UNITED
NATIONS

Informal document No. 12
(43rd GRPE session,
15-18 January 2002,
Agenda item 1.1)

WHDC

Worldwide Heavy-Duty Certification

Validation Results

Executive Summary

under contract of

Dutch Ministry of the Environment (VROM)

International Organization of Motor Vehicle Manufacturers (OICA)

Project Coordinators: Dr. Cornelis Havenith, H. Juergen Stein

Project Manager: Thomas Schweizer

Dübendorf, 2002-01-11

A TABLE OF CONTENT

B INTRODUCTION

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 harmonized **H**eavy-**D**uty **C**ertification procedure". A research program was jointly conducted by TNO Automotive (The Netherlands) and TÜV Automotive (Germany) and supported by JARI (Japan) with the goal of developing a worldwide harmonized engine test cycle. In parallel, advanced exhaust emissions measurement procedures, and an engine family concept have been developed within the ISO framework. The complete work package was funded by the Dutch Ministry of the Environment (VROM), the German Federal Environmental Agency (UBA), the Japanese Ministry of Transport (MOT), the International Organization of Motor Vehicle Manufacturers (OICA) and the Japanese Automobile Manufacturers Association (JAMA).

On the basis of a vehicle cycle (WTVC), representing the driving behavior of heavy-duty vehicles in different parts of the world (Europe, Japan, USA), a transient (WHTC) and a steady-state (WHSC) engine test cycle have been developed. Additionally, regional test cycles for Europe, Japan and the USA have been established in order to evaluate differences in emissions levels between the global approach and the regions giving them information about the air quality compromise when applying the WHDC cycle. In a first approach, the WHDC and the regional cycles were validated on the basis of emissions calculated from steady-state engine emissions maps of three European and four Japanese engines. The cycle development work is described in the final report "Development of a Worldwide Harmonised Heavy-Duty Engine Emissions Test Cycle" submitted as document TRANS/WP29/GRPE/2001/2.

Two ISO standards have been developed, one for the emissions measurement procedure for gaseous and particulate pollutants (ISO/FDIS 16183), which is still under voting, and one for the engine family concept (ISO 16185), which has already been approved. A comprehensive correlation study was and is still being conducted at different test laboratories, which showed a satisfactory correlation between the conventional CVS technique and the procedure of raw measurement and partial flow dilution technique described in ISO/FDIS 16183. The results of the correlation work will be reported at the 44th session of GRPE in June 2002.

In order to verify the general applicability of test cycles and measurement procedures, a test program was conducted at EMPA under contract of VROM and OICA with three EURO III diesel engines, one fitted with a particulate trap. This report contains the results of this study.

C OBJECTIVES OF THE PROGRAM

The objective was the validation of the WHDC cycles and measurement procedures on the basis of real test bench measurements beyond the quasistatic validation that was based on steady-state emissions maps, and did not take transient engine operation into account. In this context, validation means review of the WHDC test results in terms of plausibility compared to existing legislative certification test cycles, and includes

- Investigation of the driveability of the WHDC transient test cycle for CI engines on the basis of regression analyses between reference and actual speed, torque and power signals, and proposal of adaptation, if necessary.

- Evaluation of the ranking of engine technologies on the WHDC transient and steady-state test cycles using Euro 3 engine designs in comparison to the legislative certification test cycles.

- Comparison of raw/partial flow dilution measurement procedure to the CVS full flow dilution measurement procedure under transient conditions, including very low particulate emission levels from an engine equipped with a particulate filter.

- Evaluation of the WHDC test results vs. the results of the regional test cycles.

D TEST PROGRAM

The newly developed worldwide harmonized test cycles WHTC and WHSC and measurement procedures were validated in comparison with the regional test cycles and the legislative test cycles currently in place. The cycles investigated are listed in chapter F, below.

Three different EURO III diesel engines were tested in the program, one fitted with a particulate filter. For each engine, the following parameters were investigated and evaluated:

- comparison between transient and steady-state test cycles
- correlation between CVS and ISO measurement procedures
- evaluation of measurement accuracy and repeatability
- evaluation of the driveability of the WHDC transient cycles
- evaluation of the necessity to modify the WHDC test cycles
- evaluation of the necessity to modify the ISO measurement procedures

On all tests, the standard CVS and the test equipment according to ISO/FDIS 16183 were run in parallel. The particulates collected on the filter were analyzed for the organic and partially for the sulfate portion for two runs of each test cycle.

Each test cycle was repeated twice (three tests in total), but not at the same day in order to obtain information on the daily variabilities and the overall repeatability of the test results.

E FACILITY DESCRIPTION

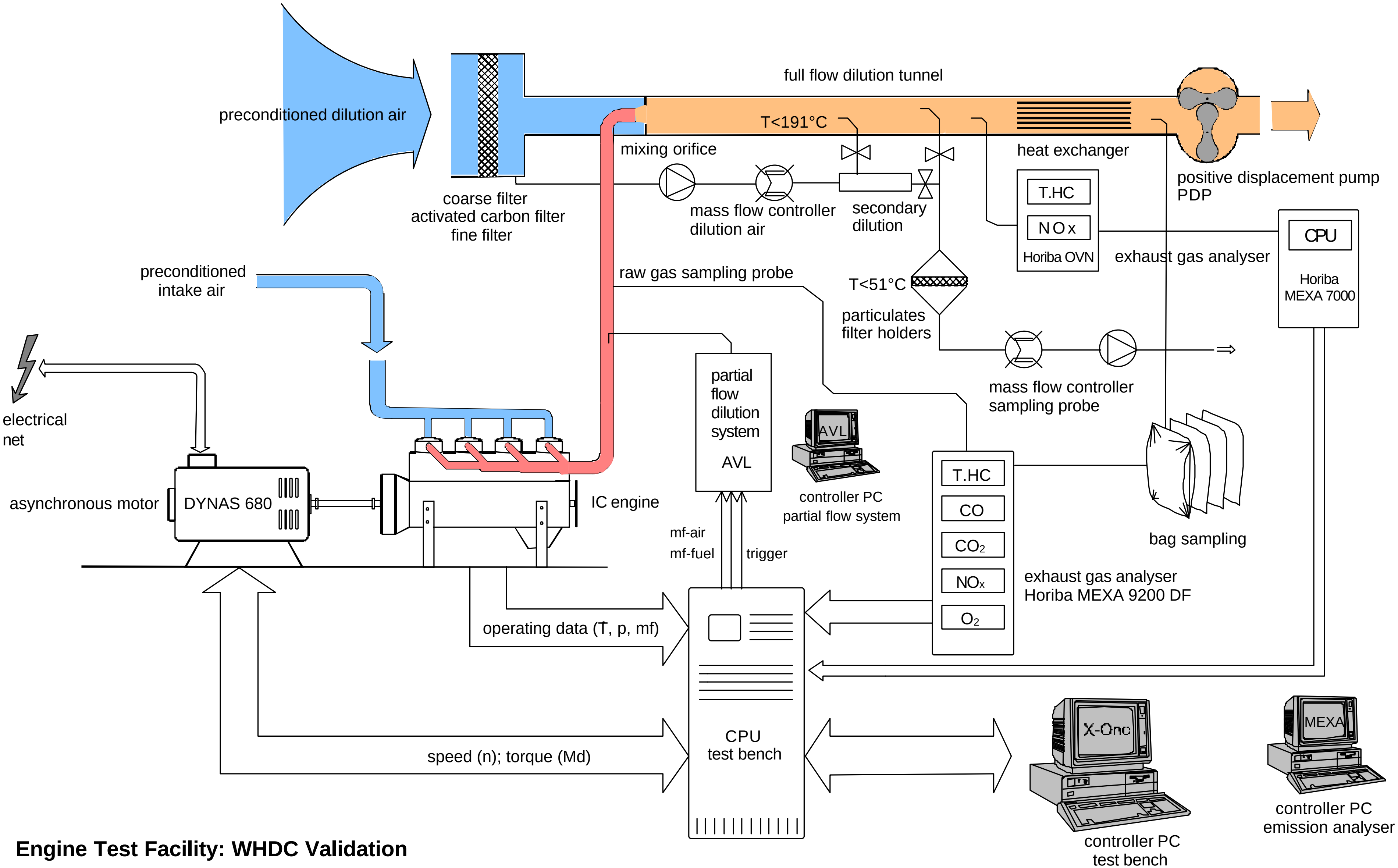
The heavy-duty test cell consists of an asynchronous motor, state of the art emission measurement equipment and a full flow dilution system for the particulate measurement. On this dynamic test bed, all currently existing test procedures can be run with engines fuelled with diesel, gasoline, natural gas or alternative fuels.

The fixed asynchronous motor (Schenck DYNAS 680) with 6-pulse static converter (AEG) for 4 quadrant operation is suitable for engines between approx. 100 kW and 680 kW (max. torque 2500 Nm, max. speed 4000 rpm).

The exhaust emission analyzer unit is a Horiba MEXA 9200 DF with four standard emissions analyzers (HFID, CLD, NDIR). Raw and diluted exhaust gas can be measured continuously during a test. The values may be recorded second by second or integrated over a test section or over the total test period. The bag analysis measures the average concentrations of the diluted gaseous emissions and of the corresponding dilution air sampled during the test in a bag.

The CVS full flow system (Pierburg 120 WT) provides a constant volume flow of the diluted exhaust gas by a positive displacement pump (PDP). Two different dilution tunnels can be chosen, the one for testing diesel engines, the other for the exhaust gas of gasoline, CNG or LPG engines.

For this project, the measurement installations were extended with a second emission analyzer system (Horiba MEXA 7000) and a partial flow dilution system (AVL) that conformed to ISO/FDIS 16183. This installation allowed the parallel measurement of raw and diluted gaseous emissions concentrations and the parallel measurement of particulates under partial flow dilution and full flow dilution conditions.



