Testing and evaluating real driving emissions with PEMS

Testing of real driving emissions (RDE) with portable emission measuring system (PEMS) in an appropriate road circuit became an obligatory element of new type approval of passenger cars since September 2017. In several projects the Laboratory for Exhaust Emissions Control (AFHB) of the Berne University of Applied Sciences (BFH) performed comparisons on passenger cars with different PEMS’s on chassis dynamometer and on road, considering the quality and the correlations of results. Particle number measuring systems (PN PEMS) were also included in the tests.

The present paper informs about influences of E85 on RDE on two flex-fuel-vehicles, discusses some aspects of different ways of evaluation with different programs, shows comparison of different types of PN PEMS and represents the effects of simulation of slope on the chassis dynamometer.

Key words: RDE evaluation, RDE with Ethanol, PN PEMS, simulation of slope and normality of RDE results.

1. Introduction

Measurement of Real Driving Emissions (RDE) becomes since this year (2017) an element of legal homologation procedure for passenger cars WLTP (Worldwide Harmonized Light-Duty Vehicles Test Procedure) [1–3]. This new procedure will enforce for new cars (introduced to the market since this year), that there will be no discrepancy between the emissions and fuel consumption values obtained in the homologation tests and in real application [4, 5].

Unlike previous vehicle emission tests, para-meters such as engine load and vehicle speed are no longer defined by a fixed pattern, but are largely determined by the traffic situation, driver behavior and the course of the route during the RDE test. [6–8].

There are new requirements and challenges for all market participants: the industry has to adapt the R&D processes of engines, [9–11]; the measuring technics, including PN PEMS are continuously improved and developed, [12, 13] and the official testing laboratories and organisations perform intense research activities in order to increase the knowledge, the experience and to adapt the testing capacities to the new requirements, [4, 5, 7, 8, 14].

In this interesting dynamic situation of progress AFHB performs several test & research projects, or working packages. Some of the recent results are presented in this paper. Several countries have objectives to substitute a part of the energy of traffic by ethanol as the renewable energy source and some manufactures introduced the FFV (Flex-Fuel Vehicles) variants and published extensive information about their R&D and performances: GM/Saab [15, 16]; Toyota [17]; VW [18]. The RDE with two FFV’s and especially with E85 were investigated in the present work.

2. Test installation

2.1. Chassis dynamometer

Parts of the tests were performed on the 4WD-chassis dynamometer of AFHB (Laboratory for Exhaust Emission Control of the Bern University of Applied Sciences, Biel, CH). The stationary system for regulated exhaust gas emissions is considered as reference. This equipment fulfils the requirements of the Swiss and European exhaust gas legislation.

- regulated gaseous components: exhaust gas measuring system Horiba MEXA-7200 CO, CO₂, infrared analysers (IR) HC_FID...flame ionization detector for total hydrocarbons CH₄_FID...flame ionization detector with catalyst for only CH₄ NO/NOₓ...chemiluminescence analyzer (CLA)
The dilution ratio DF in the CVS-dilution tunnel is variable and can be controlled by means of the CO₂-analysis. The measurements of summary particle counts in the size range 23–1000 nm were performed with the CPC TSI 3790 (according to PMP).

For the exhaust gas sampling and conditioning a ViPR system (ViPR...volatile particle remover) from Matter Aerosol was used. This system contains:

- Primary dilution – MD19 tunable rotating disk diluter (Matter Eng. MD19-2E)
- Secondary dilution – dilution of the primary diluted and thermally conditioned sample gas on the outlet of evaporative tube.
- Thermoconditioner (TC) – sample heating at 300°C.

2.2. GAS PEMS and PN PEMS

An information about the used Horiba Gas PEMS and about the gas measuring installation of the chassis dynamometer is given in Table 1.

As PN PEMS for Real Driving Emissions two systems were used and compared:

- NanoMet3 from TESTO (NM3). This analyzer works on diffusion charging (DC) principle, has an integrated sample conditioning system, as described above for chassis dynamometer and it indicates the solid particle number concentration and geometric mean diameter in the size range 10–700 nm.
Horiba OBS-ONE PN measurement system (OBS-PN). This analyzer works on the condensation particles counter (CPC) principle, has an integrated sample conditioning system (double dilution and catalytic stripper ViPR, 350°C) and it indicates the summary PN concentrations in the size range 23 to approximately 1000 nm.

