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WHDC

Worldwide Heavy-Duty Certification

Results of Validation Step 1

Final Report

under contract of

Dutch Ministry of the Environment (VROM)

International Organization of Motor Vehicle Manufacturers (OICA)

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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 the Swiss Federal Laboratories for Materials Testing and Research 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 SUMMARY AND CONCLUSIONS

D.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.

D.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.

Due to the denormalization formula, the engine speed range on the WHDC test cycles is narrow and mostly at the low side of the range. There are only a few measuring points around rated speed. The realistic applicability of the formula has to be checked with full load curves of current production engines. If the outcome is similar to the one with engines 2 and 3 in this programm, then, the formula has to be adapted.

E 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.

F 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 objective of the validation refers to the worldwide harmonized test cycles WHTC and WHSC. The regional cycles were measured for comparison purposes and better evaluation, only, and were never intended to replace the WHTC in any respect. The cycles investigated are listed in chapter H, below.

Additionally, the following 5 steady-state single modes were run:

Single mode	Engine speed/load [%]
1	40 / 100
2	30 / 50
3	50 / 25
4	65 / 50
5	rated speed / 75

Table 1: *Definition of the single modes*

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

- correlation between the different test cycles
- comparison between transient and steady-state test cycles
- correlation between CVS and ISO measurement procedures
- evaluation of measurement accuracy and repeatability
- evaluation of driveability of the transient cycles
- evaluation of possible modifications to test cycles and/or measurement procedures

On all tests, the standard CVS and the test equipment according to ISO/FDIS 16183 were run in parallel. Therefore, two gaseous components analyzer benches were used on the test cell for parallel measurement of dilute emissions with a CVS system and raw emissions according to ISO/FDIS 16183 with exhaust mass flow measurement. The following components were measured: HC, CO, NO_X, PM and CO_2.

For the particulates measurement, a full flow and a partial flow dilution system was used. The parameters for both systems were set as follows:

Dilution factor:	6 (set at speed C 100 of ESC cycle)
Filter face velocity:	60 – 80 cm/s
Sampling probe diameter:	4 or 6 mm
Transfer tube length:	max. 0.5 m
Transfer tube temperature:	200 °C
Partial flow dilution tunnel:	insulated, not heated

Table 2: *Settings of the particulate measuring systems*

The particulates collected on the filter were analyzed for the organic and partially for the sulfate portion for two runs of each test cycle.

For statistical reasons, 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. The worldwide transient cycle was run six times, three times at one day and three times at different days.

G EMPA FACILITY DESCRIPTION

The heavy-duty test cell in EMPA 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 the integrated security system to monitor gas concentrations, with a gas massflow measuring unit and a separate full flow dilution tunnel, the facility is equipped for testing engines fuelled with compressed natural gas (CNG) or liquified petroleum gas (LPG).

G.1 Dynamometer Schenck DYNAS 680

- Fixed asynchronous motor with 6-pulse static converter (AEG) for 4 quadrant operation			
- Speed- and torque measuring unit with transducer flange and telemetric data transmission (GIF)			
- Rated power of dynamometer (generating and motoring)	680	kW	
- Rated speed	4000	RPM	
- Rated torque	2500	Nm	(until 2600 RPM)
- Max. angular acceleration (unloaded)	3300	RPM 1/s	
- Accuracy of torque measurement	< 0.5	% FS (typ. 0.3 % FS)	
- Pick up frequency of speed and torque signal	256	Hz	

The asynchronous motor, the CVS system and the exhaust gas analysers are controlled by the software X-ONE from Schenck. Other measurement devices may be integrated in the test bed control unit. It is also possible to provide signals for customers applications.

The exhaust system is built according to the definition of the engine manufacturer. The location for the raw exhaust gas sample probe is between muffler/catalyst and the insulated part of the exhaust tube. At the same location, there is also the sample probe for particulates (partial flow system), smoke and opacity measurements.

For the WHDC validation program, a partial flow dilution system (AVL Smart Sampler SPC 472) was installed and supplied with the signals of air and fuel mass flow.

G.2 Infrastructure

The intake air is filtered and temperature and humidity controlled. The humidity is measured with a MBW dew point unit, the intake air massflow with a Degu-Flow sensor.

For the fuel flow measurement, two different systems are available: For diesel engines, the continuous gravimetric fuel consumption measurement is used with the double vessel system AVL 734. For gas engines, there is another system, based on the Coriolis principle. In this program, this Rheonik unit was used for the continuous exhaust gas mass flow during transient cycles.

The test bench cooling system controls the compressed air cooler, which may be installed instead of the cooler used in the vehicle, and the cooling water temperature of the engine.

G.3 Full flow CVS system Pierburg-120-WT

The dilution air is temperature controlled and filtered. After temperature conditioning, the air penetrates through coarse filters, activated carbon filters and fine filters. A flow mixing orifice improves the mixing of the exhaust gas with the dilution air in the tunnel.

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. This feature provides accurate particulate measurements, even for enhanced environmentally friendly vehicles (EEV).

After the mixing zone, there are heated probes and transfer pipes for the continuous measurement of diluted exhaust gas. One sampling line is for the hydrocarbons (heated to 190°C), the other for $NO_{X,}$ CO and CO_2 (heated to 90°C).

The sample probe for the particulates measurement, which is performed by single or double dilution, is placed at the same distance from the mixing orifice. The sampling probe has a 12.5 mm inner diameter. The standard filters used are Pallflex T60A20 with a diameter of 70 mm. At 2 mm from the primary filter, the temperature is controlled by a PT100.

A heat exchanger is used to keep the temperature of the air/exhaust gas mixture constant at 50 ±5 °C.

The sampling probes and the transfer pipes to the exhaust gas bags are situated downstream of the heat exchanger. Moreover there is a probe for additional measurements with e.g. a mass spectrometer (CI-MS) or a gas chromatograph (GC-VOC).

The constant volume flow is provided by a positive displacement pump (PDP). The flow rate can be adjusted with the motor speed to different exhaust volume flows between 25 m^3/min and 100 m^3/min.

G.4 Exhaust gas analyser

The exhaust gas measuring device is located in the operating room of the test bed. The probe location (raw, diluted, bag) can be chosen manually at the analyser itself. The system Horiba MEXA 9200 DF is equipped with four standard emissions analysers:

HFID:	measurement of gaseous hydrocarbons (THC)
CLD:	measurement of oxides of nitrogen (NO_X)
NDIR:	measurement of carbon monoxide (CO)
NDIR:	measurement of carbon dioxide (CO_2)

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.

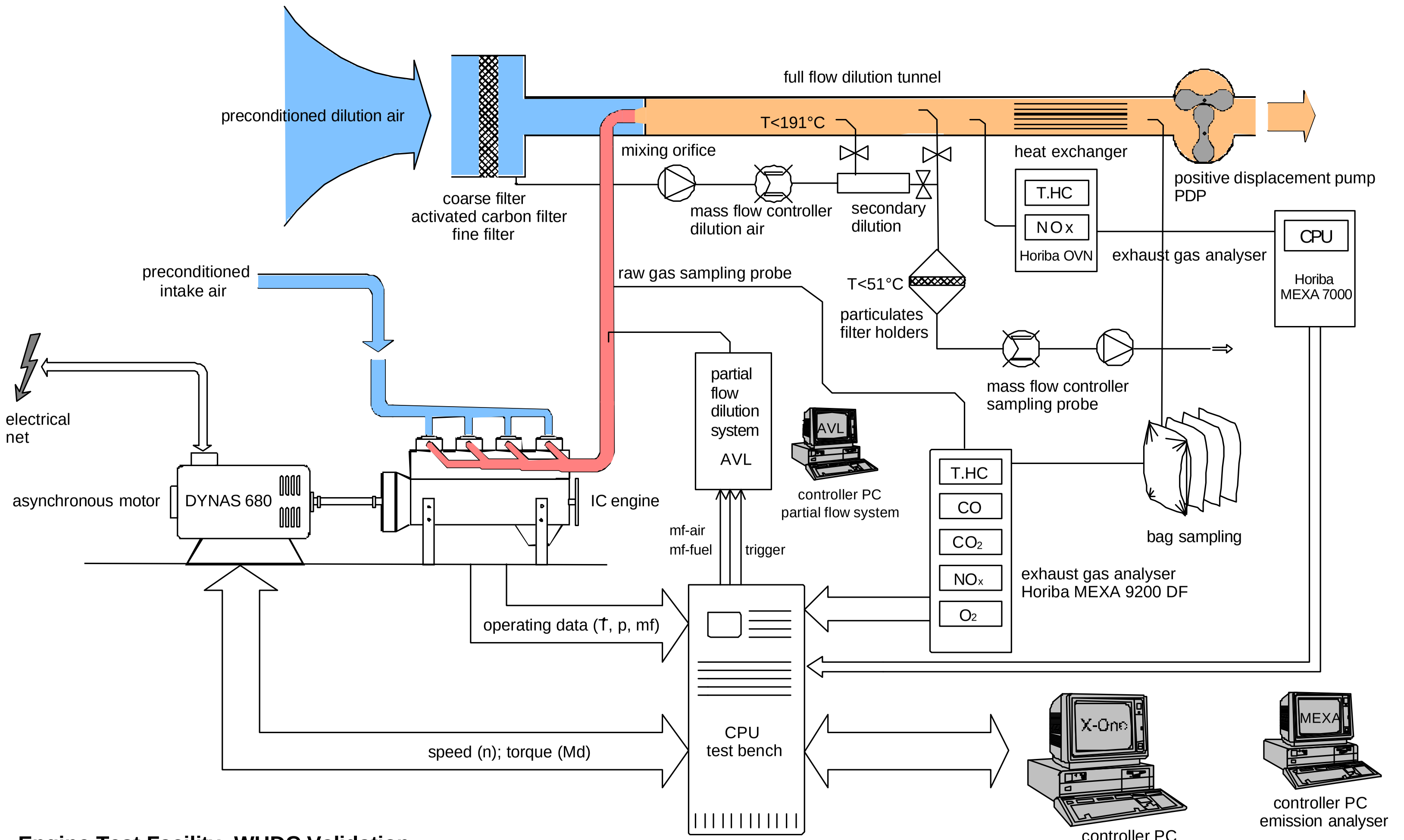
The HFID is located approximately in the middle of the raw and the diluted sample probe so that the heated transfer lines (190°C) are as short as possible. The other standard components are sampled through a separate line (90°C) to the main analyser bench. CO and CO_2 are measured dry after passing a cooling trap, NO_X is measured wet. The calculations can be made by the analyser or by the test bench control unit.

For this project, the measurement installations were extended with a second emission analyser system (Horiba MEXA 7000). This installation allowed the parallel measurement of raw and diluted gaseous emissions concentrations.

G.5 Filter weighing

Before weighing, the filters are stored in glass Petri dishes in the same room, which also houses the microbalance. The air in this room is filtered and maintained at a constant temperature and humidity.

The filter balance is a Mettler MT5 with an internal precision and a readability of 1 µg.



Engine Test Facility: WHDC Validation

H TEST CYCLES

The test cycles listed in table 3 were run in this program. The final version of the WHSC, as described in chapter H.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
Worldwide harmonized transient cycle	WHTC
Worldwide harmonized steady-state cycle	WHSC
WHSC (version 1, ESC type mode sequence)	WHSV
WHSC (version 2, R49 type mode sequence)	WHSR
WHSC (version 3, optimized approach)	WHSN
WHSC (version 4, final)	WHSM
European regional cycle	EUTC
Japanese regional cycle	JTC
U.S. regional cycle	USTC
European transient cycle	ETC
European steady-state cycle	ESC
Japanese transient cycle developed by JARI	MOT
Japanese 13-mode cycle	JAP
U.S. federal test procedure (transient cycle)	FTP

Table 3: *Test cycles investigated in the program*

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

H.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:

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

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.

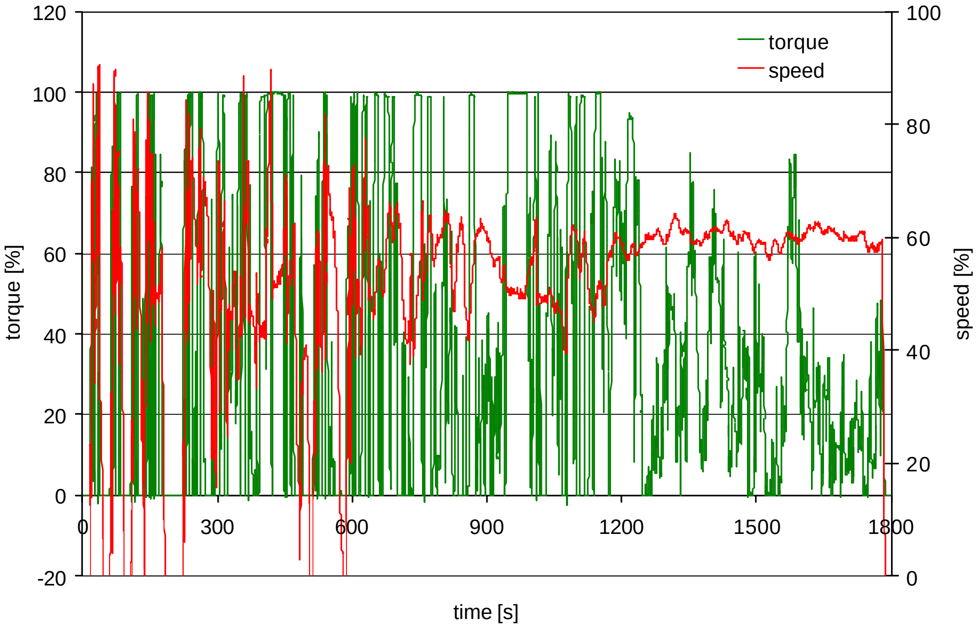


Figure 1.: *WHTC: Reference values for engine speed and torque*

H.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.

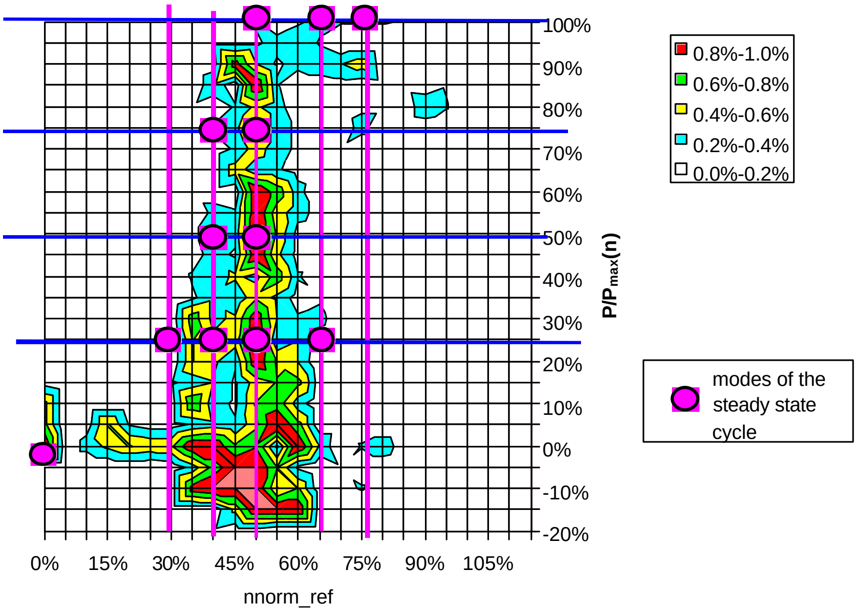


Figure 2.: *WHSC: Comparison of test modes to WHTC speed/load distribution*

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.

The reason for running the WHSC with these different orders of the test modes was to check the influence on the emission results and on the temperature level of the exhaust gas.

Both versions were investigated with engines 1 and 2. The R 49 type version of WHSC was named WHSR and is listed in table 4. The ESC type version was named WHSV and is listed in table 5. The order of the modes in the WHSV was defined based on an exhaust gas temperature profile of engine 2. Both versions consist of 15 modes.

Mode No	Speed [%]	Load [%]	WF	Sample time [s]	Mode duration [s]
1	idle	0	0.300	300	360
2	30	50	0.014	14	120
3	30	25	0.038	38	120
4	40	25	0.080	80	120
5	40	50	0.041	41	120
6	40	75	0.038	38	120
7	40	100	0.022	22	120
8	50	100	0.032	32	120
9	50	75	0.084	84	120
10	50	50	0.141	141	180
11	50	25	0.103	103	120
12	65	25	0.035	35	120
13	65	50	0.019	19	120
14	65	100	0.031	31	120
15	75	100	0.022	22	120
Sum			**1.000**	**1000**	**2100**

Table 4: *WHSR cycle (WHSC version 1)*

Mode No	Speed [%]	Load [%]	WF	Sample time [s]	Mode duration [s]
1	idle	0	0.300	300	360
2	40	100	0.022	22	120
3	50	50	0.141	141	180
4	50	75	0.084	84	120
5	30	50	0.014	14	120
6	40	75	0.038	38	120
7	30	25	0.038	38	120
8	65	100	0.031	31	120
9	50	25	0.103	103	120
10	75	100	0.022	22	120
11	65	25	0.035	35	120
12	50	100	0.032	32	120
13	40	50	0.041	41	120
14	40	25	0.080	80	120
15	65	50	0.019	19	120
Sum			**1.000**	**1000**	**2100**

Table 5: *WHSV cycle (WHSC version 2)*

For particulate measurement, the weighting factors (WF) of the load points have to be transferred into a particulate sampling time, like on the ESC. The span of these weighting factors was significantly greater in versions 1 and 2 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 extended above the target of 2 minutes taken from the ESC. With these changes, the total test cycle time increased to 35 minutes.

After the measurements with the first engine, low filter loadings (0.5...0.6 mg) on both versions of 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. It was concluded that the 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 in a three step approach 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 WHSC, which now consists of 12 modes, 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. 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 longer than for the WHTC. As a consequence, the proportion of sampling time to cycle length increased from 0.48 to 0.81 and is now much closer to the ideal value of 1 applied to transient cycles.

The resulting version 3 of WHSC was named WHSN and is listed in table 6.

Mode No	Speed [%]	Load [%]	WF	Sample time [s]	Mode duration [s]
0	Motoring		0.240		
1	0	0	0.140	280	310
2	50	100	0.025	50	80
3	50	25	0.110	220	250
4	50	75	0.050	100	130
5	40	75	0.050	100	130
6	30	25	0.060	120	150
7	65	100	0.025	50	80
8	65	25	0.060	120	150
9	50	50	0.110	220	250
10	75	100	0.025	50	80
11	40	50	0.035	70	100
12	40	25	0.070	140	170
Sum			**1.000**	**1520**	**1880**

Table 6: *WHSN cycle (WHSC version 3)*

During the measurements with the second engine, the weighting factors of version 3 were recalculated in order to even better match the WHTC speed/load distribution and were incorporated in the final version of the WHSC, which was named WHSM and which is listed in table 7. By comparing tables 6 and 7, it can be seen that the changes of the weighting factors were minor. Since the final version was completed late in the program, it was investigated for engine 3, only.

Mode No	Speed [%]	Load [%]	WF	Sample time [s]	Mode duration [s]
0	Motoring		0.240		
1	0	0	0.140	280	310
2	50	100	0.025	50	80
3	50	25	0.125	250	280
4	50	75	0.040	80	110
5	40	75	0.040	80	110
6	30	25	0.070	140	170
7	65	100	0.025	50	80
8	65	25	0.040	80	110
9	50	50	0.100	200	230
10	75	100	0.025	50	80
11	40	50	0.030	60	90
12	40	25	0.100	200	230
Sum			**1.000**	**1520**	**1880**

Table 7: *WHSM cycle (WHSC final version)*

The emissions of the different WHSC versions were compared with engine 1 and 2. The results were similar for both engines. The NO_x and PM values are exemplarily shown for engine 1 in figures 3 and 4. All results from all engines are presented in chapter K (emissions measurement results). As can be seen, the differences in the NO_x and PM emission results were within the standard deviation of the measurements. Therefore, it was decided to use the randomized ESC type version as basis for the final version of the test cycle WHSC, and to select the final version 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 8. This version of the test cycle was presented at the WHDC meeting in Geneva in May 2001 as the final product of the test cycle development [1].

	Motoring	engine load				
nnorm_ref		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 8: *WHSC: final version*

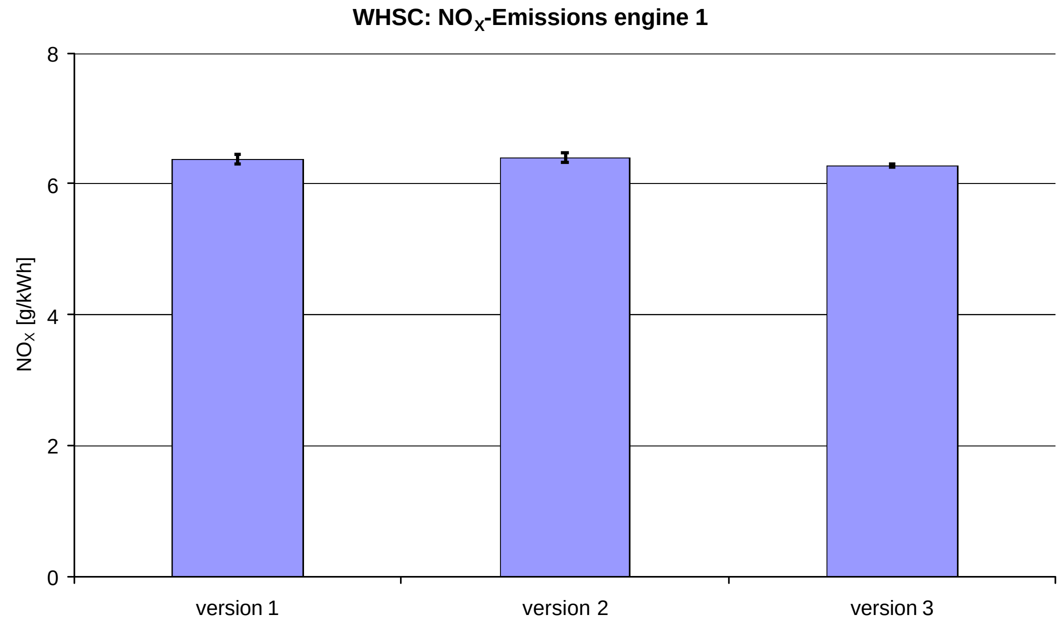


Figure 3.: *NO$_X$ emissions of engine 1 on different versions of WHSC*

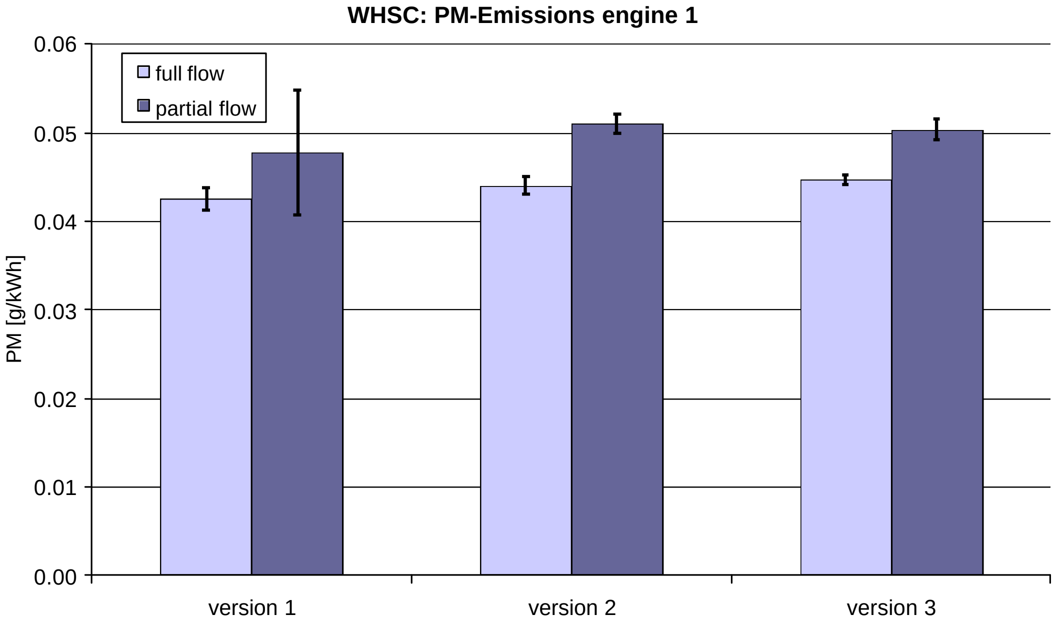


Figure 4.: *PM emissions of engine 1 on different versions of WHSC*

J ENGINE BEHAVIOUR

J.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 5.

