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Development of a Worldwide Harmonised Heavy-duty Engine Emissions Test Cycle

Final Report

ECE-GRPE WHDC Working Group

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0.1 Summary and Conclusions

Objective

The objective of the research program was the development of a worldwide 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 worldwide 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 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 of taking 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 12 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 worldwide cycle. Overall the stated regional differences will not restrict the applicability of the WHTC cycle as basis for a representative worldwide 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 12 mode points (engine speed/load combinations). The mode points were chosen in order to represent, as closely as possible, the same speed and load distribution as the transient reference engine cycle.

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 worldwide 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 worldwide 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 worldwide in-use engine operation of heavy-duty engines.

Compliance with the complete requirements of a candidate worldwide 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 worldwide harmonised certification procedure for heavy-duty engines. Further harmonisation steps are under preparation in the different WHDC sub-groups.

0.2 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**orldwide harmonised **H**eavy **D**uty **C**ertification procedure. Co-ordinated by the subgroup ”Fundamental Elements” (FE), a research program was jointly conducted since October 1998 by TNO Automotive (The Netherlands) and TÜV Automotive (formerly FiGE, Germany). The Netherlands Ministry of the Environment (VROM) and the German Federal Environmental Agency (UBA) funded this program.

The objective of the research program was to develop a worldwide 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 worldwide 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.

0.3 Outline of the Cycle Development Work

In order to develop a representative worldwide 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 0.4.2).

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 0.4.3). Development of a corresponding **reference steady state mode cycle** (step 4b, see chapter 0.4.4).

0.4 Cycle Development Results

0.4.1 The Reference Database

In order to create the reference database in-use driving behaviour data had to be combined with worldwide 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 and vehicle 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. This influences mainly the engine load distribution (higher frequencies at low load). The influence on engine speed distributions is of minor importance.

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 established from statistical information on worldwide 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.

0.4.2 The Worldwide Transient Vehicle Cycle (WTVC)

A worldwide 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.

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.**

0.4.3 The Worldwide 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 worldwide reference transient engine cycle so derived is shown in Figure 2 and Figure 3.

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 as expressed in the following formula

$$n = nnorm\_ref * (0{,}6 * n\_lo + 0{,}2 * n\_hi + 0{,}2 * n\_pref - n\_idle) / 0{,}5363 + n\_idle$$

Equation 1

with the individual n_lo, n_hi and n_pref values of this particular engine.

Unlike existing cycles (ETC, FTP) **this approach results in an individual engine speed pattern** (see Figure 4) **that best reflects in-use engine behaviour, even for future technologies.**

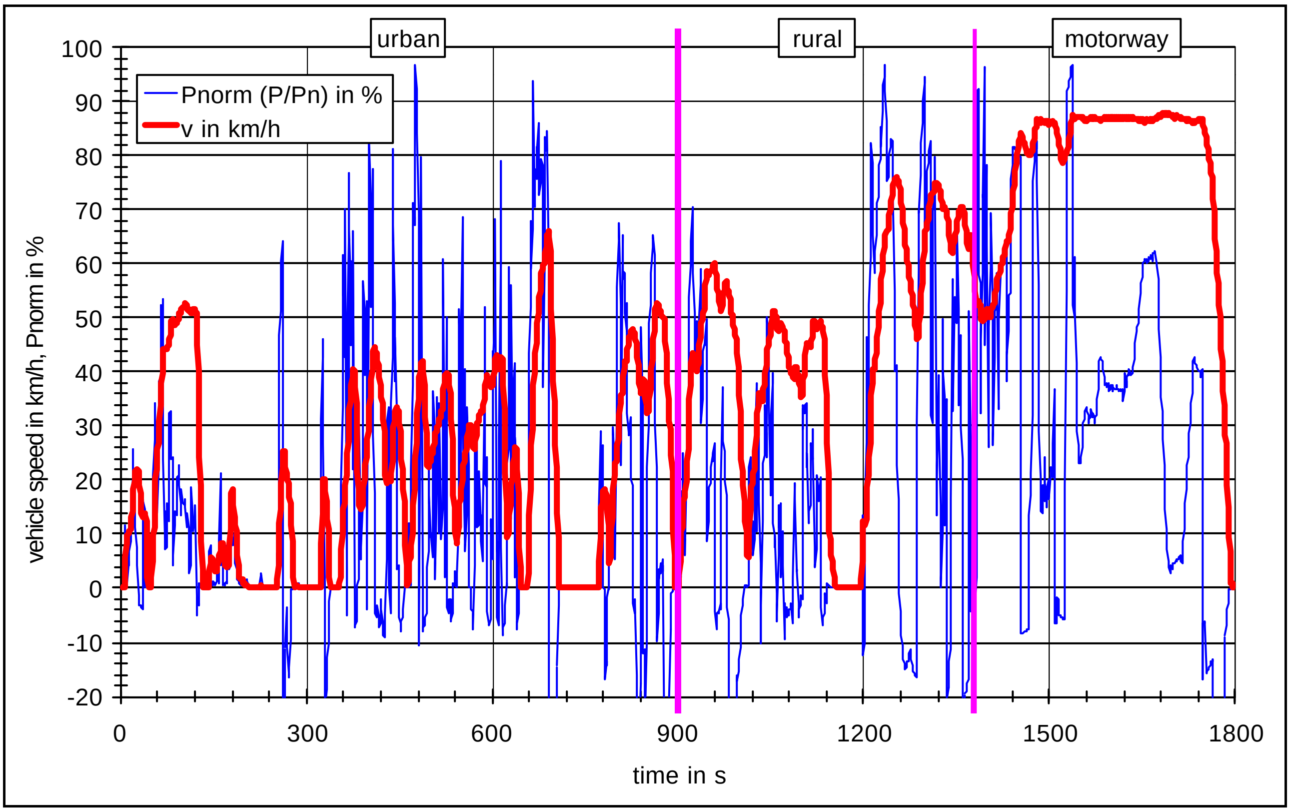

Figure 1: The worldwide transient vehicle cycle (WTVC)

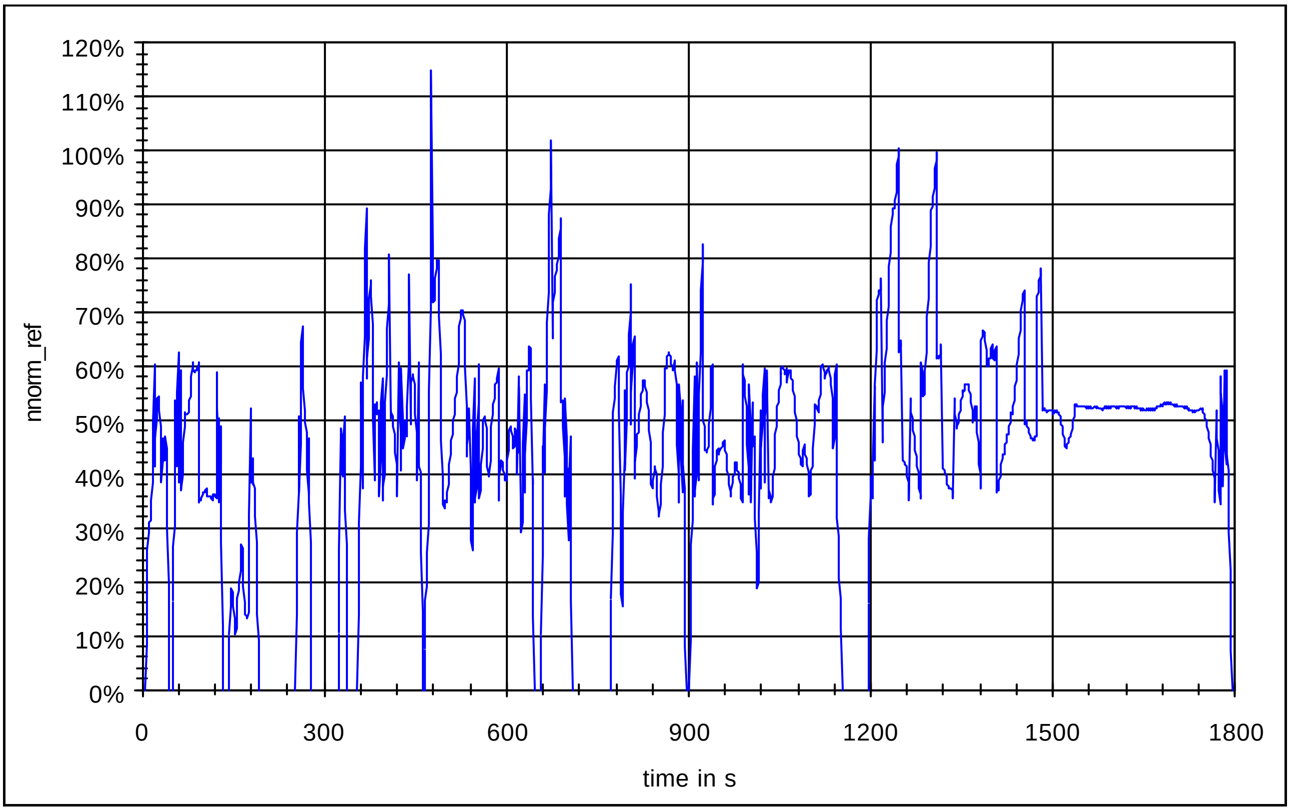

Figure 2: The speed pattern of the worldwide reference transient engine cycle (WHTC)

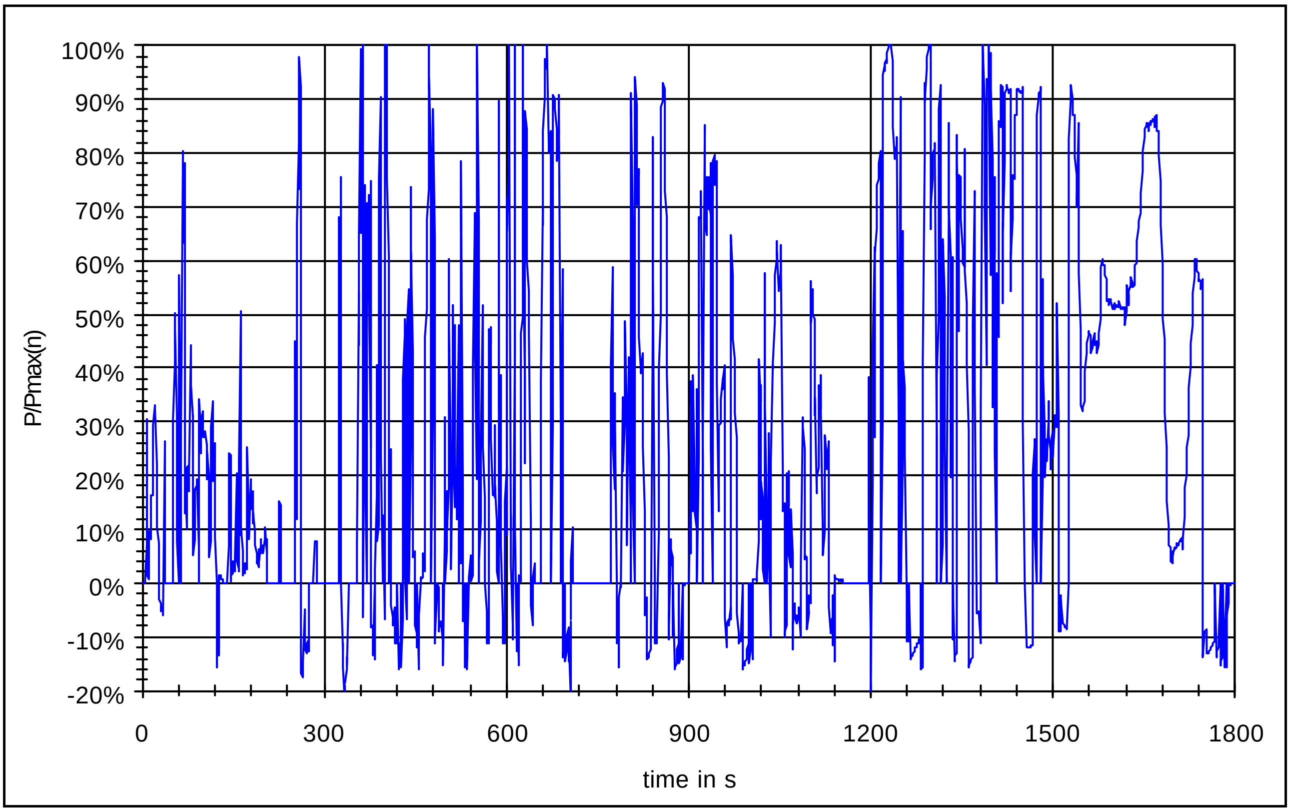

Figure 3: The load pattern of the worldwide reference transient engine cycle (WHTC)

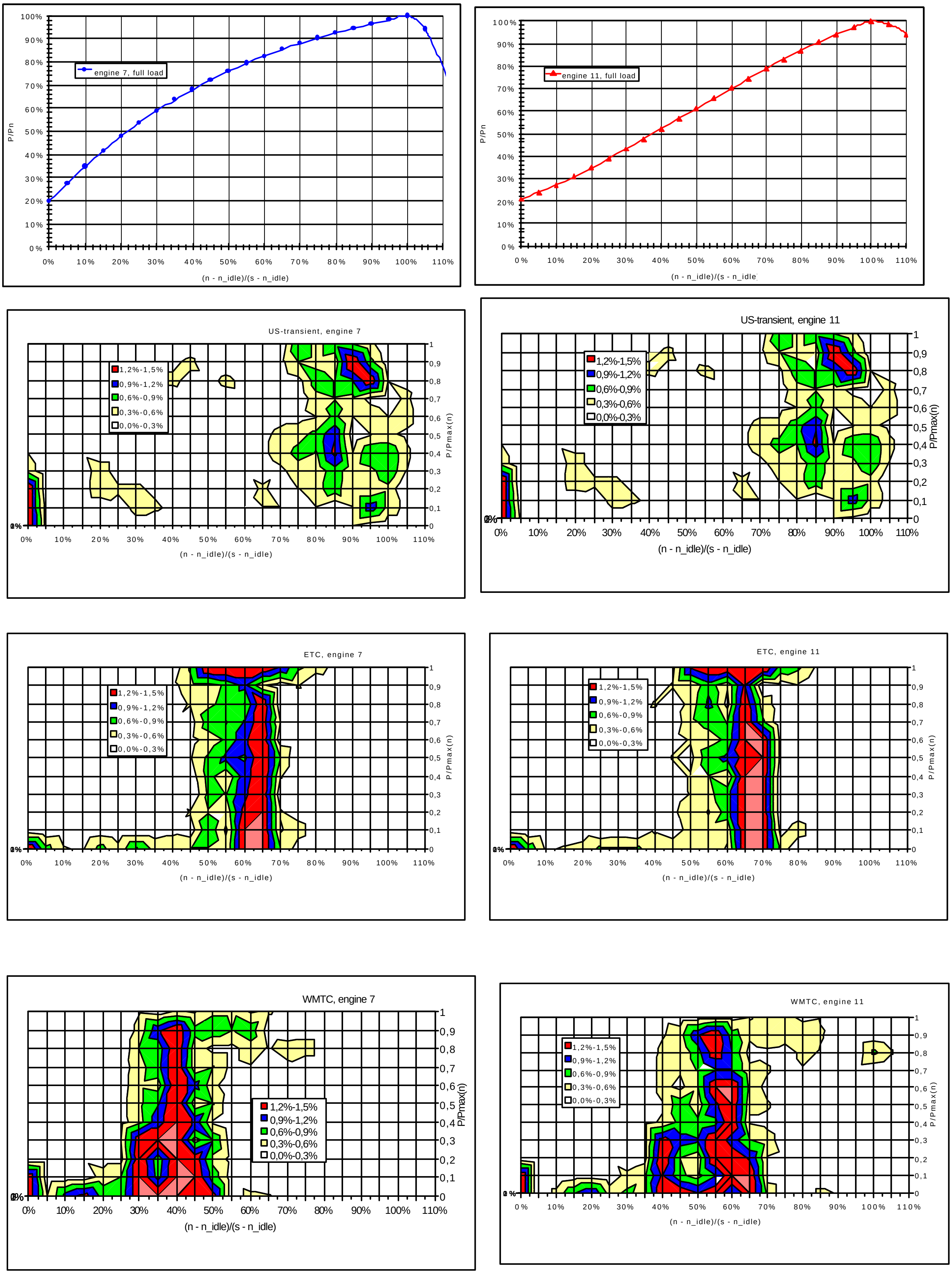

Figure 4: Comparison of the joint frequency distributions of the US-transient, the ETC and the WMTC for two engines with different full load power curves

0.4.4 The Worldwide Reference Steady State Cycle (WHSC)

In addition, a reference steady state cycle (WHSC) was developed, consisting of 12 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 5). 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.**

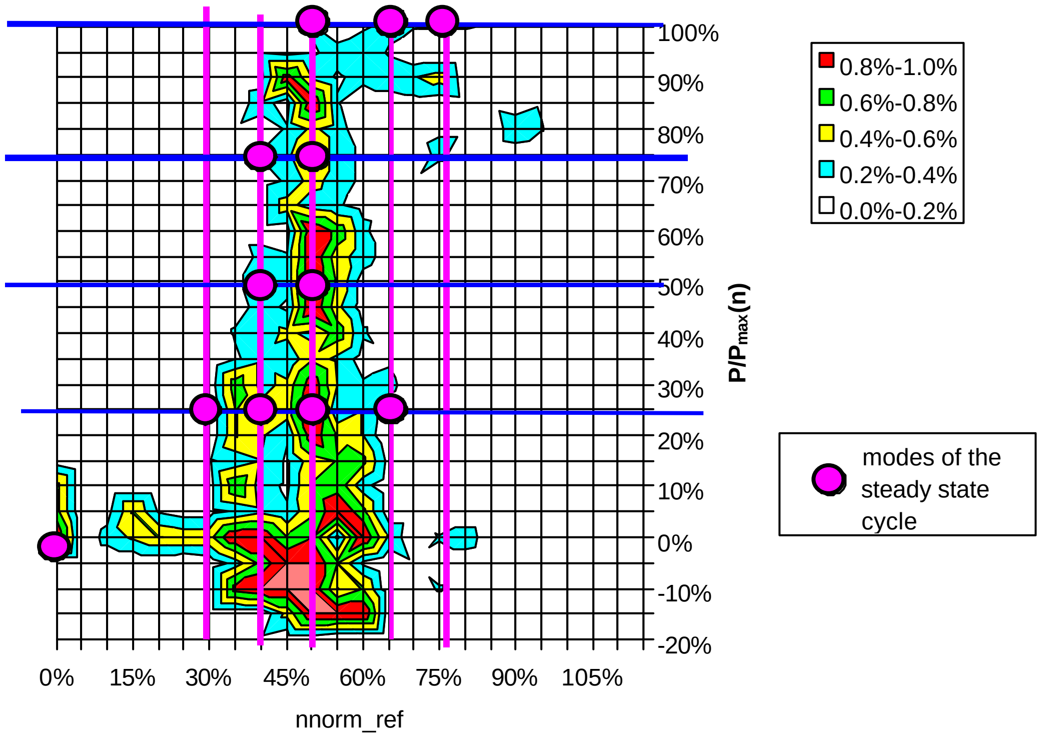

Figure 5: Engine speed/load distribution of the reference transient engine cycle as basis for the worldwide steady state cycle (WHSC)

The specification of the load points was aligned to the joint frequency distribution of the reference transient engine cycle. The motoring phase was considered separately (weighting 24%, as for the WHTC), engine power and emissions are set to zero for this phase. The weighting for idling was set to 14% in accordance with the WHTC. The number of 12 mode points was chosen in order to represent, as closely as possible, the same speed and load distribution as the transient reference engine cycle. The weighting factors are shown in Table 2.

The engine speed pattern for an individual engine under test has to be derived by denormalisation of the reference speeds using equation 1 (see page Equation 1).

	Motoring	engine load				
nnorm_ref		0%	25%	50%	75%	100%
Motoring	24.0%					
0%		14.0%				
30%			7.0%			
40%			10.0%	3.0%	4.0%	
50%			12.5%	10.0%	4.0%	2.5%
65%			4.0%			2.5%
75%						2.5%

Table 2: Mode points and weighting factors for the first draft of the worldwide steady state cycle (WHSC)

0.5 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 worldwide cycle. As these are the only differences they seem not to be invincible barriers for the applicability of the WHTC cycle as representative worldwide harmonised heavy-duty emissions test cycle.

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

0.6 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.

0.7 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 to 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 6). 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.

The results for the WHSC are in good accordance with those of the WHTC.

