Real Driving Emissions of Passenger Cars – Examples of Testing and Evaluating

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Abstract

Since September 2017, 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. Toxic exhaust emissions and their control still remain one of the major problems faced by road transport.
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, shows influence of payload for a heavy car with trailer and presents RDE of a HEV in different operating modes. This combined look on different vehicle technologies allows the comparisons of these technologies, but first of all it gives information about the potentials and limits of the used measuring procedures and tools.

The most important conclusions are:

E0 & E85

- The use of E85 fuel is advantageous for emission reduction: with E85 there is reduction of NO_x and PN for both investigated vehicles in all driving conditions.
- 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).

Payload/trailer

- Higher payload increases the cumulated emissions of CO, HC, NO_x and PN.

HEV

- The investigated hybrid vehicle confirmed a very efficient and intelligent control of energy management, of engine parametrization, as well as very low emission values.

Introduction

Testing of Real Driving Emissions (RDE) became since 2017, an element of legal homologation procedure for passenger cars WLTP (Worldwide Harmonized Light-Duty Vehicles Test Procedure), [1, 2, 3]. This new procedure will enforce for new cars (introduced to the market since September 2017), that there will be no intentional discrepancy between the emissions and fuel consumption values obtained in the homologation tests and in real application, [4, 5].

Unlike previous vehicle emission tests, parameters 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, 7, 8].

There are new requirements and challenges for all market participants: the industry has to adapt the R&D processes of engines, [9, 10, 11]; the measuring technics, including PN PEMS are continuously improved and developed, [12, 13] and the official testing laboratories and organizations 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]. In the present work, RDE with different fuels and vehicle technologies were investigated offering some new interesting insights in the results, as well as in the testing methodology.

Test installation

Chassis dynamometer test cell

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.
The regulated gaseous components are measured with exhaust gas measuring system Horiba MEXA-7200; CO, CO_2 … infrared analysers (IR); HC_{FID} ... flame ionization detector for total hydrocarbons; CH_{4FID} ... flame ionization detector with catalyst for only CH_4; NO/NO_x ... chemiluminescence analyzer (CLA).

The dilution ratio DF in the CVS-dilution tunnel is variable and can be controlled by means of the CO_2-analysis.
The measurements of summary particle counts in the size range 23-1000nm 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.

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. NM3 was used for the tests with Ethanol blend fuels.
- 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 sumamry PN concentrations in the size range 23 to approximately 1000 nm. This system was used in the tests with increased payload and with hybrid vehicle.

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

Table 1. Overview of used measuring systems.

	HORIBA MEXA 7200	**HORIBA OBS ONE**
	4x4 chassis dyno CVS	PEMS① wet
CO	NDIR	heated NDIR
CO_2	NDIR	heated NDIR
NO_x	CLD	CLD
NO	CLD	CLD
NO_2	calculated	calculated
O_2	-	-
HC	FID	-
PN	not measured	-
OBD logger	-	yes
GPS logger	-	yes
ambient (p, T, H)	yes	yes
EFM	-	pitot tube

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

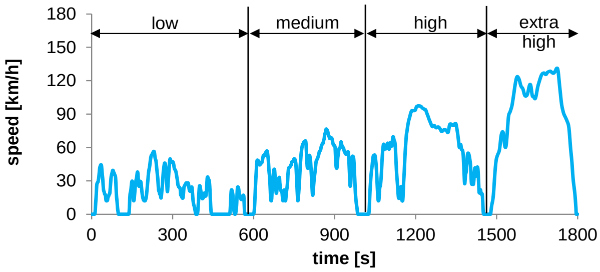


Figure 1: WLTC driving cycle

Test procedures

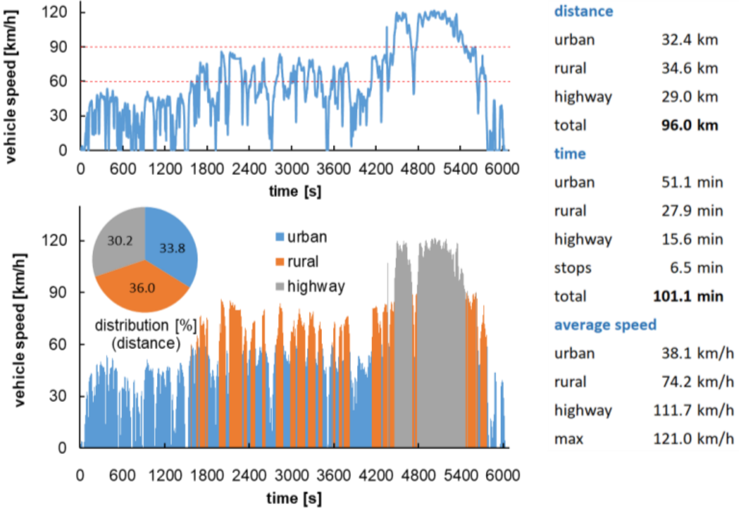
Driving cycles on chassis dynamometer

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

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 (table values ECER83); they were not increased i.e. responded to the horizontal road.

