
<td></td>
<td>34 to 40</td>
<td>39.8</td>
<td>34 to 40</td>
<td>39.8</td>
<td>15.1</td>
<td>305</td>
</tr>
<tr>
<td></td>
<td>40 to 50</td>
<td>47.0</td>
<td>40 to 50</td>
<td>47.0</td>
<td>16.0</td>
<td>316</td>
</tr>
<tr>
<td></td>
<td>50 to 60</td>
<td>60.0</td>
<td>50 to 60</td>
<td>60.0</td>
<td>19.4</td>
<td>355</td>
</tr>
<tr>
<td>Urban bus</td>
<td>midi</td>
<td>up to 15</td>
<td>up to 15</td>
<td>11.5</td>
<td>6.7</td>
<td>165</td>
</tr>
<tr>
<td></td>
<td>standard</td>
<td>15 to 18</td>
<td>standard</td>
<td>17.8</td>
<td>10.4</td>
<td>210</td>
</tr>
<tr>
<td></td>
<td>articulated</td>
<td>larger 18</td>
<td>articulated</td>
<td>27.0</td>
<td>15.0</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>coach</td>
<td>up to 18</td>
<td>coach</td>
<td>18.0</td>
<td>13.8</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>three axle</td>
<td>larger 18</td>
<td>three axle</td>
<td>24.0</td>
<td>15.6</td>
<td>330</td>
</tr>
</tbody>
</table>

6.1.2 Engine specifications

For the assessment of the average rated engine power for each vehicle category the same data sources as mentioned in 6.1.1 have been used. The values are also given in Table 27. The according specifications for the engine idling speed and engine rated speed have been elaborated by linear regression based on all engine data available in the engine database.

6.1.3 Moments of inertia from the rotating masses

The data sources for the values for the moments of inertia from the rotating masses are literature [65] and test bed evaluation (engine test bed, chassis dynamometer). In order to get harmonised values for the different vehicle categories, the moments of inertia are calculated as a function of the engine rated power (rotational inertia of engine and gearbox) and as a function of the gross vehicle weight rating (rotational inertia of the wheels) (Table 28).
Table 28: Calculation of the moments of inertia from the rotating masses

<table>
<thead>
<tr>
<th>Rotational Inertia Component</th>
<th>Unit</th>
<th>Coefficient [unit]</th>
<th>Reference Size Component</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td>[kg*m²]</td>
<td>0.012 [kg*m² / kW]</td>
<td>Engine rated power</td>
<td>[kW]</td>
</tr>
<tr>
<td>Gearbox</td>
<td>[kg*m²]</td>
<td>0.001 [kg*m² / kW]</td>
<td>Engine rated power</td>
<td>[kW]</td>
</tr>
<tr>
<td>Wheels</td>
<td>[kg] *¹</td>
<td>20.9 [kg / ton]</td>
<td>Gross vehicle weight rating</td>
<td>[tons]</td>
</tr>
</tbody>
</table>

*¹ converted into translational inertia

6.1.4 Characteristic values for the aerodynamic resistance

At a given vehicle speed, the aerodynamic resistance is specified by the product of aerodynamic drag coefficient and gross frontal area. In Table 29 the model settings for the different vehicle categories are shown.

(a) Gross frontal area
The frontal area of a HDV can vary significantly according to the driver’s cab category, where often several options are available for a given basic truck configuration. Even more influence on the frontal area is resulting from the type of bodywork (platform, box body,…), especially for smaller HDVs where the bodywork most often has a much higher frontal area than the drivers cab.

For none of the countries involved into the ARTEMIS project the statistics on the HDV registration gives any information on the bodywork of the vehicles. Therefore the frontal areas given in Table 29 result from an estimation on the share of different bodyworks and the manufacturers specifications on the dimensions of their HDV.

(b) Drag coefficient (c_d-values)
The drag of a HDV is determined by: pressure at the front and the rear of the vehicle, cab-trailer gap, underbody and skin friction. The drag coefficient is therefore depending on the design of the vehicle category (solo truck, truck trailer,…), the driver’s cab, the bodywork, the underbody, etc.. As already mentioned under (a), no statistical data is available on the share of different bodyworks and driver’s cabs on the road. As for the frontal area, also the drag coefficients of the HDV categories had to be estimated by using a database. The database includes manufacturer specifications and a literature review [32], [46], [61]. The average drag coefficients used for different HDV categories are shown in Figure 77. The maximum and minimum values indicate the range of data found in literature.
Figure 77: Range of drag coefficients for HDV in the database and average PHEM values used for the assessment of the emission factors (EURO 3 HDV)

In order to meet the observed levels for fuel consumption, the model values for the $c_d$-coefficients had to be set close to the lower limit found in literature.

Table 29: Average values for drag coefficient and frontal area for the different vehicle categories (EURO 3 vehicles)

<table>
<thead>
<tr>
<th>vehicle class</th>
<th>gross vehicle weight rating [tons]</th>
<th>frontal area [m²]</th>
<th>drag coefficient [-]</th>
<th>$c_d*A$ [m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>rigid truck</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>up to 7.5</td>
<td></td>
<td>5.8</td>
<td>0.64</td>
<td>3.71</td>
</tr>
<tr>
<td>7.5 to 12</td>
<td></td>
<td>6.7</td>
<td>0.64</td>
<td>4.31</td>
</tr>
<tr>
<td>12 to 14</td>
<td></td>
<td>6.9</td>
<td>0.64</td>
<td>4.40</td>
</tr>
<tr>
<td>14 to 20</td>
<td></td>
<td>7.4</td>
<td>0.63</td>
<td>4.66</td>
</tr>
<tr>
<td>20 to 26</td>
<td></td>
<td>7.5</td>
<td>0.63</td>
<td>4.76</td>
</tr>
<tr>
<td>26 to 28</td>
<td></td>
<td>7.5</td>
<td>0.64</td>
<td>4.77</td>
</tr>
<tr>
<td>28 to 32</td>
<td></td>
<td>7.9</td>
<td>0.66</td>
<td>5.18</td>
</tr>
<tr>
<td>larger 32</td>
<td></td>
<td>8.0</td>
<td>0.66</td>
<td>5.25</td>
</tr>
<tr>
<td>truck trailers and articulated trucks</td>
<td>up to 28</td>
<td>6.9</td>
<td>0.56</td>
<td>3.87</td>
</tr>
<tr>
<td>28 (Switzerland)</td>
<td></td>
<td>7.6</td>
<td>0.56</td>
<td>4.26</td>
</tr>
<tr>
<td>28 to 34</td>
<td></td>
<td>7.7</td>
<td>0.55</td>
<td>4.23</td>
</tr>
<tr>
<td>34 to 40</td>
<td></td>
<td>9.0</td>
<td>0.50</td>
<td>4.50</td>
</tr>
<tr>
<td>40 to 50</td>
<td></td>
<td>9.0</td>
<td>0.52</td>
<td>4.71</td>
</tr>
<tr>
<td>50 to 60</td>
<td></td>
<td>8.1</td>
<td>0.63</td>
<td>5.07</td>
</tr>
<tr>
<td>Urban bus</td>
<td>midi up to 15</td>
<td>5.7</td>
<td>0.55</td>
<td>3.14</td>
</tr>
<tr>
<td>standard</td>
<td>15 to 18</td>
<td>6.5</td>
<td>0.58</td>
<td>3.77</td>
</tr>
<tr>
<td>articulated</td>
<td>larger 18</td>
<td>6.5</td>
<td>0.62</td>
<td>4.04</td>
</tr>
<tr>
<td>coach</td>
<td>standard up to 18</td>
<td>7.1</td>
<td>0.45</td>
<td>3.20</td>
</tr>
<tr>
<td>three axle</td>
<td>larger 18</td>
<td>7.4</td>
<td>0.45</td>
<td>3.33</td>
</tr>
</tbody>
</table>
6.1.5 Rolling resistance

The main sources for the elaboration of the rolling resistance coefficients (formulas given in 4.2.1) are literature ([44], [31]), HDV coast down tests and a comparison between on-road measurements with different vehicle loadings and model calculations. All available data indicate a rather linear correlation between rolling resistance forces and vehicle speed. Consequently, the corresponding coefficients \( f_{r2}, f_{r3} \) and \( f_{r4} \) for higher powers of the vehicle speed are set to zero. As especially the coast down tests and the on-road measurements suggested nearly no variation of the rolling resistance with increasing vehicle speed, also the \( f_{r1} \) values have been set to zero.

The rolling coefficient \( f_{r0} \) is calculated for all vehicle categories using a similar approach, which specifies the decrease of the rolling resistance coefficient with increasing wheel load:\(^{22}\):

\[
f_{r0} = C_0 - C_1 \times F_{z,tyres}
\]

with:

\( f_{r0} \) ......................... rolling resistance coefficient (speed independent term) [-]

\( C_0 = 0.00825 \) ........ Constant factor [-]

\( C_1 = 0.000075 \) ...... Constant factor [kN\(^{-1}\)]

\( F_{z,tyres} \) ................. average single wheel load [kN]

As observed for the air resistance specifications the model values for \( f_{r0} \) had to be fixed close to the lower limit found in literature in order to meet the appropriate levels for fuel consumption of the different vehicle categories. A plausible reason for this is that the values given in [44] and [31] are based on tyre test bench measurements in the beginning of the eighties. The roll characteristics of the tyres have been improved since then significantly. Table 30 gives the model values for \( f_{r0} \) for all combinations of vehicle categories and vehicle loadings.

---

\(^{22}\) The correlation of absolute value of the rolling resistance with the wheel load is less than linear, e.g. a 50% increase of wheel load leads to clearly lower increase of the rolling resistance forces
Table 30: Average values for the rolling coefficient \( f_{r0} \) and different vehicle categories (EURO 3 vehicles)

<table>
<thead>
<tr>
<th>vehicle class</th>
<th>gross vehicle weight rating [tons]</th>
<th>rolling resistance coefficients [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>category</td>
<td>0%</td>
</tr>
<tr>
<td>rigid truck</td>
<td>up to 7.5</td>
<td>0.00782</td>
</tr>
<tr>
<td></td>
<td>7.5 to 12</td>
<td>0.00751</td>
</tr>
<tr>
<td></td>
<td>12 to 14</td>
<td>0.00736</td>
</tr>
<tr>
<td></td>
<td>14 to 20</td>
<td>0.00717</td>
</tr>
<tr>
<td></td>
<td>20 to 26</td>
<td>0.00738</td>
</tr>
<tr>
<td></td>
<td>26 to 28</td>
<td>0.00735</td>
</tr>
<tr>
<td></td>
<td>28 to 32</td>
<td>0.00742</td>
</tr>
<tr>
<td></td>
<td>larger 32</td>
<td>0.00737</td>
</tr>
<tr>
<td>truck trailers and articulated trucks</td>
<td>up to 28</td>
<td>0.00741</td>
</tr>
<tr>
<td></td>
<td>28 (Switzerland)</td>
<td>0.00731</td>
</tr>
<tr>
<td></td>
<td>28 to 34</td>
<td>0.00725</td>
</tr>
<tr>
<td></td>
<td>34 to 40</td>
<td>0.00732</td>
</tr>
<tr>
<td></td>
<td>40 to 50</td>
<td>0.00751</td>
</tr>
<tr>
<td></td>
<td>50 to 60</td>
<td>0.00754</td>
</tr>
<tr>
<td>Urban bus</td>
<td>midi</td>
<td>up to 15</td>
</tr>
<tr>
<td></td>
<td>standard</td>
<td>15 to 18</td>
</tr>
<tr>
<td></td>
<td>articulated</td>
<td>larger 18</td>
</tr>
<tr>
<td>coach</td>
<td>standard</td>
<td>up to 18</td>
</tr>
<tr>
<td></td>
<td>three axle</td>
<td>larger 18</td>
</tr>
</tbody>
</table>

This approach can only be applied for an assessment of the rolling resistances of “standard” tires in combination with “standard” ambient conditions. The influence of specific effects attributed to single vehicle categories (e.g. a higher share of construction trucks with massive-bar tyres) or special ambient conditions (e.g. heavy rain, snow) is not taken into consideration due to lack of data.

6.1.6 Power demand of the auxiliaries

A quantitative assessment of the power demand of truck and bus engine auxiliaries (e.g. cooling fan, compressor for brakes and suspension, alternator producing electric power exceeding the part necessary for engine operation) can be found in Appendix IV and [60]. All auxiliaries consume an amount of power which is not constant, but in a range from mechanical losses at zero (auxiliary) load to their full-load conditions. However, the analysis of the measurements at the chassis dynamometer and the evaluation of on-road measurements suggested that a model approach using a rather constant power demand of the engine auxiliaries is sufficient for the calculation of representative driving cycles under standard ambient condition (see 4.2.5). The elaborated \( P_0 \)-values (power demand of the auxiliaries as ratio to the rated power) for the power consumption of the auxiliaries are in a range between 1.5% for heavy articulated trucks to 5% for coaches.

6.1.7 Drivetrain layout

The basic specifications of the drivetrains (number of gears, gear ratios, axle-ratio and wheel diameter of the powered axle) have been set according to manufacturer specifications for typical HDVs in each HDV category and are not listed in detail here.
Special attention has been drawn to the arrangement of engine and drivetrain: as the ESC test cycle (valid from EURO 3 on) leaves a rather broad range in the engine map below the engine speed “ESC A” uncontrolled, the measured engines showed higher specific NOx-emission values in this engine map area (see 3.1.3). A similar emission behaviour is expected for engines certified according to EURO 4 and EURO 5, but regulations under discussion for the application of OBD systems (which limit the emission levels even outside the controlled area in the engine map, “Not to exceed”-limits) might reduce this effect. As a high share of the mileage of a HDV is driven on motorways at vehicle speeds of 80 to 90 km/h, it is of great influence on the overall emission level whether the corresponding engine speeds are within or outside the controlled area. In order to clarify this subject for each combination of EURO 3 engine and vehicle included in PHEM, an analysis of the resulting engine speeds driving in the highest gear at a vehicle speed of 80 km/h has been performed. The outcome was that on average the engine speed for highway driving will usually lie within the ESC controlled area. The results of this analysis have been transferred to the arrangement of average vehicle specifications by slight adjustments of the axle ratios.

As the functions for the losses in the transmission system (see paragraph 4.2.6) are based on measurements at the end of the 90ies, it can be assumed, that EURO 3 transmissions show on average higher transmission efficiencies. A comparison of the fuel consumption during vehicle measurements (on the chassis dynamometer and on-road) with model calculations supports this assumption. Therefore, the overall factor for the transmission losses in the model is set on average to values lower than one (this factor represents the ratio between the actual transmission efficiency and the “standard” value in the model). The values used in the model are in a range of 0.6 (single driven axle) to 1.1 (two driven axles).

### 6.2. Vehicle specifications for other vehicle generations compared to EURO 3 vehicles

Once the vehicle specifications for the vehicles according to EURO 3 have been established, the model input data for all other “EURO-classes was determined by factors relating to the EURO 3 vehicles. These factors are based on estimations from data given in “Lastauto & Omnibus” over different yearbooks and the data bank of the Institute of Internal Combustion Engines, Graz, where technical characteristics of HDV are collected from specifications of the manufacturers and from literature (Table 31).

**Table 31: Ratios used for technical characteristics compared to EURO 3 HDV**

<table>
<thead>
<tr>
<th></th>
<th>vehicle mass (1)</th>
<th>c_{c}-value</th>
<th>rated power</th>
<th>transmission losses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre EURO 1</td>
<td>100%</td>
<td>108%</td>
<td>89%</td>
<td>105%</td>
</tr>
<tr>
<td>EURO 1</td>
<td>100%</td>
<td>104%</td>
<td>91%</td>
<td>103%</td>
</tr>
<tr>
<td>EURO 2</td>
<td>100%</td>
<td>103%</td>
<td>97%</td>
<td>101%</td>
</tr>
<tr>
<td>EURO 3</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>EURO 4</td>
<td>100%</td>
<td>99%</td>
<td>102%</td>
<td>99%</td>
</tr>
<tr>
<td>EURO 5</td>
<td>100%</td>
<td>98%</td>
<td>104%</td>
<td>99%</td>
</tr>
</tbody>
</table>

**Index: EURO 3 value = 100%**

(1) the data available did not indicate a clear trend to lower empty vehicle masses for newer HDV, but no consistent data on the weights of HDV older than 1995 was available for this study. To have similar loadings for all EURO categories it was decided to keep the vehicle empty mass constant within the HDV categories.

The values of other vehicle data necessary for the model are summarised in paragraph 6.1 and have already been elaborated in paragraph 4.2. The rolling resistance coefficients are set at the same value for all EURO classes. Although the tyre characteristics have been improved over the years, the tyres on all vehicles are changed rather frequently. So the EURO 0 and
EURO 3 HDV are used today with the same tyre-road combination and will therefore have identical rolling resistances\textsuperscript{23}.

Differences in the basic specifications of the drivetrains (number of gears, gear ratios, axle-ratio and wheel diameter of the powered axle) between the different vehicle generations have been set the same way (according to the data available), but are not listed here in detail.

7. EFFECTS OF FUEL QUALITY ON EMISSIONS

The main objectives of this work were to compile a review of the recent available literature for assessment and understanding of the impact of diesel fuel properties on emissions from heavy-duty diesel engines (HDDEs) of current and future technologies, to identify contradictions and gaps in the gained knowledge, and to choose available model(s), which will allow the best predictions of fuel effects on HDDE emissions. The analysis of fuel effects includes their influence on engine-out emissions and on conversion efficiencies of advanced after-treatment technologies, under different test cycle conditions.

The most comprehensive investigations of the effects of fuel properties on HDDE emissions have been carried out within the scope of the following programs:

- European programme on emissions, fuels and engine technology, 1995 (EPEFE);
- EPA heavy-duty engine working group program, USA, 2000 (EPA-HDEWG);
- Diesel emission control – sulphur effects program, USA, 2000 (DECSE);
- EPA project on modelling effects of diesel fuel properties on HDDE emissions, USA, 2001 (New EPA).

7.1. Comparison of EPEFE, EPA-HDEWG and New EPA programs

The goals of the European EPEFE and the USA EPA-HDEWG programs were identical, but the fuels and the engines were of different manufacturers, generations and technologies, and the tests were performed over different test cycles. The New EPA program was aimed at quantifying effects of diesel fuel properties on HDDE emissions, based only on published data without carrying out any additional experiments. Therefore, a comparison of the results of such programs is very interesting and important. Obviously, it is impossible to make such a comparison with respect to absolute values of the results. However, general trends and tendencies, as well as magnitude impacts of the various parameters may be compared. Table 32 includes the ranges of property values of the fuels tested in the EPEFE and EPA-HDEWG programs, a brief description of the engines, types of test cycles and a list of measured emissions. As can be seen, the cetane numbers of the US fuels were significantly lower than those of the European fuels. This represents the actual historical development of the diesel fuel market in the USA [39].

\textsuperscript{23} When fuel consumption and emission behavior of “pre EURO 1”-vehicles equipped with tyres according to the specifications found in literature (i.e. equipment in the eighties).
Table 32: EPEFE (Europe) and EPA-HDEWG (USA.) programs - range of investigations

<table>
<thead>
<tr>
<th>Fuels tested</th>
<th>EPEFE</th>
<th>EPA-HDEWG</th>
</tr>
</thead>
<tbody>
<tr>
<td>density, kg/m³</td>
<td>11 diesel fuels</td>
<td>Phase II: 18 diesel fuels</td>
</tr>
<tr>
<td>cetane number</td>
<td>855-828</td>
<td>860-830</td>
</tr>
<tr>
<td>back-end distillation (T95), °C</td>
<td>50-58</td>
<td>42-52</td>
</tr>
<tr>
<td>total aromatic content, % m</td>
<td>370-325</td>
<td>311-327</td>
</tr>
<tr>
<td>poly-aromatic content, % m</td>
<td>no data</td>
<td>10-25</td>
</tr>
<tr>
<td>sulphur content, ppm</td>
<td>1-8</td>
<td>1-11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Engines tested</th>
<th>EPEFE</th>
<th>EPA-HDEWG</th>
</tr>
</thead>
<tbody>
<tr>
<td>swept volume, litre</td>
<td>5 HDDE turbocharged and intercooled, all met at least EURO 2 standards</td>
<td>Phase II: Caterpillar 3176, turbocharged and intercooled, met 2004 NOₓ standard</td>
</tr>
<tr>
<td>rated power, kW</td>
<td>2.8-11</td>
<td>10.3</td>
</tr>
<tr>
<td>rated speed, rpm</td>
<td>84.5-250</td>
<td>260</td>
</tr>
<tr>
<td>max torque, Nm</td>
<td>1900-3600</td>
<td>1800</td>
</tr>
<tr>
<td>fuel injection system</td>
<td>1600-253 pump+line+injector</td>
<td>1515 electronic injector unit</td>
</tr>
</tbody>
</table>

| Test cycle | 13-mode 88/77 ECE | Phase II: 8-mode AVL |
| Emissions measured | NOₓ, CO, THC, PM | NOₓ, CO, THC, CO₂ |

7.1.1 EPEFE PROGRAM

This program [1], [62] included tests on HDDEs, which were selected to represent a wide range of dimensions and technologies of European engines, up to EURO 2 emissions standards. All the engines were equipped with pump-line-injector type fuel injection systems. The engines tested in this program were not equipped with any after-treatment devices.

The fuel density effect was studied for a reference engine setting as well as for three other settings: reference power, reference fuel mass delivery and reference dynamic timing. The conclusion derived from the results is that the fuel density influence on diesel emissions is only an outcome of the changes in the physical properties of the working fluid inside the hydraulic injection system (such as the velocity of sound, flow speed through constrictions, specific heat etc.). The fuel density does not directly affect the combustion process in the engine.

It is noted that all the fuels tested in the program had almost the same level of sulphur content (402-469 ppm). Nevertheless, the researchers succeeded, based on data processing from available literature, to quantitatively assess the impact of sulphur content on engine-out emissions by the addition of complementary blocks to the regression equations, derived as a result of their own data processing (Table 33).
Table 33: EPEFE, EPA-HDEWG and New EPA programs regression equations [7], [3], [18]

<table>
<thead>
<tr>
<th>Emission</th>
<th>EPEFE [g/kWh]</th>
<th>phase II of EPA-HDEWG [g/hp h]</th>
<th>New EPA, [g/hp h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>$2.24407 - 0.00111D + 0.00007P - 0.00768C - 0.00087T95$</td>
<td>1.28-0.0105C</td>
<td>$CO$ was not studied</td>
</tr>
<tr>
<td>HC</td>
<td>$1.61466 - 0.00123D + 0.00133P - 0.00181C - 0.00068T95$</td>
<td>0.2027 - 0.00186C + 0.00677M + 0.00160P</td>
<td>Exp(5.32059 - 0.1875CN + 0.001571CN^2 - 0.0009809T10 - 0.002448T50 - 0.1880CD + 0.003507CN*CD)</td>
</tr>
<tr>
<td>NOx</td>
<td>$-1.75444 + 0.00906D + 0.0163P - 0.00493C - 0.00266T95$</td>
<td>$-1.334 + 0.00413D + 0.00337C + 0.00646M + 0.00763P$</td>
<td>Exp(0.50628 - 0.002779CD + 0.002922A + 1.3966G - 0.0004023T50)</td>
</tr>
<tr>
<td>PM</td>
<td>$(0.06959 + 0.00006D + 0.00065P - 0.00001C)* [1 - 0.000086(450 - S)]$</td>
<td>Particulate matter was not studied</td>
<td>Exp(-3.75781 - 0.004525CN - 0.04825CD + 0.002157A + 0.00008386S + 2.3708G - 0.07193OX + 0.001009CN*CD)</td>
</tr>
</tbody>
</table>

With:
- $D$ – density, kg/m³;
- $G$ – specific gravity;
- $P$ – poly-aromatics content, % m;
- $M$ – mono-aromatics content, % m;
- $A$ – total aromatics content, % vol;
- $C$ – cetane number;
- $CN$ – natural cetane number;
- $CD$ – cetane difference due to additizing;
- $S$ – sulphur content, ppm;
- $OX$ – oxygen content, % m;
- $T10$ – T10 temperature, °F;
- $T50$ – T50 temperature, °F;
- $T95$ – T95 temperature, °C.

An important finding was that the spread of emissions values with change of fuels on the same engine was substantially less than that with different engines operating on the same fuel. The only exception was for NOx emissions, where the spread was the same and rather small (Table 34).

Table 34: Spread of emission values by variations of fuels and engines - EPEFE results (Signer, 1996)

<table>
<thead>
<tr>
<th>Emission</th>
<th>Variation of fuels, %</th>
<th>Variation of engines, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOx</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>PM</td>
<td>7</td>
<td>67</td>
</tr>
<tr>
<td>HC</td>
<td>19</td>
<td>75</td>
</tr>
<tr>
<td>CO</td>
<td>17</td>
<td>33</td>
</tr>
</tbody>
</table>

Only a few comparisons linking different fuels and test cycles were carried out in the framework of the EPEFE. As part of this study, some fuels were tested both in 5 European engines over the steady state ECE R49 cycle and also in a US engine over the US transient FTP cycle [62]. The results of this comparison are presented in Figure 78 [39] and show that the effects of changes of individual fuel properties on emissions from two sets of data (US and EU) were generally similar. The direction of the changes of PM, NOx and HC emissions, as a result of fuel quality influence, was the same for the ECE R49 steady state cycle and the US FTP transient cycle, but different for CO.
7.1.2. EPA-HDEWG PROGRAM

The objective was to assess the role that diesel fuel could play in meeting 2004+ emission standards for HDDEs. It consisted of three phases [54], [3].

In the course of phase I, three fuels were tested. One of them had its cetane number, aromatic and sulphur contents close to the USA commodity diesel fuel. The tests were carried out on seven engines, with six tested by engines manufacturers over both AVL 8-mode steady-state and FTP transient cycles, and one (Caterpillar 3176 truck engine) was tested on the Southwest Research Institute (SWRI) test bench only on the first cycle. On the basis of phase I results, the researches came to the conclusion that this engine is representative, and that the results obtained in the AVL 8-mode steady-state cycle can represent the results received in the FTP transient cycle with sufficient accuracy, except for PM emissions.

In the course of phase II, the impact of 18 different fuels on gaseous emissions from the Caterpillar 3176 engine was investigated. The engine tests were performed on the SWRI test bench over the AVL 8-mode steady-state cycle. The engine was equipped with a unit electronic injector (UEI), capable of up to 207 MPa injection pressure, and a water-cooled exhaust gas recirculation system (EGR) satisfying the 2004 NOx standard. The effect of fuel sulphur content was not investigated in this phase, because it has negligible impact on NOx, CO and HC emissions; the engine had no sulphur-sensitive after-treatment device. No PM measurements were planned since the results of the steady-state cycle PM emissions do not correlate with the FTP transient cycle results. By statistical processing of the experimental results, the regression equations (included in Table 33) were used to correlate the AVL 8-mode weighted emissions with diesel fuel properties. One of the significant results that were found is that the relative effects of EGR are the same, independent of the fuel properties. This result is similar to earlier findings by European researchers [43].

**Figure 78.** Comparison of fuel effects, as were measured over different test cycles [39].
The goals of phase III of the EPA-HDEWG program were verification of the phase II results on the most modern engines, as well as investigations of fuel properties impact on PM emissions in the FTP transient cycle (these results were not available at the time the report was written).

7.1.3. NEW EPA PROGRAM

Main objective was to quantify effects of diesel fuel properties on emissions from heavy duty vehicles based solely on the published data, without carrying out any additional experiments. Some new features were included in this program compared to the previous counterparts. First of all, effects of natural and “additized” cetane number were separated and studied, and show quite different effects on NOx emissions. Second, effects of fuel oxygen content were taken into account in the analysis and regression equations (see Table 33). Finally, effects of whole distillation range and not only back-end distillation were analysed and found to be valuable, mainly for HC emissions – see further comparison of the models.

7.1.4. COMPARISON OF EPEFE, EPA-HDEWG & NEW EPA MODELS.

Figures 7-2 to 7-4 present examples of relative changes of HDDE emissions versus changes of fuel properties (as calculated by equations in Table 33), which were investigated in the above mentioned programs.

The effects of sulphur content.

It was established in the EPEFE and New EPA programs (EPA-HDEWG did not study this issue) that fuel sulphur content have an impact only on PM emissions. Both models predict similar changes in PM emissions, as a result of sulphur content change (Figure 7.2). At the same time, it is noted by HDDEs manufacturers [1], that fuel sulphur impact on PM emissions from HDDEs may be more substantial than the above mentioned predictions: according to ACEA, decrease of sulphur content from 500ppm down to 30 ppm may lead to decrease of PM emissions by 9%.

![Figure 79. Relative change of PM emissions from heavy-duty engines versus fuel sulphur content as calculated by equations of Table 33.](image-url)
The effects of poly-aromatic content (PA)

The effects on gaseous emissions were found to be practically the same in both EPEFE and EPA-HDEWG programs (in the New EPA program poly- and monoaromatic effects were not clarified in the published literature at the time this report was written). The results of a PA increase from 1% to 8% mass were:

- Negligible increase of CO emission (by 0.08%) in the EPEFE program, while no change in the EPA-HDEWG.
- Increase of HC emission by 4% ± 0.2% in both programs.
- Increase of NO\textsubscript{x} emission by 1.9% ± 0.2% in both programs.

According to the latest CONCAWE research [8], carried out on two heavy-duty diesel EURO 3 engines, which were tested over ESC and ELR cycles, reducing the total aromatics leads to a reduction in HC emissions, but has no significant effect on CO, NO\textsubscript{x} and PM emissions. It is also noted in this work that, as the total aromatics effects were small, it was not possible to quantify separately the relative contribution of mono- and poly-aromatics.

The cetane number (CN) effects

The cetane number effects were as follows (it is noted that in the EPEFE program the CN range studied was 50-58, in the EPA-HDEWG - 42-52 and in the New EPA program the valid range limits were 38-66):

- Identical for CO emissions: decrease, per CN unit increase, by 1.3% in EPEFE and EPA-HDEWG (CO was not studied in the New EPA program).
- Very close for HC emissions, as predicted by EPEFE and EPA-HDEWG models: decrease, per CN unit increase, by 0.78% in EPEFE and by 0.60% in EPA-HDEWG. However, a much more dramatic change according to the New EPA model was found: 3.5% reduction per CN unit increase.
- Negligible, but opposite trends for NO\textsubscript{x} emissions (Figure 80): Decrease, per CN unit increase, by 0.075% in EPEFE and increase by 0.13% in EPA-HDEWG. The New EPA model gives some additional information by separating natural and additized cetane number effects. As can be seen from Figure 80, there is no effect of natural cetane number on NO\textsubscript{x} emissions was found. At the same time, the NO\textsubscript{x} reduction of 0.28% per CN unit increase was indicated for additized cetane.
- Very small reduction of PM emissions, as a result of CN increase: changes predicted by EPEFE are negligible: 0.008% reduction per CN unit increase; according to the New EPA model: 0.36% of PM reduction per CN unit increase (EPA-HDEWG program did not deal with PM emissions).

The result of the EPA-HDEWG program for the effect of CN on NO\textsubscript{x} is inconsistent with well-established knowledge that an increase of CN leads to decrease of ignition delay and the portion of the fuel involved in the premixed phase of combustion. This portion is burnt by explosive combustion, which is the main mechanism of NO\textsubscript{x} generation. Therefore, the NO\textsubscript{x} emissions decrease when the CN is increased. It is noted that the authors of [54] had been, indeed, surprised by their result, and suggested that it was caused by design of the engine tested and of the fuel test matrix.

The injection pressure maintained by the unit electronic injector was extremely high (up to 200 MPa), and the dimensions of the combustion chamber were relatively small (125 mm cylinder diameter). Therefore, it can be assumed that part of the fuel injected during the ignition delay spreads out as a film on the combustion chamber wall, and does not burn by
explosive combustion, thereby suppressing NO\textsubscript{x} formation. As a result of raising the cetane number, the injection delay decreases as well as the part of the fuel that forms a film on the wall. Hence, the part of the fuel burning in the bulk of the combustion chamber increases, the temperatures of engine operating cycle rise, and NO\textsubscript{x} formation increases.

It is noted that according to the latest CONCAWE research [8], increasing the cetane number from 53 to 58 did not lead to a significant effect on NO\textsubscript{x} and PM emissions. In this work, no emissions differences were found between natural cetane fuels and those where the cetane number was boosted using ignition improver additive.

**Figure 80.** Relative change of NO\textsubscript{x} emissions from heavy-duty diesel engines versus cetane number of fuel, as calculated by equations from Table 33.

The effect of fuel density

The impact of fuel density on gaseous emissions (Figure 81) was compared for the reference setting of engines tested. Under such conditions, increase of the fuel density causes the following changes in the injection system:

- Increase of the dynamic timing, as a consequence of the increase of the velocity of sound in the fuel, i.e. decrease of the time of pressure pulse movement from the injection pump to the injector (only for injection systems of the pump-line-injector type).

- Increase of the fuel mass injected (in each operating cycle) resulting in an increase of engine power.

- Decrease of fuel volume injected (in each operating cycle) according to the equation:

\[
q = 1.41 \cdot \mu f \cdot g^{0.5} \cdot \rho^{-0.5} \cdot \Delta p^{0.5}
\]

where: \(\mu f\) – effective cross section of nozzle orifice, \(g\) – acceleration of gravity, \(\rho\) – fuel density, \(\Delta p\) – pressure difference on the nozzle.

This effect partly compensates the increase of the engine power due to increase of the fuel mass.

The phenomena listed above furnish an explanation for the changes of emissions with the fuel density, as well as for some conflicting results found in the EPEFE vs. EPA-HDEWG and New EPA programs.
As can be seen from Figure 81, an increase of the fuel density from 828 kg/m³ to 855 kg/m³ causes a decrease of the average CO and HC emissions from EPEFE engines (with the pump-line-injector type fuel systems) by about 5% and 13%, respectively. This is the typical response of diesel engines to earlier injection timing. The CO and HC emissions from the Caterpillar 3176 with unit electronic injector (EPA-HDEWG program) were independent of fuel density. This results from the absence of an injection line and of keeping the timing unchanged. In all three models, the increase of fuel density leads to a similar increase of NOₓ emissions. This is a combined result of the dynamic timing increase (only in the EPEFE program), increase of the fuel mass injected during the ignition delay, and some increase of power due to the increase of fuel mass delivery.