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.

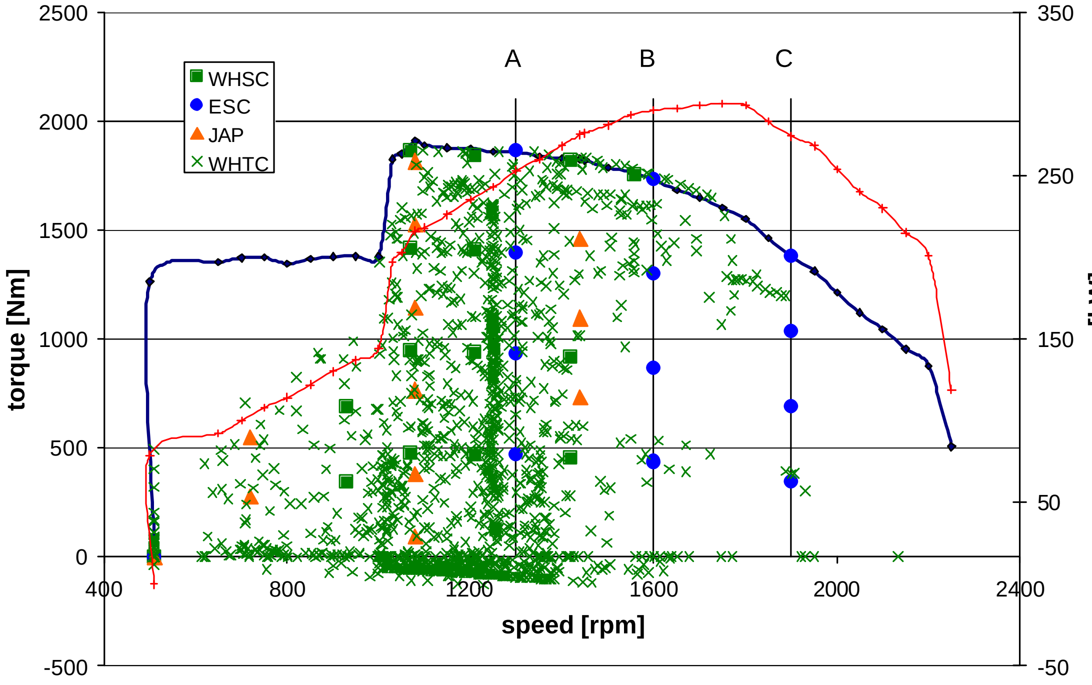


Figure 5.: *Engine 1: characteristics and test cycle measuring points*

J.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 6.

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.

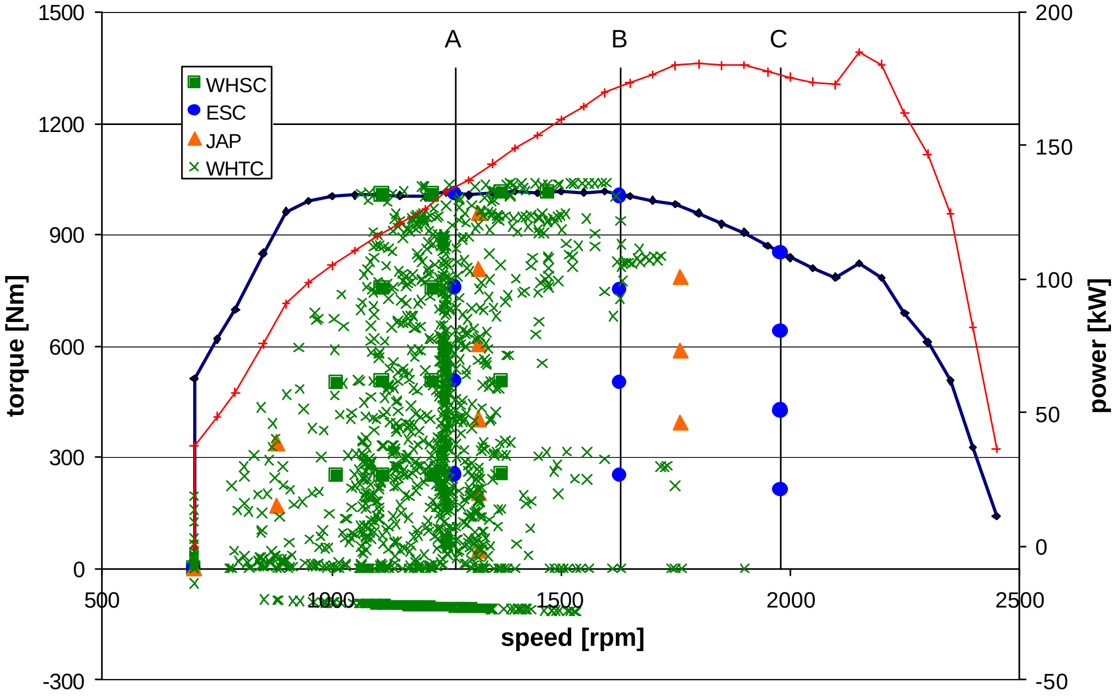


Figure 6.: Engine 2: characteristics and test cycle measuring points

J.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 7. The engine speed range in WHTC and WHSC is narrower than for engine 1 and is shifted to even lower engine speeds.

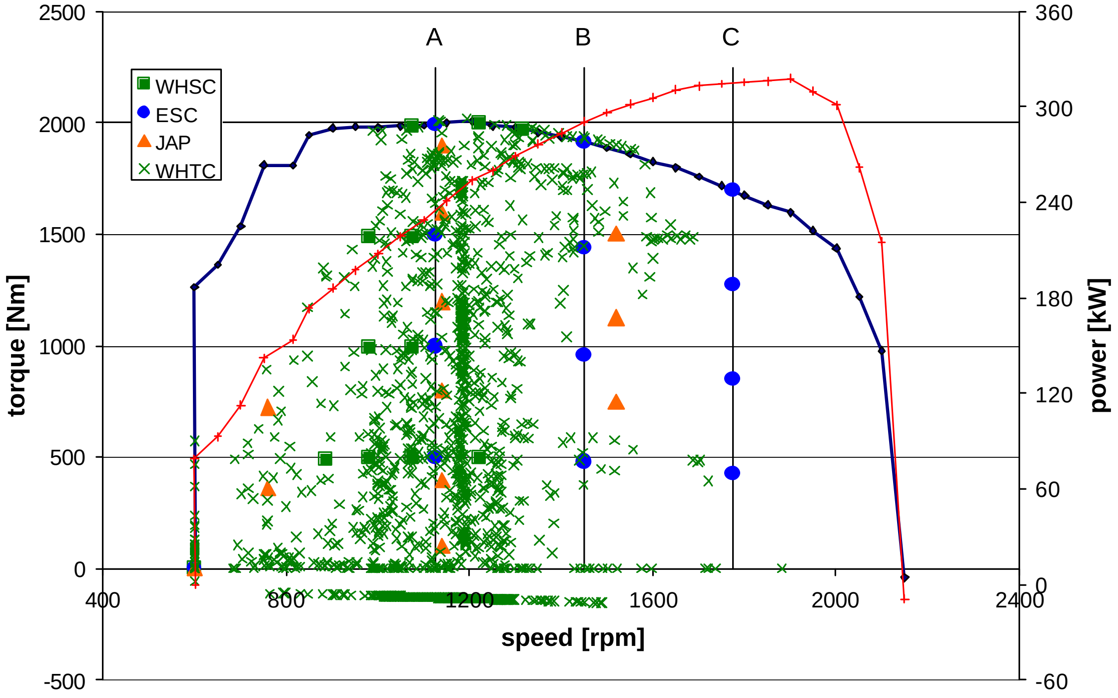


Figure 7.: *Engine 3: characteristics and test cycle measuring points*

J.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 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 9 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 5 to 7. 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}	$n_{WHTC\ (0-100\%)}$	n_{WHSC}
1	1022	2177	1100	1800	1100 – 1600	510 – 1915	510 – 1560
2	980	2360	1000	2200	1400 – 1700	700 – 1745	700 – 1470
3	884	2092	900	1900	1150 – 1500	600 – 1586	600 – 1315

Table 9: *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.

J.5 Emissions Comparison

The comparative emissions behavior of the engines is shown in figures 8, 9, 10, 11 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.

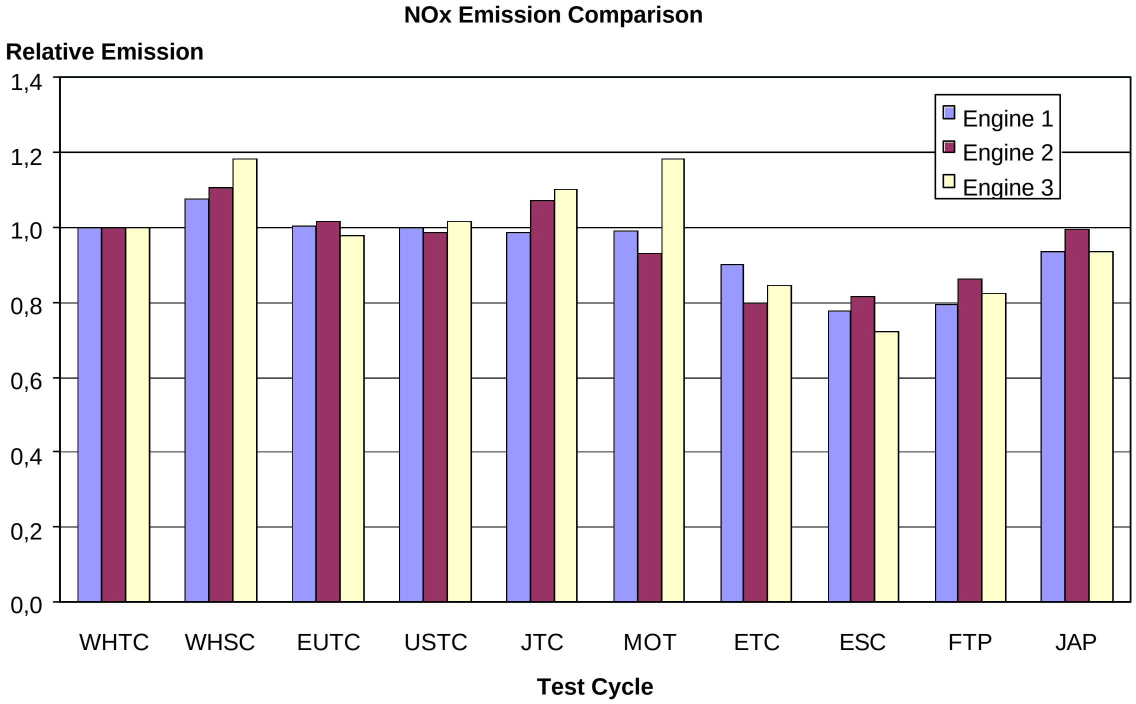


Figure 8.: *Comparison of the* NO_x *emission*

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 M.2 and figure 57.

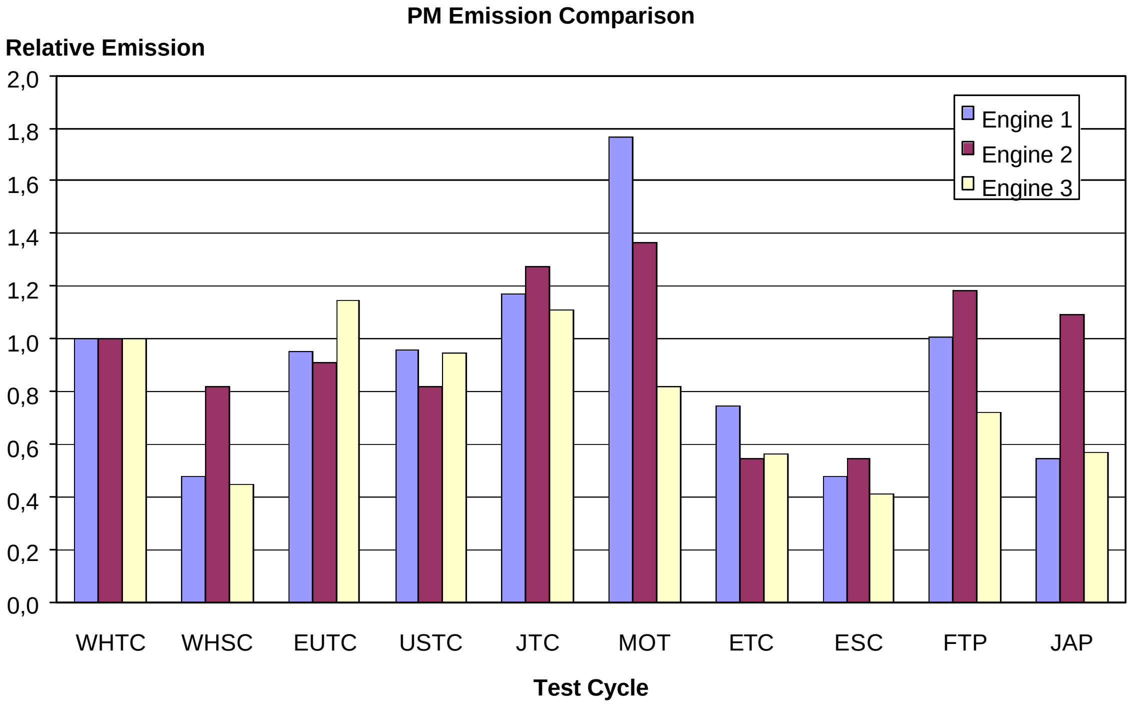


Figure 9.: *Comparison of the PM emission*

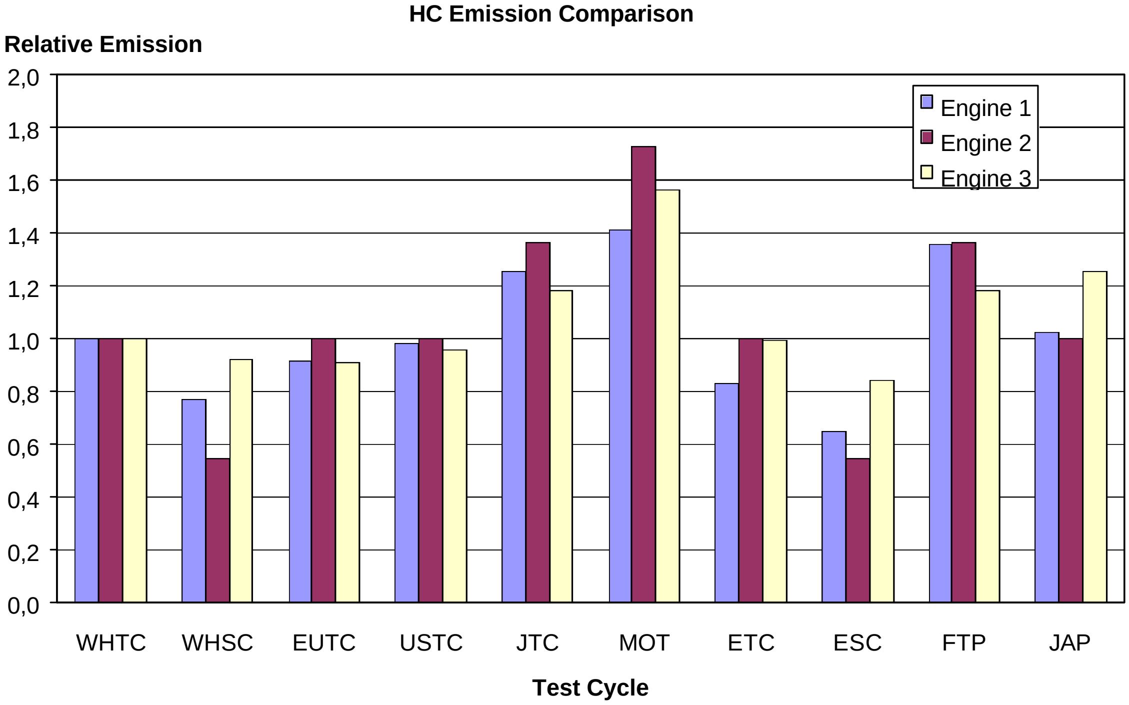


Figure 10.: *Comparison of the HC emission*

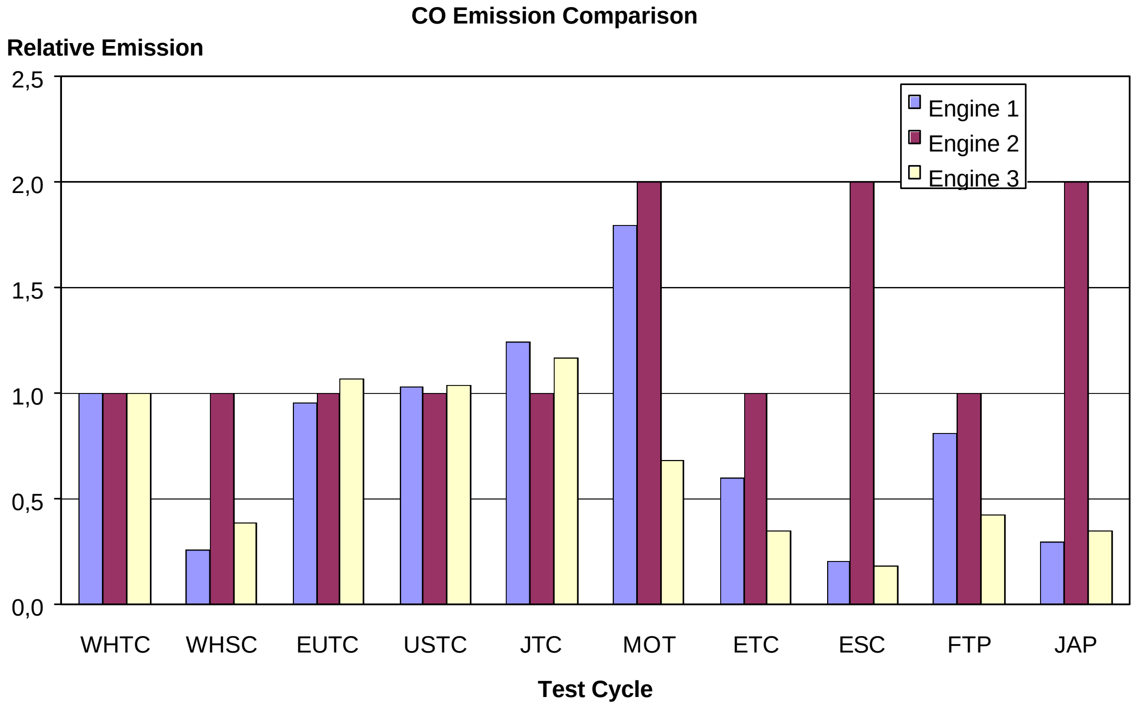


Figure 11.: *Comparison of the CO emission*

K EMISSIONS MEASUREMENTS RESULTS

In this chapter, the detailed results of the emission measurements are presented. The bars are used to show the average results of three emission tests. The light bars always represent the measuring method according to ISO/FDIS 16183, i.e. raw gas measurements and partial flow dilution. The dark bars represent the CVS measuring procedure.

The repeatability of the measurements is also included. The range (double T) in the diagrams reflects two times the standard deviation.

If percentage deviations are presented, they are based on the relative difference between the measuring values, with the measuring values of the CVS system as reference.

From three emission tests, two tests were used for filter analyses regarding to the soluble organic fraction and partially regarding to the water soluble fraction and sulfates. In the diagrams, the bars are representing the average results of two filter analyses.

K.1 Engine 1

K.1.1 Transient test cycles

Generally, the trends in the emission measurement were comparable for all transient test cycles, except for CO_2, which was only marginally influenced by the test cycles.. Three emission tests run at different days (all, but ETC) showed a higher standard deviation than those run at the same day (ETC).