Engine Test Facility: WHDC Validation

F TEST CYCLES

The test cycles listed in table 1 were run in this program. The final version of the WHSC, as described in chapter F.2 below and in more detail in the WHDC Final Report [1], was developed in this program from the original proposal of TÜV Automotive. The modifications to the original cycle and the rationale behind them are explained in chapter I. The conclusions of the study refer exclusively to the worldwide harmonized test cycles WHTC and WHSC. As indicated in the introduction, the regional cycles were measured as additional information for the respective legislators in order to evaluate differences in emissions levels between the global WHDC approach and the individual regions. They are not intended to replace the WHTC or WHSC in any respect as a potential certification test cycle.

Test cycle	**Abbreviation**
WHDC transient cycle	WHTC
WHDC steady-state cycle	WHSC
European regional cycle	EUTC
Japanese regional cycle	JTC
U.S. regional cycle	USTC
European transient cycle	ETC
European steady-state cycle	ESC
Japanese 13-mode cycle	JAP
U.S. federal test procedure (transient cycle)	FTP
Japanese transient cycle developed by JARI	MOT

Table 1: *Test cycles investigated in the program*

The two most relevant test cycles to be evaluated in this program, WHTC and WHSC, are briefly outlined below. For detailed information about the new test cycles and their development see [1].

F.1 The worldwide harmonized transient cycle (WHTC)

The transient cycle WHTC consists of 1800 second by second percentage values for engine speed and torque and is shown in figure 1. The speed values are normalized to the characteristic speeds of the TÜV Automotive substitution model, the torque values are normalized to the maximum torque of the engine under test at the corresponding engine speed. For running a test, it is necessary to translate the normalized values of the cycle into actual values for each individual engine. The first step of this denormalization procedure is speed denormalization, which determines the speed range the engine is operated on over the test cycle. The actual engine speed values are calculated with a denormalization formula containing three different engine reference speeds that characterize the engine power and torque curve at full load. This formula is used for the WHTC denormalization, since it is related to the above substitution model.

$$n = n_{NORM\_REF} * (0,6 * n_{LOW} + 0,2 * n_{HI} + 0,2 * n_{PREF} - n_{IDLE}) / 0,5363 + n_{IDLE}$$

$\mathbf{n_{LOW}}$	Lowest engine speed, where 55 % of the maximum power occur
$\mathbf{n_{HIGH}}$	Highest engine speed, where 70 % of the maximum power occur
$\mathbf{n_{PREF}}$	Minimum engine speed, where the torque is maximal

This denormalization model is different to the denormalization procedures of current test cycles, since it uses three reference speeds instead of only one reference speed as with the ETC and FTP cycles. It was believed to be more representative for in-use operation of commercial vehicles.

Once speed denormalization is completed and the actual engine speed pattern is determined, the engine torque is denormalized by calculating the actual torque from the normalized torque and the maximum torque at each speed point, as follows:

$$\text{actual torque} = \frac{\text{\% torque * max. torque}}{100}$$

Torque denormalization has been transferred from existing regulations (ETC, FTP) unchanged. It should be noted that n_{HIGH} and n_{LOW} represent the engine operating speed range, as for the ESC and ETC in the Euro 3 Directive [2]. Whereas the definition of n_{HIGH} is identical to Euro 3, n_{LOW} is defined as 55 % of maximum power instead of 50 % in Directive 1999/96/EC.

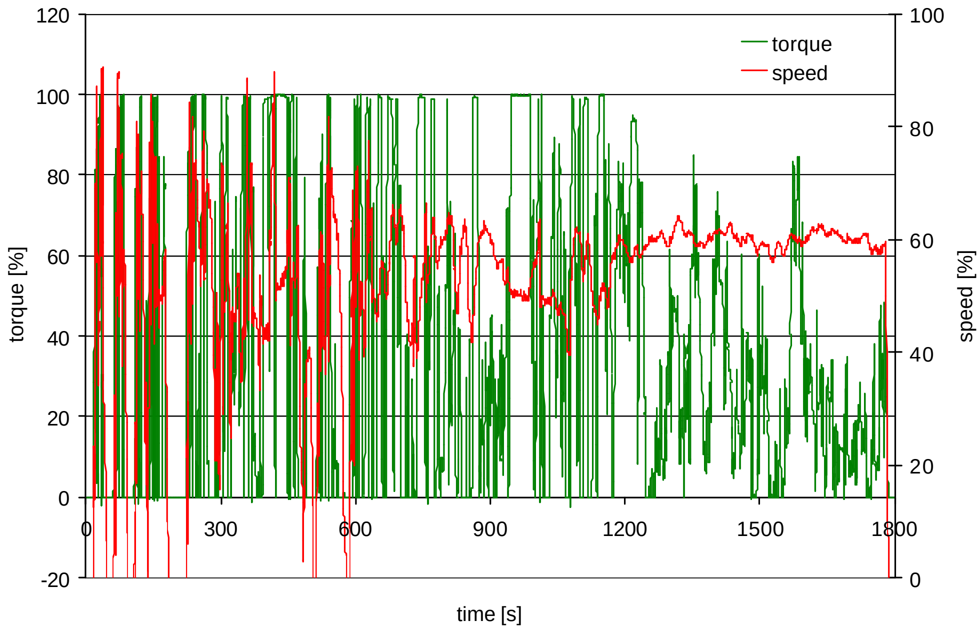


Figure 1.: *WHTC: Reference values for engine speed and torque*

F.2 The worldwide harmonized steady-state cycle (WHSC)

The steady-state cycle WHSC consists of 12 modes (engine speed/load combinations) and is shown in figure 2. The modes are based on the joint frequency distribution of normalized engine speed and load of the transient cycle (see figure 1). As with the WHTC, engine speed denormalization is based on three reference engine speeds related to the full load power curve of the engine. This approach leads to individual engine speed modes that depend on the full load power curve characteristics of the engine under test. The development of the WHSC in this program is described in detail in chapter I, below.

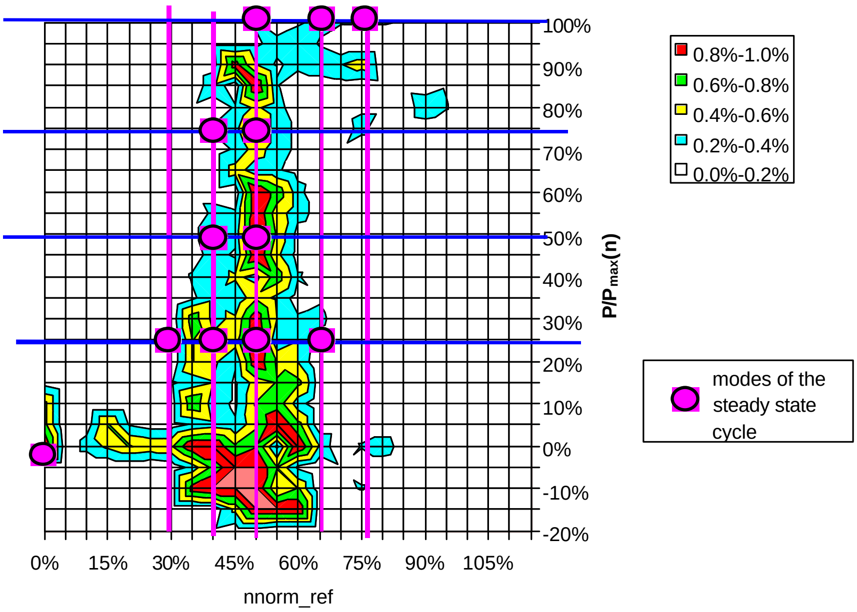


Figure 2.: *WHSC: Comparison of test modes to WHTC speed/load distribution*

G ENGINE BEHAVIOR

G.1 Engine 1

Engine 1 is a 12 litre EURO III engine with high pressure injection. Its torque and power characteristics and test cycle measuring points are shown in figure 3.

Compared to ESC, ETC and FTP, the denormalization formula of the WHDC test cycles puts more emphasis towards low engine speeds. Only a few measuring points are located around rated speed.

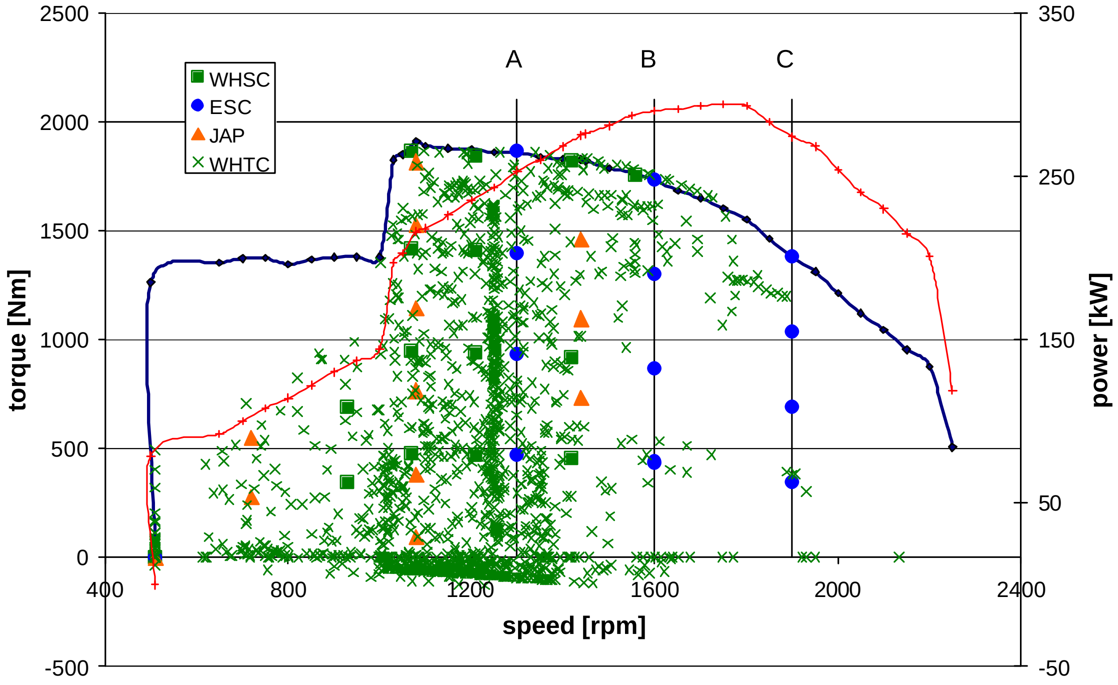


Figure 3.: *Engine 1: characteristics and test cycle measuring points*

G.2 Engine 2

This 7 litre bus engine was operated with a particulate filter (CRT-system) during all emission tests. The filter is an optional part of the engine system. Its torque and power characteristics and test cycle measuring points are shown in figure 4.