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 1.5h duration and parts of urban, rural and highway roads. Fig. 2 represents an example of a road trip from the PN PEMS test program.



distance	
urban	32.4 km
rural	34.6 km
highway	29.0 km
total	**96.0 km**
time	
urban	51.1 min
rural	27.9 min
highway	15.6 min
stops	6.5 min
total	**101.1 min**
average speed	
urban	38.1 km/h
rural	74.2 km/h
highway	111.7 km/h
max	121.0 km/h

Figure 2: AFHB, road trip for RDE

Test vehicles and fuels

The tests with Ethanol blend fuels 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)**	**DODGE RAM 2500 HDV Diesel (V3)**	**Toyota Prius III gasoline (V4)**
Number and arrangement of cylinder	4 in line	4 in line	6 / in line	Engine gasoline 1.8L DACT 16-valve with multipoint injection of 98 hp, naturally aspirated, variocam-Atkinson
Displacement cm^3	1596	1984	6.690	Electric engine of 80 hp
Power kW	132 @ 5700 rpm	132@4000 rpm	260@2800 rpm	Total power: 136 hp
Torque Nm	240 @ 1600 rpm	320@1500 rpm	1085@1600 rpm	Max. torque: 142 Nm
Injection type	Direct Injection (DI)	Direct Injection (DI)	Direct Injection (DI)	-
Curb weight kg	1554	1570	3690	Curb weight: 1500 kg
Gross vehicle weight kg	2110	2065	4200	-
Drive wheel	Front-wheel drive	Front-wheel drive	Four-wheel drive	-
Gearbox	a6	m6	a6	Gearbox: continuously variable transmission
First registration	2012	2010	2015	-
Exhaust	EURO 5a	Euro 5	Cal. LEV III/EGR, DPF, SCR	Anti-pollution standard : Euro 5b, 3WC, EGR

The tests with increased payload (with a trailer) were performed with a Dodge Ram 2500 Diesel and for the tests of a hybrid vehicle a Toyota Prius III (gasoline) was used. Fig. 4 represents these vehicles and Table 2 summarizes their most important data.

