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Development of a World-wide Harmonised Heavy-duty Engine Emissions Test Cycle

(Draft)

Executive Summary Report

ECE-GRPE WHDC Working Group

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0 Summary and Conclusions

Objective

The objective of the research program was the development of a world-wide harmonised engine test cycle for the emissions certification procedure of heavy-duty engines.

Approach

The basis of the development was the collection and analysis of driving behaviour data and statistical information about heavy-duty vehicle use for the different regions of the world. From this database a representative world-wide transient vehicle cycle (WTVC), expressed in terms of vehicle speed and normalised power pattern, was derived. A vehicle test cycle was developed because a vehicle duty cycle is much more stable over longer periods of time than an engine duty cycle. The reason being, that an engine duty cycle changes significantly with engine and drive train technology, whereas a vehicle duty cycle only changes with significant changes in traffic conditions.

However, since vehicle testing is more complex for heavy-duty vehicles than for light duty vehicles, the heavy-duty exhaust emission certification procedure utilises an engine cycle instead of a vehicle cycle. It was therefore necessary to transform the vehicle cycle (WTVC) into a reference transient engine test cycle (WHTC). This cycle was defined in terms of normalised engine speed and load and was refined with the help of a newly developed drive train model. This model is capable to take into account different engine and drive train technologies.

Based on the joint frequency distribution of engine speed and load of the transient engine cycle (WHTC) a reference steady state cycle (WHSC), consisting of 15 mode points (engine speed/load combinations), was also derived.

Cycle Development results (WVTC, WHTC and WHSC)

The developed transient vehicle cycle (WVTC) consists of vehicle speed and normalised power pattern for urban, rural and motorway operation. In order to enable the quantification of differences in the driving pattern between different regions in the world, regional vehicle and engine cycles for US, Europe and Japan were developed for comparison. These showed that the urban part is longest for the Japanese and shortest for the European regional cycle whilst for the motorway part the European regional cycle is the longest and the Japanese the shortest. The US regional cycle always follows closely the world-wide cycle. Overall the stated regional differences will not restrict the applicability of the WHTC cycle as basis for a representative world-wide harmonised heavy-duty test cycle.

In parallel to the TNO/TÜV research work MOT/JARI developed a vehicle speed cycle representative for Japan. This cycle does not exhibit large differences to the Japanese regional cycle developed by TNO/TÜV.

In addition, a reference steady state cycle (WHSC) was developed, consisting of 15 mode points (engine speed/load combinations). The number of 15 mode points was chosen in order to represent, as closely as possible, the same speed and load distribution as the transient reference engine cycle. During the test bench validation program the “feasibility” of restricting the WHSC-cycle on 13 mode points will be evaluated.

Quasistatic Emissions Validation

Based on emission calculations from steady state engine emission maps a quasistatic validation was carried out, in order to get a first estimate of the emission levels that can be expected from real test bench measurements. Three European and four Japanese engines were included in this evaluation.

On average only minor differences were observed between the NOx and particulates emission results from the WHTC and the regional cycles. The HC and CO values exhibited larger but still acceptable differences. The differences can be explained mainly by the different load factors of the regional cycles.

As with the comparison between WHTC and the regional cycles the differences between the emissions of NOX and particulates, for the WHTC and the existing certification test cycles, were also small. As expected, the differences for HC and CO were larger. A detailed analysis showed that the differences for the average emission values could be explained by differences in the frequency distributions of engine speed and load and differences in the average power output between the various cycles. Furthermore the results were influenced by the fact that the various engines were optimised for the regulated test cycles of their individual markets.

The differences between the emission results of the WHTC cycle and the various regional cycles as well as the emission differences between the engines are expected to be much smaller, once the engines have been optimised for the WHTC cycle.

Test Bench Validation Program

The quasi-static emission calculation does not take into account dynamic effects. Therefore, the quasi-static validation results can only be considered as a first evaluation of the emission levels that can be expected from the world-wide cycle when compared to existing test cycles. An extensive validation program of test bench measurements, which is planned as a next step, will provide the basis for the assessment of the developed cycles with respect to:

- ☐ the driveability and the applicability of the world-wide cycles,
- ☐ the feasibility for the adequate setting of emission standards in the different regions/countries of the world.

Conclusions

The developed reference transient engine cycle (WHTC) and the corresponding reference steady state cycle (WHSC) seem to provide a valid representation of the world-wide in-use engine operation of heavy-duty engines.

Compliance with the complete requirements of a candidate world-wide harmonised heavy-duty emissions test cycle, have to be confirmed by test bench validation measurements using engines with current and future technologies.

Complementary measures have to be defined to control off cycle emissions.

The development of a harmonised transient and steady state cycle seems to be an appropriate first step on the way to a world-wide harmonised certification procedure for heavy-duty engines. Further harmonisation steps are under preparation in the different WHDC subgroups.