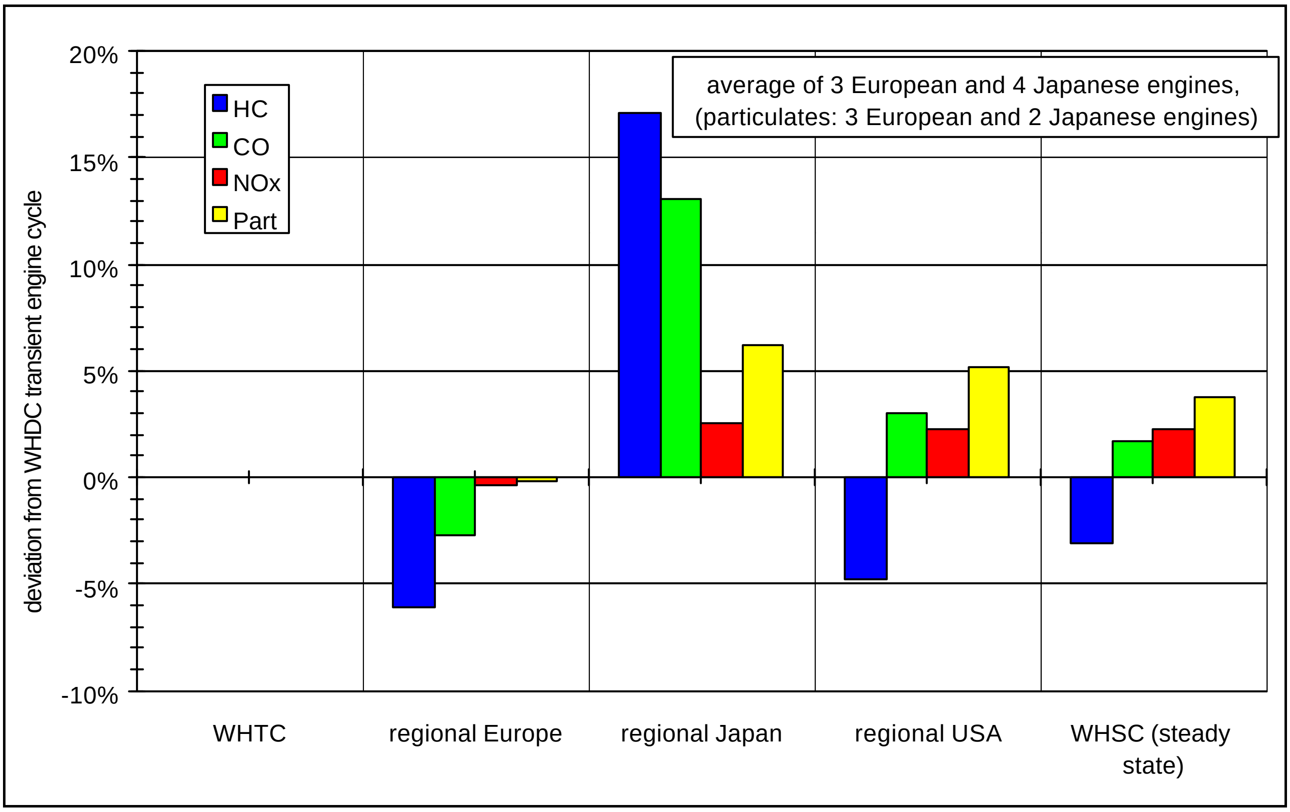

Figure 6: Results of the quasistatic emission calculation, differences between the WHTC, the WHSC and the regional transient cycles

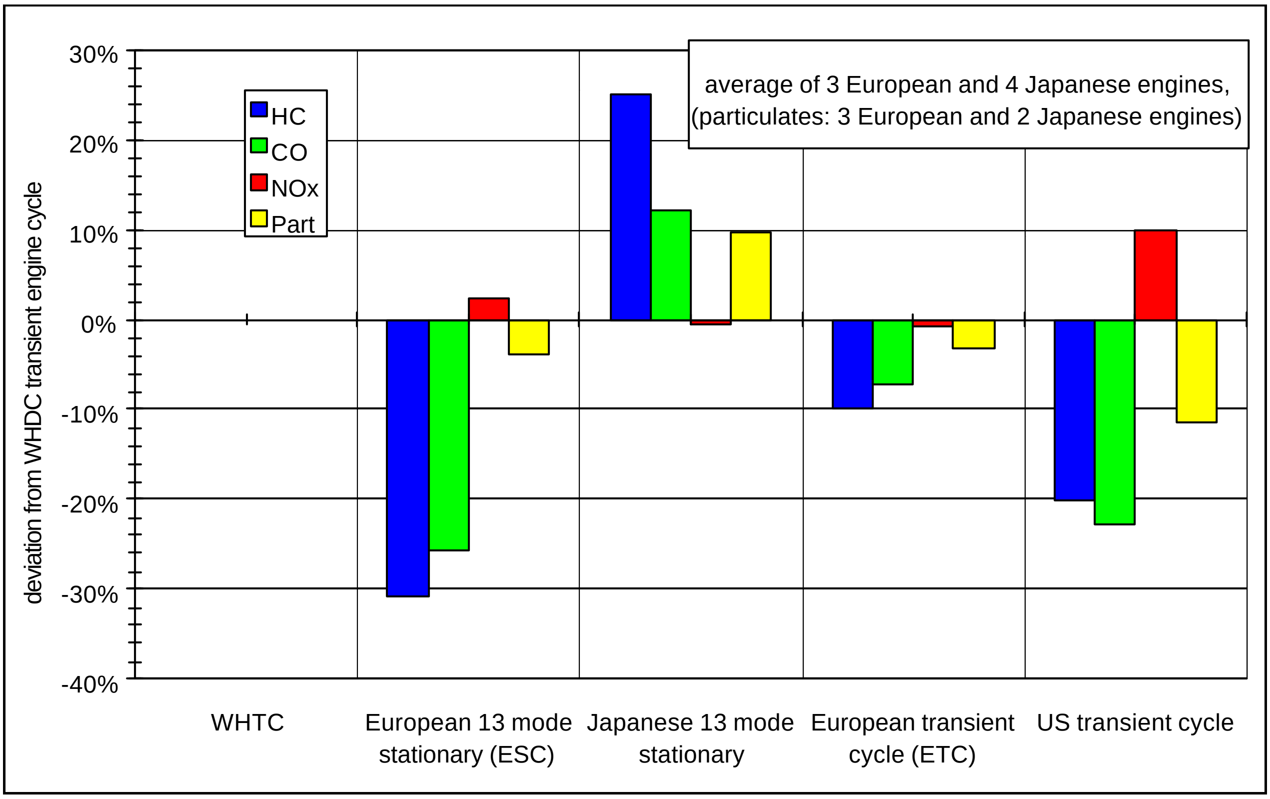

Figure 7: Results of the quasistatic emission calculation; differences between the WHTC transient engine cycle, the ETC, the ESC, the Japanese 13 mode test and the US-transient cycle

In Figure 7 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 8 to Figure 10) 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 worldwide harmonised emissions test cycle.

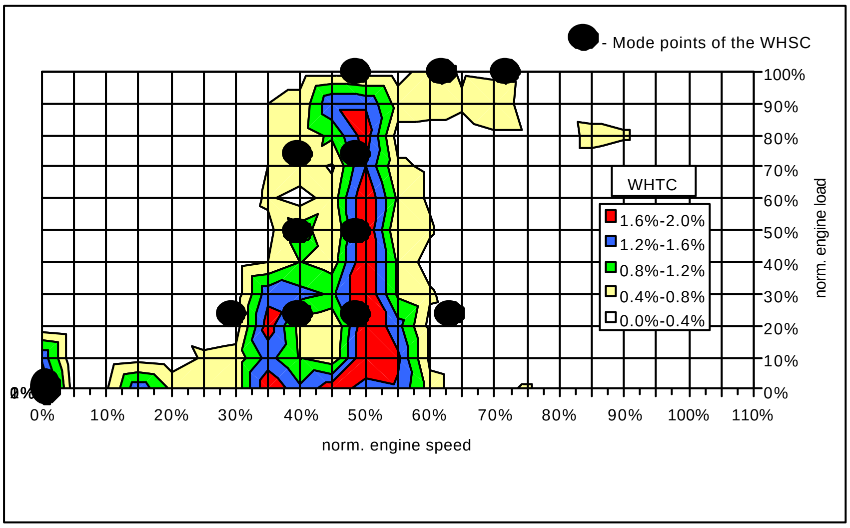

Figure 8: Engine speed/load distribution of the WHTC and WHSC

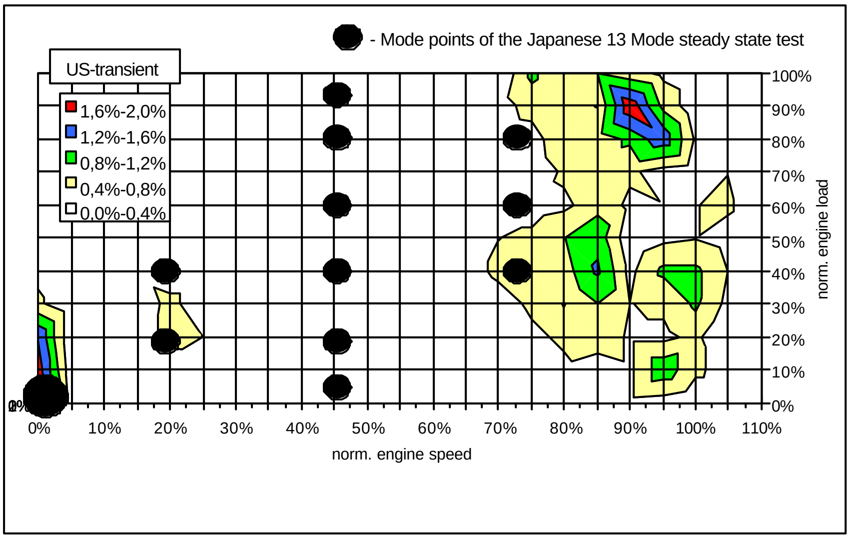

Figure 9: Engine speed/load distribution of the US-trans. cycle and the Japanese 13 mode test

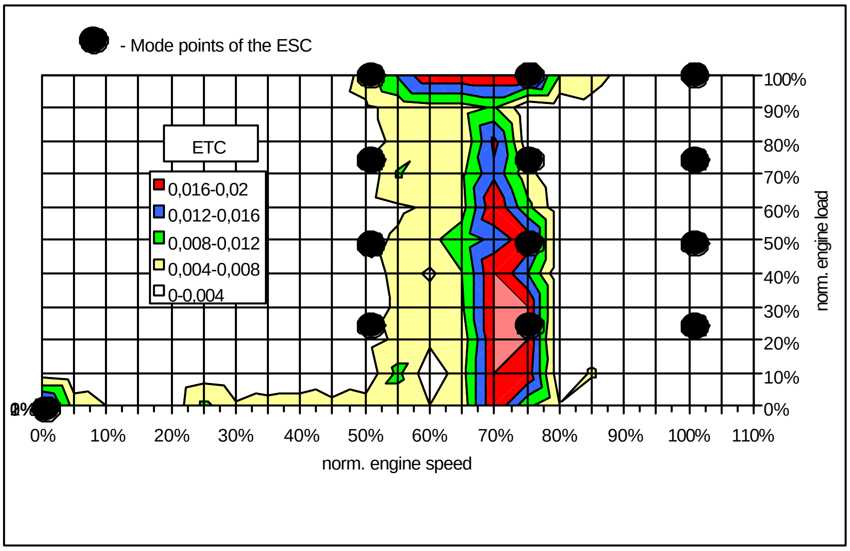

Figure 10: Engine speed/load distribution of the ETC and ESC

0.8 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 worldwide 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 worldwide 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.

1 Introduction

Type approval for exhaust emissions from heavy duty vehicles is generally conducted on an engine test bench where the engine is running under defined speed/load conditions.

In Europe, new engines are type approved on either the European Steady state Cycle and Load Response Test (ESC/ELR) which is a 13-mode test including transient smoke measurement on the ELR, and/or the European Transient Cycle (ETC), which consists of transient operation and includes elements of motoring sections.

A 13-mode steady state cycle is also used in Japan but with different modes compared to the European cycle. In the USA, the US transient cycle (FTP) is used, this has an engine speed / engine load pattern significantly different from the ETC.

The GRPE (Group of Reporters on Pollution and Energy) of the United Nations Economic Commission for Europe (UN-ECE) is responsible for the development of the technical framework of emissions regulations.

At its 34th session in June 1997, GRPE mandated the ad-hoc group WHDC with the development of a "**W**orldwide harmonized **H**eavy **D**uty **C**ertification procedure. Coordinated by the subgroup "Fundamental Elements" (FE), a research program was jointly conducted since October 1998 by TNO Automotive (The Netherlands) and TÜV Automotive (formerly FiGE, Germany). The Netherlands Ministry of the Environment (VROM) and the German Federal Environmental Agency (UBA) funded this program.

2 Objectives and Approach

The objective of the research program was to develop a world harmonised engine test cycle for the type approval test of engines for heavy-duty vehicle that is

- representative for worldwide real-life HD engine operation,
- gives highest potential to control real-life emissions,
- applicable to state-of-the-art and future technology,
- matches emissions in relative terms for accurate ranking of different engines/technologies

This means that the test cycle has to include all kinds of relevant real life operations with appropriate weightings. Furthermore the engine cycle has to be developed in a way that provides the basis for the most effective procedure to control real-life emissions, for current and future engine technologies (future engine designs as well as after treatment systems) and for engines running on alternative fuels.

The applicability of the harmonised engine test cycle for different world regions (Japan/Asia, the USA, Europe) had to be demonstrated by comparing it with regional cycles also developed within this project.

The classical way for cycle development used so far has been a two-step approach: 1st step: Creation of a reference database by combining in use data with statistical information about engine operation. 2nd step: Derivation of an engine test cycle from this database by statistical methods. This approach leads to solutions that are only representative for engine operation of the time and for which the measured in use data is unlikely to be applicable for future technologies. A comparison of driving behaviour data from different time periods led to the conclusion that the driving behaviour in terms of vehicle speed and normalised power (normalised to rated power) is much more stable over time than engine speed and engine load pattern, which can change significantly with changes in engine technology. For this reason the following, more appropriate four-step approach was adopted:

Step 1: Creation of a **reference database** (driving pattern), including all real-life situations in a representative way and classified for all important influencing parameters.

Tools: a) Classification matrix for the most important influencing parameters on engine operation of HD vehicles,

b) In-use driving behaviour data,

c) Weighting factors for each cell of the classification matrix

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

Tool: Combination of database modules, chi square statistics

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

Tool: Drive train model

Step 4: Development of a **reference transient engine cycle** that best approximates the drive train model (step 4a). Development of a corresponding **reference steady state cycle** (step 4b).

Tool: Approximation and regression analysis

The four steps consist of nine main tasks, as presented in Figure 11. The validation of the procedure by quasi-static emission calculations was included in the project, but the validation by experimental tests will be an additional task in the WHDC work program and is not part of this research work.

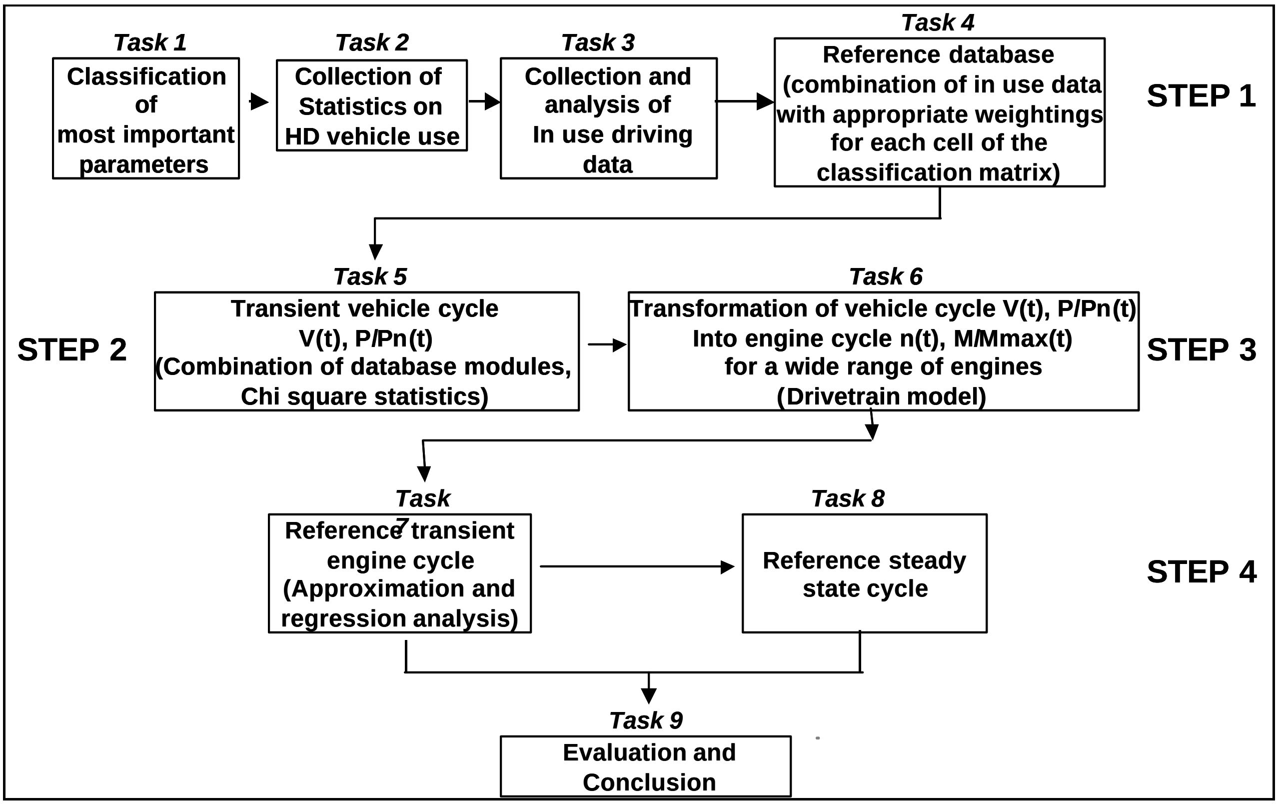

Figure 11: Different tasks for the development of representative engine test cycle

3 Classification Matrix and Collection of Statistics on HD Vehicle Use

The most important influencing parameters for HD vehicle driving behaviour are:

- road category (vehicle speed range),
- vehicle class,
- vehicle load and power to mass ratio,
- road gradient,
- traffic load and traffic control measures,

For worldwide harmonisation, the region of the world must also be taken into account.

The nominal power to mass ratio range of a vehicle is defined by the rated power of the engine, the kerb mass of the vehicle and the max. payload. The vehicle load determines the actual value. The power to mass ratio influences mainly the engine load and principally also engine speed and vehicle acceleration.

The road gradient determines the engine load and vehicle acceleration and is therefore also an important parameter. However, the road gradient is difficult and expensive to accurately monitor on a vehicle and for that reason in most cases it is not measured. Also, the route of the instrumented vehicles is, in most cases, not known. For these reasons, the road gradient was not included in the classification matrix.

Statistical information on traffic conditions and traffic control measures is generally unavailable from each country. So, the collected in use data had to be considered as representative with respect to these parameters.

Finally, different regions, different vehicle classes with power to mass ratio subclasses and different road categories were included in the final classification matrix (see Table 3).

Vehicle category	Power-to-mass ratio (kW/ton)	Region	Road type	Valid number of combinations (cells)
Light and Rigid trucks, incl. Special purpose trucks and coaches	3 classes	USA Japan Europe	Urban Rural Motorway	27
Trucks with trailers and semi-trailers	3 classes	3 classes	3 classes	27
Public transport buses	1 class	3 classes	2 classes	6
			sum	**60**

Table 3: Final classification matrix

The next goal was to fill each cell of the classification matrix with time data proportional to the total operating time of HD vehicles in real-life. This resulted in weighting factors for the in-use driving data that were used to create the reference databases. The statistical information described below was used as input information for calculating these weighting factors.

The collection of worldwide statistical information on HD vehicle use proved to be very difficult. Not only was the detailed classification of the required information a problem, but also the statistics from widely different sources were usually not coherent. In cases where information was not available or not reliable, expert views were sought and applied (from traffic consultancies, transport associations, the industry, TNO Automotive, TNO Inro and TÜV Automotive). In summary, sufficient conclusions could be derived from the statistical information received, combined with these expert views, as to the composition and use of the vehicle fleet in the three different regions of the world.

The final weighting factors are shown in Table 4. The information sources, the method to define power to mass ratio classes and the method to calculate the time shares and the weighting factors for the classification matrix are described in detail in the 2nd interim report, chapter 5 [2].

		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 4: Classification matrix with weighting factors

4 Collection and Analysis of In-Use Driving Behaviour Data

By the end of February 1999, TÜV/TNO received driving behaviour data of 65 different vehicles from Australia, Europe, Japan and USA:

- 9 light trucks (max. mass below 7,5 t) with a total mileage of 2.213 km
- 20 rigid trucks (max. mass 7,5 t or more) and 1 coach with a total mileage of 13.428 km
- 18 trailer trucks with a total mileage of 56.324 km
- 11 public transport buses with a total mileage of 2.473 km

The following steps/analyses were carried out:

- **Data processing** (check for inconsistencies, data smoothing, calculation of acceleration etc.)
- **Microtrip analysis** (standstill percentage, average speed and standard deviation of speed) Microtrips are defined as subsequent v(t) pattern that start from standstill and end at standstill.
- **Frequency distributions** (vehicle speed, acceleration, normalised engine speed and normalised engine power)
- **Vehicle speed influence** on acceleration, normalised engine speed
- **Power to mass ratio influence on** acceleration, normalised engine speed, normalised power

Detailed information about this analysis is given in the 1st interim report, chapter 4.3 [1]. The results are summarized as follows:

- The collected data covers 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 stand-still percentage and vehicle speeds
- Sections with the same average speed value show no 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 (rated power divided by the actual mass of the vehicle) influences the engine load, the engine speed and the vehicle acceleration. But the influence of power to mass ratio on engine speed and acceleration is masked by the traffic condition, especially by traffic load.
- Japanese trucks have significantly higher power to mass ratios compared to trucks in other regions in the world

After the analysis had been completed, additional in use-data for rigid trucks was delivered from the USA and further data are expected. It is planned to use these data for a more extensive validation of the US database.

5 Development and Characteristics of the Reference Database

The reference database is defined as containing a representative driving pattern (vehicle speed and normalised power data) for each cell of the classification matrix in an appropriate mix with respect to its weighting factors. The development of the reference database includes the following steps:

- Assignment of identification numbers (ID‘s) to the in-use driving data according to the classification matrix.
- Transposition of the ID in-use driving data of each cell into the reference database proportional to their weighting factors.

Besides the world harmonised reference database additional reference databases for each region were developed in order to be able to validate regional differences.

Although the reference databases are representative for the actual use of HD vehicles, they are far too long to be used as a test cycle for laboratory testing. Before the desired engine test cycles can be developed, the reference database must be compressed into a transient vehicle cycle in terms of vehicle speed and normalised power, having a suitable test length and demonstrating similar characteristics as the corresponding reference database.

Based on experience from earlier research projects, the following parameters were chosen as descriptors of the characteristics of the reference database and were used in a later step as quality criteria for the transient vehicle cycle:

- v_{ave}, (average vehicle speed)
- t_{stop}, (average stop time)
- n_{stop}, (number of stops per km)
- t_{seq}, (average sequence time)
- P, dP/dt distribution (P = engine power)

- v, a distribution (v = speed, a = acceleration)
- $P_{ave,norm}$ (average power during time the engine delivers power to drive shaft)
- RPA (relative positive acceleration))
- pf (Propulsion factor, % of time the engine delivers power to drive-shaft during operation)
- RED (Relative energy demand, energy demand of engine, related to distance driven and rated engine power)

The average normalised positive engine power is defined as the percentage of the available (normalised) engine power that is used during the cycle, excluding motoring conditions:

$$P_{ave,norm} = \frac{1}{t}\sum_{i=1}^{i=t} P_{i,norm}$$ **_Equation 2_**

With: $P_{ave,norm}$ = Average normalised positive engine power during non-motoring time (%)

$P_{I,norm}$ = Normalised positive engine power at time i during the cycle

In addition to the average vehicle speed, the dynamics of the vehicle speed pattern is of great importance. As an example, the same average vehicle speed can be the result of vehicle cruise conditions or of highly dynamic vehicle operation. The cycle parameter that describes the dynamics of the vehicle speed pattern best is the Relative Positive Acceleration (RPA). RPA is calculated from the power that is needed for all vehicle accelerations in the cycle, divided by the distance driven:

$$RPA = \frac{\int_0^T (v_i * a_i^+)dt}{x}$$ **_Equation 3_**

With: RPA = Relative Positive Acceleration

v_i = Vehicle speed at time i

a_i^+ = Vehicle acceleration at time i

x = Distance driven

RPA in combination with the average vehicle speed are the two most important parameters to describe a vehicle speed pattern.

The propulsion factor is defined as the percentage of time the engine delivers power to the drive shaft during operation:

$$pf = \frac{t_{non-motoring}}{t_{op}}$$ **_Equation 4_**

With: pf = Propulsion factor

$t_{non-motoring}$ = Time the engine delivers power to the drive-shaft during operation

t_{op} = Operational time (time the engine is running)

The Relative Energy Demand (RED) is the energy use of the engine (at the drive shaft) to drive the cycle, related to the distance driven and the rated engine power. This cycle parameter is directly related to the fuel consumption and the emission factors and is linked to the engine as well as the vehicle behaviour. The RED can be calculated from the average normalised engine power, the propulsion factor and the average operational vehicle speed:

$$RED = P_{ave,norm} * \frac{pf}{\bar{v}}$$

Equation 5

With: RED = Relative energy Demand

V bar = Average operational vehicle speed (during time the engine is turned on)

The characteristics of the reference databases are shown in Table 5

Since the reference databases are representative of real-life driving, their characteristics can be used to compare the three regions and the worldwide situation. The following observations are made:

- Since the European database contains a high fraction of motorway traffic, the average normalised engine power and the average vehicle speed are relatively high compared to those of the other two regions. On the other hand the RPA is significantly lower.
- Unlike Europe, the Japanese database contains a high fraction of urban traffic. This results in a relatively low average normalised engine power and average operational vehicle speed, compared to those of the other two regions. Consequently, the RPA is significantly higher.
- The parameters of the US database are closest to the worldwide database.