Both systems present several advantages like compactness, robustness, fast on-line response and both are recognized for legal testing purposes.

| HORIBA MEXA 7200                  | HORIBA OBS ONE                |
|---------------------------------|-------------------------------|
| 4x4 chassis dyno                | PEMS                          |
| CVS                             | wet                           |
| CO                              | NDIR                          |
| CO₂                             | heated NDIR                   |
| NO₅                             | CLD                           |
| NO                               | CLD                           |
| NO₂                             | calculated                    |
| O₂                               | calculated                    |
| HC                               | FID                           |
| PN                               | not measured                  |
| OBD logger                      | yes                           |
| GPS logger                      | yes                           |
| ambient (p, T, H)               | yes                           |
| EFM                             | pitot tube                    |

Table 1. Overview of used measuring systems

OBS - one H₂O monitored to compensate the H₂O interference on CO and CO₂ sample cell heated to 60°C

3. Test procedures

3.1. Driving cycles on chassis dynamometer

The vehicles were tested on a chassis dynamometer in the dynamic driving cycle WLTC, Fig. 1.

For the research about „slope” a part of real world cycle (like in Fig. 2) was reproduced on the chassis dynamometer.

For the research with different fuels important objective was to always keep the same procedure of changing the fuel quality. The fuel change was performed at the day preceding the tests. The fuel tank was emptied and filled with the new fuel. Than the vehicle was pushed on the chassis dynamometer, cold-started and driven in one WLTC as conditioning. Than the vehicle stayed on the chassis dyno until the next test-day.

The braking resistances were set according to legal prescriptions; they were not increased i.e. responded to the horizontal road.

3.2. On road testing

In order to reach the validity according to the actual requirements several road tests were performed. Finally, the used valid road circuit was always the same with approximately 1.5 h duration and parts of urban, rural and highway roads. Figure 2 represents an example of a road trip from the PN PEMS test program.

3.3. Test vehicles and fuels

The tests were performed with two Euro 5 flex fuel vehicles: Volvo V60 (GDI) and Audi A4 TFSI (GDI).

Both vehicles were equipped with PEMS and tested on-road with E0 & E85. Fig. 3 shows the vehicles in laboratory and Table 2 gives the most important data.

Table 2. Data of tested vehicles

| Vehicles                      | Volvo V60 T4F FFV gasoline (V1) | Audi A4 2.0 TFSI FFV gasoline (V2) |
|-------------------------------|----------------------------------|-------------------------------------|
| Number and arrangement of cylinder | 4 in line                        | 4 in line                           |
| Displacement cm³              | 1596                             | 1984                                |
| Power kW                      | 132 @ 5700 rpm                   | 132@4000 rpm                        |
| Torque Nm                     | 240 @ 1600 rpm                   | 320@1500 rpm                        |
| Injection type                | Direct injection (DI)            | Direct injection (DI)               |
| Curb weight kg                | 1554                             | 1570                                |
| Gross vehicle weight kg       | 2110                             | 2065                                |
| Drive wheel                   | Front-wheel drive                | Front-wheel drive                    |
| Gearbox                       | a6                               | m6                                  |
| First registration            | 2012                             | 2010                                |
| Exhaust                       | Euro 5a                          | Euro 5                              |
3.4. Fuels

The gasoline used was from the Swiss market, RON 95, according to SN EN228. For the tests a charge of fuel was purchased to keep always the unchanged chemistry.

As a further variants of fuels E10 and E85 were used. These are respectively blends with: 90% v gasoline and 10% v Ethanol, or with 15% v gasoline and 85% v Ethanol. The blend fuels were prepared on the basis of E85 purchased on the Swiss market.

Table 3 summarizes the most important parameters of the fuels.

| Parameter                  | Gasoline | Ethanol C₂H₅OH | E10 | E85 |
|----------------------------|----------|----------------|-----|-----|
| Density 15°C [g/cm³]       | 0.737    | 0.789          | 0.742| 0.781|
| Stoichiometric air/fuel ratio | 14.6 | 9.0 | 14.0 | 9.8 |
| Lower calorific value [MJ/kg] | 43.0 | 26.8 | 41.3 | 28.9 |
| Boiling point [°C]         | 30-200   | 78.5           |     |     |
| Research octane nbr. [-]   | 95       | 110            |     |     |
| Latent heat of evaporation [kJ/kg] | 420 | 900 |     |     |
| Oxygen content [%m]        | < 5      | 34.8           |     |     |

4. Results and discussions

4.1. Ethanol blend fuels

Figure 4 represents the comparisons of average emission values from the operation with gasoline, E10 and E85 in WLTC warm. These results are averages of 2 cycles. The warm-up procedure was always by means of a preliminary cold started WLTC.

The particle counts emissions are generally significantly reduced with Exx (more than 1 order of magnitude).