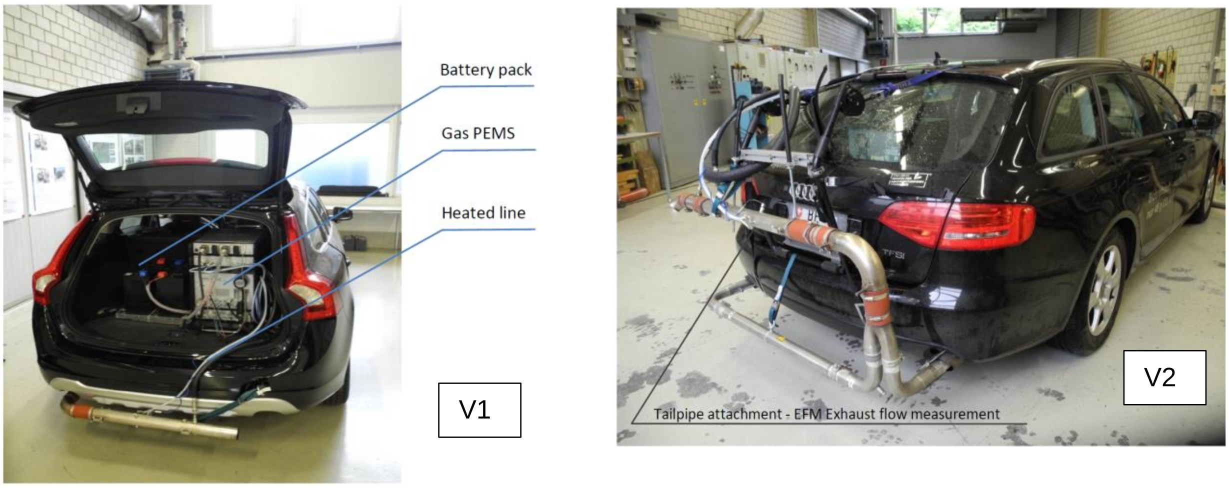


Figure 3: Tested vehicles (FFV) equipped with PEMS

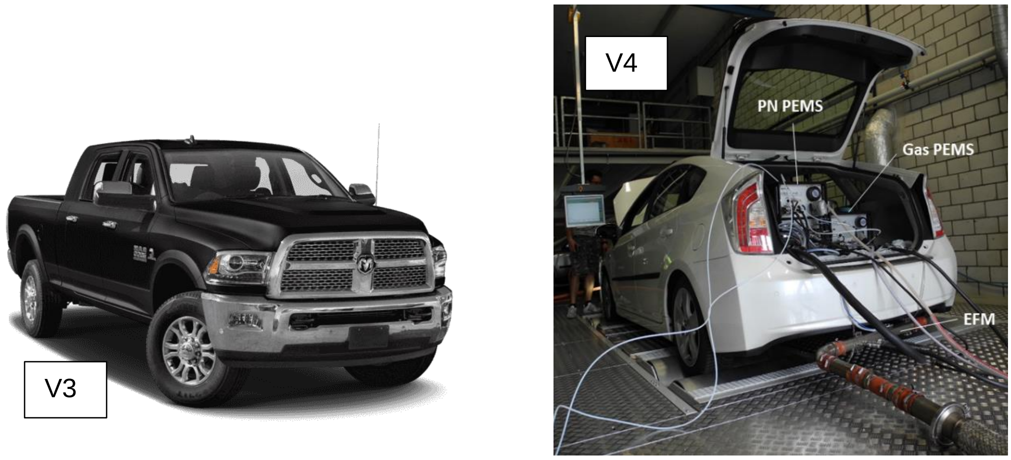


Figure 4: Tested vehicles V3 and V4 equipped with PEMS

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.

Table 3: Parameters of used fuels

		Gasoline	Ethanol C_2H_5OH	E10	E85
density 15°C	[g/cm^3]	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		

For the Diesel vehicle (V3) a Swiss market Diesel fuel, according to SN EN590 was used.

Results and discussions

Ethanol blend fuels

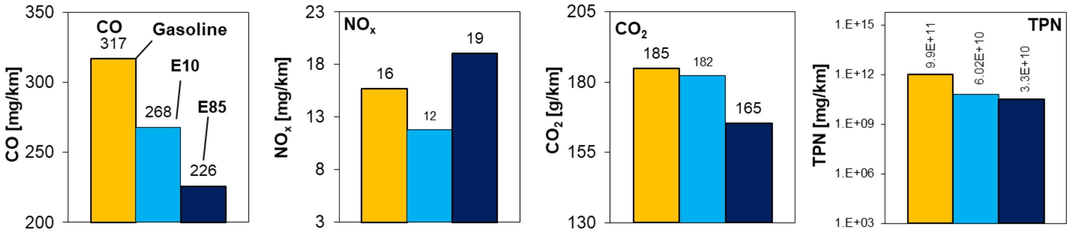


Figure 5: Emissions in WLTC warm, with gasoline E10 & E85 V1: Volvo V60 T4F, 3WC

Fig. 5 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 NO_x 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.

With each vehicle three RDE tests were performed with E0 and E85. Figures 6, 7, 8 and 9 show the cumulated results of NO_x, PN, CO_2 and CO. The tendencies are similar as in WLTC:

- E85 instead of E0 reduces significantly NO_x-emission; there is a certain dispersion of results, but this tendency is clearer than in WLTC and it is similar for both vehicles,
- PN is strongly reduced with E85 for both vehicles, which confirms the previous experiences on chassis dynamometer with vehicle V1,
- E85: CO_2 is only slightly reduced with V1 and more clearly with V2,
- E85: CO is not reduced with V1 but clearly reduced with V2 – it can be remarked that the acceleration events, very often in the last high-speed part of the cycle, can significantly contribute to the increase of cumulated emission.

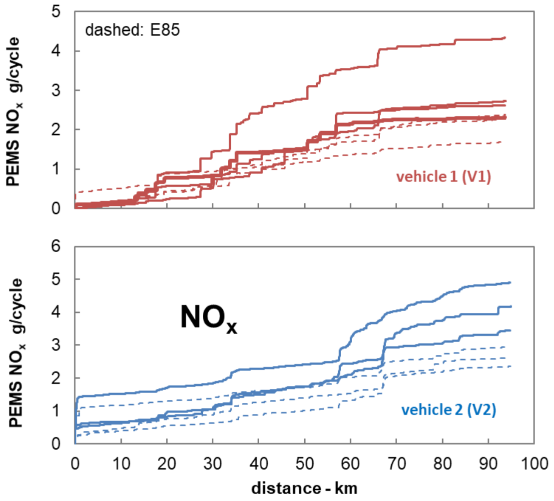


Figure 6: NO_x - Emissions during RDE with E0 and E85; Volvo V60 Flexfuel (V1); Audi A4 Flexfuel (V2)