As with engine 1, the engine speed range is quite low and narrow. The upper engine speed level is not covered by emissions measurement, in fact.

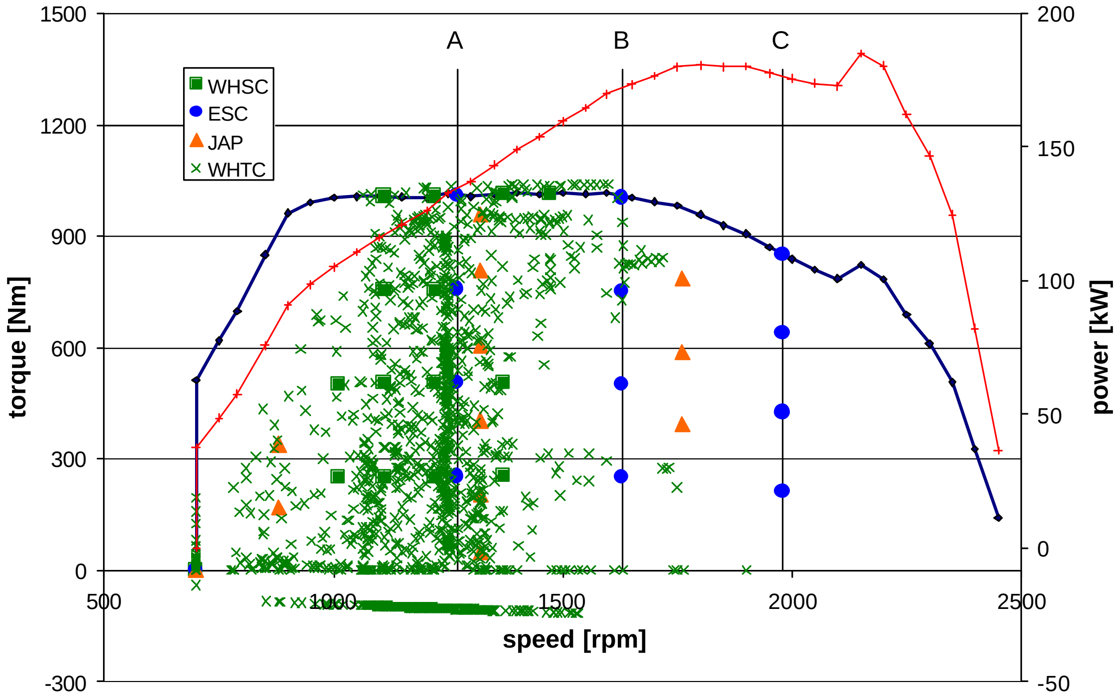


Figure 4.: *Engine 2: characteristics and test cycle measuring points*

G.3 Engine 3

This engine has a swept volume of 12 liters, and is equipped with an EGR system. Its torque and power characteristics and test cycle measuring points are shown in figure 5. The engine speed range in WHTC and WHSC is narrower than for engine 1 and is shifted to even lower engine speeds.

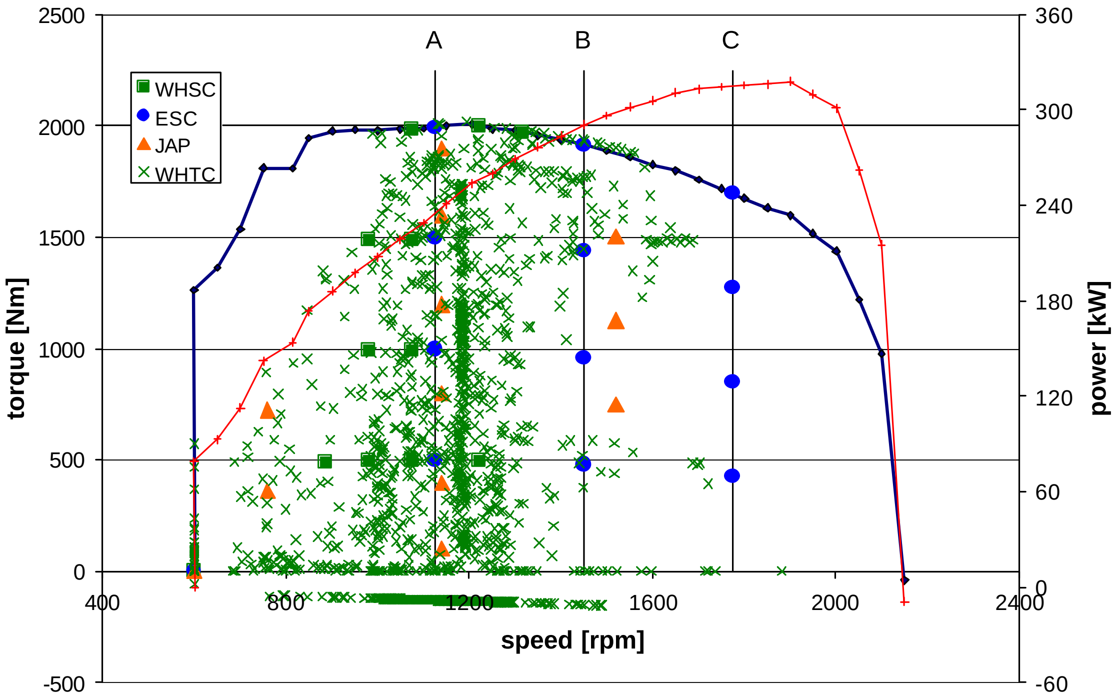


Figure 5.: *Engine 3: characteristics and test cycle measuring points*

G.4 Comparison

An important point for estimating the representativity of the cycle is the correlation between the engine speeds used on the test cycle and the engine speed range used in the vehicle, which the driver is recommended to operate on best fuel economy.

Basically, the majority of the test cycle measuring points should be within the range of low fuel consumption and above (use of available power) in order to represent the operating conditions on the road. Such a comparison is shown in table 2 between the recommended engine speed for best fuel consumption n_{LOWFC} and the speed ranges (idle excluded) covered by the WHTC and WHSC, respectively, as presented in figures 3 to 5. Those speed ranges largely coincide for engine 1. For engines 2 and 3, only the lower part of the n_{LOWFC} range is covered by the test cycles, irrespective of the engine being medium sized (7 litre) or large sized (12 litre).

engine	$n_{LOW (55\%)}$	n_{HIGH}	n_{PREF}	n_{RATED}	n_{LOWFC}	n_{WHTC}	n_{WHSC}
1	1022	2177	1100	1800	1100 – 1600	700 – 1900	900 – 1560
2	980	2360	1000	2200	1400 – 1700	800 – 1750	1000 – 1470
3	884	2092	900	1900	1150 – 1500	700 – 1650	800 – 1320

Table 2.: *characteristic engine speeds (all values in rpm)*

In order to ensure the meaningful applicability of the denormalization formula to the whole variety of engines, the formula should be validated with a number of possible full load curves of current and future engines. Depending on the outcome of this analysis, an adaptation of the denormalization formula could become necessary. It should be noted that such an adaptation would not affect the WHDC test cycles in principle, but only their application to individual engines on the test bench.

G.5 Emissions Comparison

The comparative emissions behavior of the engines is shown in figures 6, 7, 8, 9 for NO_x, PM, HC and CO, respectively. Due to the difference in actual emissions, the results have been normalized to the WHTC test cycle for each engine individually for a better comparison.

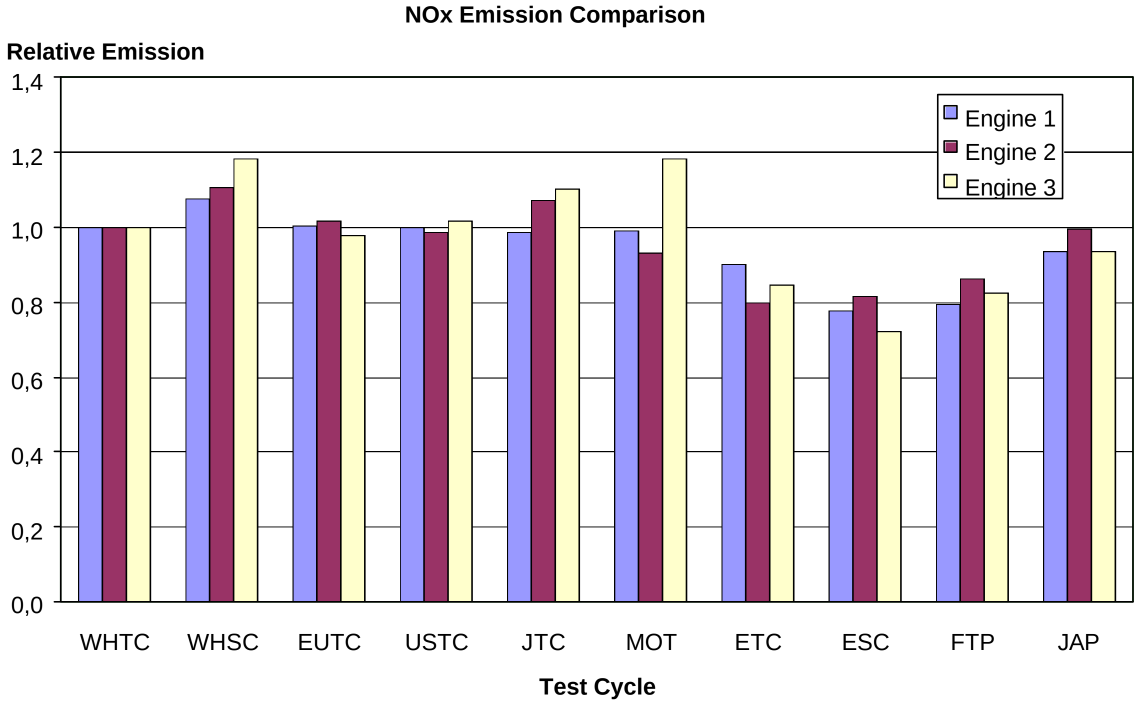


Figure 6.: *Comparison of the NO_x emission*

For NO_x, the engines turned out to be very similar over all test cycles with a few exceptions. In general, there was only a slight difference of up to 10 % between the worldwide harmonized cycle and the regional cycles including the MOT cycle. The NO_x emission on the existing legislative test cycles was generally lower than on the WHDC test cycles.