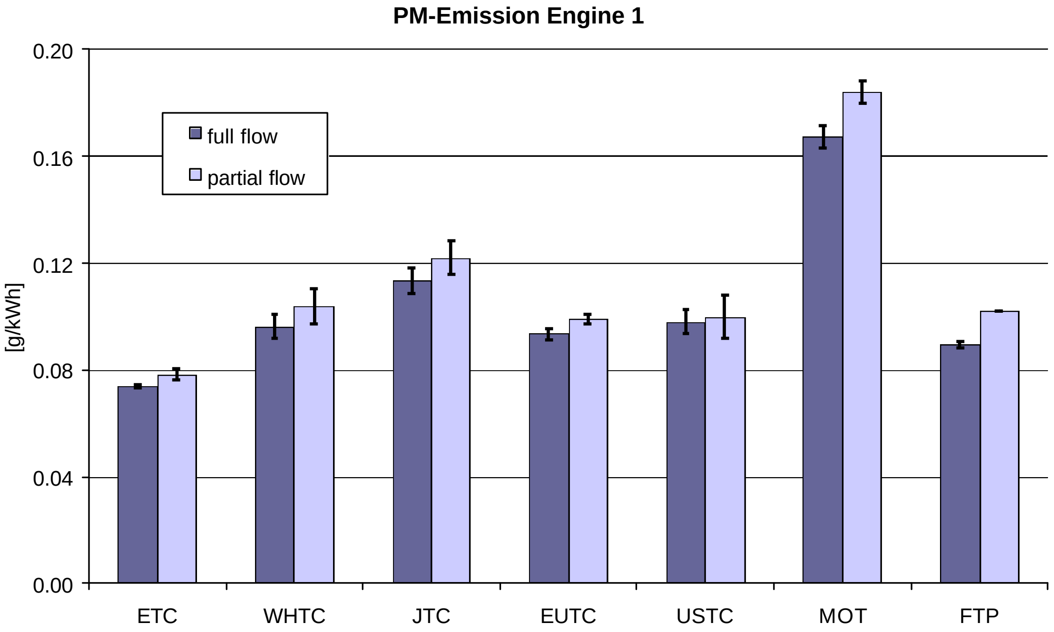


Figure 12.: *PM emissions transient test cycles*

The partial flow system measured higher PM emission on all test cycles. On most cycles, the difference was not significant (less than 7 %), since the ranges of the standard deviations were overlapping.

The frequent high acceleration rates at low engine speeds in MOT caused higher PM and CO emissions with this engine, compared to the JTC, although the data base of both test cycles was the same. In MOT, the significant difference between the systems was 9 %.

The lowest emission levels were measured in the existing test cycles ETC and FTP. Compared to ETC, the specific PM emission level increased between 20 % and 100 % depending on the test cycle (the cycle work is different as well!).

The SOF content of the particulate emissions was around 25 % for all test cycles. At FTP and MOT, there were higher values on the filters of the partial flow system, but they did not account for the overall difference between the measuring systems. On the other test cycles, the difference of the SOF content on the filters was very small and there was still a difference in total PM.

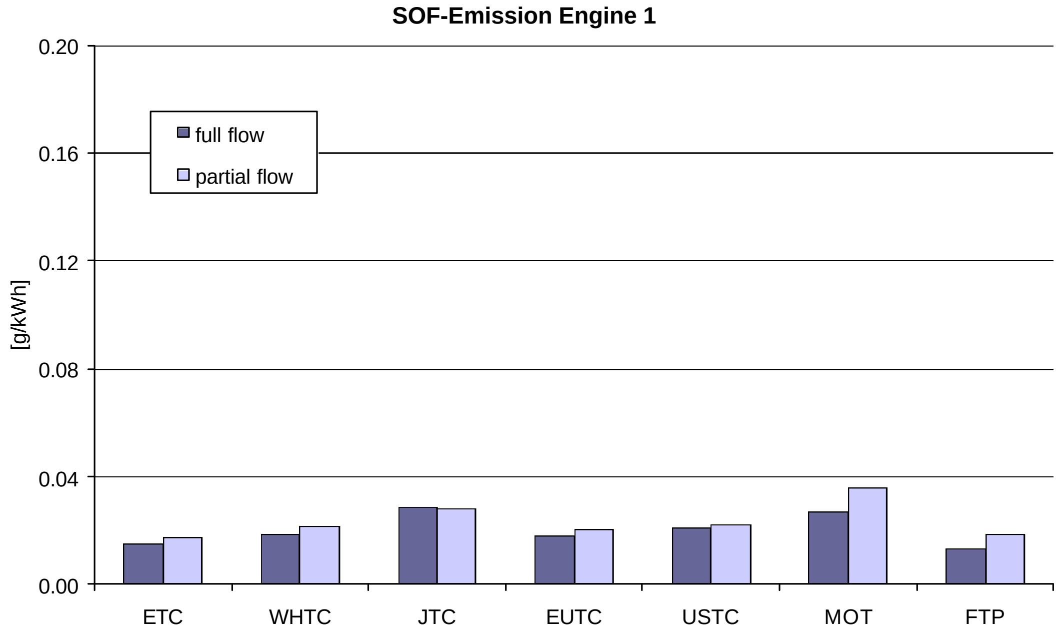


Figure 13.: *SOF emissions transient test cycles*

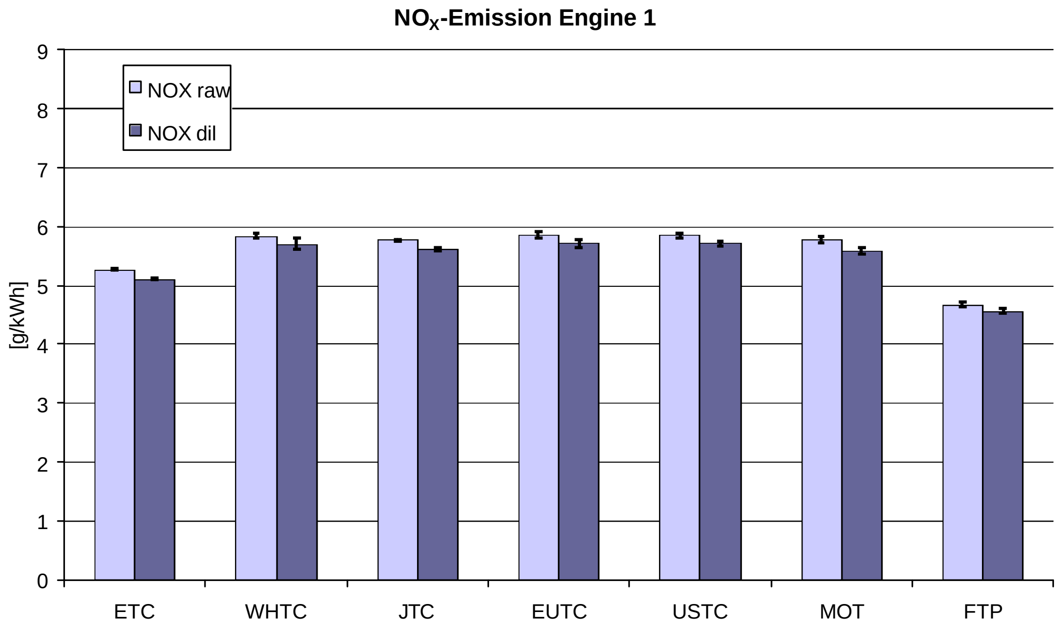


Figure 14.: *NO_X emissions transient test cycles*

Like with PM, the NO_X emissions were lowest on the legislative test cycles ETC and FTP. A very similar emission level was measured on all candidate test cycles, which was around 10 %

above the ETC value. This can be attributed to the engine operating outside the ESC control area in portions of the WHDC cycles.

There was a slight trend to higher emissions with the raw gas calculation, but the difference was within 3 % (MOT: 3.3 %), including the difference due to the newly introduced NO_X-correction factor in ISO/FDIS 16183, that was up to 1 %.

With both measuring and calculation methods, a very good repeatability of normally around 1 % standard deviation of the measured value was achieved. Only in WHTC, the repeatability was worse with 2.3 % in the diluted measurement, which was rather accidental.

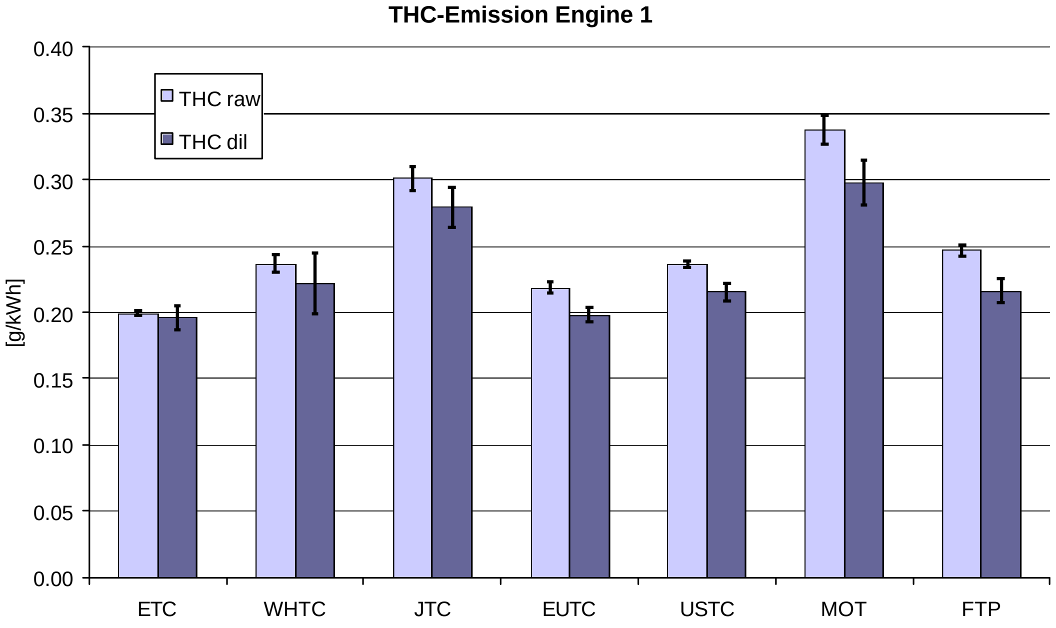


Figure 15.: *HC emissions transient test cycles*

As expected from current knowledge, a higher hydrocarbon emission level with the raw gas measurement was detected. This is due to changes of some of the hydrocarbon species during the dilution process. The differences in the results were significant for some of the test cycles.

The HC emission results on the individual test cycles showed a small dependence from the driving behaviour in the different world regions. ETC was similar to EUTC, JTC to MOT and FTP to USTC.

The concentration of HC in the diluted exhaust gas was between 6 and 8 ppm, while the ambient concentration went up to around 3 ppm. These low concentrations resulted in a worse repeatability, compared to the raw gas measurement, which is a clear advantage of the ISO/FDIS 16183 procedure.

The measurement of carbon dioxide showed very small differences between the two methods, which were 2 % and lower and a very good repeatability with a standard deviation of less than 1 % of the measured value on all test cycles.

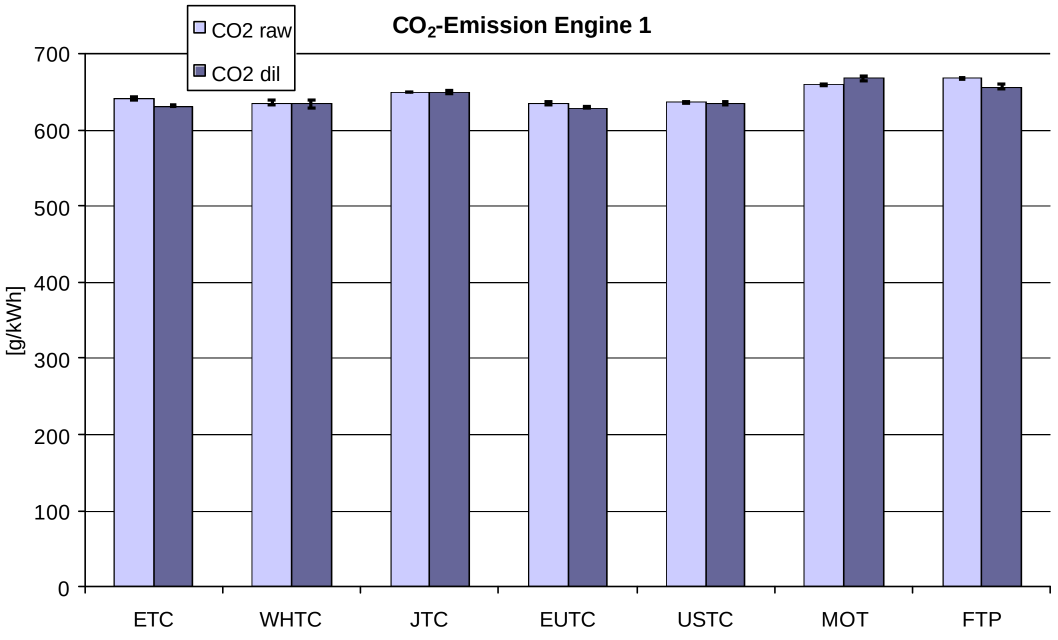


Figure 16.: *CO$_2$ emissions transient test cycles*

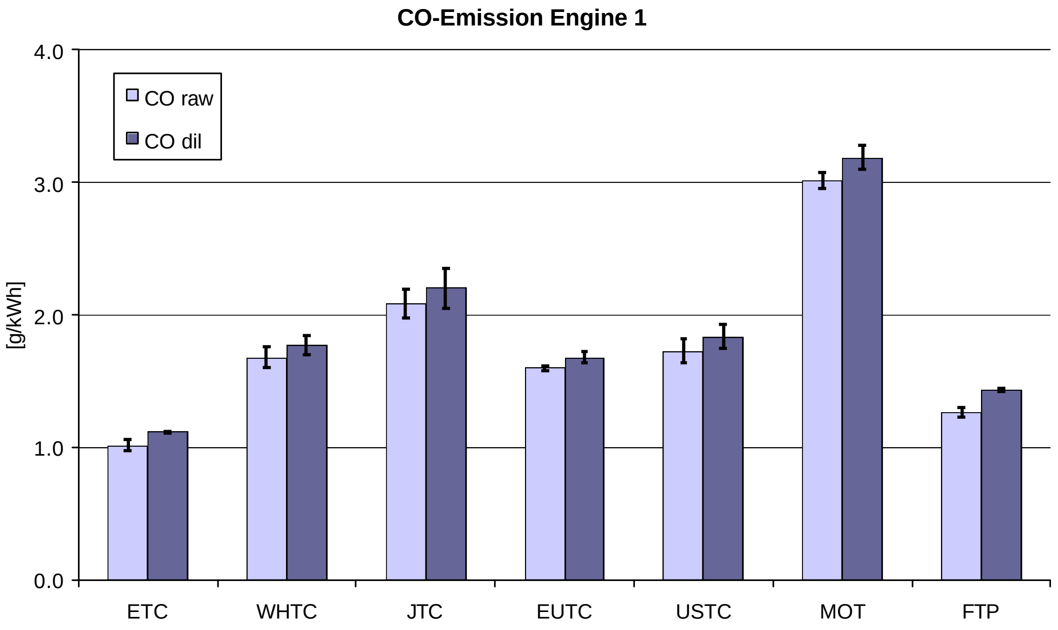


Figure 17.: *CO emissions transient test cycles*

Concerning CO, the measuring values in the diluted exhaust gas were higher compared to the raw measurement. One reason for this result was the high measuring range chosen for the raw gas measurement (1 Vol.%) due to peak emissions during fast transients. Therefore, a loss of accuracy in the mainly low emission level was the consequence.

Nevertheless, the differences between the two methods remained within 10 %, which is in absolute terms lower than 0.18 g/kWh.

K.1.2 Steady-state test cycles

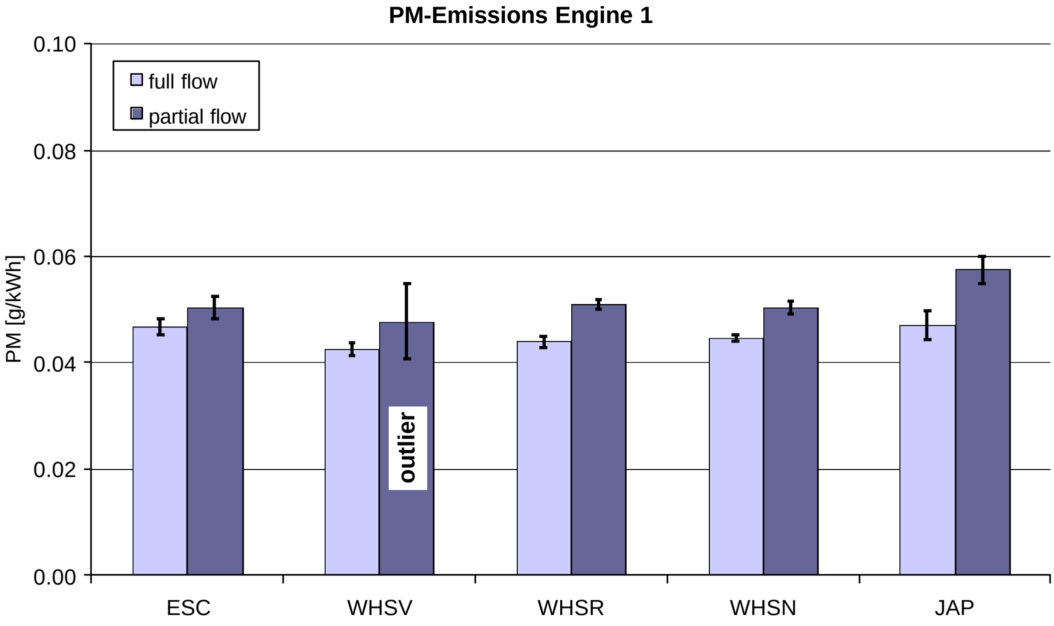


Figure 18.: *Particulate emissions steady-state test cycles*

The PM emission level was comparable for all steady-state test cycles. The partial flow system measured higher particulate values on all test cycles (up to 18 % in JAP). The significance of the difference is partly influenced by the good repeatability of the measurements (standard deviation between 2 and 6 % of the average).

The modified test cycle WHSN, as described in chapter I, was measured later in the program. It was proven that there was no major influence of the points with low weighting factors on the test cycle result and that the filter loading could be increased by 50 %.

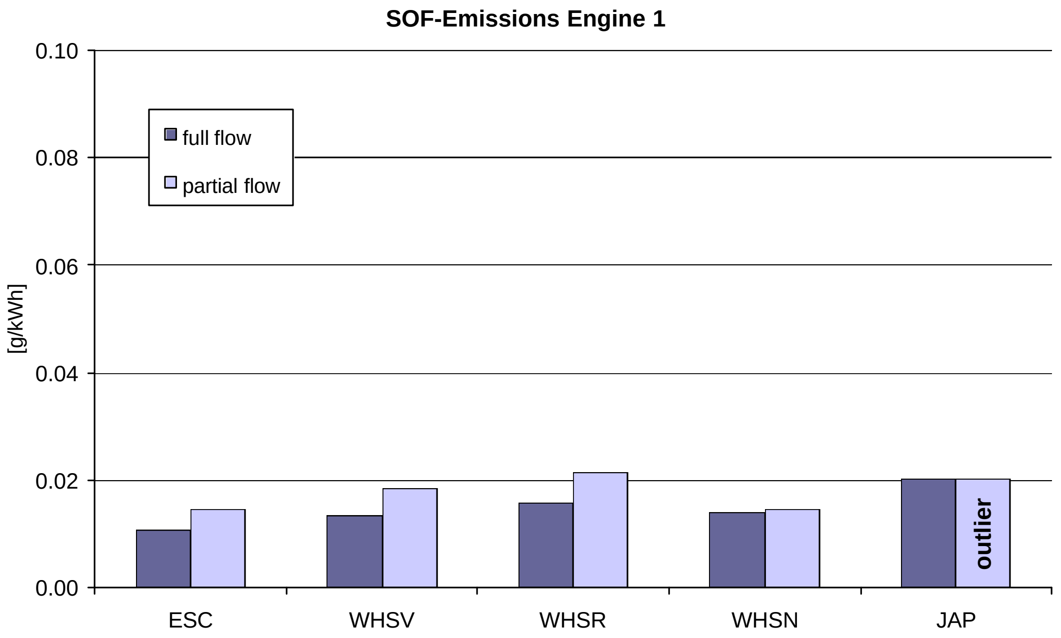


Figure 19.: *SOF emissions steady-state test cycles*

The difference between the SOF content on the filters of partial and full flow system on ESC, WHSV and WHSR was equal to the difference in total particulates. So for these test cycles, the difference between full and partial flow system could be explained by the amount of organic solubles on the filters.

This trend was not reproduced by the test cycles WHSN and JAP. On Jap, there was an outlier on the first filter analysis. The second one reproduced the trend mentioned above.

For NO_x, most of the measuring points of the different versions of WHSC were outside the NO_X control area of the current European type approval procedure, which consequently resulted in higher NO_X emissions on these test cycles.

With this engine, it was obvious, that the order of the modes in WHSC and the modifications to the test cycle had no influence on the emission result.

The repeatability of the NO_X measurement was very good, the standard deviation remained below 1.5 % of the average value.

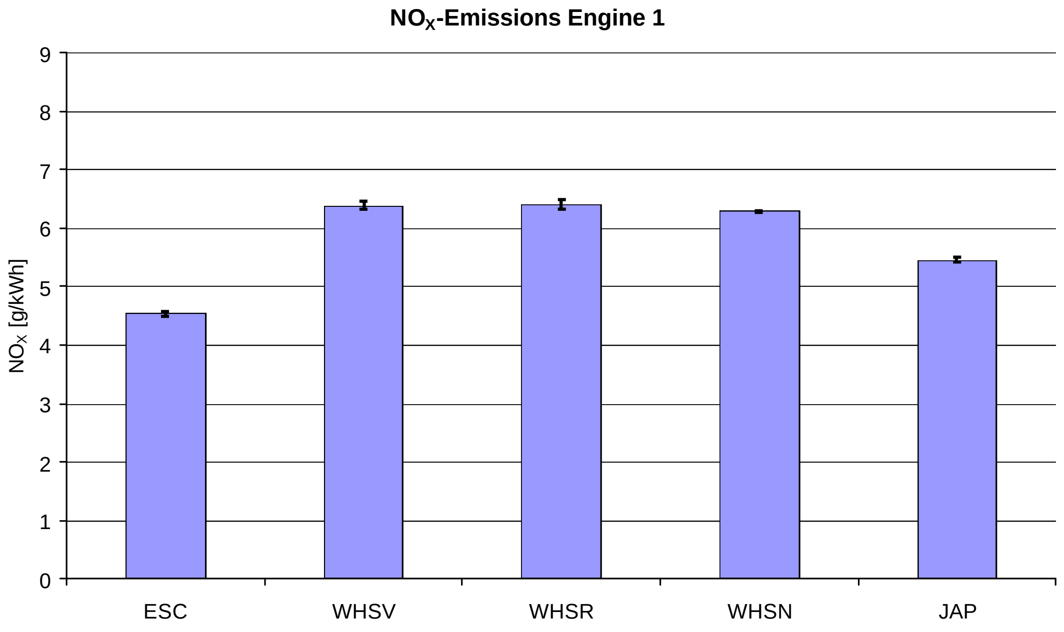


Figure 20.: *NO$_X$ emissions steady-state test cycles*

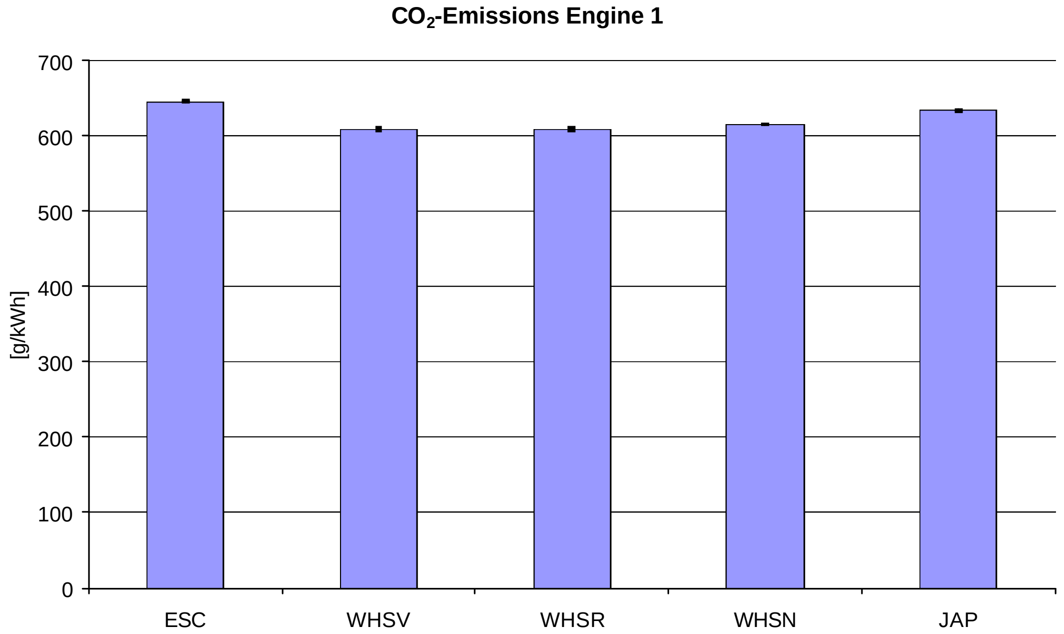


Figure 21.: *CO$_2$ emissions steady-state test cycles*

The standard deviation of the CO$_2$ emission results was below 0.5 % of the average value. The emission level was stable for all test cycles.