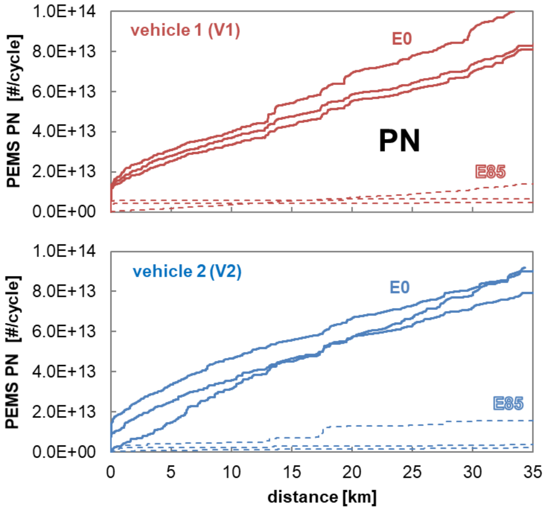


Figure 7: PN – Emissions during RDE urban part with E0 and E85; Volvo (V1); Audi (V2)

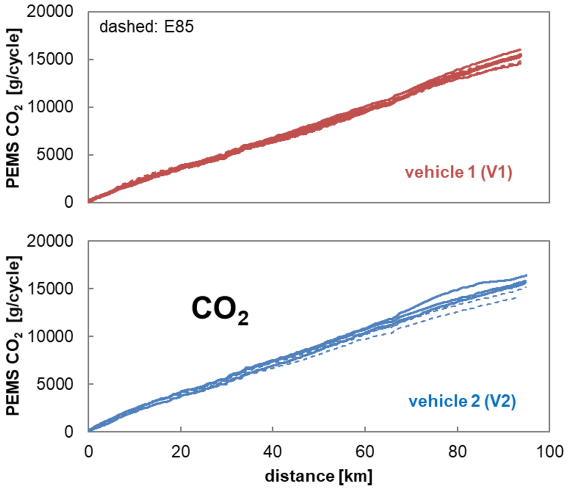


Figure 8: CO_2 – Emissions during RDE with E0 and E85; Volvo (V1); Audi (V2)

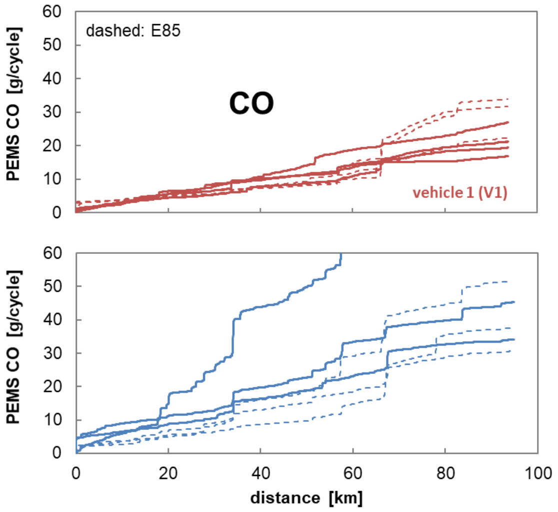


Figure 9: CO – Emissions during RDE with E0 and E85; Volvo (V1); Audi (V2)

Emissions with different payload

This part of tests was performed on the vehicle V3; Dodge Ram 2500 Diesel. In Switzerland, this vehicle is registered as a HDV since its total weight is higher than 3500 kg. The on-road testing of this vehicle for RDE is carried out, according to the procedures and on the test circuit for LDV's. This vehicle is strongly motorized with the weight/power ratio 15-30 kg/kW, comparing to usual HDV's (30t) with 40-90 kg/kW.