For PM, the situation is less straightforward, but in general the WHDC transient cycles compared quite well. The results on the FTP and JAP legislative cycles were close to the WHDC results whereas the ESC and ETC results were lower. It should be noted that the very low actual results from engine 2, which was equipped with a particulate trap, could be reproduced well with the ISO measurement procedure.

For HC, like for NO_x, the engines proved to be consistent. The HC emission on the JTC, MOT and FTP cycles was significantly higher, the HC emission on the ESC significantly lower compared to the WHTC.

For CO, the emissions behavior was quite consistent on the WHDC test cycles, but very different on the other test cycles, especially for engine 2. The results from engine 2 are much affected by the absolute CO emission being close to zero, as explained in chapter J.2 and figure 17, below.

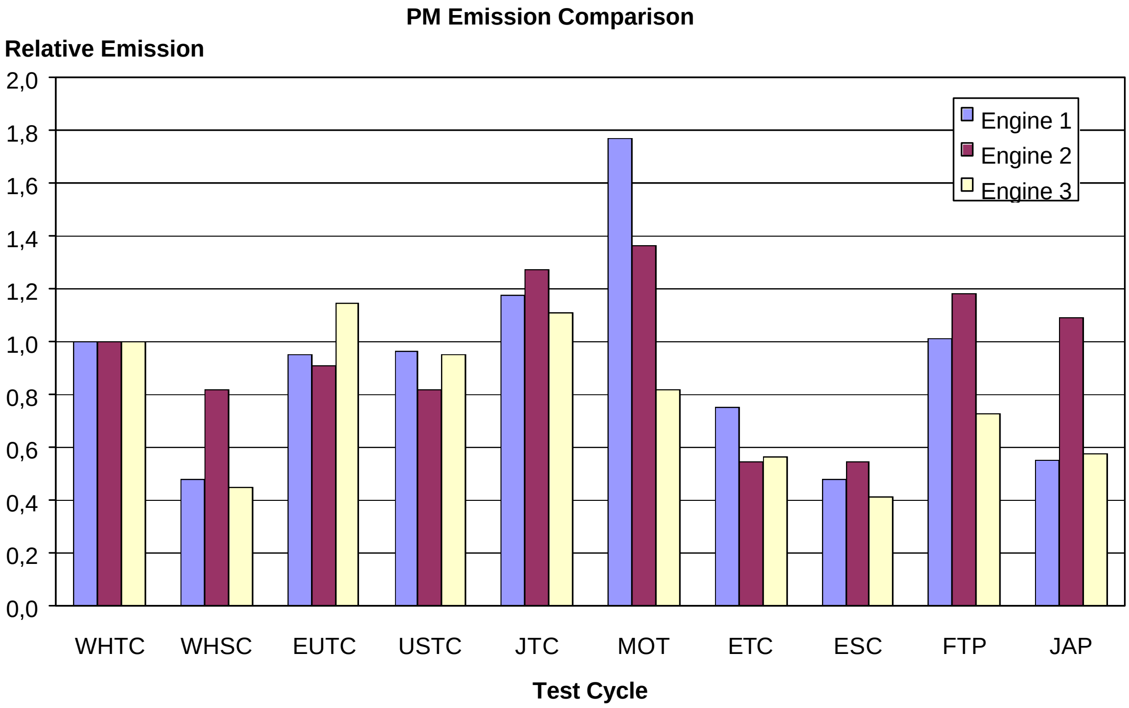


Figure 7.: *Comparison of the PM emission*

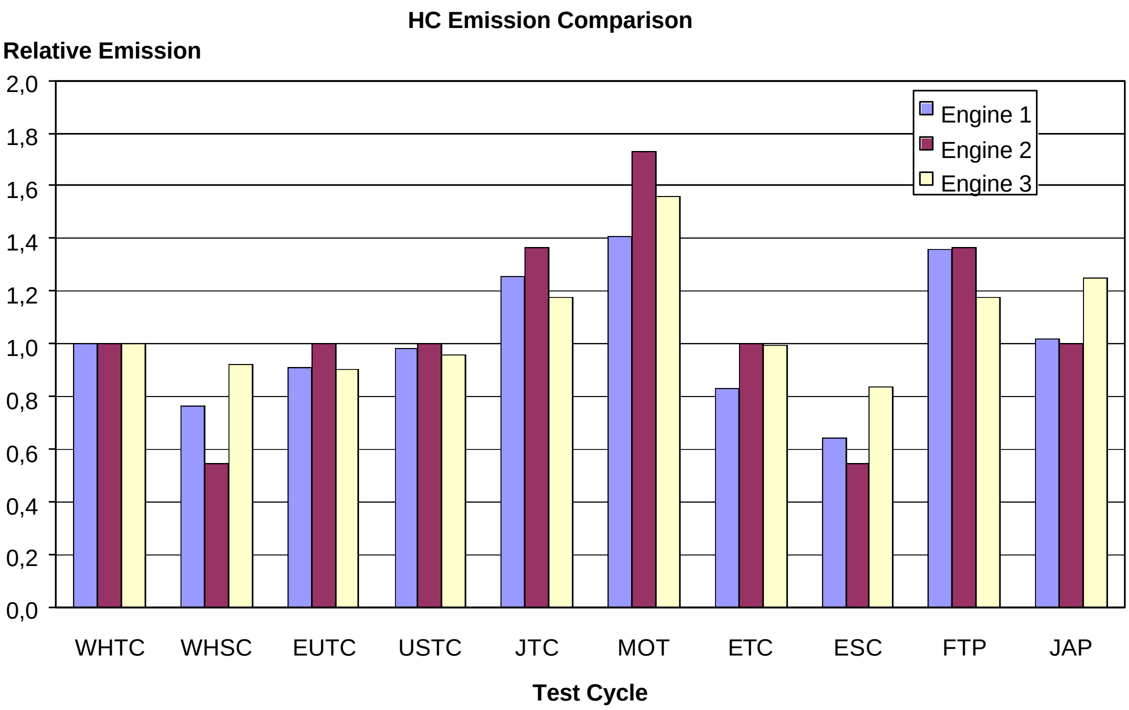


Figure 8.: *Comparison of the HC emission*

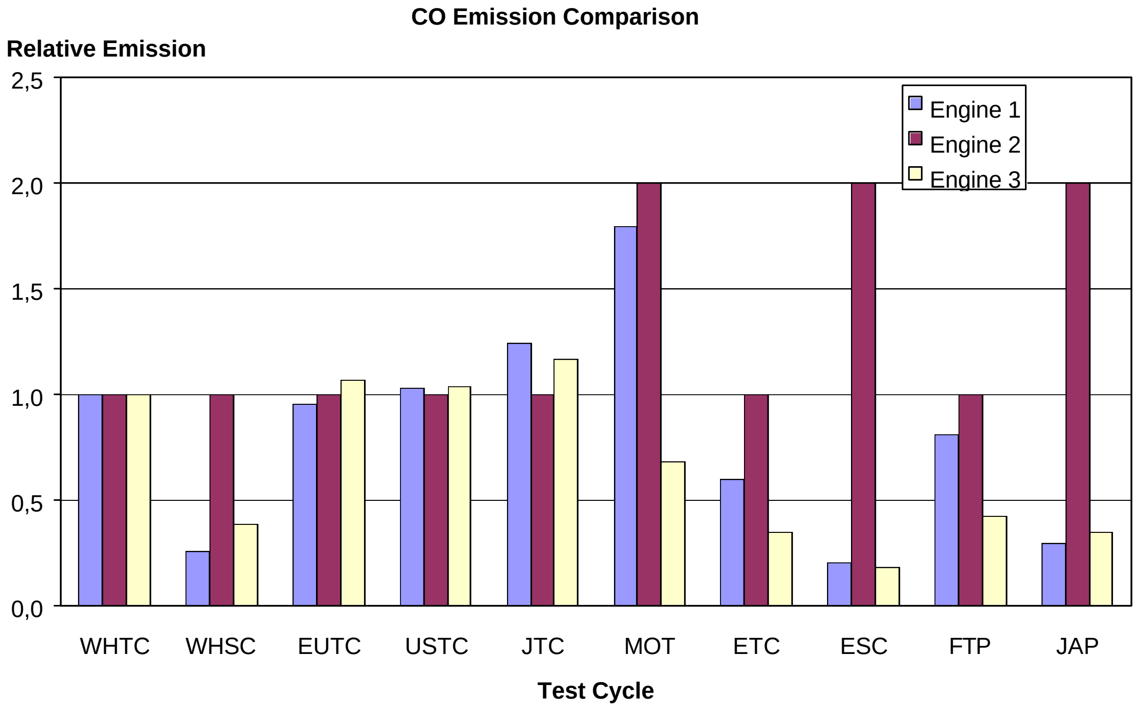


Figure 9.: *Comparison of the CO emission*

H DRIVEABILITY OF THE TRANSIENT TEST CYCLES

When running an engine over a transient cycle, the denormalized speed and torque values are the reference values that are used as command signals for the test cell control computer. At the end of the cycle, the measured signals are compared to the command signals for conformity by using linear regression analysis. The regulations allow a certain deviation from the ideal 1:1 correlation between reference and actual values, and the magnitude of the deviation is a good indicator how well the engine can follow the cycle. Therefore, the driveability of the new test cycles is primarily validated by such objective methods like comparison between reference and actual cycle work or mean cycle power and a linear regression between reference and actual values of speed, torque and power.