1 Objective of the Work Program

At its 34th session in June 1997, The UNECE Group of Experts on Pollution and Energy (GRPE), under the guidance of Working Party 29, mandated the ad-hoc group WHDC with the development of a "**W**orld-wide harmonised **H**eavy **D**uty **C**ertification procedure. Co-ordinated by the subgroup ”Fundamental Elements” (FE), a research program was jointly conducted between October 1998 and October 2000 by TNO Automotive (The Netherlands) and TÜV Automotive (formerly FiGE, Germany). This program was funded by the Netherlands Ministry of the Environment (VROM) and the German Federal Environmental Agency (UBA).

The objective of the research program was to develop a world-wide harmonised engine test cycle for the emissions certification procedure of heavy-duty engines that would:

- become a uniform global basis for engine certification regarding exhaust emissions,
- be representative of world-wide real life heavy-duty engine operation,
- give the highest potential for the control of real-life emissions,
- be applicable in the future to state-of-the-art technology,
- match emissions in relative terms for accurate ranking of different engines/technologies

All kinds of relevant real life operations have to be included in the test cycle in a weighted manner appropriate to real life occurrence and the engine speed/load distribution of the cycle must be in line with real life speed/load distributions.

2 Outline of the Cycle Development Work

In order to develop a representative world-wide test cycle it was necessary to collate data concerning:

- the driving behaviour of different vehicle classes, road categories and parts of the world,
- vehicle use statistics and
- drive train and engine design influence on engine speed and load

These data had to include all relevant real life vehicle operations which could then be weighted according to real world occurrence.

Based on these requirements the following four-step approach was chosen:

Step 1: Creation of a **reference database** of driving patterns that includes all real-life situations in representative way and classified for all important influencing parameters.

Step 2: Derivation of a **transient vehicle cycle** in terms of vehicle speed and normalised power pattern (normalised to rated power) from the reference database (see chapter 3.2).

Step 3: Transformation of the transient vehicle cycle into a transient engine cycle in terms of actual engine speed and load by a **drive train model**.

Step 4: Development of a **reference transient engine test cycle** that best approximates the drive train model (step 4a, see chapter 3.3). Development of a corresponding **reference steady state mode cycle** (step 4b, see chapter 3.4).

3 Cycle Development Results

3.1 The Reference Database

In order to create the reference database in-use driving behaviour data had to be combined with world-wide statistics on vehicle use. This was achieved using a classification matrix for the most important influencing parameters. In the final classification matrix three different regions, three different vehicle classes (with power to mass ratio subclasses) and three different road categories were included.

Concerning the driving behaviour TNO/TÜV received data of 65 different vehicles from Australia, Europe, Japan and USA. This dataset comprised:

- 9 light trucks (max. mass below 7,5 t) with a total mileage of 2.200 km
- 20 rigid trucks (max. mass 7,5 t or more) and 1 coach with a total mileage of 13.400 km
- 18 trailer trucks with a total mileage of 56.300 km
- 11 public transport buses with a total mileage of 2.500 km

Summarising and generalising the result of the driving behaviour data analysis one can state the following:

- The collected data represent the whole range of different traffic situations from congested traffic to free flowing traffic on motorways.
- Traffic load and traffic control measures are the dominant influencing parameters for standstill percentage and vehicle speeds.
- Road sections with the same average speed value show no significant differences in the driving pattern of different vehicle categories and/or regions.
- At given vehicle speeds the acceleration driving behaviour of all vehicle types is more or less uniform for all road types and regions.
- The power to mass ratio influences mainly the engine load and principally also engine speed and vehicle acceleration. But its influence on engine speed and vehicle acceleration is masked by the traffic condition, especially by traffic density.
- Japanese trucks have significant higher power to mass ratios compared to trucks of other regions in the world.

The next task was to determine weighting factors for each combination of region, vehicle class, power to mass ratio subclass and road category. This was determined on the basis of the total operating time of heavy-duty vehicles in real life and required statistical information on world-wide heavy-duty vehicle use. In some cases the information was not sufficiently detailed and had to be disaggregated with the help of expert views from traffic consultancies, transport associations and the heavy-duty vehicle industry.

The result of this task (weighting factors) is shown in Table 1.

		Europe			Japan			USA			
vehicle cat.	**power to mass ratio class**	**urban**	**rural**	**motor way**	**urban**	**rural**	**motor way**	**urban**	**rural**	**motor way**	**Sum**
rigid trucks	1	5.2%	1.8%	2.0%	3.4%	1.2%	0.9%	3.3%	1.8%	0.6%	**20.2%**
rigid trucks	2	3.1%	1.7%	2.3%	6.0%	2.1%	1.6%	4.4%	2.4%	0.8%	**24.3%**
rigid trucks	3	3.2%	2.0%	2.5%	4.0%	1.4%	1.1%	2.6%	1.4%	0.5%	**18.7%**
trailer trucks	1	0.8%	1.0%	2.2%	0.3%	0.1%	0.1%	1.1%	0.8%	0.8%	**7.1%**
trailer trucks	2	0.8%	1.0%	2.3%	0.4%	0.2%	0.1%	2.1%	1.6%	1.5%	**10.0%**
trailer trucks	3	1.0%	1.3%	2.8%	0.2%	0.1%	0.1%	2.9%	2.2%	2.1%	**12.6%**
buses	1	2.8%	1.2%	0.0%	1.4%	0.4%	0.0%	0.7%	0.5%	0.1%	**7.1%**
	Sum	**16.9%**	**9.9%**	**14.1%**	**15.7%**	**5.4%**	**3.9%**	**17.0%**	**10.7%**	**6.3%**	**100.0%**

Table 1: Classification matrix and weighting factors for the different regions, road categories and vehicle classes

The reference database is therefore a combination of representative in-use data expressed in terms of vehicle speed and normalised power pattern (normalised to rated power) for each cell of the classification matrix and with the corresponding weighting factors.