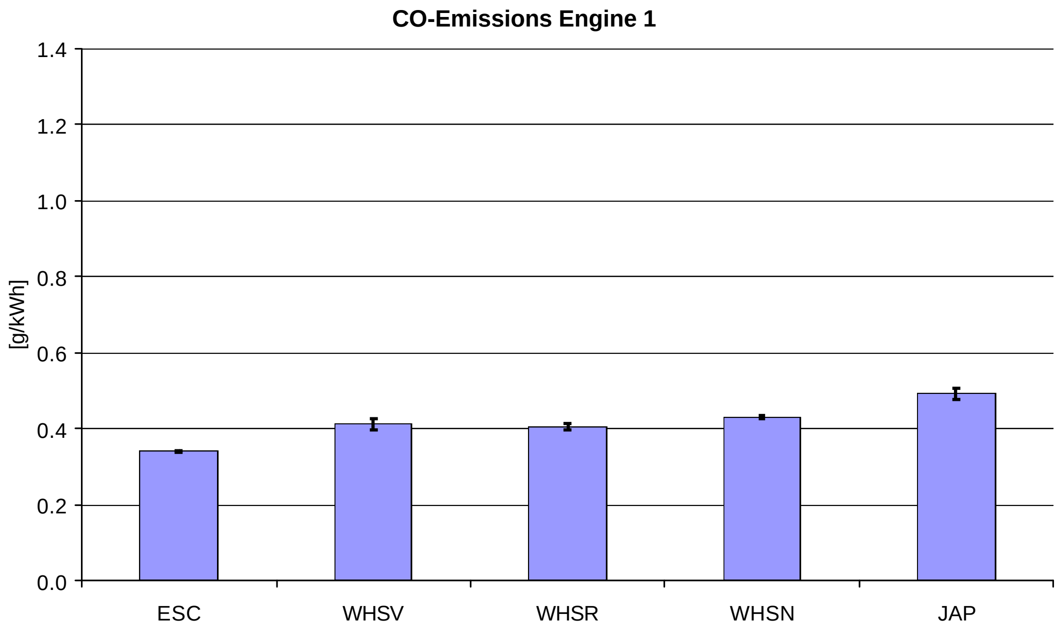


Figure 22.: *CO emissions steady-state test cycles*

With decreasing engine speed and load, an increasing CO emission level could be observed. Like for NO_X, the different versions of WHSC had no influence on the overall test cycle result. The standard deviation of the measurements is lower than 3 % of the average value.

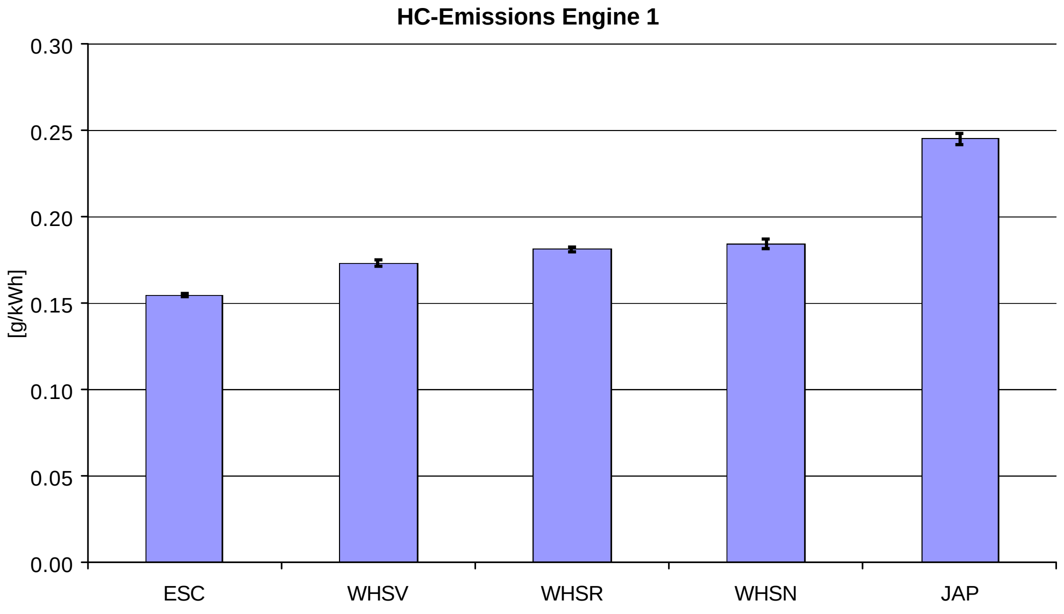


Figure 23.: *HC emissions steady-state test cycles*

A similar behaviour was observed for HC. The repeatability was even better with 1.5 % of the average.

K.1.3 Single modes

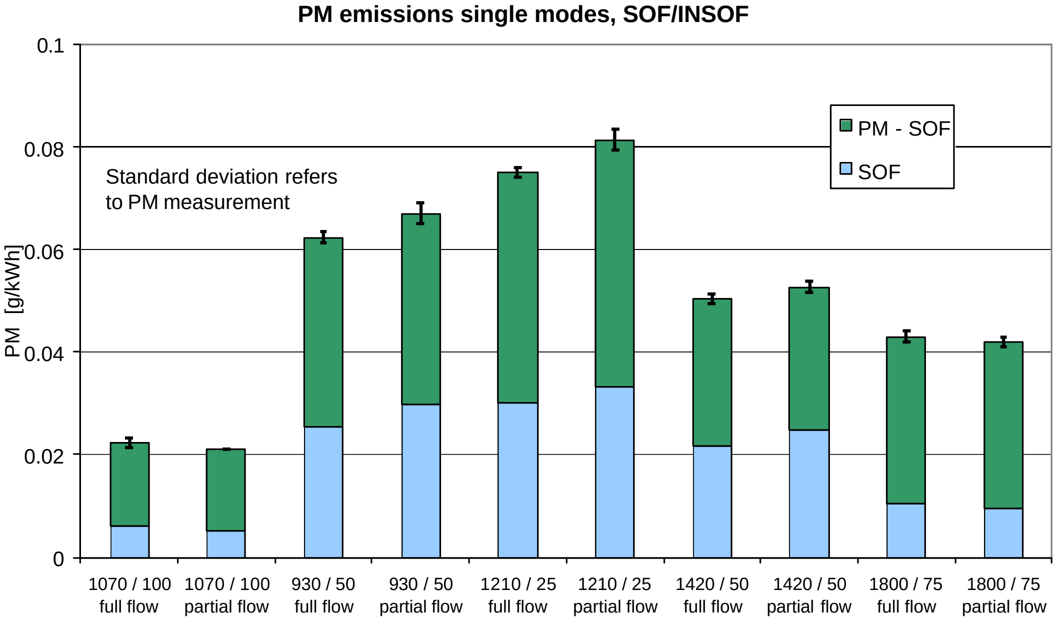


Figure 24.: *Engine 1: PM emissions single modes*

For the single mode measurements, a strongly improved repeatability could be observed due to the absence of daily variabilities: all measurements were done at the same day. The standard deviation of the measurements was lower than 3 % of the average value.

The difference between the full flow and the partial flow system depended on the test mode and did not show a clear trend. A major part of these differences was based on the SOF content being different for the individual test modes and measuring systems as well.

K.2 Engine 2

Since this engine was operated with a CRT-system, i.e. with an oxidation catalyst and a particulate filter, the particulate emissions and the gaseous emissions of hydrocarbons and carbon monoxide were lower by roughly one order of magnitude, compared to engines 1 and 3. In order to keep the readability of the diagrams, the scale of the y-axis was chosen half compared to engines 1 and 3.

K.2.1 Transient test cycles

Generally, the particulate emissions were reduced by the filter well below the european limit value for 2005 (Euro 4). The overall repeatability of the measuring results was good. With this engine, all particulate measurements done during this program remained below 0.02 g/kWh.

Again, the emission trends were comparable for all transient test cycles: the partial flow system measured higher PM emission than the full flow system. The range of the relative difference related to the full flow system was between 20 % (ETC) and 116 % (FTP). In absolute terms, the differences between the systems remained within 0.007 g/kWh for all transient test cycles. These findings confirmed the results of the earlier ISO/WHDC correlation study done at EMPA, as well [3]: The partial flow system measured significantly higher PM emissions than the full flow system, when the CRT-system was installed.

The standard deviation of the measuring results was lower than 20 % of the average value for all test cycles, which means lower than 0.002 g/kWh in absolute terms. Thereby, the repeatability was improved compared to a previous study in EMPA [3].

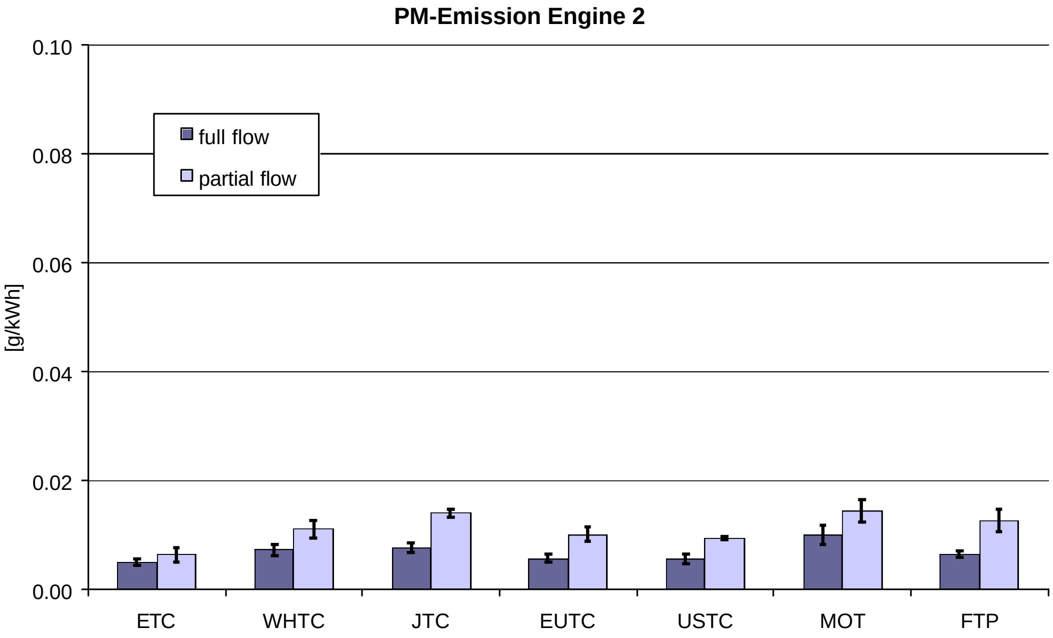


Figure 25.: *PM emissions transient test cycles*

On all test cycles, the filter loading was lower than 0.25 mg, required by ISO/FDIS 16183 for 70 mm filters, on some tests, it was even lower than 0.10 mg. The filters are looking like unloaded.

During some tests, the same amount of particulates was collected on both, primary and secondary filter (WHTC, partial flow system), on other tests, there was a negative loading on the secondary filter (single modes, full flow system).

With the first 36 filters, analyses regarding to the soluble organic fraction (SOF), the water soluble fraction (WSF) and sulfates were made. These analyses were clearly at their limit of detection. The findings are described in chapter M.1. Afterwards, it was decided to discontinue the filter analyses with this engine. Therefore, no figures with SOF contents are shown in the report.

The filter batch used for these measurements (Pallflex T60A20, 70 mm) had normal blind values for the soluble organic fraction (around 0.06 mg), but inacceptable high blind values for the water soluble fraction (around 0.6 mg).

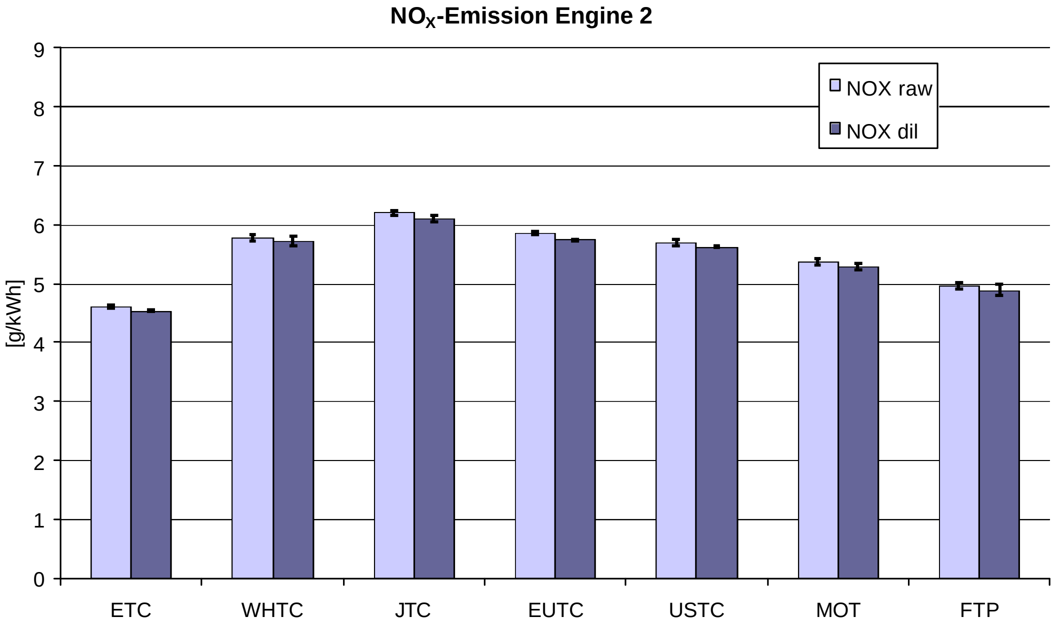


Figure 26.: *NO_X emissions transient test cycles*

Also for this engine, the NO_X emission were lowest on the legislative test cycles ETC and FTP. On the candidate test cycles, there was an increase of around 25 % (WHTC, EUTC, USTC and MOT) up to 35 % (JTC) compared to ETC, due to operation outside the ESC control area, like with engine 1.

A very slight trend to higher emissions with the raw gas calculation was detected, but generally the agreement between the two measurement methods was good: the difference was within 2 % including the influence due to the different correction factors. Like with engine 1, the standard deviation of the measurements was around 1 % of the average value.

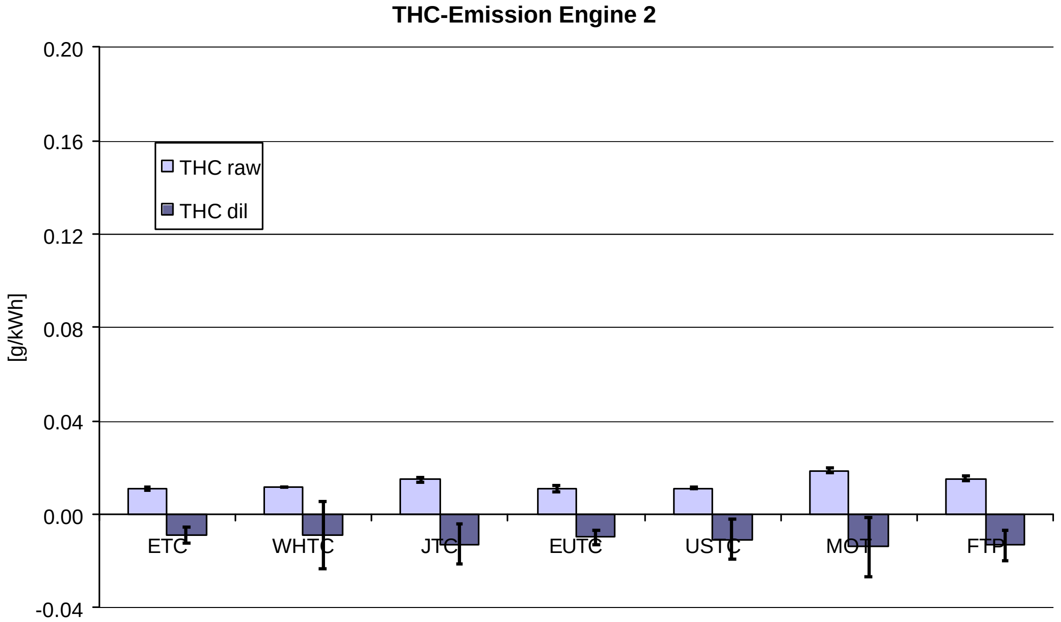


Figure 27.: *HC emissions transient test cycles*

The measurement of hydrocarbons showed some advantages of the raw gas measurement according to ISO/FDIS 16183 compared to the diluted measurement: In the raw gas, accurate and repeatable emission results were obtained, which were comparable for all transient test cycles. The standard deviation of the measurements was between 3 and 12 % of the average value.

The measurement of diluted exhaust gas was at its limit of detection, because of comparable concentrations in the diluted exhaust gas, integrated during the test cycle, and in the bag with dilution air (THC-range = 100 ppm). The integrated value of THC was between 2.1 ppm and 2.4 ppm on all test cycles, while the ambient concentration changed from 2.3 ppm to 2.8 ppm. The consequences of these close values are shown in table 10: depending on the concentration in the dilution air, the test results scattered around zero.

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 10: *THC concentrations in the diluted exhaust gas and in the dilution air*

In contrast to the measurements with engine 1, a trend to higher CO_2 emission results with the raw gas measurement was found with this engine. The differences were around 2 %, which was slightly higher than with engine 1. The repeatability of the two measuring methods was as good as with engine 1: the standard deviation remained lower than 1 % of the average value.

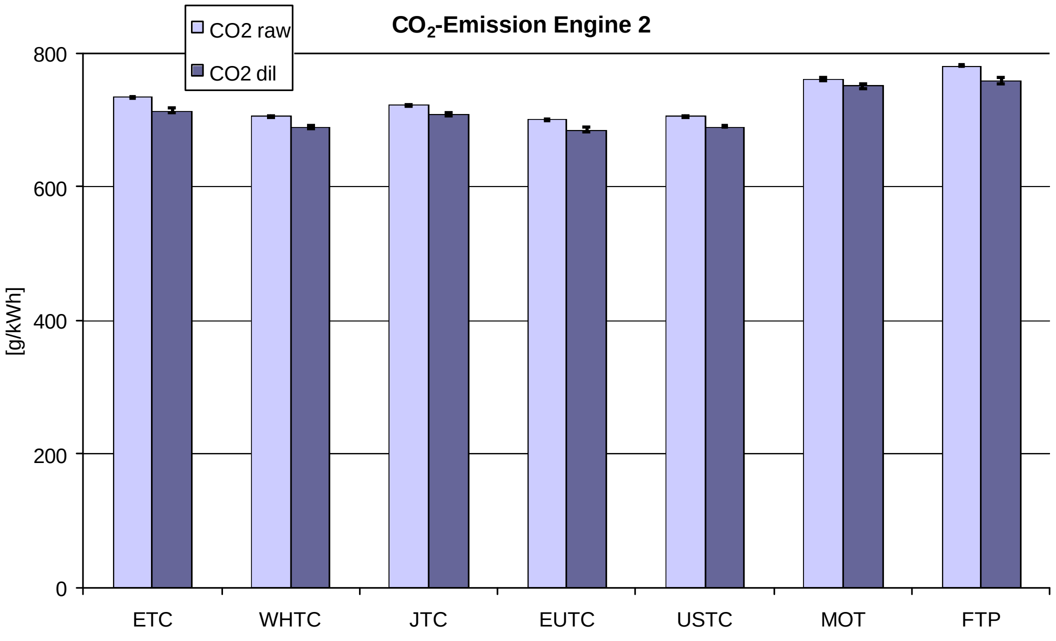


Figure 28.: *CO$_2$ emissions transient test cycles*

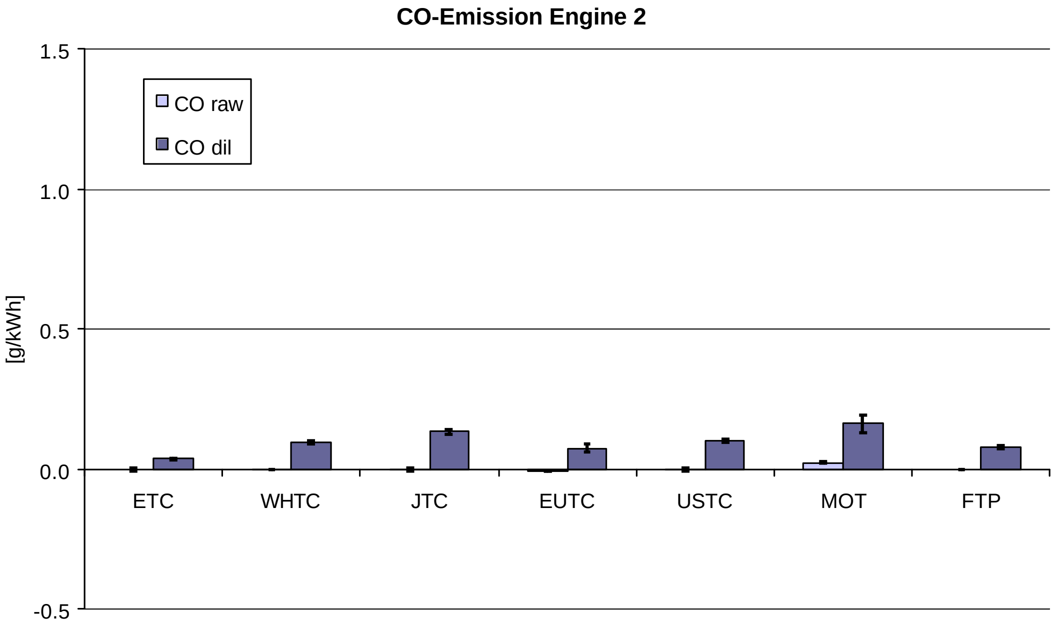


Figure 29.: *CO emissions transient test cycles*

The range for the CO measurement in the raw exhaust gas was chosen in order to cover the peak emissions, which were around 300 ppm for this engine. As mentioned already for engine 1, a loss of accuracy during the base emission level is the consequence. Therefore, slightly negative concentrations were measured with this engine during the base emission level.

