MEASUREMENT OF EMISSIONS FROM HEAVY DUTY VEHICLES MEETING EURO IV/V EMISSION LEVELS BY USING ON-BOARD MEASUREMENT IN REAL LIFE OPERATION

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ABSTRACT

New vehicles introduced on the market are designed to meet standards ruled out by legislations and directives. The regulatory system for certification of HD engines is focusing on the engine instead of the vehicle. Gradually when requirements will be tightened more sophisticated emission control systems will be introduced, and thereby questions could be raised whether real life emissions from late technology vehicles in normal operation are different from those achieved during well controlled laboratory testing of an engine.

Technology to carry out high quality testing on-road is developing and the use of portable emission measurement systems (PEMS) will play an important role for establishment of real life emission factors as well as to verify whether engines meet the set standards.

Since many years AVL MTC has been working with correlation between chassis dynamometer testing and engine testing. In 2004, the program was extended to also include the use of PEMS and testing vehicles on-road.

In Sweden a national program, financed by the Swedish Road Administration, for in-use service testing of HDV is in place since 2006 and additional activities are ongoing for development of "real life" emission factors and validation of emission performance from late engine technologies (e.g. SCR, EGR).

The results from testing underline that there are differences in emission behavior when vehicles are tested on-road in normal operation compared with testing engines/vehicles for certification purposes. There are cases when engines/vehicles are meeting set standards while testing the same vehicle on-road show 5 – 10 times higher results. Such a difference might result in severe underestimation of emissions emitted to the atmosphere.

Keywords: *Emission measurement, on-road, real life emissions, PEMS.*

1. INTRODUCTION

Before engines to be used in heavy duty on-road applications can be introduced on the market, the engine must undergo extensive testing in an engine test cell (bench testing). After approval of the results, by an approval authority, the manufacturer of the engine can introduce the engine in a variety of applications. It is full clear that emission performance from engines tested according to the requirements laid down by regulations will differ in emission behaviour compared to when vehicles are used in normal operation. This difference is much dependant upon the actual driving modes and whether aftertreatment devices are used to reduce the emissions (EGR – SCR – CRT – Particle Filter – Oxidising catalytic converter).

To verify whether engines in use are meeting set requirements is a very complicated issue, discussed both in Europe and USA for several years. A common understanding is that a cost-effective way to carry out such an important task is to introduce a method using Portable Emission Measurement Systems (PEMS).

In Europe, efforts have been made by the European Commission, DG JRC (Joint Research Centre), to design a proper and accepted method for measurement by introducing PEMS-Pilot project. The objective, presented on the web page of JRC, is explained [1] to measure emissions from combustion engines as the vehicle is being used. This technology allows real-world in-service testing and provides more data than conventional laboratories or vehicle test cells. PEMS offer a modern and innovative counterpart to check the impact of emissions for combustion engines upon the environment. They integrate accurate gas analysers, exhaust mass flow meters, weather stations, Global Positioning System (GPS) and connections to the vehicle ECU. PEMS provide a complete and very accurate real-time monitoring of the pollutants CO, HC, CO_2, NO_x and O_2 together with engine and vehicle data as well as ambient conditions. Further development will also include measurement of particles.

In USA, similar projects have been introduced by Environmental Protection Agency (EPA) and today in-use testing program is a part of the regulatory system. Further references are made to the web page [2]. The US approach is somewhat different and will not be further elaborated in this presentation.

Further development of the European PEMS-Pilot project, coordinated by JRC, will be introduction of particulate measurement (PEMS-PM) for on-road applications and to adopt the system for portable emission measurement from non-road mobile machinery (PEMS-NRMM).

To summarize, the use of PEMS will make it possible to:

- Verify whether engines used in heavy duty vehicles meet set requirements
- Verify real-life exhaust emissions from hybrid concepts
- Further develop the EU legislation, and
- Improve emission inventories by development of real-life emission factors

In this presentation we will however only focus on real-life emission measurement from heavy duty vehicles with the vehicle in normal operation.