CO-emissions are clearly reduced with increasing Exx-content. For NOₓ no regular tendencies with E10 & E85 are visible. Nevertheless, this is strongly dependent on the electronic control of this FFV and the indicated differences of few [ppm] can also be an effect of emitting dispersion.
4.2. Evaluations with EMROAD

Research of data evaluation was performed with the objective to indicate the influences of different evaluation ways on the results and their relationships.

All this research was performed for both vehicles, but only with the data from gasoline operation.

Figure 9 shows an example of comparisons of results NO\textsubscript{x} & CO in one of three RDE-attempts with both vehicles. The results are evaluated with EMROAD MAW-method (moving averaging windows) and with integration (integral average values). The cold start results are considered, or excluded (as cold start & warm-up are considered, either the period from engine start to reach 70°C coolant temperature, or a time period in maximum 5 min).

The integral values (INT) indicate higher emissions (NO\textsubscript{x} & CO) with cold start, than without cold start; this for both vehicles in the entire cycle and in the urban part. This is a usual very well-known result.

The MAW-method in contrary indicates much smaller differences “with/without cold start” for vehicle V2 and for vehicle V1 even lower CO- and NO\textsubscript{x}-values with cold start. The main reason for that is in the weighing and validation of the windows (MAW). Additionally, it must be remarked that the absolute values of the CO- and NO\textsubscript{x}-emissions are very low and the differences “with/without cold start” are insignificant.

4.2.1. Influence of weighing and validation on RDE results

The characterization of normality and completeness of a RDE trip is graphically represented in Fig. 10.

The “normality” of the windows is concluded by comparing their CO\textsubscript{2} distance-specific emissions with a reference curve. The test is complete when the test includes enough normal windows, covering different speed areas (urban, rural, motorway).
The reference dynamic conditions of the test vehicle are set out from the vehicle CO₂ emissions versus average speed measured at type approval (WLTC) and referred to as “vehicle CO₂ characteristic curve”.

During the MAW evaluation the following steps are performed:

Step 1 Segmentation of the data
Step 2 Calculation of emissions by sub-sets or “windows”
Step 3 Identification of normal windows
Step 4 Verification of test completeness and normality
Step 5 Calculation of emissions using the normal windows.

The following data are not considered for the calculation of the CO₂ mass, the emissions and the distance of the averaging windows:

- the periodic verification of the instruments and/or after zero drift verifications
- the cold start emissions previously excluded are included in evaluation since September 2017
- vehicle ground speed < 1 km/h
- any section of the test during which the combustion engine is switched off.

In Fig. 11 such CO₂ characteristic curves are represented for two of three evaluated trips of vehicle V1. The trips and their dynamic conditions are not entirely normal, since the characteristic curves are exceeding the primary tolerance of ±25% (of the average WLTC-CO₂-values).

The operation of this vehicle V1 in the urban part (at lowest speeds) is not dynamic enough and the program sets for these windows weighting factors WF < 1. At the highest speeds, there are also windows passing over the primary tolerance, because of not sufficient engine load. (The maximum speed on Swiss highway is limited to 120 km/h and...
In the present work the results of all evaluation methods (INT/MAW/PB) were compared in 3 RDE tests with and without cold start. Figure 12 gives an example of this comparison in one of the performed tests. For the same test, there is a dispersion of NOₓ- and CO-results in the scattering band of approximately ±7%.

The results with consideration of cold start are with INT & PB higher, than without cold start. For MAW-method the weighing factors of a non-valid cycle cause the lower emissions with cold start (see previous section).

Fig. 13 shows the distribution of power classes and the NOₓ/CO-emissions per class in the three RDE-trips. It can be remarked that the power class distribution, is very well repetitive, while the emissions (here especially in the test “RDE2”) can scatter considerably.

Summarizing: both methods EMROAD and CLEAR have similar but not identical results. In the last amendment to Euro 6 including RDE4 (March 2018) was stated, that the results of both evaluation methodologies were not consistent enough and the CLEAR methodology was deleted.

4.4. Simulation of slope on chassis dynamometer

Sometimes in the research activities, the on-road driving cycle is registered and reproduced on the chassis dynamometer. A simulation of slope in WLTC with constant slope (+/- 2%) in the entire cycle was performed in [19]. An increase of CO₂ & NOₓ with increased slope and no influence of slope on PN were found.
In the present work, a part of the RDE-cycle with mostly variable altitude, approximately 8 min. was selected, Fig. 14. The variable slope in this “sub-cycle” was programmed in the chassis dynamometer control system and the tests with this sub-cycle were performed on the vehicle V1. The performance of such a cycle needs a certain preparation and increased attention of the driver.