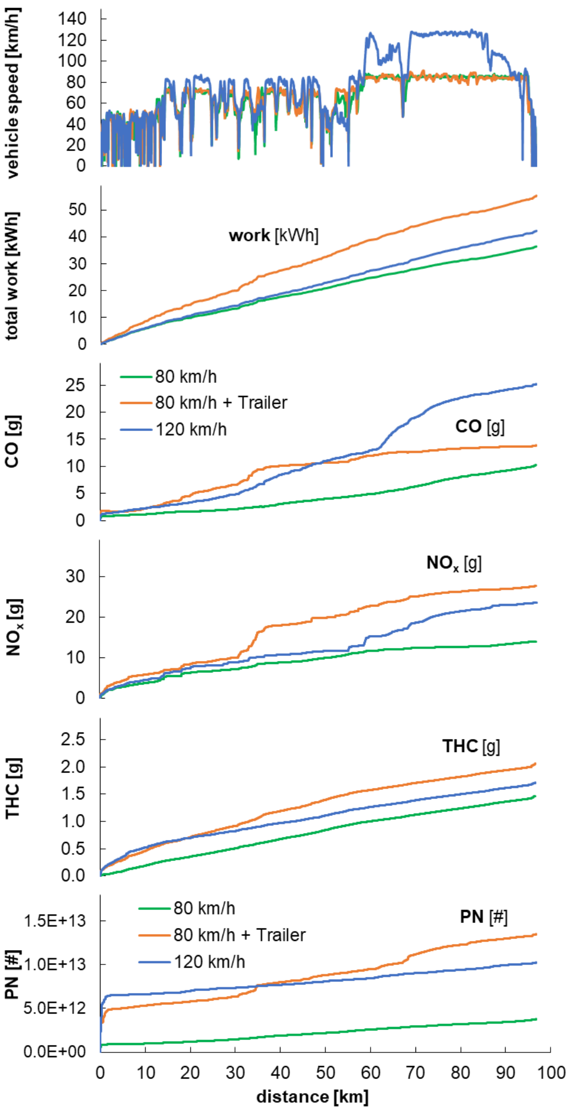


Figure 10: Influences of maximal speed and playload on real driving emissions, Dodge Ram, (V3)

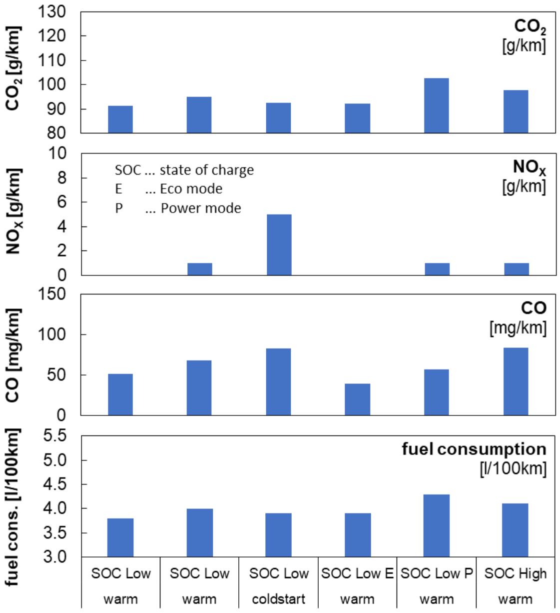


Figure 11: Integral emissions measured with PEMS in the RDE – Tests, Toyota Prius III, (V4)

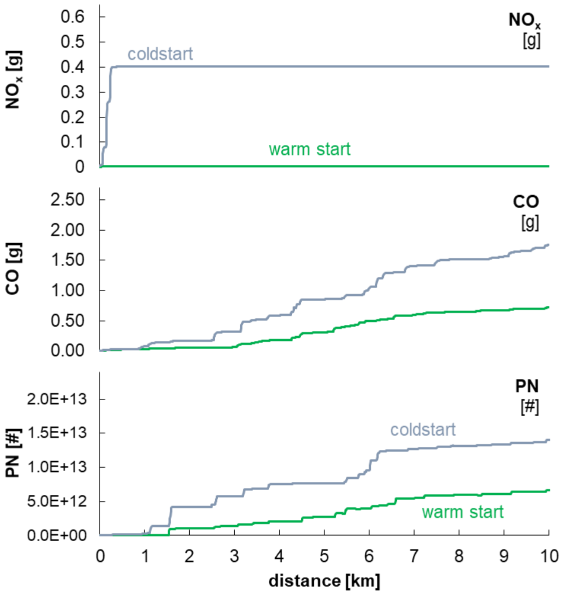


Figure 12: RDE in urban part cold / warm cumulated emissions in the RDE - Tests, Toyota Prius III, (V4)

One of the validity criteria of the windows, the MAW evaluating method for HDV's, is that the windows with average power bigger than 10% (since 2018) of a maximum engine power are recognized as valid and are considered for the calculation (according to the EU-regulation Nbr. 582/2011, Annex II). In the case of this highly motorized vehicle, only a little part of windows arrives to average power > 10%, so the NO_x emissions would be very much underestimated or even zero in some cases. It results, that this vehicle does not adapt to the HDV-regulation either.