2. CORRELATION ENGINE TESTING / CHASSIS DYNAMOMETER TESTING

When European emission regulations were introduced for engines to be used in heavy duty vehicles, the focus was to test engines in bench according to a stationary test cycle. Later, when engine management became more sophisticated and complex a transient test cycle were introduced [3]. After approval of the engine, the manufacturer is free to install the engine, sometimes with additional minor modifications/calibrations, in any application suitable for the engine without further testing.

AVL MTC, the Technical Service in Sweden related to EU directives dealing with emission measurements, operates a sophisticated emission laboratory with the ability to measure emissions from vehicles and engines. The test resources in the laboratory include several engine test cells for testing diesel fuelled as well as alternative fuelled heavy duty engines and one chassis dynamometer for tests of heavy duty vehicles.

To reduce the cost and time spend for testing of vehicles in-use, it is favourable to test a vehicle on a chassis dynamometer compared to bench testing including time to demount an engine from a vehicle, test it, and then install the engine in the vehicle again. The difference in time needed for preparation of the engine and to carry out the testing can be more than one week. The reduction in time is of course direct related to the cost for testing.

It has therefore been a high priority to establish correlation between the two types of testing. A program was started in the late 1990-ies, financed by the Swedish Environmental Protection Agency (SEPA), and very good correlation was established for stationary testing. For transient testing it is much more difficult to establish the same accuracy for correlation. Approximately 5 years ago we succeeded in finding correlation between ETC (European Transient Cycle) testing and test on chassis dynamometer in accordance with the FIGE driving cycle (The ETC cycle translated/modified to chassis dynamometer testing) on an acceptable level. The results and experience for this initial work is now the base for future tests.

3. CORRELATION CHASSIS DYNAMOMETER / ON-BOARD MEASUREMENT

In 2004, work was started to find correlation between conventional emission measurement on a chassis dynamometer and by using portable emission measurement equipment. Another topic was to find out the sensitivity of the on-board measurement device.

AVL MTC arranged for simultaneous measurement of a heavy duty vehicle on the chassis dynamometer using conventional measurement system (laboratory grade of instruments, CVS-system with full dilution tunnel) and the PEMS. The on-board measurement device was a Semtech DS system combined with an Exhaustgas Flow Meter (EFM), with a diameter of 4 inches. Testing was then carried out both according to steady state testing as well as transient testing. The result from the two methods was in agreement and it was verified that results from the chassis dynamometer tests and on-board measurement is the same.

4. ON-BOARD TESTS OF VEHICLES MEETING DIFFERENT EURO-CLASSES

To verify whether PEMS equipment is sensitive enough to distinguish emissions from vehicles meeting different Euro-classes a thorough test program was designed. Heavy duty vehicles meeting emission levels starting from Pre-Euro up to Euro III was tested on-road using the same test route. Several tests were carried out with each vehicle and, as examples, it can be seen from the results (Figure 1 and Figure 2) that the system is sensitive enough also to detect minor deviations.

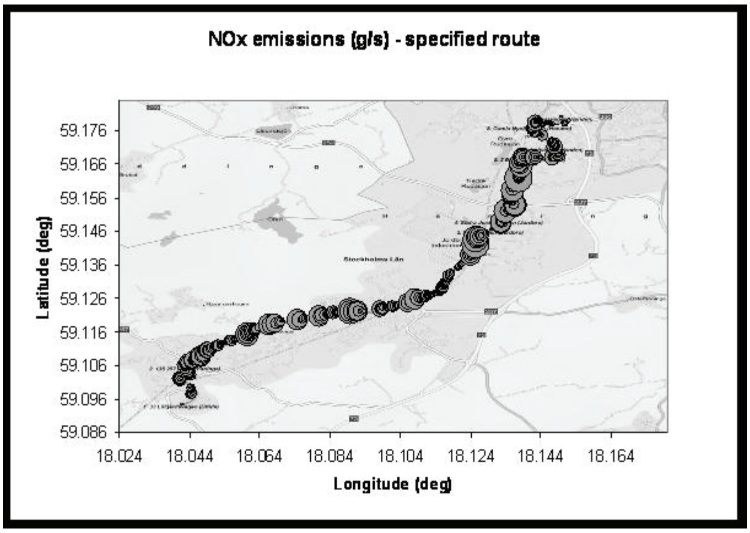

Figure 1: Emissions (g/sec) of NO_x from a heavy duty vehicle meeting Euro III requirements

