Evaluation Methods for Real Drive Emission Tests of LDV for a Future Legislation

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Introduction

Severe problems to meet air quality targets for NO_2 and PM10 as well as ambitious targets to reduce greenhouse gas emissions leads to amendments in the emission legislation for passenger cars and light commercial vehicles (LCV).

In the year 2017 a shift from the NEDC to the WLTC test cycle is foreseen. Both, the test cycle as well as the entire test procedure of the WLTP, are much closer to real driving situations than the NEDC. Although known not to be very representative for real driving (e.g. [1]), the NEDC was in place nearly unchanged since 1996.

Due to the shift to the WLTP a better agreement between emission levels in type approval and in real world driving is expected. Nevertheless a test procedure in a defined test cycle always includes the risk, that vehicle emission performance is very much optimised for this test cycle. The introduction of additional “random cycles” in the type approval would eliminate this risk but the fear that vehicles may switch to a low emission mode as soon as they detect that they are running on a chassis dynamometer still remains.

Thus it is foreseen that emissions from passenger cars and LCV have to be tested in type approval also in real world driving via PEMS (Portable Emission Measurement System) from 2017 on. In real traffic the driving situations and boundary conditions vary much, so general valid applications of emission control strategies are necessary to achieve low emission levels under all driving conditions. Unfortunately the variable conditions also lead to quite different emission levels for identical vehicles. Especially the metrics for LDV emissions [g/km] is much more sensitive against variable driving conditions than the metrics for HDV [g/kWh]. In the unit [g/km] the variable specific energy demand to overcome driving resistances [kWh/km] adds a significant variability (road gradients, driver behaviour).

Thus the variability of the test conditions relevant for the emissions has to be considered in the test evaluation to achieve a reasonable reproducibility of test results.

The method for PEMS-evaluation is still under development, so the following just gives an overview on existing options.

Emissions in Real Driving Situations

Figure 1 shows the NOx-emissions from diesel cars in the CADC compared to the emission limits as well as evaluation results from remote sensing test campaigns in different countries. Remote sensing measures the concentration in the exhaust plume for cars passing through the measurement path, thus only the ratio of NO_x to CO_2 can be gained from the measurements. Both data sources show no decrease in real world NO_x-emissions since EURO 1. The EURO 6 limits are met only by a few models yet. Thus the CADC results shown for EURO 6 cars may not be representative for the entire fleet from 2015 on. It can be assumed, that the early EURO 6 cars, which mainly are upper class vehicles, where calibrated to show also good real world emission levels while many models registered when EURO 6 becomes mandatory may perform not that well outside of the NEDC test cycle. Without adaptations in the test procedure the future car fleet may thus again not show much NO_x-reduction in real driving situations.