The regulations also permit that points may be deleted before the regression analysis is done, if the engine cannot follow the cycle for obvious reasons, e.g. if the engine management does not allow for very fast transients. A cycle derived from actual driving patterns, as the WHTC, should match with most engine management systems. Therefore, the number of points, which may be deleted (table 7 in the European Directive 99/96/EC: permitted point deletions from regression analysis [2]) is a good indicator for the realistic transformation of the real world transient events into the WHTC.

Additionally, a subjective assessment of the test cycles was made. During the test runs, any unusual operating conditions, e.g. engine events corresponding to "wrong gear shifts" or very fast changes in engine speed, and strange engine sound were tried to be detected.

H.1 Mean cycle power

The mean power produced by the engines over the different test cycles is shown in figure 10 as the average of three test runs and in relation to the WHTC (100%). One aim of the test cycle development was to be representative of in-use operation and to mirror the in-use engine power on the test bench.

For the current European test cycles ESC and ETC, the goal of in-use representativity has not been reached completely resulting in higher mean cycle power than in-use power. As a result of the better modelling, the new European regional test cycle (EUTC) has little less than half the mean cycle power compared to ETC.

For Japan, there is a good agreement in mean cycle power between the Japanese regional cycle (JTC) and the test cycle developed by JARI/MOT in parallel to the WHDC program (MOT), but the legislative test cycle JAP is about 25% higher in power.

For the USA, there is a good agreement in mean cycle power between the US regional cycle (USTC) and the legislative test cycle (FTP). However, the same mean cycle power does not necessarily result from the same engine speed and load patterns. In this case, the average engine speed is significantly lower on the USTC than on the FTP, although the mean cycle power is very similar.

The mean cycle power of the worldwide harmonized test cycles WHSC and WHTC is the average of the regional test cycles weighted by mileage operated. The USTC is nearly identical to, the EUTC slightly higher than and the JTC about 25% lower than the WHTC.

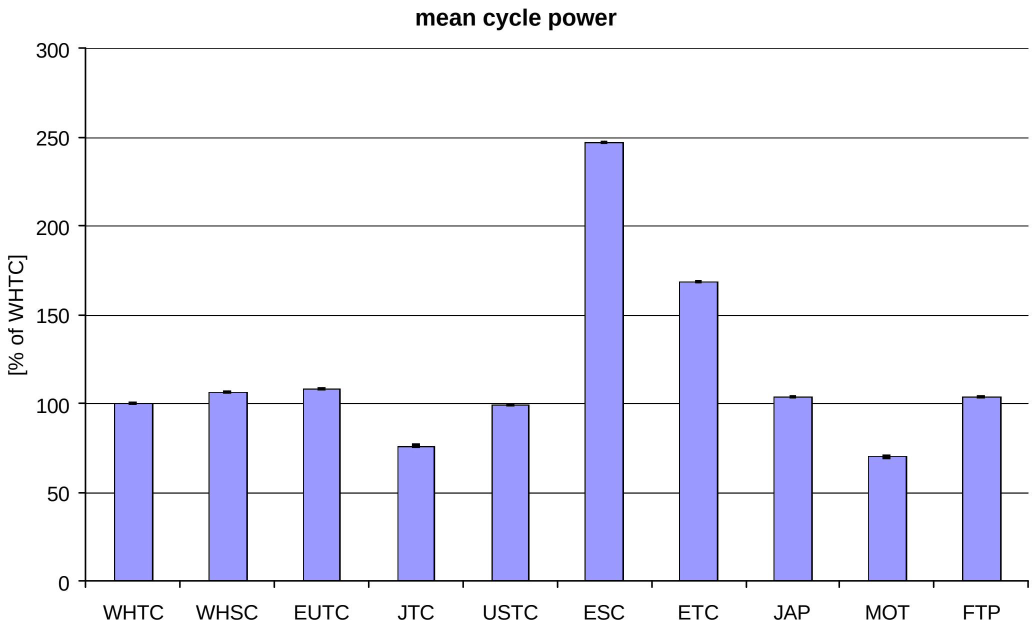


Figure 10.: *all engines:comparison of the mean cycle power*

As regards the cycle operation on the test cell, the cycle power can be repeated very accurately (very low standard deviation), no matter which test cycle is concerned.

H.2 Permitted point deletions

The most critical issue for running a test cycle on a test cell are rapid accelerations, where the engine torque cannot follow the requested reference torque, i.e. the actual torque signal is lower than the reference torque signal. To account for such rapid accelerations, it is allowed to delete those points from the regression analysis.

Figure 11 shows the average number of points deleted with the three engines tested and the corresponding standard deviation, which gives an impression of the different behavior of the individual engines.

As a conclusion, the engines can better follow the WHTC cycle than the ETC. Less than 30 points out of 1800 were deleted before the regression analysis for all three engines, pointing to a very good reflection of real world transients in the WHTC. The FTP is close to the WHTC in terms of points deleted, but the number is related to a smaller total number of 1200 points.

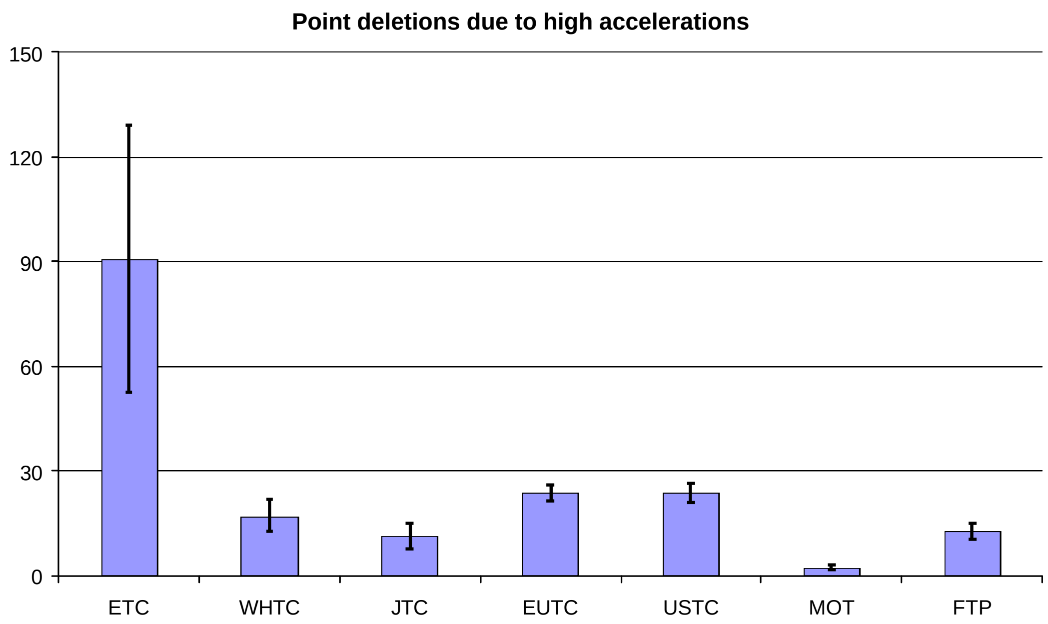


Figure 11.: *All engines: comparison of points deleted due to high acceleration rates*

H.3 Results of the regression analyses

According to EMPA's experience, the three engines tested in this program were well optimized for transient operation. The controller setting of the test bench was done with a standard procedure without a special optimization for the individual engine. Nevertheless, the results of the regression analyses were mainly below 40 % of the respective limit value.

Since the engine speed was controlled by the asynchronous motor of the test bench, it was kept very accurately at the reference value: the coefficient of determination for the speed regression was always equal to 1.0 for the WHTC test cycle.

The results of the torque and power regression were good as well. Since torque and power regression is always closely interrelated, only the results of the torque regression are presented in this report.

To compare the different engines (see figure 12), the percentage of the limit value allowed for the standard error of estimate (SE) is used for the y-axis. The bars are representing the average of all engines and the corresponding standard deviation represents the performances of the individual engines in the regression analysis.

All engines performed similarly and very well in the regression analysis. Looking at the coefficient of determination, the results of the MOT cycle were significantly less good compared to the other test cycles. Keeping in mind that the minimum value for the coefficient of determination is 0.88, there is not much room left for engines that have a slower transient response than the ones used in this program on the MOT cycle. For the WHTC on the other hand, it is very unlikely that slower response diesel engines will not pass the regression criteria.

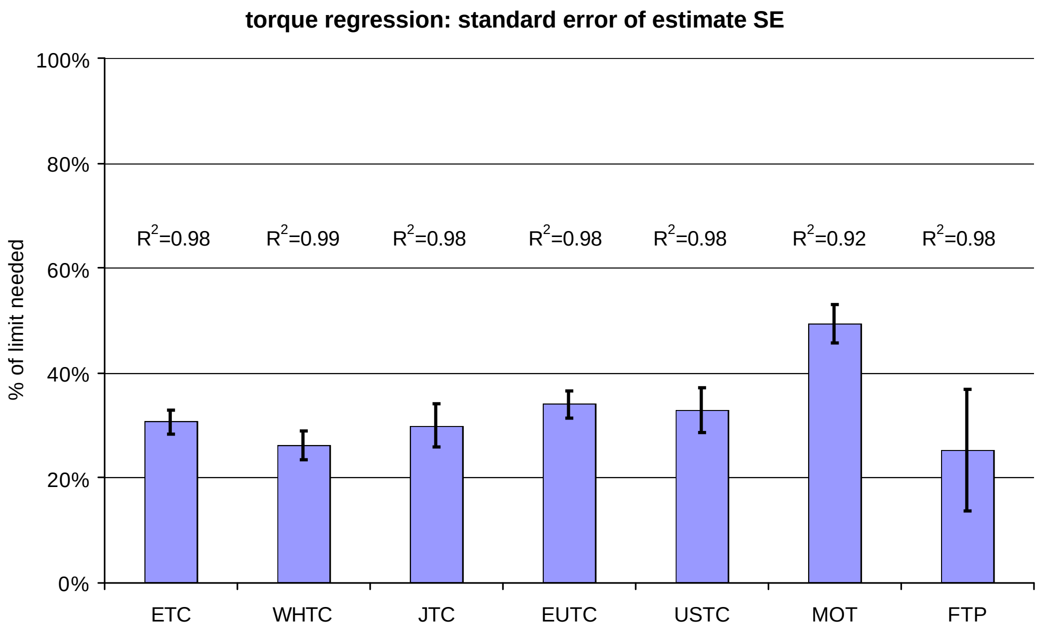


Figure 12.: *All engines: results of the torque regression*

H.4 Subjective assessment

Each test cycle was observed several times by EMPA staff members in order to detect unusual operating conditions (like very fast changes in engine speed) or strange engine sound.

