

On-road Emissions and Fuel Economy of Light Duty Vehicles using PEMS: Chase-Testing Experiment

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ABSTRACT

Portable Emissions Measurement Systems (PEMS) represent a robust and accurate solution to study the in-use emissions of combustion engines. The application of PEMS is now ranging from large engines to the smallest light-duty vehicles. The current commercially available PEMS exhibit measurement performances that are close to the ones of laboratory grade systems; when PEMS data are analysed with an adequate method, the test results allow a detailed insight into the on-road emissions performance of the vehicles with respect to their behaviour on the standard laboratory test cycles. The development of representative test cycles, which has become a typical approach in the last years, supposed to address special driving situations, now becomes less efficient because of the effort needed for their development and the poor representativeness of the results. In this light, PEMS testing offers an easy and efficient way to evaluate the vehicle emissions over a huge variety of conditions.

This paper presents the on-road gaseous emission measurements of two light-duty diesel vehicles (Fiat Scudo 2 litre and VW T5, 2.5 litre) tested simultaneously with PEMS on the same routes including urban, extra-urban (rural) and highway during chase experiments. The vehicle absolute emissions and fuel economy is reported. The real-world emission results are analysed with an averaging window approach based on CO₂ mass emission; this to provide a first qualitative insight on the variability of exhaust emissions from compression ignition combustion engines under real-world conditions. The investigation and methodology applied show much higher emissions values for real world data compared to the standard laboratory test cycles. The comparison of vehicle emissions and fuel economy performance allows an insight into the variability of emission behaviour under constant boundary conditions.

INTRODUCTION

In the effort to reduce overall emissions, the understanding of the emissions from transport gains more importance. A relevant step is represented by passing from standardized test cell procedures to the emission during real world driving. Thus the key lies in the on-board measurement during vehicle operation.

In terms of the European type approval a standard test procedure is indispensable to allow for repeatability and reproducibility of the test conditions, thus accommodating the need of reliable approval across Europe. Unfortunately, the result of the standardized procedure cannot reliably represent the fuel consumption and the emissions during the real world operation of the vehicle. Moreover, the development of representative test cycles from real world activity data, which has become a typical approach, supposed to address representative driving situations, has always been difficult for the policy maker because of the effort needed.

Portable Emission Measurement Systems (PEMS) represent a robust and one of the most accurate solutions to study the emissions of combustion engines during their real operation on road. In addition, PEMS are a cost effective solution to perform in-use emissions testing of large combustion engines from heavy-duty vehicles (HDVs) or non-road applications, as evidenced by the respective elements in the European [1, 2, 3] and US [4] legislation. The application of PEMS to Light Duty Vehicles (LDVs) remains outside the regulatory field but has also started.

One of the main objectives in the on-going official programs [5, 6] is to understand what the LDVs consume and emit under real-world driving conditions as opposed to the controlled laboratory conditions from the official driving cycles. As the performance of PEMS is sufficient to characterize the engine emissions even at relatively low levels, these systems offer an easy and effective solution to measure emissions from LDVs on the road. Following the studies of the recent years, today, PEMS are applied to a wide range of vehicles from large HDVs to small LDVs. The current commercially available PEMS

exhibit measurement performances that are close to the ones of laboratory grade systems [7]. Laboratory experiments conducted on the chassis dynamometer with LDVs using both laboratory instrumentation (Horiba 7400 series) and PEMS instrumentation in parallel showed very good agreement between the two and have been reported [7].

Analyzing PEMS data with an adequate methodology gives a detailed insight into the on-road emissions behavior of the vehicles with respect to their behavior over the standard laboratory test cycles. In this light, PEMS testing offers an easy and efficient way to evaluate the vehicle emissions over a variety of conditions.

The scope of the present paper is to present insight into real world emission measurements from LDVs using PEMS. Chase testing experiments have been conducted with two LDVs on different test routes including urban, rural and highway driving in the Milan area. Chase in this context refers to two vehicles following each other (the chaser and the chasing car), thus driving the same route and encountering the same operating conditions; both vehicles are equipped with identical PEMS and follow each other at a quasi-constant time interval in order to obtain the same operating speed profiles and have their respective exhaust gases characterized. This approach is different from what has been generally identified with chase in the literature where a lab vehicle follows a first vehicle and measures the plume of the vehicle in front [8, 9].

The paper presents the on-road gaseous emission measurements of two diesel vehicles: Fiat Scudo 2 litre (chased car) and VW T5, 2.5 litre (chasing car) tested simultaneously with PEMS over highway, rural and urban routes. The vehicle absolute emissions and fuel economy are reported.