In Fig. 10 are given the comparisons of total work of engine operating collectives and of cumulated emissions for three cases:

1. driving on the RDE circuit with maximum speed of 80 km/h
2. driving on the RDE circuit with maximum speed of 80 km/h + a trailer with 3.5t
3. driving on the RDE circuit with maximum speed of 120 km/h

The cold start (summer) was included in the tests and results. It can be summarized for the changes of the operating conditions: higher maximum speed or higher payload, that both of them increase the cumulated emissions of CO, HC, NO_x and PN.

RDE of A HEV

This section presents some results obtained with HEV Toyota Prius III (Euro 5), V4 on chassis dynamometer and on-road. This vehicle offers to the driver the choice between different modes of driving behaviour: "Normal", "Power" or "ECO" and also a limited possibility of electric driving "EV" or battery charging "B". This working package compares the emissions with different state of charge (SOC) of the batteries pack and with different driving modes. It also gives some insights in the control of strategies (EGR, throttle) of this vehicle.

Fig. 11 shows the results of some performed RDE-tests. Regarding the cycles with "SOC_{low}, warm start" a good repeatability of results can be stated.

Influence of SOC

The state of charge (SOC) of the batteries pack of this vehicle is indicated by the OBD. Depending on temperature of batteries and different other parameters the SOC is maintained by the system between approximately 40% and 80%.

The lowest SOC can be caused by driving the vehicle in electric (E) mode up to the point when the engine is started. The highest SOC can be obtained by motoring the vehicle on the chassis dynamometer (CD). After performing the driving cycles, the final SOC results in the range of about 60%. With higher SOC the probability of electric driving and the frequency of engine switch off/on increase. The effect of this is visible in WLTC (not represented here), where the test with "SOC_{high}" indicates lower CO_2 and lower fuel consumption. The emission of CO is tendentially higher than the average of cycles with "SOC_{low}". Nevertheless, the differences are small, and they are in the dispersion range of the repeated cycles with "SOC_{low}". In RDE-tests (Fig. 14), there is no tendency of lower fuel consumption with "SOC_{high}", this, because the higher SOC influences mostly the urban driving, which represents only a part of the RDE cycle. CO-values with "SOC_{high}" are similar to the values with "SOC_{low} cold start" and they are at the upper limit of the dispersion range.

The emissions of NO_x and CO are for this vehicle very low, so the indicated differences can be regarded as insignificant.

Further tendencies

It can be remarked, Fig. 12, that the cold start is the mayor reason for the increased NOx-emissions (still the absolute values of NO_x are very low). The cumulated values of all measured toxic compounds (NO_x, CO and PN) were increased with the cold start. The CO-emissions with cold start are on the upper limit of the dispersion range of all cycles. The use of driving mode "Power" (+P) shows the tendency of higher fuel consumption, but the emissions are in the usual dispersion range of all cycles. Driving in mode "Economy" (+E) does not cause any particular differences. Finally, it can be said that this tested vehicle has very low emissions and fuel consumption and that these values are only slightly influenced by different modes, such as SOC, Power, Economy and cold start.

EGR and NO$_x$- control

The strategy of Toyota uses the EGR as an important measure to reduce NO$_x$-emissions in addition to the 3WC-technology and use of variocam-Atkinson-cycle. The EGR-valve is electrically driven, which enables a quick and precise control.

Fig. 13 shows the functionality of EGR-valve opening in the initial phase of the RDE-test with cold start.

Several parameters, like: vehicle speed, engine speed, coolant temperature, catalyst temperature, battery SOC, load factor, EGR control and Lambda are registered from the engine ECU.

During the warm-up (first 1.2 km) EGR stays closed. After that it is controlled according to the events with running engine and with higher engine load, with lean operation. The lean Lambda-excursions, when the 3WC cannot reduce NO$_x$, result from engine switching off/on. The engine speed zero-value indicates, that the engine is switched-off quite often.
The engine switching strategy, sometimes lean engine operation and EGR offer very low fuel consumption and low, near-to-zero NO$_x$-emissions.
The openings of EGR-valve coincide in most cases with the peaks of CO & PN.

The analysis of vehicle stops, and engine stops revealed that the vehicle stops, in the urban part of RDE-test, are in the range between 10% and 15% of the total cycle time and the engine works between 39% and 59% of the total cycle time. In the operating mode “Power”, there is the highest portion of the “engine on time”.