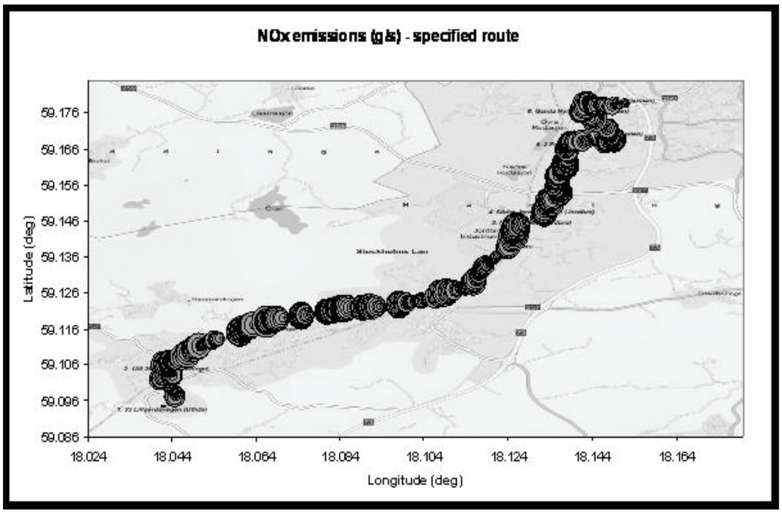

Figure 2: Emissions (g/sec) of NO_x from a heavy duty vehicle, Pre-Euro

5. SWEDISH NATIONAL PROGRAM, 2006

A national program, financed by the Swedish Road Administration (SRA), for in-service testing of heavy duty vehicles was introduced 2006. Tests were carried out both on-road using PEMS as well as on a chassis dynamometer in order to enable a comparison of the results. The program was designed in collaboration with SRA, and the tests were carried out by AVL MTC. Two manufacturers of trucks were selected and from each manufacturer three vehicles as identical as possible were chosen. The two samples of vehicles should, in addition, be as identical as possible. Three vehicles from one manufacturer were then selected also for testing on the chassis dynamometer. All trucks were of typical design for distribution of goods in cities and meeting Euro III emission requirements. Test weight was in all cases about 15 tonnes (corresponding to 50 % load.)

For the 2006 program all the testing were carried out on the “PEMS-route”. This route has been presented to JRC, in their role as coordinator for on-board measurement within Europe, including the PEMS-Pilot Project. For the actual measurements we decided to follow the PEMS test protocol, a part of the pilot program, as close as possible and thereby make it possible to relate measurement and experience from the Swedish national program to experience from other participants (vehicle manufacturer and technical services) of the PEMS-Pilot Project. The selected route was found to meet the requirements as a suitable route. The route comprises urban, rural and highway driving with an average speed of approximately 60 km/h. The distance is about 75 km and it takes roughly 80 minutes for one lap. The average time and speed will of course vary due to traffic conditions. The lay-out of the “PEMS-route” is presented below in Figure 3.