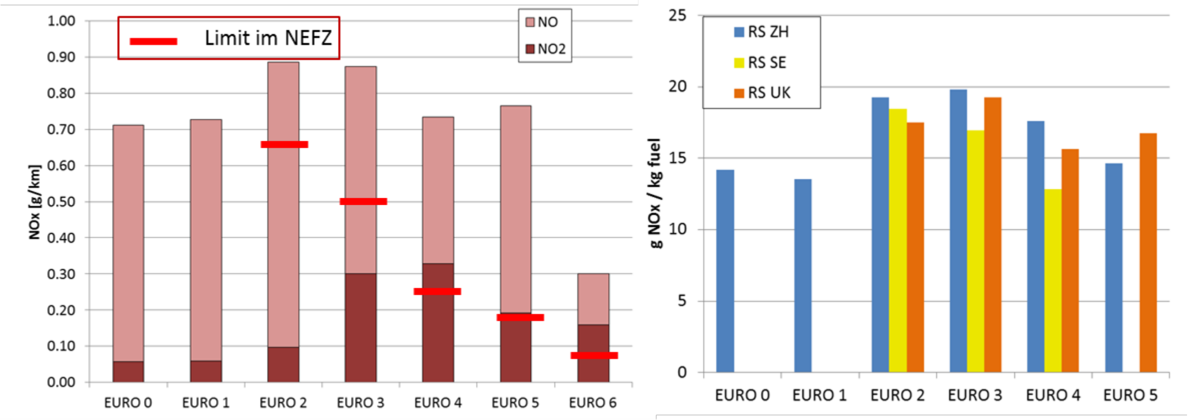


Figure 1: NO_x-emissions from Diesel-cars in real world situations: Left figure: real world chassis dyno cycle CADC (1/3-mix urban, road, motorway), right figure: results from remote sensing campaigns in different countries according to [2] (ZH…Zurich/CH; SE…Sweden; UK…England)

In the CADC the specific cycle work is approx. 0.2 kWh/km; certainly with high variability depending on the vehicle category. The NO_x-emissions from the EURO 5 cars thus are in the range of 4 g/kWh while the tested EURO 6 cars show some 1.5 g/kWh NO_x. In comparison the limits for HDE are 2 g/kWh for EURO V and 0,46 g/kWh for EURO VI.

Beside NO_x-emissions from diesel cars also particle number emissions from DI gasoline engines are a topic for real drive emission tests.

Demands for PEMS-Tests at LDV

For LDV realistic test procedures shall be introduced which ensure that the emission reduction achieved in real world operation is on the same level than in type approval. This is especially relevant for traffic situations with high relevance for ambient air quality. The procedure should carefully balance possible disadvantages in fuel efficiency and vehicle costs against achievable emission reductions.

Prerequisites are that:

1. Emissions in those driving situations, which have high influence on air quality, shall also have high impact on the PEMS test result (these are especially traffic situations with high traffic density)
2. High emissions in a relevant driving situation (e.g. stop & go) cannot be compensated by low emissions in another situation (e.g. cruising at nearly constant speed)
3. Driving situations which occur in reality with a low probability can have higher emission levels than situations which occur frequently to allow most efficient use of emission control technology to improve air quality
4. Emission testing has to be possible also by independent bodies (method shall work without demand of not generally accessible CAN data).
5. Test results shall be reproducible (at least the result if the car is above or below the RDE limits).

To meet 1 to 3 a PEMS-test ideally would have to cover well defined traffic situations with each of them having a representative mileage share and the driver would have to behave in a reasonable mix between normal, eco and sportive driving. Already due to non-existing exact definitions of “traffic situations” and “driver behaviour” this approach is not feasible. In addition suitable routes and ideal drivers will hardly be identified. Thus a combination of pre-defined boundary conditions for the route and for the ambient conditions with an intelligent evaluation method seems to be the most promising approach. The intelligence of the evaluation method should replace the requirement of running “normal driving situations in a representative way”. The method could thus be:

- Define boundary conditions for the PEMS-route (km-shares urban, road, motorway)
- Define boundary conditions for the PEMS-trip (e.g. tolerances for average speed levels)
- Boundaries for valid ambient conditions
- Evaluation of the emissions during the PEMS-trip with a different handling of usual and unusual driving situations.

Influences of the Driver and of the Route

A main problem with on-board emission testing in type approval procedures is the high influence of the driver and of the route. Figure 2 shows the evaluation of 24 different PMES trips. These trips have been driven with different cars. To evaluate driver and route influences, emissions for all trips have been simulated for an average EURO 6 vehicle with the longitudinal dynamics and emission model PHEM, e.g. [2]. Depending on the route and driver combination, the average positive engine power varies between 6 and 13 kW. The variable gradients and velocities between the routes lead to quite variable specific propulsion energy demands [kWh/km]. The NO_x-emissions simulated vary between 150 and 350 mg/km. Such variability seems not to be acceptable for manufacturers (risk to fail with a low emitting vehicle) and also not for the Commission (risk that high emitting vehicles pass due to friendly drivers on easy routes). Thus without proper evaluation methods the RDE behaviour of a car cannot be judged in a reliably way.