Nevertheless, some overflow sequences in the raw exhaust gas (the concentrations in the exhaust gas were higher than the range of the emission analyser) were detected during MOT (all tests) and JTC (one test).

Both raw and diluted CO measurements were made with the same emission analyser. The CO_2 interference was corrected for the concentrations in the raw exhaust gas. Therefore, the measurement of the concentrations in the diluted exhaust gas was overcorrected, since the interference value was lower for lower CO_2 concentrations.

As an additional information, figure 30 shows the exhaust gas temperature during the WHTC. The sample probe was just upstream the CRT-system.

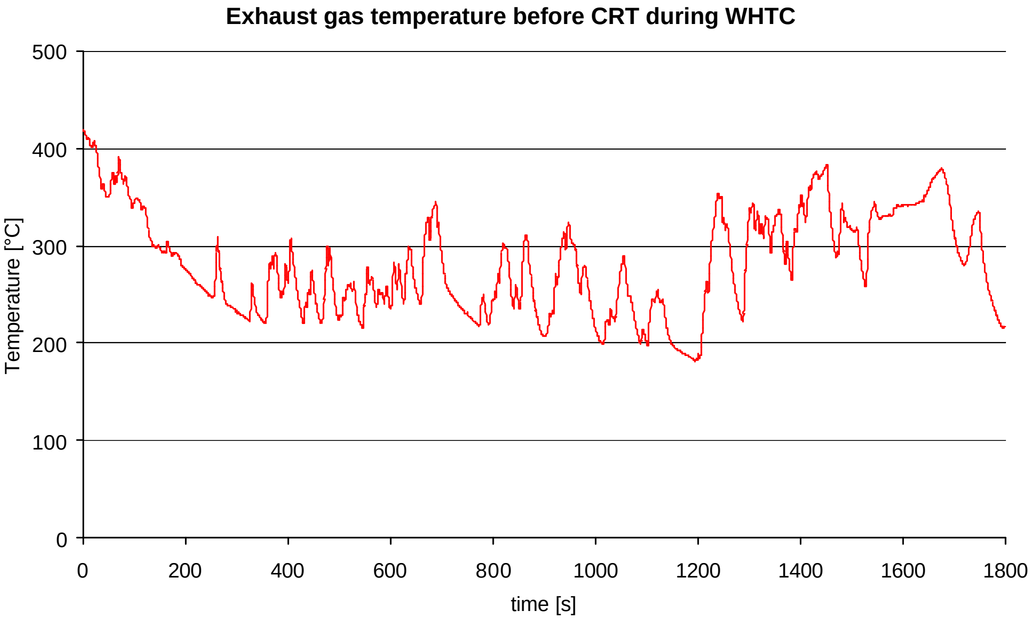


Figure 30.: *WHTC: Exhaust gas temperature*

It can be seen, that the preconditioning at full load influenced the exhaust gas temperature during the first five minutes of the test cycle. In the urban and rural part of the cycle, the exhaust gas temperature often went down to around 200 °C, a level, which was observed on WHSC only at the idle mode.

K.2.2 Steady-state test cycles

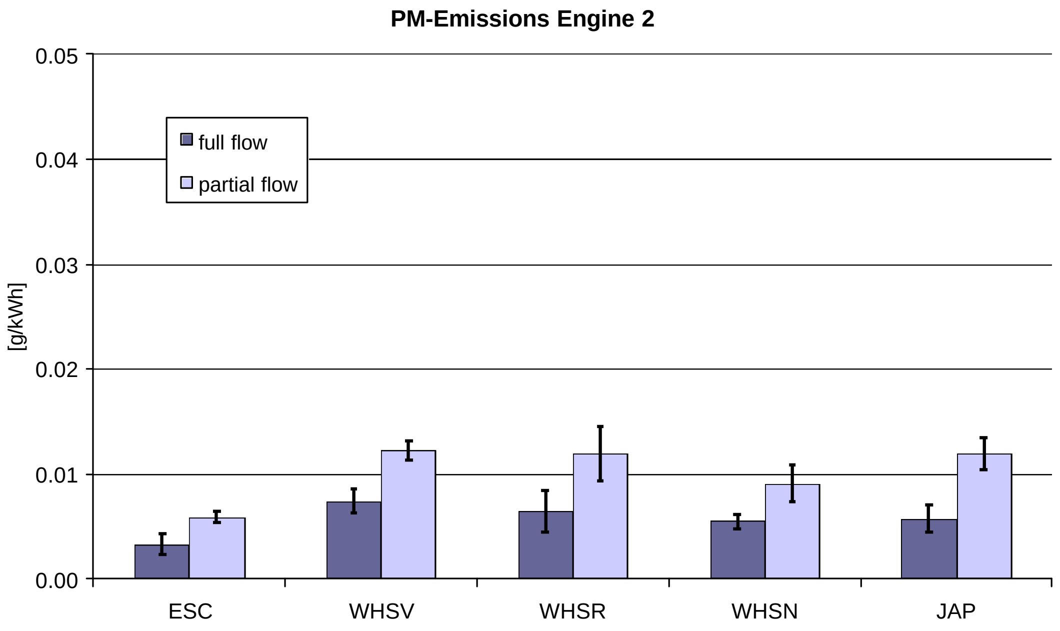


Figure 31.: *Particulate emissions steady-state test cycles*

The trends of the PM measurement on the steady-state test cycles were similar to those on the transient cycles: the partial flow system measured 65 to 107 % higher particulate emissions than the full flow system (relative difference to the full flow system). Like on the transient cycles, the standard deviation of the measurements was lower than 0.002 g/kWh in absolute terms. In percent of the average value, the repeatability is a little worse than on the transient cycles, because the average particulate emissions were lower.

Both, full and partial flow system measured slightly lower particulate emissions on the WHSN (version 3 of the WHSC).

To give an impression about the filter loading, the corresponding values are listed in table 11. Each value is the average of three tests. The filter loading on the steady-state cycles was even lower than on the transient cycles.

In order to reach the required filter loading of 0.25 mg in ISO/FDIS 16183, three emission tests of WHSN were run on the same filter pair with the result, that the filter loading was doubled only. For the detailed evaluation of the repeated test runs on the same filter pair, see chapter M.1.

WHSN:	full flow	0.125 mg
	partial flow	0.189 mg
WHSN:*	full flow	0.265 mg
	partial flow	0.289 mg
WHSR:	full flow	0.091 mg
	partial flow	0.152 mg
WHSV:	full flow	0.105 mg
	partial flow	0.157 mg
ESC:	full flow	0.093 mg
	partial flow	0.151 mg
JAP:	full flow	0.076 mg
	partial flow	0.144 mg

* three emission tests on one filter pair

Table 11: *Filter loadings on steady-state test cycles*

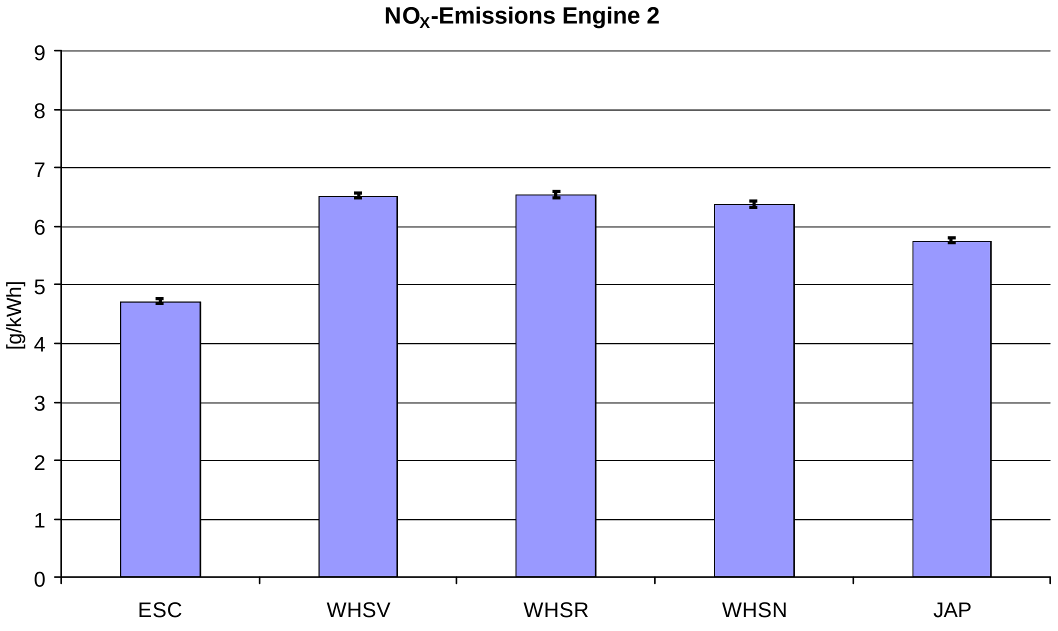


Figure 32.: *NO$_X$ emissions steady-state test cycles*

The behaviour of the NO_X emissions on the steady-state test cycles was similar to engine 1: On the three versions of the WHSC and on the JAP, higher NO_X emissions were measured compared to the ESC, because most of the test modes were below the NO_X control area of the European type approval procedure.

Again, the order of the modes in WHSC and the modifications of the test cycle had no influence on the emission result and the standard deviation of the measurements was lower than 1 % of the average value.

Also the CO_2 emissions were comparable to those of engine 1. The repeatability remained below 0.5 % of the average with this engine as well.

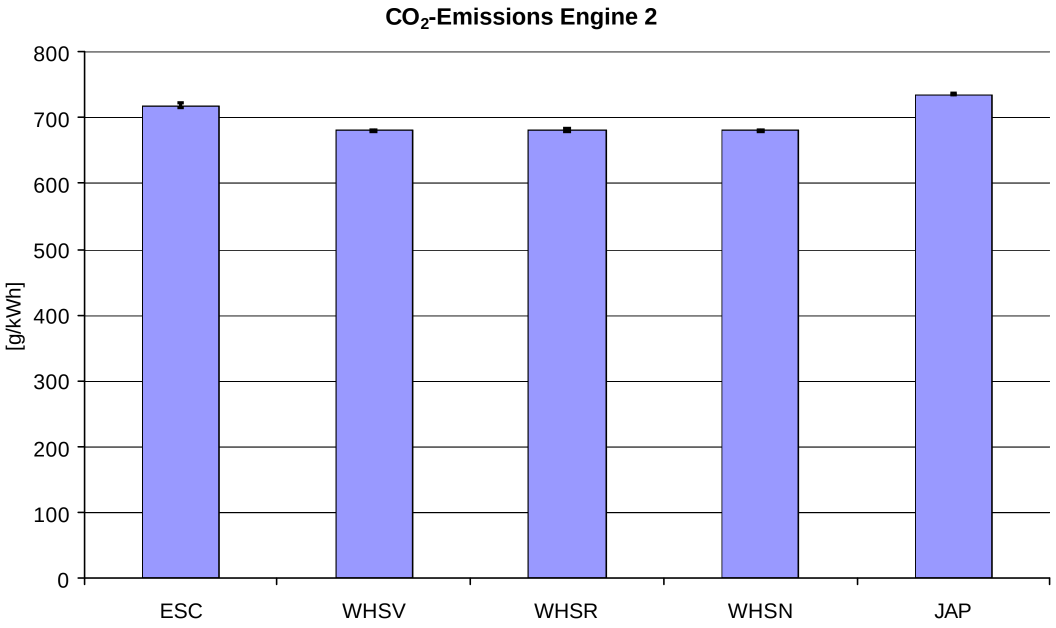


Figure 33.: *CO_2 emissions steady-state test cycles*

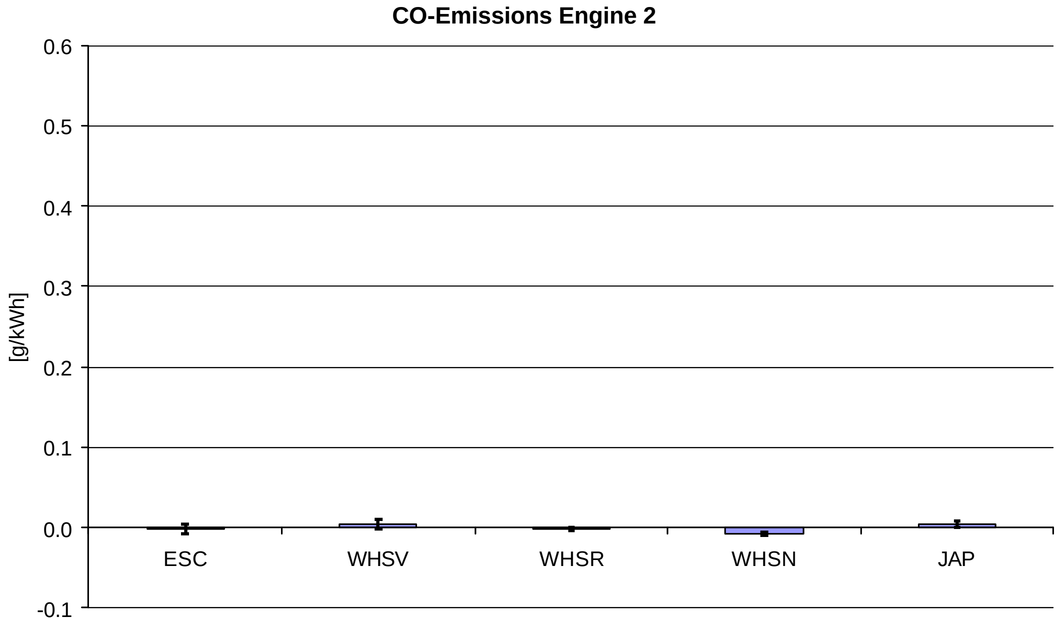


Figure 34.: *CO emissions steady-state test cycles*

The measurement of carbon monoxide was at the limit of detection of the analyser available. Concentrations in ppm of low single digit numbers would require a low emission analyser and very careful checking of interferences and calibration gases.

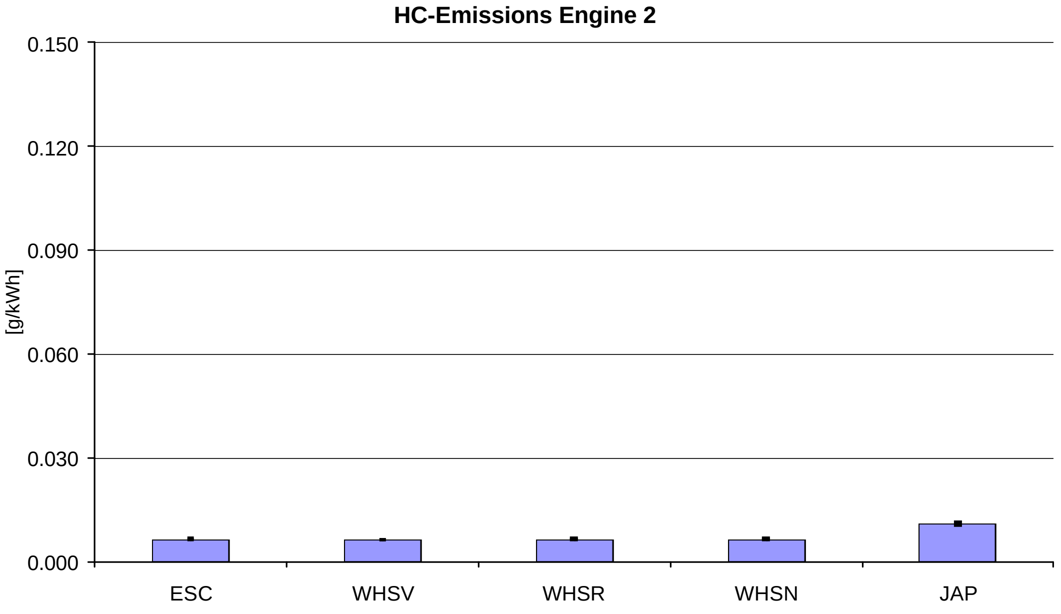


Figure 35.: *HC emissions steady-state test cycles*

The hydrocarbon emissions were similar for all steady-state test cycles. With respect to the low emission level, the standard deviation of 5 % of the average value represented a good repeatability.

The exhaust gas temperature during the different versions of the steady-state cycle WHSC was at a higher level compared to the transient test cycle WHTC. The lowest temperature was defined by the duration of the idle mode at the beginning and was similar to the lowest temperature in WHTC. Again the influence of the preconditioning at full load could be seen during the first mode. So putting the idle mode at the beginning of the test cycle avoided having even lower temperatures at idle condition.

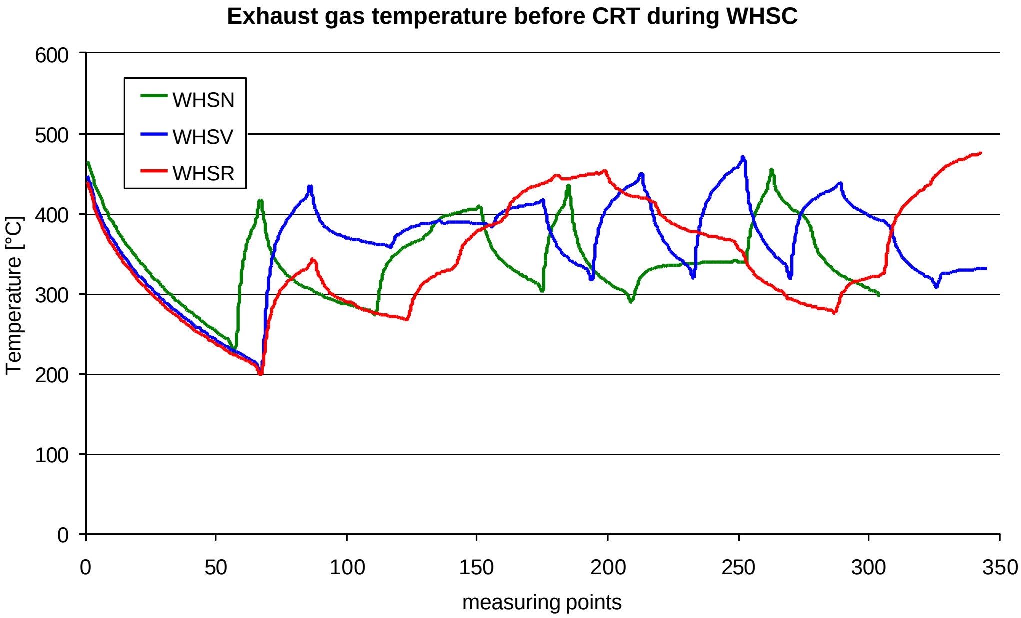


Figure 36.: *Different versions of WHSC: exhaust gas temperature*

K.2.3 Single Modes

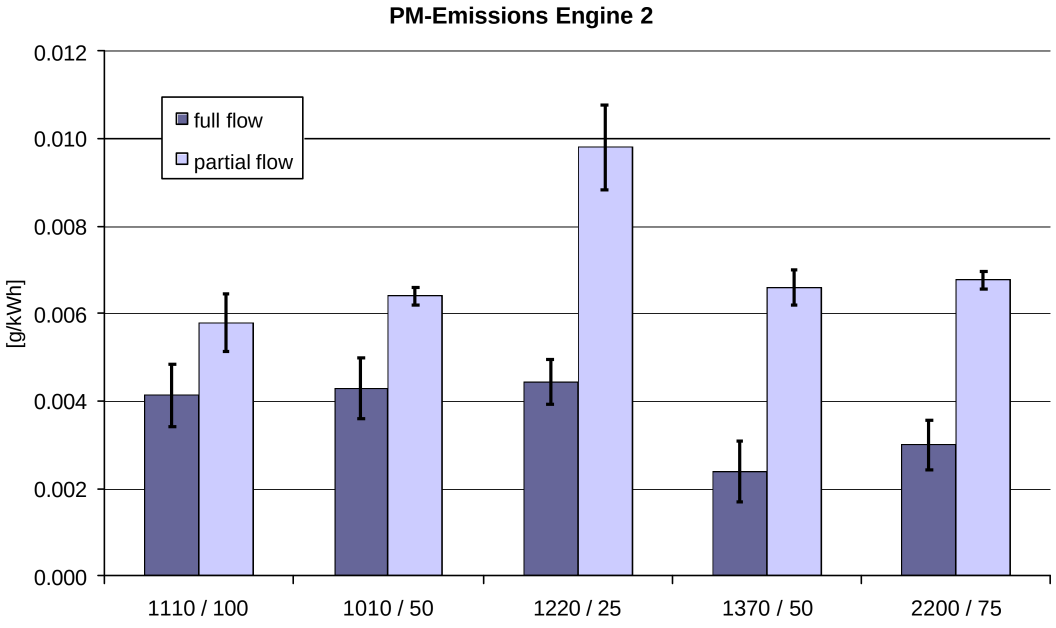


Figure 37.: *Engine 2: PM emissions single modes*

In line with the measurements on the test cycles, the partial flow system measured significantly higher particulate emissions on the single modes than the full flow system. The relative differences related to the full flow system were between 50 and 250 % depending on the test mode.

The repeatability was improved in absolute terms of emissions compared to the measurements on the test cycles. The standard deviation of these measurements was around 0.001 g/kWh. In point 4 (1370 rpm, 50 % load), this lead to a percentage repeatability of 30 % of the average.

Because of very low filter loadings, all filter analyses were cancelled.

K.3 Engine 3

K.3.1 Transient test cycles

For this engine, only two transient test cycles were run in most cases. The bars in the following figures are representing the averages of two test cycle results. Therefore, no standard deviations are shown in the diagrams and no conclusions about the repeatability can be drawn.