Characteristic values	Europe	US	Japan	Worldwide
Average P_{norm} (%)	29.4	26.1	20.0	25.8
Propulsion factor (%)	77.0	76.4	78.6	77.2
Rel. energy demand (RED) (kWh/km/kW)	0.0048	0.0050	0.0052	0.0050
Average operational speed (km/h)	47.2	39.6	30.2	40.0
Relative Positive Acceleration (RPA) (m/s^2)	0.08	0.09	0.12	0.09
Number of stops per kilometre	0.40	0.52	1.12	0.59
Average stop time (s)	17.6	21.4	18.0	18.8
Average sequence time (s)	172	153	88.5	135
Time accelerating (%)	23.9	24.0	24.0	24.0
Time decelerating (%)	20.8	20.3	20.6	20.6
Time cruising (%)	46.1	43.3	38.6	43.1
Time stop (%)	9.3	12.4	16.9	12.3

Table 5: Characteristics of the reference databases

6 The Worldwide Transient Vehicle Cycle (WTVC)

As indicated above, the reference database is too long for laboratory testing. Therefore, the database was compressed to a derivative with the same characteristics as the database and a suitable test length. This derivative is a cycle defined by vehicle speed and normalised power, and is referred to as the **worldwide transient vehicle cycle (WTVC)**. In order to be able to validate regional differences, corresponding regional vehicle cycles have been created.

This task was performed in the following steps for the world harmonised database and each of the three regional databases:

1. Assign identification numbers (IDs) to each microtrip of the reference database.
2. Calculate individual values of characteristic parameters for each microtrip.
3. Choose a series of microtrips and combine them to a test cycle.
4. Calculate individual values of characteristic parameters for this cycle.
5. Compare these values with the corresponding values of the representative database by a “Goodness of fit test” based on “chi-squared statistics”.

6. Repeat steps 3 to 5 times and choose that cycle whose values for the characteristic parameters are closest to those of the representative database.

The cycle time was chosen to be 30 minutes (1800 s.), like for the ETC. The time fractions of the urban, rural and motorway part follow from the statistics on vehicle use, and are different for the three regions considered.

Important elements of the method are the lengths of driving sequences and stops. A driving sequence is defined as a vehicle speed pattern between two stops. The lengths of the sequences and of the stops were designed to have a distribution similar to those of the reference database.

The vehicle speed-acceleration matrix (v,a-matrix) is the best characterisation of the vehicle speed driving pattern, simply due to the fact that all cycle characteristics or parameters can be derived from this matrix. For the engine power, a similar reason can also be followed, resulting in a two-dimensional matrix of normalised engine power (P) and the change of the normalised engine power in a certain time step (the 'P,dP/dt' matrix).

Therefore, the v,a- and P,dP/dt matrix of the desired test cycle must display a pattern similar to that of the reference database in order to be representative for real-life driving.

The characteristics listed earlier in Table 5 were used for comparison. Once the best combination of sequences had been established, the test cycle was finished by arranging the sequences as well as the stops in the most logical order in real-life operation, i.e. by putting the urban, rural and motorway parts behind each other for the world test cycle and each of the three regions. The separation between the road categories enables the application of different weighting factors for the different parts, for example to apply the test cycle for specific vehicles.

The complete method is described in detail in the 2nd interim report, chapter 7 [2].

The transient vehicle cycles are shown in Figure 12 to Figure 15 in terms of vehicle speed v(t) and normalised engine power Pnorm(t) over time. The normalised engine power pattern is corrected for gearshifts. The percentages of the three road categories are compared in Figure 16, Figure 17 shows the percentages of standstill, Figure 18 the average speeds and Figure 19 the average normalised positive power values.

In an additional step, the average engine power normalised to rated power of the vehicle cycles was compared with the values of the present and past heavy-duty approval test cycles for each of the three regions. The results are shown in Figure 20 to Figure 22. The present heavy duty approval test cycles are defined in terms of normalised engine speeds and percentages of engine load at these speed values. Since the normalised engine power values depend on the full load power curve of the particular engine under test, the values shown in the above mentioned figures are based on an average engine.

Compared to the world-harmonised cycle and also to the European regional cycle, the average normalised engine power is higher on the present European approval test cycles by 27% (ETC) and by 66% (ESC) (Figure 20). The difference of the ETC is caused by the fact that the time fractions of the three road types are different. The urban time fraction of the ETC is lower compared to the European regional test cycle (33% against 41%). Since the average normalised engine power in urban traffic is significantly lower (see Table 5), the value of the combined test cycle is lower. The ETC is derived from in-use driving data of fully loaded trucks with a low power-to-mass ratio. The difference between the ESC and ETC is remarkable since they both are developed from the same database.

The average normalised engine power of the present approval test cycles in the US and Japan are comparable to the regional transient vehicle cycles that have been developed in this project.

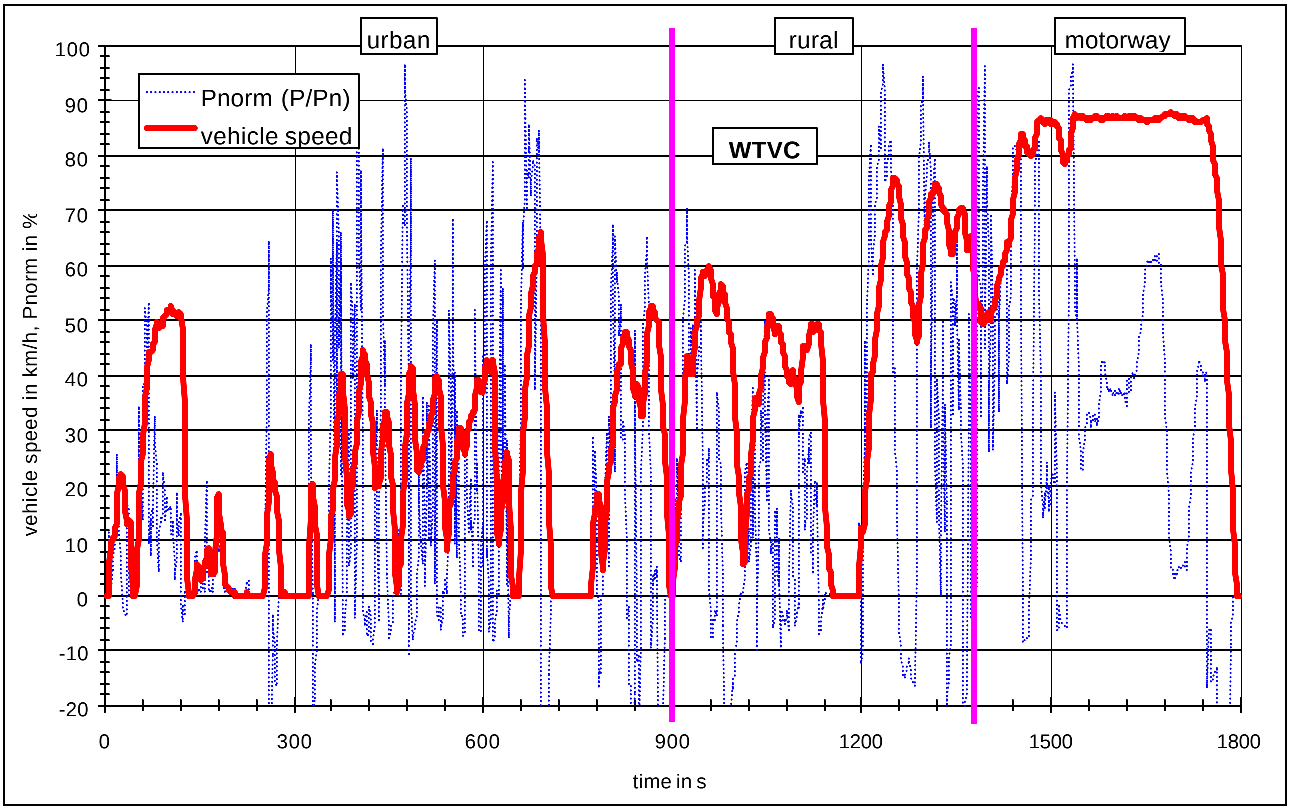

Figure 12: The World harmonised transient vehicle cycle (WTVC)