The impression is, that the WHTC is very well representing the operation of a heavy-duty on-road engine, also on a subjective basis. The accelerations and the "gear change" events are very similar to real ones in vehicles.

I DEVELOPMENT OF THE WHSC CYCLE

In principle, two possible approaches exist for running a steady-state cycle, i.e. a sequence with more gradual load changes at a given engine speed like with the ECE R 49 cycle, or a sequence with speed/load changes in a randomized order like with the ESC cycle. Both versions were analyzed with engines 1 and 2. The differences in the emission results were within the standard deviation of the measurement. Therefore, the randomized ESC type version was used for the evaluation of the results.

The weighting factors (WF) of the load points have to be transferred into a sampling time for the particulates, like on the ESC. The span of these weighting factors was significantly greater in the first version of the WHSC (0.014...0.3) compared to the ESC (0.05...0.15), making particulate sampling more difficult.

In order to provide sufficient particulate sampling at all load points, it was not reasonable to go below 10 seconds sampling time per 0.01 weighting factor, e.g. to the minimum requirement of 4 seconds per 0.01 weighting factor allowed for the ESC. But this meant accordingly, that the total time of two modes had to be increased above the target of 2 minutes taken from the ESC. With these changes, the total test cycle time went up to 35 minutes.

After the measurements with the first engine, low filter loadings (0.5...0.6 mg) on the WHSC, compared to the ESC (1.1...1.3 mg) were observed, which were too low in view of a Euro 4/5 emission level of 0.02 g/kWh. So the already mentioned big difference in the span of the weighting factors on the WHSC caused problems with filter loading and mode time (idle mode: 360 s, mode 50/50: 180 s) with the selected sampling time of 10 s per 0.01 weighting factor.

Another finding during the first measurement series was, that the cycle work of the WHSC was more than 30 % higher compared to the WHTC, although both test cycles are based on the same driving patterns.

To increase the filter loading and to adjust to the differences in cycle work, the WHSC was modified with the aim of increasing the filter loading without compromising the other features of the cycle:

1. When developing a steady-state cycle from a transient cycle, the weighting factors represent the time distribution of certain operating conditions of the transient cycle. Since engine motoring is usually not considered on a steady-state cycle, the motoring time of the ETC was added to the idle weighting factor of the ESC. A new approach has been chosen for the development of the WHSC from the WHTC. The idle mode of the WHSC was weighted according to the idle time of the WHTC (14 %). The motoring time of the WHTC was only mathematically taken into account with a weighting factor of 24 %, but without power and emissions measurement, i.e. power and emissions are zero. This was

based on the assumption, that emissions are minimal during motoring and power is zero, anyway. As a consequence, the sum of the weighting factors of the modes measured is not equal to 1 anymore, but 1 minus 0.24.

2. Three modes with low weighting factors were deleted in order to be able to increase the sampling time per mode. The weighting factors were then more closely adapted to the WHTC frequency distribution. With these modifications, the cycle work of the final version of WHSC (12-mode test) became closer to that of the WHTC.
3. The test cycle was decided to be run in a similar way to the JAP, where the particulate sampling time determines the mode time. This results in a cycle with variable mode lengths compared to the fixed mode length approach of the ESC and the ECE R 49 cycles. Each mode starts with a 30 seconds period for engine stabilization, and is then run over the period required for particulate sampling depending on the modal weighting factor. The order of the modes corresponds to the ESC strategy, i.e. the randomized mode order. All these modifications increased the total particulate sampling time over the cycle from 1000 s to 1520 s with a total cycle time of 1880 s, which is slightly higher than for the WHTC.

The emissions of the different WHSC versions were compared with engine 1 and 2. The results were similar for both engines. They are exemplarily shown for engine 1 in figures 13 and 14. As can be seen, the emissions do not differ very much, and so the final version was selected in accordance with the above three step approach. The final version of the WHSC, as considered by the steering group as the best solution, is shown in table 3.

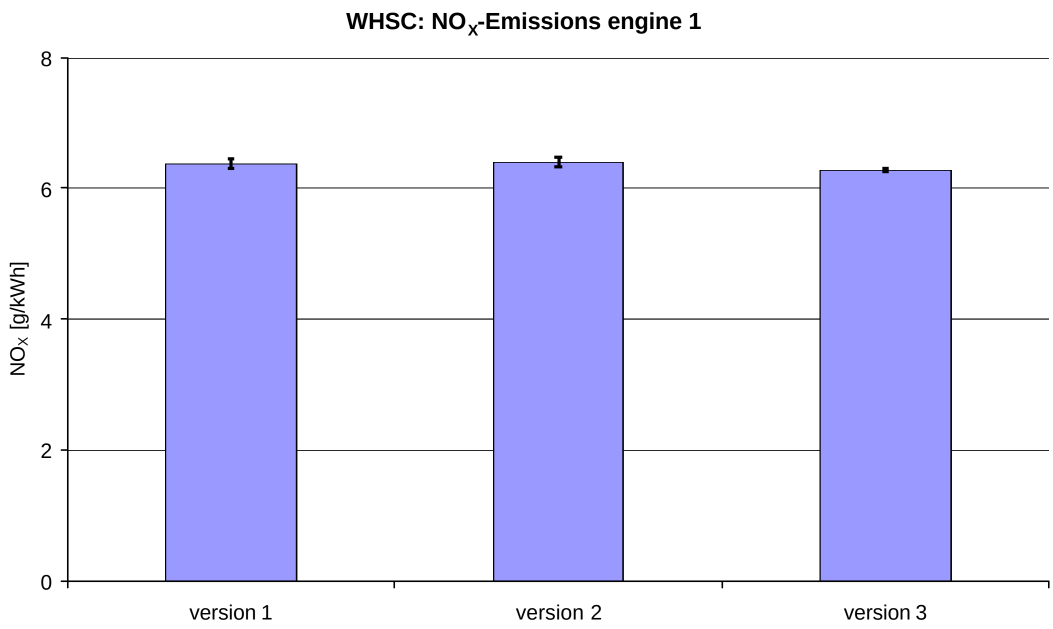


Figure 13.: *NO_X emissions of engine 1 on different versions of WHSC*

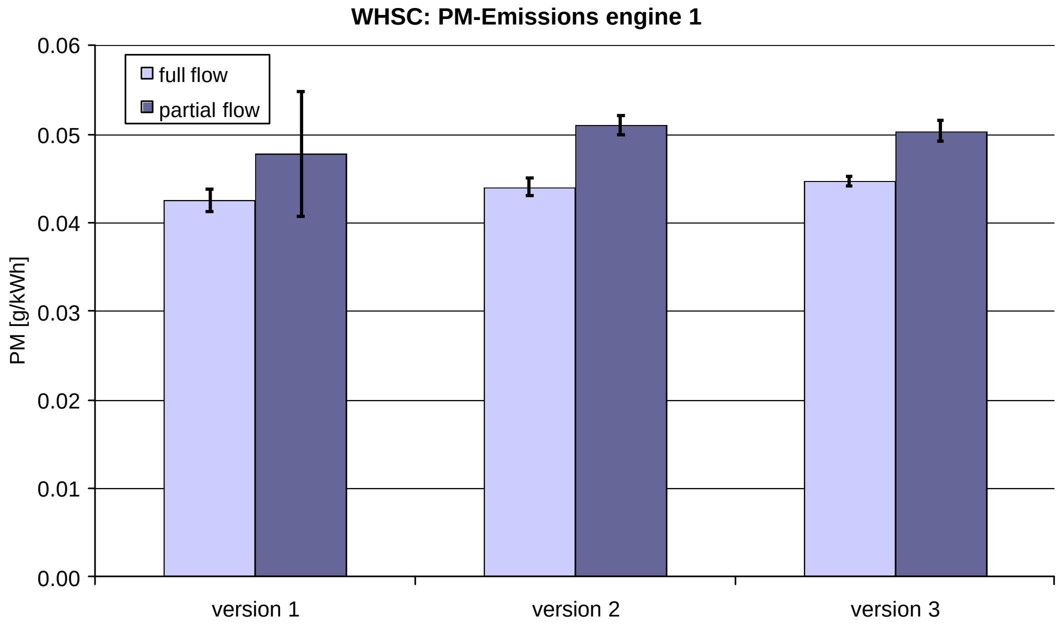


Figure 14.: *PM emissions of engine 1 on different versions of WHSC*

nnorm_ref	Motoring	engine load 0%	25%	50%	75%	100%
Motoring	0,240					
0%		0,140				
30%			0,070			
40%			0,100	0,030	0,040	
50%			0,125	0,100	0,040	0,025
65%			0,040			0,025
75%						0,025

Table 3.: *WHSC: final version*

J GASEOUS AND PARTICULATE EMISSIONS MEASUREMENT

J.1 Partial flow dilution for the particulate measurement

In the following two sections, the results regarding to the measuring technique are exemplarily shown with the worldwide harmonized test cycles WHTC and WHSC, because those were of main interest in the program. Generally, the findings are transferable to the other test cycles. As shown in figure 15, the partial flow system tended to measure slightly higher particulate emissions than the full flow system. The percentage difference was lower than 10 % for the engines without aftertreatment and increased up to 50 % for the engine with CRT-trap. These findings confirmed results from earlier correlation studies with a CRT-system [3].