3.2 The World-wide Transient Vehicle Cycle (WTVC)

A world-wide transient vehicle cycle (WTVC) was developed from the reference database and has statistically the same characteristics as the database. The cycle is expressed in terms of vehicle speed and normalised power (normalised to rated power). The reference transient vehicle cycle is shown in Figure 1.

A vehicle cycle only changes with significant changes in traffic conditions and is therefore stable over long periods of time. However, an engine cycle changes significantly with engine and drive train technology and, as a result of continuous efforts by manufacturers to improve fuel economy and vehicle driveability, cannot be considered stable.

Since vehicle testing is much more complex for heavy-duty vehicles than for light duty vehicles, the heavy-duty exhaust emission certification procedure incorporates not a vehicle cycle but an engine cycle which is expressed in terms of engine speed and load. Therefore, the developed vehicle cycle (WTVC) had to be transformed into an engine cycle.

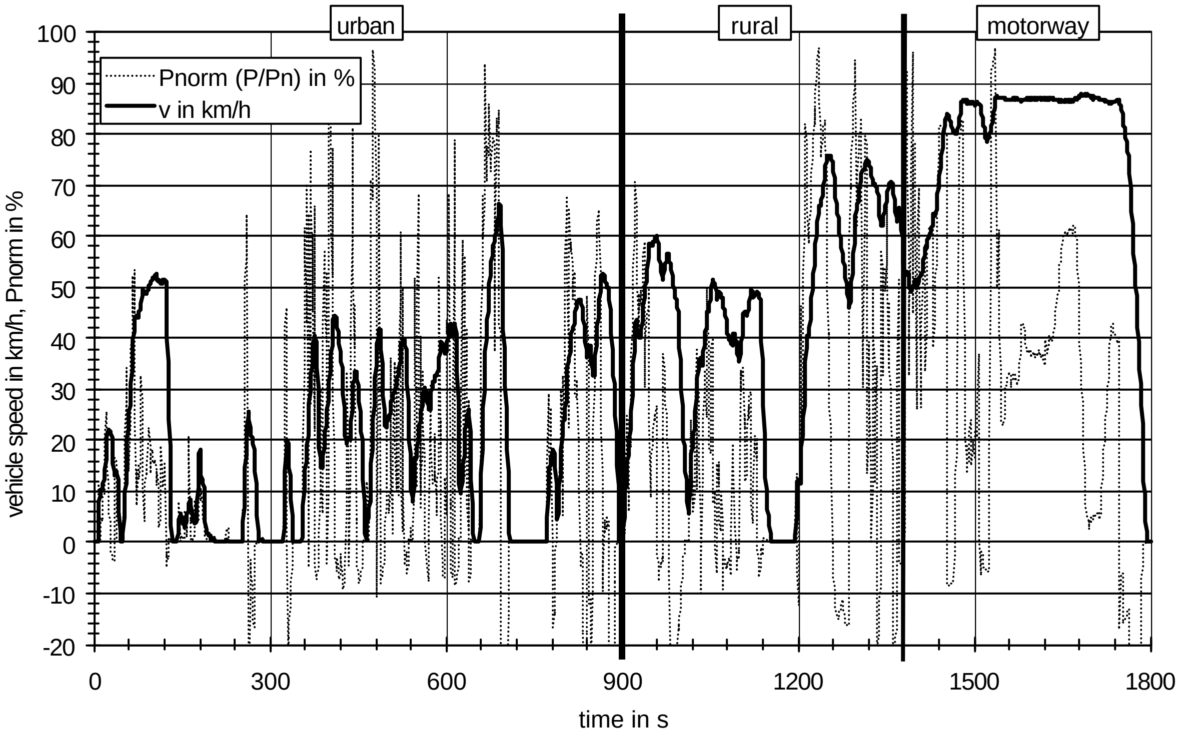

Figure 1: The world-wide transient vehicle cycle (WTVC)

To ensure that the mode distribution of speed and load during the engine certification test is in line with real life operation, a drive train model was developed to enable the transformation of the vehicle cycle into an engine test cycle. The drive train model is based on three characteristic engine speed values, which are related to the full load power curve of the engine and as such is not affected by changes in engine technology. **The drive train model transforms the vehicle cycle into an engine speed/load pattern for each individual engine.**

3.3 The World-wide Reference Transient Engine Cycle (WHTC)

The application of a drive train model would require a computer program and this would be difficult to implement in a regulation. Therefore, as a further development, the drive train model was substituted for a **reference transient engine cycle (WHTC).** This cycle relates the engine speed with the same characteristic engine speed values that were used in the drive train model. The substitution model was tested against the drive train model and found to be equivalent. The speed and load pattern of the world-wide reference transient engine cycle so derived is shown in Figure 2 and Figure 3.