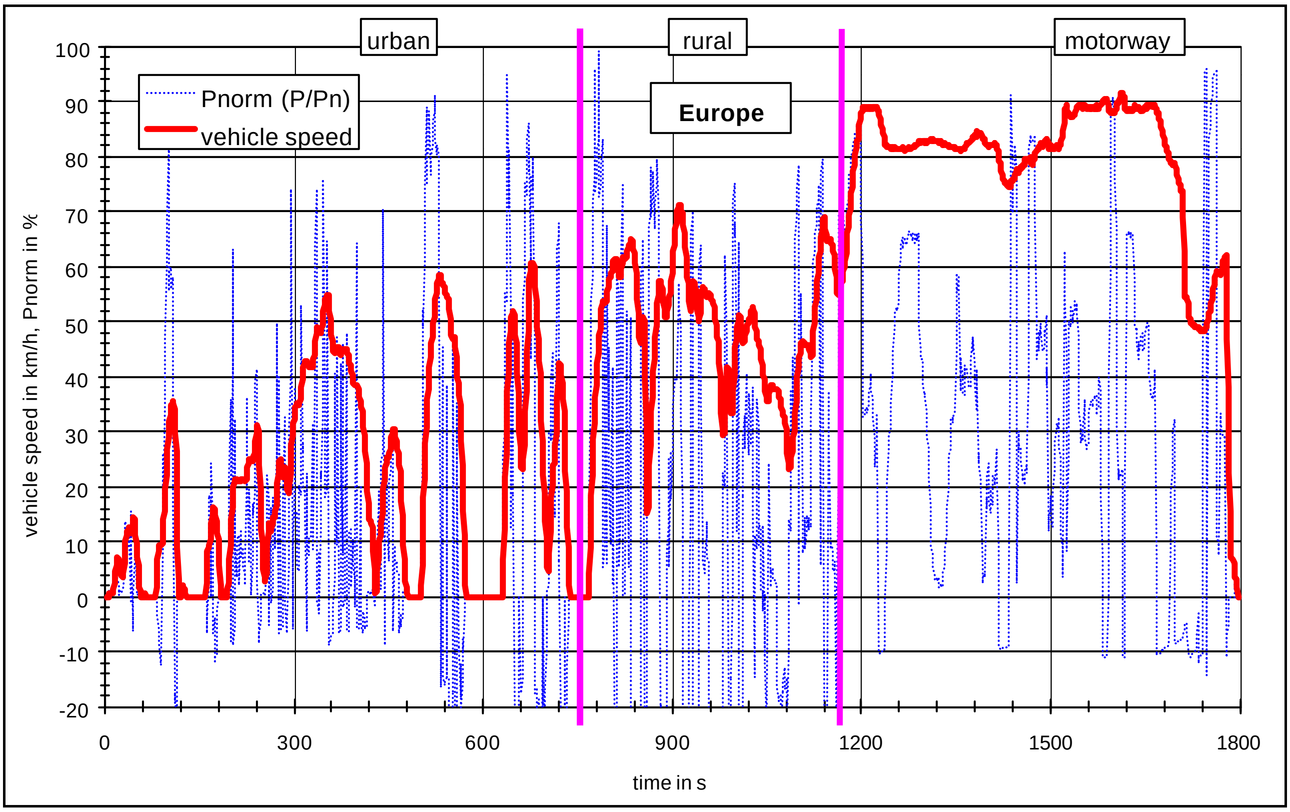

Figure 13: The European regional transient vehicle cycle

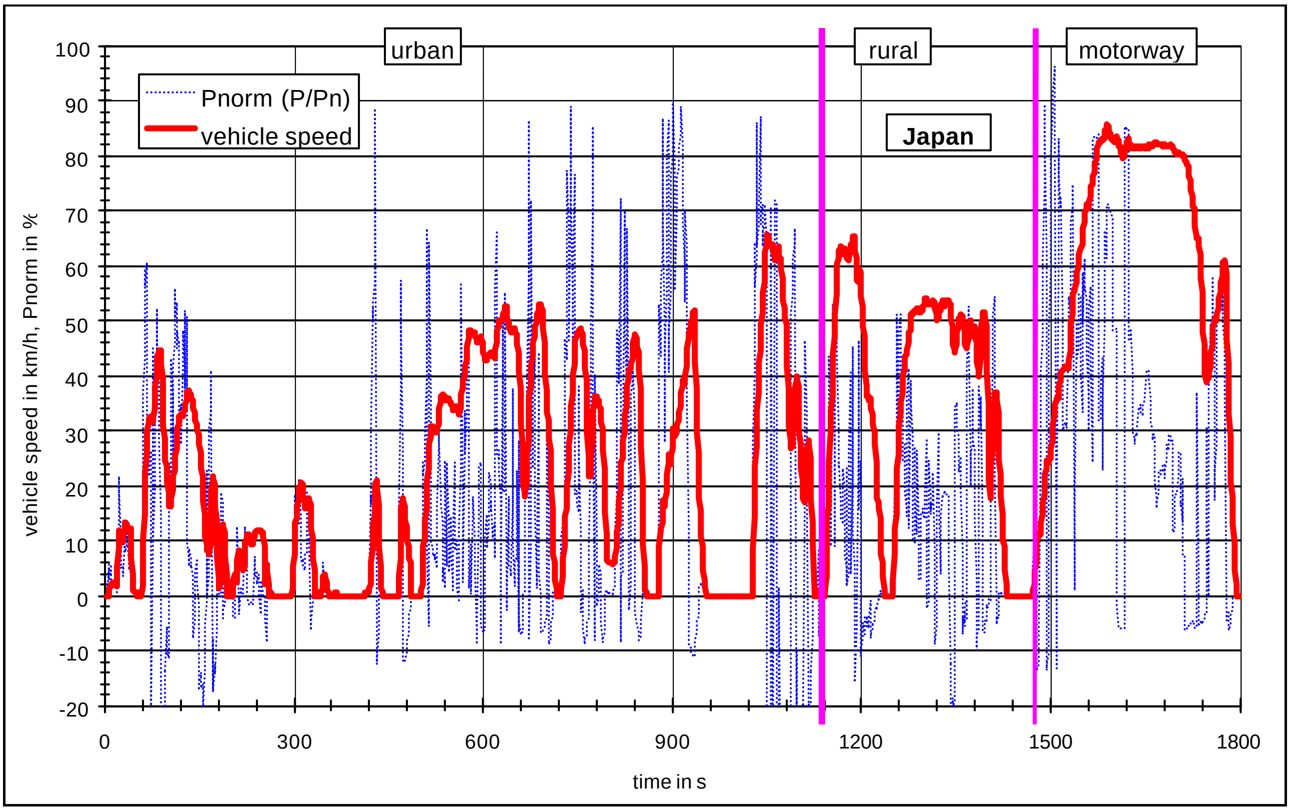

Figure 14: The Japanese regional transient vehicle cycle

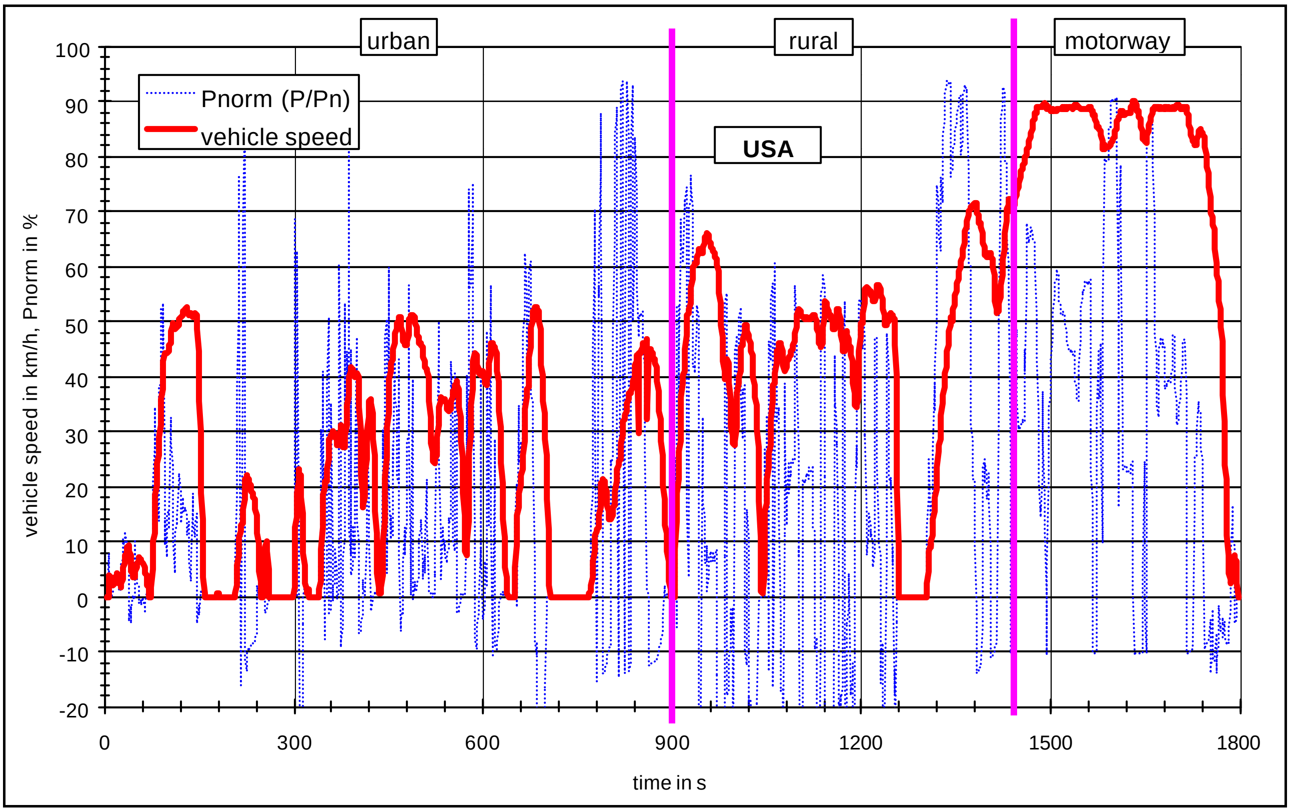

Figure 15: The US regional transient vehicle cycle

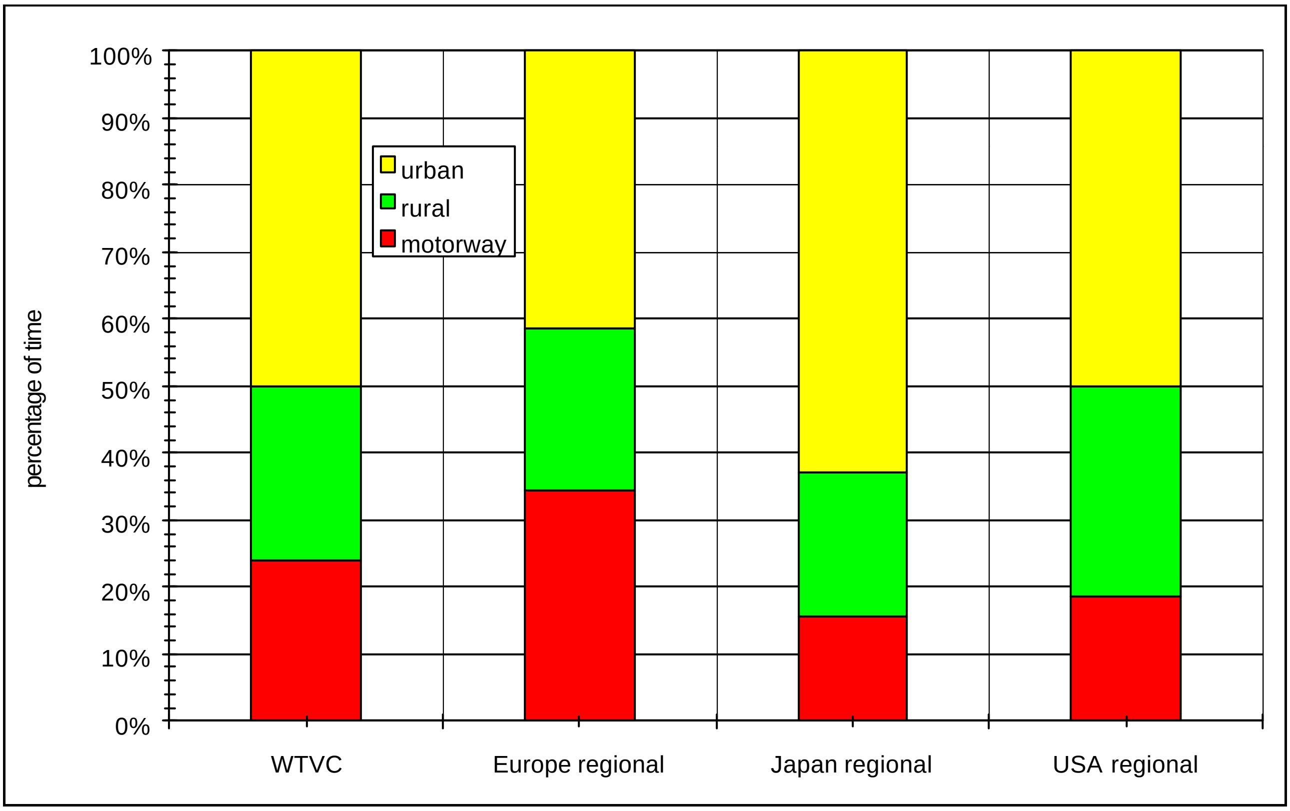

Figure 16: Composition of road categories for the transient vehicle cycles

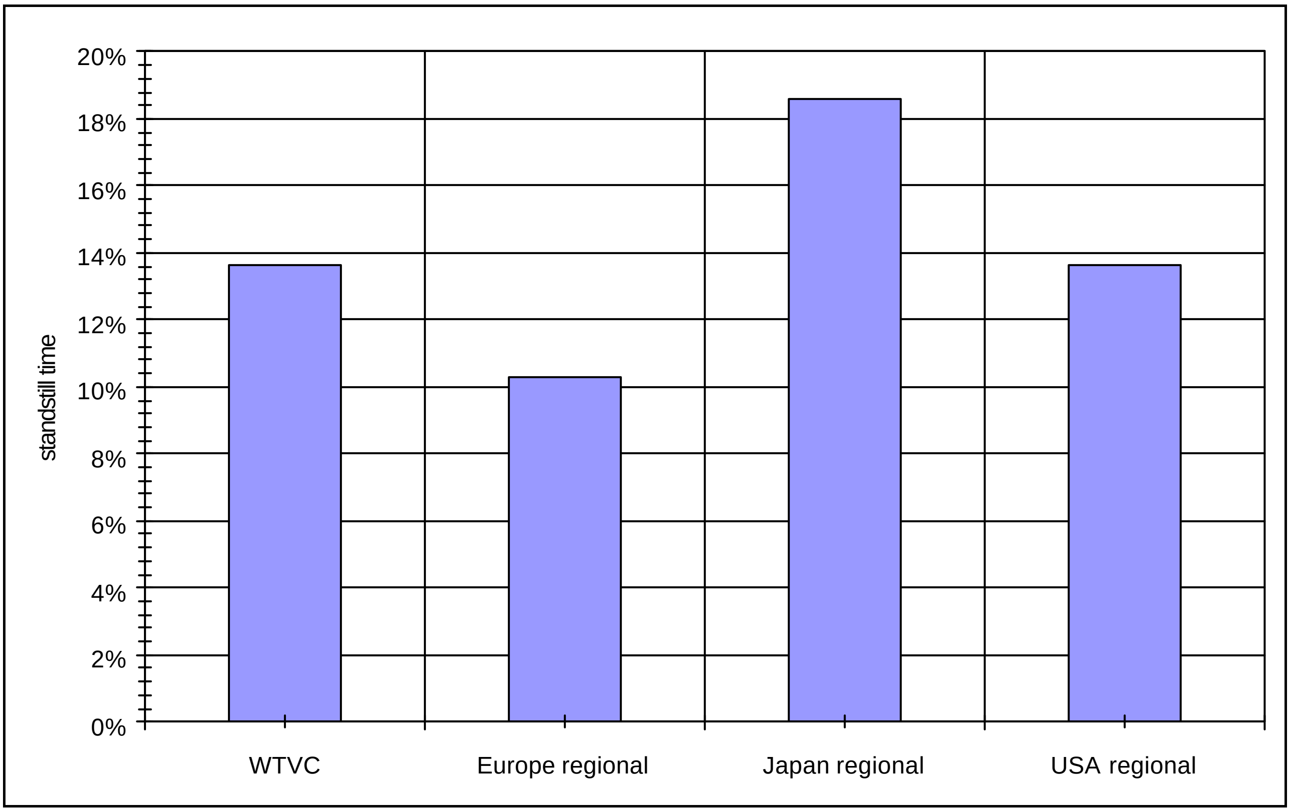

Figure 17: Percentage of standstill for the transient vehicle cycles

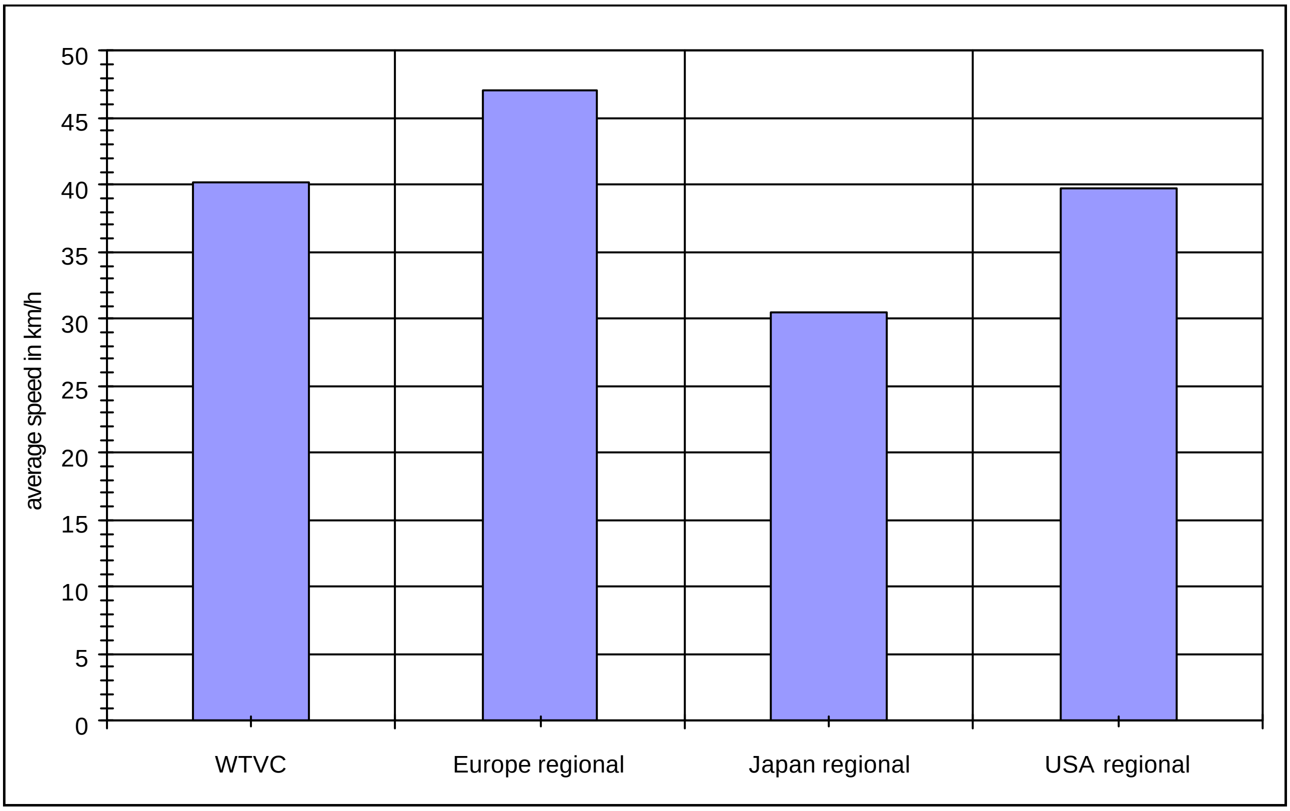

Figure 18: Average speed for the transient vehicle cycles

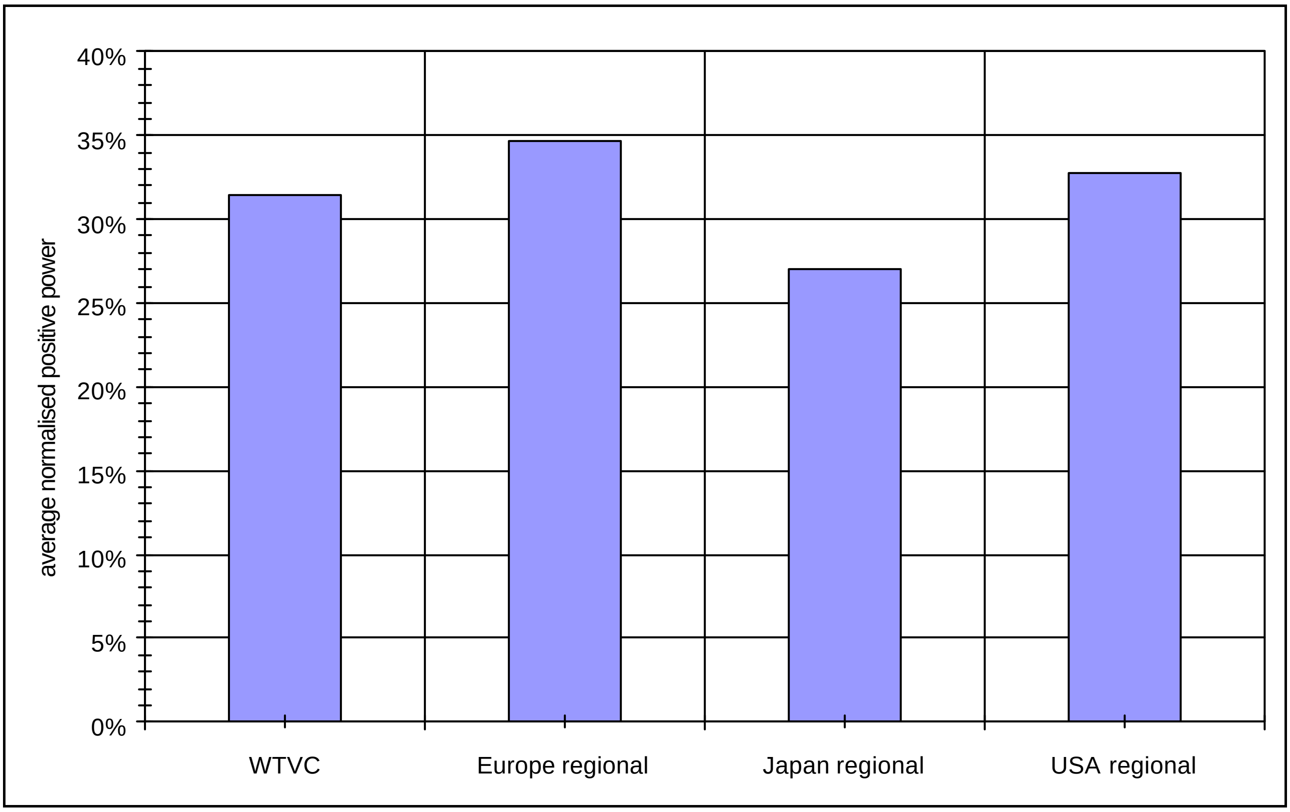

Figure 19: Average normalised pos. power for the transient vehicle cycles

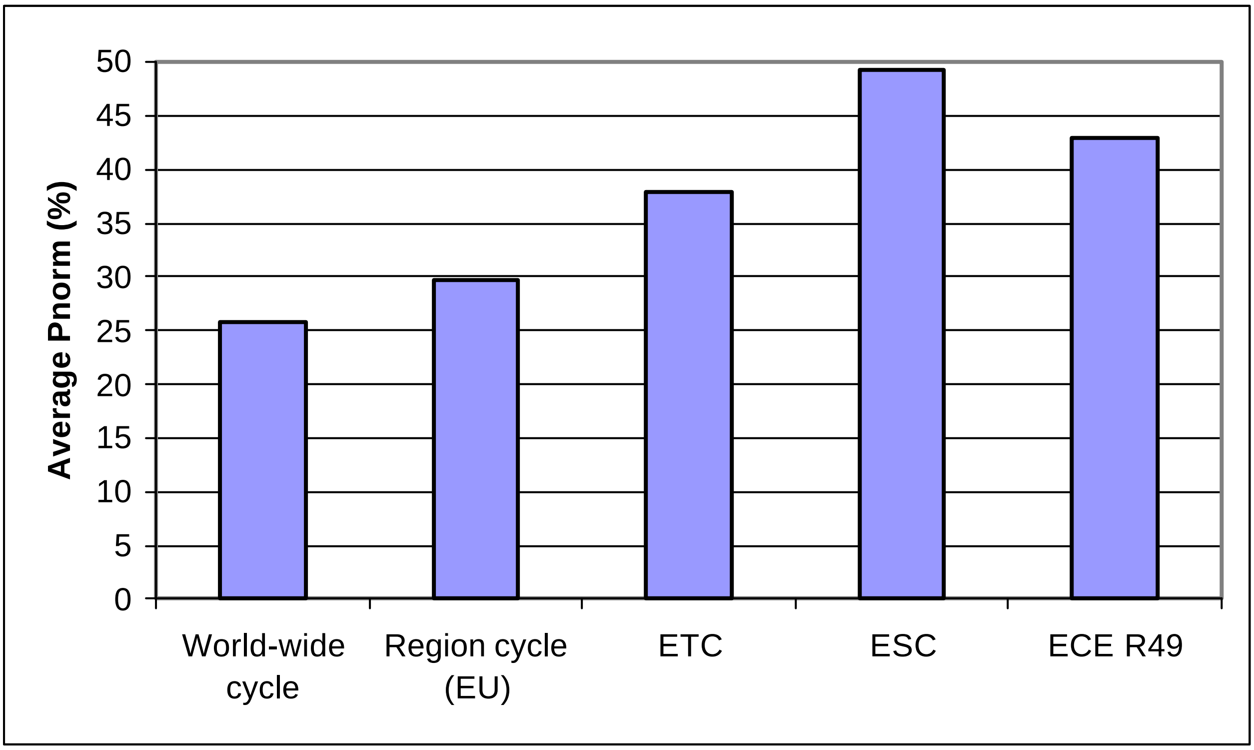

Figure 20: Comparison of average normalised engine power with European legislation test cycles

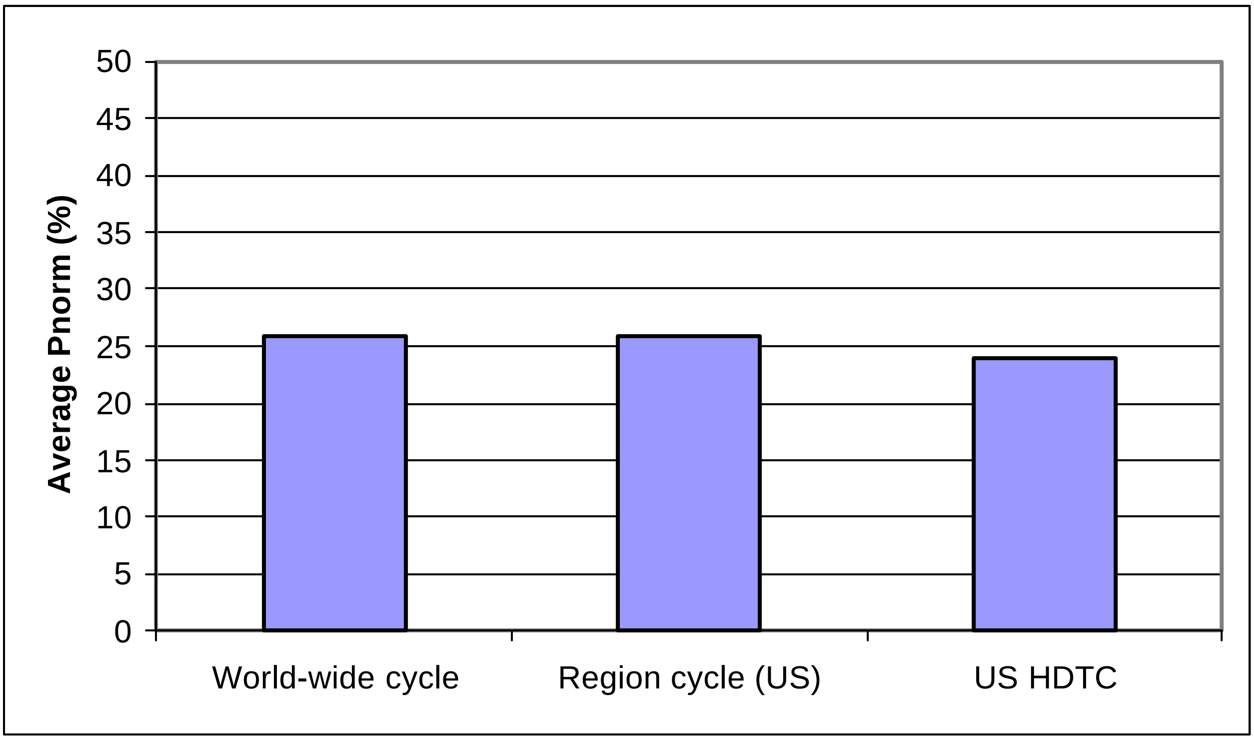

Figure 21: Comparison of average normalised engine power with US legislation test cycle

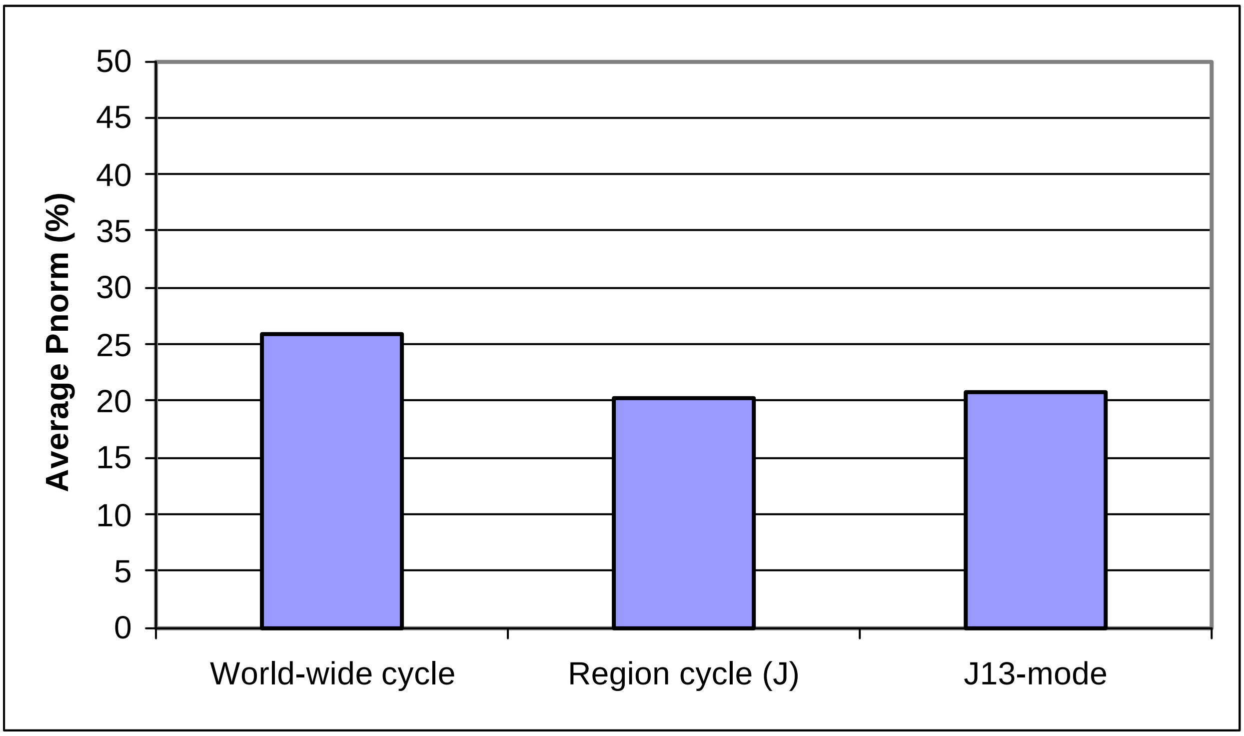

Figure 22: Comparison of average normalised engine power with Japanese legislation test cycle

7 Drive Train Model

The transient vehicle cycle(s) are v(t), Pnorm(t) pattern cycles. These patterns are much more stable over time than the engine driving patterns. To run the test on an engine test bench, these patterns were transformed into n(t), M(t) engine patterns. The characteristics of engine torque curves have changed over time and may further change in the future in order to minimise fuel consumption and to improve driveability in terms of high torque at low speeds. To make sure that the mode distribution of speed and torque during the test is in line with real life operation, a drive train model was developed for the transformation of the vehicle cycle into an engine test cycle.

The v(t), Pnorm(t) => n(t), M(t) transformation ensures the highest representativity for engines of different technologies and makes the method applicable also for future engine technologies. To calculate the output data (engine speed and engine load (P/Pmax(n)) on a second by second basis a drive train model was developed. This model consists of the following components (see Figure 23):

- a gearbox model,
- the full load power curve of the engine,
- characteristic engine speed values for the speed range and the preferred speed as basis for gear selection,
- algorithms for plausibility and consistency checks.

Unlike the existing cycles, this approach will lead to individual engine speed patterns that depend on the individual characteristics of the engine under test as is demonstrated below:

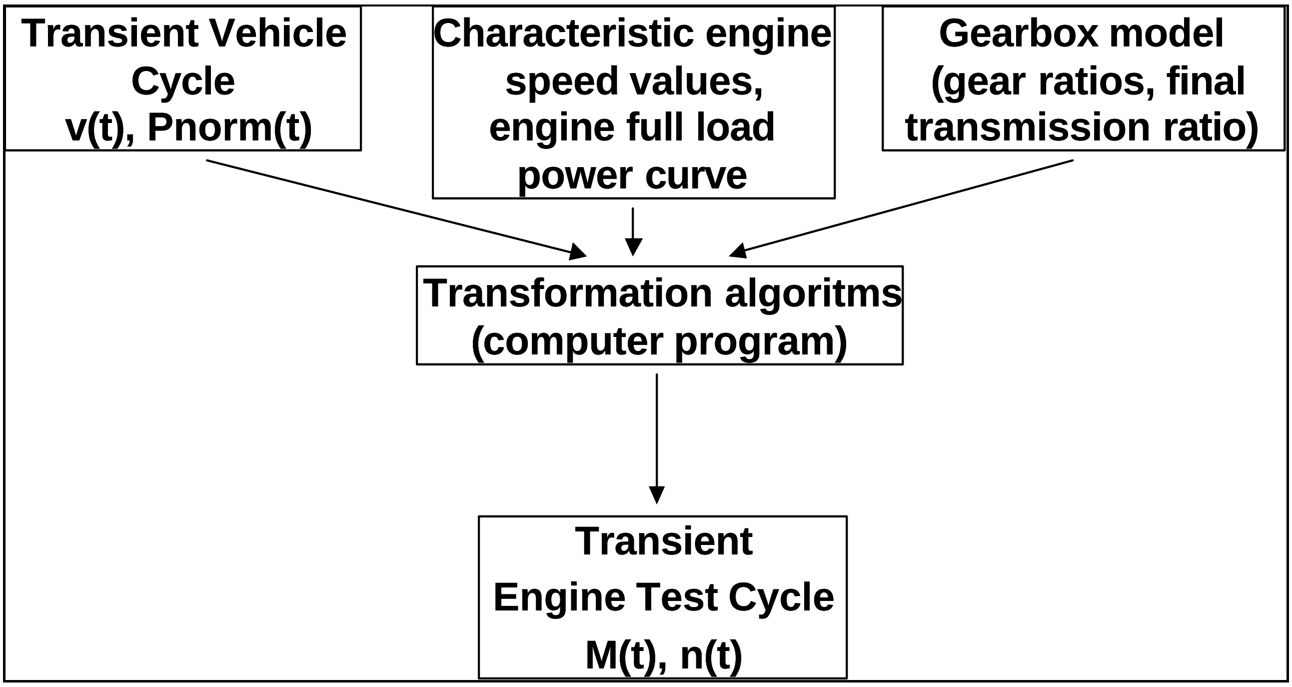

Figure 23: Block diagram of the drive train model

The following three characteristic engine speed values were used to select the appropriate gear:

- n_lo lowest engine speed where the engine produces 55% of rated power at full load,
- n_pref the minimum engine speed where the engine torque is maximum,
- n_hi the highest engine speed where the engine produces 70% of rated power at full load

n_hi and n_lo define the engine speed range for real-life operation. The speed range between idling and n_lo is only used when starting from standstill or during gearshifts. The characteristic speed values are shown in Figure 24.

The analysis of the in-use data showed that above 15 km/h an engine speed range is used where enough power for accelerations is available, if required. This turned out to be 55% of rated power as the lower limit for the power and is defined as n_lo.

The definition of the upper end of the engine speed range is mainly oriented on cycle bypass prevention. Following the results of the in-use data the upper limit of the engine speed range could be described by the rated engine. For modern electronically controlled engines the rated speed might not be clear defined because the maximum power can be provided for a range of engine speeds. This leaves the door open for cycle bypass measures. To avoid this, n_hi is defined as the highest engine speed where the power at full load is 70% of rated power.