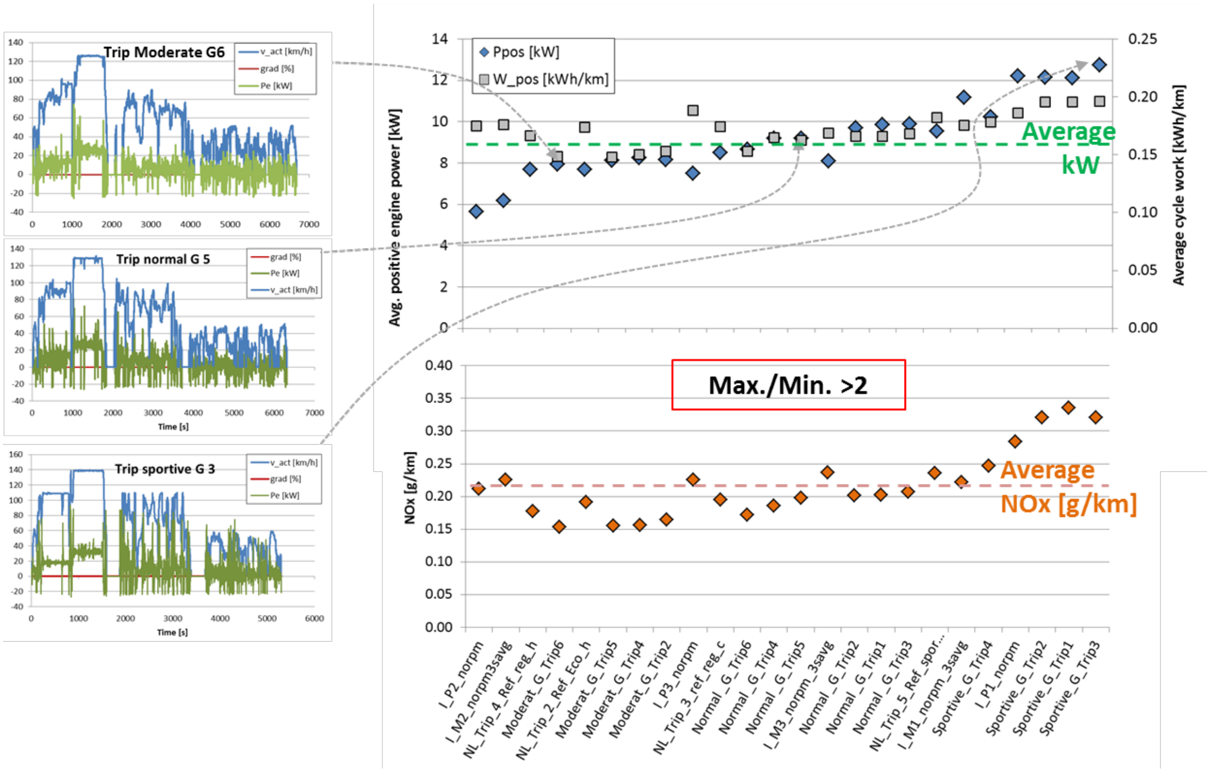


Figure 2: average positive engine power, engine work and NO_x-emissions simulated for 24 trips with the model PHEM for an average EURO 6 car. On the left side the velocity and power trajectories for 3 selected trips on one route are shown

The CLEAR Evaluation Method

To minimise influences of the driver and of the route on the test results three different options for evaluation are compared (EMROAD from DG-JRC, Speed-Binning from TNO and CLEAR from TUG). In the following the method developed by TUG is described. This method is named CLEAR (Classification of Emissions from Automobiles in Real driving) and is based on weighting the measured emissions according to the engine loads driven in the test.

Target of the development was to define the time shares in the engine map of a car resulting from “normal driving”. With such a “target frequency map”, instantaneously measured emissions of a PEMS-trip can be binned into the single engine map cells according to the actual load. Then the average emissions per cell can be weighted with the frequency corresponding to normal driving. This approach allows transforming emissions measured in any driving conditions into a normal load profile as long as all engine map regions relevant for normal driving are covered by the PEMS-trip.