The scale of the y-axis in the figures is the same like for engine 1.

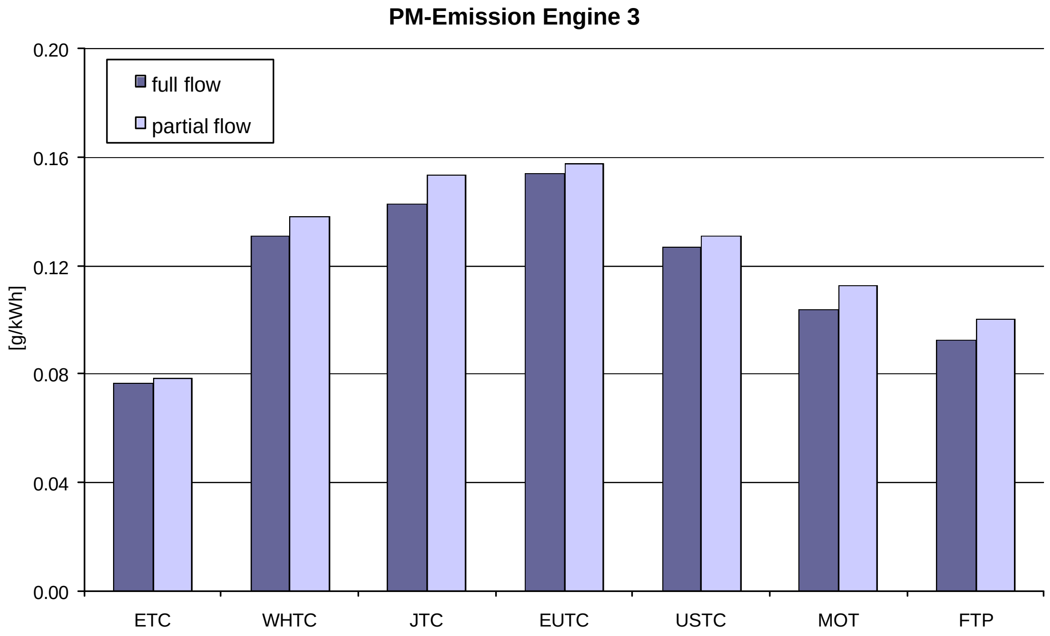


Figure 38.: *PM emissions transient test cycles*

The partial flow system measured higher PM emission on all test cycles, which was in line with the other engines. The relative differences were between 3 and 9 %.

The behaviour of the particulate emissions depending on the test cycle was different from the other engines. The high PM emission level of engine 1 on MOT was not reproduced by this engine, even an opposite trend could be observed.

The emission level on the candidate test cycles was significantly higher compared to the ETC. The increase was between 40 and 100 %.

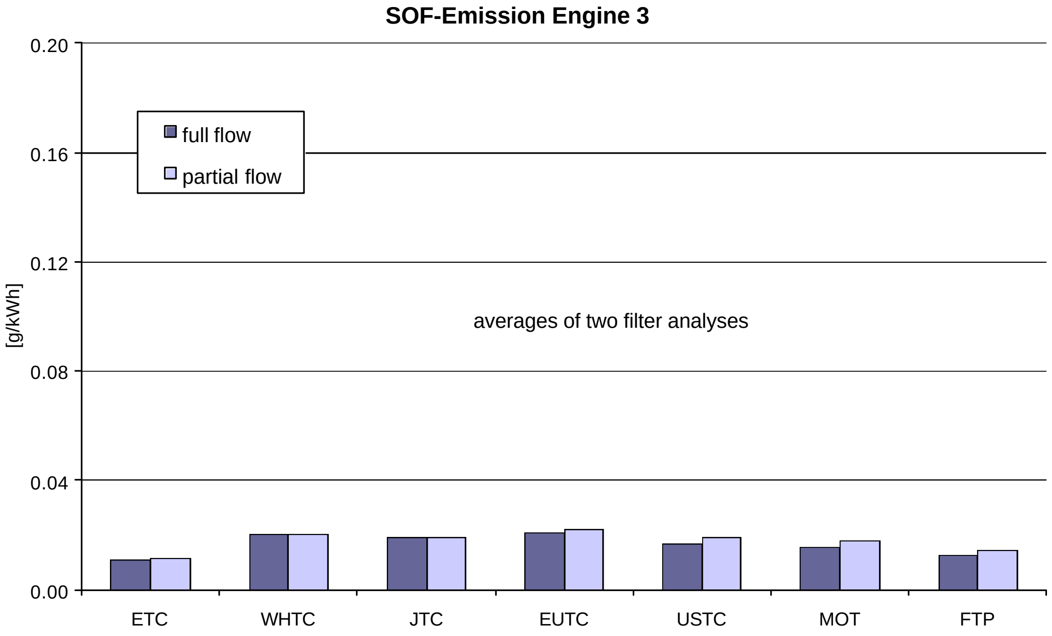


Figure 39.: *SOF emissions transient test cycles*

The SOF content on the particulate filters was around 15 % for both systems and all transient test cycles, which is a lower percentage than analysed for engine 1. But again, the difference between partial flow and full flow system could not be explained with the content of solubles on the filter.

With this engine the SOF emission on JTC and MOT was exactly at the same level like on the other candidate test cycles or slightly lower. This is the opposite trend compared to engine 1.

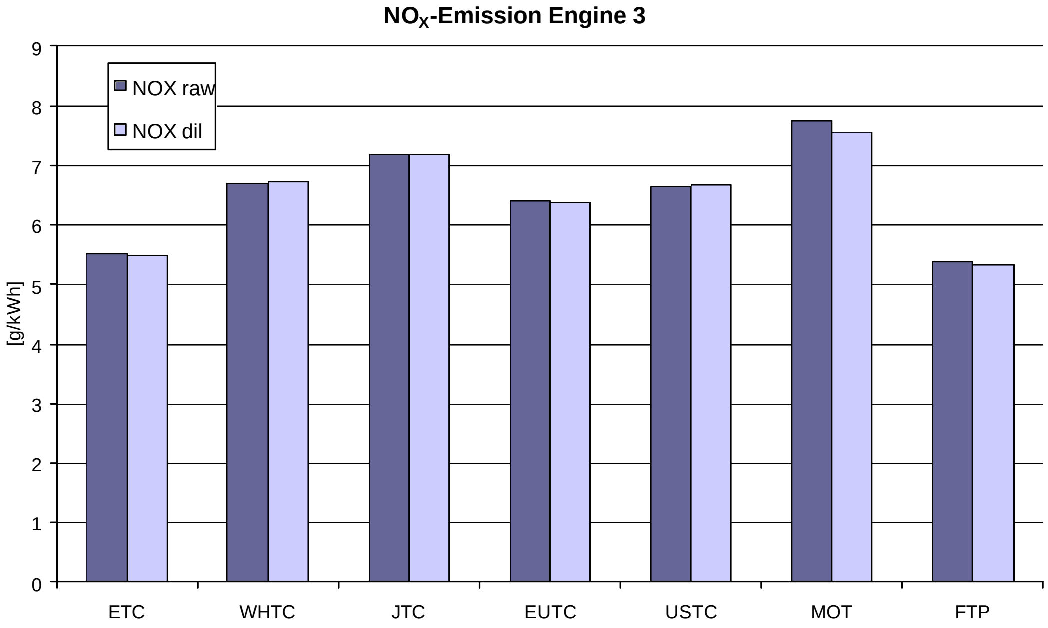


Figure 40.: *NO_X emissions transient test cycles*

Compared to the other engines, the NO_X emission level was slightly higher and more sensitive to the test cycles. The NO_X emissions on the candidate test cycles were 16 to 37 % higher compared to ETC. Again, this is due to the engine operating outside the ESC control area, which is even more critical for EGR systems, as used on this engine.

Again, there was a good agreement between the raw gas calculation according to ISO/FDIS 16183 and the diluted measurement; the difference was within 2 % including the influence because of the correction factor.

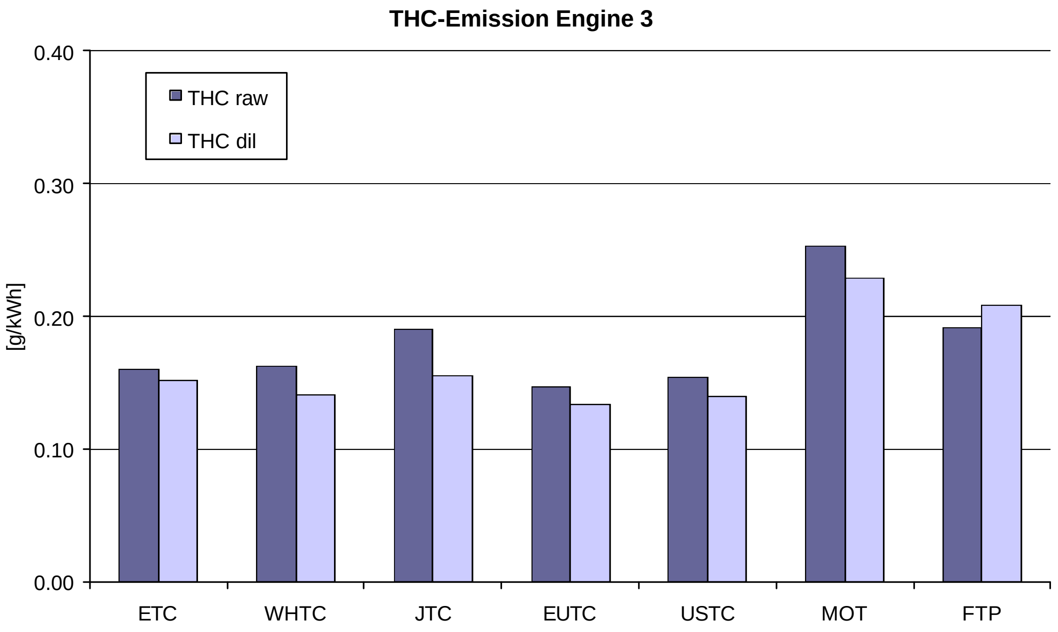


Figure 41.: *HC emissions transient test cycles*

For HC, the diluted measurement was higher on FTP than the raw measurement. This unexpected result was due to an outlier measurement on the first test. On the second FTP test, the diluted measurement was lower again than the raw one. The differences were between 6 and 19 % at a lower emission level compared to engine 1. In general, the trends were similar to the ones seen with engine 1.

Like with engine 1, the measurement of carbon dioxide showed a very good agreement between the two methods: the differences were within 1.5 % of the measured values.

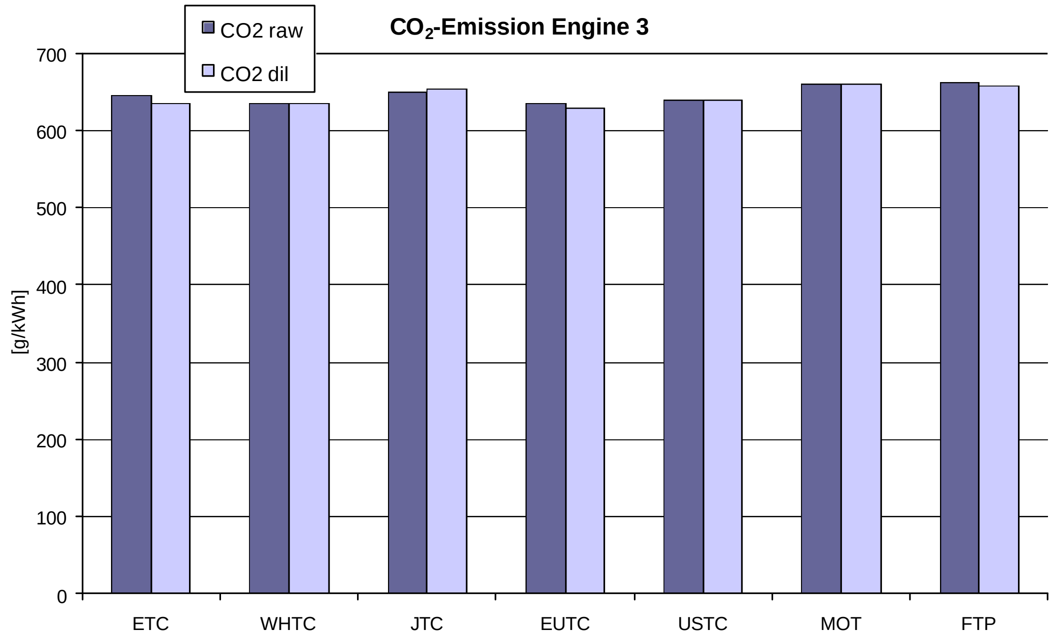


Figure 42.: *CO_2 emissions transient test cycles*

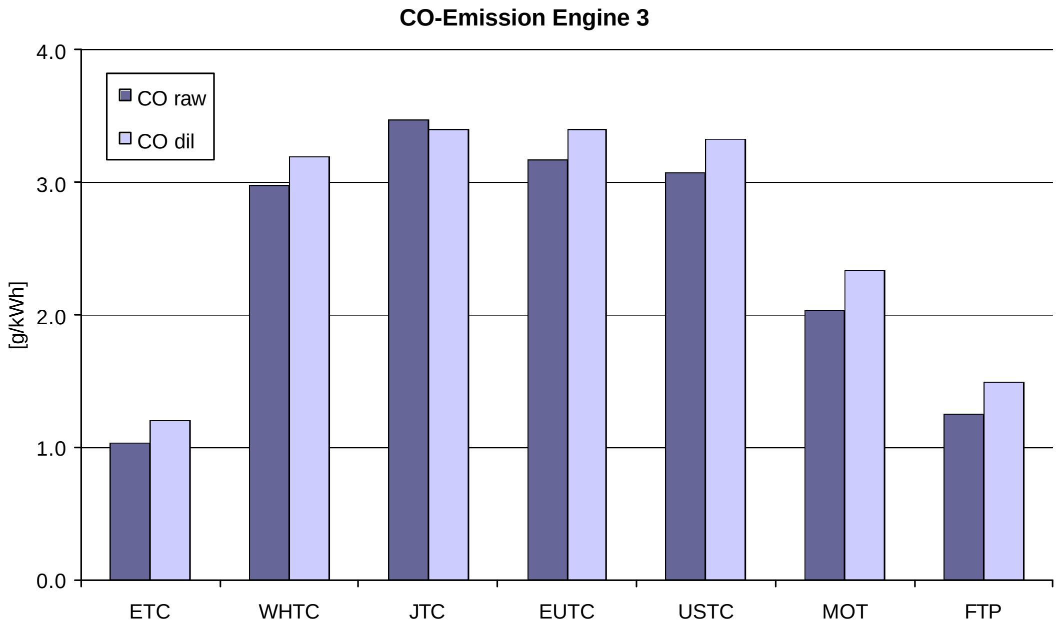


Figure 43.: *CO emissions transient test cycles*

Also for the CO measurement with engine 3, a high measuring range (1 vol.%) had to be chosen for the raw gas measurement due to peak emissions during fast transients. The emission level on the candidate cycles was about three times higher than on ETC.

The differences between raw and diluted measurement were higher compared to engine 1 (between 7 and 20 %, up to 0.3 g/kWh). The opposite trend in JTC was not consistent: the first emission test had unusually low concentrations in the diluted exhaust gas, which biased the average result. The second test correlated to the other test cycles.

Different from engine 1, the CO emissions on MOT were lower than on JTC.

K.3.2 Steady-state test cycles

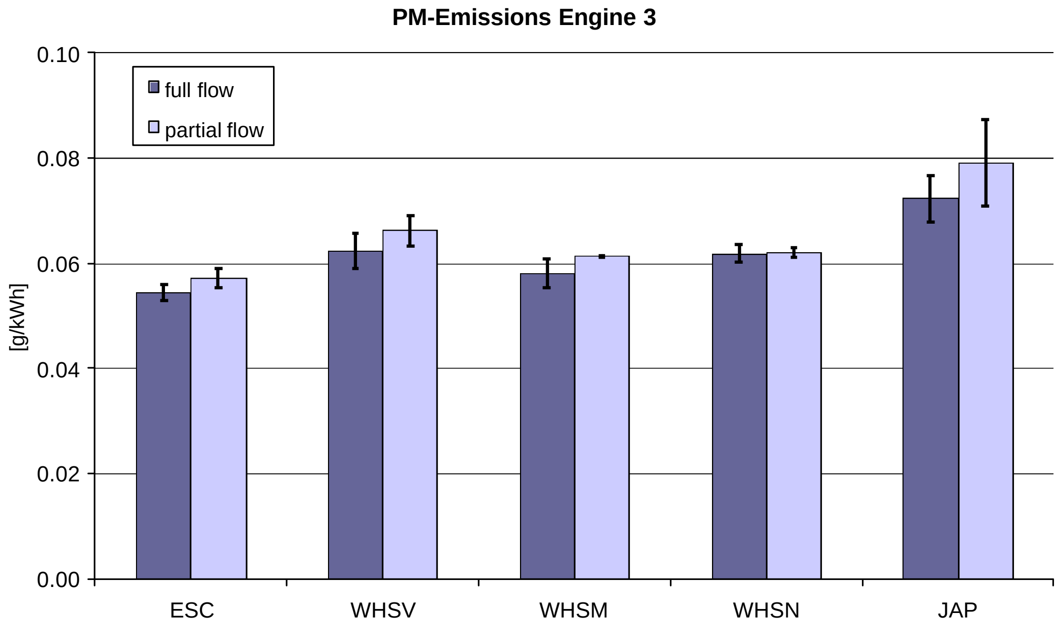


Figure 44.: *Particulate emissions steady-state test cycles*

Except for JAP, the differences between partial and full flow system and the standard deviation of the measurements were lower than 6 % of the average value. On JAP, the repeatability was around 10 %. So the agreement of the systems was better than with engine 1. A possible explanation for this was the SOF content, which was similar for the filters of both measuring systems.

With this engine, slightly lower PM emissions were measured on the modified versions of WHSC compared to version 2 (WHSV). This trend was already observed with engine 2.

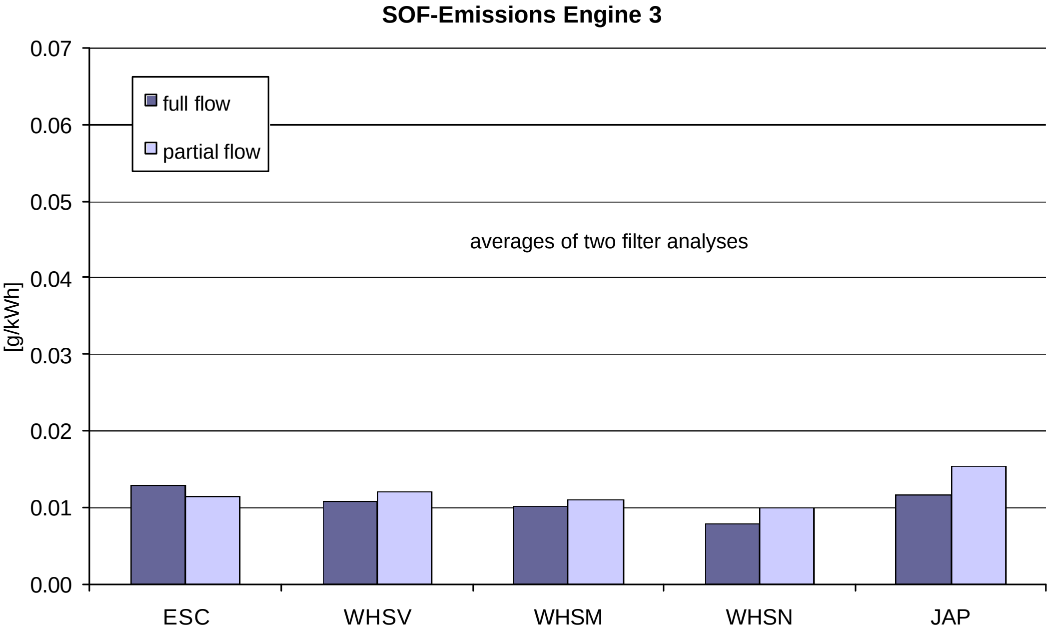


Figure 45.: SOF emissions steady-state test cycles

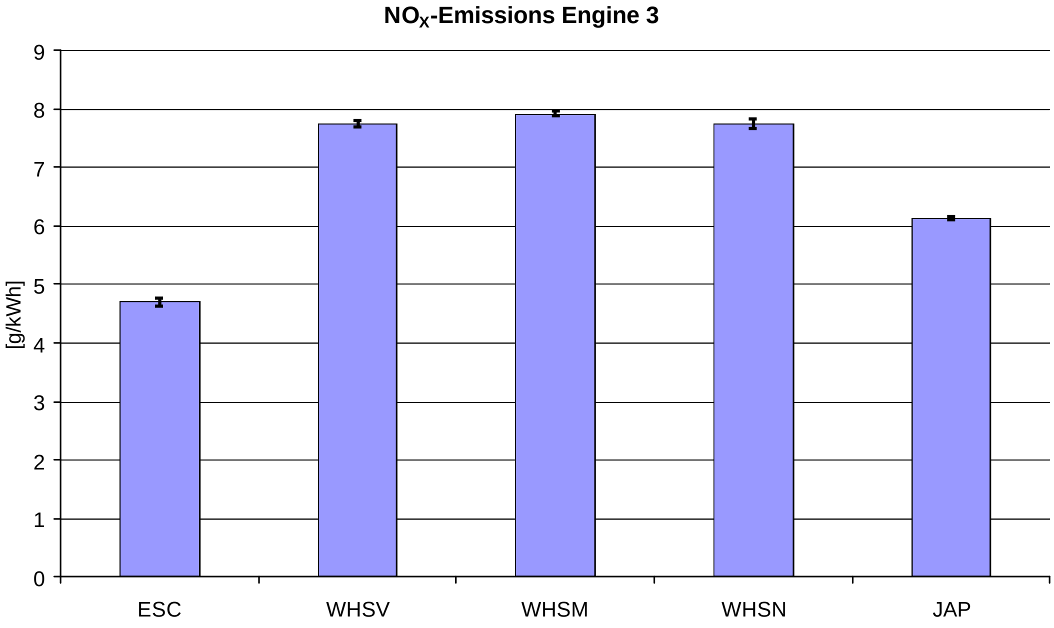


Figure 46.: NO_X emissions steady-state test cycles

The NO_X emission level on the candidate test cycles was around 60 % higher compared to ESC, because most of the measuring points were located outside the control area of the European type approval procedure, as already seen with engines 1 and 2. Since this engine was equipped with exhaust gas recirculation (EGR), the NO_X emission depended on the EGR settings, and was therefore more sensitive to the engine operating area..

Again, the different versions of the WHSC had no influence on the overall test cycle result and the repeatability of the measurements was very good: the standard deviation was lower than 1.5 % of the average value.