In this paper, a methodology is proposed to study the emissions behavior of LDVs under real-world conditions with respect to their emissions on conventional or custom chassis dynamometer test cycles. This is based on an averaging window approach based on the CO₂ emissions of the particular vehicle over the standard NEDC cycle; this to provide a first qualitative insight on the variability of exhaust emissions from compression ignition combustion engines under real-world conditions.

The averaging window approach based on a CO₂ mass does not aim at developing representative driving cycles, or at obtaining representative emissions data, but rather at providing a qualitative insight on the variability of exhaust emissions under real-world conditions, using emissions data collected with PEMS. In particular, the present paper aims at evaluating the feasibility and applicability of the method to different vehicles on similar test routes; 'chase testing' is used to compare the emissions and the fuel consumption of two vehicles tested under nearly identical real-world conditions.

STANDARD DRIVING CYCLES

The current European type approval testing of regulated tailpipe emissions (type I) is described in Directive 98/69/EC, further amendments in 2002/80/EC. The type I test cycle, also known as MVEG (Motor Vehicle Emissions Group) cycle was modified in year 2000 to NEDC (New European Drive Cycle), when the initial 40 seconds idling phase was included in the exhaust gas sampling. The type I test cycle consists of an urban drive cycle (ECE15) that is repeated four times, followed by an extra-urban drive cycle (EUDC). The NEDC speed profile is shown in Figure 1.

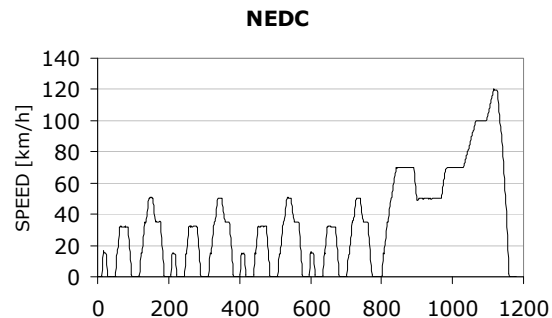


Figure 1: New European Driving Cycle (NEDC).

Prior to certification the vehicle has to soak for at least 6 hours at a temperature of 20-30°C. From 2000 onwards (Euro 3) no idling period is allowed, meaning that the emission sampling begins once the engine starts up. The main characteristics of the NEDC are listed in comparison to the US FTP-75, the Japanese JTC cycle and the ARTEMIS "real world" driving cycle in Table 1.

Emissions are usually sampled using a full flow dilution tunnel (CVS) and the total emissions are expressed in g/km for each of the regulated pollutants. Type approval testing of LDVs is done under controlled environmental conditions using a reference driving cycle (New European Drive Cycle, NEDC). For LDVs certification testing, the boundary conditions are well known and consequently there might be a risk that engines are developed in such a way that emissions are optimized at lower speed and fuel consumption optimized at higher speed. As a consequence the real world emissions and fuel consumption of LDVs may significantly differ from those measured during the laboratory test cycles. Several critical studies of the NEDC cycle have already been reported [10, 11]. The main weakness to the NEDC is due to its very smooth acceleration profile according to [10]. The engine uses only a very small area of its operating range and to fulfil the emission test engine manufacturers only have to focus on these zones [11]. More details on the standard NEDC and on the development of a driving cycle based on portable activity monitoring systems (PAMS) work in the Milan area was reported in a previous publication [7]. PAMS were used to collect the most significant emission-related engine

parameters, such as vehicle speed and position, engine speed and load, lambda sensor signal, intake air and engine coolant temperatures etc., to generate a representative cycle for Milan city driving (Milan city cycle) by using PAMS fitted on Fiat Scudo diesel vehicles running on different urban test routes downtown Milan. Main characteristics of the Milan city cycle compared to the NEDC are reported in Table 2. Tests carried out both in the laboratory and on road with PEMS showed higher exhaust emissions for the Milan city cycles compared to the standard NEDC [7]. Many studies have been conducted in order to address a “typical real traffic conditions”. Numerous studies were conducted to build up driving cycles in different contexts [13] and to demonstrate their strong influence on pollutant emissions [14, 15]. Different cycles have been proposed in the literature as a more suitable substitute to the NEDC from the Artemis [16, 17, 18] to the MOL cycle [19, 20].

Table 1: Main features of different legislative tailpipe emission type approval tests: ECE, NEDC, US FTP 75, Japanese JTC and ARTEMIS urban.