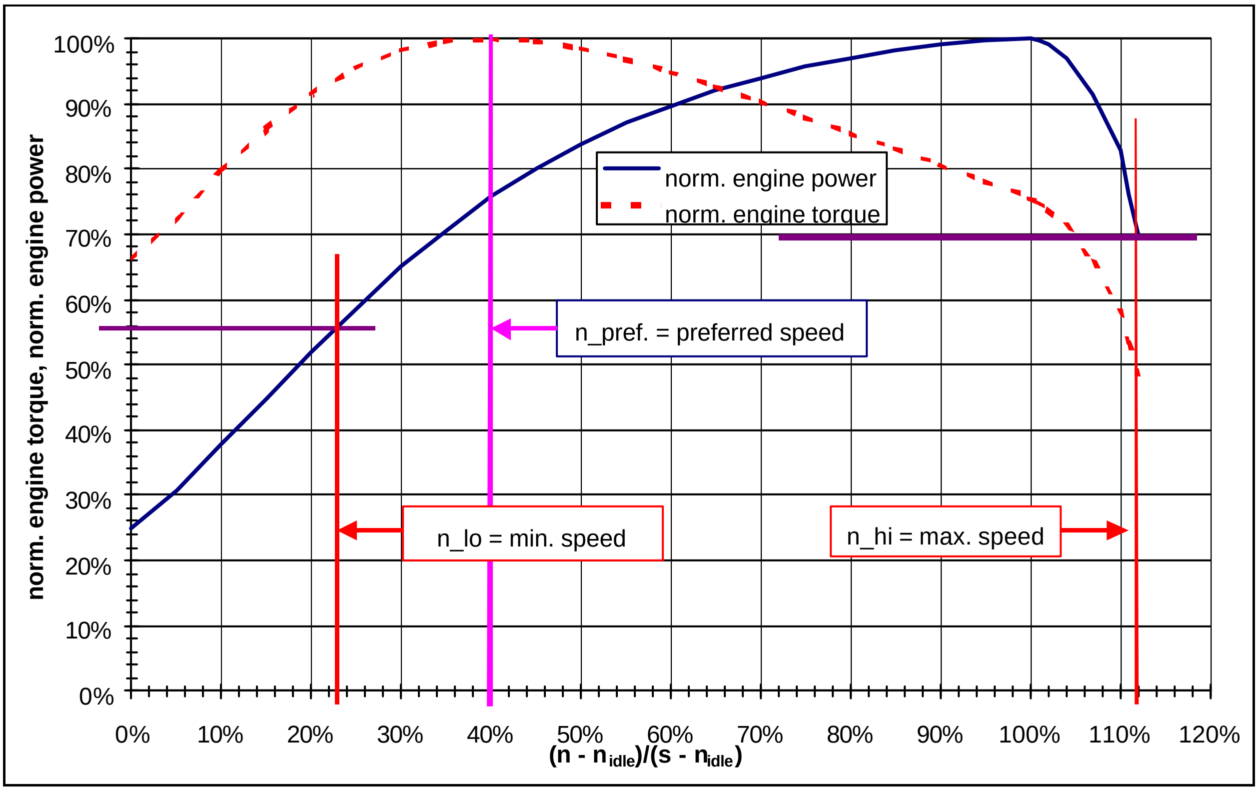

Figure 24: Characteristic engine speeds (engine torque and power at full load)

An 8-speed gearbox was chosen for the drive train model representing a good compromise over the whole range of engines. The gear ratios have been derived from the vehicle sample of the in use-data. Gears 3 to 8 are used for normal operation. Gears 1 and 2 are only used for uphill driving with extremely high gradients. For further details see the 2nd interim report, chapter 8 [2].

Finally an overall transmission ratio was defined. It was assumed, that the overall transmission ratio is linked to the target speed on motorways so, that the engine runs at the speed where the fuel consumption is minimised. Normally this is the lower end of the speed range where the engine torque is maximum. Therefore the overall transmission ratio was defined as the quotient of the minimum engine speed for maximum torque (at full load) and 87 km/h, the target speed on motorway. As a consequence, the highest gear is designed as an overdrive.

For each vehicle speed and normalised power pair the engine speed and the normalised power at full load at that speed are calculated for all gears. Those gears where the engine speed is between n_lo and n_hi and the normalised power is higher than or equal to P_norm can be used in practice. This requires an approximation of the full load power curve of the engine under test from (low) idling speed to n_hi.

In many cases, the use of more than one gear is possible, for example for cruising phases that do not demand high power values. So, an additional criterion is necessary for the gear choice. To be consistent with future technologies and with the definition of the above-mentioned overall transmission ratio, the preferred engine speed (n_pref) is defined as the minimum speed where the engine torque at full load is maximum. To avoid the possibility of this condition could leading to too low engine speeds, the preferred engine speed should be set to n_lo, if n_pref is lower than n_lo.

Figure 25 demonstrates the gear choice for different power demand. The chosen gear will be that for which the engine speed is closest to n_pref. The load factor is calculated by dividing the actual

Pnorm value of the vehicle cycle by the Pnorm value, which is available at full load for the chosen engine speed (Pnorm/(Pmax(n)/Pn)). **In summary, the drive train model fulfils the required transformation of the uniform vehicle cycle into the speed and load patterns for an individual engine.**

The drive train model has been created as a visual basic code program under MS ACCESS (Version 8.0) and tested by executing calculations with the whole reference database. To demonstrate the functionality of the drive train model two extreme full load power curves were chosen their normalised full load power curves are shown in Figure 26. These two curves build the envelopes of all other curves included in the analysis. n_lo is 26% normalised engine speed in one case and 43% in the other. The n_pref values are close to the n_lo values in both cases.

The transformation was carried out using the representative worldwide vehicle cycle. A section of the cycle is shown in Figure 27 and Figure 28. Engine 7, which has the higher torque, operates at considerably lower engine speed than would be seen in real life operation. The cumulative engine speed distribution over the cycle is shown in Figure 29. The distributions for the ETC and the US transient cycle are shown for comparison.

According to the differences in the characteristic engine speed values (n_lo, n_pref, n_hi) between the two engines the engine speed distributions of the engine test cycle are different. The most frequently used engine speeds differ by more than 14% normalised engine speed. The difference on the ETC is much smaller and on the US transient cycle nearly negligible. This demonstrates that the WHDC cycle is more representative of vehicle in-use driving behaviour than these two cycles currently used for engine type approval.

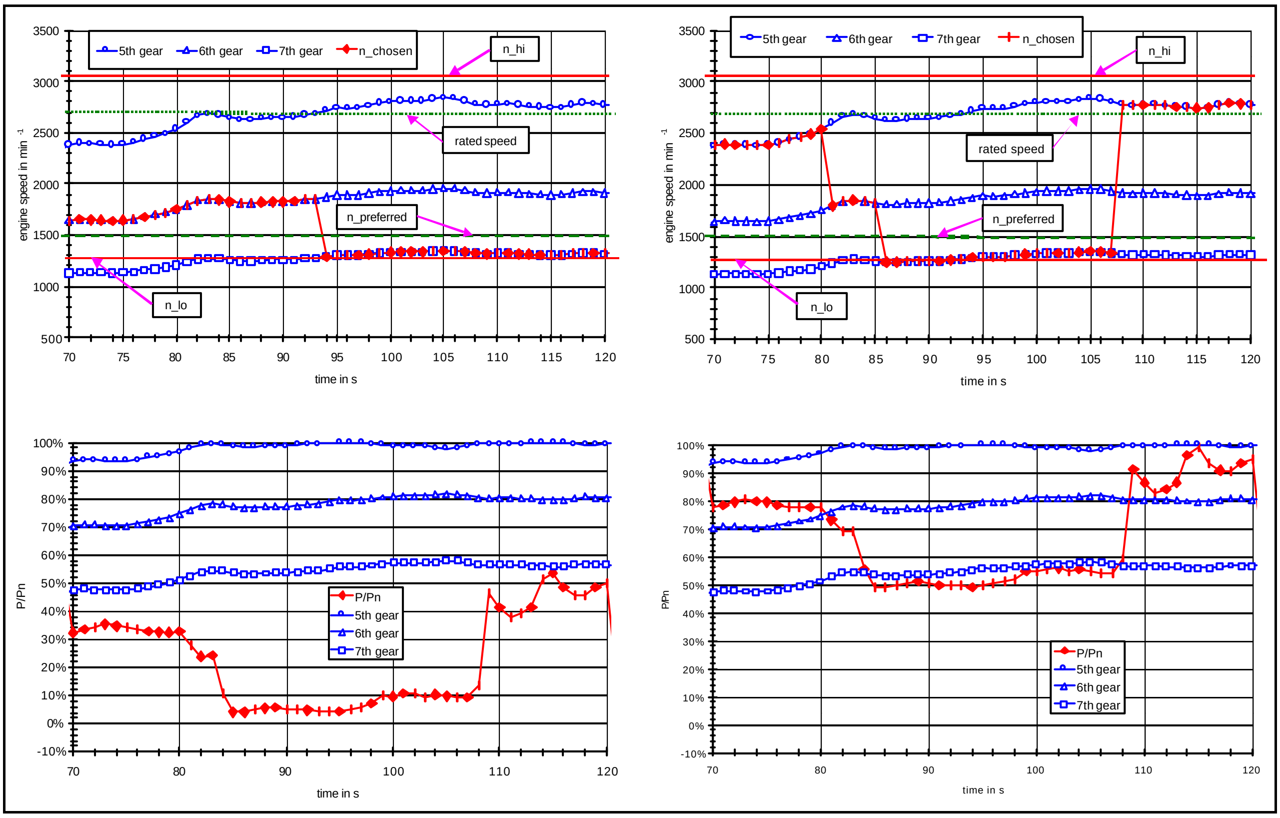

Figure 25: Gear choice examples for different power demand

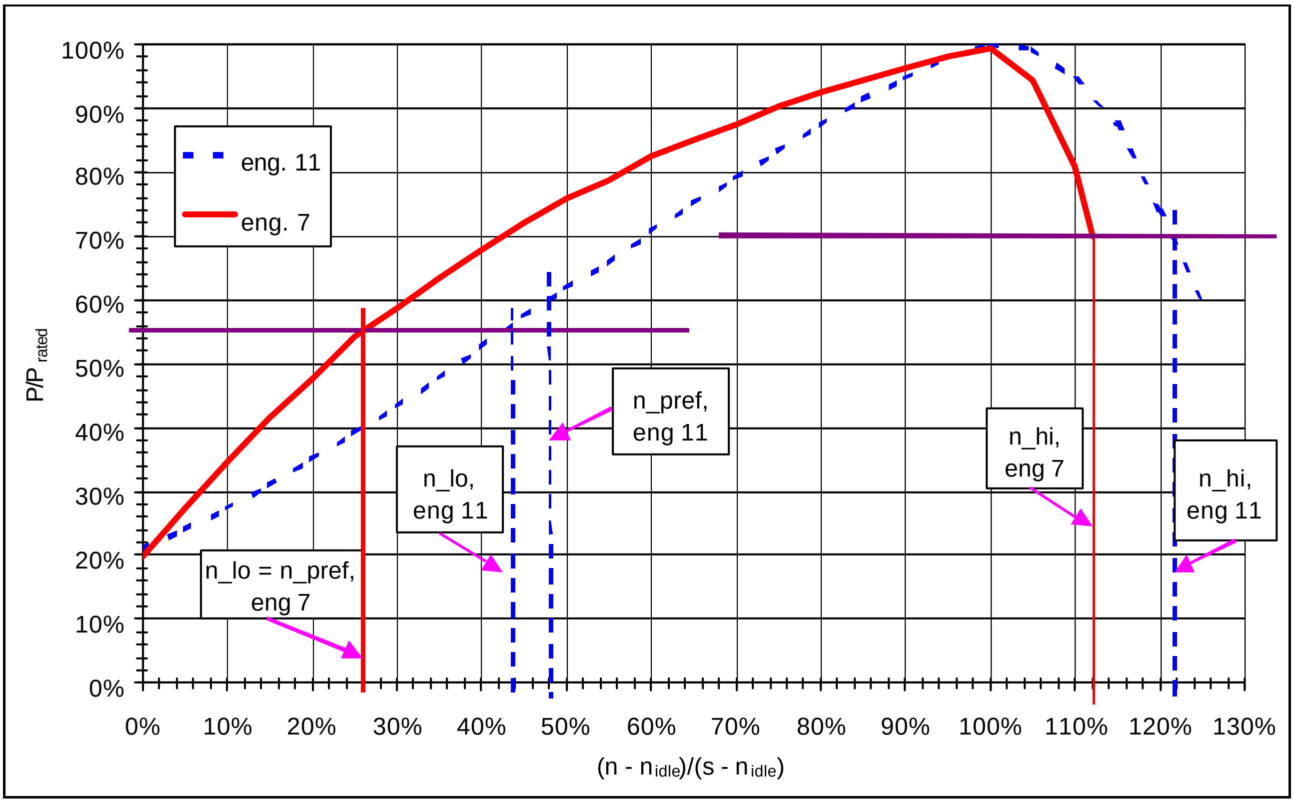

Figure 26 Full load curves chosen for the demonstration of the outcome of the drive train model

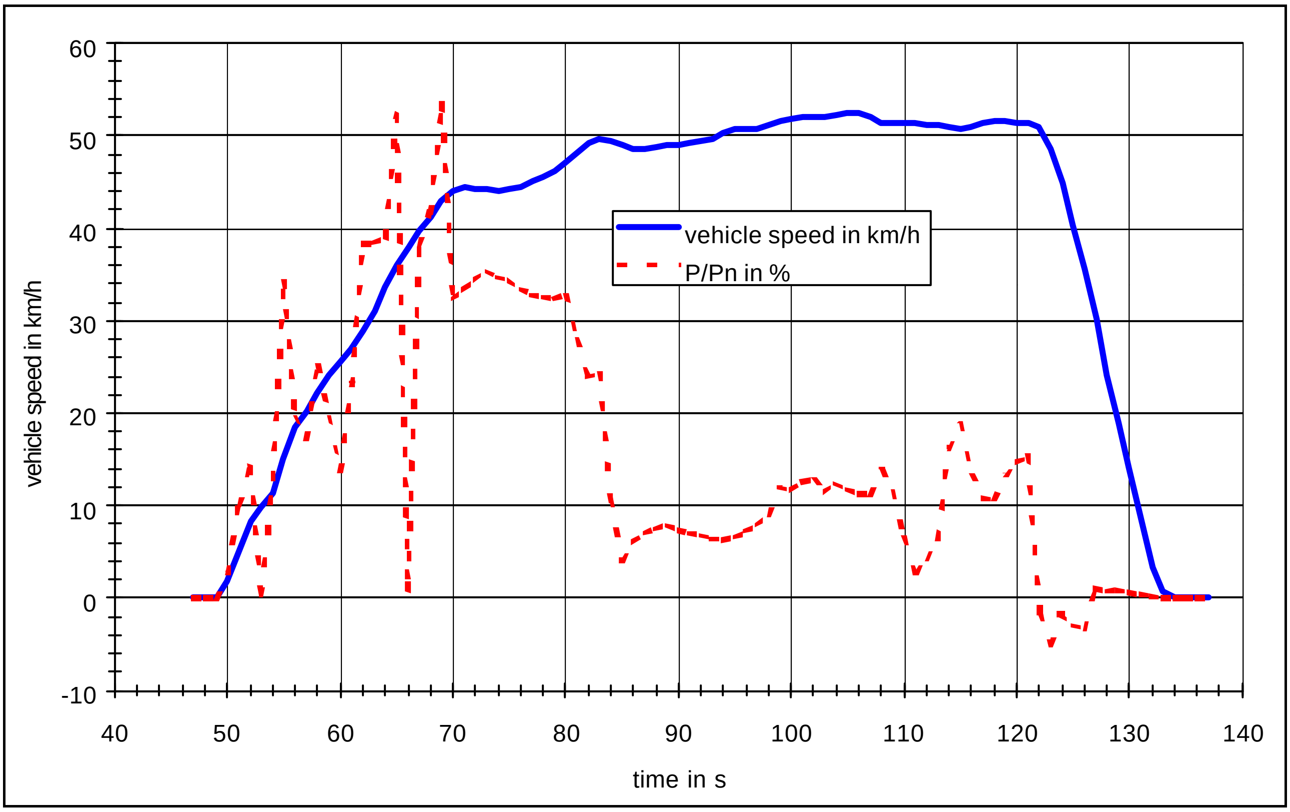

Figure 27: Driving pattern in terms of vehicle speed and normalised engine power

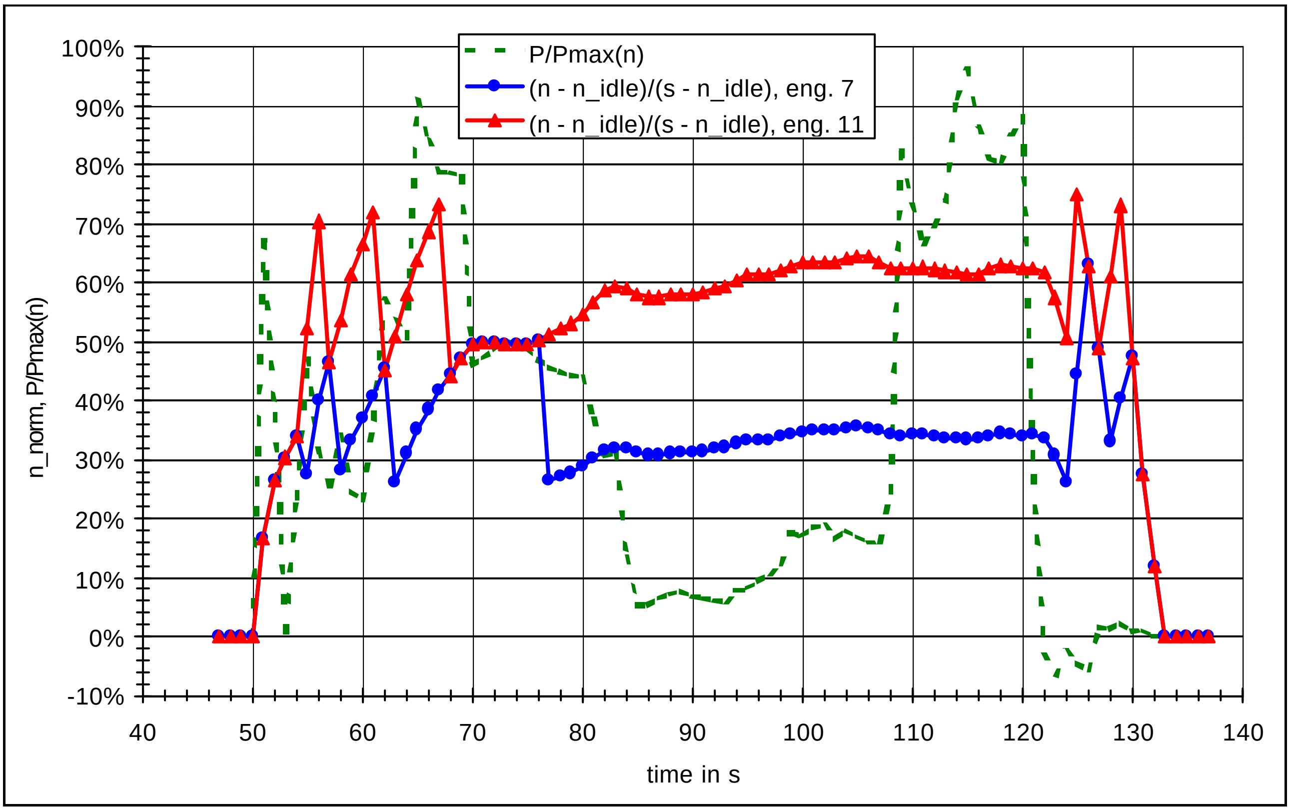

***Figure 28:** Engine pattern in terms of engine speed (normalised) and engine load for two different engines*

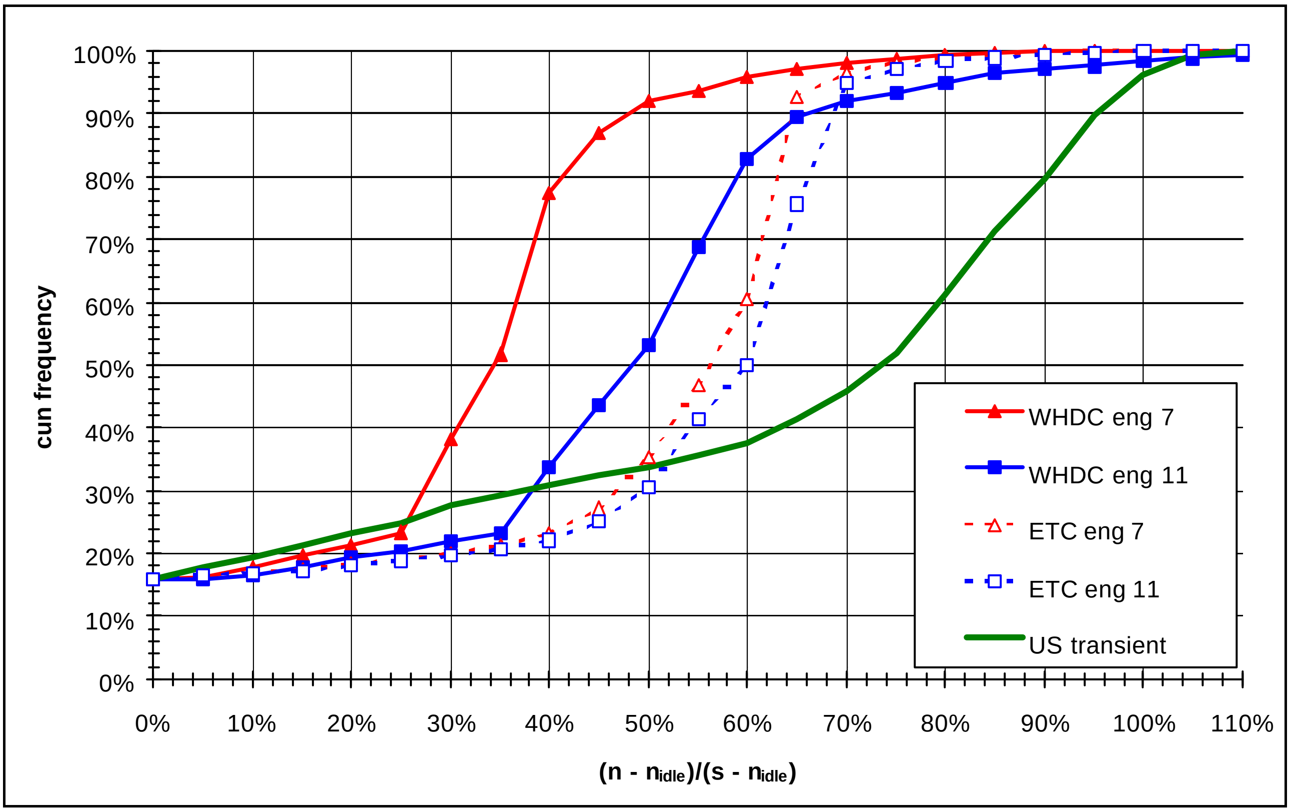

***Figure 29:** Engine speed distributions for the WHDC. Distributions for ETC and US transient cycle for comparison*

Figure 30 shows the corresponding engine load distributions. Unlike the engine speed distributions no significant difference in the engine load distributions for the WHDC between the 2 engines was found. This result is reasonable since the most influencing parameter for the engine load is the power to mass ratio that is implicitly included in the cycle load pattern. An explicit consideration of this parameter would need additional information about the vehicles for which the engines will be used and would lead to vehicle configuration tests instead of engine tests.

With the exception of the power/mass ratio consideration the drive train model provides the best estimate of the engine speed/engine load distribution in practice, even for future technologies.