Certainly the absolute values of engine power and of engine speed levels in a normal trip depend very much on the vehicle (mass, air and rolling resistance, gear box,..). To solve this problem a method for normalisation of the engine operating points had to be elaborated which results in a vehicle independent frequency patterns in the engine map. Corresponding analysis started 2012 and yielded interesting results so far.

The analysis of more than 50 cars in different trips showed, that a normalisation of the propulsion power via division by the power the vehicle needs to run in a defined combination of speed and acceleration gives very similar frequency distributions over such a normalised power. This result is very plausible, since cars are floating in the total traffic flow most of the travel time, especially in traffic situations with higher traffic density, which are most relevant for air quality. In these situations all vehicles have similar speed and acceleration patterns. Since the power demand is defined by the driving resistance (vehicle specific air and rolling resistance coefficients) and the power demand for acceleration (vehicle specific mass), the power demand of vehicles at similar speed and acceleration levels can be normalised by dividing by a vehicle specific driving power. The driving situation for normalisation just needs to have a balanced share between influence of mass, air- and rolling resistance. The best compromise was found at a speed from 70 km/h and an acceleration of 0.45 m/s². The power demand of a vehicle in this situation is called here P_{drive}. The mass and the driving resistance values to compute the power demand are taken from the type approval settings of the vehicle at the chassis dynamometer.

$$P_{drive} = v_{ref} * [m_{ref} * a_{ref} + R_0 + R_1 * v_{ref} + R_2 * v_{ref}^2]$$

With R_0, R_1, R_2 .... road load coefficients [N], [Ns/m], [Ns²/m²]

m_{ref} .... test mass of the vehicle in the NEDC [kg]

a_{ref} .... reference acceleration [0,45 m/s²]

v_{ref} .... reference velocity [19,4 m/s], i.e. 70 km/h

The normalisation of the power simply is done with a division by P_{drive}:

$$P_{norm} [-] = P_e [kW] / P_{drive} [kW]$$

Figure 3 and Figure 4 show the frequency distribution for different trips of different vehicles in one picture over absolute engine power and in another picture over normalised power. Figure 3 shows examples from the data base on WLTP-short-trips, where neither the route nor the driver is known. For validation of this data set a test campaign at TU Graz was performed where three quite different vehicles were driven by different drivers in very different driving styles on the same route with 87 km length. After normalisation with P_{drive} all trips where the drivers stated “normal” driving behaviour show very similar frequencies in the normalised power bins. Aggressive trips show higher shares in higher engine power bins while eco-driving leads to higher shares in lower power bins (Figure 4). Also the low influence of the rated engine power was confirmed by the data evaluation. The share of time driven in high power ranges is low, even for the BMW. This is also plausible since high power is used only if the driver can accelerate freely. At high power the acceleration time is rather short. So in total even high powered vehicles show less than 1 % time share in power bins with P_{norm} > 3.5.