The absolute difference between the systems was below 0.007 g/kWh for all engines, i.e. it remained the same with or without aftertreatment system. If the reproducibility of different full flow systems is taken into account, the agreement between full and partial flow system is good in this program.

Compared to the results in [3], the repeatability of the particulate measurement with CRT-trap was much better. For all transient test cycles, the standard deviation was at or below 20 % of the average value of three tests. In absolute values, the standard deviation was between 0.001 g/kWh and 0.003 g/kWh. The major reason for this improved repeatability was the sulfur free (2 ppm) diesel fuel used for this program.

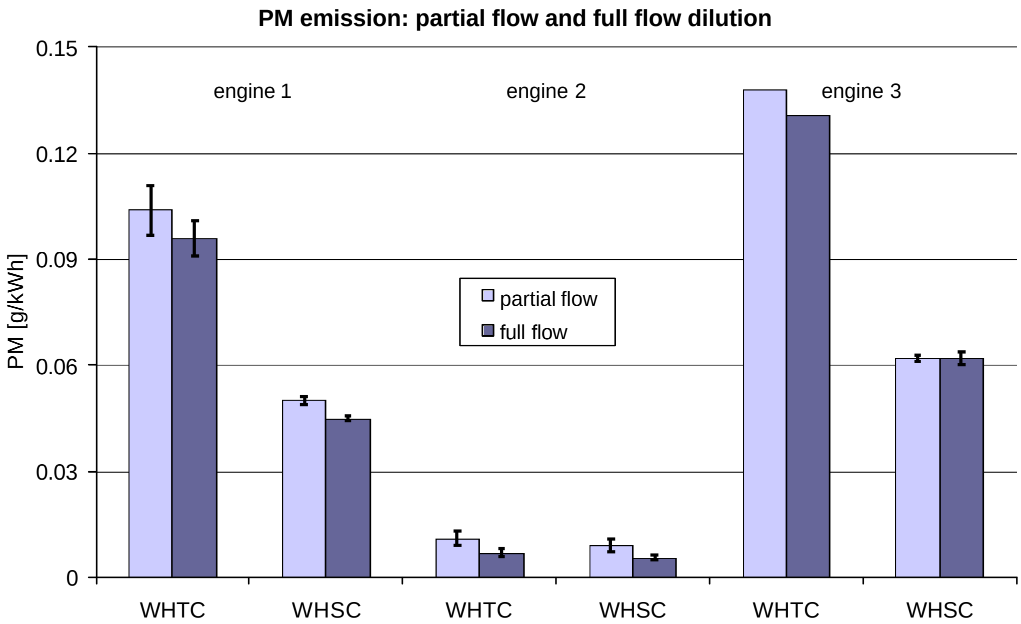


Figure 15.: *All engines: PM emission results in WHTC and WHSC*

During the program, the following aspects of particulate measurement were investigated.

J.1.1 Filter loading:

With the particulate emission level requested for the near future, the filter loading obtained in the test cycles is expected to be below the proposed limit in the ISO/FDIS 16183 for 70 mm filters. Therefore, the measurement procedure needs further refinement on the basis of error estimates.

J.1.2 Repetition of emission tests on the same filter pair:

Repeating the test cycle in order to increase the filter loading, like it is allowed in Directive 1999/96/EC and ISO/FDIS 16183, is questionable. The more repetitions were made, the lower the specific emission got, as shown in table 4. This also needs further investigation.

Test cycle	Test runs	Loading [mg]	Emissions [g/kWh]
WHTC	1	0.139	0.0072
WHTC	3	0.252	0.0044
WHSC	1	0.125	0.0055
WHSC	3	0.265	0.0039

Table 4.: *filter loading and emissions depending on the number of runs on the same filter pair*

J.2 Raw exhaust gas measurement under transient conditions

To carry out the raw gas calculations, the emissions data of the WHTC had to be time aligned with the exhaust gas mass flow, represented by the sum of fuel and air mass flow. For this time alignment, the so-called T50-time was used. The T50-time includes the flow through the sampling line.

Generally, the results were in good agreement with the measurements of the diluted exhaust gas, as shown in figures 16 to 19.

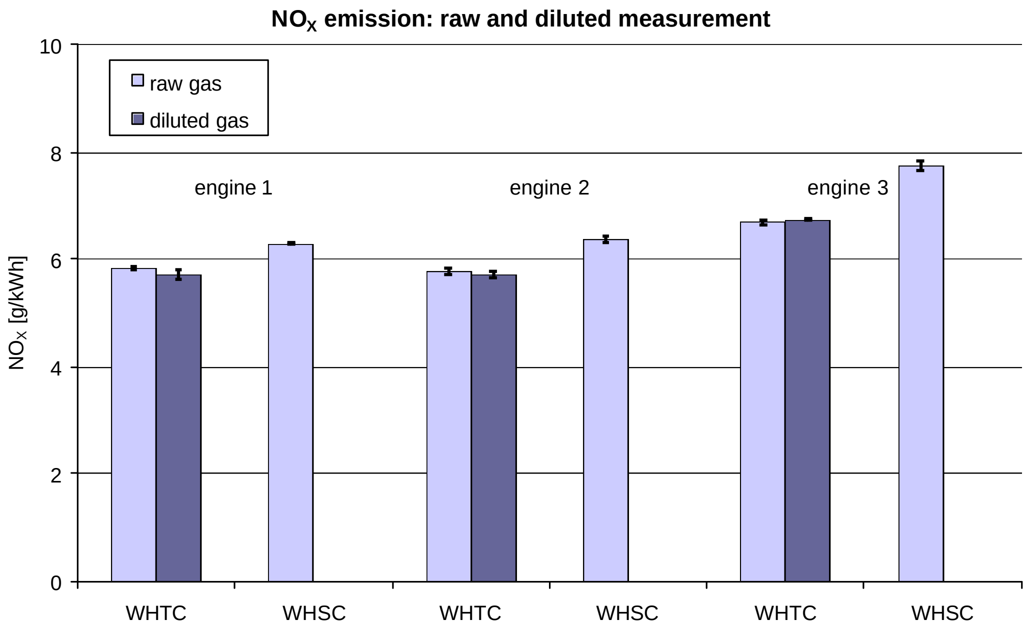


Figure 16.: *Nitrogen oxides: comparison between raw and diluted measurement*

For the nitrogen oxides (figure 16), the difference between raw and diluted measurement was below 3 % for all test cycles and engines, which is considered a very good agreement.

For carbon monoxide (figure 17), the range of the raw emissions was much larger than for NO_X. A base line emission level of a two-digit number in parts per million (ppm) is alternating with emission peaks sometimes up to 3 % of volume.

Therefore the measuring range selected for covering the emission peaks leads to loosing accuracy of the low concentrations occuring during most of the cycle. This effect caused negative concentration values in the raw exhaust gas with engine 2, where an oxidation catalyst was part of the particulate filter (measuring range: 300 ppm CO).

Nevertheless, the difference between raw and diluted emission measurement was at or below 0.4 g/kWh, and the repeatability of the two methods was comparable.

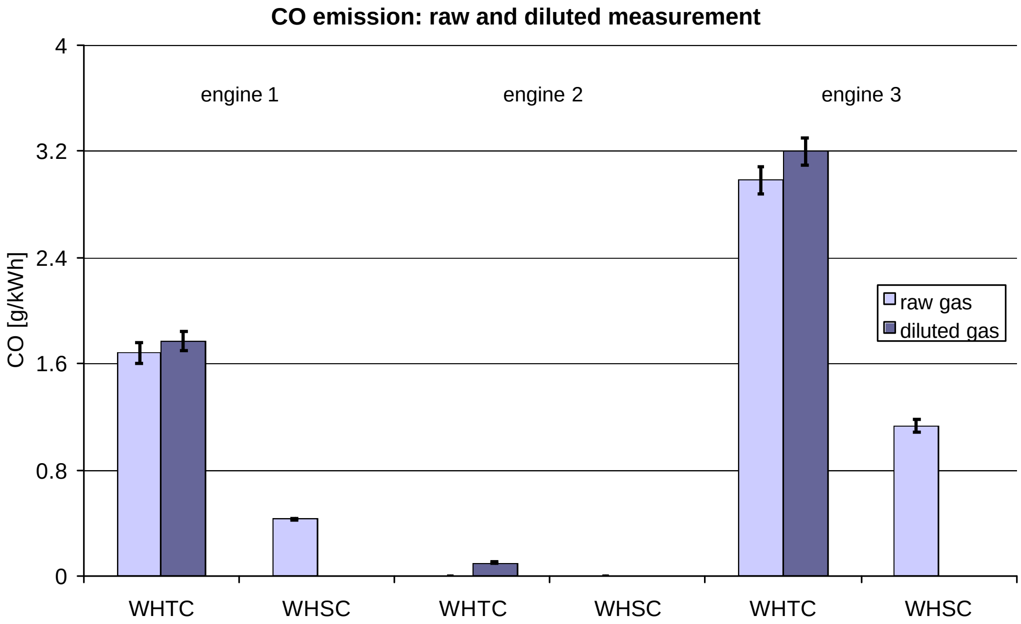


Figure 17.: *Carbon monoxides: comparison between raw and diluted measurement*

For hydrocarbons (figure 18), the diluted measurement was mostly lower than the raw measurement, which was in line with the current knowledge. The difference between the two values was significant in some cases. The relative differences went up to 20 % for some test cycles, but the absolute difference remained lower than 0.04 g/kWh.