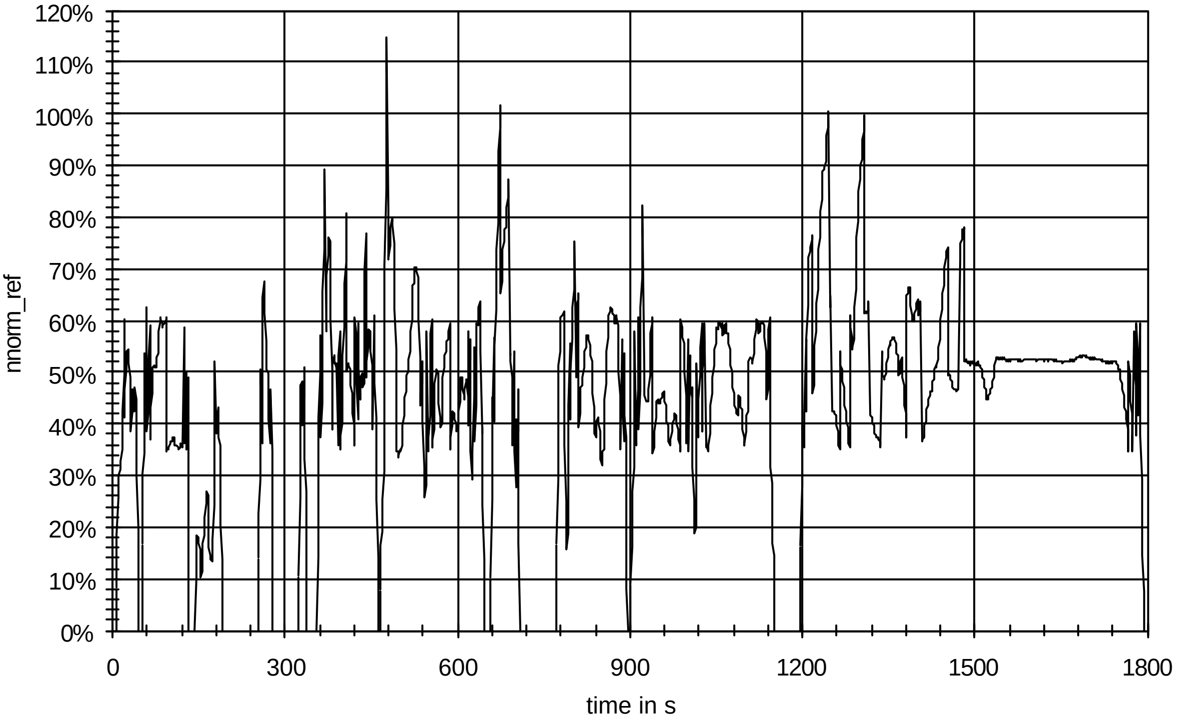

Figure 2: The speed pattern of the world-wide reference transient engine cycle (WHTC)