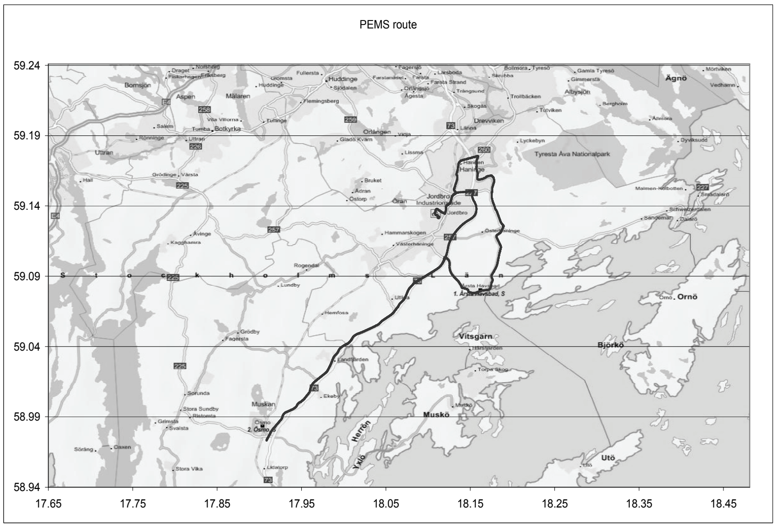

Figure 3: PEMS route 2006 – 2007 program

Three vehicles from the same manufacturer and with the vehicles as identical as possible were tested on the chassis dynamometer. The results from tests according to the both the European Stationary Cycle (ESC) and the modified version (FIGE driving cycle) of the European Transient Cycle, showed very good reproducibility as can be seen in Table 1 below.

Table 1: Chassis dynamometer test, driving cycles ESC & FIGE (ETC), 3 different vehicles

Driving Cycle	Vehicle No.	CO (g/kWh)	HC (g/kWh)	NO_x (g/kWh)	Part. (g/kWh)	CO (g/km)	HC (g/km)	NO_x (g/km)	Part. (g/km)
ESC	1	0.59	0.28	4.59	0.09	-	-	-	-
	2	0.57	0.26	4.44	0.14	-	-	-	-
	3	0.53	0.21	4.53	0.12	-	-	-	-
FIGE (ETC)	1	-	-	-	-	1.98	0.32	5.29	0.11
	2	-	-	-	-	2.22	0.30	5.22	0.11
	3	-	-	-	-	2.41	0.27	5.49	0.12

Please note that results from the different test methods (ESC vs. FIGE), presented in Table 1, can not be compared with each other due to different methods for calculation. Information related to engine power/torque is missing for the FIGE driving cycle, and results in g/kWh is difficult to present. It is therefore only possible to compare the results from the same driving cycle.

For the on-road testing each vehicle from the two manufacturers was tested on the "PEMS-route" three times. Unfortunately, results of one vehicle from each manufacturer have to be disqualified due to equipment malfunction. The results from each separate manufacturer show that the emissions and fuel consumption not differ between vehicles to a large extent, however the difference between the two manufacturers differs much more. If this difference between manufacturers is due to different strategy for engine management or something else is difficult to say. Further analyzes of the detailed results might show that manufacturer intentionally use various emission strategies for management of changes in vehicle speeds and engine loads. In the table below, the average distance specific emissions and fuel consumption are presented. Notable is the difference in CO emissions and fuel consumption for vehicles produced by manufacturer A resp. B.

Table 2: Average distance specific test results from on-road testing of 4 vehicles

Manufacturer	Vehicle	CO (g/km)	HC (g/km)	NO_x (g/km)	CO_2 (g/km)	Fc (l/100 km)
A	1	2.46	0.38	4.63	677	25.6
A	3	3.52	0.33	4.83	677	25.9
B	4	0.60	0.48	3.65	538	20.5
B	5	0.63	0.44	3.76	536	20.5

The same values from the measurements are used to calculate the brake specific emissions and presented in Table 3. In this context it is important to know that all information about engine power and torque for calculation of brake specific emissions is based on signals coming from the electronic control unit (ECU) located in the vehicle. Those signals are entered into the PEMS computer via the on-board diagnostic contact.

For vehicle 5, manufacturer B the brake specific emissions could not be calculated since occasionally we lost the signal from the electronic control unit (ECU) during the testing.

Table 3: Average brake specific test results from on-road testing of 3 vehicles

Manufacturer	Vehicle	CO (g/kWh)	HC (g/kWh)	NO_x (g/kWh)	CO_2 (g/kWh)	Av. Power (kW)
A	1	2.18	0.34	4.10	599	64
A	3	3.15	0.29	4.33	606	65
B	4	0.64	0.44	3.75	531	77

Results from the testing covering the program 2006 can be found in a report on the website of Vägverket (Swedish Road Administration) [4]

6. SWEDISH NATIONAL PROGRAM, 2007

The test program for 2007 includes chassis dynamometer testing as well as on-road testing of three city-buses from three different manufacturers. The selected buses were approved in accordance with emission requirements for Euro IV/V and equipped with different emission control systems/concepts. Additionally, three heavy duty trucks from one manufacturer were tested on-road. The same basic engine was installed in all trucks, but the vehicles are used for different purposes implying minor changes in overall calibration of the power train. Target was to find vehicles or vehicle combinations with the highest permissible weight i.e. up to 60 tonnes in operation on the Swedish road net.