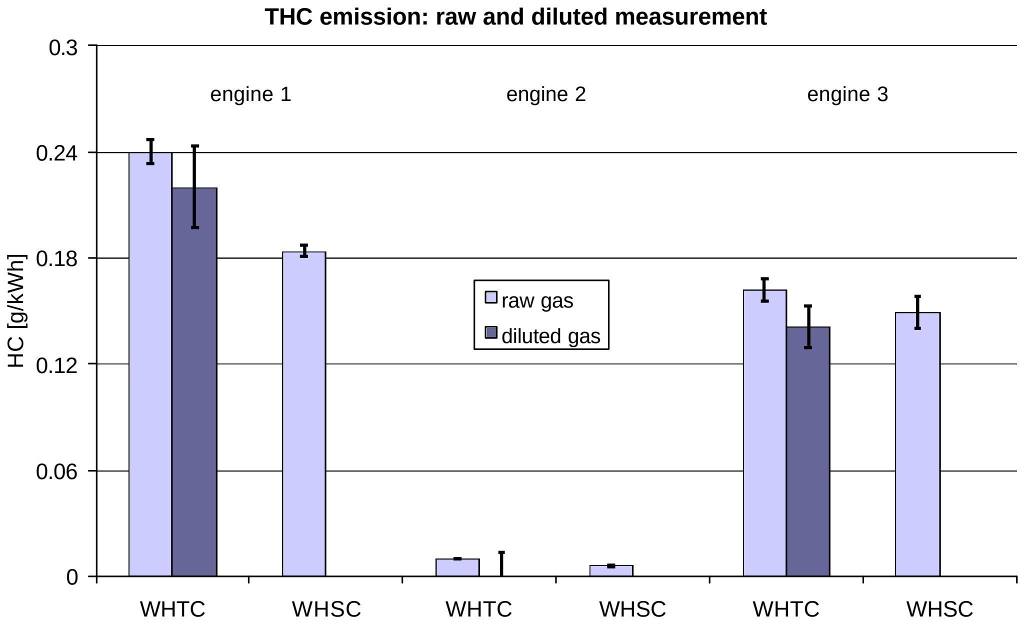


Figure 18.: *Total hydrocarbons: comparison between raw and diluted measurement*

An advantage of the new measurement procedure of ISO/DIS 16183 is the clearly improved repeatability: In most cases, the standard deviation of the raw gas measurements was around half of the one of the diluted measurements.

As regards the measurements with the CRT-trap, the diluted measurement is at its limit of detection: A drift of 0.4 ppm in the background (dilution air) turned the emission result from +0.01 g/kWh to –0.01 g/kWh (see table 5 below).

Test Cycle	Bag_{AIR} [ppm]	Integrator [ppm]	Test result [g/kWh]
WHTC2	2.7	2.4	-0.013
WHTC4	2.3	2.4	0.01

Table 5.: *Total hydrocarbons: concentrations in the diluted exhaust gas and the dilution air (engine 2)*

For carbon dioxide (figure 19), again a very good agreement between the two measuring methods was observed: The relative difference was lower than 3 % for all test cycles and engines.

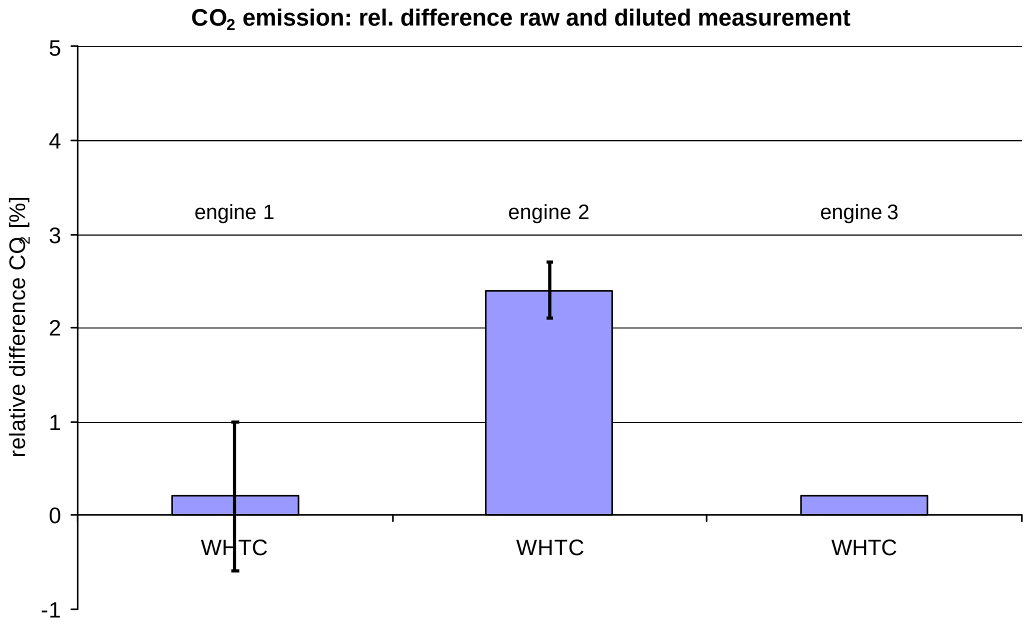


Figure 19.: *Carbon dioxides: relative comparison between raw and diluted measurement*

K SUMMARY AND CONCLUSIONS

K.1 WHDC test cycles

In terms of cycle work, the WHDC test cycles represent typical in-use operation of commercial vehicles. The regional test cycles are in good agreement with the current legislative test cycles with the exception of Europe where the reduction of the cycle work compared to ESC and ETC is evident.

Due to the denormalization formula, the engine speed range on the WHDC test cycles is relatively narrow and mostly towards the low side of the operating range compared to today's certification test cycles. There are only a few measuring points around rated speed.

The driveability of the WHTC on the test bench is good. Compared to the current cycles, an improvement is obvious. The results of the torque and power regression are below 40 % of the limit value permitted by today's regulations, which is equally good as the low number of points deleted from the regression analysis. Also in the subjective impression, the WHTC is representing very well the in-use driving behavior of state-of-the-art heavy duty engines. In total, the driveability results do not suggest any further changes to the WHTC.

The operation of the WHSC on the test bench is an improvement over the ESC, especially in terms of particulate sampling time. The WHSC is much better suited for measuring low particulate emissions than the ESC.

The ranking of the engine technologies tested in this program was very consistent over the WHDC test cycles for all regulated emissions components (NO_x, PM, HC, CO), and over all test cycles including the current legislative test cycles for NO_x and HC. For PM and CO, some differences were observed between the WHDC cycles and the legislative test cycles.

K.2 Measurement procedures

The agreement between full and partial flow dilution system was good in this program, especially, if the reproducibility of different full flow systems in a round robin test is taken into account. The partial flow system measured slightly higher values than the full flow system. Increase of the filter loading through the repetition of test runs on the same filter pair turned out to be questionable.

The raw gas measurement generally showed a good agreement to the diluted measurement. For nitrogen oxides and carbon dioxide, the differences between raw and diluted measurement were below 3 % for all test cycles and engines. For carbon monoxide, the relative differences were between 5 and 20 % for the engines 1 and 3 due to the high span of concentration and even higher for engine 2 due to the low emission level. In absolute numbers, the differences were lower than 0.4 g/kWh, which is acceptable with respect to the CO emission standard.

Due to the higher gas concentrations in the raw gas, the ISO measurement procedure is advantageous for very low emitting engines, e.g. with aftertreatment systems. A clear improvement is the raw measurement for hydrocarbons: the repeatability of the measurement went down to half of the value with the diluted measurement.

L RECOMMENDATIONS

In order to ensure the meaningful applicability of the denormalization formula to the whole variety of engines, the formula should be validated with a number of possible full load curves of current and future engines. Depending on the outcome, an adaptation of the formula could be necessary without changing the cycles in principle.

The measurement of particulates needs further refinement in order to measure future emission levels more accurately. Such modifications may include ideas of the U.S. 2007 regulations.

The raw gaseous emissions measurement according to ISO/FDIS 16183 proved to be a valuable alternative to the CVS procedure for diesel engines. The applicability to throttled engines, i.e natural gas engines, has to be verified.

M ABBREVIATIONS

CI	Compression ignition
CLD	Chemiluminescent detector
CNG	Compressed natural gas
CRT	Continuously regenerating trap
CVS	Constant volume sampling
DIS	Draft international standard
EGR	Exhaust gas recirculation
EMPA	Swiss federal laboratories for materials testing and research
ESC	European steady-state cycle
ETC	European transient cycle
EUTC	European regional transient cycle
FDIS	Final draft international standard
FTP	Federal test procedure
GRPE	Group of experts on pollution and energy
HFID	Heated flame ionization detector
ISO	International standardization organization
JAMA	Japanese automobile manufacturers association
JAP	Japanese 13-mode test
JARI	Japanese automotive research institute
JTC	Japanese regional transient cycle
LPG	Liquefied petroleum gas
MOT	Japanese ministry of transport

MOT	Japanese transient cycle, developed by JARI/MOT
NDIR	Nondispersive infrared analyzer
OICA	International organization of motor vehicle manufacturers
PDP	Positive displacement pump
SE	Standard error of estimate
UBA	German federal environmental agency
UN-ECE	United Nations economic commission for Europe
USTC	U.S. regional transient cycle
VROM	Dutch ministry of the environment
WF	Weighting factor
WHDC	Worldwide harmonized heavy-duty certification
WHSC	Worldwide harmonized steady-state cycle
WHTC	Worldwide harmonized transient cycle
WTVC	Worldwide transient vehicle cycle

N REFERENCES

[1] Heinz Steven: **Development of a worldwide harmonized heavy-duty engine emissions test cycle – final report**, informal document No. 2, 42nd GRPE session

[2] European Directive 1999/96/EG

[3] Thomas Schweizer: **WHDC investigation program**, informal document No. 1, 39nd GRPE session

[4] ISO/FDIS 16183: **Heavy duty engines – Measurement of gaseous emissions from raw exhaust gas and of particulate emissions using partial flow dilution systems under transient test conditions**