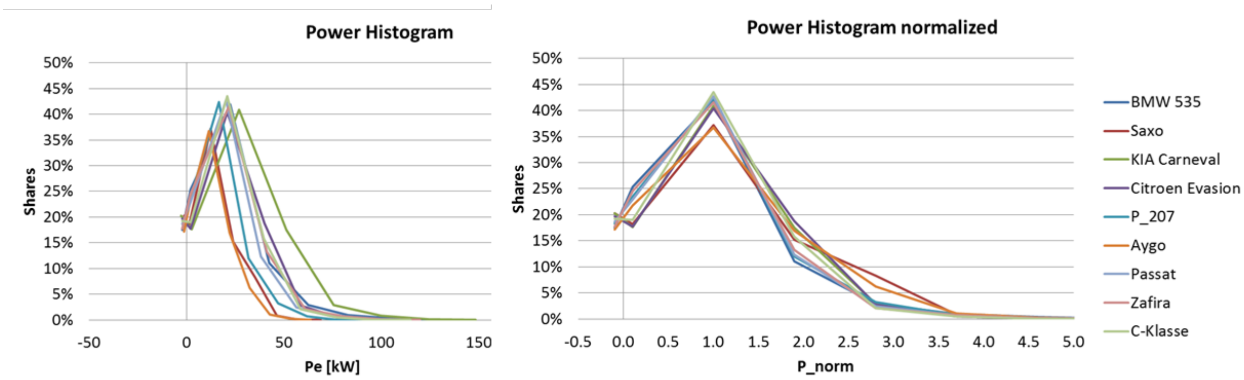
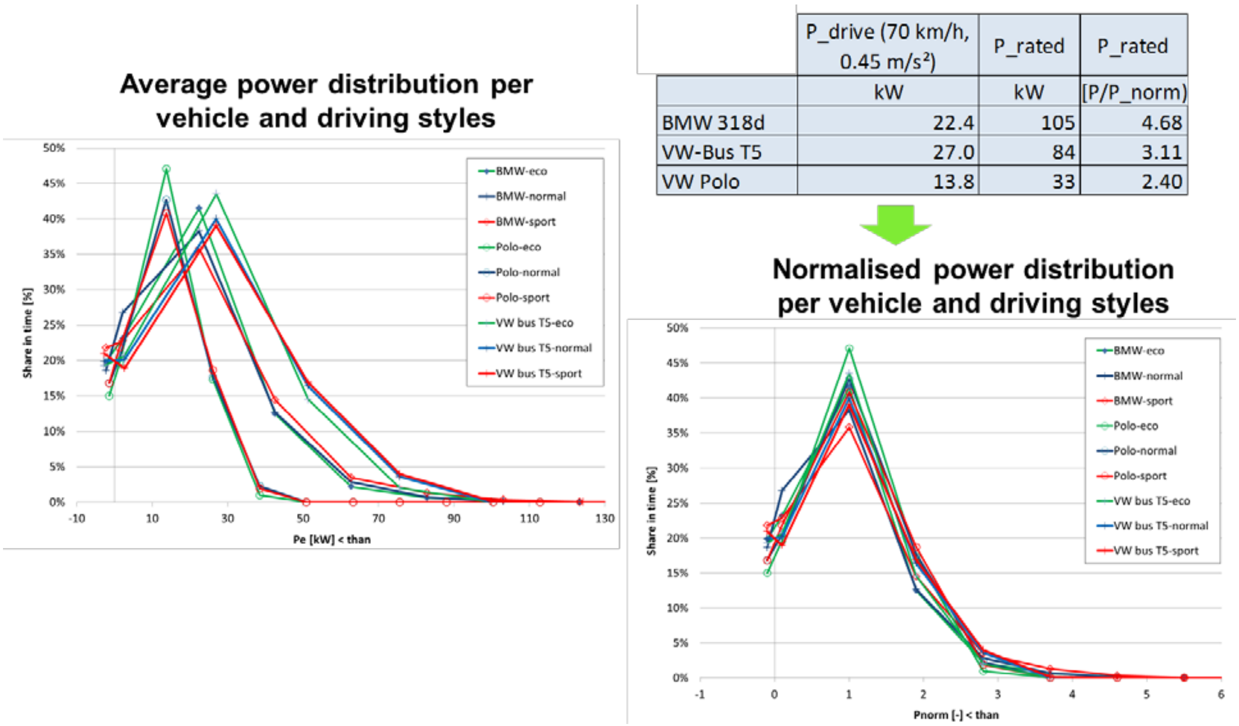


Figure 3: frequency of power demand levels in trips from different vehicles from the WLTP-Short-Trip-data-base (containing different routes and different drivers) left figure: plotted over absolute power, right figure: plotted over normalised power



	P_drive (70 km/h, 0.45 m/s²)	P_rated	P_rated
	kW	kW	[P/P_norm)
BMW 318d	22.4	105	4.68
VW-Bus T5	27.0	84	3.11
VW Polo	13.8	33	2.40

Figure 4: frequency of power demand levels in trips from different vehicles from tests at TU Graz (all on the same route but with different drivers) left plotted over absolute power, right over normalised power.