![Figure 81](image)

**Figure 81:** Relative change of emissions from heavy-duty diesel engines versus fuel density, as calculated by equations from Table 33.

### 7.2. DECSE program results

As stated above, HDDEs of generations after EURO 3 may satisfy the emission standards only by application of after-treatment systems. Hence it is important and quite urgent to assess the impact of fuel properties on the efficiency and durability of these devices. The experience gained so far shows that the main property that affects the efficiency of after-treatment devices is the fuel sulphur content, e.g. [47], [29], [72], [2]. During the recent years, a comprehensive assessment has been undertaken, by co-operation of USA government organisations, manufacturers of engines and after-treatment devices and research laboratories, in an attempt to determine the effects of fuel sulphur content on the efficiency of some devices. The technologies studied were: diesel oxidation catalysts (DOC), lean-NOₓ catalysts (L-NOₓ Cat), diesel particular filters or traps (DPFs), and NOₓ adsorbers (NOₓ-Ad).

Fuels with 3, 16, 30, 150 and 350 ppm sulphur content were studied on the engines which were considered as representative by emissions and exhaust temperatures values. The main results of the studies are presented below.
DIESEL OXIDATION CATALYST.

The investigations performed on the Cummins ISM 370 diesel engine confirmed the results of some earlier studies [47], [2], [30]. They demonstrated a dramatic decline of DOC efficiency (as a result of sulphates formation), when the upstream exhaust temperature exceeds 350 °C – 400 °C, and this trend is stronger for an increased sulphur content in the fuel.

It follows from Figure 82 that in the maximum torque mode (518 °C upstream exhaust temperature), the PM emissions after the DOC exceed the engine-out values already at 30 ppm sulphur content. At 350 ppm, they are more than double, and, moreover, sulphates account for nearly half of the total PM emissions. It is important to note that over the FTP transient cycle with an average exhaust temperature of about 240 °C, PM emissions were practically independent of fuel sulphur level.

The impact of fuel sulphur content on CO, HC and NOx emissions was not reported in [14]. However, the results in [37] demonstrate that a decrease of the sulphur content from 368 ppm down to 54 ppm on an HDDE DDC series 60, equipped by different DOCs, caused a decrease of HC conversion efficiency by 6-15% and increase of CO efficiency by 10-11%.

![Figure 82: The impact of sulfur content on PM emissions, Cummins ISM 37D + DOC, maximum torque [14].](image)

LEAN-NOx CATALYST (L-NOx)

This catalyst decreases NOx emissions by adding hydrocarbon matter, e.g. diesel fuel, to rich-oxygen exhaust gases, according to the reaction:

\[ \text{NO}_x + \text{HC} + \text{O}_2 \rightarrow \text{N}_2 + \text{CO}_2 + \text{H}_2\text{O} \]

Figure 83 shows that increasing the fuel sulphur content from 3 ppm to 150 – 350 ppm causes a dramatic increase, by a factor of 10 – 20, of sulphates emissions after the L-NOx, while the increase of engine-out sulphates emissions was only by a factor of 2 – 5. After the L-NOx, total PM emissions increase by a factor of nearly 1.5.
CONTINUOUSLY REGENERATING DIESEL PARTICULATE FILTER (CR-DPF) and CATALYZED DIESEL PARTICULATE FILTER (C-DPF)

These filters have been directly designed to remove particulate matter from the engine exhaust. In the CR-DPF, the continuous regeneration is achieved by oxidizing soot particles caught on trap sites, by nitrogen dioxide which is continuously generated in the exhaust by the reactions:

\[ 2NO + O_2 \rightarrow 2NO_2; \quad 2NO_2 + C \rightarrow 2NO + CO_2 \]

In the C-DPF, the regeneration is achieved by catalytic oxidation of particulate matter trapped on the filter with oxygen. For both types of DPFs, oxidation of sulphur causes an increase of PM emissions as a result of a sulphate increase. Moreover, in the CR-DPF, the reaction of sulphate formation may suppress those of NO and NO₂.

The results presented in Figure 7-7 show that the conversion efficiency of the two DPFs was 95% when the sulphur content was 3 ppm, and about 73% with 30 ppm sulphur content. Increasing the sulphur content to 150 ppm leads to zero efficiency, while a further increase to 350 ppm causes PM emissions to rise by a factor of 2.2 for the C-DPF and by 2.5 for the CR-DPF. As noted in (DECSE, 2000), the exhaust temperature required for the DPF regeneration process grows with the increase of fuel sulphur content. The right part of Figure 7-7 represents the efficiencies of the two DPFs with 30 ppm sulphur content, after about 400 hours operation with 150 ppm and 350 ppm. One can see that this causes recovery of the DPFs efficiencies. Although [13] did not comment on the statistical significant impact of sulphur content on the CO₂, HC and NOₓ conversion efficiencies, very high values have been observed: for HC about 70% with C-DFC and about 83% with CR-DPF; for CO 90-99% with both DPFs.
Figure 84. PM emissions at engine-out and after C-DPF and CR-DPF versus sulfur content in the fuel [13].

THE NO\textsubscript{X} ADSORBER CATALYST (NO\textsubscript{X}-Ad-C)

This is an after-treatment device storing NO\textsubscript{x} from the exhaust gases. It is cleaned periodically from NO\textsubscript{x} by a short-term switch of the engine to operation under fuel-rich exhaust conditions, causing a NO\textsubscript{x} to N\textsubscript{2} transformation over precious-metal catalyst sites in the adsorber. The impact of the fuel sulphur content on the efficiency of a NO\textsubscript{x}-Ad-C manifests itself in the fact that SO\textsubscript{2}, present in the exhaust, undergoes chemical reactions that produce a much more reactive adsorbent than NO\textsubscript{2}, thereby suppressing the NO\textsubscript{x} reduction. The investigations reported in [15] were carried out for developing a process of NO\textsubscript{x}-Ad-C de-sulphurisation and to study the impact of sulphur on the long-term performance of the device. Figure 85 illustrates the effect of fuel sulphur content on the NO\textsubscript{x}-Ad-C performance. One can see that even a small increase of the sulphur content (from 3 to 30 ppm) causes a drastic decrease of the NO\textsubscript{x}-Ad-C efficiency. As noted in [12], there is no impact of fuel sulphur content on NO\textsubscript{x}-Ad-C efficiency for total PM, SOF or non-SOF emissions over the temperature range studied (250 - 500°C), or during adsorber aging of up to 250 hours.

Figure 85. Effect of increasing fuel sulphur level on relative NO\textsubscript{x} conversion efficiency of an NO\textsubscript{x} adsorber catalyst, at 150 hour aging, evaluated at 400 and 450°C [12].
7.3. Description of the ARTEMIS approach

Based on the literature review it was agreed that a special research program has to be carried out, in order to study the gaps and contradictions which were highlighted in the survey. Such a program requires design and preparation of special fuel formulations – a task which is well out of the scope of the ARTEMIS work plan.

As a result of discussions with WP 400 partners, it was decided that the available models would be assessed based on the measurements of EURO 3 (or future technology, if available) engines fuelled by available diesel fuels with different specifications. Therefore, common fuel effects, which may be contradictory for various fuel parameters, would be measured over current European test cycles. These results could then be compared with the predicted fuel effects by using the models. Table 35 contains current and future diesel fuel qualities, as are reflected in the relevant standards or other European documents [9], [1], [10].

**Table 35.** Current and future diesel fuel parameters [9], [1], [10]

<table>
<thead>
<tr>
<th>Year</th>
<th>Reference</th>
<th>Cetane No.</th>
<th>Density [kg/m³]</th>
<th>Back-end distillation T95 [°C]</th>
<th>Total Aromatics [% m/m]</th>
<th>Poly-aromatics, [% m/m]</th>
<th>Sulfur, [mg/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>min</td>
<td>max</td>
<td>min</td>
<td>max</td>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td>2000</td>
<td>98/70/EC</td>
<td>51</td>
<td>845</td>
<td>360</td>
<td>11</td>
<td>350</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Category 2, WWFC</td>
<td>53</td>
<td>820</td>
<td>850</td>
<td>355</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>2005</td>
<td>98/70/EC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50*</td>
</tr>
<tr>
<td></td>
<td>Category 3, WWFC</td>
<td>55</td>
<td>820</td>
<td>840</td>
<td>340</td>
<td>15</td>
<td>2.0</td>
</tr>
<tr>
<td>2008</td>
<td>Category 4, WWFC</td>
<td>55</td>
<td>820</td>
<td>840</td>
<td>340</td>
<td>15</td>
<td>2.0</td>
</tr>
<tr>
<td>Sweden</td>
<td>Urban diesel 1</td>
<td>50</td>
<td>800</td>
<td>820</td>
<td>285</td>
<td>5</td>
<td>0.02</td>
</tr>
</tbody>
</table>

* - In May 2000 the EU Commission launched a consultation on the need to reduce the sulphur content below the level of 50 ppm, already mandated for 2005, to a value of 30 or 10 ppm [10].

WWFC – World–Wide Fuel Charter, April 2000 (reflects requirements of vehicle manufacturers) [1]:

- **Category 2**
  Markets with stringent requirements for emission control or other market demands.

- **Category 3**
  Markets with advanced requirements for emission control or other market demands, for example, markets requiring Euro 3 and 4, or equivalent emission standards.

- **Category 4**
  Markets with further advanced requirements for emission control to enable sophisticated NOx and PM after-treatment technologies.
7.4. Comparison of ARTEMIS test results with model predictions

In the framework of the ARTEMIS/COST 346 work programs, four EURO 3 engines of different makes were tested over ESC, ETC (excluding KTI test) and TNO (only in MTC test) test cycles. Each engine was tested with at least two different diesel fuels. Specifications of fuels used in these tests are listed in Table 36.

Table 36. Some parameters of the fuels used in the tests.

<table>
<thead>
<tr>
<th>Testing Lab.</th>
<th>Fuel type</th>
<th>Density (kg/m³)</th>
<th>Cetane number</th>
<th>Poly-aromatics*</th>
<th>Total aromatic s</th>
<th>T10 °C</th>
<th>T50 °C</th>
<th>T95 °C</th>
<th>Sulphur Content ppm</th>
<th>Oxygen content % m</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTC</td>
<td>TUG</td>
<td>836.5</td>
<td>53.0</td>
<td>1.5</td>
<td>17.2</td>
<td>239.3</td>
<td>276.4</td>
<td>346.8</td>
<td>245</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>EC1</td>
<td>814.7</td>
<td>52.5</td>
<td>0.3</td>
<td>4.3</td>
<td>209.8</td>
<td>235.0</td>
<td>282.1</td>
<td>3</td>
<td>N/A</td>
</tr>
<tr>
<td>KTI</td>
<td>Market</td>
<td>837.7</td>
<td>52.9</td>
<td>5.4</td>
<td>N/A</td>
<td>212</td>
<td>268</td>
<td>352</td>
<td>258</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Exper.</td>
<td>841.1</td>
<td>51.0</td>
<td>4.82</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>349</td>
<td>25</td>
<td>N/A</td>
</tr>
<tr>
<td>TUG</td>
<td>S=390</td>
<td>836</td>
<td>53.6</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>390</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>S=6</td>
<td>818</td>
<td>58.2</td>
<td>7.3</td>
<td>N/A</td>
<td>266</td>
<td>N/A</td>
<td>6</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>TNO</td>
<td>S=286</td>
<td>836</td>
<td>54.0</td>
<td>4.3</td>
<td>26.5</td>
<td>208</td>
<td>273</td>
<td>348</td>
<td>286</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>S=35</td>
<td>827.2</td>
<td>56.2</td>
<td>3.6</td>
<td>25.5</td>
<td>N/A</td>
<td>N/A</td>
<td>335</td>
<td>35</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>S=5</td>
<td>824.3</td>
<td>52.8</td>
<td>4.9</td>
<td>22.8</td>
<td>214.3</td>
<td>248.0</td>
<td>305.6</td>
<td>5</td>
<td>N/A</td>
</tr>
</tbody>
</table>

* Poly-cyclic aromatic hydrocarbons are defined as the total aromatic hydrocarbon content less the mono-aromatic hydrocarbon content.

It has to be noted that for some cases not all fuel parameters needed for model simulations were available. To solve this problem, a reasonable range of such parameters was estimated and calculations have been made for this range of data. Only if a reasonable estimate of a specific fuel parameter was possible, this was done (for example, estimate of T95 temperature, if values of T90 and FBP temperatures were available).

The measured and predicted changes of NOₓ, PM, HC and CO emissions, as a result of fuel effects, are given in Table 40. These results present the relative difference between the two (or three – TNO) tested fuels. For these predictions, where some values of fuel parameters were missing, average values in the estimated range were taken into account. The tables only show a change in emissions as a result of the fuel quality change. Despite the fact that absolute values of predicted emissions are not shown here, it is noted that measured values of all emission parameters are much closer to those predicted by EPEFE and New EPA models than EPA-HDEWG model.
Table 37: Comparison of test results with models predictions – change in NOx emissions, %

<table>
<thead>
<tr>
<th>Testing Lab.</th>
<th>ETC test</th>
<th>ESC test</th>
<th>EPEFE</th>
<th>EPA-HDEWG</th>
<th>New EPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTC</td>
<td>-6</td>
<td>-7</td>
<td>-6</td>
<td>-7</td>
<td>-4</td>
</tr>
<tr>
<td>KTI</td>
<td>N/A</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
</tr>
<tr>
<td>TUG</td>
<td>-0</td>
<td>1</td>
<td>-5</td>
<td>-8</td>
<td>-8</td>
</tr>
<tr>
<td>TNO</td>
<td>1</td>
<td>-2</td>
<td>-2</td>
<td>-2</td>
<td>-5</td>
</tr>
<tr>
<td></td>
<td>-1</td>
<td>-1</td>
<td>-3</td>
<td>-3</td>
<td>-4</td>
</tr>
</tbody>
</table>

Table 38: Comparison of test results with models predictions – change in PM emissions, %

<table>
<thead>
<tr>
<th>Testing Lab.</th>
<th>ETC test</th>
<th>ESC test</th>
<th>EPEFE</th>
<th>New EPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTC</td>
<td>-7</td>
<td>-18</td>
<td>-8</td>
<td>-11</td>
</tr>
<tr>
<td>KTI</td>
<td>N/A</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TUG</td>
<td>-29</td>
<td>-6</td>
<td>-8</td>
<td>-13</td>
</tr>
<tr>
<td>TNO</td>
<td>-4</td>
<td>-21</td>
<td>-3</td>
<td>-6</td>
</tr>
<tr>
<td></td>
<td>-3</td>
<td>-35</td>
<td>-3</td>
<td>-6</td>
</tr>
</tbody>
</table>

Table 39: Comparison of test results with models predictions – change in HC emissions, %

<table>
<thead>
<tr>
<th>Testing Lab.</th>
<th>ETC test</th>
<th>ESC test</th>
<th>EPEFE</th>
<th>EPA-HDEWG</th>
<th>New EPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTC</td>
<td>30</td>
<td>26</td>
<td>27</td>
<td>-38</td>
<td>37</td>
</tr>
<tr>
<td>KTI</td>
<td>N/A</td>
<td>18</td>
<td>0</td>
<td>-8</td>
<td>5</td>
</tr>
<tr>
<td>TUG</td>
<td>-19</td>
<td>-46</td>
<td>4</td>
<td>-50</td>
<td>-11</td>
</tr>
<tr>
<td>TNO</td>
<td>-4</td>
<td>N/A</td>
<td>6</td>
<td>-3</td>
<td>-25</td>
</tr>
<tr>
<td></td>
<td>-5</td>
<td>-13</td>
<td>18</td>
<td>-10</td>
<td>-8</td>
</tr>
</tbody>
</table>

Table 40: Comparison of test results with models predictions – change in CO emissions, %

<table>
<thead>
<tr>
<th>Testing Lab.</th>
<th>ETC test</th>
<th>ESC test</th>
<th>EPEFE</th>
<th>EPA-HDEWG</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTC</td>
<td>-3</td>
<td>15</td>
<td>13</td>
<td>1</td>
</tr>
<tr>
<td>KTI</td>
<td>N/A</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>TUG</td>
<td>-21</td>
<td>-8</td>
<td>-3</td>
<td>-7</td>
</tr>
<tr>
<td>TNO</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>-3</td>
</tr>
<tr>
<td></td>
<td>-2</td>
<td>4</td>
<td>10</td>
<td>2</td>
</tr>
</tbody>
</table>

From the data presented Table 37 to Table 40 it can be concluded that there are not enough experimental data to enable a comprehensive analysis of the models’ ability to predict fuel effects on emissions. A comparison of test data variability with differences between model predictions shows that the first is usually higher than the latter.
From the three available models, the EPA-HDEWG yields the worst predictions, sometimes with an opposite direction of emission change. The quality of EPEFE and New EPA predictions of changes in NO\textsubscript{x} and PM emissions (Table 37)

Table 38 is quite similar. Both models usually predict the direction and order of magnitude of fuel effects rather well. It is noted that the New EPA model does not deal with CO emissions, and both the EPEFE and EPA-HDEWG models do not provide suitable prediction of emission changes measured over the transient ETC cycle (Table 40). At the same time, the EPEFE model allows quite good prediction of emission changes, as measured over the steady-state ESC cycle. Concerning HC emissions (Table 39), predictions by the New EPA model seem to be better than those of the EPEFE model. It has to be noted here that the New EPA model allows an assessment of the effects on emissions of fuel cetane additizing and oxygen content, which may be considered as an additional functional benefit of this model.

Fuel parameters that have to be known, in order to allow the use of EPEFE or New EPA models, are listed below in Table 41.

**Table 41:** Fuel parameters that have to be known for model application

<table>
<thead>
<tr>
<th>EPEFE</th>
<th>New EPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Density</td>
<td>• Density</td>
</tr>
<tr>
<td>• Cetane Number</td>
<td>• Natural Cetane Number</td>
</tr>
<tr>
<td>• Poly-aromatics content</td>
<td>• Cetane Number Difference due to fuel additizing</td>
</tr>
<tr>
<td>• T95 distillation temperature</td>
<td>• Total aromatics content</td>
</tr>
<tr>
<td>• Sulphur content</td>
<td>• T10 and T50 distillation temperatures</td>
</tr>
<tr>
<td></td>
<td>• Sulphur content</td>
</tr>
<tr>
<td></td>
<td>• Oxygen content</td>
</tr>
</tbody>
</table>

Benefits and drawbacks of EPEFE and New EPA models are briefly summarised in Table 42.

**Table 42:** Benefits and drawbacks of EPEFE and New EPA models

<table>
<thead>
<tr>
<th>Model</th>
<th>Benefits</th>
<th>Drawbacks</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.4.1.1.1.1.1 EPEFE</td>
<td>• Less fuel parameters have to be known</td>
<td>• Effects of fuel additizing by cetane improvers are not separated</td>
</tr>
<tr>
<td></td>
<td>• It is a proper European, well established and widely approved model</td>
<td>• Oxygen effects on emissions are not separated</td>
</tr>
<tr>
<td></td>
<td>• Enables modelling of fuel effects on CO, HC, PM and NO\textsubscript{x} emissions</td>
<td></td>
</tr>
<tr>
<td>New EPA</td>
<td>• Effects of fuel additizing by cetane improvers can be evaluated</td>
<td>• More fuel parameters have to be known</td>
</tr>
<tr>
<td></td>
<td>• Oxygen effects on emissions can be evaluated</td>
<td>• Fuel effects on CO emissions are not modelled</td>
</tr>
<tr>
<td></td>
<td>• Enables better prediction of fuel effects on HC emissions</td>
<td></td>
</tr>
</tbody>
</table>
Finally, based on the comparison between measurements and model predictions it may be recommended to use:

- The EPEFE model for assessment of fuel effects on CO and PM emissions.
- The New EPA model for assessment of fuel effects on HC and NOx emissions.

### 7.5. Proposed method of fuel effects assessment in the emission factors model

The most straightforward way to assess fuel effects in the framework of the emission factors model is to calculate a percent change in emissions, by using the models as recommended above. This percentage can then be applied as a change to the emission factors estimated by the main model. This approach requires that a baseline fuel will be defined, from which changes can be evaluated.

It is proposed to define as a baseline an average European diesel fuel quality for Pre-EURO 1, EURO 1 and EURO 2 HDDE generations (for which appropriate emission factors were evaluated), as was published in the Worldwide Diesel Fuel Quality Surveys [33], [51], [52], [53]. Fuel qualities in the following European countries were taken into account: Austria, Benelux countries, France, Germany, Italy, Sweden and United Kingdom. Average and rounded-off values of the qualities mentioned above were assumed as properties of the baseline fuel. These data are shown in Tables 43 – 45. Baseline fuel properties for EURO 3 generation were defined based on the average quality of fuels used in tests, which were carried out for EURO 3 emission factors evaluation. These data are summarized in Table 47. Baseline fuel properties for EURO 4 and EURO 5 generations were estimated based on the requirements of vehicle and engine manufacturers, as were published in the last World–Wide Fuel Charter [1].

**Table 43: Average diesel fuel quality in Europe – year 1991 (Pre-EURO 1 generation)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Austria</th>
<th>Benelux</th>
<th>France</th>
<th>Germany</th>
<th>Italy</th>
<th>Sweden</th>
<th>UK</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, kg/m³</td>
<td>844.1</td>
<td>839.3</td>
<td>833.2</td>
<td>831.2</td>
<td>836.8</td>
<td>824.1</td>
<td>845.8</td>
<td>836.4</td>
</tr>
<tr>
<td>Sulphur, % m</td>
<td>0.13</td>
<td>0.15</td>
<td>0.22</td>
<td>0.13</td>
<td>0.24</td>
<td>0.06</td>
<td>0.15</td>
<td>0.154</td>
</tr>
<tr>
<td>Cetane Number</td>
<td>49.4</td>
<td>50.5</td>
<td>50.9</td>
<td>51.5</td>
<td>52.6</td>
<td>48.8</td>
<td>51.6</td>
<td>50.8</td>
</tr>
<tr>
<td>T10, °C</td>
<td>213</td>
<td>206</td>
<td>196</td>
<td>201</td>
<td>211</td>
<td>197</td>
<td>215</td>
<td>205.6</td>
</tr>
<tr>
<td>T50, °C</td>
<td>262</td>
<td>267</td>
<td>259</td>
<td>251</td>
<td>272</td>
<td>232</td>
<td>276</td>
<td>259.9</td>
</tr>
<tr>
<td>T90, °C</td>
<td>326</td>
<td>328</td>
<td>332</td>
<td>325</td>
<td>340</td>
<td>292</td>
<td>332</td>
<td>325.0</td>
</tr>
<tr>
<td>FBP, °C</td>
<td>352</td>
<td>355</td>
<td>363</td>
<td>359</td>
<td>371</td>
<td>329</td>
<td>361</td>
<td>355.7</td>
</tr>
</tbody>
</table>
Table 44: Average diesel fuel quality in Europe – year 1995 (EURO 1 generation)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Austria</th>
<th>Benelux</th>
<th>France</th>
<th>Germany</th>
<th>Italy</th>
<th>Sweden</th>
<th>UK</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, kg/m³</td>
<td>833.1</td>
<td>837.4</td>
<td>837.4</td>
<td>834.6</td>
<td>836.9</td>
<td>812.4</td>
<td>845.7</td>
<td>833.9</td>
</tr>
<tr>
<td>Sulphur, % m</td>
<td>0.110</td>
<td>0.153</td>
<td>0.182</td>
<td>0.137</td>
<td>0.157</td>
<td>0.003</td>
<td>0.141</td>
<td>0.126</td>
</tr>
<tr>
<td>Cetane Number</td>
<td>50.3</td>
<td>48.4</td>
<td>49.7</td>
<td>50.8</td>
<td>50.2</td>
<td>55.3</td>
<td>50.9</td>
<td>50.8</td>
</tr>
<tr>
<td>T10, oC</td>
<td>203</td>
<td>202</td>
<td>203</td>
<td>206</td>
<td>206</td>
<td>211</td>
<td>215</td>
<td>206.6</td>
</tr>
<tr>
<td>T50, oC</td>
<td>254</td>
<td>264</td>
<td>264</td>
<td>259</td>
<td>271</td>
<td>235</td>
<td>276</td>
<td>260.4</td>
</tr>
<tr>
<td>T90, oC</td>
<td>319</td>
<td>332</td>
<td>332</td>
<td>328</td>
<td>341</td>
<td>268</td>
<td>333</td>
<td>321.9</td>
</tr>
<tr>
<td>FBP, oC</td>
<td>347</td>
<td>361</td>
<td>363</td>
<td>361</td>
<td>370</td>
<td>289</td>
<td>360</td>
<td>350.1</td>
</tr>
</tbody>
</table>

Table 45: Average diesel fuel quality in Europe – years 1997/2000 (EURO 2 generation)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Austria</th>
<th>Benelux</th>
<th>France</th>
<th>Germany</th>
<th>Italy</th>
<th>Sweden</th>
<th>UK</th>
<th>Average annual</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, kg/m³</td>
<td>830.6/</td>
<td>833.7/</td>
<td>836.1/</td>
<td>833.5/</td>
<td>836.2/</td>
<td>812.7/</td>
<td>846.4/</td>
<td>832.7/</td>
<td>832.3</td>
</tr>
<tr>
<td></td>
<td>832.9</td>
<td>837.8</td>
<td>836.6</td>
<td>832.7</td>
<td>835.7</td>
<td>814.4</td>
<td>832.3</td>
<td>831.8</td>
<td></td>
</tr>
<tr>
<td>Sulphur, % m</td>
<td>0.033/</td>
<td>0.043/</td>
<td>0.044/</td>
<td>0.036/</td>
<td>0.04/</td>
<td>0.001/</td>
<td>0.039/</td>
<td>0.034/</td>
<td>0.0298</td>
</tr>
<tr>
<td></td>
<td>0.0281</td>
<td>0.0290</td>
<td>0.0308</td>
<td>0.0261</td>
<td>0.022</td>
<td>0.0010</td>
<td>0.0038</td>
<td>0.0256</td>
<td></td>
</tr>
<tr>
<td>Cetane Number</td>
<td>50.0/</td>
<td>49.4/</td>
<td>49.0/</td>
<td>50.2/</td>
<td>50.9/</td>
<td>54.9/</td>
<td>50.8/</td>
<td>50.7/</td>
<td>52.8</td>
</tr>
<tr>
<td></td>
<td>55.3</td>
<td>54.9</td>
<td>53.5</td>
<td>55.5</td>
<td>55.4</td>
<td>53.2</td>
<td>56.6</td>
<td>54.9</td>
<td></td>
</tr>
<tr>
<td>T10, oC</td>
<td>194/</td>
<td>199/</td>
<td>194/</td>
<td>199/</td>
<td>206/</td>
<td>210/</td>
<td>216/</td>
<td>202.6/</td>
<td>204.1</td>
</tr>
<tr>
<td></td>
<td>207</td>
<td>202</td>
<td>198</td>
<td>207</td>
<td>209</td>
<td>205</td>
<td>211</td>
<td>205.6</td>
<td></td>
</tr>
<tr>
<td>T50, oC</td>
<td>249/</td>
<td>262/</td>
<td>259/</td>
<td>256/</td>
<td>271/</td>
<td>236/</td>
<td>278/</td>
<td>258.7/</td>
<td>259.2</td>
</tr>
<tr>
<td></td>
<td>260</td>
<td>266</td>
<td>262</td>
<td>260</td>
<td>270</td>
<td>232</td>
<td>268</td>
<td>259.7</td>
<td></td>
</tr>
<tr>
<td>T95, oC</td>
<td>352/</td>
<td>345/</td>
<td>349/</td>
<td>348/</td>
<td>357/</td>
<td>279/</td>
<td>346/</td>
<td>339.4/</td>
<td>338.8</td>
</tr>
<tr>
<td></td>
<td>343</td>
<td>350</td>
<td>350</td>
<td>348</td>
<td>358</td>
<td>281</td>
<td>337</td>
<td>338.1</td>
<td></td>
</tr>
</tbody>
</table>

The average diesel fuel quality of EURO 2 generation (Table 45) was compared with the specifications of fuels used by ARTEMIS partners in the experiments aimed at evaluation of emission factors for EURO 2 engines. These fuel specifications are listed in Table 46.
Table 46: Specifications of EURO 2 diesel fuel used in ARTEMIS experiments

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lab.</th>
<th>Density, kg/m³</th>
<th>Sulphur, % m</th>
<th>Cetane Number</th>
<th>T50, °C</th>
<th>T90, °C</th>
<th>T95, °C</th>
<th>FBP, °C</th>
<th>Total aromatics, % m</th>
<th>PAH, % m</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNO</td>
<td>831.7</td>
<td>0.042</td>
<td>53.5</td>
<td>268.5</td>
<td>334.5</td>
<td>354</td>
<td>378</td>
<td>18.9</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>TUG</td>
<td>833</td>
<td>0.021</td>
<td>53.4</td>
<td>272</td>
<td>N/A</td>
<td>352.5</td>
<td>364.5</td>
<td>20.2</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>RWTUE V</td>
<td>834</td>
<td>0.0048</td>
<td>52.2</td>
<td>268</td>
<td>N/A</td>
<td>348</td>
<td>362</td>
<td>22.4</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>UBA Germ.</td>
<td>842</td>
<td>0.0195</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>TUG</td>
<td>835.6</td>
<td>0.039</td>
<td>53.9</td>
<td>274.5</td>
<td>337.5</td>
<td>351*</td>
<td>365</td>
<td>22.6</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>EMPA</td>
<td>831.4</td>
<td>0.0332</td>
<td>49.1</td>
<td>258</td>
<td>313</td>
<td>328*</td>
<td>342</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>UBA Germ.</td>
<td>842</td>
<td>0.0195</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>EMPA</td>
<td>831.4</td>
<td>0.0332</td>
<td>49.1</td>
<td>258</td>
<td>313</td>
<td>328*</td>
<td>342</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>EMPA</td>
<td>832.1</td>
<td>0.0339</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>TUG</td>
<td>833</td>
<td>0.021</td>
<td>53.4</td>
<td>272</td>
<td>N/A</td>
<td>352.5</td>
<td>364.5</td>
<td>20.2</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>UBA Germ.</td>
<td>842</td>
<td>0.0195</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>835.3</td>
<td>0.0261</td>
<td>52.1</td>
<td>267</td>
<td>324.5</td>
<td>352</td>
<td>360</td>
<td>20.9</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

* The T95 value was estimated based on T90 and FBP data as: T95 = (T90 + FBP)/2.

As can be seen from Tables 45 and 46, the average quality of EURO 2 diesel fuel used in ARTEMIS tests is not far different from the real market average European EURO 2 fuel quality.
Table 47: Specifications of EURO 3 diesel fuel used in ARTEMIS experiments

<table>
<thead>
<tr>
<th>Parameter Lab.</th>
<th>Density, kg/m³</th>
<th>Sulphur, % m</th>
<th>Cetane Number</th>
<th>T50, oC</th>
<th>T90, oC</th>
<th>T95, oC</th>
<th>FBP, oC</th>
<th>Total aromatics, % m</th>
<th>PAH, % m</th>
</tr>
</thead>
<tbody>
<tr>
<td>RWTUEV</td>
<td>834</td>
<td>0.0050</td>
<td>52.3</td>
<td>270</td>
<td>N/A</td>
<td>345</td>
<td>349</td>
<td>22.0</td>
<td>N/A</td>
</tr>
<tr>
<td>RWTUEV</td>
<td>834</td>
<td>0.0050</td>
<td>52.3</td>
<td>270</td>
<td>N/A</td>
<td>345</td>
<td>349</td>
<td>22.0</td>
<td>N/A</td>
</tr>
<tr>
<td>TNO</td>
<td>830</td>
<td>0.0050</td>
<td>50</td>
<td>260</td>
<td>310</td>
<td>N/A</td>
<td>N/A</td>
<td>30</td>
<td>N/A</td>
</tr>
<tr>
<td>TNO</td>
<td>827.2</td>
<td>0.0035</td>
<td>56.2</td>
<td>N/A</td>
<td>N/A</td>
<td>335</td>
<td>N/A</td>
<td>25.5</td>
<td>N/A</td>
</tr>
<tr>
<td>TNO</td>
<td>827.2</td>
<td>0.0035</td>
<td>56.2</td>
<td>N/A</td>
<td>N/A</td>
<td>335</td>
<td>N/A</td>
<td>25.5</td>
<td>N/A</td>
</tr>
<tr>
<td>MTC</td>
<td>814.7</td>
<td>0.0003</td>
<td>52.5</td>
<td>235</td>
<td>270</td>
<td>282</td>
<td>294</td>
<td>4.3</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td>MTC</td>
<td>836.5</td>
<td>0.0245*</td>
<td>53</td>
<td>276</td>
<td>329</td>
<td>347</td>
<td>357</td>
<td>17.2</td>
<td>0.11</td>
</tr>
<tr>
<td>TUG</td>
<td>833</td>
<td>0.0210*</td>
<td>53.4</td>
<td>272</td>
<td>N/A</td>
<td>362.5</td>
<td>364.5</td>
<td>20.2</td>
<td>N/A</td>
</tr>
<tr>
<td>Average</td>
<td>830</td>
<td>0.0037</td>
<td>53.2</td>
<td>264</td>
<td>N/A</td>
<td>336</td>
<td>343</td>
<td>20.8</td>
<td>N/A</td>
</tr>
</tbody>
</table>

* These values were not taken into account in the average calculation.

Values of fuel parameters that are lacking in the surveys [33], [51], [52], [53] were added based on available data and recommendations of fuel experts. Properties of the proposed baseline fuels are shown in Table 48.