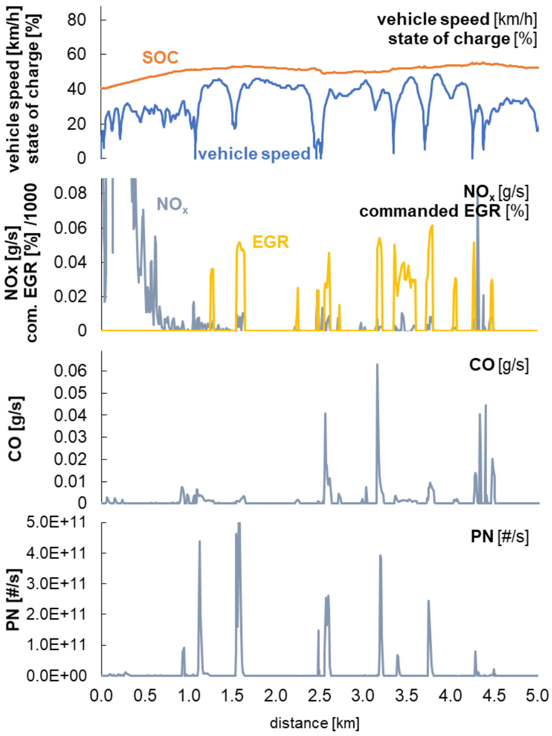


Figure 13a: Influence of EGR on NO$_x$, CO & PN; example RDE cold, (no 11), urban part, Toyota Prius III, (V4)

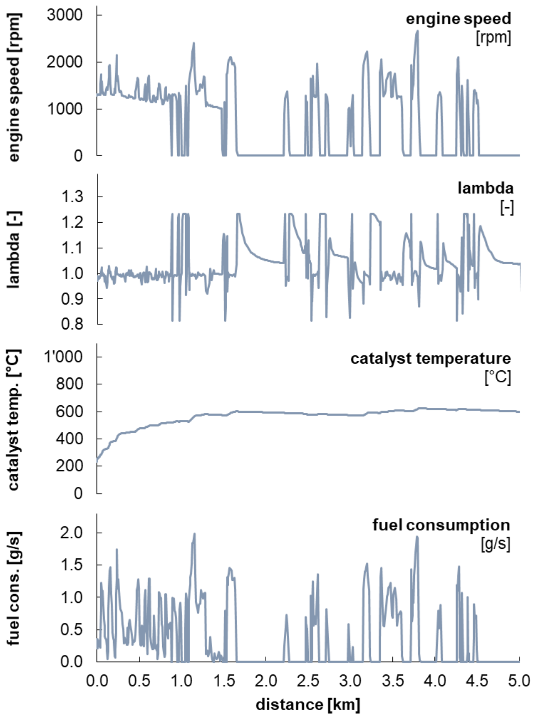


Figure 13b: ECU engine operating parameters in the RDE cycle cold, (no 11), urban part, Toyota Prius III, (V4)

Positions of accelerator vs. throttle

Fig. 14 shows the correlations of throttle positions and accelerator positions for different modes of vehicle operation. These values are extracted from the OBD. It can be commented that in the mode “Eco”, more accelerator pedal action is necessary to obtain a certain opening of the throttle valve. Inversely, in the mode “Power”, the throttle opening reacts more sensibly on the accelerator positions. It can be concluded that this way of throttle control underlines or supports the subjective attitude of the driver.

Battery pack charging

Tests of battery pack charging were performed by means of motoring the vehicle on chassis dynamometer.
Two tests were driven in mode "D" (normal driving) and one test in mode "B" (braking, battery charging).

Fig. 15 represents the used speed profile, the resulting engine speeds and SOC. In mode "B", the charging progress is much quicker, and the engine speed is stronger increased to promote the charging. In mode "D", the battery charging is slower and when SOC attains c.a.50% the engine is stopped and due to the motoring (by CD) the SOC continues to increase slowly.
By the attempts of discharging the battery pack on CD, it was observed that at SOC around 40% the engine is automatically started to recharge the batteries and attaining nearly SOC 50% the engine switch-off and the electric driving are again enabled.
The SOC of this vehicle can vary between 40% and 80%.

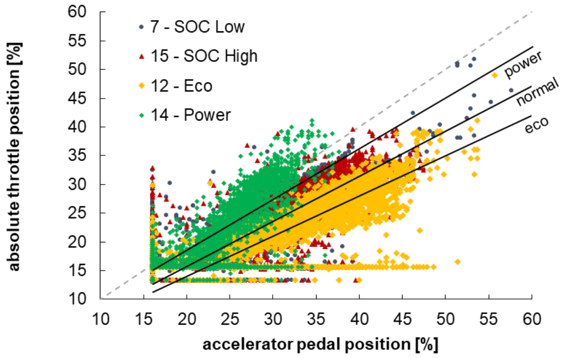


Figure 14: Distribution of throttle vs. accelerator positions in different driving modes, (no 7, 12, 14, 15), Toyota Prius III, (V4)