The driving data from 40 cars from the WLTP-short-trip-data base has been used to set up the target frequencies for the normalised power bins („Target Power Pattern" in Figure 5) which shall represent typical normal driving.

In a CLEAR evaluation first the Target Power Pattern is de-normalised for the tested vehicle by multiplication of the normalised power on the x-axis with the vehicle specific P_{norm}–value. Then the highest power bins are adapted to the vehicles rated power. Then 3 second moving averages of the instantaneous emission signals are sorted into the power bins according to the actual power at the wheels. Then in each power bin the average emission value is calculated which is finally weighted with the frequency of this bin in the Target Power Pattern. The sum of the weighted emissions per bin is the total emission result in [g/h]. The vehicle speed is then binned and weighted similarly to the emissions giving the weighted average speed [km/h]. The final test result is simply gained from dividing [g/h] by [km/h]. With this method any PEMS-trip is converted into a trip with a "normal" power distribution.

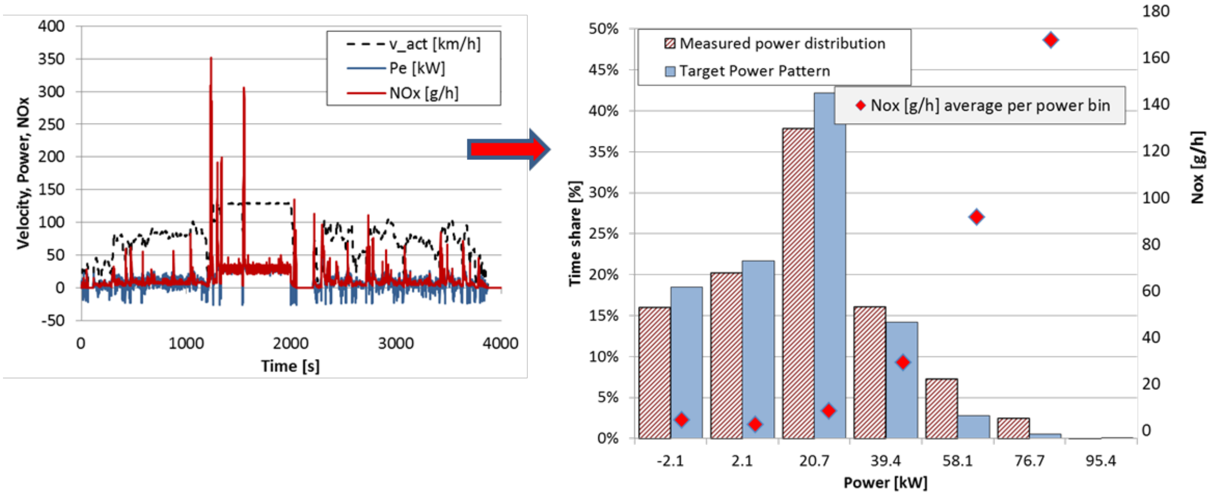


Figure 5: Schematic picture of the CLEAR Method for PEMS-evaluation

CO_2 based method

To overcome the problem to get access to a high quality power signal from the CAN by independent test labs, a method was developed to calculate the power at the wheel hubs from the instantaneous signal of measured CO_2-emissions. The method makes use of the well-known “Willans-Lines” which show the fuel consumption of an engine as function of the engine power for constant engine speed levels what typically results in a quite straight line over a wide range of the engine load.

Here we use a vehicle specific Willans-Line, which plots the CO_2-emissions over the average positive power at the wheel. To do so, either the 2 phases of the NEDC or in future the 4 phases of the WLTP can be used. If only hot starts are tested in PEMS, the phases 2, 3 and 4 from the WLTP shall be used if not an extra hot start test is available. Figure 6 shows as example the result of a EURO 6 car.