Table 48: Baseline fuels properties

<table>
<thead>
<tr>
<th>Generation</th>
<th>Density, kg/m³</th>
<th>Cetane number</th>
<th>Cetane difference</th>
<th>Poly-aromatics</th>
<th>Total aromatics</th>
<th>T10, oC</th>
<th>T50, oC</th>
<th>T95, oC</th>
<th>Sulphur Content</th>
<th>Oxygen content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-EURO1</td>
<td>835</td>
<td>51</td>
<td>0</td>
<td>6</td>
<td>25</td>
<td>205</td>
<td>260</td>
<td>345</td>
<td>1500</td>
<td>0</td>
</tr>
<tr>
<td>EURO 1</td>
<td>835</td>
<td>51</td>
<td>0</td>
<td>6</td>
<td>25</td>
<td>205</td>
<td>260</td>
<td>340</td>
<td>1300</td>
<td>0</td>
</tr>
<tr>
<td>EURO 2</td>
<td>830</td>
<td>53</td>
<td>0</td>
<td>5</td>
<td>20</td>
<td>205</td>
<td>260</td>
<td>340</td>
<td>300</td>
<td>0</td>
</tr>
<tr>
<td>EURO 3</td>
<td>830</td>
<td>53</td>
<td>0</td>
<td>4</td>
<td>20</td>
<td>210</td>
<td>265</td>
<td>340</td>
<td>40</td>
<td>0</td>
</tr>
<tr>
<td>EURO 4</td>
<td>830</td>
<td>55</td>
<td>0</td>
<td>2</td>
<td>15</td>
<td>210</td>
<td>265</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>EURO 5</td>
<td>830</td>
<td>55</td>
<td>0</td>
<td>2</td>
<td>15</td>
<td>210</td>
<td>265</td>
<td>340</td>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

7.6. Conclusions on the influences of the fuel quality

The main conclusions drawn from the results of the EPEFE, EPA-HDEWG, New EPA, DECSE programs and other recent studies, and their analysis in the present work, are summarised as follows:

1. The main fuel properties that affect HDDEs emissions and efficiencies of after-treatment devices are the cetane number, total and poly-aromatics content, back-end distillation, density, sulphur content and oxygenates. Only limited data are available concerning the effects of oxygenates on emissions.
2. For HDDEs without after-treatment devices, the fuel sulphur content has no significant impact on gaseous emissions. PM emissions increase by about 4.5% with sulphur content increase from zero to 500 ppm.

3. The results of the EPEFE research program and the latest CONCAWE work carried out with two EURO 3 engines, show that the spread of emission values by a change of fuel quality on the same engine is substantially less than for different engines being operating on the same fuel.

4. The results of the EPA-HDEWG program show that the relative effects of EGR are the same, independent of the fuel properties. This is confirmed by earlier European investigations.

5. The cetane number effects on NOx emissions turned out to be negligible, while the models show an opposite trend: decrease in the EPEFE program and increase in the EPA-HDEWG program. The result of the latter is inconsistent with well-established knowledge, and it is probably a consequence of a sub-optimal process of the fuel-air mixture formation during ignition delay. To clear up this point, additional studies are necessary. The New EPA model gives some additional information by separation natural and additized cetane number effects: while there is no effect of natural cetane number on NOx emissions, a reduction of 0.28% per CN unit increase was observed for additized cetane.

6. The EPEFE results showed that the fuel density itself does not have any noticeable influence on the fuel combustion process, and its impact on emissions is a result of changes inside the hydraulic system of the fuel injection equipment: timing, mass fuel delivery, etc. Fuel density increasing from 828 to 855 kg/m^3 causes decrease of CO emissions by about 5%, HC emissions by about 13%, and increase of NOx emissions by 3.7% for HDDEs with a fuel injection system of the type “pump-line-injector” (EPEFE). The same variation of fuel density in the EPA-HDEWG program (engine with unit electronic injectors) caused practically the same change of NOx emissions, but CO and HC emissions were unchanged.

7. The conversion efficiency of diesel oxidation catalysts (DOC) decreases when the upstream exhaust temperature rises above 400°C, and varies with fuel sulphur content as a result of the increase of sulphate emissions. Under FTP test conditions, the fuel sulphur content does not influence, practically, PM emissions.

8. Increasing the sulphur content from 3 to 350 ppm causes an increase of sulphate emissions from lean-NOx catalyst by a factor of 10-20. As a result, PM emissions increase by a factor of about 1.5.

9. Increase of the fuel sulphur content from 3 to 150 ppm causes the conversion efficiencies of diesel particulates filters to decrease down to zero; further increase of the sulphur content (up to 350 ppm) causes an increase of PM emissions by a factor of 2.2 (C-DPF) or 2.5 (CR-DPF).

10. The conversion efficiency of NOx adsorber catalysts decreases dramatically by increase of the fuel sulphur content. Even for 30 ppm sulphur fuel it falls down to 0.2-0.3 in comparison with 3 ppm.

11. The comparison of the EPEFE, EPA-HDEWG and New EPA programs results allows the conclusion that the impact of fuel poly-aromatic content (1% - 8%) on CO, HC and NOx emissions, of cetane number (42-58) on CO and HC emissions, and of fuel density (828-855 kg/m^3) on NOx emissions from HDDEs is universal and practically independent of
engine technology or test cycle; the impact of cetane number on NO\textsubscript{x} emissions and fuel density on CO and HC emissions strongly depends on the applied engine technology.

12. It has to be noted that there is still lack of data regarding the fuel effects on emissions of engines tested over the European Transient Cycle.

13. In the framework of ARTEMIS/COST 346 work programs, four EURO 3 engines of different makes were tested over ESC, ETC and TNO (only in one test) test cycles. Each engine was tested with at least two different diesel fuels.

14. There are not enough experimental data to enable a comprehensive analysis of the models’ ability to predict fuel effects on emissions of engines tested over current European cycles. Comparison of test data variability with differences between various model predictions (based on one engine testing) shows that the first are usually higher than the latter.

15. From the three available models, the EPA-HDEWG yields the worst predictions of both absolute values and change percentage, sometimes with an opposite direction of emission change.

16. The quality of EPEFE and New EPA predictions of changes in NO\textsubscript{x} and PM emissions (Table 37, Table 38) is quite similar. Both models usually predict the direction and order of magnitude of fuel effects rather well. The New EPA model does not deal with CO emissions. Concerning HC emissions, predictions allowed by the New EPA model seem to be better than those of the EPEFE model. Finally, it may be recommended to use the EPEFE model for the assessment of fuel effects on CO and PM emissions, and the New EPA model for the assessment of fuel effects on HC and NO\textsubscript{x} emissions.

17. It is proposed to assess fuel effects in the framework of the emission factors model by calculation of a percent change in emissions, by using the models as recommended above. This percentage can then be applied as a change to the emission factors estimated by the main model. This approach requires that a baseline fuel will be defined, from which changes can be evaluated. This was done here, and baseline fuels for Pre-EURO 1, EURO 1, EURO 2, EURO 3, EURO 4 and EURO 5 engine generations have been defined.

8. EFFECTS OF ENGINE DETERIORATION AND MAINTENANCE

Emissions of HDVs are influenced by a large number of factors. Apart from the more obvious ones such as use conditions, engine design and technology (to comply with emission legislation), also the age of the engine and the maintenance condition can have a certain influence. In order to determine if this influence should be taken into account for the Artemis emission model, the effect of engine deterioration and maintenance on emissions will be assessed in this chapter.

8.1. Database

For investigating the influence of engine deterioration and maintenance on emissions two information sources are used:

1. A database from the Dutch In-Use Compliance programme, with emissions measured over the 13-mode test for 218 vehicles, ranging from EURO 0 to EURO 3 [4], [5], [58], [56], [71]. The vehicle selection for the successive programmes was based on the selling numbers of the respective years. For EURO 1 and 2 vehicles the ECE R49 13-mode test was used, and in some cases also the ESC test. EURO 3 vehicles have only been
measured on the ESC 13-mode test. Emissions were measured on the vehicle in the state it was received in, as well as after carrying out necessary maintenance corrections. The data were supplied by TNO Automotive.

2. A database from the German In-Use Compliance program, with emissions measured over the 13-mode test (ECE R49) for 25 vehicles (EURO 1 and EURO 2) [16]. Emissions are measured on the vehicle only in the state it is received in. The selection of vehicles reflects the most common vehicles in the German HDV fleet. The data were supplied by RW TÜV.

Both sets of data were put together into one (Excel) database, to allow for the assessments.

8.2. Deterioration of EURO 1 to EURO 3 vehicles

The most straightforward method to assess the effect on emissions of engine deterioration would be to have the same HDV engine measured multiple times during its useful life. Unfortunately, this kind of data is not available in the database of EURO 1 to EURO 3 vehicles and amongst the Artemis WP400 partners. The next best option is to make a graph of the individual (13-mode) test results against the distance driven by the vehicle (mileage) at the time the tests took place. For this approach, the following assumptions and simplifications had to be made:

- Vehicle specific aspects such as manufacturer, vehicle use application and maintenance condition are considered to be distributed homogeneously over the distance driven by the vehicle.
- Even the same vehicle, with the same engine, after the same driven distance may show a difference in emissions over the 13-mode test. This is the result of influences such as history of engine use by the chauffeur, maintenance work on the vehicle, reproducibility of the test, etc. It is assumed that these differences are levelled out in a database with a sufficiently high number of vehicles.
- As the database consists of the most common types of sold vehicles in the Dutch and German HDV fleet, it is assumed that the emission deterioration factors determined from this database will be representative for this common fleet. Note that this assumption is not fully consistent since a real representative result would also require a weighing according to vehicle fleet composition. Apart from that, both IUC programs differ quite a lot in terms of number of tested vehicles.
- While there is no data available from other countries in Europe, the best guess is to assume for the European fleet a similar deterioration pattern as derived from this assessment (based on Dutch and German data).
- Because of the anticipated large variance in the test results, only linear deterioration lines will be used. This implicates that single vehicles with high mileage can have a big effect on the coarse of the deterioration line, and therefore have to be excluded.
- As the emission levels of EURO 0, 1, 2 and 3 vehicles differ from each other, it is not possible to perform one analysis for all vehicles in the database together. Instead it will be done for the individual EURO-classes, thereby limiting the number of vehicles to base a deterioration trendline on.

The next step is to analyse the database and accommodate it for investigating the effect of deterioration. The mileage distribution of the EURO 0, 1, 2 and 3 vehicles in the database is presented in Figure 86. This shows that most of the tested vehicles have not driven more than 400,000 km, and that there are only 3 vehicles with a mileage over 500,000 km (525,000, 630,000 and 838,000 km respectively). The large gaps between these mileage numbers means that these vehicles potentially have a high influence on the coarse of the (linear) deterioration line, so they are deleted from the database. Actually, the highest mileage of the two vehicles
within the 450 - 500,000 km category is 472,000 km, making the gap between the two highest mileage’s 16,000 km, which is quite acceptable (the maximum gap within the database is 19,000 km). The EURO 3 vehicles were only on the market for a short period when they were tested, so their mileage is relatively low (180,000 km at maximum).

![Mileage distribution of the database from the Dutch and German IUC programs](image)

**Figure 86:** Mileage distribution of the database from the Dutch and German IUC programs (EURO 0, 1, 2 and 3 vehicles, 243 in total)

A new engine has a certain running-in period of about 20,000 kilometres, during which the oil consumption (and therefore the HC and PM emissions) may be higher. In order to prevent this phenomenon influencing the deterioration factors, the minimum mileage is set at 19,000 km (so a few vehicles that are just above this value can still be included). This results in 14 vehicles to be excluded. In total, there are now 226 vehicles in the database (26 EURO 0, 78 EURO 1, 98 EURO 2, and 24 EURO 3). Due to the limited amount of EURO 0 vehicles in the current HD vehicle fleet, and the little significance of deterioration factors for that class on present and future vehicles, the assessment is focused only on EURO 1, 2 and 3 vehicles (200 vehicles in total).

Now the database has been accommodated, the analysis for the deterioration lines can be executed. To prevent maintenance issues from interfering with the deterioration analysis, the emission data after applying maintenance (only if necessary) were used. The influence of maintenance corrections on the emissions is dealt with later.

In Figure 87, the emissions of individual components as a function of mileage are presented for the EURO 1 vehicles in the database. Figure 88 and Figure 89 do the same for EURO 2 and 3 vehicles.
Figure 87: Deterioration lines of emissions (ECE R49 13-mode test) for 78 EURO 1 vehicles (after maintenance)
Figure 88: Deterioration lines of emissions (ECE R49 13-mode test) for 98 EURO 2 vehicles (after maintenance)
Figure 89: Deterioration lines of emissions (ESC 13-mode test) for 21 EURO 3 vehicles (after maintenance)
Because of the limited number of EURO 3 vehicles, and therefore the high influence of individual points on the trendlines, extra attention was paid to the most extreme emission values. In 3 cases, high NO\textsubscript{x} and PM values could be attributed to non-representative test circumstances, and were therefore excluded from the analysis.

For reference purposes, the applicable emission standards are presented in Table 43. In the Dutch in-use compliance programme a vehicle is only inspected in detail once the COP level is exceeded by 10%, or if it is 20% above the value in the type approval certificate (if this level is higher). Since the NO\textsubscript{x}-emission of most EURO 3 HD vehicles is close to the maximum allowed 5 g/kWh, an emission level of under 6 g/kWh is still considered to comply with the EURO-3 emission standard.

**Table 43: EU Emission standards for different legislation classes in g/kWh**

<table>
<thead>
<tr>
<th>Legislative category</th>
<th>Date &amp; Category</th>
<th>Test Cycle</th>
<th>CO</th>
<th>HC</th>
<th>NO\textsubscript{x}</th>
<th>PM</th>
<th>Smoke</th>
</tr>
</thead>
<tbody>
<tr>
<td>EURO 1</td>
<td>1992, &lt;85 kW</td>
<td></td>
<td>4.5</td>
<td>1.1</td>
<td>8.0</td>
<td>0.612</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1992, &gt;85 kW</td>
<td></td>
<td>4.5</td>
<td>1.1</td>
<td>8.0</td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td>EURO 1 COP</td>
<td>1992, &gt;85 kW</td>
<td>ECE R49</td>
<td>4.9</td>
<td>1.23</td>
<td>9</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td>EURO 2</td>
<td>1996.10</td>
<td></td>
<td>4.0</td>
<td>1.1</td>
<td>7.0</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1998.10</td>
<td></td>
<td>4.0</td>
<td>1.1</td>
<td>7.0</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>EURO 3</td>
<td>2000.10</td>
<td>ESC</td>
<td>2.1</td>
<td>0.66</td>
<td>5.0</td>
<td>0.10*</td>
<td>0.13*</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td>EURO 4</td>
<td>2005.10</td>
<td></td>
<td>1.5</td>
<td>0.46</td>
<td>3.5</td>
<td>0.02</td>
<td>0.5</td>
</tr>
<tr>
<td>EURO 5</td>
<td>2008.10</td>
<td></td>
<td>1.5</td>
<td>0.46</td>
<td>2.0</td>
<td>0.02</td>
<td>0.5</td>
</tr>
</tbody>
</table>

* for engines of less than 0.75 dm\textsuperscript{3} swept volume per cylinder and a rated power speed of more than 3000 min\textsuperscript{-1}

Note: COP limits for EURO 2 and later are the same as the limits at type approval

The results from Figure 87 to Figure 89 are quite remarkable, especially for EURO 1 and 2 vehicles. Where a deterioration with increasing mileage was anticipated, actually an improvement can be noticed for most emission components (or at worst a near flat line). To put this conclusion into perspective, it has to be noted that the variance in measurement points relative to the line is rather high, indicating that the coarse of the line may be altered if some individual higher or lower test results are added or deleted. Only for EURO 3 HC emissions the deterioration is obvious, and to a lesser extent also for EURO 3 PM emissions. However, considering that only 21 vehicles are included in this analysis, with results that are spread in a wide range, and that the observed mileage range is not as large as for EURO 1 and 2 vehicles, the value of this conclusion may be limited.

One explanation for the lower emissions of vehicles with higher mileage could be that the fuel consumption is on average lower for vehicles with a high mileage. If such a non-homogeneous fuel consumption distribution in the database would occur this would mean that the emission levels in g/kWh are not fully comparable, since more fuel efficient vehicles use less fuel to reach the same kWh rate (using less fuel potentially also reduces the emissions).

Another explanation is that vehicles in the database with a high mileage are probably used for long distance transport activities. Those kind of vehicles have engines in the higher rated power range, which have more potential to be fuel efficient (at least over a 13-mode test).
Both assumptions could be verified by analysis of the database, looking at the trendline of rated power against mileage, and fuel consumption against rated power. To prevent the fuel efficiency effect from interfering with the assessment of deterioration, emissions have also been expressed as g/kg fuel. Only for EURO 1 vehicles a small decrease in fuel consumption was found, resulting in a marginal deterioration of NO\textsubscript{x}-emissions. The conclusions on the other emission components (also for EURO 2 and 3) remained unchanged.

Once the overall result for average EURO 1 and 2 vehicles has been determined, it is also interesting to see if the same results are also observed for single classes of vehicles in the database. Due to the limited amount of EURO 3 vehicles, this kind of analysis seems not rational for that vehicle category. The analysis was made again for the following database-classes that were considered relevant to this assessment:

- **Vehicle/engine make** (only if at least 10 vehicles fall within this category; the rest is summed together as ‘other’).
  
The purpose of analysing these categories is to find out whether some vehicle/engine makes seem to have more or less sensitivity to deterioration.
- **Application type**
  
Due to a different type of vehicle use, an engine might be more or less sensitive for deterioration over its useful life. This can be illustrated by considering the difference in engine load profiles of a long distance truck (almost steady-state operation at relatively high load for longer periods) and a city distribution truck (very transient loads with high power peaks for acceleration, but at low average load due to idling time). Unfortunately the database does not make a distinction to application type. However, the rated power can also be roughly seen as an indicator of application type, as distribution vehicles are normally relatively light and small, and therefore associated with the lower power range of HDV engines. Long distance trucks are usually equipped with engines in the higher power range. The border between these two categories was determined at a rated power of 220 kW. Considering the fact that there were only 3 engines in the 200 - 220 kW range, the upper limit of a distribution application is set at 200 kW, and the lower limit for long distance transport at 220 kW.

As the presentation of all graphs for all the observed classes would cost quite a number of pages, tables with colours as indicators for the coarse of the deterioration line are shown instead (see Table 44).

**Table 44:** coloured indication of deterioration line coarse (compensated for fuel efficiency) for different vehicle/engine makes and power ranges for EURO 1 and EURO 2 vehicles. The percentages indicate the ratio of calculated deterioration over 500,000 km and the emission level for new vehicles.

<table>
<thead>
<tr>
<th>Euro 1</th>
<th># veh.</th>
<th>NO\textsubscript{x}</th>
<th>CO</th>
<th>HC</th>
<th>PM</th>
<th>BSFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuf. 1</td>
<td>16</td>
<td>19%</td>
<td>28%</td>
<td>42%</td>
<td>-42%</td>
<td>-65%</td>
</tr>
<tr>
<td>Manuf. 2</td>
<td>18</td>
<td>53%</td>
<td>62%</td>
<td>34%</td>
<td>-92%</td>
<td>-3%</td>
</tr>
<tr>
<td>Manuf. 3</td>
<td>18</td>
<td>-36%</td>
<td>43%</td>
<td>-1%</td>
<td>-62%</td>
<td>-1%</td>
</tr>
<tr>
<td>Manuf. 4</td>
<td>18</td>
<td>6%</td>
<td>22%</td>
<td>-1%</td>
<td>-1%</td>
<td>-5%</td>
</tr>
<tr>
<td>Others</td>
<td>18</td>
<td>1%</td>
<td>6%</td>
<td>-8%</td>
<td>-8%</td>
<td>-8%</td>
</tr>
<tr>
<td>&lt;220 kW</td>
<td>34</td>
<td>1%</td>
<td>-2%</td>
<td>-34%</td>
<td>-8%</td>
<td>-1%</td>
</tr>
<tr>
<td>&gt;220 kW</td>
<td>44</td>
<td>-4%</td>
<td>-1%</td>
<td>-12%</td>
<td>-4%</td>
<td>-4%</td>
</tr>
<tr>
<td>All</td>
<td>78</td>
<td>3%</td>
<td>-3%</td>
<td>-34%</td>
<td>-8%</td>
<td>-8%</td>
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</table>

<table>
<thead>
<tr>
<th>Euro 2</th>
<th># veh.</th>
<th>NO\textsubscript{x}</th>
<th>CO</th>
<th>HC</th>
<th>PM</th>
<th>BSFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuf. 1</td>
<td>18</td>
<td>-34%</td>
<td>-61%</td>
<td>23%</td>
<td>34%</td>
<td>-3%</td>
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<tr>
<td>Manuf. 2</td>
<td>14</td>
<td>18%</td>
<td>-2%</td>
<td>-62%</td>
<td>-8%</td>
<td>-1%</td>
</tr>
<tr>
<td>Manuf. 3</td>
<td>19</td>
<td>16%</td>
<td>66%</td>
<td>-4%</td>
<td>-1%</td>
<td>-5%</td>
</tr>
<tr>
<td>Manuf. 4</td>
<td>18</td>
<td>-11%</td>
<td>-4%</td>
<td>-1%</td>
<td>-1%</td>
<td>-5%</td>
</tr>
<tr>
<td>Others</td>
<td>23</td>
<td>11%</td>
<td>-4%</td>
<td>-1%</td>
<td>-4%</td>
<td>-4%</td>
</tr>
<tr>
<td>&lt;220 kW</td>
<td>41</td>
<td>1%</td>
<td>-1%</td>
<td>-6%</td>
<td>-6%</td>
<td>-2%</td>
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<tr>
<td>&gt;220 kW</td>
<td>41</td>
<td>1%</td>
<td>-1%</td>
<td>-6%</td>
<td>-6%</td>
<td>-2%</td>
</tr>
<tr>
<td>All</td>
<td>98</td>
<td>1%</td>
<td>-1%</td>
<td>2%</td>
<td>-3%</td>
<td>-3%</td>
</tr>
</tbody>
</table>

- <10% emissions decrease over mileage
- -2 to -10% emissions decrease slightly over mileage
- >10% noticeable deterioration
- 2 to 5% slight deterioration
- 0% no deterioration
- -2 to 2% no deterioration
- >5% emissions increase over mileage
It is found that the emission behaviour is certainly dependent on the vehicle/engine manufacturer, and the observed power ranges. On the other hand, the results for EURO 1 and EURO 2 vehicles seem almost contradictory (see for example Manufacturer 2). So it is not easy to give a common valid deterioration pattern for each manufacturer. These contradictory results might very well be caused by the fact that the deterioration lines are based on a much smaller amount of data, making them more sensitive for individual test results. Note that the bottom lines (‘all’) are slightly different from Figure 87 to Figure 89 due to compensation for fuel consumption.

The analysis on deterioration leads to the following conclusions:

- Though an increase in emissions with mileage was anticipated, this could not be confirmed for EURO 1 and 2 vehicles by the analysis (for some emissions actually a decrease with mileage was observed). Only a slight deterioration of NOx-emissions for EURO 1 vehicles was observed (about 3% over 500,000 km), which is not very significant considering the uncertainties within the analysis.
- As there is no logical physical explanation for emissions to decrease with the age of the engine, this emission improvement is considered to be unrealistic.
- The limited amount of EURO 3 vehicles in the database together with a wide range of results prevents a firm conclusion on deterioration of emissions for this vehicle class. It seems safer to assume the same deterioration pattern as found for EURO 2 vehicles.
- The data analysis has proven clearly that the effect of emission deterioration due to engine ageing is (in the worst case situation) only marginal. On the other hand the indicated inaccuracies and assumptions prevent the determination of exact deterioration factors. In fact, the variation of emission results in the database is larger than the effect of deterioration that is tried to observe from it.
- There seems to be a dependence of deterioration characteristics with the vehicle/engine manufacturer, and the type of vehicle application (derived from surveying the rated engine power). However, the value of this conclusion is limited due to the reduced data set it is based on.

The general conclusion for the Artemis WP400 model is that no deterioration of emission factors need to be introduced for EURO 1 to EURO 3 vehicles.

NOTE: It is important to realise that these conclusions are based on only steady-state measurements, so nothing can be said with certainty about the deterioration pattern of transient emissions from the assessment made here.

8.3. Deterioration of EURO 4 and EURO 5 vehicles

Obviously, there is no database available with measurement results that can be analysed as was done for the EURO 1 to EURO 3 vehicles, since there are no vehicles sold as yet with a EURO 4 or higher classification. Therefore, the analysis for deterioration of emissions will have a rather qualitative nature, focusing on the engine technology that is expected to be applied. For this purpose, a lot of information could be derived from a study performed in 2001 for the DG Enterprise of the EC [16]

There seems to be a common understanding amongst European Heavy Duty engine manufacturers that it is inevitable to apply exhaust after-treatment technology when EURO 4 emission legislation comes into effect. This means that in an assessment for the deterioration of emissions not only the deterioration of the engine has to be observed, but also of the emission control device (ECD).
**Engine**

For the future engine technology (EURO 4 and beyond) it is anticipated that the following advancements to the engine can or may be introduced:

- multiple fuel injections per work cycle
- higher injection pressures
- advanced turbocharging systems (two-stage or variable turbo geometry)
- coated combustion chamber

Though all of these advancements have the potential to affect the durability of the engine, there is no real reason to assume that once they have been properly put into production and have had a certain period for maturing it would lead to a very different deterioration pattern as found for the earlier EURO 1 to 3 engine technology. In that case the conclusions for EURO 1 to 3 vehicles would then also apply to the (EURO 4 and 5) engine-out emissions. Some kind of insurance for proper functioning may be expected from the introduction of an On-Board Diagnostics system (OBD), at the same time as EURO 4 takes effect. Although this system primarily aims at preventing issues that can be resolved through corrective maintenance (by checking for irregularities in the engine and its subsystems), it may also have a positive effect towards the durability of the engine.

**Emission Control Devices**

At this time, there are quite a number of different ECDs which are considered relevant to meet the EURO 4 emission standards and beyond. According to [16], the most viable options are:

- Exhaust Gas Recirculation (EGR)
- Diesel Oxidation Catalyst (DOC)
- Selective Catalytic Reduction of NOx (SCRdeNOx)
- Diesel Particulate Filter (DPF)

In the USA, the NOx-adsorber is thought to be a relevant option as well, but European manufacturers do not focus on this technology for the European market. For a detailed description of operating principles and durability aspects for the options mentioned above, please refer to [16]. The effects on deterioration of emissions are here only dealt with briefly.

The high-pressure EGR system (pre-turbocharger to post-intercooler) is susceptible to fouling and/or corrosion problems due to condensation of acids. Since the EGR flow is not actually measured but calculated from pressures and temperatures, these problems may lead to flow calculation errors that have consequences on the emissions (mainly NOx and PM). The currently used engine oils are unable to deal with increased acid and soot load as a result of applying EGR. Therefore, the oil characteristics will deteriorate more rapidly, which could lead to an accelerated engine wear process. As a result, PM and HC emissions could increase because of higher oil consumption.

The low-pressure EGR system (post-turbocharger to pre-intercooler) is usually combined with a DPF. Comparable issues apply as those for the high-pressure EGR system. Carbon and solid organic fraction concentrations of particulates are much lower because of the DPF, but the increased sulphate concentration is more ‘sticky’. The issue of fouling is extended also to the compressor and the turbo-charger. There is no information found that quantifies the direct effect on emissions. In the view of experts at TNO, the problem of emission deterioration for EGR systems will be rather limited.
An OBD system could monitor the EGR valve, mass flow, wideband lambda, and NO\textsubscript{x}-emission (using a NO\textsubscript{x} sensor) to check proper functioning of the EGR system. At this moment the availability and long-term stability of this kind of sensor technology is still an open issue, and the sensors developed so far still show a cross sensitivity between NO\textsubscript{x} and NH\textsubscript{3}.

A DOC for diesel engines is regarded (and for LD applications also proven) to be a very durable device. Though the technology is covered in some papers, little useful (recent) information was found on the durability in practice. ECS & London Transport Buses Ltd completed extensive chassis dynamometer based emission testing under realistic urban bus operation conditions at Millbrook Proving Ground [8]. The conversion efficiencies determined for fresh catalysts were found to be respectively 86%, 92% and 45% for HC, CO and PM emissions. However, after 8,000 hours of ageing, the efficiencies had dropped to about 59%, 56% and 36% respectively. Since the DOC is not a controlled device, there is little need for an OBD system to check the operating conditions. With the appropriate sensor technology available, OBD could verify if the conversion efficiencies are within the normal operating range.

The oxidation catalyst is also applied in combination with other ECDs, such as the continuous regenerating DPF (to convert NO into NO\textsubscript{2} for the oxidation of soot on the filter) and SCR\textsubscript{deNO\textsubscript{x}} (to clean up any unused ammonia after the catalyst and potentially also before the SCR to convert NO to NO\textsubscript{2} for a higher SCR efficiency).

The SCR\textsubscript{deNO\textsubscript{x}} technology is applied in both automotive and industrial applications, and has shown that the durability is generally quite good. The aqueous urea, used in most automotive SCR\textsubscript{deNO\textsubscript{x}} systems, has poor lubrication properties. This may lead to excessive wear to pump elements and dosage components which results in insufficient injection quantities and eventually failure. A good calibration of the system is required (especially during transient operation) to ensure that the urea dosage will keep matching the NO\textsubscript{x} in the exhaust flow, optimising the trade-off between NO\textsubscript{x} reduction and ammonia slip. The introduction of NO\textsubscript{x} and NH\textsubscript{3} sensors in the future will allow the urea dosing to be controlled more accurately in a closed loop, and also ensure better system monitoring through OBD. At this moment the availability and long-term stability of this kind of sensor technology is still an open issue, and the sensors developed so far still show a cross sensitivity between NO\textsubscript{x} and NH\textsubscript{3}.

The NO\textsubscript{x}-conversion efficiency of the catalyst may possibly drop somewhat over the useful life of the vehicle (at maximum 10% over 500,000 km [16]).

DPF’s show a sensitivity for the ash emission, as a result of additives used in lubrication oil. For the future, new oil quality grades are under development that will produce lower ash emissions.

Field tests seem to indicate that particulate filter technology can be regarded as being durable (at least for relatively modern engines), provided that low sulphur diesel fuel is used, the lubrication oil consumption can be kept at a low level, and the conditions (exhaust temperature, NO\textsubscript{x}-emission) are favourable for regeneration of the filter. However, durability over the useful life of the vehicle has yet to be demonstrated. An important drawback of the DPF technology is that the filter temperature is somewhat difficult to control, while high temperatures have negative (and non-reversible) effects on the filter performance. Monitoring of the differential pressure over the filter (connected to an OBD system) can detect the effect of regeneration and filter damage (possibly in combination with filter temperature measurement). In the future, the problem of ash collection in the filter may improve when engine lubricants are developed with metal additives that produce less ash quantities.
Most of the emission control devices show a sensitivity to sulphur in the diesel fuel. When the future emission limits will enforce the use of emission control devices, diesel fuel and lubrication oil with a limited sulphur content will have to be permanently available. The maximum sulphur content of the fuel would be 50 ppm, but preferably a better quality is aimed for (e.g. 15 ppm, similar to the quality used in the USA). For a NOx-adsorber, even a further reduction of sulphur would be required (<3 ppm).

Apart from durability issues, the emission control device may also be tampered with, for different kinds of reasons. Tampering covers susceptibility towards the removal, modification and non-maintenance of the device, all of which can increase exhaust gas emissions. Systems most susceptible to tampering are those requiring the refilling of a chemical reactant, e.g. urea in an SCRdeNOx system, since there is no incentive to the vehicle operator to replenish used reactant. Monitoring the level of the chemical tank through OBD could be used to respond with a fuel and/or performance penalty by an intervention of the engine management system. The possibilities for sanctioning measures (fuel and/or performance penalty) will increase if NOx and PM sensors are introduced in the future.

The conclusions for the deterioration of EURO 4 and 5 engine technologies are the following:

- There is no reason to assume that the deterioration pattern of engine-out emissions would differ much from engines of earlier EURO class engines.
- Installed ECDs can deliver a contribution to deterioration of specific emission components as a result of ageing, malfunctioning or even tampering.
- Some of the anticipated deterioration aspects (mainly malfunctioning and tampering, but possibly also deterioration) can be prevented by installation of an OBD system, which will be mandatory from the moment ECDs can be expected to be used on HD engines (EURO 4 and beyond).
- ECDs containing catalysts will show some emission deterioration over the useful life of the vehicle due to ageing processes. At this moment it is hardly possible to give exact percentages since the technology is very premature, and only little data is available. Percentages given in this paragraph can only be treated as indicative.

Finally, it should be noted that engines equipped with ECDs will potentially show higher emission levels in real-life driving situations compared to stationary (and possibly even) transient testcycles, due to the increased possibilities for cycle optimisation.

8.4. Effects of maintenance

In the Dutch In-Use Compliance program, vehicles are tested first in the condition they are received in. If the test result is significantly higher than the emission values measured in the type approval test (>20% or >10% above emission limit, whichever is higher), the maintenance condition of the engine is checked. When it appears that adjustments are needed or malfunctions are found (especially emission related ones), the cause for this will be discovered and restored by carrying out corrective maintenance actions. After that, the engine is re-tested, in order to check the effect of the maintenance corrections on the emissions. The database with test results makes a perfect source for analysing the relation between maintenance and emissions, as the emissions before and after maintenance are both available on the same vehicle. However, the co-operation of vehicle owners to the programme is voluntarily, therefore vehicles that have severe maintenance deficiencies will probably not enter the programme. For the same reason engines with chiptuning will also not be
encountered, though there are signs that this is becoming more and more common. The database contains 39 EURO 1 and 29 EURO 2 vehicles that required maintenance (52% of tested EURO 1 vehicles and 33% of EURO 2 tested vehicles). None of the 24 tested EURO 3 vehicles that were monitored had emission problems related to maintenance issues. Unfortunately, the data from the German IUC project lacks this detail of information, and is therefore left out of the database.

Evidently, nothing can be said with certainty about EURO 4 and 5 vehicles. Some kind of insurance for proper functioning may be expected from the introduction of an On-Board Diagnostics system (OBD), at the same time as EURO 4 takes effect. This system aims at preventing issues that can be resolved through corrective maintenance, by checking for irregularities in the engine and its subsystems.

In the analysis the focus is laid first on NO\textsubscript{x} and PM, being the most critical emission components of HD diesel engines. Figure 90 shows these emissions for EURO 1 and 2 vehicles in the database that needed one or more maintenance corrections. The little markers give the results for the individual vehicles before (diamond) and after (square) carrying out maintenance, while the two big markers present the average of all vehicles before and after.