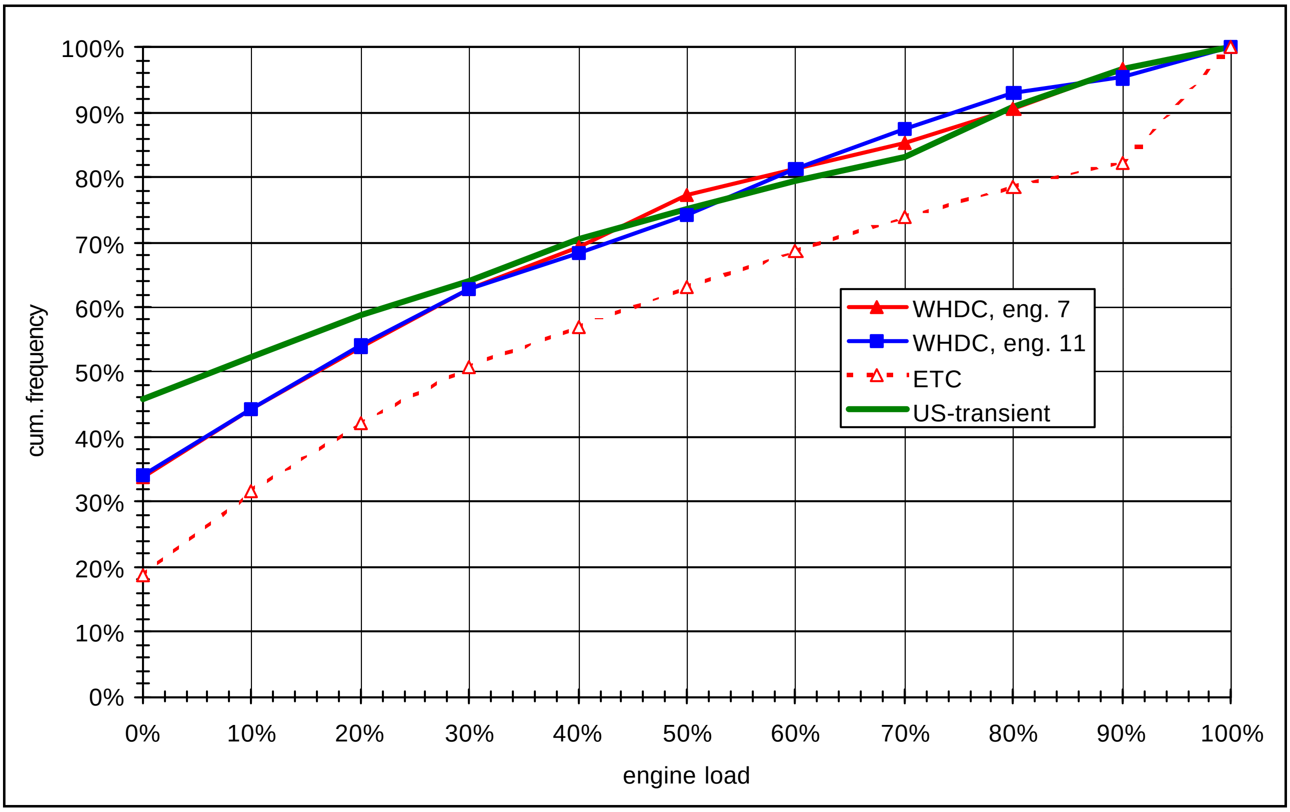

Figure 30: Engine load distributions (positive load part) for the WHDC. Distributions for ETC and US transient cycle for comparison

8 Substitution of the Drive Train Model by a Reference Transient Engine Cycle (WHTC)

8.1 Approach

As it is difficult to implement the computer based calculation module of the drive train model into regulatory language, the possibility of substituting the drive train model with a reference cycle in terms of normalised engine speed and load (time series) was investigated in a further task. In this task only engine speed was considered, since the engine load distributions of the drive train model did not show significant differences (see Figure 30). It was carried out by the following steps:

- Calculation of the individual engine cycles in terms of n(t), P/Pmax(n,t) from the vehicle cycles for a wide range of engines with the drive train model.
- Choice of one particular engine as reference engine.
- Normalisation of the reference engine‘s cycles using the same characteristic engine speed values (n_lo, n_pref, n_hi) as the drive train model. The result defines the reference engine test cycle.
- Calculation of individual engine cycles by denormalisation of the reference cycle for the same range of engines as in step 1.
- Calculation of the sum of squared differences between the individual cycles derived from the drive train model in step 1 and the denormalised reference cycles.
- Repeat steps 3 to 5 with modified weightings for n_lo, n_pref and n_hi and choose the weightings with the best fit.
- Repeat steps 2 to 6 with another reference engine
- Choose the combination that fits best with the original individual cycles.

The 1st step began with an analysis of the full load power curves of different engines to find extreme and average cases. The engines selected cover the whole range of different full load power curves. Also different engine technology stages were included. The individual engine cycles based on the WHDC were calculated with the drive train model. The result is shown in Figure 31.

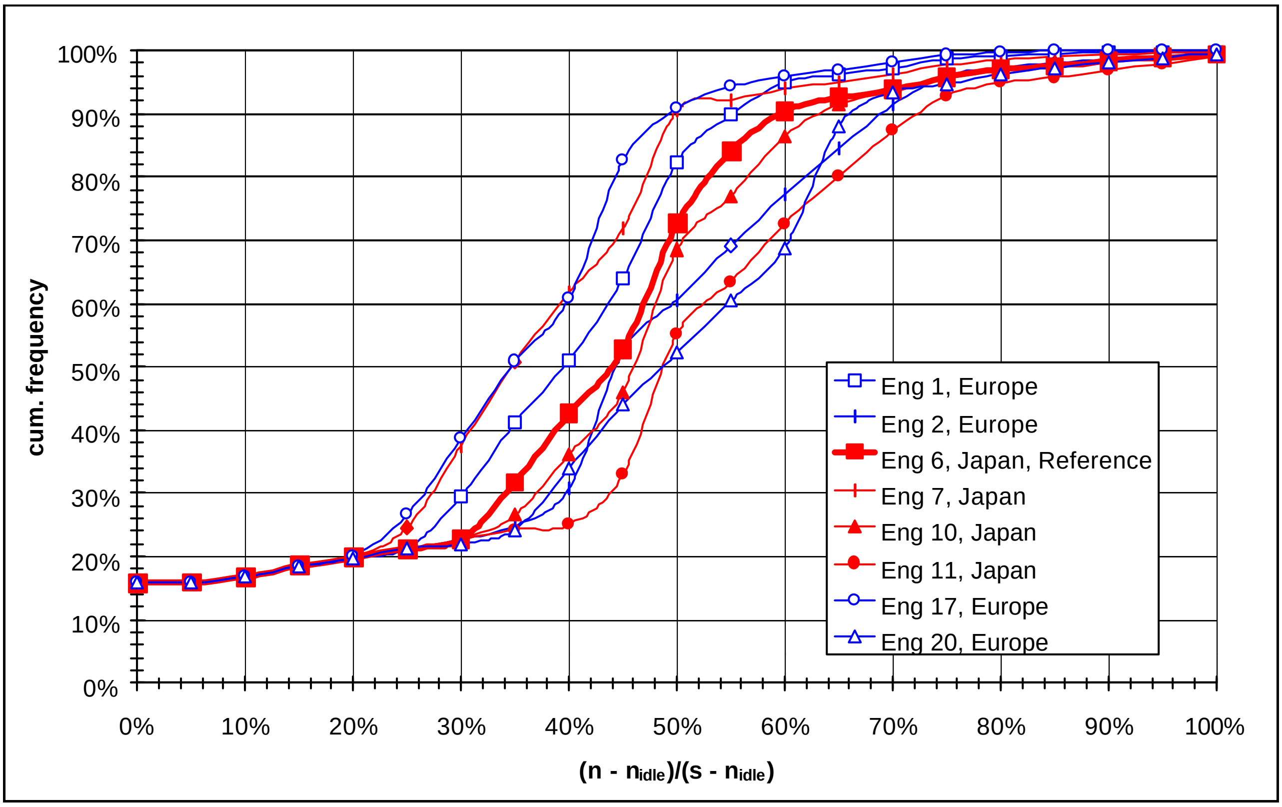

Figure 31: Frequency distributions of engine cycles calculated with the drive train model on the basis of the WTVC for different engines

8.2 The Worldwide Reference Transient Engine Cycle (WHTC)

In the 2nd step, a reference engine was selected whose engine test cycle calculated with the drive train model could be used to define the reference test cycle, i.e. an engine whose speed distribution represents the average of all engines. Its engine cycle is shown in Figure 32 and Figure 33. This cycle is the basis for the reference cycle.

To calculate the normalised speeds for the reference cycle the following formula was used in step 3:

$$nnorm\_ref = \frac{0{,}5363 * (n - n\_idle)}{a * n\_lo + b * n\_hi + c * n\_pref - n\_idle}$$

Equation 6

The factor 0,5363 ensures that the nnorm_ref values are identical with the n_norm values ((n – n_idle)/(s – n_idle)) for the reference engine. In total 58 different combinations of a, b and c were tested. The combination a = 80%, b = 10 %, c = 10 % resulted in the best fit, followed by a series of combinations whose goodness of fit were slightly but not significantly poorer. In order to get a better balance between the three characteristic engine speed values (n_lo, n_hi, n_pref) the combination a = 60%, b = 20 %, c = 20 % was chosen as the best compromise. Figure 34 shows the time pattern of these normalised speeds.

In step 4, the test speeds for a particular engine were then denormalised using the following formula

$$n = nnorm\_ref * (a * n\_lo + b * n\_hi + c * n\_pref - n\_idle) / 0{,}5363 + n\_idle$$

Equation 7

with the individual n_lo, n_hi and n_pref values of this particular engine.

The difference between the normalised speed values of each pair of cycles (based on the drive train model and Equation 7) was calculated second by second. The least square method was used to choose the optimal combination and to check the quality of the approximation.

Figure 35 shows the frequency distributions of normalised engine speed calculated with the drive train model on the basis of the WTVC and the reference cycle method (WHTC) for engines with extreme full load power curves. As can be seen, the results of the reference cycle method are in good agreement with the drive train model method.

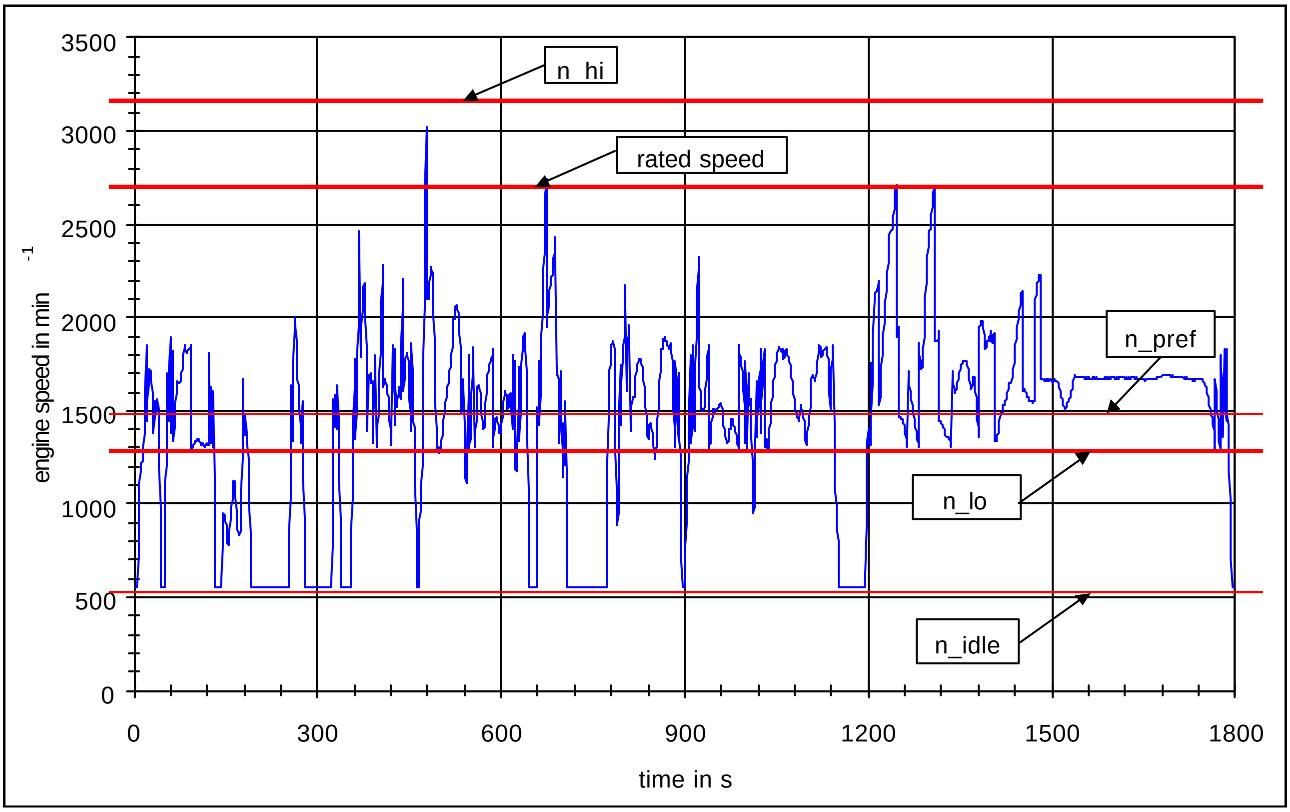

Figure 32: WHDC engine speed cycle of the reference engine

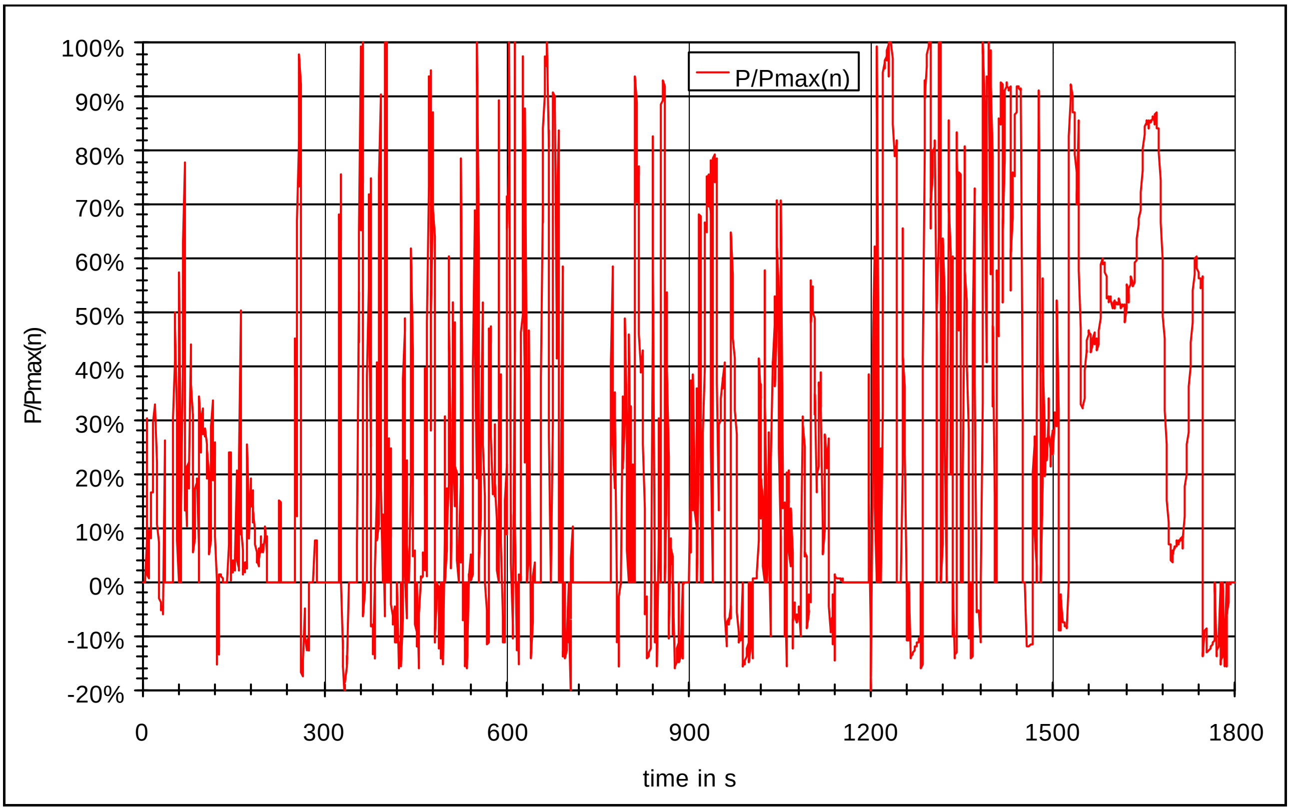

Figure 33: WHDC engine load cycle for the reference engine

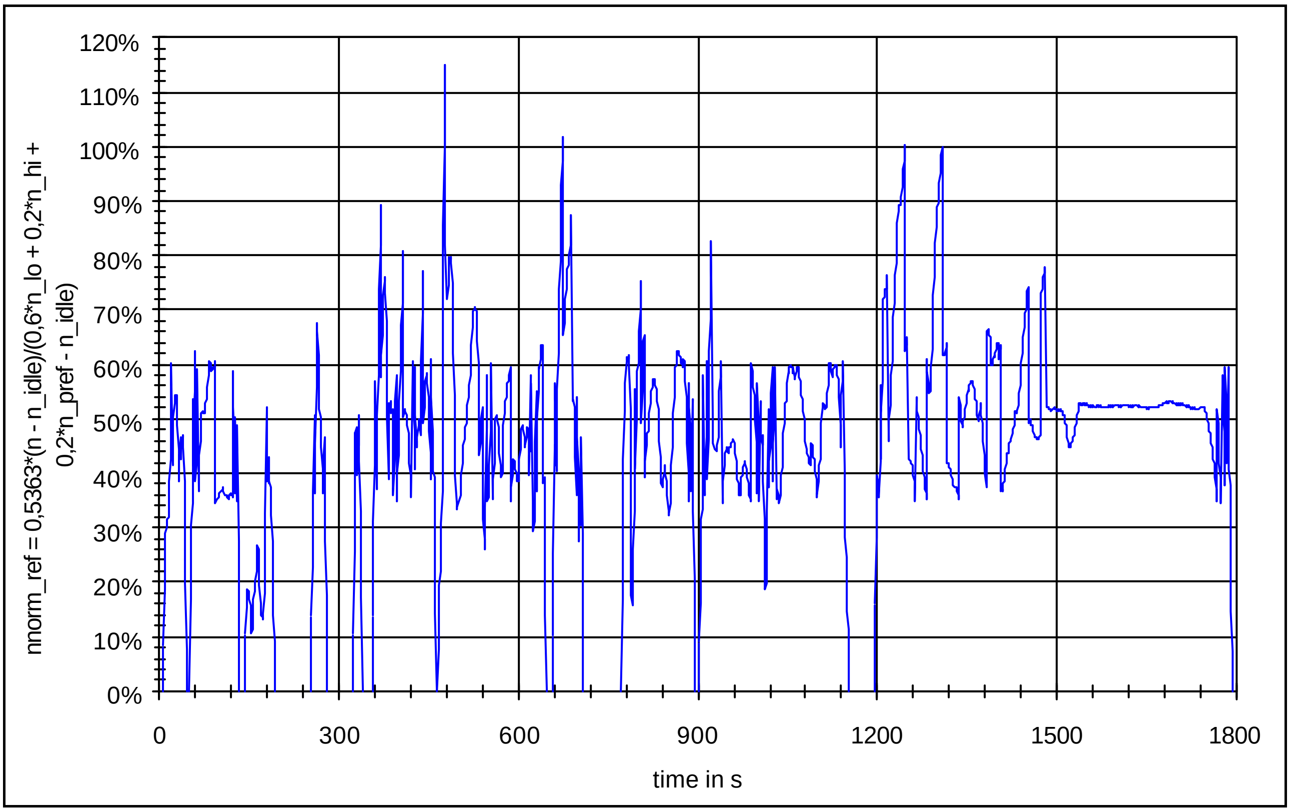

Figure 34: Reference engine speeds of the worldwide reference transient engine cycle (WHTC)

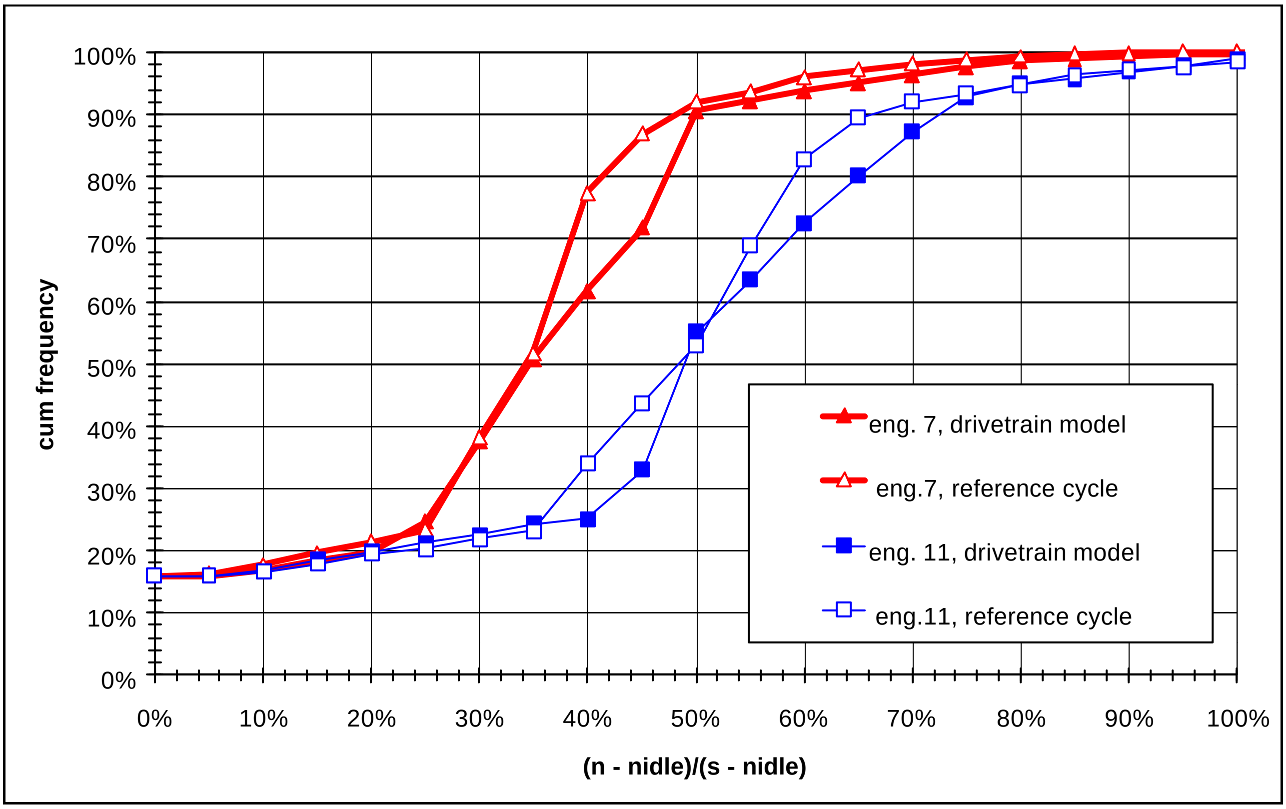

Figure 35: Distribution of norm. engine speeds calculated with the drive train model and with the reference cycle.

9 Development of the Worldwide Reference Steady state Cycle (WHSC)

In addition to the world harmonised transient test cycle, a steady state mode test cycle was developed, consisting of a limited number of engine speed-torque combinations (mode points) and showing weighting factors that lead to a similar engine load distribution compared to the transient test cycle.