Tests of the buses were carried out on-road in the same way as for the trucks included in the program for 2006. The results from testing according to the PEMS-route, in general, showed low emissions as can be seen from Table 4 and 5 below. The results (distance specific and brake specific) are the average results from three tests of the different vehicles.

The buses were tested in the same manner on the chassis dynamometer as the trucks included in the program for 2006. From the chassis dynamometer testing it was shown that the engine installed in the buses fulfilled the emission requirements for the respective Euro class (IV/V).

Table 4: Distance specific test results, on-road testing ("PEMS-route"), 3 different city-buses

Bus	Av. Sp (km/h)	CO (g/km)	HC (g/km)	NOx (g/km)	Fc. (l/100km)	Em. Concept
A	59.3	0.22	0.00	4.57	30.3	EGR/Ox.cat
B	56.3	1.00	0.01	2.13	27.1	SCR/Filter
C	59.2	1.11	0.02	1.95	30.0	SCR/Filter

Table 5: Brake specific test results, on-road testing ("PEMS-route"), 3 different city-buses

Bus	Av. Speed (km/h)	CO (g/kWh)	HC (g/kWh)	NOx (g/kWh)	Av. Power (kW)	
A	59.3	0.19	0.00	4.06	67	33 % of max
B	56.3	0.78	0.00	1.66	73	28 % of max
C	59.2	0.82	0.02	1.43	80	32 % of max

An interesting observation is related to measurement of NO_x from bus "B" were the measured values ranged from 1.03 – 2.42 – 3.16 g/km and 0.8 – 1.65 – 2.53 g/kWh for the repeated tests. Average ambient temperature and average exhaust temperature for the three tests are almost the same, and the highest probability is that the temperature in the beginning of each test is the cause for the big variations.

Since the buses were equipped with different emission concepts, the objective was also to investigate whether the buses were low emitting when driving on-road in normal operation. Based on experience, the operation of aftertreatment device is very much dependant on the exhaust temperature and it was interesting to verify whether a driving cycle with expected low temperature of the exhaust gases should result in low emissions.

Additional test was carried out on an actual bus route in a southern suburban area of Stockholm. The selected bus route takes about 35 minutes with an average speed of about 20 km/h. The distance is 14 km. During the test drive the bus was stopped for 30 seconds on every second bus stop to simulate passengers leaving and entering the bus, thus the idle part of the driving is as high as 35 %, and thereby influencing the results for the distance specific emissions. On the other hand however, this is the way a city-bus is operated. This kind of gentle driving, despite high level of transient behaviour, might have an influence on the exhaust temperature and the performance of aftertreatment devices. As shown by the result in Table 6, some aftertreatment device is not working as expected and both distance specific emissions of NO_x and fuel consumption is increased, while the average speed is decreased compared to the PEMS-route.

Table 6: Distance specific test results, on-road testing ("Bus-route"), 3 different city-buses

Bus	Av. Speed (km/h)	CO (g/km)	HC (g/km)	NO_x (g/km)	Fc. (l/100km)	Em. Concept
A	23.2	0.61	0.14	7.27	43.5	EGR/Ox.cat
B	18.7	1.43	0.06	10.72	41.9	SCR/Filter
C	23.5	4.50	0.05	3.41	45.6	SCR/Filter

A further calculation of the result from testing the buses on the "bus-route" was carried out and presented in Table 7, below. Instead of presenting the emission results in grams/km (distance specific emissions), the emissions are presented in grams/kilowatt hour (brake specific emissions). Not surprisingly the bus equipped with SCR and with the lowest average exhaust temperature exhibits the highest NO_x emissions. Finally, during the test runs, only less than 20 % of the maximum power of the engine is utilized.