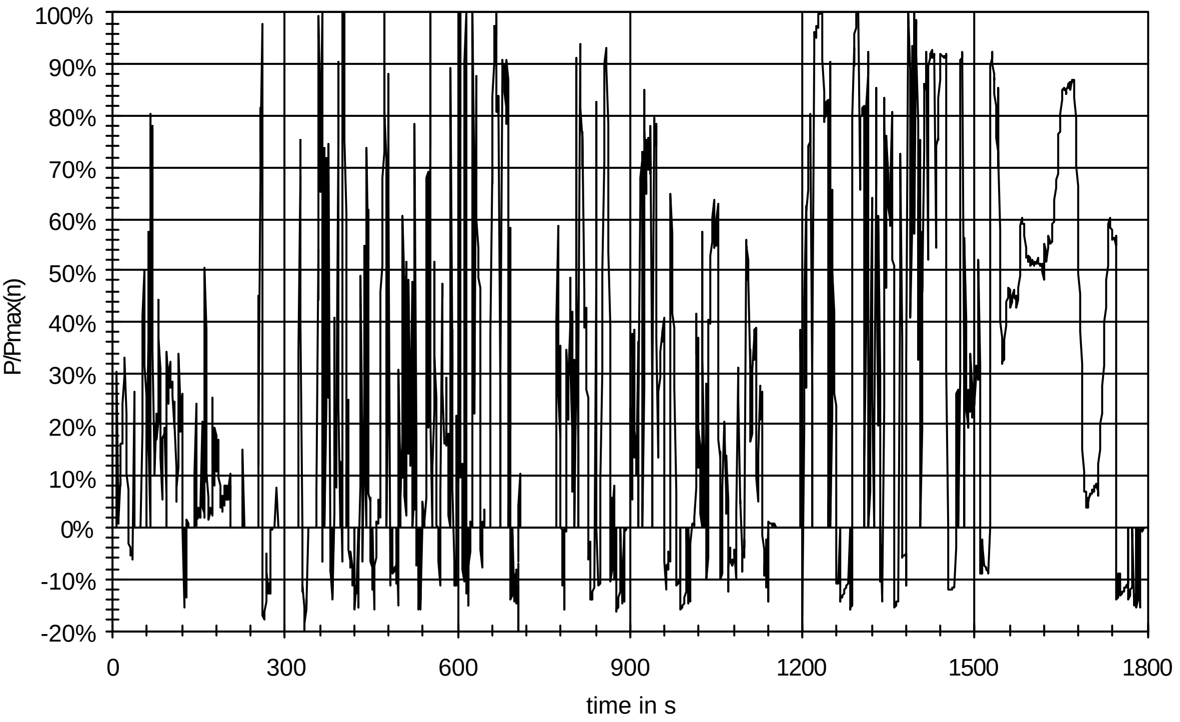

Figure 3: The load pattern of the world-wide reference transient engine cycle (WHTC)

The engine speed pattern for an individual engine under test has to be derived by denormalisation of the reference speed pattern of the reference cycle. For the denormalisation the above-mentioned three characteristic engine speed values are used and are related to the individual full load power curve of the particular engine. **Unlike existing cycles** (ETC, FTP) **this approach results in an individual engine speed pattern that best reflects in-use engine behaviour, even for future technologies.**

3.4 The World-wide Reference Steady State Cycle (WHSC)

In addition, a reference steady state cycle (WHSC) was developed, consisting of 15 mode points (engine speed/load combinations). The steady state modes are based on the joint frequency distribution of normalised engine speed and load of the reference transient engine cycle (see Figure 4). As before, the engine speed normalisation is based on three characteristic engine speed values related to the full load power curve of the engine. **This approach leads to individual engine speed modes depending on the full load power curve characteristics of the individual engine under certification test conditions.**

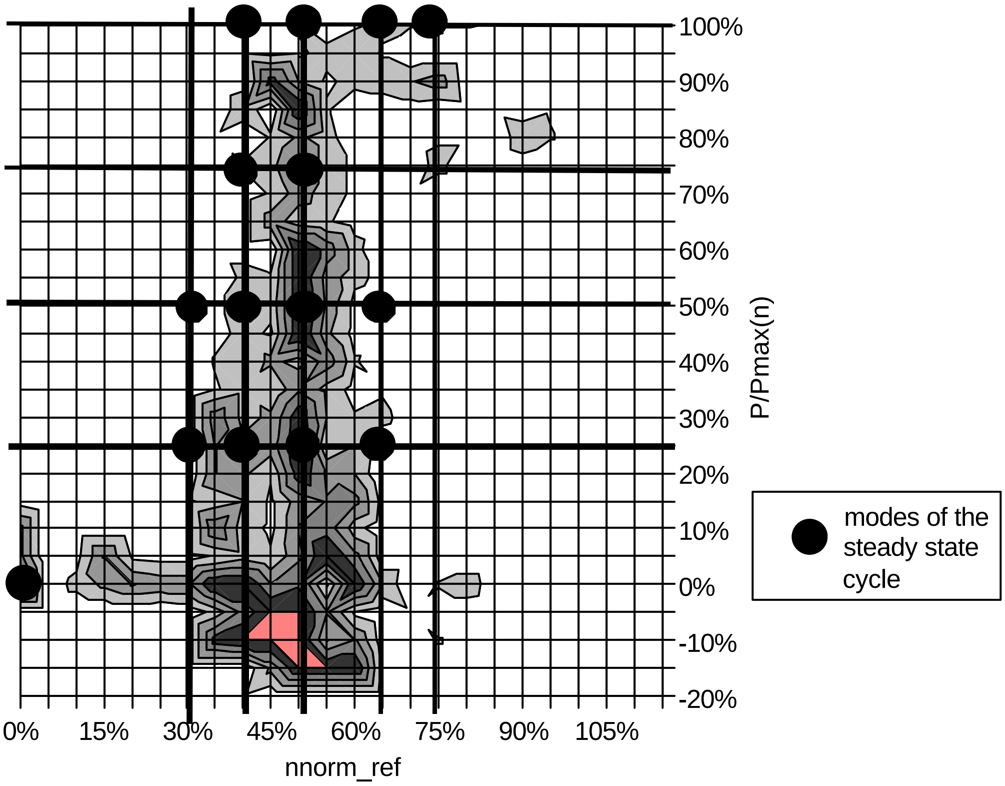

Figure 4: Engine speed/load distribution of the reference transient engine cycle as basis for the world-wide steady state cycle (WHSC)

The specification of the load points was aligned to the joint frequency distribution of the reference transient engine cycle, but without taking into account motoring phases. To compensate the missing motoring phases the weighting factor for idling was increased compared to the reference transient engine cycle. The weighting factors are shown in Table 2.

	engine load				
nnorm ref	**0%**	**25%**	**50%**	**75%**	**100%**
0%	30%				
30%		3,8%	1,4%		
40%		8,0%	4,1%	3,8%	2,2%
50%		10,3%	14,1%	8,4%	3,2%
65%		3,5%	1,9%		3,1%
75%					2,2%

Table 2: Mode points and weighting factors for the world-wide steady state cycle (WHSC)

The number of 15 mode points was chosen in order to represent, as closely as possible, the same speed and load distribution as the transient reference engine cycle. During the test bench validation program the “feasibility” of restricting the WHSC-cycle on 13 mode points will be evaluated.