![Figure 90: NO\textsubscript{x} and PM emissions (13-mode test) of EURO 1 and 2 vehicles before and after maintenance (all defects)](image)

The reduction in emissions by applying maintenance is on average for both EURO 1 and 2 hardly noticeable for NO\textsubscript{x} (3 or 2% respectively) and moderate for PM (15% and 23%). The different effects on NO\textsubscript{x} and PM can be explained by first looking at the type and occurrence of malfunctions on these engines (see Figure 91).
An incorrect pump delivery or bad condition of injectors will normally result in a higher PM emission, while an incorrect injection timing usually leads to a NO\(_x\) problem. These first two categories (especially for EURO 2) have a higher probability of occurrence than the incorrect injection timing, so the corrective maintenance will have more consequences for PM than for NO\(_x\). This is one explanation for the higher reduction of PM emissions in Figure 90. A second one is found by looking at the (relative) level of exceeding NO\(_x\) and PM emission limits. As the PM emissions -before maintenance- show relatively high levels compared to NO\(_x\) (especially for EURO 2), a maintenance correction has a higher potential to reduce PM. In other words, an increase in PM due to a maintenance deficiency is usually higher than an increase in NO\(_x\) due to an incorrect injection timing.

Figure 91 also learns that maintenance issues that were quite common on EURO 1 vehicles, are becoming more rare for EURO 2. This is mainly the result of introducing engine management systems and electronic fuel pumps on EURO 2 vehicles. This trend is continuing towards EURO 3 and beyond, so incorrect timing and fuel pump delivery seem to become issues of the past. The only real maintenance issue that will probably remain, is a bad condition of the fuel injectors. In the absence of legislative durability requirements and with ever increasing fuel injection pressures, this type of defect may increase in the future. However, this has not been substantiated by the results of the EURO 3 vehicles tested so far in the in-use compliance programme. Figure 92 focuses on the emission effect of replacing worn out fuel injectors.
Figure 92: NOx and PM emissions (13-mode test) of EURO 1 and 2 vehicles before and after injector replacement

The reduction of PM emissions by replacing the defective injectors amounts to 18% on average for EURO 2 (23% for EURO 1). Usually a problem with the fuel injectors is thought to be associated with a high age of the engine. However, the mileage distribution of vehicles that needed injector replacement does not support this idea (see Figure 93), indicating that the injector condition is rather independent of the mileage. Other factors of influence are the driving pattern (driving in urban areas seems more demanding on the injectors) and the fuel quality (especially the additives used).

Figure 93: Mileage distribution of maintenance shortcomings for EURO 1 and 2 HD vehicles (value at the right of the bars indicates the number of vehicles in the particular mileage range)

The analysis of maintenance corrections has also been performed for the other two legislated emission components (HC and CO). The overall results, including those of Figure 90, are summarised in Table 45. The (expected) overall effect has been calculated by multiplying the percentage of vehicles needing maintenance by the average reduction in emissions, imposed by applying the necessary corrective maintenance actions. The reductions have been compensated for potential differences in fuel consumption as a result of the maintenance correction, since this will have a secondary influence on the emission level of the tests.
Table 45: Average emission effects as a result of maintenance activities, and the expected overall effect on average EURO 1 and 2 fleet (compensated for fuel consumption differences)

<table>
<thead>
<tr>
<th>Percentage of vehicles needing maintenance</th>
<th>EURO 1</th>
<th>EURO 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average effect on PM</td>
<td>-15%</td>
<td>-23%</td>
</tr>
<tr>
<td>Average effect on NO(_x)</td>
<td>-3%</td>
<td>-2%</td>
</tr>
<tr>
<td>Average effect on CO</td>
<td>-17%</td>
<td>-4%</td>
</tr>
<tr>
<td>Average effect on HC</td>
<td>2%</td>
<td>-11%</td>
</tr>
<tr>
<td>Overall effect on PM</td>
<td>-8%</td>
<td>-7%</td>
</tr>
<tr>
<td>Overall effect on NO(_x)</td>
<td>-1%</td>
<td>-1%</td>
</tr>
<tr>
<td>Overall effect on CO</td>
<td>-9%</td>
<td>-1%</td>
</tr>
<tr>
<td>Overall effect on HC</td>
<td>1%</td>
<td>-4%</td>
</tr>
</tbody>
</table>

The analysis on maintenance leads to the following conclusions:

- As a result of deficiencies in the maintenance condition of HD engines, emissions may increase, especially PM. About 52% of the tested EURO 1 vehicles needed maintenance; for EURO 2 this concerned 33% of the vehicles. None of the 24 tested EURO 3 vehicles had emission problems related to the maintenance condition.

- The introduction of electronic fuel pumps and engine management systems has a positive effect on this situation, as problems with timing or fuel pump delivery become less viable to occur. For EURO 3 this will be commonly applied technology, and so far the experiences in the Dutch In-Use Compliance testing project support this expectation.

- The most important maintenance issue at this moment and in the future concerns the condition of the fuel injectors. Wear of the nozzles or an incorrect opening pressure may result in serious increases of PM emissions (up to 23% on average). For the future this problem could show more often, due to higher injection pressures. However, for the first (relatively new) 24 EURO 3 vehicles no injector problems have appeared.

- Though the fuel injectors were expected to deteriorate with increasing mileage of the vehicle, no correlation of such kind could be established.

- For individual cases the rise in emissions (especially PM) can be quite spectacular, but on an overall fleet basis, the effect of maintenance corrections on emissions stays at a relatively low level (a few percentages, up to 9% at maximum).

A pragmatic approach for adding a ‘maintenance module’ to the emission model is to assume for the entire EURO 1 and 2 vehicle classes an increase in emissions (as a result of the actual maintenance condition) according to the expected overall effect shown in Table 45. For EURO 3 technology (electronic fuel pumps and engine management system) the condition of the fuel injectors can be expected to be the main issue. However, this has not been substantiated by recent measurements on EURO 3 vehicles, where none of the 24 vehicles had injector problems [71]. On the other hand, these vehicles were relatively new, with odometer readings not exceeding 180,000 km. Based on the EURO 2 data, around 20% of the vehicles show deficiencies related to the injectors, resulting in an average PM increase of some 18% (see Figure 92). Over the vehicle fleet this means an average increase of 3-4% for EURO 2 vehicles, and probably less for EURO 3 vehicles (based on recent experiences with
EURO 3 vehicles). For the other emission components of EURO 3 vehicles the rise (in absolute emissions) is expected to be insignificant.

It is important to realise that these conclusions on maintenance are based on only steady-state measurements, so it is not a certainty that transient emissions show the same response to maintenance issues. For that reason it is not possible to predict the influence of maintenance on real-life emissions to a certainty. Furthermore, it has to be noted that this analysis was based on vehicles that were voluntarily supplied by their owners to the measurement programme. For obvious reasons it is not unlikely that very poor maintained vehicles did not participate in this program.

9. EMISSION FACTORS CALCULATED

As mentioned before, 170,000 combinations of vehicle categories, vehicle loadings, EURO-classes, driving cycles and road gradients have been simulated with the model PHEM.

It is not possible to list all simulation result in this report. The results are available in the electronic data base of the ARTEMIS emission model. In the following principle results are summarised for single vehicle categories.

9.1. Influence of the emission legislation and driving cycles

Figure 94 shows the simulated fuel consumption and NO\textsubscript{x} emission factors for the vehicle category truck trailers and articulated trucks 34-40 tons maximum allowed gross weight. The fuel consumption values dropped from “pre EURO 1” to EURO 2 by more than 15% on average over all cycles. The more stringent NO\textsubscript{x} limits and the broader controlled engine speed range of the ESC test for EURO 3 lead to an increase in the fuel consumption in the range of 4% from EURO 2 to EURO 3. The application of an SCR exhaust gas aftertreatment system will allow a further optimisation of the fuel consumption. Compared to EURO 3 engines a reduction of 7% for EURO 4 engines and of 5% for EURO 5 engines are predicted. The simulated NO\textsubscript{x} emissions correspond to the findings from the engine tests. EURO 2 has about 5% higher NO\textsubscript{x} emissions than EURO 1. The NO\textsubscript{x} emission level of the EURO 3 vehicle are below EURO 2 again, but the trend depends on the driving cycle. While on fast highway cycles EURO 3 is approximately 20% below EURO 2, in slow stop & go traffic the emission levels of EURO 2 and EURO 3 engines are nearly equal. This results from the different engine loads of the cycle. In the stop & go cycle a high share of low engine speeds occur where the ESC has no test points. As discussed in chapter 3.1.3 the engines are optimised for low fuel consumption in these ranges, resulting in relatively high NO\textsubscript{x} levels. On average over the cycles the NO\textsubscript{x} emissions of EURO 4 are 40% lower and for EURO 5 more than 60% lower than for EURO 3.

\[24\] The shown results shall only be seen as an example, since the results are often different for other combinations of vehicle categories, vehicle loading and road gradients.
**Figure 94:** Simulated fuel consumption and NO\textsubscript{x}-emission factors for truck trailers and articulated trucks 34 to 40 tons, 50% loaded, 0% road gradient

Figure 95 shows the results for particulate matter and HC for the same HDV category. Particulate emissions dropped by nearly 60% from “pre EURO 1” to EURO 2 vehicles. This reduction is even higher for smaller HDV since the larger engines introduced cleaner technologies within the “pre EURO 1” category first (chapter 4.4.2). For the EURO 3 vehicles on average about the same PM emission level is simulated than for EURO 2, but with different levels for the cycles under consideration. Again the emissions in slow cycles are relatively high for EURO 3 while in the highway cycles the particle levels from EURO 3 are clearly lower than EURO 2. For EURO 4 and EURO 5 vehicles a reduction of more than 80% is predicted compared to EURO 3.

For HC emissions clear reductions were found from EURO 1 to EURO 2. Because of the oxidation catalyst in the exhaust gas aftertreatment system from EURO 4 on the HC emissions are predicted to be almost negligible. Quite similar results were found for CO, but both, CO and HC are no critical exhaust gas components of HDV.
9.2. Influence of road gradients and driving cycles

Roads are rather seldom absolutely flat and the road gradient has a high influence on the engine loads pattern and the emission levels; in the following the influence of 6% road gradient\(^{25}\) for the same HDV category as before is shown (truck trailer and articulated trucks 34-40t).

\(^{25}\) The results are not linear over changing road gradients, thus an interpolation of the influence of other road gradients is very inaccurate for some cases. Together with the influence of the vehicle loading (which has higher effects at higher gradients), the use of simplified “gradient factors” and “loading factors”, as used in some other
As described before, the model PHEM reduces the cycle speed profile if it cannot be followed with the given engine power performance. Figure 96 compares the average speeds for the basic cycle (0% road gradient) with the results for the same cycle with 6% road gradient. As expected, the velocity of basic cycles with higher speeds is reduced most, slow cycles can be followed nearly complete with 6% road gradient and the 50% loaded HDV. Additionally, older HDV with a lower rated engine power have to reduce their speed at gradients slightly more than modern ones.

![Graph comparing average cycle speed](image1)

**Figure 96:** Average cycle speed from the basic cycle (0% gradient) and simulated average cycle speed with 6% gradient

Fuel consumption and emissions are heavily influenced by the road gradient (Figure 97). For almost all exhaust gas components the emission level increases clearly at higher road gradients (at lower gradients the situation varies according to the EURO category, driving cycle and exhaust gas component).

For the situation of 6% gradient, both fuel consumption and NO\textsubscript{x} rise by 100% to 350% compared to driving on the flat road. While the increase of the fuel consumption is similar for all EURO classes, a lower increase of NO\textsubscript{x} is predicted for higher EURO classes. Lowest effects are expected for EURO 4 and EURO 5.

![Graph comparing fuel consumption and NO\textsubscript{x} emissions](image2)

**Figure 97:** Comparison of fuel consumption and NO\textsubscript{x} emissions on a flat road to 6% road gradient

models can not be recommended.
Figure 98 gives the comparison of 6% and 0% road gradient for particulate matter and HC emissions. Again clear differences are predicted between the engine generations. While the highest increase of PM emissions is predicted at slow average cycles speeds for EURO 2 vehicles, the highest increase of PM emissions at fast cycles is calculated for EURO 1 engines. The influence of gradients for EURO 4 and EURO 5 is predicted to be much smaller.

Figure 98: Comparison of particulate and HC emissions on a flat road to 6% road gradient

9.3. Comparison of the HDV emission factors with the results in different versions of the “Handbook on Emission Factors”

This paragraph gives a comparison of the ARTEMIS HDV emission factors with the according values in two different versions of the “Handbook on Emission Factors”:

- HBEFA 2.1 [35], (published February 2004)
- HBEFA 1.2 [22], (emission factors for HDV published in 1995)

The ascertainment of the HDV emission factors for the latest version HBEFA 2.1 has been performed similar to ARTEMIS using the emission model PHEM. The results in the HBEFA 1.2 have been gained with a completely different methodology which is described in [22].

9.3.1 Comparison with HBEFA2.1 [35]

Although the same emission model was used in the latest HBEFA version, changes occur because of:

a) Further development of the emission model
b) Introduction of a new set of driving cycles

a) Further development of the emission model

The main changes in the since February 2004 in the emission model can be summarized as follows:

1. Update of the data collection

Since the introduction of the HBEAF 2.1 new data on engine test bed measurements has been available. Especially for the emission standard EURO 3 the number of included engines has been doubled (from 12 to 24). Hence the
average emission maps and the transient correction functions have been updated. The changes of the overall emission level have been rather small, only the shapes of the engine maps changed slightly (e.g. increase of PM emissions at high engine speeds, decrease at low engine speeds)

2. Introduction of correction functions for fuel consumption in consideration of the engine size (see paragraph 4.4.2)

The effects of the engine size correction are changes from an increase of fuel consumption of 8% for the smallest simulated engines up to a decrease of 3% for the biggest engines.

3. New estimations for the emission behavior of engines for the future emission standards EURO 4 and EURO 5 (compare paragraph 5.2)

- Despite the rigorous limits for NO\textsubscript{x}, it is now assumed, that the application of a SCR system allows a clear reduction (in a range of 5 to 7%) of fuel consumption compared to EURO 3 engines, whereas in the HBEFA an increase was assumed.

- Compared to the assumptions for the HBEFA2.1 mainly due to the announced regulations for OBD-diagnostics the estimated NO\textsubscript{x}-emissions outside the type approval area in the engine map have been clearly reduced.

- Base measurements on a pilot engine equipped with a SCR systems, also the predictions on the emissions of PM, HC and HC have been updated in terms of a reduction compared to the predictions in the HBEFA2.1 (-30% to –50% for PM, -90% for CO, -95% for HC).

4. Adaptations in the average engine maps in the area with engine speeds near idling and positive engine load lead to an increase of simulation results for driving cycles with high shares of idling and driveaways (impact mainly on fuel consumption and NO\textsubscript{x}-emissions in a range of 10 to 20% for driving cycles with low average speeds)

5. Vehicle data on coaches and partially for urban busses have been updated. Compared to the HBEFA2.1:

- the vehicle empty weights and the engine rated power have been increased (coaches)

- the specific values for the aerodynamic resistance have been reduced (coaches, urban busses)

The remaining model modifications, which are not mentioned here in detail (e.g. improved gear shift model, modifications of the axle ratios) improved the model plausibility but have comparatively lower effects on the model results. As an example, Figure 99 and Figure 100 show a comparison of emission factors calculated for the ARTEMIS project (PHEM version February 2005) and for the HBEFA2.1 (PHEM version February 2004). The comparison is performed for the vehicle category “truck trailers and articulated trucks 34-40 tons maximum allowed gross weight”, 50% vehicle loading and 0% road gradient, using identical sets of driving cycles (HBEFA2.1) for both model versions.
types of roads, speed limits and traffic densities. A straight comparison of fuel consumption
100 different velocity patterns, which allows for a finer allocation of results for different
patterns, whereas in the ARTEMIS project the set of “basic” cycles is expanded to more than
HBEFA cycles no definite counterpart can be specified in the large set of ARTEMIS cycles.

In Figure 101 to Figure 105 the model results for fuel consumption and emissions in the
HBEFA2.1 the basic set of driving cycles for trucks consisted of 16 different velocity

cycles with 0% road gradient. With increasing road gradient the power demand for overcoming the climbing
resistance becomes dominant for fuel consumption and emissions, downhill driving of HDV in general causes low (or almost zero) emissions.

26 The influence of the velocity pattern on fuel consumption and emissions of HDV is maximum for driving
cycles with 0% road gradient. With increasing road gradient the power demand for overcoming the climbing
resistance becomes dominant for fuel consumption and emissions, downhill driving of HDV in general causes low (or almost zero) emissions.
In general the covered range of fuel consumption and emission results for the new ARTEMIS cycles show no significant change compared to the values for the HBEFA.

Figure 101: Comparison: cycles ARTEMIS vs. cycles HBEFA 2.1 (0% road gradient); fuel consumption, vehicle: truck trailer / articulated truck 34-40 tons, 50% loaded

Figure 102: Comparison: cycles ARTEMIS vs. cycles HBEFA 2.1 (0% road gradient); NOx emissions, vehicle: truck trailer / articulated truck 34-40 tons, 50% loaded
Figure 103: Comparison: cycles ARTEMIS vs. cycles HBEFA 2.1 (0% road gradient); PM emissions, vehicle: truck trailer / articulated truck 34-40 tons, 50% loaded

Figure 104: Comparison: cycles ARTEMIS vs. cycles HBEFA 2.1 (0% road gradient); HC emissions, vehicle: truck trailer / articulated truck 34-40 tons, 50% loaded
Table 46 tries to make a direct comparison of HBEFA2.1 and ARTEMIS driving cycles for three main traffic situations. Only for the traffic situation “motorway” two correspondent cycles can be allocated clearly. The ARTEMIS counterparts for the HBEFA2.1 “standard” cycles for rural and urban driving have been chosen according to similar average cycle speeds. Differences for simulated fuel consumption and emission factors can especially be observed for the traffic situation “motorway”, which is more dynamic (with same average speed of 86 km/h) in ARTEMIS cycle. This leads to an increase compared to the HBEFA results for fuel consumption (+10%), PM (+45%), and CO emissions (+150%) for this EURO 3 vehicle.

Table 46: Comparison of fuel consumption and emissions for different driving cycles (ARTEMIS vs. HBEFA2.1) for three main traffic situations; vehicle: truck trailers and articulated trucks 34-40 tons maximum allowed gross weight, EURO 3, 50% loading

<table>
<thead>
<tr>
<th>main traffic situation</th>
<th>specifications of compared driving cycles</th>
<th>average speed [km/h]</th>
<th>fuel cons. [g/km]</th>
<th>NOx [g/km]</th>
<th>HC [g/km]</th>
<th>CO [g/km]</th>
<th>PM [g/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>motorway</td>
<td>HBEFA 2.1 highway standard 0% gradient (“1020”)</td>
<td>86.2</td>
<td>218.2</td>
<td>5.9</td>
<td>0.29</td>
<td>1.07</td>
<td>0.113</td>
</tr>
<tr>
<td></td>
<td>ARTEMIS rural motorway, speedlimit 130km/h, freeflow</td>
<td>86.3</td>
<td>238.0</td>
<td>6.0</td>
<td>0.25</td>
<td>2.63</td>
<td>0.167</td>
</tr>
<tr>
<td>deviation</td>
<td></td>
<td>0%</td>
<td>9%</td>
<td>2%</td>
<td>-13%</td>
<td>145%</td>
<td>47%</td>
</tr>
<tr>
<td>rural</td>
<td>HBEFA 2.1 rural road (“3020”)</td>
<td>66.1</td>
<td>240.3</td>
<td>6.8</td>
<td>0.29</td>
<td>1.42</td>
<td>0.131</td>
</tr>
<tr>
<td></td>
<td>ARTEMIS rural distributor road, speedlimit 100km/h, freeflow</td>
<td>70.2</td>
<td>239.9</td>
<td>7.2</td>
<td>0.29</td>
<td>1.42</td>
<td>0.125</td>
</tr>
<tr>
<td>deviation</td>
<td></td>
<td>6%</td>
<td>0%</td>
<td>6%</td>
<td>2%</td>
<td>0%</td>
<td>-5%</td>
</tr>
<tr>
<td>urban</td>
<td>HBEFA 2.1 urban, main road (“4020”)</td>
<td>47.0</td>
<td>282.4</td>
<td>8.0</td>
<td>0.41</td>
<td>1.78</td>
<td>0.172</td>
</tr>
<tr>
<td></td>
<td>ARTEMIS urban, district distributor road, speedlimit 70 km/h, freeflow</td>
<td>48.1</td>
<td>282.1</td>
<td>8.1</td>
<td>0.39</td>
<td>2.02</td>
<td>0.170</td>
</tr>
<tr>
<td>deviation</td>
<td></td>
<td>2%</td>
<td>0%</td>
<td>1%</td>
<td>-4%</td>
<td>13%</td>
<td>-1%</td>
</tr>
</tbody>
</table>
9.3.2 Comparison with the HBEFA 1.2 [22]

Unfortunately, the vehicle data used in the former version of the Handbook on Emissions Factors [22] was not defined in any document. Additionally, the results above show that the relative ratio of the emission factors between the different EURO categories depend very much on the loading, the cycle and the road gradient. The results of the Handbook on Emission Factors (HBEFA 1.2) suggest that constant factors have been used between the EURO categories. Therefore, a comparison of the results of the new model PHEM and [22] is only indicative.

For a rough comparison the HDV category “truck trailer and articulated truck 34 to 40t” is used. In the new model this category has 39.8 tons maximum allowed gross weight (Table 27), with an empty vehicle weight of 15.1 tons. A loading of 50% corresponds to 12.35 tons. The simulations in [22] may have been done for any maximum allowed gross weight between 34 tons and 40 tons. What is regarded as a “half loaded” vehicle is also not defined since the vehicle empty weight is unknown. Anyhow, for the HDV category “truck trailer and articulated truck 34 to 40t” the simulated fuel consumption for “pre EURO 1”-vehicles corresponds quite well, so it is assumed that the vehicle characteristics are reasonably similar.

The fuel consumption values simulated for three main traffic situations (motorway, rural, urban) in ARTEMIS are slightly lower than in the HBEFA 1.2 (Figure 106), especially for highway driving. The NO\textsubscript{x} emission factors simulated for “pre EURO 1” and “EURO 1” are on the same level in ARTEMIS and HBEFA1.2. As expected, the updated NO\textsubscript{x} emission factors simulated by PHEM for EURO 2 and EURO 3 are much higher than for HBEFA 1.2. Since the engine emission maps for “pre EURO 1” are mainly from the same source for PHEM and HBEFA 1.2, the agreements for these EURO categories was expected. EURO 2 and EURO 3 engines have not been measured for HBEFA 1.2 but were determined by considering the drop of the emission limits in the type approval. In contrast, PHEM uses measured engine maps for those categories.

![Graph](image.png)

**Figure 106:** Comparison of the fuel consumption and NO\textsubscript{x} emission factors calculated by the model PHEM with the emission factors from the Handbook Emission Factors (HBEFA 1.2) for three driving cycles (0% road gradient, 50% loaded truck trailer and articulated truck 34 to 40t)

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27 The comparison was performed for the same set of cycles mentioned in the paragraph above.
The new emission factors for particulate matter of “pre EURO 1” and EURO 1 are lower for urban and rural and higher for motorway driving compared to the HBEFA1.2 (Figure 107). For the EURO 2 vehicle and highway driving PHEM simulates more than double PM emissions compared to the old emission factors, whereas for rural and urban driving ARTEMIS and HBEFA1.2 give nearly equal predictions. The PM emissions for the emission standard EURO 3 are in general higher in the ARTEMIS emission model. For HC the new emission factors are in general on a lower level.

Figure 107: Comparison of the particulate and HC emission factors calculated here (model PHEM) with the emission factors from the Handbook Emission Factors (HBEFA 1.2) for three driving cycles (0% road gradient, 50% loaded solo truck 14-20t)

For CO the emission factors are rather similar for the “pre EURO 1” category. For newer HDV PHEM gives much higher CO emissions. Most likely the emission factors from HBEFA 1.2 were reduced according to the type approval values for EURO 1 to EURO 3. In reality, the CO emission levels of HDVs have already been far below the limit values for EURO 1 so there was no need to reduce CO systematically for EURO 2 and EURO 3 engines. Thus, CO was reduced only as a side effect of measures to reduce particulate emissions and other improvements in the combustion technology. Anyhow, the emission levels for CO are still in line with the limits and are not critical from the environmental point of view.

Figure 108: Comparison of the CO emission factors calculated here (model PHEM) with the emission factors from the Handbook Emission Factors (HBEFA 1.2) for three driving cycles (0% road gradient, 50% loaded solo truck 14-20t)
9.4. Emission factors for PM number and PM active surface area

For the implementation in the ARTEMIS model also emission factors for PM number and PM active surface area have been calculated. For this task, which was originally not foreseen in the framework of the WP400 agenda, a simplified model approach based on data from the PARTICULATES project [69] was applied.

From engine test bed measurements on 7 HD engines the average results in the three subcycles of the ETC (urban, rural, motorway) have been available. For the following measured quantities the work specific values (per kWh positive engine work) have been calculated:

- Active surface area [cm²]
- Number of total particles [#]
- Number of solid particles smaller 50nm [#]
- Number of solid particles between 50nm and 100nm[#]
- Number of solid particles between 100nm and 1000nm [#]

This was done for the engine concepts “EURO 2”, “EURO 2 + retrofitted CRT system” (only solid particles), “EURO3”, “EURO 3 + retrofitted CRT system”, “EURO 4 with CRT system” (only solid particles) and “EURO 5 with SCR system” (only solid particles). For the engine generations EURO 1 and earlier no measurement data on PM number emissions was available. All results are based on measurements with “D4”-diesel fuel (exception: engine concept “EURO 3 + retrofitted CRT system, where only measurements with D5 diesel fuel have been available).

Further details regarding used measurement systems and tested engines in the PARTICULATE project can be found in [69]. A summary on the findings concerning diesel particle emissions from Light Duty Vehicles and Heavy Duty Engines is also published in [48].

The calculation of the distance based emission factors for the ARTEMIS model (values per kilometer) for PM number and PM active surface area for a certain combination of vehicle, loading, traffic situation and road gradient was then done by multiplication of the work specific number or surface values (per kWh positive engine work) with the according value for positive engine work per kilometer from the simulation with PHEM.

10. MODEL VALIDATION

The validity of emission factors or models in real world situations can be investigated by on-road emission measurements (validation of the simulation results for single vehicles) or by tunnel measurements (validation of the results for the emission level of the vehicle fleet).

10.1. On-road measurements

A tractor-semitrailer with a curb mass of 40 tons was used for an on-road measurement campaign performed by EMPA (Switzerland). The concentrations of several gaseous emissions, mass flows, pressures, temperatures, engine speed and torque were measured during trans-alpine driving across Switzerland. After the on-road measurements, the engine was dismounted from the vehicle, and measured on an engine test bed over several cycles. The laboratory and on-road measurement equipment were operated in parallel.
For the validation of PHEM emission results with the on-road measurements, the standard parameter set for the “average tractor-semitrailer 34 to 40 tons maximum allowed gross weight” was used. Only very vehicle-specific data were replaced by the values for the tested vehicle. These include the engine emission maps with the transient correction functions (gained from the engine test bed measurements), the transmission ratios of the gearbox and the total vehicle mass. As model input for the simulation of the on-road emissions, the measured on-road vehicle speed and road gradient were used.

A brief presentation of the validation results is given in Figure 109. The simulation of the required engine work based on the vehicle specifications and the trip data (vehicle speed and road gradient) matches the measured values almost exactly (deviations 0 to 4%). The measured and simulated values for fuel consumption agree within ±2%, the NOx emissions are underestimated by the model within 0 to 4%. The simulation of THC and CO differs from the measured values by –3%...–15% 28. Based on these on-road measurements, it can be concluded that the simulated fuel consumption and emissions match the measured on-road values very well.

![Comparison of simulation and on-road measurement](image_url)

**Figure 109:** Comparison of simulation and on-road measurement

A more detailed description of the on-road measurement campaign and the comparison between measurements and model results can be found in [64].

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28 This on-road measurement campaign focused on gaseous emissions, although on-road particle emission data would also be of significant interest. The question of reasonable and comparable particle emission measurement techniques, other than the regulated filter weighting method using full-flow dilution of the exhaust gases, remains unsolved as long as no common opinion is established in the scientific community regarding alternative laboratory techniques.
10.2. Road Tunnel Measurements

The validity of emission factors or models in real world situations can also be investigated by tunnel measurements. Traffic flow (split into passenger cars and HDV for each lane) as well as air flow are recorded and the measured pollution concentrations can be compared to the estimations based on emission factors.

Such measurements were performed in the Plabutschntunnel in November 2001, which serves as a by-pass for the City of Graz, Austria.

The Plabutschntunnel is a 10 km long one-bore tunnel with two lanes (operated in counter flow), carrying the A9 Highway (Pyhrnautobahn). It is divided into 5 ventilation sections and operated as a transverse ventilation system. The sampling site was located some 4 km inside the tunnel, in the middle of ventilation section 3, where a homogeneous mixture of air and pollutants could be assumed. A container equipped with a standard air quality monitoring device (AQM) was installed in a pull off bay within the considered ventilation section. The road gradient in this section is +/- 1%.

The measured data was statistically analysed by using a non-linear regression approach. Based on this analysis the estimation for the fleet emission factors of the passenger cars and heavy duty vehicles could be derived for each driving direction (i.e. in this case +/- 1% road gradient).

The emissions measured in the mentioned ventilation section were also recalculated with the model PHEM. Assumptions of the loading conditions and the fleet composition have been necessary since this information was not available from the monitoring of the traffic flow. This data on the HDV fleet composition was taken from the updated data set for Austria for the Handbook on Emission Factors [23].

The emission factors for the Plabutschntunnel were simulated in three different ways:

1. Using the actual version (at that time) of the Handbook on Emission Factors 1.2
2. Using the model PHEM with the same driving cycle as in (1)
3. Using the model PHEM with the a driving cycle recorded in the Plabutschntunnel (in the mentioned part of the tunnel, separate cycle for +1% and –1% road gradient)

The driving cycles already available in the HBEFA -each with –2%, 0% and 2% road gradient- were used to interpolate the emission factors for +1% and –1% road gradient. This approach is in accordance with the use of the updated HBEFA (=Version 2.1).

The emission factors gained from these calculations were corrected with regard to the ambient conditions in the tunnel, which are promoting the generation of NOx (lack of humidity, higher temperature). The correction was done with the help of the correction function according to the EC regulations. The results are shown in Figure 110 and Table 47.
Figure 110: Comparison of emission factors gained by tunnel measurements and by calculation with HBEFA 1.2 and the new model PHEM

Table 47: Emission factors gained by tunnel measurements and by calculation

<table>
<thead>
<tr>
<th>Emission-Factors NOx [g/km]</th>
<th>Measurement Nov 2001 (95% confidence interval in fine-print letters)</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Basis</td>
<td>HBEFA 1.2</td>
</tr>
<tr>
<td>Road Gradient +1%</td>
<td>Correction (ambient conditions)</td>
<td>10.48</td>
</tr>
<tr>
<td>Road Gradient -1%</td>
<td>Basis</td>
<td>6.19</td>
</tr>
<tr>
<td></td>
<td>Correction (ambient conditions)</td>
<td>10.00</td>
</tr>
<tr>
<td></td>
<td>Result</td>
<td>15.79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>14.01</td>
</tr>
</tbody>
</table>

As expected the HBEFA 1.2 shows a clear under-estimation of the NOx emission level (compare paragraph 9.3.2). The second validation step, using the model PHEM, shows higher NOx values for the same driving cycle as used in HBEFA 1.2, but the level of the actually measured emissions is still not reached. Since the driving cycles in the HBEFA give the road gradient only in 2% steps, the emission factor for +/- 1% gradient had to be gained by means of linear interpolation from emission factors of other road gradients. The influence of gradient, loading and driving cycle on the emission level of heavy duty vehicles is remarkably high and often non-linear. A correct assessment of these non-linear interrelations can only be achieved by detailed simulation of the combination of all relevant parameters. In a third step the model PHEM was used with a driving cycle measured in the Plabutsch tunnel and the actual road gradients (“PHEM+Plabutsch-Cycle”). The results of this simulation are to a high degree in line with the emission factors gained from the road tunnel measurements. A detailed description can be found in [23].

At the moment all data indicates that the emission model Phem, comprising also the input data for delivering fleet emission factors, is quite accurate for predicting the emissions of HDV in any traffic situation. Highest accuracy can be reached with a simulation of driving cycles measured exactly for the traffic situation under consideration. Using the emission factors prepared for ARTEMIS and for the HBEFA 2.1 saves the effort for measuring driving behaviour and for extra simulation runs with Phem but can increase the error since it is not possible to cover all potential real world traffic situations with predefined driving cycles exactly.
11. EMISSION FACTORS FOR ALTERNATIVE ENGINE CONCEPTS

To elaborate emission factors for alternative engine concepts similarly to diesel driven HDV based on measured engine emission maps certainly would be possible but rather expensive. Alternative engine concepts, like e.g. natural gas engines, are well below the level of volume production as diesel engines are. Therefore, differences in the emission behaviour and in the durability of single makes and models can occur, see e.g. [50], [48]. These differences require a significant number of engines or vehicles to be measured to obtain representative emission factors for alternative concepts. It was agreed, that the measurement campaign should aim at diesel engines, to get reliable data for the propulsion system installed in more than 99% of the HDV.

Emission factors for alternative concepts therefore had to be estimated from available literature and measurement results from the data collection within WP 400. Currently, the only alternative fuels that have reached appreciable shares in the HDV market are bio diesel, compressed natural gas (CNG) and liquefied petroleum gas (LPG). Other concepts, like hybrid vehicles, are only available in small (pilot) series so no reliable measurements on their emission level can be found as yet. Also for modern LPG driven HDVs no satisfactory data on emission levels was found, so no emission factors are indicated for this concept here.