Figure 15 shows the average results with/without slope simulation, obtained with both systems: GasPEMS and bags (CVS). The slope simulation yields higher values of CO, CO$_2$ & fuel consumption, the NO$_x$-values nevertheless are not influenced. Both measuring systems indicate similar absolute values of results.

4.4.1. Comparisons of PN-PEMS

During the investigations with simulation of slope following PN measuring systems were included with sampling at tailpipe (TP): CPC, NM3 and OBS-PN (see explanations in section 2).

Figure 16 shows the average results of 5 trials with/without slope simulation. Both PN-PEMS indicate nearly the same PN-values but both systematically slightly lower, than CPC-readings. NM3 shows a higher dispersion of results.

The simulation of slope has no influence on the PN emissions.
5. Conclusions
Following conclusions can be mentioned:

5.1. E0 & E85
• The use of E85 fuel is advantageous for emission reduction: with E85 there is reduction of NO\textsubscript{x} and PN for both investigated vehicles in all driving conditions.
• The volumetric fuel consumption with E85 is generally higher, due to the lower heat value of this fuel.
• Both vehicles attain similar levels of emissions at the end of RDE cycle, while the dispersion of results for each vehicle/fuel variant is much larger than on the chassis dynamometer (in WLTC).

5.2. Evaluations with EMROAD
• The normality and weighing of the windows have an influence on the final emission results and the characteristic curve of the trip (CO\textsubscript{2} vs. speed) is recommended to be inside of the primary tolerance band of ±25% with WF = 1.

5.3. EMROAD vs. CLEAR
Both methods of evaluations of results EMROAD and CLEAR have similar but not identical results. The CLEAR methodology was deleted in the last version of RDE legislation (March 2018).

5.4. Slope and PN-PEMS
• The slope has an impact on emissions of CO and CO\textsubscript{2} (fuel consumption) and it should be considered during the reproduction of RDE driving cycles on the chassis dynamometer.
• Nanoparticle emissions are principally independent on slope.
• Both investigated PN PEMS working with different measuring principles (DC vs. CPC) indicate nearly the same PN-values.

Nomenclature

| Abbreviation | Description |
|--------------|-------------|
| AFHB         | Abgasprüfstelle FH Biel, CH |
| ASTRA        | Amt für Strassen (CH) |
| BAFU         | Bundesamt für Umwelt, (Swiss EPA) |
| CD           | chassis dynamometer |
| CLA          | chemiluminescence analyser |
| CLD          | chemiluminescence detector |
| CLEAR        | RDE evaluation program from TUG with PB |
| CPC          | condensation particle counter |
| CVS          | constant volume sampling |
| DAQ          | data acquisition |
| DC           | diffusion charging |
| DF           | dilution factor |
| DI           | Direct Injection |
| DiSC         | diffusion charge size classifier |
| E0           | gasoline (zero Ethanol) |
| E85          | 85% vol. Ethanol |
| EC           | European Commission |
| ECE          | Economic Commission Europe |
| ECU          | electronic control unit |
| EFM          | exhaust flowmeter |
| EMROAD       | RDE evaluation program from JRC with MAW |
| GDI          | gasoline direct injection |
| GMD          | geometric mean diameter |
| HC           | unburned hydrocarbons |
| INT          | integral average values |
| JRC          | Joint Research Centre (EC) |
| LFE          | laminar flow element |
| MAW          | moving averaging windows |
| MFS          | mass flow sensor |
| NM3          | NanoMet3 |
| NO           | nitrogen monoxide |
| NO\textsubscript{2} | nitrogen dioxide |
| N\textsubscript{2}O | nitrous oxide |
| NO\textsubscript{x} | nitric oxides |
| n.v.         | non-valid |
| OBD          | on-board diagnostics |
| OBS-ONE      | Horiba Gas PEMS |
| OBS-PN       | Horiba PN PEMS |
| OP           | operating point |
| PB           | Power Binning |
| PEMS         | portable emission measuring systems |
| PMP          | EC Particle Measuring Program |
| PN           | particle number |
| PN-PEMS      | PEMS with PN measuring device |
| RDE          | real driving emissions |
| TC           | thermoconditioner |
| TFZ          | Technologie- und Förderzentrum für Nachwachsende Rohstoffe, Straubing, D |
| TP           | tailpipe |
| TUG          | Technical University Graz |
| TWC          | three way catalyst |
| V1           | vehicle 1 |
| V2           | vehicle 2 |
| ViPR         | nanoparticle sample preparation with volatile particles remover |
| WLTC         | worldwide harmonized light duty test cycle |
| WLTP         | worldwide harmonized light duty test procedure |
| 3WC          | three way catalyst |

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