4 Regional Cycles

In order to enable the quantification of differences in the driving pattern between different regions in the world, additional regional vehicle cycles and regional reference transient engine cycles were developed. Comparison of the relative cycles showed that the urban part is longest for the Japanese and shortest for the European regional cycle whereas the motorway part is longest for the European and shortest for the Japanese regional cycle. The US regional cycle always follows closely the world-wide cycle. On the whole the stated regional differences seems not to be an invincible barrier for the applicability of the WHTC cycle as representative world-wide harmonised heavy-duty emissions test cycle.

It has to be pointed out that the regional cycles were only used for evaluation reasons.

5 Japanese Activities on Cycle Development

A regional vehicle speed cycle representative for Japan was also developed under a MOT/JARI project. When compared with the Japanese regional vehicle cycle developed by TNO/TÜV, average speed and idling time ratio were about the same. Idle time frequency and short-trip length frequency also showed similar trends in both the TNO/TÜV and MOT/JARI regional vehicle cycles. With respect to acceleration patterns, the MOT/JARI cycle exhibits a higher acceleration frequency than the TNO/TÜV, however, in other domains the distributions of speed and acceleration were similar for both cycles. So, it can be concluded that the

Japanese regional vehicle cycle developed by TNO/TÜV and the vehicle speed cycle developed by MOT/JARI do not exhibit large differences.

To transform the vehicle cycle into an engine test cycle MOT/JARI used their own, independently developed vehicle model. The engine speed/load frequencies of the engine test cycle developed by MOT/JARI show almost the same distribution as those developed by TNO/TÜV.

6 Quasistatic Validation

A quasistatic validation was carried out, based on emission calculations from steady state engine emission maps. The main reason for this task was to get a first estimate of the emission levels that can be expected from real test bench measurements and compare these with corresponding levels for existing test cycles. A further reason was to evaluate whether the harmonised cycle (WHTC) could accommodate regional differences not only with regard to the cycle load factors but also with regard to emission levels Three European and four Japanese engines were included in this evaluation..

The evaluation showed that on average only minor differences are observed between the emissions results of the WHTC and the regional cycles for NOx and particulates (Figure 5). For HC and CO higher differences were expected, but the results were still in a relatively narrow range. These differences can partly be explained by the different power output of the engine for the various regional cycles.