11.1. Compressed Natural Gas (CNG)

Compressed natural gas is used in SI engines with special fuel injection for the gaseous fuel. Former concepts of CNG engines were driven nearly exclusively stoichiometric ($\lambda=1$) with controlled 3-way catalysts. This concept was able to reach very low emission levels for NO$_x$, CO, HC and PM, at least as a new engine. Durability tests for modern vehicles are not commonly available, former concepts partially showed a poor emission stability over live time. A main disadvantage of this concept is the much lower fuel efficiency compared to diesel engines. Energy consumption from stoichiometric CNG engines is at least 10% higher as for diesel driven HDV. At part load conditions, the disadvantage may rise to 20% or more.

For this reason, several of the today’s CNG buses are equipped with lean burn CNG engines, a technology offering principal benefits in fuel efficiency compared to the stoichiometric SI engine. A disadvantage of the lean burn engine is that the catalytic converter does not reduce the NO$_x$-emissions for lean burn conditions. Thus, the same principle trade off between NO$_x$ and fuel efficiency occurs like for diesel engines (see e.g. paragraph 5.1). Therefore, the use of CNG not necessarily gives benefits in the NO$_x$-emission level of the HDV. The potential heavily depends on the application of the electronic engine management system and the compromise between fuel efficiency and low emissions in real world driving accepted by the engineers.

Table 48 summarises the emission levels of modern CNG engines as a ratio to the EURO 3 emission factors. Data source are [24] and [50], where both, diesel buses and modern CNG buses were measured in real world test cycles on HDV roller test beds. Since individual vehicles, both for diesel and even more for CNG, can show big differences in the emission levels, the results in Table 48 have to be seen as indicative for the average changes expected from today’s point of view.

The results show that CNG can be a quite clean technology. Compared to EURO 4 diesel engines the advantages of CNG given in Table 48 would diminish, since EURO 4 and EURO 5 limits requires clear reductions in NO$_x$ and PM emission levels for the diesel engines. Of course, further emission reductions could also be achieved for CNG vehicles.
Table 48: Emission levels of a CNG propelled HDV in relation to the emission factors of a EURO 3 HDV (ratios based on real-life [g/km] for emission and [MJ/km] for the energy consumption values)

<table>
<thead>
<tr>
<th>Technology</th>
<th>NOx</th>
<th>PM</th>
<th>CO</th>
<th>THC</th>
<th>NMHC</th>
<th>FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel EURO 3</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>CNG EEV (1)</td>
<td>85%</td>
<td>10%</td>
<td>15%</td>
<td>300%</td>
<td>25%</td>
<td>120%</td>
</tr>
</tbody>
</table>

(1) Enhanced Environmental Friendly Vehicle with lean burn concept. Note: measured emissions of single CNG driven HDV partially differ significantly from the values given here, depending on the manufacturer, the mileage and the test cycle.

11.2. Biodiesel

The European „Biofuels Directive“ – stating that a 5.75% share of the fuel used in 2010 is biofuel- may for the HDV sector to a large extent be realized by biodiesel. If the existing directives for the fuel quality are met (ÖNORM C1190, DIN-Norm 51606, EN 14214, EN 590), biodiesel can be used in many HDVs without large complications, as long as important criteria for the storage of biodiesel and the method for replacement of the fossil diesel are considered, see e.g. [6].

While the blending of up to 5% biodiesel does not affect the emission levels very much, the use of pure biodiesel certainly has an effect on the emission behavior of the diesel engines. Measurements indicate an increased NOx emissions by 10% to more than 20%, and reduced PM emissions. Large differences were observed in single measurements concerning the reduction in PM emissions. For some combinations of vehicle and test cycle even an increased PM emission was found for biodiesel, see e.g. [24], [48].

Also the source of biodiesel (vegetable oil from rapeseed, palm, soybean etc.; used cooking oil or animal fat from tallow, yellow grease, etc.) has influences on the emission changes resulting from fossil fuel being substituted by biodiesel [6]. Therefore, the emission changes by a shift from fossil diesel to biodiesel given in Table 49 have to be seen as average values. The emission changes given here are averaged values from [24], [48] and [6].

Table 49: Emission levels of HDV driven with biodiesel instead of fossil diesel (ratios based on g/km emission and fuel consumption values)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>NOx</th>
<th>PM</th>
<th>CO</th>
<th>THC</th>
<th>NMHC</th>
<th>FC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional diesel (EURO 3 technology)</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>Bio diesel (1)</td>
<td>120%</td>
<td>80%</td>
<td>75%</td>
<td>60%</td>
<td>50%</td>
<td>115%</td>
</tr>
</tbody>
</table>

(1) Average ratios if fossil diesel is replaced by bio diesel (RME or FAME). Note: single measured results differed by more than 15% from the values given here, depending on the vehicle, the biodiesel and the test cycle.

12. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

In total 33 Heavy Duty engines and 48 Heavy Duty vehicles have been measured within the work of COST 346, D.A.CH.-NL. and ARTEMIS WP400. Additional data on measurements from 69 engines and 3 vehicles was gained from the data collection campaign. This set of information represents the largest consistent data base for heavy duty emissions available within Europe.
The resulting emission model PHEM (Passenger car and Heavy duty Emission Model) is capable of making use of the data from all 102 engines. For the elaboration of emission factors for ARTEMIS, the model PHEM was run with the data sets for average HDV according to certification level (EURO 0 to EURO 5), the size category (<7.5t up to 60t), different vehicle loadings, and a set of representative driving cycles. For the “Handbook Emission Factors for Road Transport, HBEFA” a different set of driving cycles was calculated with PHEM already in the year 2003 [27].

The data structure and the model have proved to be capable of fulfilling all demands in a flexible and fast way until now. Validation of the results was performed via tunnel studies and on board measurements and showed a satisfying accuracy, e.g. [23], [64].

After the finalization of the projects a stable platform for up to date and future assessments of emission factors for HDVs was created. A main open actual topic is a more extensive measurement program on relevant vehicle parameters such as the rolling resistance coefficients, drag coefficients transmission losses and the power demand of the auxiliaries of the “average” HDV. Due to the existing bandwidth in vehicle specifications, tyre design and road surface, fleet emission factors should be based on a broader data than available yet.

At the moment all data indicates that the emission model PHEM is quite accurate for predicting the emissions of HDVs in any traffic situation. The highest accuracy can be reached with a simulation of driving cycles measured exactly for the traffic situation under consideration. Using the emission factors prepared for ARTEMIS avoids the effort of measuring driving behaviour and for extra simulation runs with the emission model, but can increase the error since it is not possible to cover all potential real-life traffic situations with predefined driving cycles.

Due to the large and non-linear effects of vehicle size and vehicle loading as well as of the driving cycle and the road gradient on the resulting emission factors, the use of simple correction factors for these model parameters in combination with speed dependent regression functions for the basic emission factors is not recommended where high accuracy is needed.

The results of the measurement campaign and the data collection as well as the calculated emission factors show that HDV manufacturers are mainly focused at a high cost-effectiveness in the design of their engines and vehicles. Consequently, HDVs have durable engines and low fuel consumption at reasonable vehicle costs. As a result, the diesel engines up to EURO 3 prove to have very stable emission levels over their lifetime, which is a helpful side-effect for the purpose of emission simulation.

Meeting the emission limits at type approval is a necessary boundary condition but reaching high fuel efficiency clearly has a much higher market value for manufacturers than low real-world emissions. Since the market situation encourages manufacturers to optimise fuel consumption wherever possible, the old ECE R49 13-mode type approval test was not able to guarantee low NO$_x$-emissions for the new generation of electronically controlled engines from the year 1996 on.

Since engine technology has progressed quite rapidly since 1996, and even a further technological leap will be required for EURO 4 and EURO 5, it is not a certainty that the combination of the ESC and ETC cycles in the current type approval test will be sufficient to prevent real-life emission levels being significantly higher than at type approval data (due to off-cycle optimisation). Therefore the type approval limits and the type approval test procedure have to be well balanced to gain cost-effective benefits for air quality. Only lowering the limit values is not sufficient and clearly gives an incentive to apply off-cycle optimisations.
Even an ideal type approval system for currently used technologies may show shortcomings for future technologies. Thus, in-use tests on the complete vehicle, based on random real-world driving and using on-board emission measurement equipment or roller test bed measurements, are likely to become an important tool in the future if low emissions are to be guaranteed. With the EURO 4 legislation taking effect this year (2005), new engine and aftertreatment technologies are expected to be introduced. In order to be able to respond while these technologies are still in production, an in-use testing program would have to be started soon.

If properly designed, these in-use tests could also be used for updating the ARTEMIS emission factor model with new data. In ARTEMIS WP 300 it was shown that the passenger car module of the model PHEM can transfer instantaneous emission measurements from transient cycles on the roller test bed into useful engine emission maps to produce emission factors [78]. This method could lower the costs for updates significantly since measurements on the engine test bed for in-use EURO 4 and EURO 5 HDV may become very expensive, due to the complex technology. Even more, engine tests without special engine control units may become almost impossible for future HD engines, so new test methods are necessary if tests which are independent from the manufacturers are to be performed.

As EURO 4 and EURO 5 vehicles are now entering the market, a measurement program to update the emission factors is highly recommended. Since the emission behaviour of EURO 4 and EURO 5 HDVs is very hard to predict at the moment and no production vehicle with such technologies was available for measurements until now, there is a clear need to start such a program soon.

Especially for monitoring the compliance with existing European emission and air quality targets for NOx and PM10, regular updates of the emission factors based on measurements for the actual engine technologies seem to be highly relevant.
13. REFERENCES


[8] CONCAWE: Evaluation of diesel fuel cetane and aromatics effects on emissions from EURO 3 engines, Report no. 4/02; Brussels, March 2002


[10] CONCAWE: Impact of a 10 ppm sulphur specification for transport fuels on the EU refining industry, Report no. 00/54; Brussels, October 2000


[12] DECSE program: Interim Data Report No. 2; October 1999


[22] Hassel D., Jost P. et al.: Abgas-Emissionsfaktoren von Nutzfahrzeugen in der Bundesrepublik Deutschland für das Bezugsjahr 1990; Luftreinhaltung UFO PLAN-Nr. 104 05 151/02; TÜV-Rheinland Sicherheit und Umweltschutz GmbH im Auftrag des Umweltbundesamtes; Berlin 1995


[26] Hausberger S. et. al.: Results from the Review and Model Description, Deliverable 11 within the EU-5th Framework Project ARTEMIS, March 2001


[33] Infineum World-Wide Winter Diesel Fuel Quality Survey 2000


[38] Lastauto Omnibus Katalog: years 1995 to 2004


[46] Nakamura S. et.al: LES Simulation of Aerodynamic Drag for Heavy Duty Trailer Trucks; proceedings of the ASME Fluid Division Summer Meeting; Montreal, Quebec; July 14 to 18 2002


[49] Ntziachristos L. et al.: Background Document to the Workshop on EU Policies to Improve the Contribution of Urban Busses and other captive Fleets to Air Quality; Brusseles, 2005-01-14


[59] Roumégoux J-P.: The SIMULCO software: description of modelling and examples of application; Development and Application of Computer Techniques to Environmental Studies, Envirosys 96; Como, Sept. 1996
[64] Soltic P., Hausberger S.: On-Road Emission Measurements and Emission Modelling Results for a Tractor-Semitrailer in Trans-Alpine Operation; 13th International Scientific Symposium Transport and Air Pollution; Boulder, Colorado USA; September 13-15, 2004
[67] Steven H.: Auswertung des Fahrverhaltens von schweren Motorwagen; FIGE GmbH; BUWAL; 1995
[71] TNO: Data of project In-Use Compliance Programme Trucks 2001 – 2003, not published yet in an official public report


[77] Verkiel M.: Ontwikkeling van het voertuigsimulatieprogramma ADVANCE, Technical University Delft, MT OEMO 96/09, May 1997, Delft (only available in Dutch language)

[78] Zallinger M., Hausberger St., Ajtay D., Weilenmann M., (2005) ARTEMIS WP 300 – Task 332 Instantaneous emission modeling applications, final report to the Commission, Graz
APPENDIX I:

DATA COLLECTION FORMATS

The standard formats of the data collection sheets are given below.

Notes: please fill in the data you have available and leave out data which is not available (e.g. you will have no data on the vehicle if you measured the engine only.

| Data filled in by: | (Name and organisation) |
| The engine is a: | (series production / pilot production / prototype) |

### ENGINE DATA

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>engine make</td>
<td></td>
<td></td>
</tr>
<tr>
<td>engine type</td>
<td></td>
<td></td>
</tr>
<tr>
<td>engine code</td>
<td></td>
<td></td>
</tr>
<tr>
<td>year of first registration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>certification level</td>
<td></td>
<td></td>
</tr>
<tr>
<td>rated engine power</td>
<td>kW</td>
<td></td>
</tr>
<tr>
<td>idle engine speed</td>
<td>rpm</td>
<td></td>
</tr>
<tr>
<td>sweep volume per cylinder</td>
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<td></td>
</tr>
<tr>
<td>number of cylinders</td>
<td></td>
<td></td>
</tr>
<tr>
<td>compression ratio</td>
<td>kg.m²</td>
<td></td>
</tr>
<tr>
<td>type of fuel injection system</td>
<td></td>
<td></td>
</tr>
<tr>
<td>aspiration method</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mileage driven</td>
<td>km</td>
<td></td>
</tr>
</tbody>
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### Special features:

<table>
<thead>
<tr>
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<th>Unit</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGR (yes/no)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>particulate trap (yes/no)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>alternative fuel (specify)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>other # 1 (specify)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>other # 2 (specify)</td>
<td></td>
<td></td>
</tr>
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### VEHICLE DATA

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
<td>model</td>
<td></td>
<td></td>
</tr>
<tr>
<td>type</td>
<td></td>
<td></td>
</tr>
<tr>
<td>year of first registration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>registration number</td>
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<td></td>
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<tr>
<td>normal use</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vehicle mileage</td>
<td>km</td>
<td></td>
</tr>
<tr>
<td>vehicle weight (without payload)</td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td>maximum allowed gross weight</td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td>air resistance value</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cross sectional area</td>
<td>m²</td>
<td></td>
</tr>
<tr>
<td>rotating mass factor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>power demand of auxiliaries</td>
<td>kW on average</td>
<td></td>
</tr>
<tr>
<td>Rolling resistance values</td>
<td>m²g/(Fr₂ + Fr₁ * v²)</td>
<td>v = speed m/s</td>
</tr>
<tr>
<td>Fr₁</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fr₂</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Other special features, please explain here:
**Transmission:**

<table>
<thead>
<tr>
<th>Value</th>
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</thead>
<tbody>
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<tr>
<td>make</td>
<td></td>
<td></td>
</tr>
<tr>
<td>model</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Transmission values:**

<table>
<thead>
<tr>
<th>Value</th>
<th>Unit</th>
<th>Comment</th>
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</thead>
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<tr>
<td>axle ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>diameter of wheels</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>transmission gear 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>transmission gear 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>transmission gear 3</td>
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<td></td>
</tr>
<tr>
<td>transmission gear 4</td>
<td></td>
<td></td>
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<tr>
<td>transmission gear 5</td>
<td></td>
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</tr>
<tr>
<td>transmission gear 6</td>
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</tr>
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<td>transmission gear 9</td>
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<td>transmission gear 10</td>
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</tr>
<tr>
<td>transmission gear 11</td>
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<tr>
<td>transmission gear 12</td>
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<tr>
<td>transmission gear 13</td>
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<td>transmission gear 14</td>
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<td>transmission gear 15</td>
<td></td>
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<tr>
<td>transmission gear 16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>transmission gear 17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>transmission gear 18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Remarks:**

* rotating mass factor: ratio of the force needed to accelerate the rotating masses to the force needed to accelerate the vehicle mass in linear motion.

If you use a formula for calculating the force for acceleration of rotating masses or another methodology, please specify it here:

** power demand from auxiliaries: unit is kW power demand from vehicle engine

If you use a formula for calculating the power or another methodology, please specify it here:

** Additional data available

** Notes:** if you have data available, please specify as text what you have.

formats for the data exchange will be defined depending on what is available

** Detailed data on Auxiliaries:**

<table>
<thead>
<tr>
<th>Description of data available</th>
</tr>
</thead>
<tbody>
<tr>
<td>e.g. air conditioning</td>
</tr>
<tr>
<td>e.g. power demand [kW] as function of ...</td>
</tr>
</tbody>
</table>

** Definition of transmission efficiency:**

<table>
<thead>
<tr>
<th>Description of data available</th>
</tr>
</thead>
<tbody>
<tr>
<td>manual gearbox</td>
</tr>
<tr>
<td>e.g. power lost as function of rpm and torque</td>
</tr>
</tbody>
</table>
**Full load curve:**

*Comment*: number of values (lines) to be filled in is free, data given here is an example with 24 values

**Fuel used:** (standard diesel, Biodiesel, CNG, ...)

<table>
<thead>
<tr>
<th>Column A</th>
<th>Column B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal engine speed [rpm]</td>
<td>Power [kW]</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**STEADY STATE ENGINE TESTS**

Notes: you can use separate sheets for the steady state tests (e.g. one for ESC and one for 13-mode). Simply copy the formats in to a new inserted sheet.

**Description of test cycle:** ECE R49 - 13 Mode test

<table>
<thead>
<tr>
<th>Test conditions:</th>
<th>Auxiliary equipment fitted during test:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test conditions:</td>
<td><strong>kW</strong></td>
</tr>
<tr>
<td>Date of measurement</td>
<td>#1 (specify)</td>
</tr>
<tr>
<td>Humidity</td>
<td>#2 (specify)</td>
</tr>
<tr>
<td>Air temperature</td>
<td>#3 (specify)</td>
</tr>
<tr>
<td>Atmospheric pressure</td>
<td>#4 (specify)</td>
</tr>
<tr>
<td>Mean point of CVS dilution air</td>
<td>#5 (specify)</td>
</tr>
<tr>
<td>Oil temperature at start of test</td>
<td>#6 (specify)</td>
</tr>
<tr>
<td>Coolant temperature at start of test</td>
<td>°C</td>
</tr>
<tr>
<td>Fuel specification:*****</td>
<td></td>
</tr>
<tr>
<td>Fuel type</td>
<td>diesel, biodiesel, CNG, ...</td>
</tr>
<tr>
<td>Density</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Distillation - 50% volume</td>
<td>°C</td>
</tr>
<tr>
<td>Distillation - 90% volume</td>
<td>°C</td>
</tr>
<tr>
<td>Distillation - 95% volume</td>
<td>°C</td>
</tr>
<tr>
<td>Flash point</td>
<td>°C</td>
</tr>
<tr>
<td>Cold filter plugging point</td>
<td>°C</td>
</tr>
<tr>
<td>Smoke</td>
<td>m³/m</td>
</tr>
<tr>
<td>Sulfur content</td>
<td>% mass</td>
</tr>
<tr>
<td>Ash content</td>
<td>% mass</td>
</tr>
<tr>
<td>Water content</td>
<td>% mass</td>
</tr>
<tr>
<td>Additives (specify)</td>
<td></td>
</tr>
<tr>
<td>Gross (upper) calorific value</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Oxygenates</td>
<td>% mass</td>
</tr>
</tbody>
</table>

**Emission map** (all values according to ESC procedures, e.g. NOX-correction, ...):

<table>
<thead>
<tr>
<th>Power [kW]</th>
<th>Nominal engine speed [rpm]</th>
<th>Measured fuel consumption [g/h]</th>
<th>NOx [g/h]**</th>
<th>CO [g/h]</th>
<th>HC [g/h]***</th>
<th>PM [g/h]</th>
<th>CO2 [g/h]</th>
<th>Smoke opacity [m]****</th>
<th>Torque [Nm]</th>
<th>Intake air flow humidity [g/h]</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Power [kW]</th>
<th>Nominal engine speed [rpm]</th>
<th>Measured fuel consumption [g/h]</th>
<th>NOx [g/h]**</th>
<th>CO [g/h]</th>
<th>HC [g/h]***</th>
<th>PM [g/h]</th>
<th>CO2 [g/h]</th>
<th>Smoke opacity [m]****</th>
<th>Torque [Nm]</th>
<th>Intake air flow humidity [g/h]</th>
</tr>
</thead>
</table>

**Notes:**

- You can use separate sheets for the steady state tests (e.g. one for ESC and one for 13-mode).
- Simply copy the formats into a new inserted sheet.
### Transient ENGINE TESTS

**Notes:** you can use separate sheets for the steady state tests (e.g., one for ESC and one for 13-mode). Simply copy the formats in to a new inserted sheet.

**Description of test cycle:**

**Auxiliary equipment fitted during test:**

<table>
<thead>
<tr>
<th>Test conditions:</th>
<th>Auxiliary equipment fitted during test:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date of measurement</td>
<td># 1 (specify) kW</td>
</tr>
<tr>
<td>Humidity %</td>
<td># 2 (specify) kW</td>
</tr>
<tr>
<td>Temperature °C</td>
<td># 3 (specify) kW</td>
</tr>
<tr>
<td>Atmospheric pressure bar</td>
<td># 4 (specify) kW</td>
</tr>
<tr>
<td>Dew Point of CVS dilution air °C</td>
<td># 5 (specify) kW</td>
</tr>
<tr>
<td>CVS pump rate m³/h</td>
<td># 6 (specify) kW</td>
</tr>
<tr>
<td>Ambient temperature at start of test °C</td>
<td></td>
</tr>
<tr>
<td>Oil temperature at start of test °C</td>
<td></td>
</tr>
<tr>
<td>Coolant temperature at start of test °C</td>
<td></td>
</tr>
</tbody>
</table>

**Fuel specification:**

<table>
<thead>
<tr>
<th>Fuel type (diesel, biodiesel, CNG,...)</th>
<th>Cetane number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density kg/m³</td>
<td>@ 15°C</td>
</tr>
<tr>
<td>Ignition 50% volume °C</td>
<td></td>
</tr>
<tr>
<td>Ignition 95% volume °C</td>
<td></td>
</tr>
<tr>
<td>Flash point °C</td>
<td></td>
</tr>
<tr>
<td>Cold filter plugging point °C</td>
<td></td>
</tr>
<tr>
<td>Antimonial content % mass</td>
<td></td>
</tr>
<tr>
<td>Ash content % mass</td>
<td></td>
</tr>
<tr>
<td>Water content % mass</td>
<td></td>
</tr>
<tr>
<td>Sulfur content % mass</td>
<td></td>
</tr>
<tr>
<td>Oxygenates % mass</td>
<td></td>
</tr>
</tbody>
</table>

**Test evaluation ETC:**

<table>
<thead>
<tr>
<th>Power/Work</th>
<th>Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>kW</td>
<td>kWh</td>
</tr>
<tr>
<td>47.6</td>
<td>21.2</td>
</tr>
</tbody>
</table>

**Modal values:**

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Torque [Nm]</th>
<th>Engine speed [rpm]</th>
<th>Measured fuel consumption</th>
<th>NOX ***</th>
<th>CO</th>
<th>HC ****</th>
<th>PM*****</th>
<th>CO2</th>
<th>Smoke opacity******</th>
<th>C_DPA</th>
<th>additional values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Other special features, please explain here:**
### CHASSIS DYNAMOMETER TESTS

**Description of test cycle:** Name of the driving cycle

<table>
<thead>
<tr>
<th>Test conditions:</th>
<th>Auxiliary equipment fitted during test:</th>
</tr>
</thead>
<tbody>
<tr>
<td>State of measurement</td>
<td>extremity</td>
</tr>
<tr>
<td>Vehicle loading</td>
<td>kg</td>
</tr>
<tr>
<td>Humidity</td>
<td>%</td>
</tr>
<tr>
<td>Air temperature</td>
<td>°C</td>
</tr>
<tr>
<td>Atmospheric pressure</td>
<td>bar</td>
</tr>
<tr>
<td>Exhaust dynamometer inertial mass</td>
<td>kg</td>
</tr>
<tr>
<td>Dewpoint of CVS dilution air</td>
<td>°C</td>
</tr>
<tr>
<td>CVS pump rate</td>
<td>m³/h</td>
</tr>
<tr>
<td>Oil temperature at start of test</td>
<td>°C</td>
</tr>
<tr>
<td>Coolant temperature at start of test</td>
<td>°C</td>
</tr>
<tr>
<td>Auxiliary equipment fitted during test:</td>
<td></td>
</tr>
<tr>
<td># 1 (specify)</td>
<td>kW</td>
</tr>
<tr>
<td># 2 (specify)</td>
<td>kW</td>
</tr>
<tr>
<td># 3 (specify)</td>
<td>kW</td>
</tr>
<tr>
<td># 4 (specify)</td>
<td>kW</td>
</tr>
<tr>
<td># 5 (specify)</td>
<td>kW</td>
</tr>
</tbody>
</table>

#### Fuel specification:***

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Diesel, biodiesel, CNG, ...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Octane number</td>
<td></td>
</tr>
<tr>
<td>Distillation - 50% volume</td>
<td>°C</td>
</tr>
<tr>
<td>Distillation - 90% volume</td>
<td>°C</td>
</tr>
<tr>
<td>Distillation - 95% volume</td>
<td>°C</td>
</tr>
<tr>
<td>Flash point</td>
<td>°C</td>
</tr>
<tr>
<td>Cold filter plugging point</td>
<td>°C</td>
</tr>
<tr>
<td>viscosity</td>
<td>mm²/s @ 40°C</td>
</tr>
<tr>
<td>Sulfur content</td>
<td>% mass</td>
</tr>
<tr>
<td>aromatics content</td>
<td>% mass</td>
</tr>
<tr>
<td>ash content</td>
<td>% mass</td>
</tr>
<tr>
<td>Water content</td>
<td>% mass</td>
</tr>
<tr>
<td>Flash point</td>
<td>°C</td>
</tr>
<tr>
<td>Gross (upper) calorific value</td>
<td>MJ/kg</td>
</tr>
<tr>
<td>Oxygenates</td>
<td>% mass</td>
</tr>
</tbody>
</table>

#### Other special features, please explain here:

<table>
<thead>
<tr>
<th>Other special features, please explain here:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

#### Average values measured for the total cycle:

| Engine power | kW |
| Engine speed | rpm |
| Indicated fuel consumption | g/h |
| CO | g/h |
| NOx | g/h |
| CO2 | g/h |
| Smoke opacity | |
| Other # 1 (specify) | |
| Other # 2 (specify) | |
| Other # 3 (specify) | |
| Other # 4 (specify) | |

#### Modal values:****

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Vehicle speed [km/h]</th>
<th>Road gradient [%]</th>
<th>Simulated tractive force [kN]</th>
<th>Measured fuel consumption</th>
<th>NOx*****</th>
<th>CO</th>
<th>HC******</th>
<th>PM*******</th>
<th>CO2</th>
<th>Smoke opacity*****</th>
<th>additional values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

---

* 본문에서 제공된 정보는 첨부된 문서의 내용을 자연스럽게 읽어낸 결과입니다. **전기차**에 대한 문서입니다. **CHASSIS DYNAMOMETER TESTS**에 관한 내용을 정리한 것입니다. **Test conditions**와 **Auxiliary equipment fitted during test**의 항목을 포함하고 있습니다. **Fuel specification**과 **Other special features, please explain here**도 포함되어 있습니다. **Average values measured for the total cycle**와 **Modal values**도 제시되어 있습니다. 이 정보를 기반으로 원문을 자연스럽게 읽어낼 수 있습니다.
Coast down for HDV

**COASTDOWN DATA**

**Description of test cycle:** Coast-down

**Test conditions:**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>date of measurement</td>
<td>dd/mm/yy</td>
</tr>
<tr>
<td>vehicle loading</td>
<td>kg</td>
</tr>
<tr>
<td>humidity</td>
<td>%</td>
</tr>
<tr>
<td>air temperature</td>
<td>°C</td>
</tr>
<tr>
<td>atmospheric pressure</td>
<td>bar</td>
</tr>
<tr>
<td>wind speed</td>
<td>m/s</td>
</tr>
<tr>
<td>wind direction</td>
<td>degrees</td>
</tr>
<tr>
<td>road surface type</td>
<td></td>
</tr>
<tr>
<td>road surface conditions</td>
<td>wet, dry, ice etc.</td>
</tr>
<tr>
<td>road gradient</td>
<td>%</td>
</tr>
</tbody>
</table>

**Coastdown results:**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX II:

MEASUREMENTS NOT INCLUDED IN THE MODEL

For several measured vehicles no corresponding measurements at the engine test bed were available or the information on the vehicle specifications and the driving cycles was not complete. Hence these measurements were not appropriate for a direct validation of the emission model.

Table 50 gives an overview on all these measurements, which have not been directly included in the development of the emission model.

Table 50: Measurements not included in emission model

<table>
<thead>
<tr>
<th>Vehicle (make and model)</th>
<th>Engine Certification Level</th>
<th>Rated power [kW]</th>
<th>Test facility</th>
<th>Tested cycles</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAN L2000 X</td>
<td>EURO 1</td>
<td>115</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>LEYLAND DAF / FA 45 150</td>
<td>EURO 2</td>
<td>134</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>OPTARE METRORIDER X</td>
<td>EURO 1</td>
<td>96</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>OPTARE METRORIDER X</td>
<td>EURO 2</td>
<td>94</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>MAN 18.430 X</td>
<td>EURO 1</td>
<td>309</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>LEYLAND OLYMPIAN X</td>
<td>EURO 1</td>
<td>134</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>SCANIA L113 X</td>
<td>EURO 2</td>
<td>191</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>VOLVO B10B X</td>
<td>EURO 1</td>
<td>191</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>SCANIA P94 X</td>
<td>EURO 2</td>
<td>162</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>VOLVO OLYMPIAN X</td>
<td>EURO 2</td>
<td>183</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>SCANIA P93ML4X2R220 X</td>
<td>EURO 1</td>
<td>162</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>VOLVO FH12 X</td>
<td>EURO 2</td>
<td>309</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>IVECO MP340 TIPPER X</td>
<td>EURO 2</td>
<td>254</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>VOLVO FL12 TIPPER X</td>
<td>EURO 2</td>
<td>309</td>
<td>FIGE Cycle</td>
<td>TRL</td>
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<tr>
<td>VOLVO FL7 HIAB X</td>
<td>EURO 1</td>
<td>191</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>VOLVO FL12 HIAB X</td>
<td>EURO 2</td>
<td>309</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>MERCEDES 1317 HIAB X</td>
<td>EURO 1</td>
<td>155</td>
<td>FIGE Cycle</td>
<td>TRL</td>
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</tr>
<tr>
<td>MERCEDES 1317 HIAB X</td>
<td>EURO 2</td>
<td>125</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>NEOPLAN CITYLINER X</td>
<td>EURO 1</td>
<td>272</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>NEOPLAN X</td>
<td>EURO 2</td>
<td>213</td>
<td>FIGE Cycle</td>
<td>TRL</td>
<td></td>
</tr>
<tr>
<td>Vehicle (make and model)</td>
<td>Gross vehicle weight (tons)</td>
<td>Engine Certification Level</td>
<td>Rated power [kW]</td>
<td>Test facility</td>
<td>Tested cycles</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>----------------------------</td>
<td>----------------------------</td>
<td>------------------</td>
<td>---------------</td>
<td>---------------</td>
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<tr>
<td>TRANSLINER</td>
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</tr>
<tr>
<td>Scania 4 series</td>
<td>X</td>
<td>EURO 2</td>
<td>162</td>
<td>chassis</td>
<td>FIGE Cycle</td>
</tr>
<tr>
<td>Leyland DAF 45</td>
<td>X</td>
<td>EURO 2</td>
<td>107</td>
<td>chassis</td>
<td>FIGE Cycle</td>
</tr>
<tr>
<td>MAN 8-163</td>
<td>X</td>
<td>EURO 2</td>
<td>115</td>
<td>chassis</td>
<td>FIGE Cycle</td>
</tr>
<tr>
<td>Volvo FL6</td>
<td></td>
<td>EURO 2</td>
<td>154</td>
<td>chassis</td>
<td>FIGE Cycle</td>
</tr>
<tr>
<td>Iveco Flatbed</td>
<td>X</td>
<td>EURO 2</td>
<td>130</td>
<td>chassis</td>
<td>FIGE Cycle</td>
</tr>
<tr>
<td>Mercedes 814</td>
<td>X</td>
<td>EURO 2</td>
<td>100</td>
<td>chassis</td>
<td>FIGE Cycle</td>
</tr>
<tr>
<td>DAF LS160M / Citybus</td>
<td>X</td>
<td>EURO 2</td>
<td>160</td>
<td>on-board real traffic: urban, rural</td>
<td>VITO</td>
</tr>
<tr>
<td>MAN E2866DOH/Citybus (CNG lambda one)</td>
<td>X</td>
<td>EURO 1</td>
<td>169</td>
<td>on-board real traffic: urban, rural</td>
<td>VITO</td>
</tr>
<tr>
<td>VH A300D / Citybus</td>
<td>X</td>
<td>EURO 1</td>
<td>169</td>
<td>on-board real traffic: urban</td>
<td>VITO</td>
</tr>
<tr>
<td>VH A120-06 /Citybus</td>
<td>X</td>
<td>Pre EURO1</td>
<td>129</td>
<td>on-board real traffic: urban</td>
<td>VITO</td>
</tr>
<tr>
<td>VH A300D Citybus</td>
<td>X</td>
<td>EURO 2</td>
<td>162</td>
<td>on-board real traffic: urban</td>
<td>VITO</td>
</tr>
<tr>
<td>DAF2300 /Refuse haule (biodiesel)r</td>
<td>Pre EURO1</td>
<td></td>
<td>168</td>
<td>on-board real traffic: urban</td>
<td>VITO</td>
</tr>
<tr>
<td>DAF GS160M/Citybus</td>
<td>X</td>
<td>EURO 2</td>
<td>160</td>
<td>test cycles and real traffic</td>
<td>VITO</td>
</tr>
<tr>
<td>MAN D0826 LUH03 - Bus</td>
<td>X</td>
<td>EURO 1</td>
<td>157</td>
<td>on-board real traffic: urban, rural, highway</td>
<td>VITO</td>
</tr>
<tr>
<td>MAN D0826 LUH12 - Bus</td>
<td>X</td>
<td>EURO 2</td>
<td>162</td>
<td>on-board real traffic: urban, rural, highway</td>
<td>VITO</td>
</tr>
<tr>
<td>Iveco Solo 100E15</td>
<td>X</td>
<td>EURO 1</td>
<td>105</td>
<td>chassis</td>
<td>Testcycles: &quot;Eco&quot; 20,40; &quot;Nerv&quot; 20,40,60,80</td>
</tr>
<tr>
<td>Renault VI R340 T1</td>
<td>X</td>
<td>EURO 2</td>
<td>249</td>
<td>chassis</td>
<td>Testcycles: &quot;Eco&quot; 20,40,60,80; &quot;Nerv&quot; 20,40,60,80</td>
</tr>
<tr>
<td>Renault VI M250.12C</td>
<td>X</td>
<td>EURO 2</td>
<td>184</td>
<td>chassis</td>
<td>Testcycles: &quot;Eco&quot; 20,40,60,80; &quot;Nerv&quot; 20,40,60,80</td>
</tr>
<tr>
<td>Renault VI R340 T1</td>
<td>X</td>
<td>EURO 1</td>
<td>249</td>
<td>chassis</td>
<td>Testcycles: &quot;Eco&quot; 20,40,60,80; &quot;Nerv&quot; 20,40,60,80</td>
</tr>
<tr>
<td>Renault VI Premium 340.18T</td>
<td>X</td>
<td>EURO 2</td>
<td>249</td>
<td>chassis</td>
<td>Testcycles: &quot;Eco&quot; 20,40,60,80; &quot;Nerv&quot; 40,80</td>
</tr>
<tr>
<td>VOLVO FH12 D12 A420</td>
<td>X</td>
<td>EURO 2</td>
<td>309</td>
<td>chassis</td>
<td>Testcycles: &quot;Eco&quot; 20,40,60,80</td>
</tr>
</tbody>
</table>

A straight comparison of measured and calculated results for specific combinations of vehicle and driving cycle could not be performed with these measurements, as the according data are not complete. Therefore it was decided to pool all comparable results from measurement and simulation for each emission component and EURO-class as a function of average speed of the driving cycle and to compare the covered ranges of the emission levels with the
predictions for the average emission levels simulated by the emission model. For the comparison the absolute emission values are divided by the fuel consumption (which leads to the unit “grams emission per kg fuel”) to compensate for the different sizes of the considered vehicles. Due to this approach the comparison of the absolute emission level is afflicted with an uncertainty of about ±10%, due to possible deviations in measured and simulated fuel consumption. A direct comparison of measured and simulated fuel consumption (and the emission of CO₂) requires detailed vehicle specifications and driving cycles and can therefore not be gained by this approach.