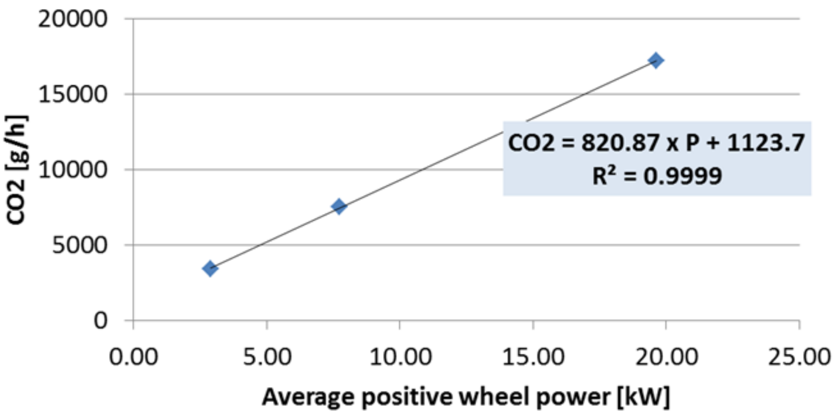


Figure 6: Willans-Line calculated from a chassis test of a EURO 6 diesel car

With the Vehicle-Willans-Parameters as input, CLEAR calculates from the 1 Hz CO_2-signal the power as follows:

1) Input D and k from Willans Line (CO_2 [g/h] = D + k x Power [kW])
   Which results in: Power [kW] = (CO_2 [g/h] – D) / k
2) Set power at wheel hubs to zero when vehicle speed is zero (idling cannot be identified exactly by the Willans Function)

Then the usual CLEAR evaluation goes ahead using calculated power instead of a measured one. The method proved so far to give sufficiently accurate power trajectories to apply the CLEAR method.

Examples for Evaluation Results

Figure 6 compares the NO_x-emissions from three cars for the PEMS-trips already shown in Figure 2. The emissions of the cars again have been simulated with the model PHEM. The generic cars have following background:

- A generic low NO_x car, which combines the best NO_x levels of all EURO 6 cars tested at TU-Graz (lowest value taken per engine map cell)
- An average of the tested EURO 6 cars
- A generic high NO_x car, which combines the worst NO_x levels of all EURO 6 cars tested at TU-Graz (highest value taken per engine map cell)

The simulated NO_x-emissions in the PEMS-trips show large overlapping between the different vehicles where the NO_x levels of the lower emitting vehicle are higher in demanding cycles than the NO_x levels of the higher emitting vehicle in less demanding cycles. After application of the CLEAR evaluation the overlapping disappears. The still higher emissions at sportive driving styles result from the higher engine speed levels at these trips, which are not influenced by the normalisation method. For future complying vehicles a reasonable NO_x reduction efficiency will be demanded also at engine speeds above the NEDC levels. However, a check if the engine speed distribution is in a normal range by the evaluation method could be useful and is tested at the moment. Due to the different gear box types it proved so far, that a “normalised engine speed pattern” which is valid for all cars cannot be set up. As alternative the WLTC gear shift rules may serve to define a “normal range”. Beside the engine speed also the distribution of driving dynamics are analysed (distribution of the positive changes of the power within 3 seconds over the cycle). A comparison of the dynamics with a “normal level” could secure that the driver is not acting too aggressive or too stationary for normal driving.