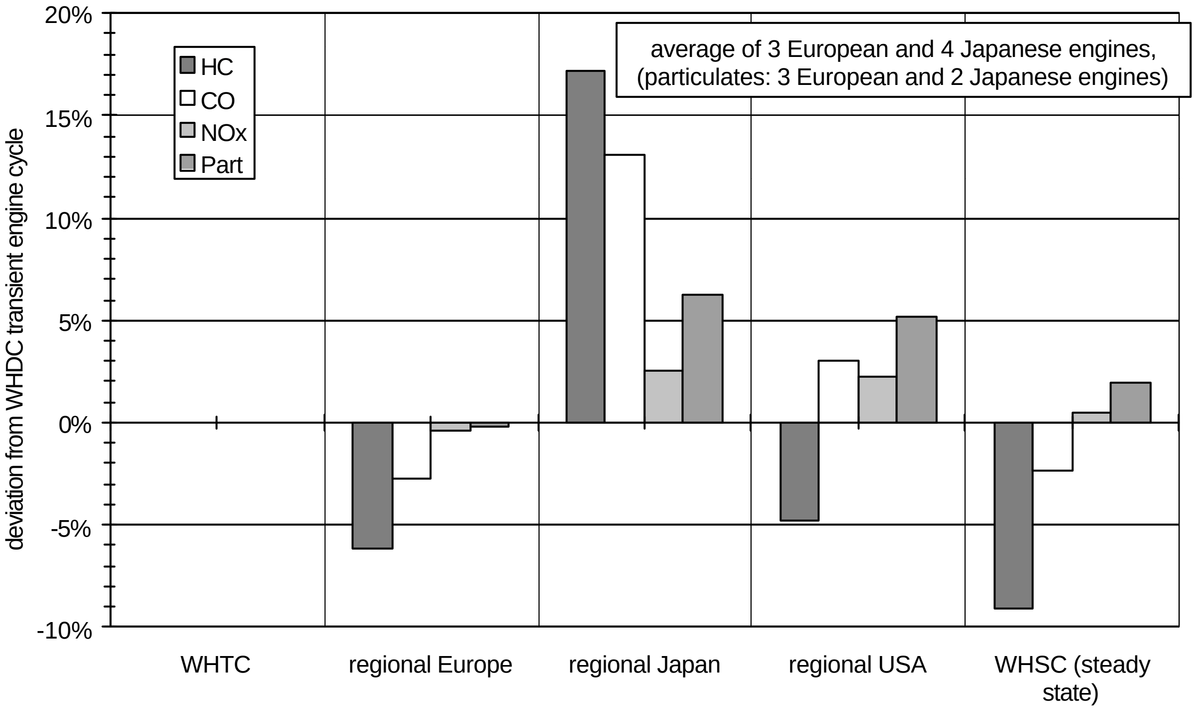

Figure 5: Results of the quasistatic emission calculation, differences between the WHTC, the WHSC and the regional transient cycles

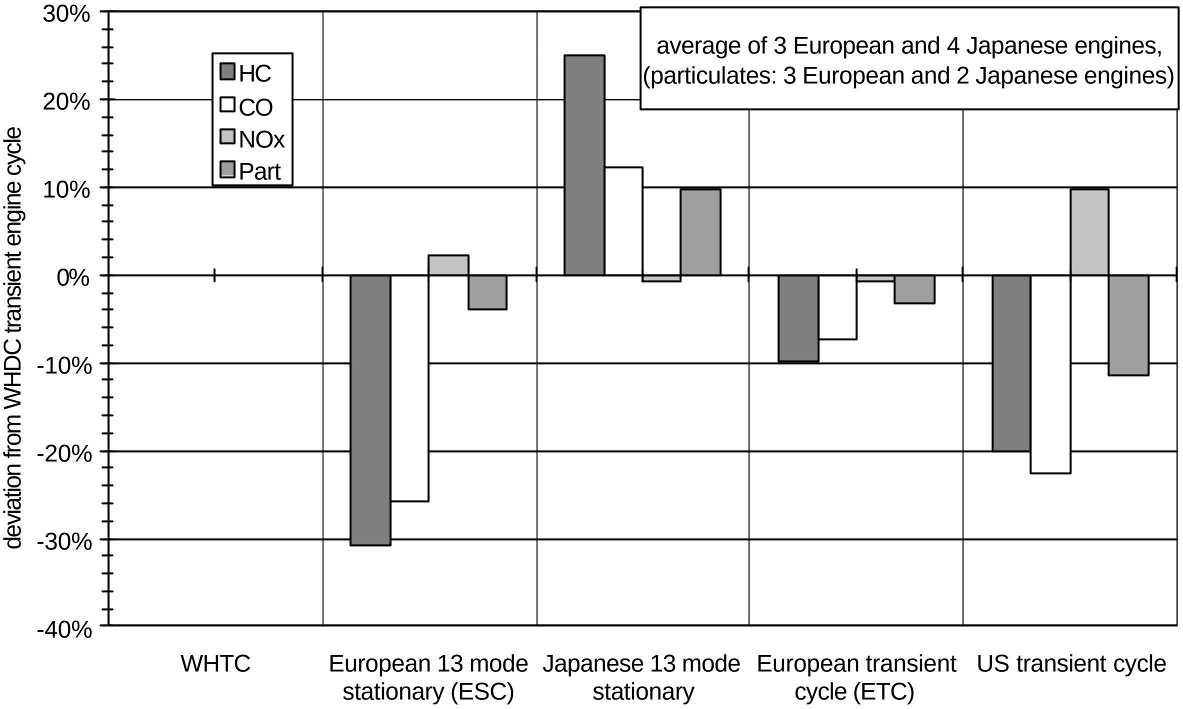

Figure 6: Results of the quasistatic emission calculation; differences between the WHTC transient engine cycle, the ETC, the ESC, the Japanese 13 mode test and the US-transient cycle

In Figure 6 the emission results of the WHTC are compared with those of existing certification test cycles. The differences are reasonably small for NOx and particulates. As expected, the differences for HC and CO are higher. A more detailed analysis showed that the differences for the average values could be explained by differences in the frequency distributions of engine speed and load (see Figure 7 to Figure 9) and differences in the average power output between the cycles. Further emission differences between the engines could be related to individual differences in their emission maps, which were optimised for the regulated test cycles of their individual markets.

The described differences between the emission results of the WHTC cycle and the various regional cycles as well as the emission differences between the engines are expected to be much smaller, once the engines have been optimised for the WHTC cycle.

The indications from the results of the quasistatic validation are that the test bench validation will confirm the applicability of the WHTC cycle as a world-wide harmonised emissions test cycle.