The development was based on the following requirements:

- Same methodological approach as for the reference transient engine cycle:
  - Engine speed / engine load points based on the engine speed / engine load distribution of the reference transient engine cycle
  - Similar engine load distribution compared to the reference transient engine cycle
  - Engine test speeds expressed as normalised speeds dependent on engine characteristics (according to reference transient engine cycle)
  - Denormalisation of these reference speeds analogous to the transient engine cycle
- 12 engine speed-torque combinations: one idle point and up to four torque levels on five different engine speeds

- Weighting factor of each mode point in the same order of magnitude
- Same set of weighting factors for different engines
- Possibility to apply “Control Area” in which emissions should be “controlled”

Based on these requirements, the world harmonised steady state mode test cycle was developed in three steps, on the basis of the results of the reference engine:

- Analysis of the engine speed / engine load distribution of the reference engine
- Specification of test speeds and calculation of the normalised test speeds
- Specification of load points and weighting factors of the mode points

Following the same methodological approach as was used for the transient engine cycle, the steady state modes were based on the engine speed / engine load distribution of the reference engine cycle, this is shown in Figure 36. The engine speeds most frequently used in real life operation range from 30% to 65%. Consequently these two speeds were chosen as test speeds. Two additional test speeds within this range were specified at 40% and 50%, the latter being the most frequently used speed. Another speed at 75% was chosen which defines the end speed for acceleration phases, where a high amount of power is needed (for example uphill travelling). These engine speeds are complemented by the idle mode. The reference speeds were calculated according to Equation 6 (see page 40), using the characteristic speed values n_lo, n_pref, n_hi of the reference engine.

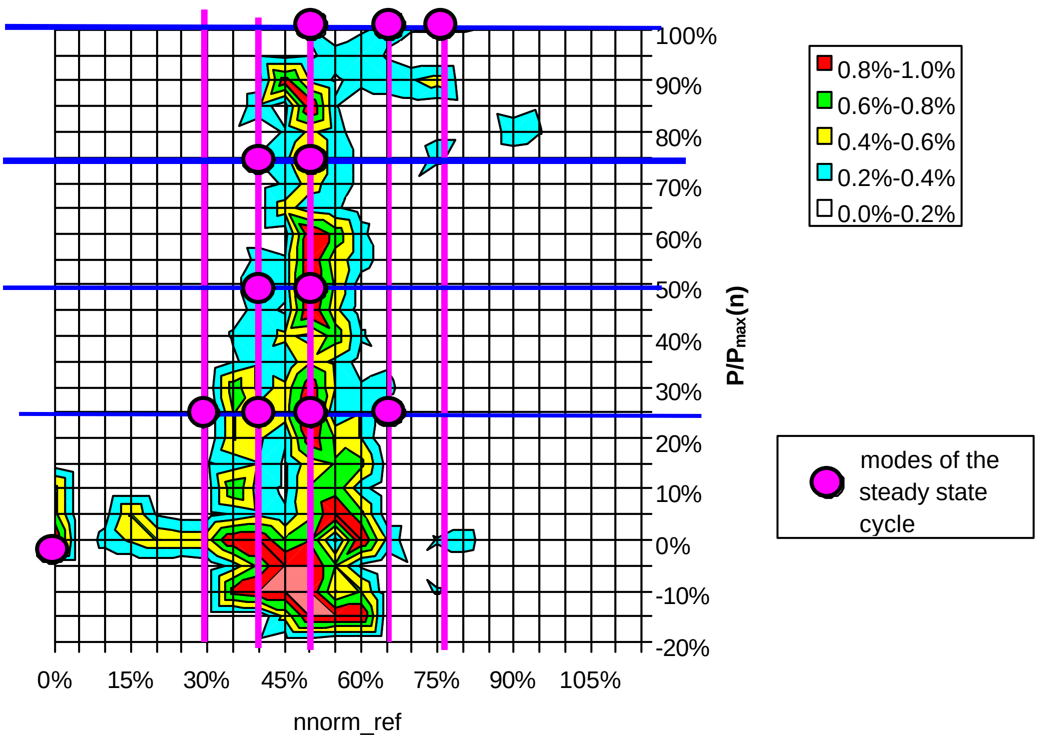

Figure 36: Engine speed / load distribution of the reference transient engine cycle as basis for the mode points of the steady state cycle

The specification of the load points was aligned to the joint frequency distribution of the reference transient engine cycle. The motoring phase was considered separately (weighting 24%, as for the WHTC), engine power and emissions are set to zero for this phase. The weighting for idling was set to 14% in accordance with the WHTC. The 25% and 50% load values were specified in line with the frequency distribution of the transient reference cycle. Following this approach, the 85% value would also have had to be chosen as third load point but to ensure that full load points are also included, the 75% and 100% load values were specified instead.

In a next step, rectangles were defined around each speed/load point, whose boundaries are equidistant from adjacent points. The sums of frequencies within these rectangles were used as a basis for the specification of the weighting factors. Normalising the sum to 100% derived the final weightings. The result is shown in Table 6.

	Motoring	engine load				
nnorm_ref		**0%**	**25%**	**50%**	**75%**	**100%**
Motoring	24.0%					
0%		14.0%				
30%			7.0%			
40%			10.0%	3.0%	4.0%	
50%			12.5%	10.0%	4.0%	2.5%
65%			4.0%			2.5%
75%						2.5%

Table 6: Mode points and weighting factors for the first draft of the world harmonised steady state mode cycle (nnorm_ref - see Equation 6, page 40)

For running a test, the test speeds for a particular engine are then denormalised using Equation 7 (see page 41) with the individual n_lo, n_hi and n_pref values of this particular engine.

In accordance with the ESC testing procedure, the summed average emission will be calculated in the following way:

$$e_{g/kWh} = \frac{\sum_{i=1}^{13} e_i * WF_i}{\sum_{i=1}^{13} P_i * WF_i}$$ ***Equation 8***

With $e_{g/kWh}$ = Summed average emission in g/kWh

e_i = Emission in mode point i (g/h)

P_i = Engine power of mode point i (kW)

WF_i = Weighting factor of mode point i (-)

10 Quasistatic Validation

To be able to estimate the differences that can be expected in the emission values between the world-harmonised cycle and the regional cycles or other existing cycles, a quasi-static validation step based on steady state engine emission maps was carried out. These maps consist of emission values (in g/h) for a series of engine speed / engine load combinations including idling.

The calculation approach is summarised below:

- For each second of a transient cycle the emission is calculated by 2-dimensional interpolation according to the actual engine speed and engine load.
- If the engine load is negative, the emission is assumed to be zero.
- The second by second emissions are summarised and divided by the sum of the positive energy of the cycle.
- An analogous method is used for steady state cycles taking into account the weighting factors for the summation process.

The following cycles were included in this validation step:

- World harmonised transient engine cycle (WHTC),
- regional transient engine cycle for Europe,
- regional transient engine cycle for Japan,
- regional transient engine cycle for USA,
- World harmonised 15 mode steady state cycle (WHSC, first version),
- European 13 mode steady state cycle (ESC),
- Japanese 13 mode steady state cycle,
- European transient cycle (ETC),
- US transient cycle.

Three European and four Japanese engines were included in this evaluation. The full set of emissions calculations (HC, CO, NOx and particulates) and test cycles were not available for all engines. On average only minor differences were observed between the emissions results of the WHTC and the regional cycles for NOx and particulates (Figure 37). For HC and CO higher differences were recognised, but the results were still in a reasonably narrow range. The differences can partly be explained by the different average positive power of the cycles (see Table 7). The results for the WHSC are in good accordance with those of the WHTC.

In Figure 38 the emission results of the WHTC are compared with those of existing certification test cycles. An engine speed / engine load distribution for idling and the potions of these cycles with pos. engine power are shown as examples in Figure 39 to Figure 41.

Figure 42 shows the distributions of the transient cycles for two engines with different full load power curves. For the steady state cycles, the speed/load combinations of the modes are indicated but not the weighting factors. A comparison of the average positive power is shown in Table 7 for all cycles and the same engine.

The engine speed / engine load distributions for the WHTC and the existing certification test cycles are significantly different. The idling percentages of the transient cycles are as follows: WHTC 16%, WHSC 30%, US transient test cycle 42,6%, Japanese 13 mode steady state cycle 41%, ETC 6,5%, ESC 15%. Despite of these differences, the average differences for NOx and particulates are in a reasonably narrow range. As expected, the differences for HC and CO are higher. Since the emission results are related to the average positive energy output of the engine, the differences on the emissions caused by speed differences are partly compensated by differences in the average positive power.

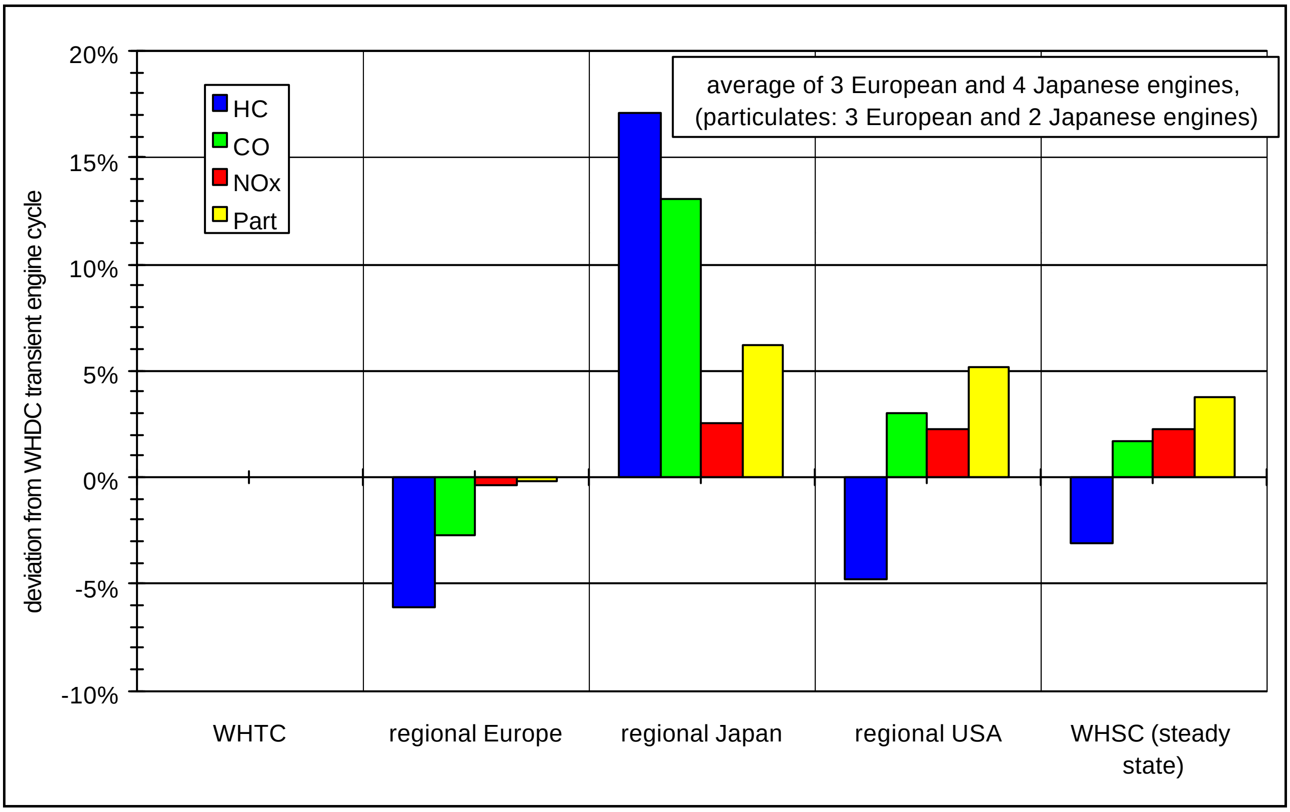

Figure 37: Results of the quasistatic emission calculation, differences between the WHTC, the WHSC (first version) and the regional transient cycles

Test Cycle	Deviation from WHTC
WHTC	0.0%
Europe, regional	9.9%
Japan, regional	-24.3%
USA, regional	-0.6%
WHSC	1.7%
ETC	54.4%
ESC	146.3%
Japanese 13 mode	-7.3%
US transient	2.3%

Table 7: Differences of average normalised positive power in relation to the WHTC (averages of all engines)

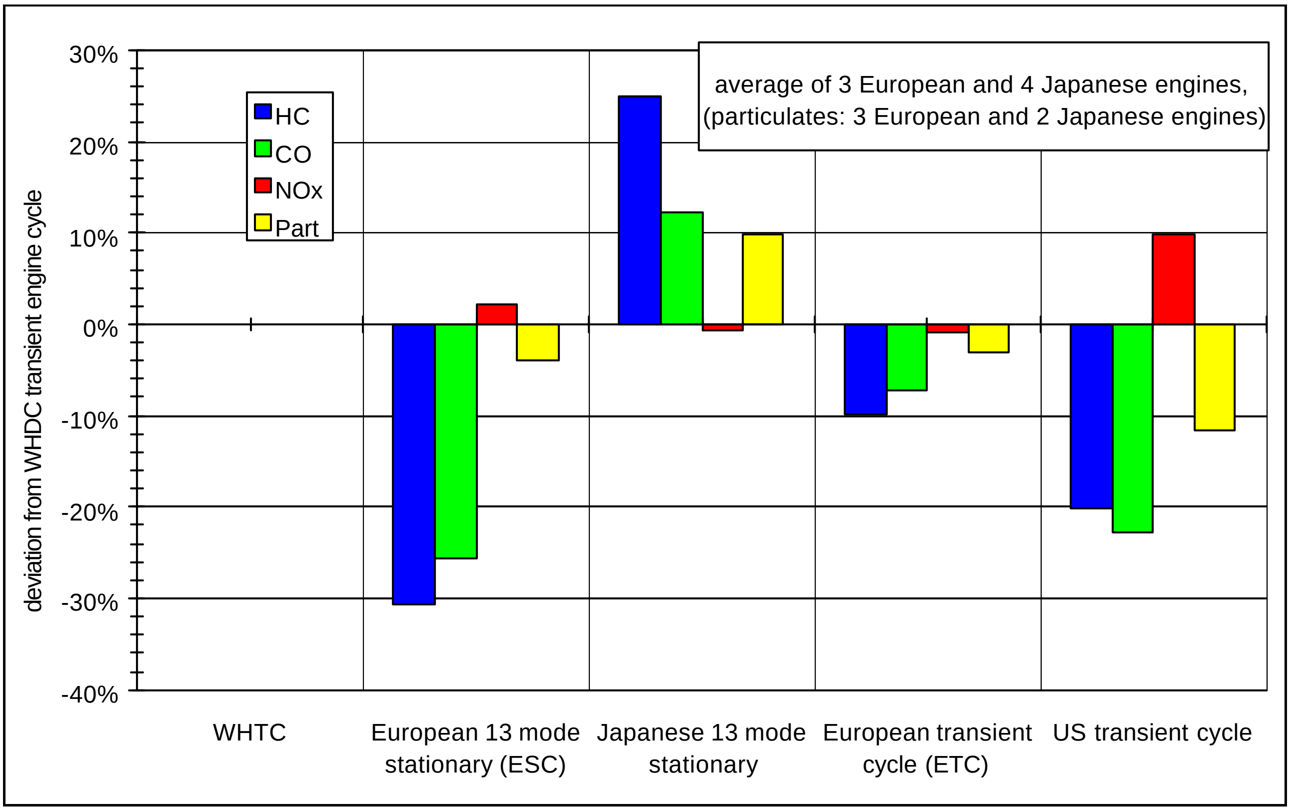

Figure 38: Results of the quasistatic emission calculation; differences between the WHTC transient engine cycle, the ETC, the ESC, the Japanese 13 mode test and the US transient cycle

Concerning NOx and particulates, no big differences were found for the average of seven engines. In general, the emissions of the Japanese regional cycle are higher than the WHTC. For the European cycle it is the other way round. The emissions of the European cycle are closest to the WHTC, while the biggest differences to the WHTC are found for the US regional cycle. The differences correlate quite well with the differences in the average positive power.

The comparison of the results for the WHTC with the results of existing or near future cycles also looks promising, at least 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 39 to Figure 41) and differences in the average power output between the cycles (see Table 7). 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

A more detailed analysis showed that the differences for the average emission values can be explained by differences between the cycles concerning the frequency distributions of engine speed and load and the average power output. The differences between the engines were normally in the range of +/- 10% in relation to the average. The European and the Japanese 13 mode steady state cycles and the US transient test cycle show higher differences between the engines, especially for particulates, NOx and CO (up to +/- 25%). These differences can be explained to one part by the fact that three engines are optimised to European certification regulations and four engines to Japanese certification regulation and are to the other part related to individual differences in the emission maps of the engines. **Based on the results of the quasistatic validation it can be expected that the test bench validation will support the applicability of the WHTC cycle as a worldwide harmonised emissions test cycle.**

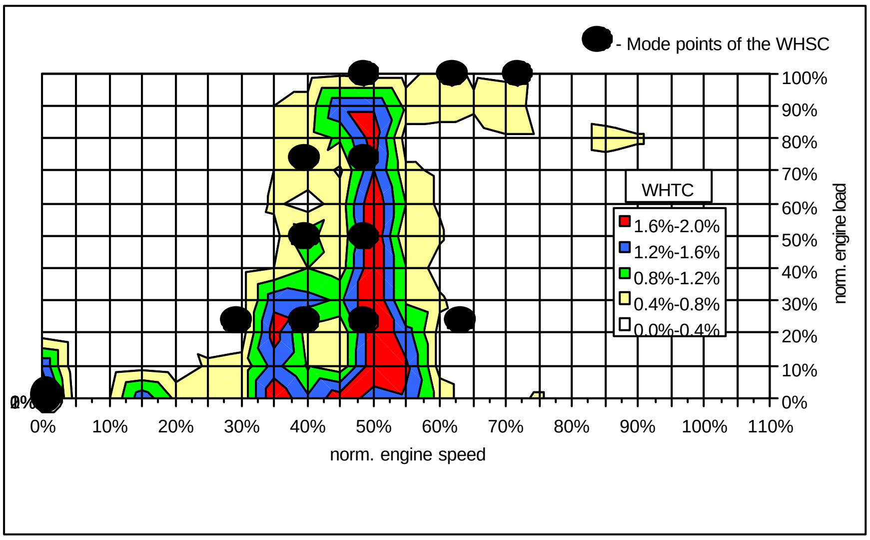

Figure 39: Engine speed/load distribution of the WHTC and WHSC (first version)

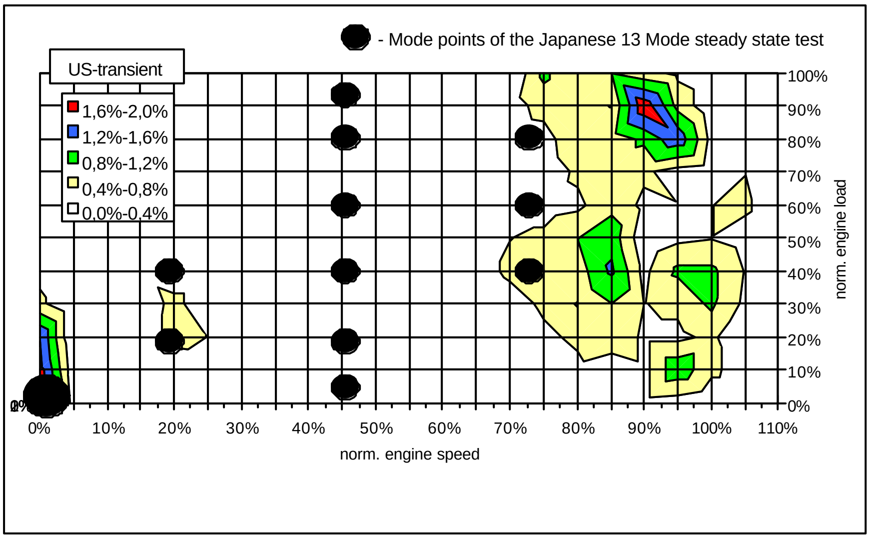

Figure 40: Engine speed/load distribution of the US-trans. cycle and the Japanese 13 mode test

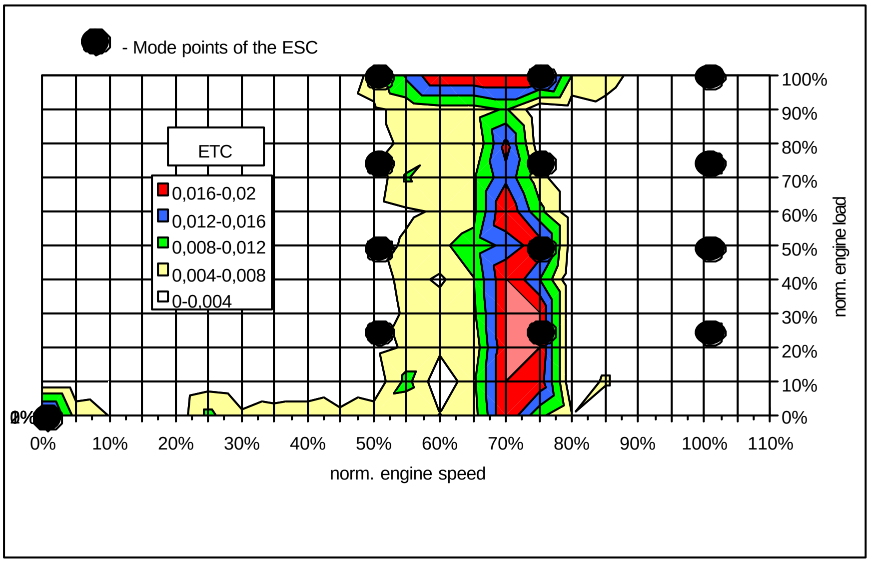

Figure 41: Engine speed/load distribution of the ETC and ESC

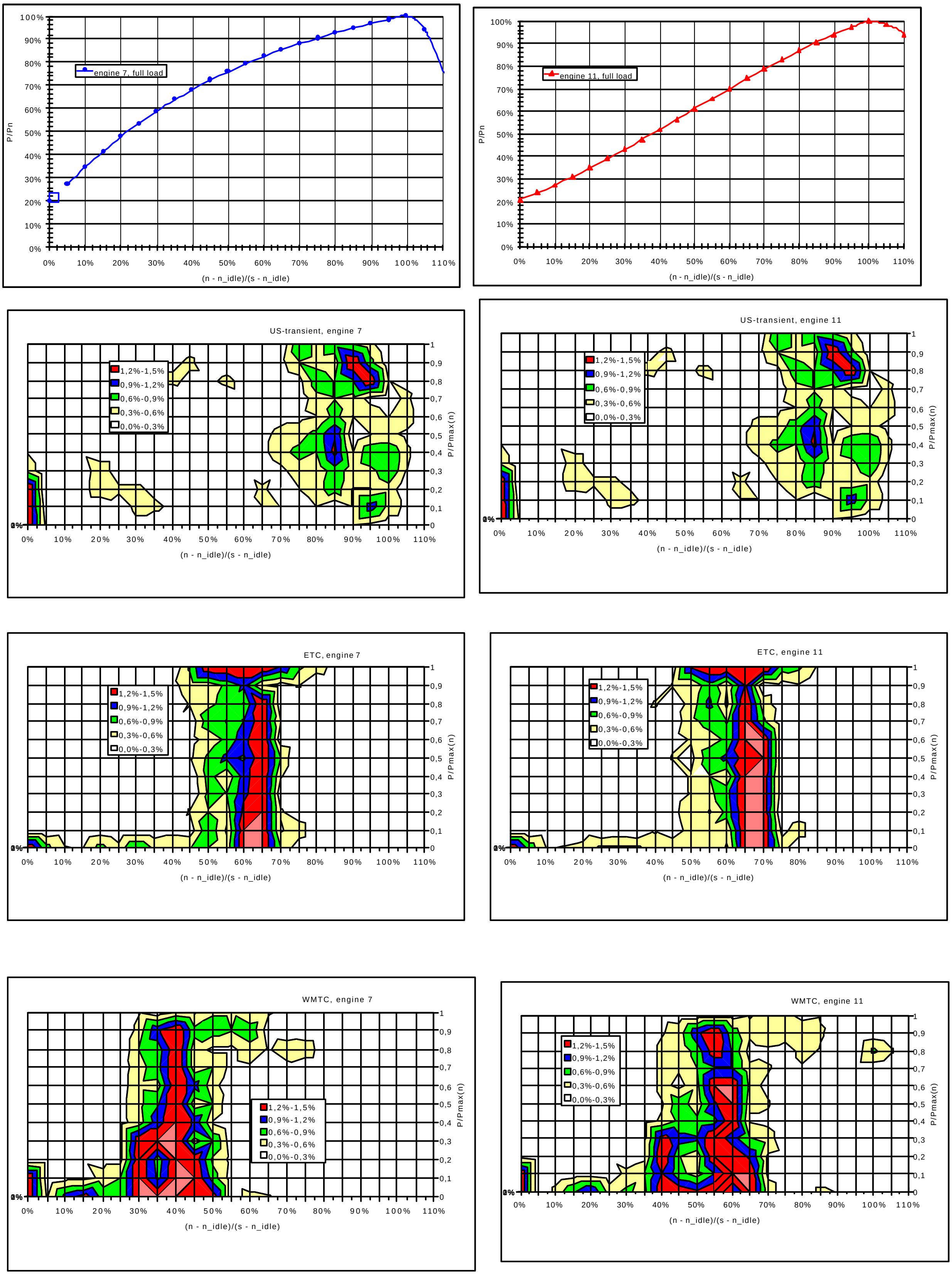

Figure 42: Comparison of the joint frequency distributions of the US-transient, the ETC and the WMTC for two engines with different full load power curves