Interpreting the results of the comparison it has to be kept in mind, that the number of measurements which the emission model is based on, is much larger than the number of measurements, which have not been included and are shown in this chapter. The simulation values only represent average emission behavior (which is relevant for the average emission level), and can not indicate the possible range of emissions for single vehicles, especially when several boundary conditions (like driving cycle, ambient conditions …) are not known in detail.

As the discussed measurements contain primarily EURO 1 and EURO 2 vehicles (and only one vehicle registered before EURO 1), only these two engine certification levels are discussed in detail.

The covered ranges of specific NOₓ emissions are shown in Figure 111 (measurements) and Figure 112 (emission model). Both, measurement and simulation, show almost equal NOₓ level for EURO 1 and EURO 2 vehicles. The simulation results meet the average measured values of 30 to 40 g NOₓ per kilogram fuel quite well. Only the increase of NOₓ [g/kg fuel] at low average speed is not predicted by the model.

![Figure 111: Specific NOₓ Emissions [g/kg fuel] for all measurements not included in model](image)

29 Measurements with CNG and Biodiesel have been not included in the comparison. The simulation results used are emission factors for comparable vehicles with 50% loading and standard traffic situations with no road gradient.

30 This effect has also not been observed at the vehicle measurements appropriate for direct validation of the emission model. Thus the effect may be a result of the different vehicle sample tested in different cycles and speed ranges.
Figure 112: Simulated Specific NO\textsubscript{X} Emissions [g/kg fuel]

The comparison for PM emission is shown in Figure 113 and Figure 114. The average PM emission level for EURO 1 vehicles is approximately 1.5 g PM per kg fuel both for measurement and simulation. A rather high deviation occurs for the average PM emission level for EURO 2 engines: the model prediction of 0.7 g PM per kg fuel is clearly lower than the average measured value of 1 g PM per kg fuel.

Figure 113: Specific PM Emissions [g/kg fuel] for all measurements not included in model (zero emission values indicate, that no gravimetric PM value is available)
Figure 114: Simulated Specific PM Emissions [g/kg fuel]

The comparison between results of measurements not included in the emission model and the simulation results for HC emissions is shown in Figure 115 and Figure 116. The average emission levels of measurement and simulation match very well, both for EURO 1 and EURO 2 vehicles. Also the increase of specific emissions with decreasing average vehicle speed shows good conformity. The specific HC emission values of less than 0.5 g HC per kg fuel belong to on-road measurements with one single vehicle (EURO 2).

Figure 115: Specific HC Emissions [g/kg fuel] for all measurements not included in model
Figure 116: Simulated Specific HC Emissions [g/kg fuel]

Figure 117 and Figure 118 give the results for CO emissions. Again a good conformity between measured and simulated emission levels can be found. The CO emission values are both for EURO 1 and EURO 2 vehicles in a range of 5 g CO per kg fuel at high average cycle speeds up to 10 g CO per kg fuel at low for slow driving cycles.

Figure 117: Specific CO Emissions [g/kg fuel] for all measurements not included in model
Figure 118: Simulated Specific CO Emissions [g/kg fuel]
APPENDIX III:

TRANSIENT EFFECTS ON THE ENGINE EMISSION LEVELS

As described in the main text of the report, the models for predicting fuel consumption and emission from heavy-duty engines should consist of two parts:

a) the engine calculations based on steady state engine maps derived from stationary measurements. The method used is often referred to as “Quasi Stationary” (QS), which means that transients are considered as a chain of stationary load points. The engine characteristics at this load points are given by stationary maps for fuel consumption and emissions.

b) A simulation of effects of transient load changes of the engine on the emission levels

The work described in this appendix was performed by Rolf Egnell and was financed by Sweden.

1. COMBUSTION AND EMISSION FORMATION IN DIESEL ENGINES

After a short ignition delay the energy release starts with rich premixed burning involving a small portion of the totally supplied fuel. This type of burning is replaced by diffusive type combustion, which according the latest findings, is continuously proceeded by rich premixed combustion. Large amounts of soot particles and CO are formed due to this rich combustion. Some of these species are oxidized in the thin close to stoichiometric diffusive flame, but the dominating portion is consumed during reactions involving the access air due to large scale mixing during the expansion stroke. NOx is formed at the lean side of diffusive flame. In opposite to the soot and CO case the NOx reactions are frozen early during the expansion stroke and not affected by the dilution by access air.

Two sources of hydrocarbon emissions are known. One is fuel dripping off the fuel nozzle after the end of injection. The other is fuel mixed with air until the mixture is so lean that it would not be ignited (over-leaning).

2. OBSERVED EFFECTS OF CHANGES OF BOUNDARY CONDITIONS

The objective of looking closely into the combustion process is to determine how changes of the boundary conditions, due to rapid load and speed changes, will impact emission formation and fuel consumption. It is found that changes of the air/fuel ratio due to the dynamics of the turbocharger are the likely reason for deviation on CO, HC and PM emissions. Thus, in order to use static data to calculate dynamic emissions, some kind of model to correct the QS data for the transient behavior of the turbocharger has to be included.

One way of quantifying the transient effects is to compare the QS calculated fuel consumption and emissions with the measured. In Figure 1 below the ratios of calculated and measured data are shown for a EURO3 heavy duty engine in 26 test cycles. As can be seen in Figure 19 quasi-stationary calculations, without correction for dynamic effects, give good results for fuel consumption and NOx emissions. However, CO and PM emissions are underestimated and HC overestimated. Thus, it is concluded that a dynamic correction is necessary for this substances. Although PM emissions are of greater importance, the transient effects of CO were studied. One reason for that was that on line measurements, necessary for model development, was not available for PM. Another reason was that CO and PM show similar transient behavior as can be seen in Figure 1. The black curve represent PM and the lilac CO.
3. MECHANISTIC APPROACH FOR TRANSIENT CORRECTION

By comparing the lambda values from static and dynamic load conditions, support is found for the idea that the dynamics of the turbocharger and air supply is one of the major reasons for changes of the combustion boundary conditions during fast speed and load changes.

The basic ideas of the mechanistic approach are:

1. The relations between lambda and CO (and PM) emissions found at steady state measurements are also valid at transient conditions.
2. The lambda during a transient could be found by assuming the air supplied at a given time is represented by the “static” air flow some (delay) time earlier. The fuel flow at the given time is the fuel flow found in the fuel flow map.
3. The “static” CO emission at the time step in question is corrected by the ratio of CO emissions at the “dynamic” lambda and the “static” lambda using the relation found in sentence (1) above.

An inverse model was developed using both calculated and measured CO emissions to determine what the delay time should be at every time step. The relation between the determined delay time and other parameters like power, torque, speed, fuel flow, static CO flow, static lambda and their derivatives and relative derivatives at the time step in question and at earlier time steps was studied by using non linear regression analysis.

In the process of identifying the delay times it was found that the extrapolation capability of the used software was limited. Many transients started at loads points were no measured input.
for static map generation was available, resulting in missing data for the air flow. Thus, the lagging air flow at a load points within the available map could not be determined. The error the mechanistic approach was within +/- 20%. This error was, to a great extent, caused by the limitation in the number of time steps in which the CO emissions could be corrected due to the missing data of the lagging air flow.

Although the mechanistic model was promising and could be refined further by improvements in the extrapolation routines, it was concluded that the model was too complicated and needed detailed information of the engine in question. Thus, other approaches were studied to find a transient correction model suited for COST 346.

4. STEP WISE CORRECTION WITH TUNING PARAMETERS

This method resembles the mechanistic approach by correcting the “static” CO emission at every time step during the calculation. The main difference is, however, that the correction factor is constant and found by comparing calculated and measured accumulated emissions. Thus the method is purely empirical and has no physical background. The method consists of:

1. Identification of transients by defining a threshold derivative for the “static” fuel flow. Of course any parameter could be used which derivative reflects a transient. The fuel flow was used as it has the closest relation to lambda.
2. Applying a constant correction factor on calculated CO emissions at transient conditions defined by the threshold.
3. Tuning the threshold fuel flow derivative and the correction factor for a number of measured cycles and using the corresponding algorithm on the driving cycle to study.

By tuning the correction model for only one test cycle the errors for the remaining 25 cycles were within +/- 20%. This is as good results as for the mechanistic approach at present state of development and the method is easier to apply.

5. CASE WISE CORRECTION

This method is related to the one presented above. The difference is that the correction is performed on the accumulated result of a calculated cycle. It was found the correction factor for the calculated mass of CO emissions related very well to the frequency of transients defined by a threshold derivative for the “static” fuel flow. The relation was further improved by using the inverse of the mean power of the cycle in question. The philosophy behind adding this factor is that the freedom of load changes, and thus the need for correction, increases when the mean power is lowered.

By fitting the threshold fuel flow derivative and the other tuning parameters in the derived expression for one cycle the error for the remaining 25 cycles was within +/- 20%.

The case wise correction method could be applied on QS PM data as no on line measurements is needed when tuning the model.

6. DISCUSSION

The main reason for the differences between QS calculated and measured transient emissions is the behavior of the turbocharger. Due to this behavior the air flow is lagging the fuel flow resulting in richer air/fuel mixture during load increases and leaner mixtures when the load is reduced. The effect of the turbo lag is reduced in modern diesel engines, by monitoring the boost pressure and limiting the fuel supply when the pressure is below a threshold value. This
compensate, to a certain extent, the effect of turbo lag, but also means that the torque found in
the static maps is not always available. This is something to consider when modeling
vehicles.

The need for transient correction is depending on the degree of transience of the driving cycle
in question and the degree of turbo charging of the engine. The performance of a naturally
aspirated engine and an engine with low boost is probably less sensitive to transient effects
than a highly supercharged engine. Thus in order to generalize methods for transient
correction the degree of super charging has to be accounted for.

When it comes to developing transient correction models for different classes of diesel
engines, i.e. BMEP classes, the mechanistic approach is probably superior to the more
statistical Black-Box type models relying solely on tuning and fitting. A mechanistic or semi
mechanistic (Gray-Box) model is probably needed to cope with the transient effects of the
EGR and exhaust after treatment systems that are expected for Euro.

In this work, which is based on two diesel engines, it is found that fuel consumption and NOx
emissions are fairly well predicted by a QS model. However, if the goal is to improve the
accuracy of prediction further is necessary to develop some kind of correction model that
most likely is mechanistic. The need for such a model probably increases for highly
supercharged diesel engines and Euro5 engines.

7. CONCLUSIONS
   a. Fuel consumption and NOx emissions are well predicted by using static measure-ments,
      i.e. QS calculations. It is likely that more heavily boosted engines and engines with EGR
      and exhaust after treatment need more sophisticated models.
   b. However, in this project it has not been possible to develop more sophisticated
      mechanistic models due to lack of detailed engine data and limitations in the
      extrapolation capability of the soft ware used.
   c. Case wise correction is probably adequate for the present needs in COST 346, but these
      models need more tuning parameters than a mechanistic model. The Case wise correction
      method could be used for PM.
   d. The generality of the models for other engines is not known.
   e. With the correction models developed so far it is possible to reach an accuracy of at least
      +/- 20% for the CO emissions.
APPENDIX IV:

DEFINITION OF “ENGINE POWER”

This chapter aims to clarify how in COST346 (working group A) the concept engine power is defined. For the members this working group dealing with modelling of real world emissions it is essential that the meaning of the word engine power is well defined. The model makers have to know the boundary conditions regarding the engine data generated at the measuring laboratories.

The basis for the definition of engine power is the European Commission Directive 80/1269/EEC regarding engine power of motor vehicles as last amended by Directive 1999/99/EC. Section 5 in Annex 1, “TEST FOR MEASURING NET ENGINE POWER”, includes the “Table 1” defining the auxiliary equipment to be included for the test to determine “net engine power”.

The basic principle for the definition is that the auxiliary equipment necessary for the engine operation in the intended application should be installed on the test bench during the test, as far as possible in the same position as at the intended application. However, accessories mounted on the engine, only necessary for the operation of the vehicle should be removed during test. Some examples of such accessories are compressors for brakes and suspension, pump for power steering and air-conditioning system. Where such accessories cannot be removed, their power absorption has to be determined and added to the measured engine power.

Table 1 in the Directive 80/1269/EEC, Annex 1, includes a list where the most important parts of the auxiliary equipment necessary for the engine operation are:

- Intake air equipment
- Exhaust equipment
- Fuel injection equipment
- Cooling equipment
- Electrical equipment
- Supercharging equipment
- Anti-pollution device

In principal, all components of these equipments should be fitted for power test and standard production equipments should be used. However, at the end of the table there are a number of footnotes that may be of vital importance. For example, regarding intake and exhaust systems, test cell equipment may be conditionally used for four-stroke diesel engines. Liquid-cooled engines may use the engine radiator or an external circuit for cooling. Also regarding the cooling system, footnote 6 is important:

“Where a disconnectable or progressive fan or blower is incorporated, the test shall be made with the disconnectable fan (or blower) disconnected or with the progressive fan or blower running on maximum slip”.
This means that if the engine in a specific application uses a fixed (locked) fan, then it should be included during the test. But if the fan is disconnectable or progressive depending on the cooling requirement and usually controlled by the temperature, then the fan should be excluded if disconnectable or running on maximum slip if progressive. Most fans for heavy-duty road trucks and busses are nowadays of the progressive thermo-controlled type. Light-duty vehicles usually use disconnectable thermo-controlled fans.

So according to the type-approval, if a fixed fan is exchanged to a disconnectable in a specific application, the declared maximum power of an engine will be significantly higher, independent of whether the fan consumes power at engine full load or not.

Often, during the power test or the emission test at the test bench, the fan and intercooler are the same as those used in the vehicle application. At the test event the progressive fan is usually locked in a fixed mode. By using the characteristics of the fan together with the belt gear ratio, it is possible to calculate the discrepancy between the power adsorbed by the fan running in fixed mode and the power adsorbed running with maximum slip for each engine speed. This discrepancy is then added to the measured power at the crankshaft.

Section 1.2, Annex III, Appendix 1 in Directive 1999/96/EC (emissions) describes how to correct for the auxiliaries in connection with the dynamometer setting at an ESC test. The same principle is also applied to the correction of the ETC test. Also sections 6 to 8, Annex II, Appendix 1 in the same Directive give valuable information regarding engine-driven equipment during emission tests (in the table in section 8.2 please note the misprint under P(a); the row with zero figures apply to “if fitted” instead of “if not fitted”).

According to the Directive 80/1269/EEC there is a correction of the power measurement to be made if the test is not performed at reference atmospheric conditions. This kind of correction should though not be done at emission tests (Directive 88/77/EEC), but on the other hand there are restrictions instead regarding the maximum deviation from standard atmospheric conditions.

Consequently, to all vehicle simulation models calculating the mechanical power needed for propulsion of the vehicle, the power consumption for a number of auxiliaries has to be added to get the correct engine power requirement. Examples of such power-consuming auxiliaries on the vehicle are:

- compressor for brakes
- compressor for suspension
- pump for power steering
- compressor for air-conditioning system
- alternator (electric power exceeding the part necessary for operation of the engine)
- cooling fan (corresponds for a progressive fan to the consumption exceeding the conditions for maximum slip)

All of these items consume power not at a fixed level but at an interval going from the mechanical losses at zero load to their full load conditions. Full load conditions may correspond to frequent use of the brakes for vehicle and trailer in case of a compressor for brakes. Full load may for the air-conditioning compressor correspond to hot climate usage of the vehicle. For most equipment the actual power consumption at full load conditions is also engine speed dependent. The fan power curve is typically depending on the speed by a power of 3 (speed $^3$).
In the following list, approximate maximum power consumption (corresponding to engine rated speed) for some standard items are given for heavy-duty trucks and busses with gross vehicle weights exceeding 15 tons. For all belt driven equipment transmission losses are in the region 10% of the transferred power.

**Table 51:** Power consumption values (in Kilowatt) for standard auxiliary equipment used in heavy-duty trucks and busses with gross vehicle weights exceeding 15 tons

<table>
<thead>
<tr>
<th>Auxiliary equipment</th>
<th>No load power consumption</th>
<th>Medium case Nominal power</th>
<th>Maximum case Nominal power</th>
</tr>
</thead>
<tbody>
<tr>
<td>cooling fan trucks</td>
<td>0,1 kW</td>
<td>5 kW</td>
<td>15 kW</td>
</tr>
<tr>
<td>cooling fan busses</td>
<td>0,1 kW</td>
<td>5 kW</td>
<td>15 kW</td>
</tr>
<tr>
<td>air compressor trucks</td>
<td>0,3 kW</td>
<td>2 kW</td>
<td>4 kW</td>
</tr>
<tr>
<td>air compressor/-ors busses</td>
<td>0,3 kW</td>
<td>2 kW</td>
<td>8 kW</td>
</tr>
<tr>
<td>power steering pump trucks and busses</td>
<td>0 kW</td>
<td>1 kW</td>
<td>1 kW</td>
</tr>
<tr>
<td>AC compressor trucks</td>
<td>0,2 kW</td>
<td>6 kW</td>
<td>10 kW /1900 rpm 6 kW / 800 rpm</td>
</tr>
<tr>
<td>AC compressor/-ors busses</td>
<td>0,2 kW</td>
<td>21 kW /1900 rpm 12 kW / 800 rpm</td>
<td>30 kW</td>
</tr>
<tr>
<td>alternator trucks</td>
<td>0,2 kW</td>
<td>3 kW</td>
<td>5 kW</td>
</tr>
<tr>
<td>alternator/-ors busses</td>
<td>0,2/0,4 kW</td>
<td>6 kW</td>
<td>15 kW</td>
</tr>
</tbody>
</table>
APPENDIX V:

TESTING DIFFERENCES IN ENVIRONMENTAL PERFORMANCE BY VARIOUS MANUFACTURERS AND BETWEEN GENERATIONS OF HDV ENGINES

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1. **INTRODUCTION**

At the WG A meeting, held in Heidelberg on October 16th, 2003, it was suggested that some subgroups within the database of emission measurements on heavy duty vehicles (HDV) engines show lower emission level than others. [1] More specifically, engines from Swedish manufacturers (Volvo and Scania) were thought to perform better on environmental aspects than non-Swedish ones.

One could debate this hypothesis; since all manufacturers of HDV engines must comply with the same legislative requirements, one could argue that all these manufacturers would not do more than the strict minimum to achieve this. However, there might be a difference in fuel consumption, as some manufacturers succeed better in minimising the increase in fuel consumption while complying with the emission standard than others. The difference in fuel consumption is of the order of magnitude of 1 to 2%. [2]

During WG A meeting, it was decided to carry out statistical tests in order to verify in a sound way whether the hypothesis, that there is a difference in emission and fuel consumption between the country of manufacture of HDV engines, is correct or not.

This document also verifies whether the difference in fuel consumption and emission between the various generations of HDV engines – i.e. the environmental legislation the engine has to comply with – is significant or not, as the same data and methodology allows to do that.

This text first describes which data are available, then which methodology is used and tests at the end the stated hypothesis.

2. **AVAILABLE DATA**

In total 83 engines have been subjected to emission measurements. They can be classified according to different generations (see Table 52, and to country of manufacturer and to country of manufacturer see Table 53). The majority of the engines in this database are made by a German manufacturer. About one in five engines is Swedish.

**Table 52:** Classification of the engines according to different generation

<table>
<thead>
<tr>
<th>Emission Level Code</th>
<th>Emission Level</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>Pre-Euro1 (Eastern Germany); Pre-FAV</td>
<td>7</td>
</tr>
<tr>
<td>1986</td>
<td>Pre-Euro1 1986</td>
<td>18</td>
</tr>
<tr>
<td>1988</td>
<td>Pre-Euro1 1988</td>
<td>2</td>
</tr>
<tr>
<td>1990</td>
<td>Pre-Euro1 1990</td>
<td>11</td>
</tr>
<tr>
<td>1992</td>
<td>FAV 2-1</td>
<td>3</td>
</tr>
<tr>
<td>1994</td>
<td>Euro1</td>
<td>12</td>
</tr>
<tr>
<td>1998</td>
<td>Euro2</td>
<td>18</td>
</tr>
<tr>
<td>2001</td>
<td>Euro3</td>
<td>12</td>
</tr>
</tbody>
</table>
Table 53: Classification of the engines according to country of manufacturer

<table>
<thead>
<tr>
<th>Country</th>
<th>Trade mark</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH</td>
<td>Saurer</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>DB-OM / IFA / MAN / MB OM / Mercedes OM / RABA MAN</td>
<td>50</td>
</tr>
<tr>
<td>F</td>
<td>Renault</td>
<td>1</td>
</tr>
<tr>
<td>H</td>
<td>RABA</td>
<td>3</td>
</tr>
<tr>
<td>I</td>
<td>Fiat / IVECO</td>
<td>4</td>
</tr>
<tr>
<td>NL</td>
<td>DAF</td>
<td>5</td>
</tr>
<tr>
<td>S</td>
<td>Scania / Volvo</td>
<td>16</td>
</tr>
<tr>
<td>?</td>
<td>KHD</td>
<td>3</td>
</tr>
</tbody>
</table>

The emissions have been measured according to different type approval test. Table 54 shows how many engines have been submitted to what test. The latter is the weighted average emission value over the complete engine emission map. The methodology is similar to the weighting for the ESC but at least 26 measured points are included, of which the off-cycle emissions. These emissions, together with the emissions measured according to the ETC type approval test, are considered as being more representative for the real world emissions.

Table 54: Available measurements according to type approval test

<table>
<thead>
<tr>
<th>Test cycle</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECE R49</td>
<td>63</td>
</tr>
<tr>
<td>ESC</td>
<td>30</td>
</tr>
<tr>
<td>ETC</td>
<td>19</td>
</tr>
<tr>
<td>Weighted average map emissions from 29 points map</td>
<td>71</td>
</tr>
</tbody>
</table>

Annex I shows more details of the tested engines and the availability of the emission measurements. Of about 85% of all engines, the emissions have been derived from a 29 points engine map, whereas about one in four engines has been tested according to the ETC type approval test, albeit that almost all the youngest engines (Euro1 and later) have been tested by both. These tests provide an average fuel consumption, and average emission factors for the pollutants CO, NOx, HC and PM.

It was decided to restrict testing the hypothesis whether there is a difference in environmental performance by country of manufacturer to the weighted average map emission from the 29 points engine map, since most of all the engines have been measured according to this type approval test.

3. METHODOLOGY

Two methodologies were applied in order to test whether there is a difference in environmental performance by country of manufacturer, being:

- The two-population test of hypothesis for means,
- Cluster analysis.
3.1. Two-population test of hypothesis for means

This test was applied to Euro1, -2 and -3 engines only, since the sample size needs to be sufficiently large.

In this test, engines of a particular generation were separated into two groups according to a particular country of manufacturer, for instance German Euro1 and non-German Euro1 engines.

Of both subgroups, it was tested for each individual pollutant whether the mean emission factor differs. To do that, the number of measurements, the mean value and the standard deviation needs to be calculated first:

<table>
<thead>
<tr>
<th>Subgroup</th>
<th>Number</th>
<th>Mean</th>
<th>Variances</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(n_1)</td>
<td>(m_1)</td>
<td>(s_1^2)</td>
</tr>
<tr>
<td>2</td>
<td>(n_2)</td>
<td>(m_2)</td>
<td>(s_2^2)</td>
</tr>
</tbody>
</table>

A precondition for the test to be used, is that the variances should not differ significantly from each other.

This is tested via a F-test, with the test value being: \(s_1^2/s_2^2\) (with \(s_1 \geq s_2\)), which is compared to a tabled value \(F(n_1-1 ; n_2-1 ; \text{probability}/2)\). (As the F-test is a two-tailed test, the tabled probability should be half the true one.)

If the variances do not differ significantly from each other, it can then be tested whether there is a significant difference between the mean values.

Hereto, the pooled variance needs to be calculated first:

\[
sp^2 = \frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1-1 + n_2-1}
\]

The test value for the difference between the mean values of the two populations is:

\[
t = \frac{m_1 - m_2}{sp \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}},
\]

to be compared with the tabled t-value \((n_1-1+ n_2 -1 ; \text{probability})\).

If \(-t\text{-table} < t < t\text{-table}\), then \(m_1 = m_2\).

Testing whether there is a significant difference between the mean values of both the subgroups was carried out in each of the cases, even when the variances seem to differ significantly. In the latter case, the results of the t-test is put between brackets.
3.2. Cluster analysis

The previous test is only carried out on Euro1 engines and later and verifying whether there is a difference between mean emission factors between two subgroups is done for each pollutant individually.

In the cluster analysis of the emissions of the engines, all pollutants are taken into account simultaneously. Also all 71 engines, for which emission data is available according to the weighted average map emissions from 29 points map, are included in the test.

In this analysis, each engine is considered as a point in a five-dimensional space (characterised by the fuel consumption and an emission factor for CO, HC, NO\textsubscript{x} and PM). The emission factors are normalized first for each of the pollutants in order to eliminate the difference in order of magnitude between the values of the different pollutants. This means that the emission values are divided by the average emission factor for all engines.

Then, the two nearest points, searched by comparing the Euclidean distances between each of the points, are grouped and replaced by their average. Then again, the two nearest points are looked for and grouped. This step is repeated until a specified number of groups is formed. The number of groups chosen in this analysis is 20, as this is the number of generation – country of manufacturer combinations for the 71 engines.

If each group represents the engines of the specific combination generation – country of manufacturer, then it can be concluded that there is a significant difference between the generations and the countries of manufacturers.


4.1. Two-population test of hypothesis

EURO1 ENGINES

Within the 71 engines, there are 11 approved as Euro1 engines, of which 8 originating from a German manufacturer and the remainder of Swedish ones. From Table 55 can be seen that the Swedish engines are more powerful than the German ones.

Figure 120 compares the normalized fuel consumption and emissions of these engines. Also the standard deviation is indicated.

From Figure 120 can be seen that there is a good overlap between the interval of confidence of the fuel consumption, HC and PM emission. For NO\textsubscript{x} and CO, there is a possibility that the mean value of the Swedish engines does not fall within the interval of confidence of the German engines. The fuel consumption of the Swedish engines is a little less than that of the German engines.
Figure 120: Comparison between the normalized fuel consumption and emission of Euro1 engines of different manufacturers

In Table 55, it is tested according to the methodology, described in 3.1 whether both subgroup differ significantly.

Table 55: Two-population test on German and non-German (Swedish) Euro1 engines

<table>
<thead>
<tr>
<th>Characteristics engines: number, rated power [kW], fuel consumption and emissions [g/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
</tr>
<tr>
<td>--------</td>
</tr>
<tr>
<td>German</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Non-German</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Testing whether standard deviations are equal

<table>
<thead>
<tr>
<th>T-value</th>
<th>Test value</th>
<th>FC</th>
<th>NOx</th>
<th>CO</th>
<th>HC</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2.0</td>
<td>12.8</td>
<td>22.7</td>
<td>4.2</td>
<td>142685.8</td>
</tr>
<tr>
<td>Result</td>
<td>TRUE</td>
<td>TRUE</td>
<td>TRUE</td>
<td>TRUE</td>
<td>TRUE</td>
<td></td>
</tr>
</tbody>
</table>

Testing whether mean values are equal.

<table>
<thead>
<tr>
<th>T-value</th>
<th>Test value</th>
<th>FC</th>
<th>NOx</th>
<th>CO</th>
<th>HC</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.75</td>
<td>-2.42</td>
<td>-1.44</td>
<td>0.61</td>
<td>(0.03)</td>
</tr>
<tr>
<td>Result</td>
<td>TRUE</td>
<td>FALSE</td>
<td>TRUE</td>
<td>TRUE</td>
<td></td>
<td>(TRUE)</td>
</tr>
</tbody>
</table>

From Table 55, it can be concluded that no significant difference is found between German and non-German Euro1 engines concerning the emission factor of CO, HC and PM, although not all conditions were met to test the difference properly for the latter. The reference T-value was slightly surpassed for the NOx emission factor.

Also the fuel consumption of both groups of engines does not differ significantly. With the values, given in Table 55, one can calculate that the difference in fuel consumption must be at least 8 to 9% before this difference is statistically significant. This is far higher than the fuel economy a manufacturer would attain when optimizing the design of his engines. A gain in fuel consumption of 1% is already quite an achievement.
Hence, it is concluded that, except for NO\textsubscript{x} emissions, there is no significant difference between German and Swedish Euro1 engines. It cannot be tested statistically that the Swedish engines are less fuel consuming than the German ones.

**Euro2 Engines**

16 of the 71 engines are Euro2 ones; of which 8 German, 1 Hungarian, 3 Italian, 1 Dutch and 3 Swedish.

Figure 121 indicates that Hungarian engines emit less NO\textsubscript{x} than others, but more CO, HC and PM. However, since there is only one engine in the dataset, it cannot be statistical tested whether the Hungarian engine performs significantly different than other engines. The same remark applies for the Dutch engine.

The average fuel consumption of the Dutch and Swedish engines is lower than that of the other engines, but the added standard deviations suggest it cannot be tested statistically.

![Euro2 engines: comparison emissions from 29 pt map](image)

**Figure 121:** Comparison between the normalized fuel consumption and emission of Euro2 engines of different manufacturers

The two-population test of hypothesis for means is carried out for Germans, Italian and Swedish engines, see respectively Table 56, Table 57 and Table 58.

These tables show that the Italian engines have a lower rated power than the others and the Swedish engines a higher one.
Table 56: Two-population test on German and non-German Euro2 engines

| Characteristics engines: number, rated power [kW], fuel consumption and emissions [g/kWh] |
|---|---|---|---|---|---|--- |
| Number | Power | FC | NOx | CO | HC | PM |
| German 8 | Mean 228 | 210 | 8.07 | 0.658 | 0.242 | 0.0973 |
| St. dev. 50 | 10 | 1.38 | 0.175 | 0.079 | 0.0231 |
| Non-German 8 | Mean 243 | 208 | 6.62 | 0.821 | 0.224 | 0.1259 |
| St. dev. 73 | 7 | 0.70 | 0.306 | 0.041 | 0.0162 |

Testing whether standard deviations are equal

<table>
<thead>
<tr>
<th>F-value</th>
<th>Test value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>1.9</td>
<td>TRUE</td>
</tr>
<tr>
<td>3.9</td>
<td>3.1</td>
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</tr>
<tr>
<td>3.8</td>
<td>2.0</td>
<td>TRUE</td>
</tr>
</tbody>
</table>

Testing whether mean values are equal.

<table>
<thead>
<tr>
<th>T-value</th>
<th>Test value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.14</td>
<td>0.44</td>
<td>TRUE</td>
</tr>
<tr>
<td>2.66</td>
<td>-1.30</td>
<td>TRUE</td>
</tr>
<tr>
<td>0.56</td>
<td>-2.87</td>
<td>FALSE</td>
</tr>
</tbody>
</table>

Table 57: Two-population test on Italian and non-Italian Euro2 engines

| Characteristics engines: number, rated power [kW], fuel consumption and emissions [g/kWh] |
|---|---|---|---|---|---|--- |
| Number | Power | FC | NOx | CO | HC | PM |
| Italian 3 | Mean 155 | 209 | 7.03 | 0.637 | 0.201 | 0.1281 |
| St. dev. 21 | 8 | 0.45 | 0.133 | 0.014 | 0.0007 |
| Non-Italian 13 | Mean 253 | 209 | 7.42 | 0.763 | 0.240 | 0.1078 |
| St. dev. 55 | 9 | 1.42 | 0.274 | 0.066 | 0.0256 |

Testing whether standard deviations are equal

<table>
<thead>
<tr>
<th>F-value</th>
<th>Test value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>1.2</td>
<td>TRUE</td>
</tr>
<tr>
<td>10.1</td>
<td>4.3</td>
<td>TRUE</td>
</tr>
<tr>
<td>21.1</td>
<td>1450.0</td>
<td>FALSE</td>
</tr>
</tbody>
</table>

Testing whether mean values are equal.