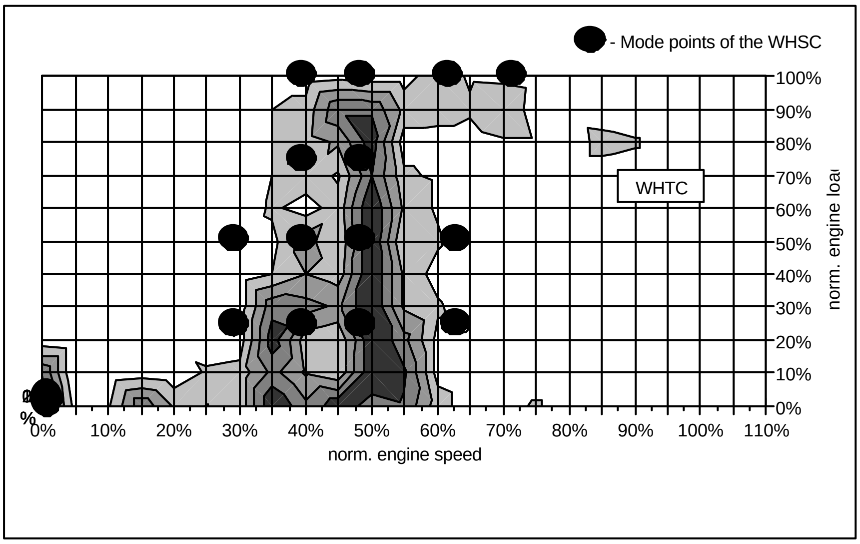

Figure 7: Engine speed/load distribution of the WHTC and WHSC

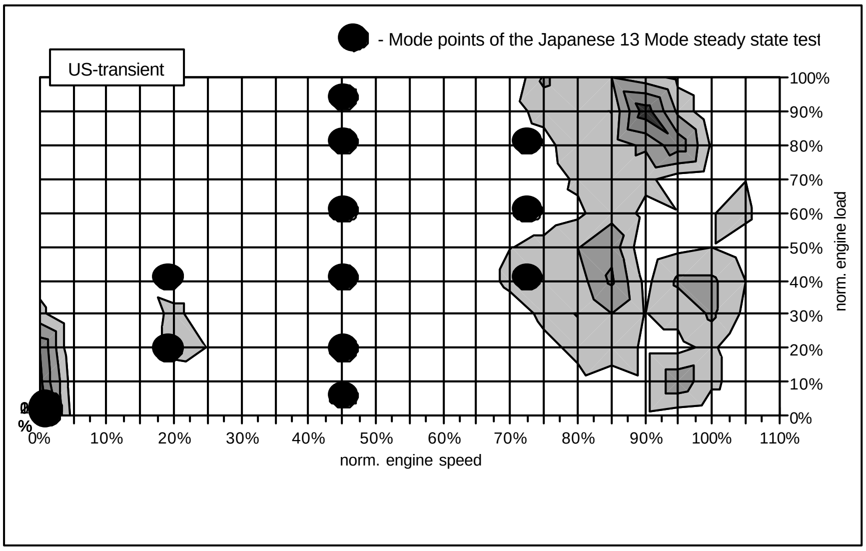

Figure 8: Engine speed/load distribution of the US-trans. cycle and the Japanese 13 mode test

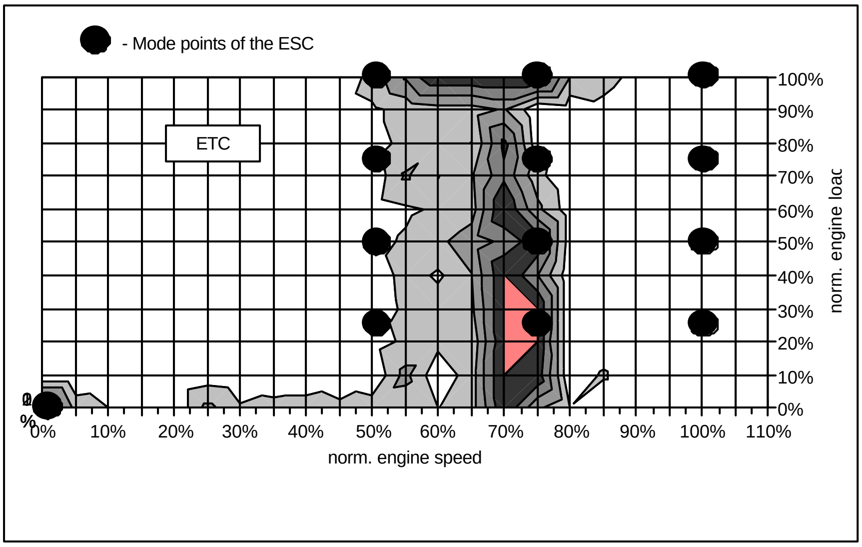

Figure 9: Engine speed/load distribution of the ETC and ESC

7 Test Bench Validation Program

The quasi-static emission calculation does not take into account dynamic effects. Therefore, the quasi-static validation results can only be considered as a first evaluation of the emission levels that can be expected from the world-wide cycle when compared to existing test cycles. An extensive validation program of test bench measurements, which is planned as a next step, will provide the basis for the assessment of the developed cycles with respect to:

- ☐ the driveability and the applicability of the world-wide cycles,
- ☐ the feasibility for the adequate setting of emission standards in the different regions/countries of the world.

Complementary measures have to be defined to control off cycle emissions.

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