11 Validation by Measurements

SCOPE AND OBJECTIVES

As the quasi-static emission calculation described in the previous chapter does not take into account dynamic effects, its results can only be considered as a first approximation for the expected emissions. Consequently a validation program, which is based on test bench measurement results, must follow this step. Although this program is out of the scope of this research project, a short overview is described in this chapter, together with the validation parts of the ISO activities under the scope of the WHDC. The objectives can be summarised as follows:

- Validation of the WHDC test cycle, the ISO measurement procedures, and the procedures for steady state single modes using Euro 3 and future engine designs on the basis of a three step program, and comparison to current exhaust emissions test procedures.
- Investigation of the driveability of the WHDC test cycle for CI and SI engines on the basis of regression analysis between reference and actual speed and torque signals, and proposal of adaptation, if necessary.
- Comparison of ISO measurement procedure to CVS measurement procedure under transient and steady-state conditions especially at very low emission levels from engines with after treatment systems
- Evaluation of the validated procedures in a worldwide round robin test with the participation of technical services, engine manufacturers, research labs and government laboratories (step 3)

STEP 1: WORK TO BE UNDERTAKEN AT ONE TEST LAB

In a first step the following test bench measurements will be carried out by one test laboratory:

Test engines and fuels:

- 1 Euro 3 engine,
- 1 Euro 3 engine with particulate trap,
- 1 Euro 3 engine with EGR

Test cycles:

- Current European cycles: ESC, ELR, ETC, 3 random points,
- Current US transient cycle (FTP),
- Current Japanese 13-mode cycle (JAP),
- WHTC cycle and regional transient cycles (EU, USA, Japan), WHSC steady state
- MOT/JARI Japanese transient cycle,
- 5 steady state single modes

Correlation Study:

- Each test to be run 3 times,
- Correlation between the different cycles,
- Correlation between partial and full flow systems for PM mass emission,
- Correlation between raw and dilute measurement for CO, HC and NOx emissions,
- Evaluation of measurement accuracy and repeatability at low emission levels

Evaluation of the outcome of step 1 and conclusions for step 2

STEP 2: WORK TO BE UNDERTAKEN AT TWO/THREE TEST LABORATORIES

In a second step the following test bench measurements will be carried out by two or three test laboratories:

Selection of test labs

Selection of test engines and fuels

- Euro 3 and Euro 4 engines from step 1 for direct comparison,
- 2 or 3 additional engines depending on availability,
  - Euro 4 or equivalent,
  - Japanese and US engines (emissions stage 2004/2005)
- 1 lean burn gas engine

Test cycles:

Same as step 1

Correlation study:

- Same as step 1

Evaluation of the outcome of step 2 and final conclusions

STEP 3: ROUND ROBIN TEST

- Details to be considered later
- Cost to be borne by participants
- Start around October 2001

12 References

[1] Development of a Worldwide Heavy-Duty Engine Test Cycle, 1st Interim Report, May 1999

[2] Development of a Worldwide Heavy-Duty Engine Test Cycle, 2nd Interim Report, May 2000

13 Annex 1 - Overview of the Japanese Activities concerning the WHDC

13.1 Introduction

In Japan, as part of WHDC activities, a survey of driving conditions for middle and heavy duty trucks was conducted by the Environment Agency and the Ministry of Transport (MOT). The collected data were submitted to a fundamental element subgroup together with data on a survey of driving conditions conducted by the Japan Automobile Research Institute (JARI).

Furthermore, under MOT supervision, these data were analysed independently at JARI and, in this way, TNO/TÜV activities were supported and the feasibility of TNO/TÜV analysis was verified.

At JARI thus far, experience has been gained in the development of a method for generating driving cycles to be used for measuring exhaust gas emission factors. The method focuses on items that impact on emission factors (idle time distribution, short-trip length, speed-acceleration distribution). In the MOT/JARI project, a driving cycle, which reflects the driving conditions in Japan, was developed by this method and its feasibility was verified through comparisons with the representative Japanese regional driving cycle developed at TNO/TÜV.

13.2 Development of a representative Japanese regional driving cycle under the MOT/JARI project

Engine test cycles are used within exhaust gas emission regulations as a tool for reducing air pollution. Consequently, for proper representative engine test cycles, it is especially important that the engine load frequency distribution of actual driving, which has an impact on emissions, be reflected. The steps in developing an engine test cycle are shown in *Figure 43*.

In considering the factors that impact upon emissions, a distinction should be made between idle vehicles and running vehicles. When a vehicle is idling or at a standstill, the distribution of each idling time period, not just the total idling time period (or idle time ratio), is crucial. For vehicles equipped with a catalytic converter or other exhaust after-treatment device, the idling time period has an impact on the catalyst temperature and this in turn affects the catalyst conversion rate and emissions.

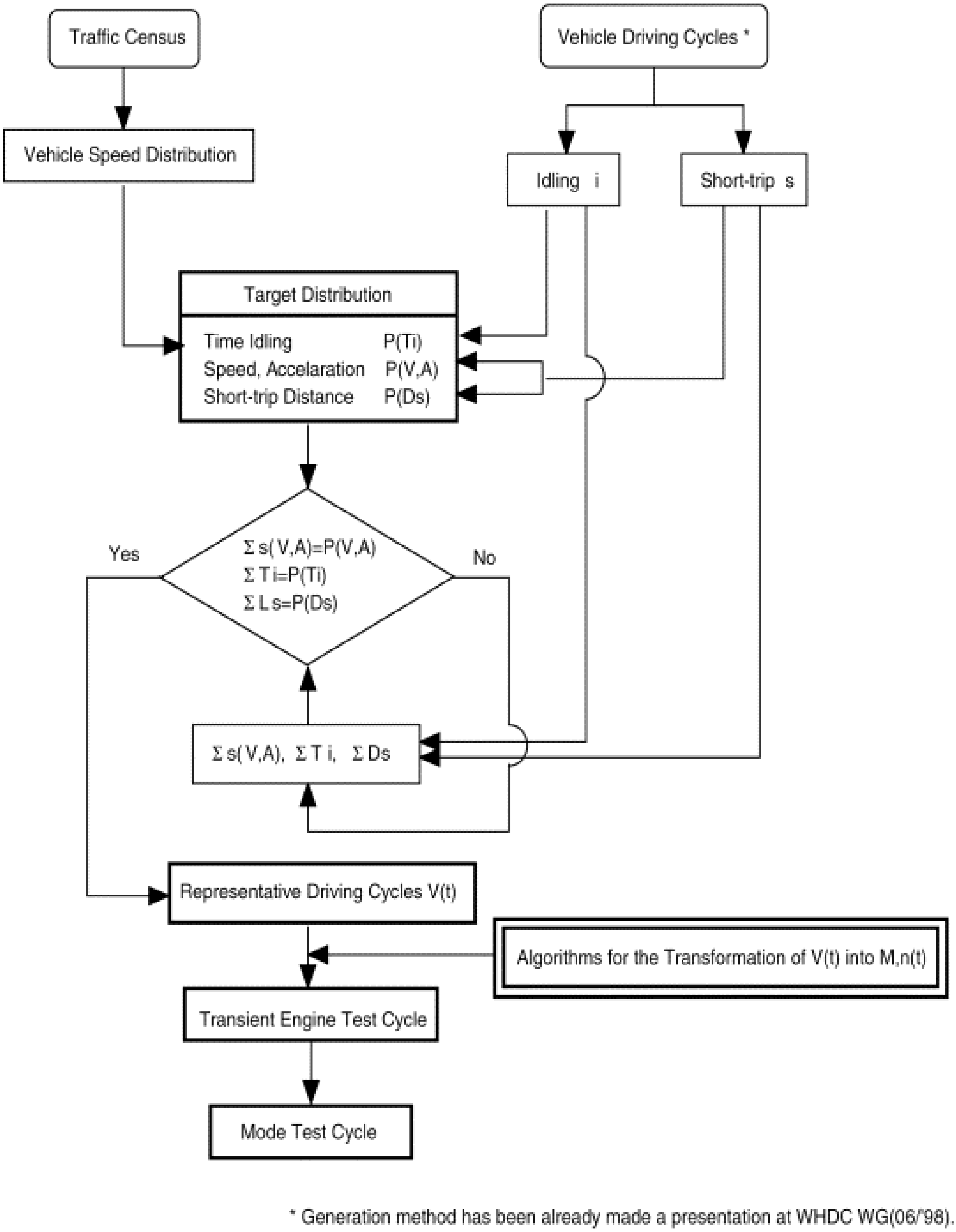

Figure 43: Flow chart for the development of representative engine test cycles (MOT/JARI project)

Engine load is also important when the vehicle is running. Engine load while a vehicle is travelling on the road is expressed in terms of driving resistance as indicated below.

R = Rr+Ra+Rs+Rb ***Equation 9***

Where,

R ; driving resistance

Rr ; rolling resistance

Ra ; aerodynamic drag

Rs ; climbing resistance or downgrade force

Rb ; acceleration resistance

Rolling resistance (Rr) occurs while the vehicle is running, and is affected by short-trip length. Aerodynamic drag (Ra) is affected by vehicle speed distribution since it is proportional to the square of the vehicle speed. Acceleration resistance (Rb) is proportional to acceleration rate, and it is affected by engine load especially during acceleration, along with acceleration speed distribution. The variables affecting emissions can thus be listed as follows.

- Idle time distribution
- Short-trip length distribution
- Speed-acceleration distribution

Using the above-mentioned approach, driving cycles were developed at JARI according to average speed (approx. 10 km/h step) and power to mass ratio. This was because driving cycle average speed affects emission factors and because a difference in the speed and acceleration distributions during acceleration mode can be noted when the power to mass ratio differs. JARI's classification of power to mass ratio is identical to that of TNO's definition in WHDC work.

Next, in order to construct the representative Japanese driving cycle using driving cycles classified by average speed and power to mass ratio, the driving speed frequency distribution was determined using data from a traffic census, and weighting factors were assigned to driving cycles classified by average speed and reflected in the representative driving cycle. At this time, the vehicle category weighting factors classified by power to mass ratio were identical to that determined by TNO in WHDC work. While the data from surveys of driving conditions provided by Japan covered only light trucks and rigid trucks, the representative driving cycle was developed from statistical data on these vehicle categories. The legislative driving cycle in Japan (1800 seconds) is shown in *Figure 44*. In the data from a traffic census, the percentages of urban and rural roads and of motorways were 84% and 16%, respectively. The overall average speed was about 28 km/h.

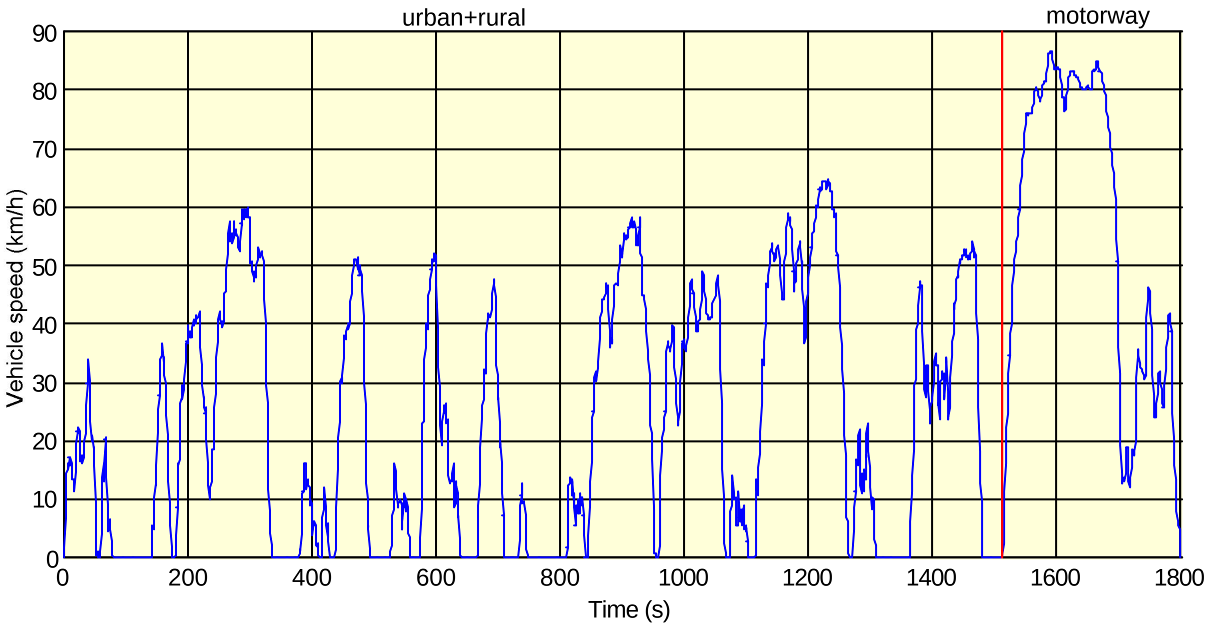

Figure 44: Reference Japanese driving cycle

	Vehicle category	Ave. speed of driving cycle km/h	Idle time ratio %	Ave. acceleration at acceleration mode m/s^2	Cruise time ratio %	Ave. cruising speed at cruise mode km/h
Japanese cycle from TNO/TÜV	All categories	30.5	20.1	0.44	28.2	49.6
Japanese cycle from JARI	Single unit trucks	27.8	22.3	0.54	15.9	50.9

Table 8: Comparison of TNO/TÜV cycle and MOT/JARI cycle (Japanese cycle)

Of the tasks performed by TNO/TÜV for developing engine test cycles, Task 6 (the 30 minute transient test cycle) can be compared with the MOT/JARI project. Here, the two mutually developed Japanese regional driving cycles were compared. Since the characteristic values considered in the method of creation used by TNO/TÜV differ from those considered in the JARI method, even if the same driving data are used, the resultant regional driving cycles would not be completely identical. The regional driving cycle has been developed following repeated technological discussions between TNO/TÜV and MOT/JARI concerning mutual methods.

Presented in Table 8 are the results of a comparison of the general outlines of Japanese regional driving cycle by TNO/TÜV and by MOT/JARI. Although the data upon which the driving cycles are based differ by vehicle category, average speeds and idling time ratios are practically identical.

With respect to the TNO/TÜV cycle and MOT/JARI cycle, comparisons of idle time frequency and of short-trip length frequency are depicted in Figure 45 and Figure 46, respectively. In both cycles, idle time frequency and short-trip length frequency show similar tendencies.

Lastly, a comparison of vehicle speed-acceleration distribution in the two cycles at acceleration mode is presented in Figure 47. Since the data upon which the driving cycles are based differ by vehicle category, a general statement cannot be made, but in the MOT/JARI cycle there is a higher frequency of acceleration events at low speed. Nevertheless, the distributions of speed and acceleration are similar in both cycles.

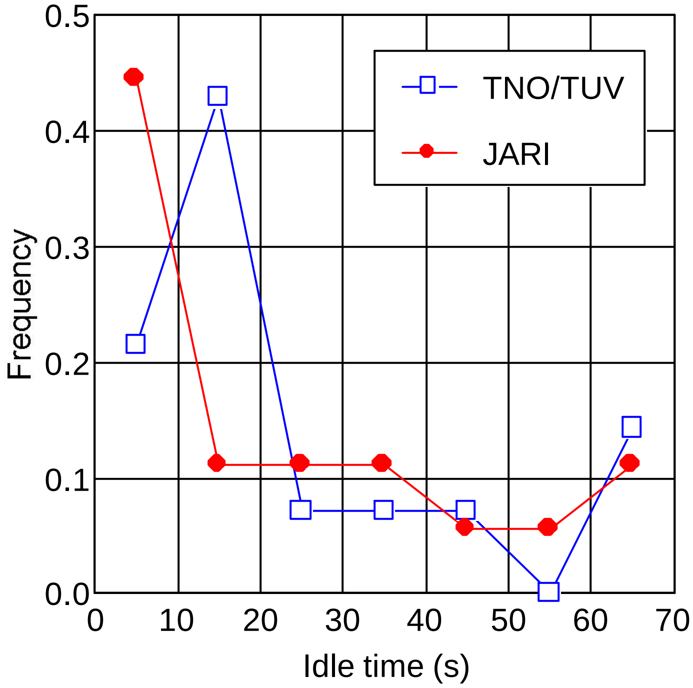

Figure 45: Comparison of idle time freq.

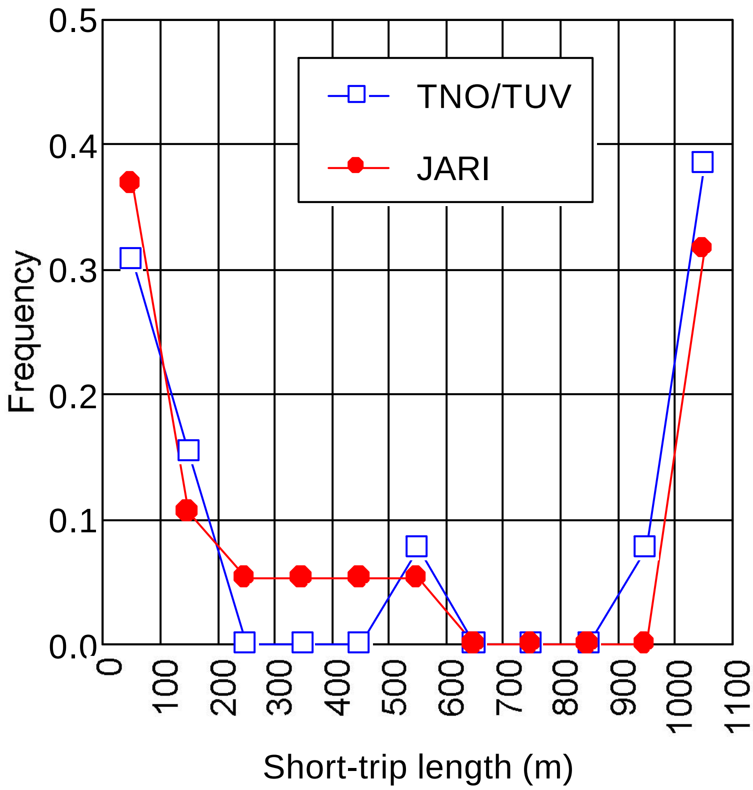

Figure 46: Comparison of short-trip length freq.

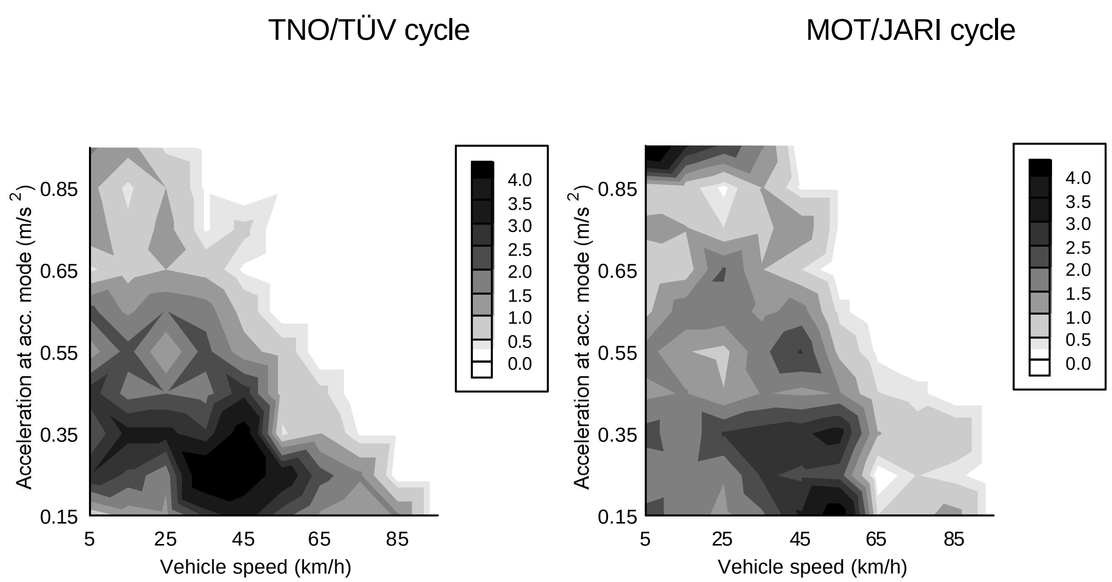

Figure 47: Comparison of vehicle speed-acceleration distribution at acceleration mode

13.3 Summary

In the MOT/JARI project, efforts were made to develop a driving cycle, which reflects the driving conditions in Japan and therefore real world engine operation. In this report, a comparison was made between the MOT/JARI cycle and the Japanese regional driving cycle created by TNO/TÜV. The results can be summarized as follows:

- A driving cycle representative of Japan was developed under the MOT/JARI project. The percentages of urban and rural roads and of motorways were 84% and 16%, respectively, and the overall average speed was about 28 km/h.
- In the regional driving cycle of Japan developed by TNO/TÜV, average speed and idling time ratio were about the same as those in the MOT/JARI cycle.
- Idle time frequency and short-trip length frequency followed similar trends in both the TNO/TÜV and MOT/JARI regional driving cycles.
- In the MOT/JARI cycle, acceleration exhibited a higher frequency at low speed. In other domains, however, the distributions of speed and acceleration were similar in both cycles.
- From the above mentioned, we can conclude that the Japanese regional driving cycle developed by TNO/TÜV and the cycle by MOT/JARI do not have large difference, and the result is almost the same.

In the further study, it would be necessary to compare the equality of the two test cycles with respect to emission behaviour.