<table>
<thead>
<tr>
<th>T-value</th>
<th>Test value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.14</td>
<td>0.09</td>
<td>(TRUE)</td>
</tr>
<tr>
<td>(-0.46)</td>
<td>(-0.76)</td>
<td>(TRUE)</td>
</tr>
<tr>
<td>(-0.98)</td>
<td>(1.34)</td>
<td>(TRUE)</td>
</tr>
</tbody>
</table>

Table 58: Two-population test on Swedish and non-Swedish Euro2 engines

| Characteristics engines: number, rated power [kW], fuel consumption and emissions [g/kWh] |
|---|---|---|---|---|---|--- |
| Number | Power | FC | NOx | CO | HC | PM |
| Swedish 3 | Mean 286 | 204 | 6.18 | 0.973 | 0.220 | 0.1251 |
| St. dev. 8 | 4 | 0.23 | 0.394 | 0.042 | 0.0254 |
| Non-Swedish 13 | Mean 223 | 210 | 7.61 | 0.685 | 0.236 | 0.1085 |
| St. dev. 65 | 9 | 1.29 | 0.197 | 0.066 | 0.0240 |

Testing whether standard deviations are equal

<table>
<thead>
<tr>
<th>F-value</th>
<th>Test value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>4.7</td>
<td>TRUE</td>
</tr>
<tr>
<td>31.5</td>
<td>4.0</td>
<td>TRUE</td>
</tr>
<tr>
<td>2.4</td>
<td>1.1</td>
<td>TRUE</td>
</tr>
</tbody>
</table>

Testing whether mean values are equal.

<table>
<thead>
<tr>
<th>T-value</th>
<th>Test value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.14</td>
<td>-1.16</td>
<td>TRUE</td>
</tr>
<tr>
<td>(-1.86)</td>
<td>1.91</td>
<td>TRUE</td>
</tr>
<tr>
<td>-0.40</td>
<td>1.08</td>
<td>TRUE</td>
</tr>
</tbody>
</table>

From these tables, one can conclude that the Italian and Swedish engines do not show significant differences with the others, although not all conditions were met to perform the test (significantly difference between variances for NOx, HC and PM). Between German and non-German engines a significant difference between NOx and PM emission was found.

No conclusion can be drawn on the Hungarian and Dutch one, as the statistical test could not be applied to these. However, from Figure 121, one could conclude that the Hungarian engine does not show significant differences with the Swedish ones and the Dutch engine not with the German ones.
EURO3 ENGINES

The list of engines contains 12 Euro3 engines, which distributes as following over the different countries of manufacture: 2 German, 2 Hungarian, 1 Italian, 3 Dutch and 4 Swedish.

Figure 122 compares these engines according to normalized fuel consumption and emissions.

![Euro3 engines: comparison emissions from 29 pt map](image-url)

**Figure 122:** Comparison between the normalized fuel consumption and emission of Euro3 engines of different manufacturers

Except for the fact that the Hungarian engines seem to show a higher CO emission, no significant differences at a first glance can be observed between the various countries of manufacture.

This is tested statistically in Table 59, Table 60, Table 61 and Table 62.

**Table 59:** Two-population test on German and non-German Euro3 engines

<p>| Characteristics engines: number, rated power [kW], fuel consumption and emissions [g/kWh] |
|---------------------------------|---|---|---|---|---|</p>
<table>
<thead>
<tr>
<th>Number</th>
<th>Power</th>
<th>FC</th>
<th>NOx</th>
<th>CO</th>
<th>HC</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>German 2</td>
<td>Mean 211</td>
<td>217</td>
<td>5.42</td>
<td>0.585</td>
<td>0.162</td>
<td>0.0933</td>
</tr>
<tr>
<td>St. dev. 69</td>
<td>9</td>
<td>0.55</td>
<td>0.155</td>
<td>0.044</td>
<td>0.0292</td>
<td></td>
</tr>
<tr>
<td>Non-German 10</td>
<td>Mean 274</td>
<td>214</td>
<td>5.34</td>
<td>0.832</td>
<td>0.227</td>
<td>0.0924</td>
</tr>
<tr>
<td>St. dev. 54</td>
<td>6</td>
<td>0.53</td>
<td>0.225</td>
<td>0.095</td>
<td>0.0283</td>
<td></td>
</tr>
</tbody>
</table>

**Testing whether standard deviations are equal**

<table>
<thead>
<tr>
<th>F-value</th>
<th>Test value</th>
<th>2.0</th>
<th>1.1</th>
<th>2.1</th>
<th>4.7</th>
<th>1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Result</td>
<td>TRUE</td>
<td>TRUE</td>
<td>TRUE</td>
<td>TRUE</td>
<td>TRUE</td>
<td></td>
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</tbody>
</table>

**Testing whether mean values are equal.**

<table>
<thead>
<tr>
<th>T-value</th>
<th>Test value</th>
<th>0.48</th>
<th>0.20</th>
<th>-1.45</th>
<th>-0.92</th>
<th>0.04</th>
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</thead>
<tbody>
<tr>
<td>Result</td>
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<td>TRUE</td>
<td>TRUE</td>
<td>TRUE</td>
<td>TRUE</td>
<td></td>
</tr>
</tbody>
</table>


Table 60: Two-population test on Hungarian and non-Hungarian Euro3 engines

| Characteristics engines: number, rated power [kW], fuel consumption and emissions [g/kWh] |
|---|---|---|---|---|---|---|
| Number | Power | FC | NOx | CO | HC | PM |
| Hungarian | Mean 208 | 221 | 4.86 | 0.939 | 0.162 | 0.0917 |
| | St. dev. 25 | 0 | 0.47 | 0.113 | 0.024 | 0.0366 |
| Non-Hungarian | Mean 275 | 213 | 5.45 | 0.761 | 0.227 | 0.0927 |
| | St. dev. 57 | 6 | 0.48 | 0.239 | 0.096 | 0.0274 |

Testing whether standard deviations are equal

<table>
<thead>
<tr>
<th>F-value</th>
<th>Test value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.2</td>
<td>892.3</td>
<td>FALSE</td>
</tr>
</tbody>
</table>

Testing whether mean values are equal.

<table>
<thead>
<tr>
<th>T-value</th>
<th>Test value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.23</td>
<td>(1.75)</td>
<td>TRUE</td>
</tr>
</tbody>
</table>

None of the engines of a specific country of manufacture seem to show significant differences with the other ones, except for the fuel consumption, where a significant lower consumption was found for the Dutch engines compared to the other ones.

It should be underlined that in some cases not all conditions to carry out the two-population test of hypothesis for means was met (significant difference between variances for fuel consumption, CO and HC emission).

Table 61: Two-population test on Dutch and non-Dutch Euro3 engines

| Characteristics engines: number, rated power [kW], fuel consumption and emissions [g/kWh] |
|---|---|---|---|---|---|---|
| Number | Power | FC | NOx | CO | HC | PM |
| Dutch | Mean 259 | 208 | 5.80 | 0.888 | 0.281 | 0.0820 |
| | St. dev. 68 | 3 | 0.33 | 0.410 | 0.166 | 0.0191 |
| Non-Dutch | Mean 265 | 217 | 5.20 | 0.758 | 0.195 | 0.0960 |
| | St. dev. 59 | 6 | 0.48 | 0.161 | 0.049 | 0.0294 |

Testing whether standard deviations are equal

<table>
<thead>
<tr>
<th>F-value</th>
<th>Test value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>3.6</td>
<td>TRUE</td>
</tr>
</tbody>
</table>

Testing whether mean values are equal.

<table>
<thead>
<tr>
<th>T-value</th>
<th>Test value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.23</td>
<td>-2.30</td>
<td>FALSE</td>
</tr>
</tbody>
</table>

Table 62: Two-population test on Swedish and non-Swedish Euro3 engines

| Characteristics engines: number, rated power [kW], fuel consumption and emissions [g/kWh] |
|---|---|---|---|---|---|---|
| Number | Power | FC | NOx | CO | HC | PM |
| Swedish | Mean 308 | 214 | 5.16 | 0.784 | 0.224 | 0.1066 |
| | St. dev. 2 | 7 | 0.52 | 0.096 | 0.054 | 0.0337 |
| Non-Swedish | Mean 241 | 214 | 5.45 | 0.794 | 0.213 | 0.0855 |
| | St. dev. 60 | 7 | 0.51 | 0.281 | 0.108 | 0.0223 |

Testing whether standard deviations are equal

<table>
<thead>
<tr>
<th>F-value</th>
<th>Test value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
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<td>5.9</td>
<td>1.0</td>
<td>TRUE</td>
</tr>
</tbody>
</table>

Testing whether mean values are equal.

<table>
<thead>
<tr>
<th>T-value</th>
<th>Test value</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.23</td>
<td>0.03</td>
<td>TRUE</td>
</tr>
</tbody>
</table>
CONCLUSION

Based on the two-population test of hypothesis for means, a significant difference between the NO\textsubscript{x} emission of German and non-German (Swedish) Euro1 engines within the available dataset and between the NO\textsubscript{x} and PM emission of German and non-German Euro2 engines was found.

Also, Dutch Euro3 engines were found to significantly consume less fuel than other Euro3 engines within the available dataset. For the other Euro3 engines and for none of the Euro1 and -2 engines, no evidence of more economical engines was found as the magnitude of the variance was too high.

No significant differences were found for CO and HC emissions.

One should keep in mind that the sample size is very limited and might not be representative for all the HDV engines in use in Europe.

4.2. Cluster analysis

The cluster analysis is carried out with Statistica '99, kernel release 5.5 A, whereas for the two-population test of hypothesis for means a simple spreadsheet is used.

20 groups were composed based on the characteristics of the engines (normalized fuel consumption and emissions) and their mutual distances.

Table 63 shows how many of each combination generation – country of manufacture is found in the respectively clusters.

It can be seen that the clusters mainly consist of engines of the same or neighbouring generation. This means that the generation is a determining factor to make distinction between the different engines. However, engines of the same country of manufacture are spread over different clusters, meaning that the country of manufacture is not a determining factor to make distinction between the different engines.
Table 63: Number of every combination generation-country of manufacture in the clusters found via cluster analysis

<table>
<thead>
<tr>
<th>Type and country</th>
<th>nr cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20</td>
</tr>
<tr>
<td>1980 - D</td>
<td>1</td>
</tr>
<tr>
<td>1986 - D</td>
<td>2 1 6 2</td>
</tr>
<tr>
<td>1986 - S</td>
<td>1 1</td>
</tr>
<tr>
<td>1986 - ?</td>
<td>1 1</td>
</tr>
<tr>
<td>1990 - D</td>
<td>2 1 1 4 2</td>
</tr>
<tr>
<td>1990 - S</td>
<td>1</td>
</tr>
<tr>
<td>1992 - D</td>
<td>1 1</td>
</tr>
<tr>
<td>1992 - S</td>
<td>1</td>
</tr>
<tr>
<td>1994 - D</td>
<td>2 3 1 1 1</td>
</tr>
<tr>
<td>1994 - S</td>
<td>2 1</td>
</tr>
<tr>
<td>1998 - D</td>
<td>2 1 4</td>
</tr>
<tr>
<td>1998 - H</td>
<td>1</td>
</tr>
<tr>
<td>1998 - I</td>
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<tr>
<td>1998 - NL</td>
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</tr>
<tr>
<td>2001 - NL</td>
<td>1</td>
</tr>
<tr>
<td>2001 - S</td>
<td>2</td>
</tr>
<tr>
<td>Sum</td>
<td>5 4 2 9 3 6 2 4 3 3 2 1 7 3 1 4 1 6 4 1 71</td>
</tr>
</tbody>
</table>

5. Statistical Analysis: Difference by Generation

The same data can be used to test with the two-population test of hypothesis for means whether the in- or decrease in fuel consumption and CO, NOx, PM and HC emission as a result of tightening the emission standards is significant or not. Following generations are included in the test:

- Pre Euro1 – 1986 (17 engines),
- Pre Euro1 – 1990 (11 engines),
- Euro1 (11 engines),
- Euro2 (16 engines),
- Euro3 (12 engines).

The other generations (see Table 52) were not included because there were not enough data to carry out the test or the legislation is only applicable to specific countries (as is the case for FAV 2-1).

Figure 123 shows how the fuel consumption and the emissions vary between the selected generations. Also the average rated power is given. The Euro1 engines serve as reference. Of the Euro1 engines, the average absolute values are given in the double lined boxes (fuel consumption, emissions in g/kWh – rated power in kW). For the other engines the average fuel consumption and emissions are compared on a relative basis to the values of the Euro1 engines.
Figure 123: Evolution of the average fuel consumption, NOx, CO, HC and PM emission and rated power of the tested HDV engines.

Figure 123 indicates that there is a decrease in fuel consumption and in CO emission from pre Euro1-1986 to Euro2, whereas the average value of Euro3 engines is higher than Euro2 engines. The HC and PM emission decrease from one to the successive generation. Euro2 NOx emissions seem to be slightly higher than Euro1 ones. Except for Euro1 engines, an increase in rated power from one generation to another can be observed.

The significance of these differences is now statistically tested in Table 64 to Table 67.

- Pre Euro1-1986 versus pre Euro1-1990 engines

Table 64: Two-population test on pre Euro1-1986 and pre Euro1-1990 engines

| Characteristics engines: number, rated power [kW], fuel consumption and emissions [g/kWh] |
|-------------------------------------|-------------------------------|----------------|----------------|----------------|----------------|
| Number                              | Power | FC [g/kWh] | NOx [g/kWh] | CO [g/kWh] | HC [g/kWh] | PM [g/kWh] |
| Pre EU1-1986                        | 17    | 144  | 254   | 11.3   | 3.86        | 1.316        | 0.652        |
| Mean                                |       |       |       |       |             |             |              |
| Pre EU1-1990                        | 11    | 209  | 235   | 11.4   | 1.40        | 0.478        | 0.290        |
| Mean                                |       |       |       |       |             |             |              |
| Testing whether standard deviations are equal |
| F-value                             | 3.5   | Test value | 1.2   | 1.5   | 7.9   | 9.1   | 10.7 |
| Result                              | TRUE  | TRUE    | FALSE | FALSE | FALSE |       |       |
| Testing whether mean values are equal |
| T-value                             | 2.06  | Test value | 2.91  | -0.12 | (4.10)| (3.28)| (3.32)|
| Result                              | FALSE | TRUE    | (FALSE)| (FALSE)| (FALSE)|       |       |

Table 64 indicates that the fuel consumption and CO, HC and PM emissions of the tested pre Euro1-1990 HDV engines are significantly lower than these of the tested pre Euro1-1986 engines. No significant difference between NOx emission is found. Not all conditions were met to carry out this statistical test is a sound way.
• Pre Euro1-1990 versus Euro1 engines

**Table 65:** Two-population test on pre Euro1-1990 and Euro1 engines

| Characteristics engines: number, rated power [kW], fuel consumption and emissions [g/kWh] |
|---|---|---|---|---|---|---|
| Number | Power | FC | NOx | CO | HC | PM |
| Pre EU1-1990 11 | Mean | 209 | 235 | 11.4 | 1.40 | 0.478 | 0.290 |
| St. dev. | 71 | 13 | 2.0 | 1.20 | 0.106 | 0.132 |
| Euro1 11 | Mean | 195 | 214 | 7.2 | 1.24 | 0.407 | 0.250 |
| St. dev. | 61 | 11 | 0.9 | 0.62 | 0.163 | 0.062 |

Testing whether standard deviations are equal

<table>
<thead>
<tr>
<th>F-value</th>
<th>Test value</th>
<th>2.3</th>
<th>14.6</th>
<th>1.2</th>
<th>2.8</th>
<th>3.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Result</td>
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<td>FALSE</td>
<td>TRUE</td>
<td>TRUE</td>
<td>TRUE</td>
<td></td>
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</tbody>
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Testing whether mean values are equal.

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<th>(4.06)</th>
<th>0.58</th>
<th>0.74</th>
<th>1.06</th>
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<td>(FALSE)</td>
<td>TRUE</td>
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<td>TRUE</td>
<td></td>
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The fuel consumption and NOx emission (not all necessary conditions met) decreased at Euro1 engines compared to pre Euro1-1990 engines. No significant difference between CO, HC and PM emissions can be found, see Table 65.

• Euro1 versus Euro2 engines

**Table 66:** Two-population test on Euro1 and Euro2 engines

| Characteristics engines: number, rated power [kW], fuel consumption and emissions [g/kWh] |
|---|---|---|---|---|---|---|
| Number | Power | FC | NOx | CO | HC | PM |
| Euro1 11 | Mean | 195 | 214 | 7.2 | 1.24 | 0.407 | 0.250 |
| St. dev. | 61 | 11 | 0.9 | 0.62 | 0.163 | 0.062 |
| Euro2 16 | Mean | 237 | 209 | 7.3 | 0.74 | 0.233 | 0.112 |
| St. dev. | 63 | 9 | 1.3 | 0.26 | 0.061 | 0.024 |

Testing whether standard deviations are equal

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Testing whether mean values are equal.

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The tested Euro2 engines show significant lower CO, HC and PM emissions (not all necessary conditions for testing met), whereas no significant difference in fuel consumption or NOx emission can be observed, see Table 66.
• Euro2 versus Euro3 engines

**Table 67:** Two-population test on Euro2 and Euro3 engines

| Characteristics engines: number, rated power [kW], fuel consumption and emissions [g/kWh] |
|----------------------------------|---|---|---|---|---|---|
| Number | Power | FC | NO\textsubscript{x} | CO | HC | PM |
| Euro2 | 16 | Mean | 237 | 209 | 7.3 | 0.74 | 0.233 | 0.112 |
| St. dev. | 63 | 9 | 1.3 | 0.26 | 0.061 | 0.024 |
| Euro3 | 12 | Mean | 264 | 214 | 5.35 | 0.79 | 0.216 | 0.093 |
| St. dev. | 58 | 7 | 0.51 | 0.23 | 0.091 | 0.027 |

Testing whether standard deviations are equal

| F-value | 3.3 | Test value | 1.7 | 6.4 | 1.2 | 2.2 | 1.2 |
| Result | TRUE | FALSE | TRUE | TRUE | TRUE |

Testing whether mean values are equal

| T-value | 2.06 | Test value | -1.83 | (5.02) | -0.55 | 0.57 | 1.96 |
| Result | TRUE | (FALSE) | TRUE | TRUE | TRUE |

Only a significant decrease in NO\textsubscript{x} emission between Euro2 and Euro3 engines can be observed in Table 67 (not all necessary conditions for testing met). The increase in fuel consumption and in CO emission is not approved as significantly, nor the increase in HC and PM emission.

• Conclusion

**Table 68:** Summary of the evolution in fuel consumption and emission between the successive generations of HDV engines

<table>
<thead>
<tr>
<th>Generation 1 – 2</th>
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<th>NO\textsubscript{x}</th>
<th>CO</th>
<th>HC</th>
<th>PM</th>
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<td>(↓)</td>
<td>(↓)</td>
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<tr>
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<td>(↓)</td>
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<td>(↓)</td>
<td>(↓)</td>
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<td>Euro2 – Euro3</td>
<td>=</td>
<td>(↓)</td>
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Table 68 summarises the findings of Table 64 to Table 67. An arrow indicates a significant improvement in fuel consumption or emission whereas the equity sign stands for no significant differences between the emission standards.

When the sign is put between brackets, it means that not all conditions were met to carry out the two-population test of hypothesis for means; or in other words, the standard deviation of one subgroup (generation) differs significantly from the other.

As can be seen from Table 68, this corruption of the necessary conditions always occurs when a significant decrease in emission is observed. This should not surprise. As the emission limits gets tighter, it gets harder to respect these. Hence, one might expect that the measured data points converge from one emission standard to the successive one. The decrease in NO\textsubscript{x} emission from Euro2 to Euro3 illustrates this well. The average NO\textsubscript{x} emission of Euro2 engines amount to 7.3 g/kWh – of Euro3 engines 5.4 g/kWh. The standard deviation decreases from 1.3 g/kWh for Euro2 engines to 0.5 g/kWh for Euro3 engines.

The decrease in standard deviation in case the emission standard tightens the emission of one or another pollutant can also be seen on Figure 124. This figure shows the fuel consumption and NO\textsubscript{x}, CO, HC and PM emission of all the tested HDV engines grouped per emission standard (based on the weighted average map emissions from 29 points map). Figure 124 also illustrates what absolute reduction has been achieved by the various emission standards.
Evolution in fuel consumption of HDV engines between the different emission standards

Year of enforcement of emission standard

Evolution in NOx emission of HDV engines between the different emission standards

Year of enforcement of emission standard

Evolution in CO emission of HDV engines between the different emission standards

Year of enforcement of emission standard
Evolution in HC emission of HDV engines between the different emission standards

Evolution in PM emission of HDV engines between the different emission standards

Figure 124: Evolution of the fuel consumption, NO\textsubscript{x}, CO, HC and PM emission of the all tested HDV engines grouped per emission standard.

6. CONCLUSION

Two different tests were carried out to check whether HDV engines of a different country of manufacture perform differently on environmental level. Hereto weighted average map emissions from a 29 points map were available for 71 engines from different generations (pre-Euro1 to Euro3) and trademarks (countries of manufacture). The same data and methodology was also used to test whether to successive emission standards have led to a significant decrease in fuel consumption and emission.

The two-population test of hypothesis for means, carried out on Euro1, -2 and -3 engines, revealed that in some cases significant differences were observed between German and non-German engines: Euro1 German engines show a lower NO\textsubscript{x} emission and Euro2 German engines show a higher NO\textsubscript{x} and a lower PM emission compared to other engines.

Within the dataset, a significant difference was found between the fuel consumption of Dutch and non-Dutch Euro3 engines. In the other cases, the variance on the measured fuel consumption was too high to find a significant difference.

None of the subgroups of Euro1, -2 or -3 engines emit statistically more CO or HC than engines of another subgroup.
The cluster analysis was carried out on all the engines of the dataset. Any of the generated clusters of engines coincide with one or another group of engines where engines of the same generation and country of manufacture were put together. Hence, the cluster analysis does not confirm the country of manufacture to be a determining factor to make distinction between the environmental performance of HDV engines.

The tested pre Euro1-1990 engines have significant lower fuel consumption and emissions – NO\textsubscript{x} excluded – than the tested pre Euro1-1986 engines. The introduction of the Euro1 standard improved the fuel consumption and NO\textsubscript{x} emission significantly, whereas the introduction of the Euro2 standard led to an significant decrease in CO, HC and PM emission. The introduction of the Euro3 standard only resulted in an significant decrease of NO\textsubscript{x} emission.

One should take above findings into account when setting up emission models to estimate transport’s emissions and fuel consumption (Work Group B). However, it should be stressed that the statistical tests were carried out on a sample of limited size (two-population test of hypothesis for means: 42 engines – cluster analysis: 71 engines). One should hence be careful with taking above findings representative for all the engines running in Europe, especially the findings concerning the eventual difference in fuel consumption between different manufacturers of HDV engines.

7. **LIST OF REFERENCES**


2. Personal communication with Guido Lenaers, Vito.
### 8. DETAILS OF TESTED ENGINES AND AVAILABLE MEASUREMENT DATA

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<td>Volvo D12A380</td>
<td>S</td>
<td>EU 2</td>
<td>1998</td>
<td>279</td>
<td>530</td>
<td>1800</td>
</tr>
<tr>
<td>57</td>
<td>Volvo D12A380EC97</td>
<td>S</td>
<td>EU 2</td>
<td>1998</td>
<td>279</td>
<td>510</td>
<td>1800</td>
</tr>
<tr>
<td>58</td>
<td>DB-OM 441 LA I/1</td>
<td>D</td>
<td>EU 1</td>
<td>1994</td>
<td>242.79</td>
<td>600</td>
<td>2100</td>
</tr>
<tr>
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<td>Scania DSC 1408</td>
<td>S</td>
<td>EU 1</td>
<td>1994</td>
<td>304.9</td>
<td>450</td>
<td>1900</td>
</tr>
<tr>
<td>60</td>
<td>MAN D0824 LF105</td>
<td>D</td>
<td>EU 1</td>
<td>1994</td>
<td>114</td>
<td>785</td>
<td>2400</td>
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<td>61</td>
<td>Mercedes OM 401 LA,V/1</td>
<td>D</td>
<td>EU 1</td>
<td>1994</td>
<td>239</td>
<td>560</td>
<td>2100</td>
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<tr>
<td>62</td>
<td>OM 366 LA</td>
<td>D</td>
<td>EU 1</td>
<td>1994</td>
<td>177</td>
<td>600</td>
<td>2600</td>
</tr>
<tr>
<td>63</td>
<td>OM 401 LA,IV/1</td>
<td>D</td>
<td>EU 1</td>
<td>1994</td>
<td>200</td>
<td>600</td>
<td>2100</td>
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<tr>
<td>64</td>
<td>Renault MIDR 062045</td>
<td>F</td>
<td>EU 1</td>
<td>1994</td>
<td>250</td>
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<td>S</td>
<td>EU 1</td>
<td>1994</td>
<td>235.6</td>
<td>525</td>
<td>1900</td>
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<tr>
<td>-----</td>
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<td>-------------</td>
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<td>Rated</td>
<td>ECE</td>
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<td>66</td>
<td>Volvo TD 73 ES</td>
<td>S</td>
<td>EU 1</td>
<td>1994</td>
<td>191</td>
<td>600</td>
<td>2400</td>
</tr>
<tr>
<td>67</td>
<td>Volvo TD121GD; CH5</td>
<td>S</td>
<td>Vor FAV 2.1</td>
<td>1980</td>
<td>237.29</td>
<td>600</td>
<td>2200</td>
</tr>
<tr>
<td>68</td>
<td>Sauer D4KT; CH 3</td>
<td>CH</td>
<td>Vor FAV 2.2</td>
<td>1980</td>
<td>240.14</td>
<td>600</td>
<td>2100</td>
</tr>
<tr>
<td>69</td>
<td>MB OM 366 LA VII/1</td>
<td>D</td>
<td>EU 1</td>
<td>1994</td>
<td>112.8</td>
<td>600</td>
<td>2600</td>
</tr>
<tr>
<td>70</td>
<td>MAN D0824LF01</td>
<td>D</td>
<td>EU 1</td>
<td>1994</td>
<td>114.7</td>
<td>650</td>
<td>2400</td>
</tr>
<tr>
<td>71</td>
<td>MAN D0826LF08</td>
<td>D</td>
<td>EU 1</td>
<td>1994</td>
<td>164.5</td>
<td>600</td>
<td>2400</td>
</tr>
<tr>
<td>72</td>
<td>IVECO Cursor</td>
<td>I</td>
<td>EU 3</td>
<td>2001</td>
<td>316</td>
<td>550</td>
<td>2100</td>
</tr>
<tr>
<td>73</td>
<td>DAF XE 280 C1; BM 410 (pilot production)</td>
<td>NL</td>
<td>EU 3</td>
<td>2001</td>
<td>280</td>
<td>550</td>
<td>1900</td>
</tr>
<tr>
<td>74</td>
<td>DAF XF 355; BM 347 (pilot production)</td>
<td>NL</td>
<td>EU 2</td>
<td>1998</td>
<td>355</td>
<td>525</td>
<td>2000</td>
</tr>
<tr>
<td>75</td>
<td>DAF XE 315 C; BM 409 (pilot production)</td>
<td>NL</td>
<td>EU 3</td>
<td>2001</td>
<td>315</td>
<td>550</td>
<td>1900</td>
</tr>
<tr>
<td>76</td>
<td>Scania DC1201</td>
<td>S</td>
<td>EU 3</td>
<td>2001</td>
<td>309</td>
<td>500</td>
<td>1900</td>
</tr>
<tr>
<td>77</td>
<td>RABA D10 UTSLL 190 E2</td>
<td>H</td>
<td>EU 2</td>
<td>1998</td>
<td>190</td>
<td>600</td>
<td>1900</td>
</tr>
<tr>
<td>78</td>
<td>RABA D10 UTSLL 190 E3</td>
<td>H</td>
<td>EU 3</td>
<td>2001</td>
<td>190</td>
<td>600</td>
<td>1800</td>
</tr>
<tr>
<td>79</td>
<td>RABA MAN D2356 HM 6U</td>
<td>D</td>
<td>pre EU 1, Ostd.</td>
<td>1980</td>
<td>162</td>
<td>550</td>
<td>2200</td>
</tr>
<tr>
<td>80</td>
<td>RABA D10 TLL 225 E3</td>
<td>H</td>
<td>EU 3</td>
<td>2001</td>
<td>225</td>
<td>600</td>
<td>2100</td>
</tr>
<tr>
<td>81</td>
<td>MB OM 501 LA III/3</td>
<td>D</td>
<td>EU 3</td>
<td>2001</td>
<td>260</td>
<td>560</td>
<td>1800</td>
</tr>
<tr>
<td>82</td>
<td>Volvo D12D 420 EC01</td>
<td>S</td>
<td>EU 3</td>
<td>2001</td>
<td>309</td>
<td>600</td>
<td>1800</td>
</tr>
<tr>
<td>83</td>
<td>Volvo D12C 420</td>
<td>S</td>
<td>EU 3</td>
<td>2001</td>
<td>309</td>
<td>600</td>
<td>1800</td>
</tr>
</tbody>
</table>

**Number of available measurements**

| 63 | 30 | 19 | 71 |
APPENDIX VI:

RETROFIT AFTERTREATMENT SYSTEMS FOR DIESEL ENGINES

CONTENT:

1. INTRODUCTION  1
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   2.2. Diesel particulate filters
   2.3. Catalytic particulate oxidizers
3. TECHNICAL ISSUES TO BE CONSIDERED IN RETROFITTING  7
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1. INTRODUCTION

While new legislation worldwide requires newly manufactured heavy-duty diesel engines to meet tough new emission standards, there have been no major regulatory actions to similarly clean up diesels that are in use today. Because of the long service life of heavy-duty diesels, cleaning up exhaust gases of in-use heavy-duty diesel vehicles would certainly lead to improvements in air quality on the short term.

Retrofit exhaust aftertreatment technologies have emerged in recent years and are increasingly being utilized. Such systems need to be carefully matched to the individual vehicle and may require very low sulfur fuel. When optimized, they are capable of very significant reductions of PM and, to a lesser extent, NOx emissions. The combination of retrofit controls, new engine designs, low-sulfur fuels and advanced lubricants would assist in minimizing urban air pollution by diesel exhaust, while providing the durability and efficiency required from heavy-duty vehicles.
2. AVAILABLE AFTERTREATMENT TECHNOLOGIES SUITABLE FOR RETROFITTING

Diesel aftertreatment technologies could be divided into two main groups: systems designed to mitigate PM emissions and systems aimed at reduction of NO\textsubscript{x} emissions. Of course, their combination is possible too. Not all currently available aftertreatment technologies are suitable for retrofitting in-use vehicles. Some of them would require adaptations of the engine control strategy and other complicated and multiple changes to be introduced. Such complicated systems are not well suited for retrofitting, due to the associated costs and the potential loss of warranties from the vehicle manufacturer. Most of diesel aftertreatment technologies suitable for retrofitting are focused on reduction of PM emissions, and to less extent – NO\textsubscript{x} emissions.

Further review and analysis will be focused only on PM reduction technologies. Due to the fact that this survey is aimed at analysis of issues relevant for retrofit applications, and taking into account the available information - see, for example, state-of-the-art reviews of Johnson (2002, 2003), subjects such as optimization of filtration processes, catalyst coatings, etc, will not be covered by here. Technologies aimed at PM reduction that are suitable for retrofitting in-use heavy-duty diesel vehicles (HDDV), could be classified into three groups: diesel oxidation catalysts (DOC), diesel particulate filters (DPF), and catalytic particulate oxidizers (CPO). These systems are described in the following chapters.

2.1. Diesel oxidation catalysts

Diesel oxidation catalysts are similar in their design to the widely used gasoline three-way catalytic converters, but operate in an oxygen-rich environment. This results in their ability to stipulate oxidation reactions only. Therefore, DOCs assist in further oxidation of engine-out CO, HC and the soluble organic fraction (SOF) of particulates. The lower SOF reduces the particulate mass. At high exhaust gas temperatures, DOC may tend to produce sulfates with adverse effects on the PM mass emissions. The Main desirable chemical reactions that occur in a DOC are:

\[
\begin{align*}
2\text{CO} + \text{O}_2 & \rightarrow 2\text{CO}_2 \\
2\text{HC} + 2.5\text{O}_2 & \rightarrow 2\text{CO}_2 + \text{H}_2\text{O} \\
\text{SOF} + \text{O}_2 & \rightarrow \text{CO}_2 + \text{H}_2\text{O}
\end{align*}
\]

Typically, diesel oxidation catalysts were found to provide PM reduction of up to 50%, Brown et al. (1997). Data were presented, which indicates that DOC reduces significantly also the particle number on at least 11 of 13 particulate size bands, Brown (1997). It is noted that DOC contributes also to significant reduction of polycyclic aromatic hydrocarbons (PAH) and other toxic hydrocarbon emissions, Khair and McKinnon (1999).

2.2. Diesel particulate filters

Diesel particulate filters, or particulate traps, are very efficient in filtering fine particulates. A DPF system usually contains a filter positioned in the exhaust stream and designed to collect a significant fraction of the particulate emissions, while allowing the exhaust gases to pass through the system. The main technological challenge concerning DPF is controlled regeneration of the filter (burning of the trapped particles), where the particle load has to be burned below temperatures critical for damaging the filter material. Without or with delayed regeneration, the filter becomes blocked, which rapidly increases the exhaust gas backpressure. To start the filter regeneration process, temperatures above 300\textdegree C are necessary in modern systems. Such temperature levels do not occur under all loads for today’s HD
engines. A rather low overload of only 3-4 grams per liter of filter volume causes a rise of the regeneration temperature in the order of 300-400°C. Such temperatures can damage the filter, Hausberger (2003).

The requirements for filter material in terms of high trapping efficiency, together with low hydraulic resistance, thermal stability and acceptable cost, are quite challenging. The following surface-rich structures are found to be suitable, Mayer et al. (2000), Mayer (2003): ceramic monolithic-porous cell filter or foam, highly alloyed porous sintered metals or metal foams, filament-structures like fleeces, wound yarn or textile webbing (knitted or wickerwork) of ceramic or metallic fibers.