The CO_2 emissions were similar on all steady-state test cycles and the standard deviation of the measurements lower than 0.5 % of the average.

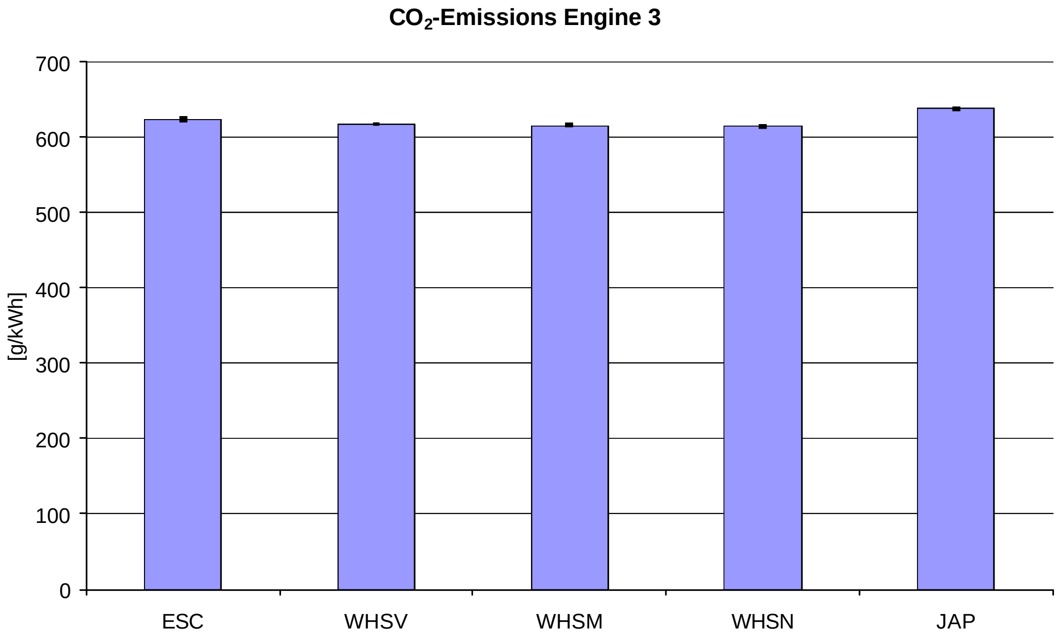


Figure 47.: *CO_2 emissions steady-state test cycles*

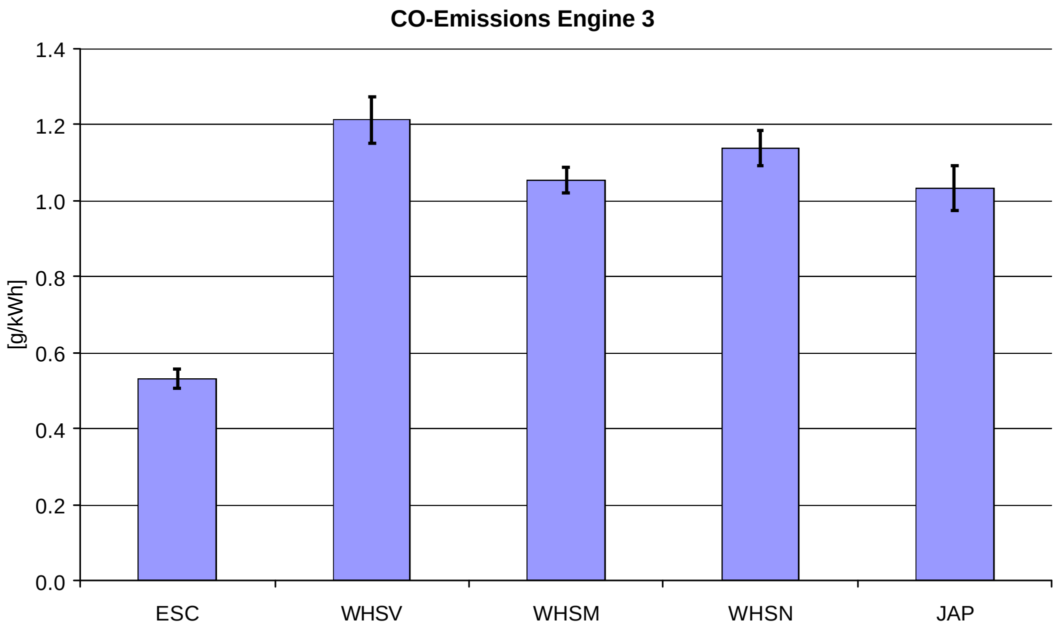


Figure 48.: *CO emissions steady-state test cycles*

The sensitivity of the CO emissions to the test cycle was quite high. On the candidate cycles, they were doubled compared to ESC. Considering this, the differences between the three versions of the WHSC were rather small.

The standard deviation of these measurements was between 3 and 6 % of the average result.

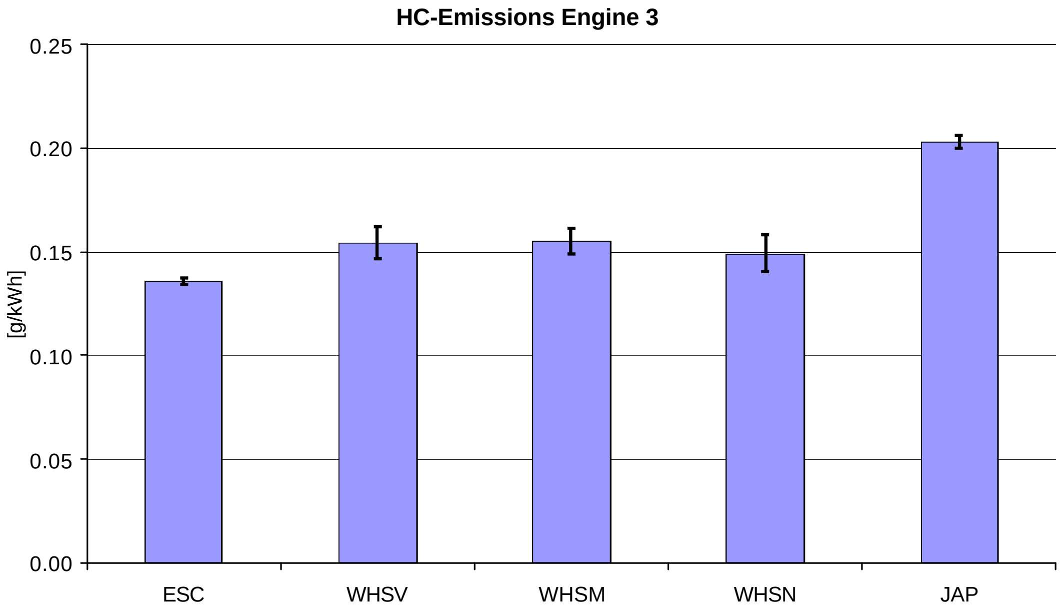


Figure 49.: *HC emissions steady-state test cycles*

The THC emissions were similar to the ones measured with engine 1 in terms of emission level and in terms of test cycle dependence. The repeatability was less good than with engine 1: the standard deviation increased up to 6 % of the average.

K.3.3 Single modes

The emission results of both particulate measuring systems were within 5 % difference. Depending on the test mode, one or the other system measured the higher emissions. Like on the steady-state test cycles, also the SOF content on the filters was similar for both systems. The values of the SOF content were lower compared to engine 1.

Due to the absence of daily variabilities, the standard deviation of the results was lower than 3.5 % of the average PM emission result.

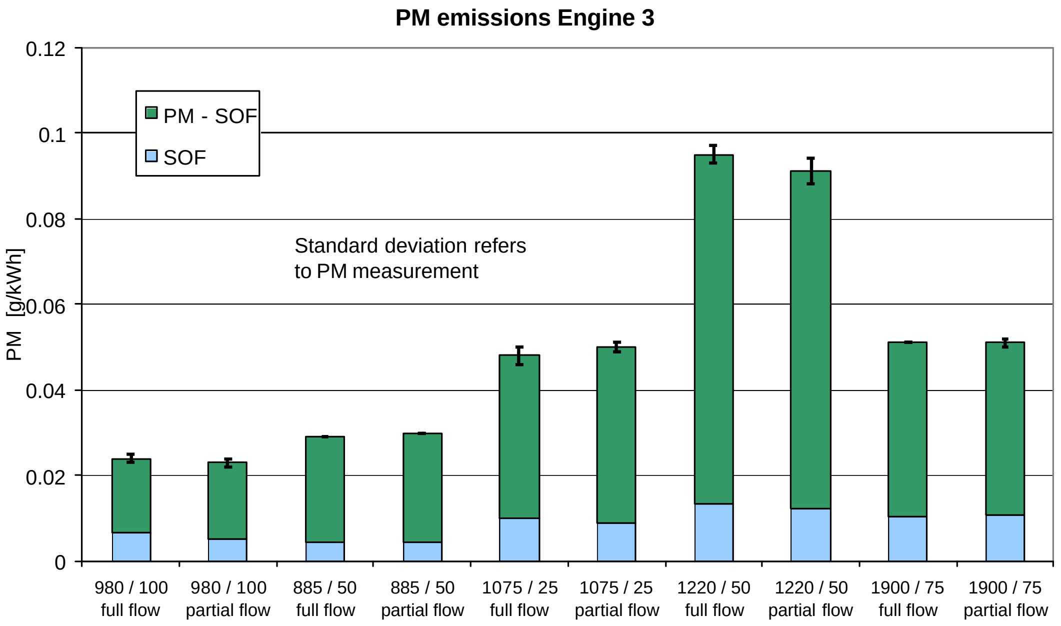


Figure 50.: *PM emissions single modes*

L 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.

L.1 Mean cycle power

The mean power produced by the engines over the different test cycles is shown in figure 51 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.

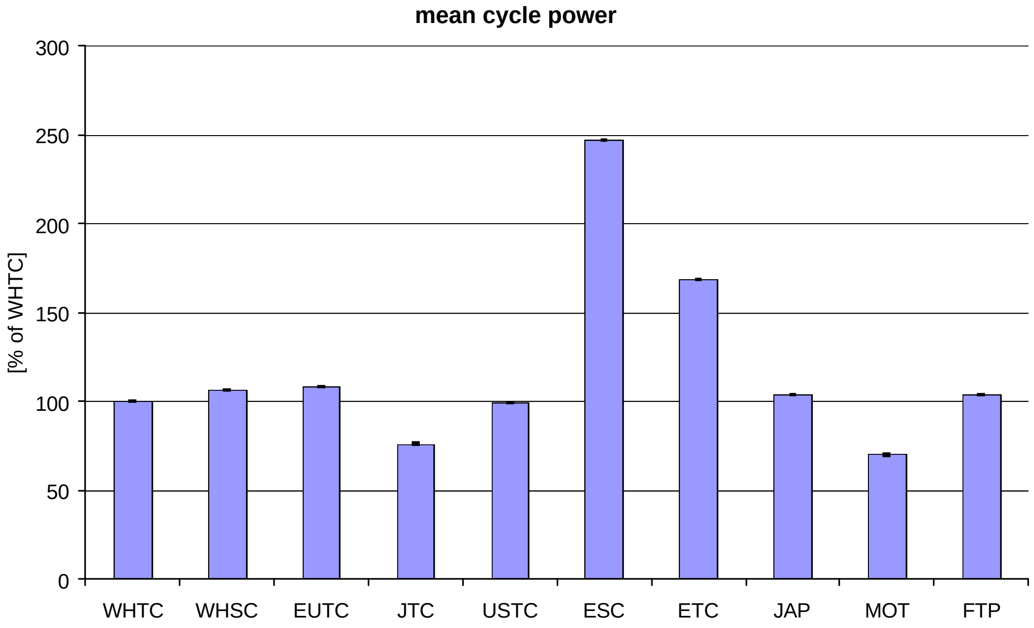


Figure 51.: *All engines: comparison of the mean cycle power*

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.

L.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 required 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 52 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.

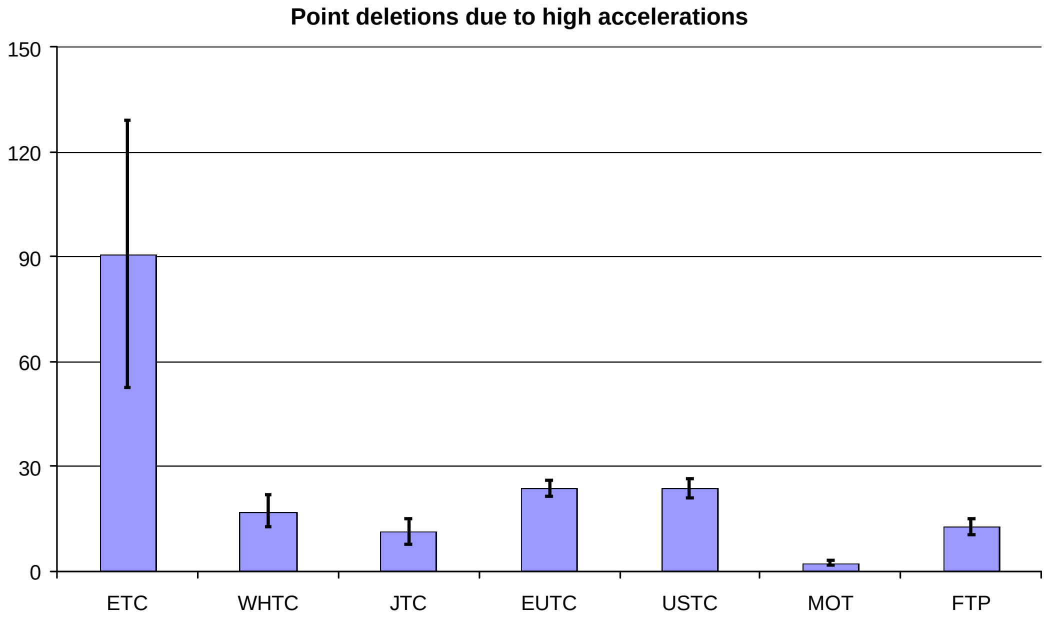


Figure 52.: *All engines: comparison of points deleted due to high acceleration rates*

Nevertheless, the regions with high accelerations in WHTC were further examined in order to find reference values, which cannot be followed by all the engines. Only two seconds of the test cycle were deleted for all engines and all repeats of the test cycle. These were the seconds 402 and 1384 (see table 12). All the other deletions could only be attributed to specific engines or test repeats.

As a consequence, there is no need of introducing changes to the WHTC test cycle from a driveability viewpoint.

	engine 1	engine 1	engine 2	engine 2	engine 3	engine 3
1				258	258	258
2					259	259
3					260	260
4			326	326		
5			359	359		
6			360	360	360	360
7	402	402	402	402	402	402
8	403	403		403		
9			473	473	473	473
10			614	614		614
11			660	660		
12					661	661
13	662	662		662	662	662
14		664				
15		665	665	665		
16		666				
17		813	813	813		813
18	856	856			856	856
19	857	857				
20			1220			
21	1221	1221			1221	1221
22		1222				
23					1229	
24					1230	
25					1231	
26		1232			1232	1232
27	1233	1233			1233	1233
28	1234	1234				
29					1290	1290
30	1295	1295			1295	
31	1296	1296			1296	
32	1297	1297			1297	
33	1298	1298			1298	
34	1384	1384	1384	1384	1384	1384
35	1385	1385		1385	1385	1385
36	1529	1529			1529	1529

Table 12: *All engines: seconds of WHTC to be deleted due to too hard accelerations*

L.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 53), 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.

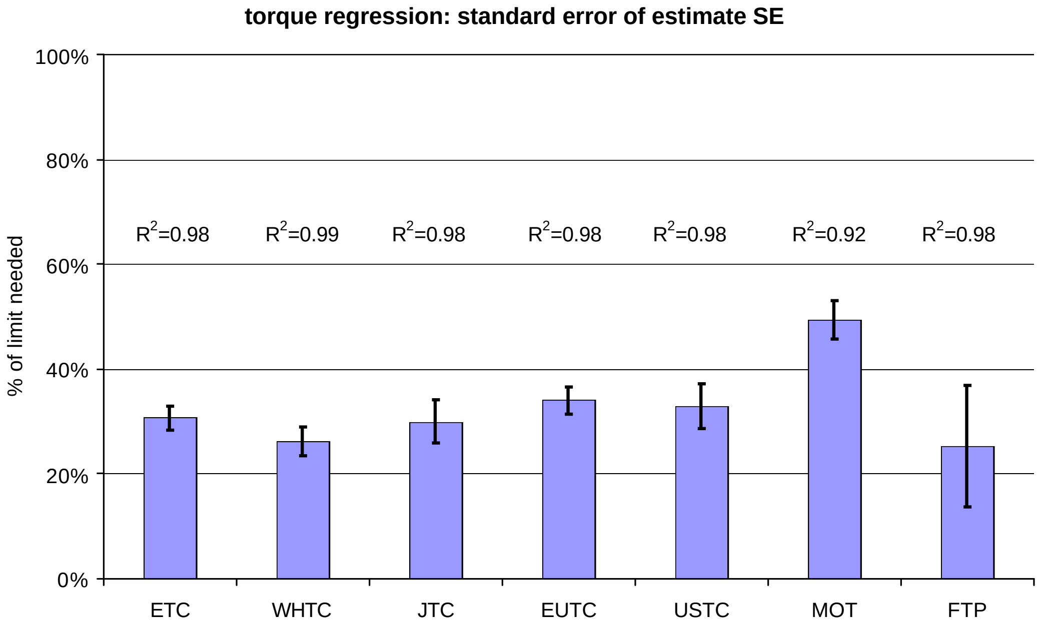


Figure 53.: *All engines: results of the torque regression*

L.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.

M GASEOUS AND PARTICULATES EMISSIONS 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.

M.1 Partial flow dilution for the particulates measurement

As shown in figure 54, 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.

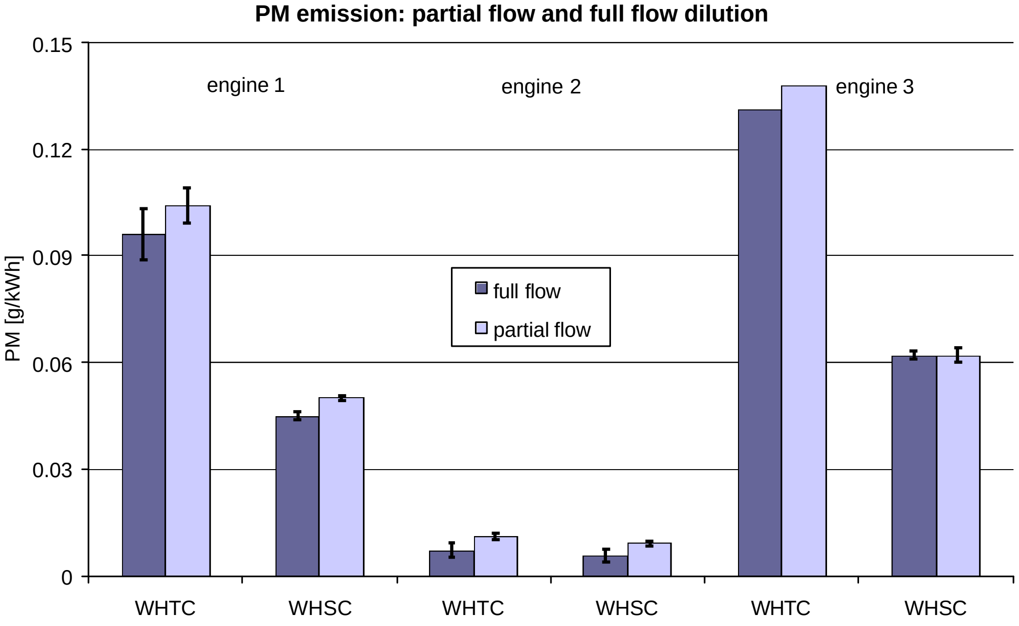


Figure 54.: *All engines: PM emission results on WHTC and WHSC*

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

M.1.1 Filter loading:

With the particulate emission level required 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, because the values measured with engine 2 equipped with a CRT-trap were significantly below this limit.

Additionally the observation was made, that in some tests the loading was equal on primary and secondary filter (WHTC, partial flow system) and in other tests the loading on the secondary filter was negative (single mode, full flow system), i.e there was a release from the filter during the emission test. One reason for this finding are the high blind values of the T60A20 Pallflex filters used.

Therefore, the measurement procedure needs further refinement on the basis of error estimates.

M.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 emissions got, as shown in table 13. 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 13: *filter loading and emissions depending on the number of runs on the same filter pair*

M.1.3 Filter analyses:

Two different batches of Pallflex filters T60A20 (70 mm) were used for this program, the first one for engine 1 and the second one for engine 2 and 3.

The first batch met the expectations regarding to the blind values for the soluble organic fraction SOF (0.061 mg) and the water soluble fraction WSF (0.135 mg).

The analyses of the blank filters of the second batch brought forth very high blind values (0.48 mg) for the water soluble fraction. Meanwhile the blind value for the soluble organic fraction (0.06 mg) came up to the expectations.

For engine 1, only SOF extractions were made in order to explain differences between the particulate measurement systems. The result was, that the filters of the partial flow system generally contained the higher amount of SOF than the filters of the full flow system. In most cases, these differences were in line with the differences measured for the total particulate matter.

With the filters of engine 3, a complete analysis containing SOF, WSF and sulfates was started. After the first measurements, it became clear, that these analyses did not make sense, because the obtained values for the watersolubles and the sulfates were far below the detection limit. Therefore, the analyses were continued, but restricted to the SOF extraction. The results presented similar SOF contents on the filters of both measurement systems.

Most interesting were the analyses of the filters from engine 2 with CRT-trap. Also a full analysis was started, the results are shown in table 14. Since the loading on the primary and on the secondary filter was the same, both filters were analysed. Due to obvious detection problems of all measuring methods, this work was completely stopped after 24 filters.

In the table, the light cells contain reasonable and repeatable values. The results in the dark cells were completely useless. Nevertheless a few conclusions can be drawn:

Although an oxidation catalyst was installed, the measured sulfates were very low or not detectable. This was effected by the sulphurfree (2 ppm) diesel fuel.

On an average the overall blind values were around 0.5 mg, which meant partially five times higher than the filter loading with particulate matter.