Table 7: Brake specific test results, on-road testing ("Bus-route"), 3 different city buses

Bus	Av. Power (kW)	CO (g/kWh)	HC (g/kWh)	NO_x (g/kWh)	Ex. temp (°C)	Amb temp (°C)
A	19 % of max	0.36	0.08	4.36	318	8.3
B	14 % of max	0.72	0.03	5.39	198	16.2
C	18 % of max	2.33	0.02	1.77	231	7.0

Included in the program for 2007 were also testing of heavy duty trucks. Three vehicles were selected for tests and all equipped with the same basic engine. All trucks were tested in their normal operation and driven by the normal driver and thus not on the same test route. The different applications were:

- Vehicle I, transport of paper, test weight 60 tonnes
- Vehicle II, transport of asphalt, test weight 50 tonnes
- Vehicle III, sludge collection, test weight 15 tonnes (empty vehicle)

The vehicles are certified according to emission requirements for Euro IV and the exhaust emission control system includes a system for EGR (Exhaust Gas Recirculation).

The results presented in Table 8 show the average results from three test runs, except for the sludge collector when only one test run with an empty vehicle was possible. Further, the idle period for the sludge collector (when it is working) is omitted from the results. Based on the results, conclusions can be drawn that emission of NO_x and exhaust temperature is liked to the actual load carried by the vehicles. Emissions of CO and HC seem not that sensitive for the load factor.

Table 8: Brake specific test results, on-road testing, 3 trucks with same basic engine

Truck	Aver. Power (kW)	CO (g/kWh)	HC (g/kWh)	NO_x (g/kWh)	Ex. temp (°C)	Test route (distance/time)
I	42 % of max	0.76	0.15	7.41	268	82 km / 92 minutes
II	47 % of max	0.74	0.09	5.86	236	55 km / 51 minutes
III	26 % of max	0.76	0.15	4.80	167	13 km / 20 minutes

Values from the same measurement as above are calculated as distance specific emissions (g/km) and the results are presented in Table 9. The tendency is still the same with highest NO_x results for the heaviest vehicle. CO emissions are on the same level and with the engine management strategy selected by the manufacturer it seems that CO is not load dependent.

Table 9: Distance specific test results, on-road testing, 3 trucks with same basic engine

Truck	Av. Sp (km/h)	CO (g/km)	HC (g/km)	NO_x (g/km)	Fc. (l/100km)
I	53.7	1.8	0.36	17.9	53.0
II	64.2	1.7	0.20	13.2	43.6
III	38.8	1.6	0.31	11.2	30.3

7. CONCLUSIONS

From the program for years 2006 and 2007 important lessons could be learned that highlights the importance to use PEMS for emission measurement.

- Vehicles/engines often meet set standards when tested according to regulations
- On-road testing with vehicles in normal operation (outside regulated areas) could result in high levels of NO_x
- Emission result (especially for NO_x) will be very different due to design of driving route (highway vs. city driving)
- Special attention must be given to the exhaust temperature, and it seems vital that starting temperature must be the same for good repeatability of the results. In addition also for the performance of aftertreatment device.
- Use of PEMS can easily verify manufacturers strategy for emission control concepts
- PEMS will make it possible to test vehicles in low ambient temperatures
- PEMS is a robust and reliable system for measurement, meeting acceptable criteria for quality and accuracy

8. ACKNOWLEDGEMENT

Without assistance from manufacturer of the tested vehicles, it should not have been possible to carry out the project in the given time frame. Further, some results should not have been possible to reach.

Supplier of the measurement equipment (Sensors Europe GmbH) has been of great assistance by sorting out questions and giving advice about handling of the equipment.

DG JRC have contributed to the program by giving advice how to proceed, make software available for calculation of the results, and last but not least quality assurance of the final results.

Staff at AVL MTC has been of assistance to operate the chassis dynamometer test cell as well as with the adoption of vehicles to fit the measurement equipment.

Finally, we are grateful to Swedish Road Administration for financing the project

9. REFERENCES

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