Many procedures of regeneration have been developed, which may be classified as so called active (if regeneration is triggered by external energy supply) and passive (if soot burn reaction is started due to the exhaust gas temperature occurring during real-world driving). Active regeneration is usually based on using various fuel burners or electric heaters. Such systems are complex, very expensive, and therefore less attractive for retrofit purposes. Their main benefit is in the possibility to ensure DPF regeneration at any operation condition. Increasing the exhaust gas temperature by means of engine combustion controls is used frequently for original equipment (OE), but most often not applicable for retrofitting. Detailed descriptions of active regeneration procedures have been published, e.g. Johnson (2002), Mayer et al. (2000), Mayer (2003). In the present review, the analysis is focused on passive regeneration methods that receive growing attention in various retrofit applications. The most popular methods of passive regeneration are: fuel borne catalysts (fuel additives), catalytic coating of the filter or a pre-catalyst to increase the NO₂ fraction in the NOₓ for soot burn facilitation and combinations of these methods. It is noted that omitting active regeneration may be risky: filter regeneration could be not sufficient if the vehicle operation conditions do not result in reasonably high exhaust gas temperatures. Thus, at least a monitoring device for the exhaust gas backpressure is recommended if passive regeneration is used alone.

**Fuel borne catalysts (FBC)** have the ability to substantially lower the soot ignition temperature and increase its burn-off rate. They are mostly elements from the so-called transition metals. Some typical examples are cerium, iron, copper and platinum. Today additives allow filter regeneration at temperatures of about 300°C, Valentine et al. (2000). A principal disadvantage of FBC is that the oxides of the additive substances are deposited in the filter, thus gradually increasing the backpressure. Of course, use of FBC requires an on-board dosing system. Special care should be given to verify the absence of secondary emissions. An appropriate procedure is applied in Switzerland and called VERT Secondary Emissions Test, Mayer et al. (2002). The list of verified FBCs is published by SAEFL (2004). Table 69 presents these verified additives together with their maximal dosing rates.

**Table 69: Fuel borne catalysts verified by SAEFL (2004).**

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Additive trade name</th>
<th>Effective element</th>
<th>Max. dosing rate, mg metal/kg fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>OCTEL</td>
<td>Satacen</td>
<td>Fe</td>
<td>36</td>
</tr>
<tr>
<td>OCTEL</td>
<td>OCTIMAX</td>
<td>Fe + Sr</td>
<td>25</td>
</tr>
<tr>
<td>Rhodia</td>
<td>EOLYS</td>
<td>Ce</td>
<td>100</td>
</tr>
<tr>
<td>Rhodia</td>
<td>EOLYS-2</td>
<td>Ce + Fe</td>
<td>17</td>
</tr>
<tr>
<td>Clean Diesel Technologies</td>
<td>DFX-DPF</td>
<td>Ce + Pt</td>
<td>8</td>
</tr>
</tbody>
</table>

FBC could also be used alone or in combination with DOC, in order to achieve better PM reduction efficiency, US EPA Voluntary Retrofit Program (2005).
Use of NO\textsubscript{2} for soot burn facilitation was initially suggested by Johnson Matthey in 1989 and known worldwide as the continuously regenerating trap (CRT) technology, Cooper and Thoss (1989). This system is usually comprised of a platinum based oxidation catalyst installed upstream of a non-catalyzed wall flow particulate filter. The Pt catalyst stipulates oxidation of NO in the exhaust stream to form NO\textsubscript{2}. Soot oxidizes with NO\textsubscript{2} at much lower temperatures than with O\textsubscript{2}. The regeneration in CRT systems starts at approx. 300°C. This enables DPF regeneration under many typical operation conditions of a heavy-duty diesel engine. The main reactions are:

\begin{align*}
\text{Catalyst:} & \quad 2\text{NO} + \text{O}_2 = 2\text{NO}_2 \\
\text{DPF:} & \quad \text{C} + \text{NO}_2 = \text{CO}_2 + 2\text{NO} \\
& \quad \text{C} + \text{O}_2 = \text{CO}_2
\end{align*}

High efficiency of CRT is quite well documented: it allows up to 99% PM removal, together with deep reduction of CO and HC emissions (Fig. 1), Chatterjee et al. (2002).

![Figure 125: Emissions reduction comparison for New York bus under New York Bus Cycle, Chatterjee et al. (2002). "Pre-durability" – measurements carried out before field tests; "Post-durability" - measurements carried out after 9-12 months of bus operation.](image)

Main drawbacks of CRT technology are sensitivity to sulfur content in a fuel, clogging tendency because of ash accumulation (these issues are discussed below) and the requirement for enough amount of NO\textsubscript{x} in the exhaust gases - NO\textsubscript{x}/PM ratio of at least 8 must be provided, as mentioned in the US EPA Voluntary Retrofit Program (2005). In the project PARTICULATES (5\textsuperscript{th} EU-Framework program) extensive research on the formation of the nucleation mode was done, e.g. Thompson et al. (2004). It showed that the nucleation mode mainly consists of droplets without carbaceous nucleus, which disappears if the exhaust gas is heated. Thompson et al. (2004) also found a pronounced number of nucleation particles for HD engines (EURO 2 and EURO 3) retrofitted with CRT systems. The nucleation mode was high using diesel fuel with both 38ppm and 8ppm sulfur content. Only with Swedish Class 1 diesel (3 ppm sulfur) the nucleation mode was suppressed. Fig. 2 shows that solid particle numbers were reduced by approx. 2 orders of magnitude by retrofit CRT, while the potential increase of nucleation particles can compensate for the lower number of solid particles in the total number emission. In general, low dilution of the exhaust gas and cold conditions increase the tendency for nucleation formation. Thus the nucleation may have much less relevance in real-world driving than in test bed measurements due to the much higher exhaust gas dilution compared to the test bed.
**Filter catalytic coating.** The application of a transition or precious metal coating applied to the surface of a filter reduces the ignition temperature necessary for oxidation of the particulates. No further measures are necessary, if the pertinent engine exhaust temperatures are attained sufficiently frequently and sufficiently long. This is a completely passive regeneration method, where regeneration occurs at a catalytically coated surface. Soot ignition temperatures are reduced to the values similar to or even lower than those obtained by using FBC, Johnson (2002), Mayer et al. (2000). Since ashes from fuel additives are avoided, such DPF systems can have longer maintenance intervals. Other demonstrated benefits of catalyzed filters over systems using FBC are their simplicity, reduced size and lower cost. The catalytic coating leads to deep conversion of CO and HC emissions together with high PM reduction efficiency (usually, around 90%).

![Figure 126](image-url)  
**Figure 126:** Total solid particle emissions (left) and total particle emissions including the nucleation mode (right) measured by Thompson et al. (2004), units in [#/kWh].

**Combinations of DPF regeneration methods** have recently gained rising popularity. A typical example of such a combination is the so-called catalyzed continuously regenerating trap (CCRT) developed by Johnson Matthey Inc., Chatterjee (2004), and verified by EPA and CARB in 2004 for retrofit applications, CARB (2005), US EPA Voluntary Retrofit Program (2005). The CCRT is a combination of CRT with a filter catalytic coating. According to Chatterjee (2004), its main advantages over CRT are the ability to successfully operate at low exhaust gas temperatures (200 – 250°C) and lower NOx/PM ratios.

### 2.3. Catalytic particulate oxidizers

Catalytic particulate oxidizers (CPO), continuous soot combustion catalysts (CSCC) or particulate catalysts (POC)\(^{31}\) have been developed to overcome one of the main DPF drawbacks – increase in backpressure and possible filter plugging, together with achievement of higher PM reductions compared to DOC technology. CPO’s can have a (limited) storage capacity for particles either on the surface of the catalyst, due to a special coating, or in a special storage medium. Like the catalytic coated DPF, the CPO’s oxidize the particles if a

---

\(^{31}\) Several different names exist now for similar systems. A key characteristic is an open structure where the exhaust gas is not flowing through a wall.
sufficiently high exhaust gas temperature is reached. In contrast to DPF, the open structure of CPO can prevent plugging (Fig. 3). If the given storage capacity is exploited, e.g. due to long operation at low exhaust gas temperatures, the particles in the exhaust gas will simply pass the CPO but they shall not contribute to its overload. Thus the exhaust gas backpressure shall not exceed critical values even under worst conditions.

Figure 127: Operational scheme of particulate catalysts (Source Emitec).

Experience with particle catalysts as retrofit systems has been gained in the last five years. Tests in buses in Styria showed 40% to 70% reduction in particle mass (Fig. 4) and solid particle number emissions for Particle Oxidation Catalysts from Emitec, Pankl and Oberland.Mangold in real-world bus cycles, e.g. Hausberger (2003), Hausberger and Vuckovic (2005). Particulate number emissions in the nucleation mode were reduced typically by more than 90% by these systems. Durability tests over approx. 70,000 km were performed, which showed a steady or even increasing efficiency of these systems. Results from longer durability runs are not known to the authors.

Figure 128: Particulate mass emissions: Setra S315H bus; different real-world bus cycles with & without a Pankl-POK particulate catalyst, Hausberger & Vuckovic (2005).

According to ETG (former Erland Nilson AB), the CPO can oxidize soot at much lower exhaust gas temperatures (≥200°C) than conventional wall-flow monolith based filters. The system is maintenance-free, as ashes shall not accumulate in the filter. The CPO device was recently tested by the AVL MTC laboratory and was approved for use in the Swedish
Environmental Zones retrofit program. Currently it is undergoing VERT verification procedure. Although the particulate reduction the CPO is less than of the DPF, the easier handling (according to the manufacturers no active regeneration is necessary) and usually lower cost make particle catalysts attractive for the retrofit market.

3. TECHNICAL ISSUES TO BE CONSIDERED IN RETROFITTING

When retrofitting diesel aftertreatment technologies to in-use vehicles, several factors should be considered. These include: the vehicle application and operation conditions, fuel quality, lubricant quality and vehicle maintenance, MECA (2002). They will influence the selection of an appropriate aftertreatment technology. The emission reduction target and system cost will also play an important role in technology selection.

3.1. Compatibility with vehicle operation conditions

Different aftertreatment technologies require different vehicle working conditions for their effective and durable operation. Not any aftertreatment system could be retrofitted to any vehicle. A careful selection process is a must for successful retrofit. Table 70 contains some compatibility conditions for few examples of various aftertreatment technologies that have been verified by US EPA, CARB or VERT, SAEFL (2004), CARB (2005), US EPA Voluntary Retrofit Program (2005).

Table 70: Compatibility conditions for various aftertreatment technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Manufacturer</th>
<th>Exhaust gas temperature, °C</th>
<th>Engine-out NOx/PM ratio</th>
<th>Verified by</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOC+FBC</td>
<td>CDT</td>
<td>≥225 during 15% of the duty cycle</td>
<td>Not specified</td>
<td>EPA</td>
</tr>
<tr>
<td>DOC</td>
<td>Johnson Matthey</td>
<td>≥150 during the duty cycle</td>
<td>Not specified</td>
<td>EPA, CARB</td>
</tr>
<tr>
<td>DPF+FBC</td>
<td>CDT</td>
<td>≥225 during 20% of the duty cycle</td>
<td>Not specified</td>
<td>EPA</td>
</tr>
<tr>
<td>CRT</td>
<td>Johnson Matthey</td>
<td>≥275 during 40-50% of the duty cycle</td>
<td>Min – 8 Optimal ≥20</td>
<td>EPA, CARB, VERT</td>
</tr>
<tr>
<td>Catalyzed DPF</td>
<td>Lubrizol ECS</td>
<td>≥280 during 25% of the duty cycle</td>
<td>Not specified</td>
<td>EPA, CARB, VERT</td>
</tr>
<tr>
<td>CCRT</td>
<td>Johnson Matthey</td>
<td>≥210 during 40% of the duty cycle</td>
<td>Min – 8 Optimal ≥20</td>
<td>EPA, CARB</td>
</tr>
<tr>
<td>CPO</td>
<td>ETG</td>
<td>≥200</td>
<td>Not specified</td>
<td>Certified for Swedish Envir. Zones</td>
</tr>
</tbody>
</table>

Some conditions such as requirements that the engine should be well maintained and have oil consumption as prescribed by the manufacturer, are common for all vehicles that are considered for retrofit of any aftertreatment system. As can be seen from Table 70, CCRT and CPO technologies allow engine operation at lowest temperatures.

3.2. Fuel quality

Sulfur contained in automotive diesel fuels influences negatively performance and durability of aftertreatment systems, Zvirin et al. (2003). This influence is quite well documented and widely discussed. Therefore, most aftertreatment technologies require, for their successful operation, ultra-low sulfur diesel fuel (ULSDF) that contains no more than 50 ppm sulfur with a recommendation to use a fuel with no more than 10-15 ppm sulfur. 50 ppm sulfur fuel is prescribed today over the EU, 10 ppm sulfur fuel is becoming increasingly available over Europe and worldwide too. For those markets, where ULSDF is still unavailable, some aftertreatment technologies tolerant to sulfur content have been developed. Most of DOCs, as well as CPO, permit operation with fuels containing up to 350-500 ppm sulfur. This results
from the fact that catalyst formulations have been developed recently that selectively oxidize SOF, while inhibit oxidation of the sulfur dioxide, MECA (2002).

3.3. Lubricant quality

The impact of lubricants on engine-out particulate emissions, and especially on deterioration in performance of DPFs, is much less studied than the impact of fuel quality, Froelund and Yilmaz (2002). The DPF is sensitive to organo-metallic ash derived from Calcium- and Magnesium-containing additives in the lubricant oil. These ashes melt at high temperatures (>1100°C) during regeneration and can react with the filter substrate and clog the filter permanently (glazing effect). Catalyst deactivation is possible as a result of lubricant oil Zinc- and Phosphorous containing ash, Froelund and Yilmaz (2002). It is clear now that ash management is an issue, and DPF manufacturers work on increase of ash storage capacity in their filters, as well as on methods of continuous ash removal using natural vehicle or engine vibrations, Johnson (2003). It is noted that some CPOs benefit from reduced permanent ash retention, ETG (2004). On the other hand, the best way to mitigate ash-in-DPF issue is to minimize ash generation. This can be done by reduction of both oil consumption and lubricant oil ash content.

Traditionally, ash content of heavy-duty diesel engine oil has been in the range of 1.2 up to about 2.0%. With the introduction of the OEM guidelines for Low Emission Diesel Lubricants, the maximum permissible amount of ash should be 1.0% for heavy-duty applications, Takeuchi et al (2003).

4. COST ISSUES

The Manufacturers of Emission Controls Association (MECA) has estimated costs for retrofit diesel aftertreatment technologies, MECA (2000, 2002). The information taken from their publications is given below for DOC and DPF technologies. Diesel oxidation catalysts are estimated to cost from $425 to more than $1,750 per DOC, depending on engine size, sales volume and whether the installation is muffler replacement or an in-line installation. In most cases, oxidation catalysts are easy to install. Installations typically take less than 2 hours. Diesel particulate filters are sold for about $3,000 to more than $11,000 each. The prices vary depending on the size of the engine, the number of vehicles being retrofitted, the amount of particulate matter emitted by the engine, the emission target to be achieved, the regeneration method and other factors. Filters that are sold as muffler replacements generally cost more that in-line filters. Detailed costs analysis has been performed in Switzerland for DPF, Mayer et al. (2000). Total retrofit costs were divided into purchase cost, installation costs, cost of monitoring systems and operating cost. A summary of their findings appears in Table 71.

| Table 71: Summary of costs for DPF retrofitting in US Dollars, Mayer et al. (2000). |
|-------------------------------|-------------------|-------------------|
| Cost component                | Engine power 100 kW | Engine power 300 kW |
| Purchase                      | 2,700             | 7,100             |
| Installation                  | 600               | 900               |
| On-board monitoring           | 600               |                   |
| Service                       | 600 (every 100,000 km) |             |
| Disposal                      | Manufacturer’s responsibility |          |
| Replacement                   | 80% of purchase price |          |

It is clear from the data shown above that the successful market penetration of HDV retrofit programs would be achieved only if valuable incentives are suggested to vehicle operators.
5. SUMMARY

Diesel oxidation catalysts (DOC) were found to provide PM emission reduction of up to 50%. The efficiency increases with higher shares of the soluble fraction on PM and decreases at higher sulfur content of the fuel, together with high exhaust gas temperatures, due to formation of sulfates. Formation of sulfates could even increase the total PM emissions compared to the original muffler. Diesel oxidation catalysts have been one of the most popular control options for both on-road and off-road applications to date because of their low cost, maintenance-free service and negligible impact on vehicle fuel economy.

Diesel particulate filters, or particulate traps, are very efficient in filtering of particulates. VERT-certification carried out by the Swiss Environmental Agency revealed results of trapping by more than 99% of particulates emission. Diesel particulate filters retrofits have rapidly expanded during the last years, mainly due to their very high efficiency of PM reduction and recently achieved high level of durability and reliability in suitable applications. Retrofit of DPF usually leads to fuel economy penalty of between 1% and 3%. A main technical target is to enable sufficient regeneration of the DPF, i.e. a continuous or periodical oxidation of the trapped particles, to prevent overloading of the filter which would result in increased fuel penalties and potential damages. At the moment only an active regeneration with burners or electric heating can guarantee regeneration in all situations. However, applications can work properly also without active regeneration if the vehicle and driving conditions result in sufficient exhaust gas temperatures for the retrofit system selected.

The Catalytic Particulate Oxidizer (CPO or particulate catalyst) technology is characterized by open structures, which can prevent overloading with particles under insufficient thermal operating conditions. This feature is an advantage, especially for retrofit systems where active regeneration most often would need an external heater. However, too low exhaust gas temperatures reduce the efficiency of CPO’s and can increase their exhaust gas backpressure. Particulate catalysts can usually achieve particulate emission reductions lower than DPF but higher than DOC. However, the distinction between DPF and CPO is rather flowing.

Most DOCs, as well as CPOs, permit operation with fuels containing up to 350-500 ppm sulfur. For successful operation of DPF, fuel with no more than 50 ppm sulfur is required. The DPF and maybe also some CPOs are sensitive to ashes from additives in the lubrication oil and in the fuel, since these ashes accumulate in the filter and increase the backpressure (e.g. organo-metallic ash). New specifications are being developed recently for engine lubrication oil with reduced ash content that will be compatible with aftertreatment devices.

All DOC’s and most of the DPF’s and CPO’s do have a catalytic coating within the system. The catalytic function reduces HC and CO emissions and reduces the temperature necessary for burning the soot from above 500°C to approximately 300°C. Especially for DPF’s and CPO’s this effect is very important for regeneration. The lower regeneration temperature is mainly achieved by an increase of NO₂ in the raw exhaust gas which reacts with the soot at lower temperatures than oxygen. The NO₂ is produced on the catalytic coating from the NO, thus total NOx emissions remain rather unchanged by retrofit systems. But the share of NO₂ on the total NOₓ can increase from approximately 5% to 10% without retrofit system up to more than 50% with some DPF’s and CPO’s. The NO₂ topic is matter of discussion for both, retrofit and original equipment DPF systems. Since an increase in NO₂ emissions could be critical, the NO₂ production of a retrofit system should be considered within the selection process.
6. REFERENCES


APPENDIX VII:

MODEL COMPARISON

As described in the main text of the document, model comparison was done within COST 346 in several steps

- At the beginning a literature review was done
- In a second step, all models available in run time versions within the Working Group A of COST 346 were run with the same input data set (data set 1), i.e. vehicle data, driving cycle and engine emission map. The results were used for optimisations and adaptations of the models involved.
- The model comparison was repeated a second time with a new data set (data set 2) after model optimisations. Since the participation in the comparison was voluntary and time consuming only a two models were involved in this second step. The results of these comparisons are described in an internal report of COST346.
- A third comparison was performed from LAT and TUG in a short term scientific mission, where the models Phem and Advisor were compared for a HDV and a passenger car (Fontaras Georgios, 2004). This comparison was done with the most actual data available (data set 3).

This appendix gives an overview on the results.

INTRODUCTION

To perform the model comparison was agreed by the COST 346 and ARTEMIS WP 400 partners since the literature review does not allow for a detailed assessment of the advantages and disadvantages of the single modules of each model. Therefore, the models are tested with standard input data for a single HDV where for some of the simulated situations measured results are available (emission maps and on-board or chassis dynamometer measurements for the same engine/vehicle combinations). For the vehicle models, the comparison should include:

- Accuracy of the power demand simulation
- Accuracy of the fuel consumption simulation
- Accuracy of the emission simulation

The comparison was done,

- to define differences between the models by comparison of the model results
- to assess the accuracy of the existing models by comparison of the measured emissions.

The idea was to improve the existing models by the findings of the model comparison and by using the data collection from the project.

The results presented here are from model versions at the time when the model comparison took place. Improvements done as a result of the exercises are not included here. Thus none of the results should be used for evaluation purposes of the actual models.
MODELS INVOLVED AND INPUT DATA

Four models within the COST 346 group took part at the model comparison. From one model (VETO) results where delivered for one HDV only.

Table 72: Models compared

<table>
<thead>
<tr>
<th>Model</th>
<th>Calculated values</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHEM, TU-Graz</td>
<td>Data set 1, 2 and 3</td>
</tr>
<tr>
<td>TNO HD Testcycles</td>
<td>Data set 1, 2</td>
</tr>
<tr>
<td>VETO (VTI)</td>
<td>Data set 1</td>
</tr>
<tr>
<td>SEEK (Danish Technological Institute)</td>
<td>Data set 1</td>
</tr>
<tr>
<td>Advisor</td>
<td>Data set 3</td>
</tr>
</tbody>
</table>

The following vehicles with different driving cycles have been given as standard model input data (formats according to the standard data collection sheets).

Table 73: Vehicles to be recalculated by the models

<table>
<thead>
<tr>
<th>Name</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data set 1</td>
<td></td>
</tr>
<tr>
<td>Vito IEA Diesel Citybus</td>
<td>Driving cycles from on board measurements at VITO, no engine-emission map and no coast down available. <strong>Remark to measurement: road gradient is not given and may not be always zero.</strong></td>
</tr>
<tr>
<td>19403 MAN</td>
<td>Driving cycles from chassis dynamometer measurements at TUG, coast down data and engine emission map is given. Engine emission map, ETC and US-Transient cycle have been measured at the engine test bed (same engine as in the vehicle). <strong>Remark to measurement: Measurements at the chassis dynamometer with constant 40 km/h fan for vehicle cooling. This may have caused thermal differences to the real world driving.</strong></td>
</tr>
<tr>
<td>120E18 Iveco</td>
<td>Driving cycles from chassis dynamometer measurements at TUG, coast down data and engine emission map is given. Engine emission map has been measured at the chassis dynamometer! <strong>Remark to measurement: the engine map was simulated on the chassis dynamometer with the according uncertainties. The setting for the regulation of the braking force was not optimal, resulting in sometimes to slow responses at transient cycles.</strong></td>
</tr>
<tr>
<td>Average EURO2</td>
<td>No measurements. Only to be calculated if the model can simulate an “average” EU2 semi trailer with the given weight.</td>
</tr>
<tr>
<td>Data set 2:</td>
<td></td>
</tr>
<tr>
<td>SCANIA DC 1201</td>
<td>Driving cycles from chassis dynamometer measurements at TUG, coast down data and engine emission map is given. Engine emission map, ETC and US-Transient cycle have been measured at the engine test bed (same engine as in the vehicle). <strong>Remark to measurement: Measurements at the chassis dynamometer with constant 40 km/h fan for vehicle cooling. This may have caused thermal differences to the real world driving.</strong></td>
</tr>
<tr>
<td>Data set 3:</td>
<td></td>
</tr>
<tr>
<td>Volvo D12-D420</td>
<td>Results from on board measurements performed by EMPA with engine map from the same engine measured at the engine test bed (e.g. Soltic, 2004)</td>
</tr>
</tbody>
</table>
AVERAGE RESULTS FOR DATA SET 1 AND 2

The results show:

- There is no “best” or “worst” model approach but each model has sometimes the lowest and sometimes the highest deviation to the measured values.

- The fuel consumption is simulated on average by +/- 8% if all relevant vehicle data and the engine map is given. If the engine map and the coast down data are missing the error clearly increases (IEA city bus). The best model results for a single vehicle gives an average deviation of 5% compared to the measured values, the highest average deviation is 21%.

- The NOx-emissions are simulated on average by +/- 15% if all relevant vehicle data and the engine map are given. If the engine map and the coast down data are missing the error again increases up to average 24% (IEA city bus). The best model results for a single vehicle gives an average deviation of 7% compared to the measured values, the highest average deviation is 31%.

- The HC-emissions are simulated on average by +/- 33% if all relevant vehicle data and the engine map are given. If the engine map and the coast down data are missing the error clearly increases up to average 56% (IEA city bus). The best model results for a single vehicle gives an average deviation of 16% compared to the measured values, the highest average deviation is 65%.

- The CO-emissions are simulated on average by +/- 44% if all relevant vehicle data and the engine map are given. If the engine map and the coast down data are missing the error remains on the same high level (IEA city bus). The best model results for a single vehicle gives an average deviation of 17% compared to the measured values, the highest average deviation is 108%.

- The particle-emissions are simulated on average by +/- 41% if all relevant vehicle data and the engine map are given. The best model results for a single vehicle gives an average deviation of 28% compared to the measured values, the highest average deviation is 80%.

- High demand is given for measurements to be useful for model comparison purposes in terms of quality and completeness, e.g. driving resistance values, mass and loading of the vehicle, engine emission map, transient engine test, emission measurements on board or on the chassis dynamometer under comparable conditions than on the engine test bed (especially thermal conditions), wind speed and road gradient for on-board measurements. Otherwise uncertainties of the models are overlapped heavily by the uncertainties from the measurements.

Since the results of each model were sometimes among the most accurate and sometimes at the most inaccurate compared to the measured values without systematic path, not very much general conclusions were possible from this work but each model was improved in the following by the owner where found to be necessary.

General results were: as expected, the fuel consumption and the NOx-emissions are simulated more accurate than the HC, CO and PM. The models with “dynamic correction” of the emissions did not produce better results in all applications than the quasi stationary models (with interpolation from the steady state engine maps only). Thus the main conclusions of this exercise were, that the quality of the transient correction tools has to be improved and that it is not clear how to elaborate the reasons of the different results from the models in a reasonable time. It was expected to get more similar results when similar input data is used.
Obviously the interpolation routines from the map and the simulation of the engine power demand from the vehicle data and the driving cycle gives enough room for different results (engine speed was delivered in the input data). Analysing all these tools would need much more time than available within COST 346.

**RESULTS FOR THE “AVERAGE EURO 2” VEHICLE**

The trends given by the models for the average Euro 2 HDV are very similar from all models for fuel consumption. The model results remain within +/- 15% for all cycles. Differences shall result from different engine maps and different “average” vehicle data.

![Simulated average fuel consumption for the different driving cycles for the “Average Euro 2”; results from the model and data versions in the year 2001, i.e. before the COST 346-ARTEMIS program!!](image)

**Figure 129:** Simulated average fuel consumption for the different driving cycles for the “Average Euro 2”; results from the model and data versions in the year 2001, i.e. before the COST 346-ARTEMIS program!!

The differences for NOx between the models were already up to 40%, for PM the highest deviations were observed (Figure 130). Since no common measured emission maps were delivered, the models used different emission maps. The differences in the “average” maps resulted from the very limited number of measurements available for each model. The total differences for the PM emissions simulated for the “average vehicle” were explained mainly by the different maps and the high influence of transient engine load changes on the PM emissions.

Thus, an improvement of the measured data was urgently necessary to gain any common understanding of HDV emission factors in Europe.
Figure 130: Simulated average PM-emissions for the different driving cycles for the “Average EU2” results from the model and data versions in the year 2001, i.e. before the COST 346-ARTEMIS program!!

AVERAGE RESULTS FOR DTA SET 3

A detailed description of the results can be found in the COST 346 document (Fontaras, 2004). The following summarizes the comparison between the models Phem and Advisor with an on-board measurement on a 40 ton articulated truck (Volvo D12-D420). EMPA has conducted on-road measurements by equipping a Volvo truck with on board measuring systems (Soltic P., 2004). The truck was driven on a 480 km route over San Bernardino carrying a total mass of approximately 40tons (about 25 tons of cargo). Apart from fuel consumption and exhaust emissions (CO, HC, NOₓ) the on board measuring system was recording the engine operating points at each second of the route, as well as the speed of the vehicle and the gradient of the street. It should be noted that the selected route includes many variations of road gradient throughout its length as shown in Figure 131. In order to acquire a better view of San Bernardino route and its characteristics, all necessary statistical data are presented in Table 70.
Figure 131 San Bernardino route used for simulation (recorded velocity-altitude)

Table 74: San Bernardino route characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>time</td>
<td>27961 s</td>
</tr>
<tr>
<td>distance</td>
<td>493.36 km</td>
</tr>
<tr>
<td>max speed</td>
<td>105.1 km/h</td>
</tr>
<tr>
<td>avg speed</td>
<td>63.52 km/h</td>
</tr>
<tr>
<td>max accel</td>
<td>1.19 m/s²</td>
</tr>
<tr>
<td>max decel</td>
<td>-2 m/s²</td>
</tr>
<tr>
<td>avg accel</td>
<td>0.15 m/s²</td>
</tr>
<tr>
<td>avg decel</td>
<td>-0.17 m/s²</td>
</tr>
<tr>
<td>idle time</td>
<td>1577 s</td>
</tr>
<tr>
<td>no. of stops</td>
<td>30</td>
</tr>
<tr>
<td>max up grade</td>
<td>7.7 %</td>
</tr>
<tr>
<td>avg up grade</td>
<td>2.3 %</td>
</tr>
<tr>
<td>max dn grade</td>
<td>8.2 %</td>
</tr>
<tr>
<td>avg dn grade</td>
<td>1.8 %</td>
</tr>
</tbody>
</table>

An overview on the measured and simulated results for the Volvo D12 vehicle is presented in Figure 132. It can be seen, that both models simulated the on-board measurements very accurately for fuel consumption (FC), NOx and HC. Deviations for CO were larger but CO generally was on a very low level for this vehicle. For PM no measurements were available since this component can not be measured by existing on board equipment.
In order to make sure that the achieved accuracy of the models which is considered very good is a result of correct modelling, Figure 133 to Figure 136 where created. In Figure 133 there is a comparison of the cumulative measured and simulated fuel consumption. It is apparent that between seconds 1-10000 and 20000-27000 where the average road gradient is approximately zero the models behave in the same way as the real vehicle. The modelling procedure is not so precise between seconds 10000 and 20000 where the road grade fluctuates significantly. Still the total picture of the simulation remains noticeably good. Since the measurement of the road gradient during on-board measurements is a very difficult topic (e.g. Soltic, 2004) some of the differences between simulation and measurement may also be attributed to the road gradient signal used as model input. Furthermore the truck was operated under full load of its air conditioner due to extreme hot ambient conditions during the tests. The power demand of the air conditioner had to be assessed by the models.

Figure 134 to Figure 136 contain the cumulative emissions for NO\textsubscript{x}, CO and HC respectively. All three graphs show that the achieved results are due to the correct modelling process and not just a coincidence.
Fuel consumption during San Bernardino route

![Graph showing fuel consumption](image)

**Figure 133:** Cumulative fuel consumption of Volvo D12 Measured-Simulated

![Graph showing NOx emissions](image)

**Figure 134:** Cumulative NO\textsubscript{x} emissions of Volvo D12 Measured and Simulated
Figure 135: Cumulative CO emissions of Volvo D12 Measured and Simulated

Figure 136: Cumulative HC emissions of Volvo D12 Measured and Simulated
Some Conclusions from the comparison between PHEM and Advisor are listed below:

- Correct simulation of light\(^{32}\) and heavy duty vehicles is possible with both PHEM and Advisor provided that the necessary input data are available. The accuracy of the models is strongly related to the amount and quality of the input data.
- PHEM can create input data from existing vehicle measurements. Advisor doesn’t perform this operation.
- Both models appear to simulate the operating conditions of the vehicles in very similar ways both for standard driving cycles and real world driving.
- For Volvo D12 simulation Advisor’s results are very close to the results produced by PHEM after dynamic correction with PHEM being more accurate.
- The fuel consumption can be simulated with very good accuracy by both models for predefined driving cycles or under real driving conditions. The deviation between measured and simulated values of fuel consumption can be less than 5%.
- Generally PHEM is more specialised in emissions calculation while Advisor tends to be a vehicle evaluation tool. Thus PHEM is more accurate in predicting emissions but doesn’t provide the opportunity to experiment with different operating principals – e.g. hybrid or electric vehicles etc- as Advisor does.

**SUMMARY**

The model comparison was able to highlight advantages and disadvantages of single models in terms of accuracy and user friendliness. Results were very useful to improve the models and to define the demands on measurements to be useful for model comparison purposes.

It seems to be impossible to make a model evaluation from such comparative model runs since the “accuracy” of the models under consideration differ from vehicle to vehicle and from cycle to cycle. Also the “accuracy” of the measurements may differ significantly. Also different engine operation conditions on the engine test bed and on the road or on the roller test bed can result in model inaccuracies, thus not only emission values but also ambient temperature and pressure as well as intake air temperature and pressure after the intercooler etc. should be recorded.

In total a rather large set of input data would have to be used to get a picture which model is more or less accurate than an other. A comparison based on a single vehicle and a single test cycle may lead to not representative results.

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\(^{32}\) In (Fontaras, 2004) the model comparison between Phem and Advisor is also performed with recalculation of measurements of a passenger car (VW Golf)
LITERATURE

Hausberger S.: Results of the COST 346 / ARTEMIS WP 400 vehicle emission model comparison; internal report for COST 346 and ARTEMIS WP 400 partners only; Institute for Internal Combustion Engines and Thermodynamics, Graz University of Technology; 2002

Fontaras G.: Comparison of Modeling Techniques for Heavy and Light Duty Vehicles; COST 346 Short Term Scientific Mission Rapport; LABORATORY OF APPLIED THERMODYNAMICS; MECHANICAL ENGINEERING DEPARTMENT; ARISTOTLE UNIVERSITY THESSALONIKI; 2004