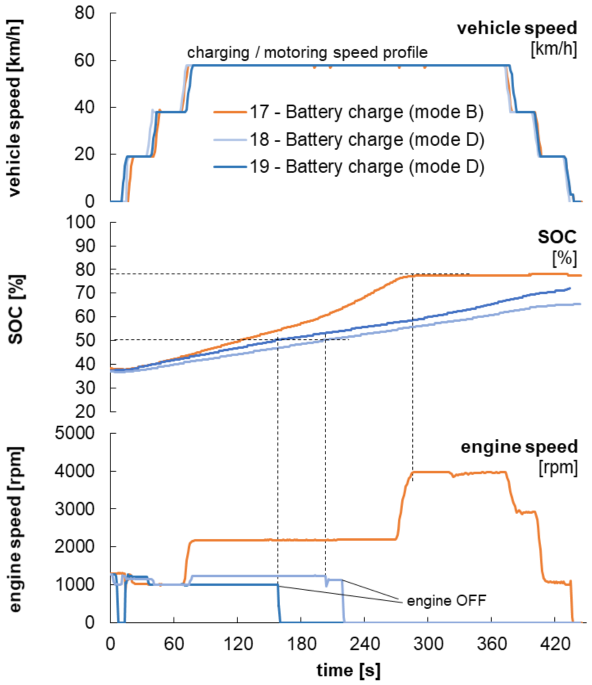


Figure 15: Attempts of battery charging in modes "B" (Brake) and "D" (Drive), chassis dynamometer in motored mode, Toyota Prius III, (V4)

Conclusions

Following conclusions can be mentioned:

E0 & E85

- The use of E85 fuel is advantageous for emission reduction: with E85 there is reduction of NO$_x$ 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).

Payload/trailer

Higher maximum speed, or higher payload increase the cumulated emissions of CO, HC, NO_x and PN.

HEV

- There is a good repeatability of results obtained with PEMS on the chassis dynamometer and on-road.
- Depending on temperature of batteries and different other parameters the SOC is maintained by the system between approximately 40% and 80%.
- The tested vehicle has very low emissions and fuel consumption and these values are only slightly influenced by different modes, such as SOC, Power, Economy and cold start.
- There are: higher CO- and NO_x-emissions at cold start and higher fuel consumption in the driving mode "Power".
- A rapidly controlled EGR is an important measure to reduce NO_x-emissions in addition to the 3WC-technology and variocam-Atkinson-cycle.
- The engine switching strategy, sometimes lean engine operation and EGR offer very low fuel consumption and low, near-to-zero NO_x-emissions.
- The openings of EGR-valve cause often CO- and PN-peaks.
- In the real world driving on the RDE-circuit the engine works between 39% and 59% of the total cycle time, with the highest share in driving mode "Power".
- In the driving modes "Power" or "Economy", there are different control strategies of throttle position versus accelerator position, which support the wish of the driver.
- The maximal charging of the battery pack, up to SOC ~80%, is possible only in the operating mode "B".

Acknowledgement

The authors express gratitude to the Swiss Federal Offices for Environment (BAFU) and for Roads (ASTRA) for the financial support of these activities.

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Abbreviations

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
CPC	condensation particle counter
CVS	constant volume sampling
c/w	cold/warm
DC	diffusion charging
DF	dilution factor
DI	Direct Injection
E0	gasoline (zero Ethanol)
E85	85% vol. Ethanol
EC	European Commission
ECE	Economic Commission Europe
ECU	electronic control unit
EFM	exhaust flow meter
EGR	exhaust gas recirculation
EMROAD	RDE emissions evaluation program
GDI	gasoline direct injection
GMD	geometric mean diameter
HC	unburned hydrocarbons
HD	heavy duty
HDV	heavy duty vehicle
HEV	hybrid electric vehicle
INT	integral average values
LDV	light duty vehicle
LFE	laminar flow element
MAW	moving averaging windows
MFS	mass flow sensor
NM3	NanoMet3
NO	nitrogen monoxide
NO_2	nitrogen dioxide
N_2O	nitrous oxide
NO_x	nitric oxides
OBD	on-board diagnostics
OBS-ONE	Horiba Gas PEMS
OBS-PN	Horiba PN PEMS
OP	operating point
PEMS	portable emission measuring systems
PF	Pitot flow meter
PMP	EC Particle Measuring Program
PN	particle number
PN-PEMS	PEMS with PN measuring device
RDE	real driving emissions
SOC	state of charge
TP	tailpipe
TWC	three way catalyst
V1-V4	vehicle 1 – vehicle 4
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 catalys