Test cycle [mg]	filter loading [mg]	amount evaporated [mg]	SOF [mg]	SOF % of filter loading	WSF [mg]	Sulfates µg / test
ETC1 full/prim	0.106	0.004	0.055	52.36	neg.	7
ETC1 part/prim	0.113	-0.018	0.061	54.42	neg.	10
WHT2 full/prim	0.105	-0.006	0.028	27.14	neg.	neg.
WHT2 part/prim	0.084	-0.026	0.034	41.07	neg.	4
WHT3 full/prim	0.091	-0.017	0.018	20.33	neg.	4
WHT3 part/prim	0.095	-0.024	0.049	52.11	neg.	neg.
ESC2 full/prim	0.080	0.009	0.127	159.37	neg.	neg.
ESC2 part/prim	0.094	-0.003	0.053	56.91	neg.	neg.
ETC2 full/prim	0.093	-0.001	0.046	48.92	neg.	4
ETC2 part/prim	0.076	-0.005	0.072	95.39	neg.	neg.
ETC2 full/sec	0.048	-0.003	0.007	15.62	neg.	11
ESC2 full/sec	0.026	-0.003	0.007	15.62	neg.	1
ETC2 part/sec	0.070	-0.016	0.062	89.29	neg.	8
ESC2 part/sec	0.057	-0.032	0.019	34.21	neg.	neg.
ESC1 full/prim	0.083	-0.011	-0.002	-1.81	neg.	0
ESC1 full/sec	0.022	-0.029	-0.017	-75.00	neg.	neg.
ESC1 part/prim	0.102	-0.017	0.041	39.71	neg.	neg.
ESC1 part/sec	0.066	-0.050	-0.047	-70.45	neg.	neg.
WHT2 full/sec	0.055	-0.025	-0.009	-15.45	neg.	1
WHT2 part/sec	0.088	-0.044	0.018	21.02	neg.	8
WHT3 full/sec	0.034	-0.040	-0.005	-13.24	neg.	5
WHT3 part/sec	0.088	-0.030	0.027	31.25	neg.	6
ETC1 full/sec	0.072	-0.021	0.013	18.75	neg.	7
ETC1 part/sec	0.099	-0.024	0.037	36.87	neg.	3

Meanvalue blankfilters:	0.068 mg		0.481 mg	0.026 mg
Standard deviation :	0.029 mg		0.128 mg	0.005 mg
Detection limit:	0.153 mg		0.866 mg	0.040 mg

Table 14: *engine 2 (CRT-system): filter analyses*

M.2 Raw exhaust gas measurement

To carry out the raw gas calculations, the data rows of the emissions 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. The values for the raw gas analyser bench used are shown in figure 55.

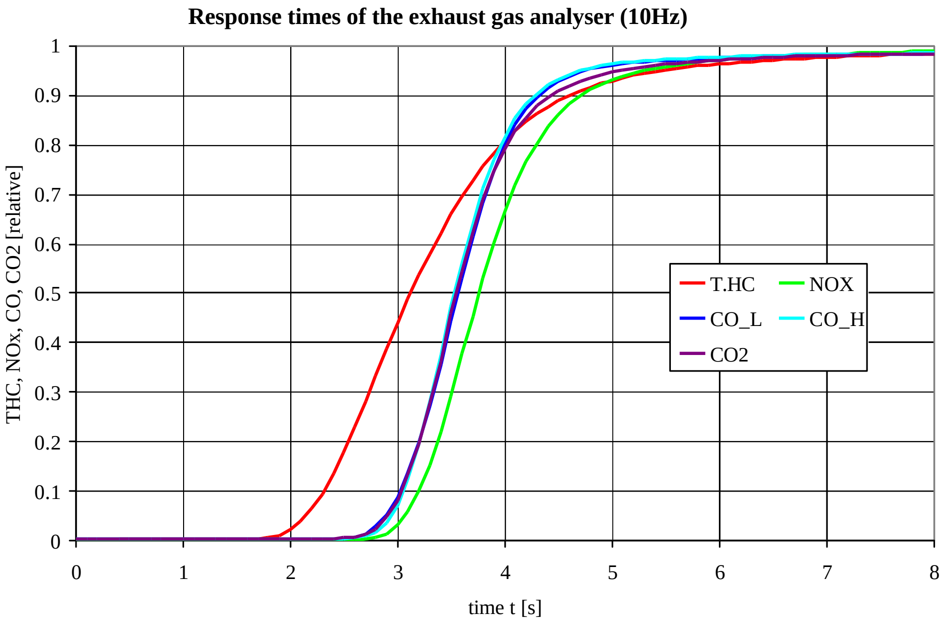


Figure 55.: Response and rise times of the emission analysers

The comparison between raw and diluted measurement is shown in figures 56 to 59.

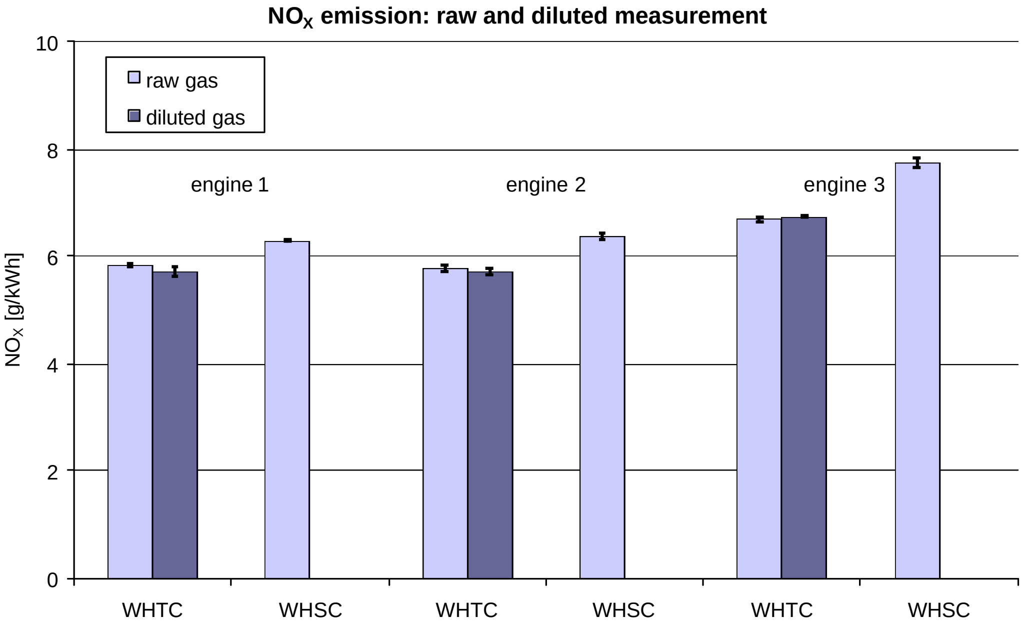


Figure 56.: *Nitrogen oxides: comparison between raw and diluted measurement*

For NO_x (figure 56), the difference between raw and diluted measurement was below 3 % for all test cycles and engines, which was a very good agreement. Additionally it has to be considered, that partially 1 % of the difference is caused by the new NO_X correction factor taking into account the intake air temperature as well (see formula below). With the same correction factor, the agreement would be even better. The repeatability of both of the two measurement procedures is excellent. The standard deviation of the individual measurements was within 2 % of the average.

$$K_{HD} = \frac{1}{1 - 0.0182 \times (H_a - 10.71) + 0.0045 \times (T_a - 298)}$$

For CO (figure 57), 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) was 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 absolute difference between raw and diluted emission measurement was at or below 0.4 g/kWh, and the repeatability of the two methods was comparable.

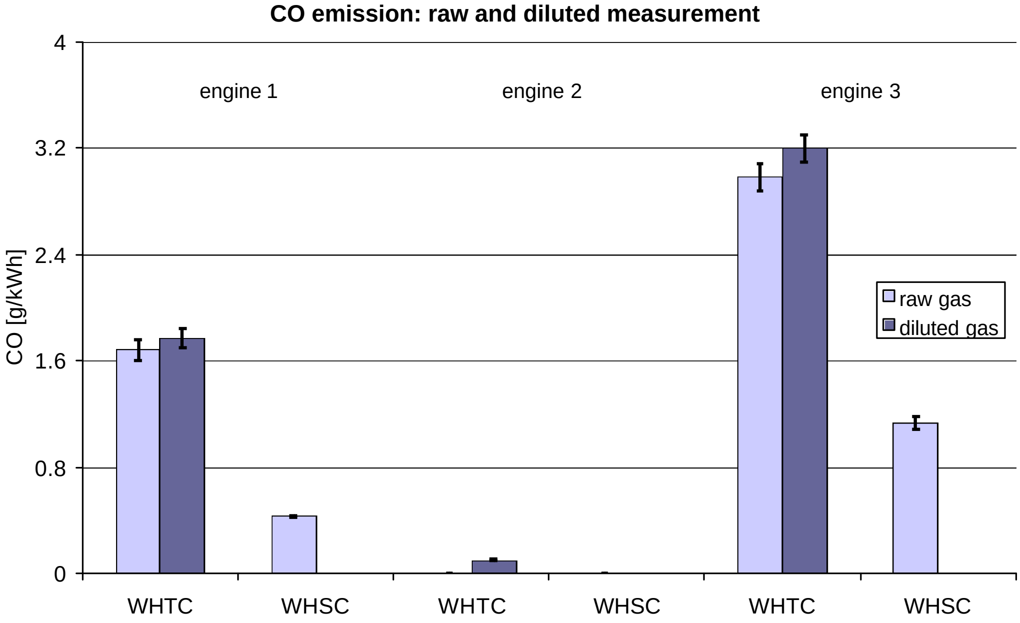


Figure 57.: *Carbon monoxide: comparison between raw and diluted measurement*

For HC (figure 58), 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.

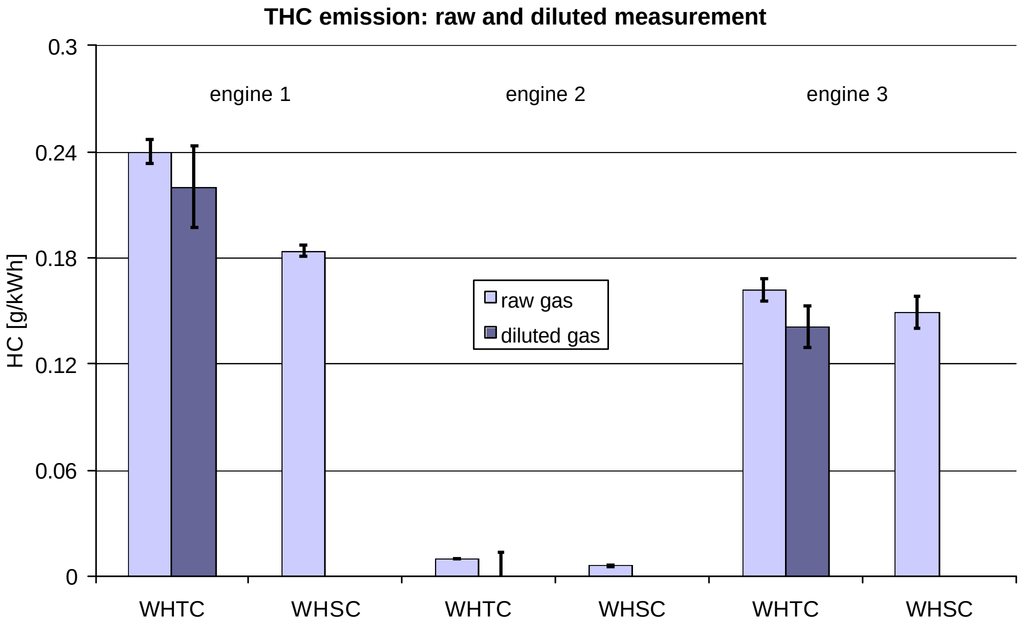


Figure 58.: *Total hydrocarbons: comparison between raw and diluted measurement*

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-system, 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 15).

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

For CO_2 (figure 59) 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.

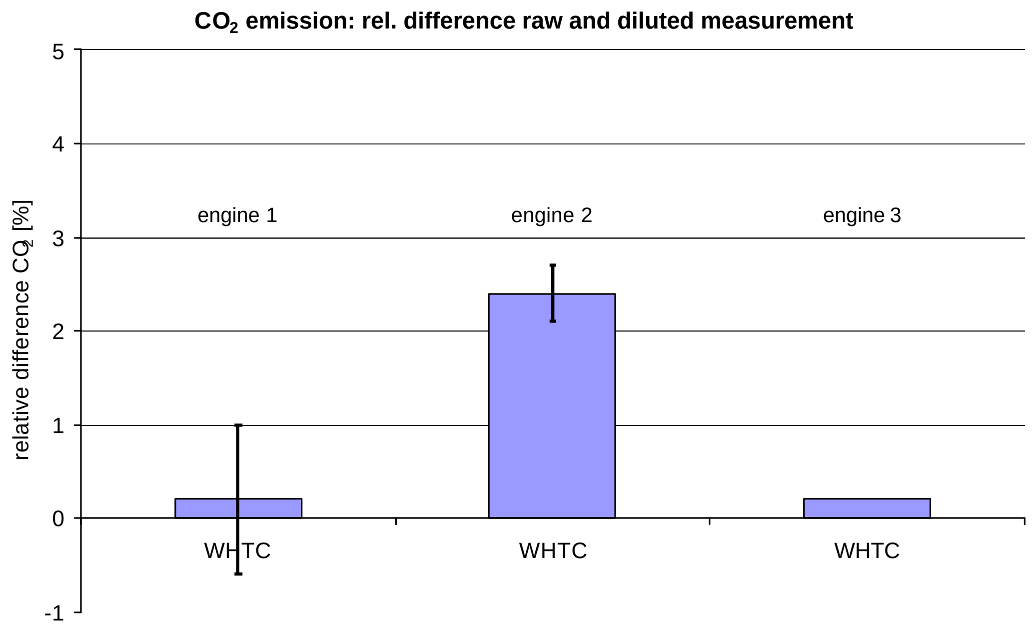


Figure 59.: *Carbon dioxides: relative comparison between raw and diluted measurement*

M.3 Comparison of the test cycles

An overall comparison of the regulated emissions over all test cycles, i.e. of both steady-state and transient test cycles, is shown in figures 60 to 63. The diagrams contain the average test cycle results of all engines on all test cycles and the corresponding standard deviations, except for engine 3 when only two emission tests were run. Due to the good agreement of the measurements according to ISO/FDIS 16183 with the legislative measurement procedure, these comparisons are presented with the results of the raw exhaust measurement and the partial flow system.

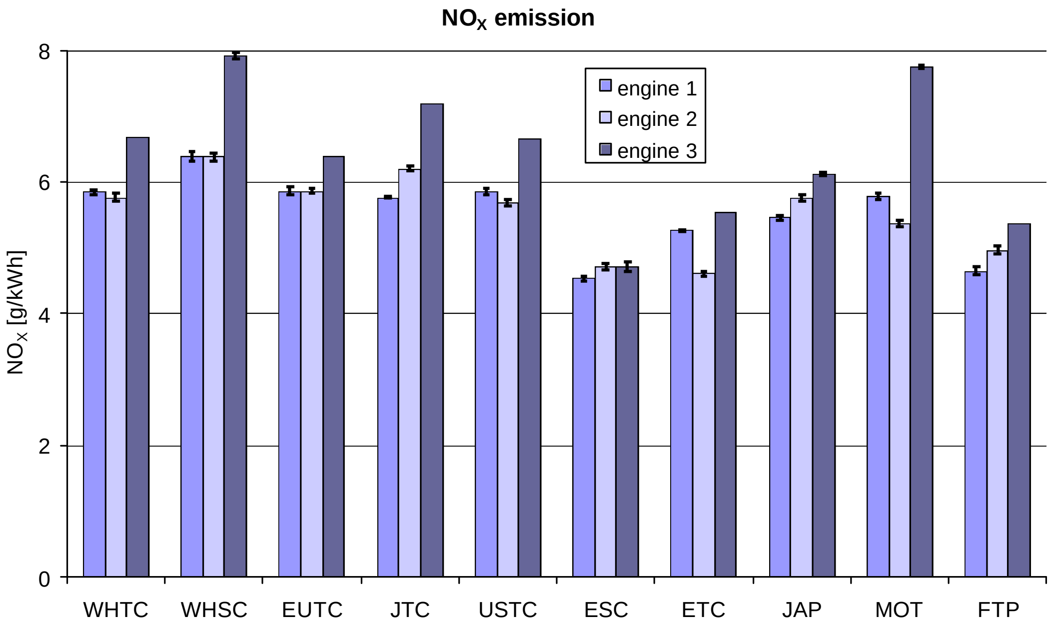


Figure 60.: *All engines: NO_X emission results*

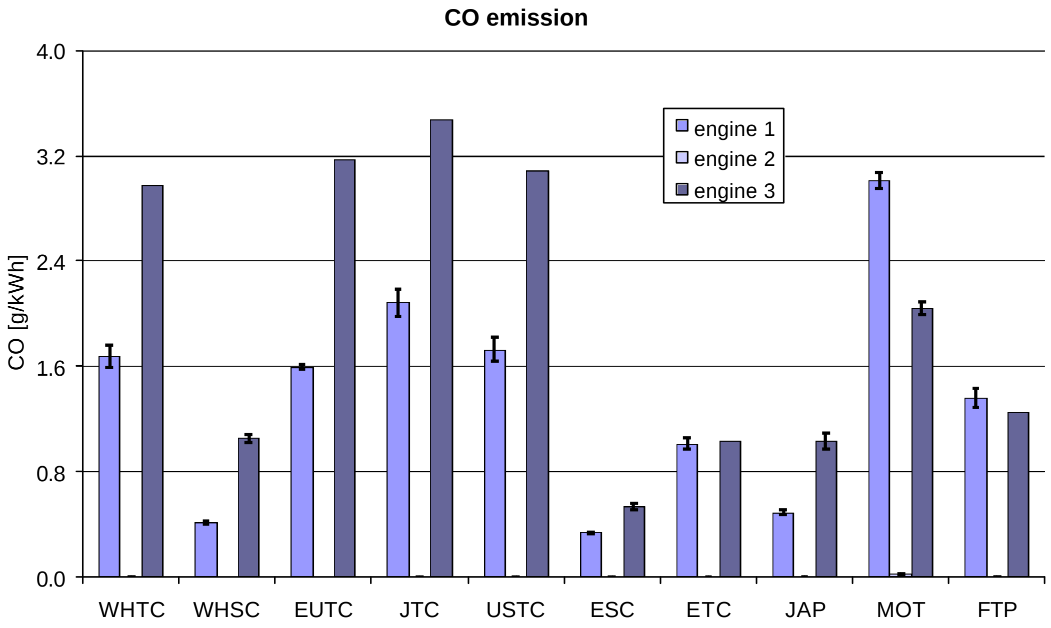


Figure 61.: *All engines: CO emission results*

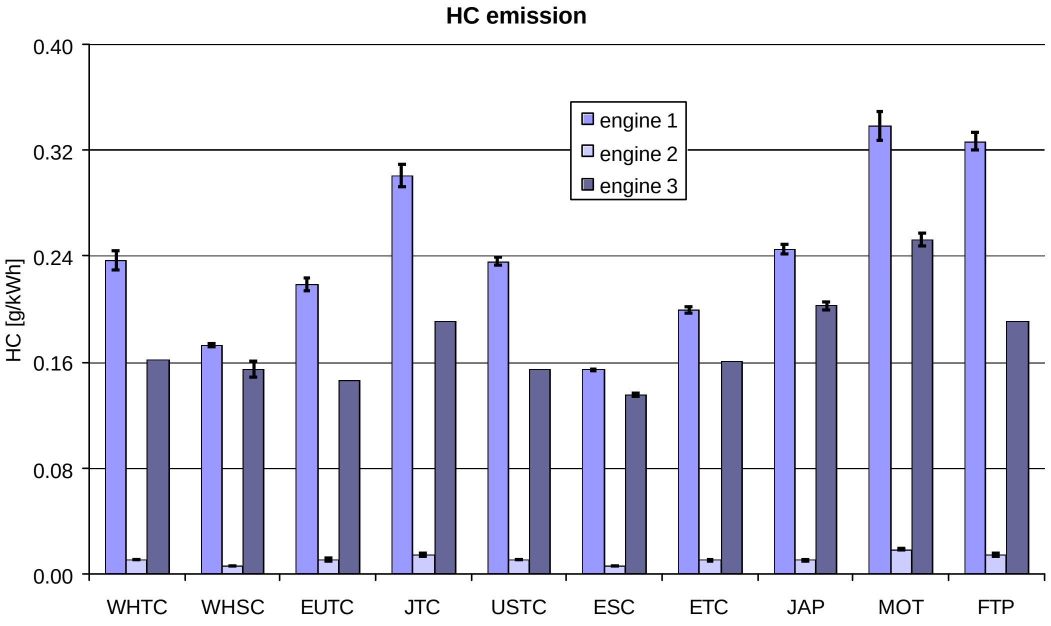


Figure 62.: *All engines: HC emission results*

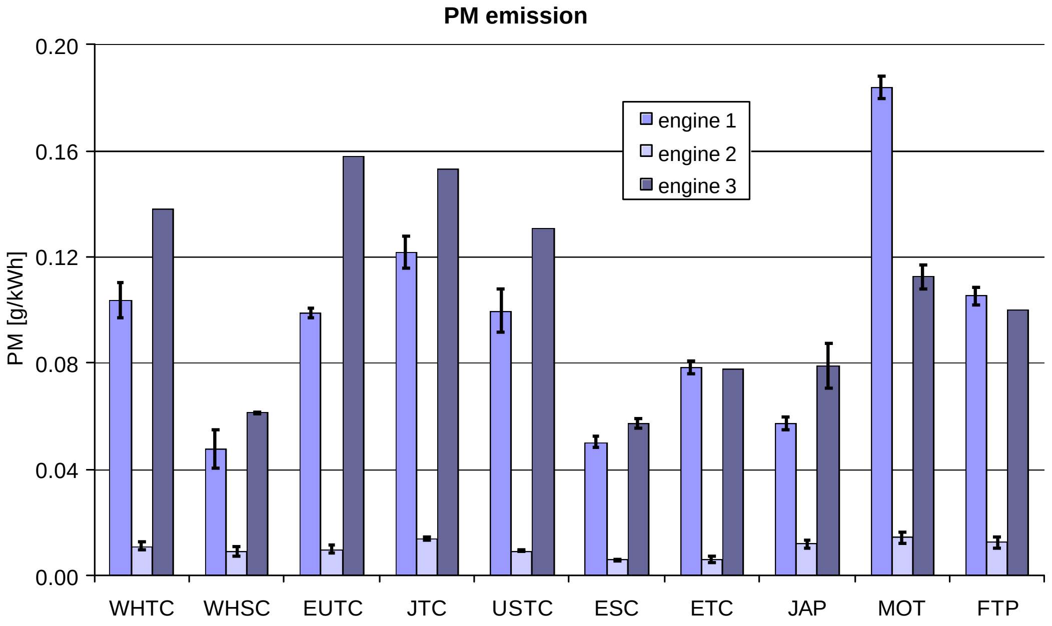


Figure 63.: *All engines: PM emission results*

N 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

O 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/EC

[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**