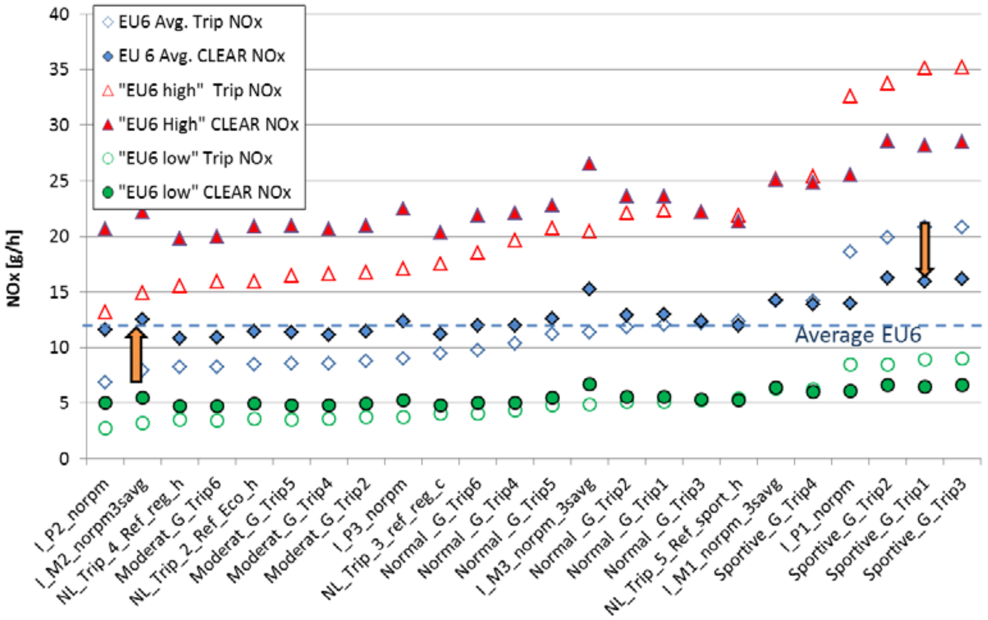


Figure 7: NO_x-emissions simulated for three different EURO 6 cars in 24 different PEMS-trips with different routes and driving styles comparing trip average emissions with results after evaluation with the CLEAR-method

The evaluation results are available from CLEAR also separated to urban, road and motorway parts oft he trip. A separate evaluation avoids the possibility to compensate high emissions in one road category (e.g. urban) by low emissions in another category (e.g. cruising at 110 km/h on the highway).

The evaluation methods are systematically tested since November 2013 with sets of real PEMS-tests. Results are expected before summer 2014.

Beside the development of the evaluation method also further efforts to optimise PEMS-equipment to reduce size and weight and to increase safety in operation.

Summary and Outlook

To On-board-emission-measurement with PEMS is a new component to control RDE emissions from cars and LCV. The test procedure aims mainly at reducing diesel NO_x-emissions, which did not drop since EURO 1 legislation. The alternative option of introducing random test cycles on the chassis dynamometer is discussed at the moment only as fall back option for particle number testing if no sensors are available for on-board operation in the near future.

Which evaluation method shall be applied to the PEMS-test-results from LDV is open yet. The CLEAR method presented here is well in line with the demands:

1. The weighting of the measured emissions with frequencies of different power demand bins representing normal driving ensures, that driving situations important for air quality have high influence on the test results
2. A separate evaluation of urban, road and motorway ensures that the vehicles have to show in all road categories low emission levels.
3. The weighting of emissions according to real world frequencies of power demands ensures that technologies for emission control are selected which then also show good efficiency in real driving.
4. The CO_2-based power calculation ensures, that the tests can be maintained also by independent labs.
5. The power distribution at the wheel of a vehicle in normal driving is independent of the propulsion technology used, thus also hybrids and other alternative vehicles can be evaluated with this method. In cases the CO_2-method does not work sufficiently to determine the wheel power, a torque meter rim may be used to obtain independent and accurate power signals.

Further optimisations oft he method based on the experiences gained from the evaluation of many PEMS-tests are under development.

7. Literature

[1] Melios G. et. al.: Parameterisation of fuel consumption and CO_2 emissions of passenger cars and light commercial vehicles for modelling purposes; EMISIA SA Report No: 10.RE.005.V1; for DG-JRC; 2010

[2] Hausberger S., Rexeis M., Kühlwein J., Luz R.: Emission Factors from the Model PHEM for the HBEFA Version 3.2.; TU-Graz, Institute for Internal Combustion Engines and Thermodynamics; 09. 2013

[3] Hausberger S., Furian N.: Options for an RDE measurement methodology for LDV; 9th Diesel Emissions Conference & AdBlue Forum Europe 2013; 18th-20th June, Düsseldorf, Germany