	NEDC	US FTP-75	JTC 10-15 mode	ARTEMIS Urban
Trip duration (s)	1180	1874	660	993
Trip distance (km)	11.007	17.77	4.16	
Average speed (km/h)	33.6	34.1	22.7	17.67
Max. speed (km/h)	120	91.2	70	57.7
$v \leq 30$ km/h (s)	545	747	403	708
$30 < v \leq 50$ km/h (s)	382	715	40	256
$50 < v \leq 70$ km/h (s)	139	186	88 15 mode	23 (>50)
$v > 90$ km/h (s)	85	~ 30	-	-
Idling (s)	330	~349	187	240

Table 2: Characteristics of the test cycles used [7].

Cycle	Length [km]	Average Speed [km/h]	Maximum Speed [km/h]	Duration [s]
NEDC	11	33.54	120	1180
MILAN CITY	7	14.14	50	1800

VEHICLE TEST CONDITIONS AND INSTRUMENTATION

Vehicles

The vehicle characteristics and specifications are reported in Table 3. Vehicle testing was carried out with a Fiat Scudo 2 litre and a VW T5 2.5-I-TDI (128 kW) with no DPF having a CO₂ emissions over the NEDC of 208 and 218 g/km respectively. Standard commercial diesel fuel from the same batch was used for both vehicles.

Table 3: Characteristics of the test vehicles.

Vehicle brand and type	Fiat Scudo Diesel JTD	VW T5 Diesel TDI
Engine capacity [litre]	2.0	2.5
After-treatment system	Oxidation catalyst only – No DPF	Oxidation catalyst only – No DPF
Emissions standards	Euro3 Class II	Euro4 Class II
CO ₂ emissions NEDC (g/km)	208	218
EURO 3 Limits Class II (g/km)	CO: 0.80 NOx: 0.65 HC+NOx: 0.72 PM: 0.07	
Euro 4 Limits Class II (g/km)	CO: 0.63 NOx: 0.33 HC+NOx: 0.39 PM: 0.04	

Instrumentation and test set-up

The PEMS instrumentation used for exhaust gas emission measurements was a Semtech DS from Sensors Inc. This instrument meets the performance requirements (accuracy, linearity, etc.) needed to measure the exhaust gas concentrations of the regulated pollutants and the exhaust mass flow for both Euro 3 and Euro 4 diesel vehicles, as set by official standards [4].

To measure the exhaust flow, the Semtech DS uses exhaust mass flow meters (EFMs) equipped with differential pressure devices and thermocouples. The relationship between the pressure, temperature and the exhaust mass flow is explained by the Bernoulli principle. Such technique, also known as “averaging Pitot”, was proven to be reliable over time and accurate enough during the large number of testing hours conducted in previous studies [5, 6]. For this LDV application a 2 inches flow tube diameter was

used for the Fiat Scudo and a 2.5 inches for the VW T5 van; the EFM accuracy over a typical test cycle is better than $\pm 3.0\%$ of the reading, with a resolution of $0.003 \text{ m}^3/\text{min}$ and an exhaust temperature range that goes from ambient to 550°C . Table 4 below summarizes the main characteristics of the Semtech DS in terms of measurement technique, ranges and accuracy for the different analysers as reported by the instrument manufacturer.

Table 4: Characteristics of Semtech DS exhaust gas analysers [21].

	Method	Range	Resolution	Accuracy
CO ₂	NDIR	0-20%	.01%	$\pm 0.1\%$ or $\pm 3\%$ of reading
CO	NDIR	0-8%	10 ppm	50 ppm or $\pm 3\%$ of reading
		0-8%	.001%	3% or 0.02% of reading
THC	HFID	0-100 ppm	0.1 ppm	2 ppm or $\pm 1\%$ of reading
		0-1000 ppm	1 ppm	5 ppm or $\pm 1\%$ of reading
		0-40,000 ppm	1 ppm	10 ppm / $\pm 1\%$ of reading
NO	NDUV	0-2500 ppm	1 ppm	15 ppm or $\pm 3\%$ of reading
NO ₂	NDUV	0-500 ppm	1 ppm	10 ppm or $\pm 3\%$ of reading

Comparison between the Semtech DS and the Horiba test cell gas analysers over both the standard NEDC and Milan City cycle has been carried out but for the Fiat Scudo only. Good agreement was found on both cycles between test cell instrumentation and PEMS; in this context data are reported only for the NEDC cycle, more details may be found in [7].

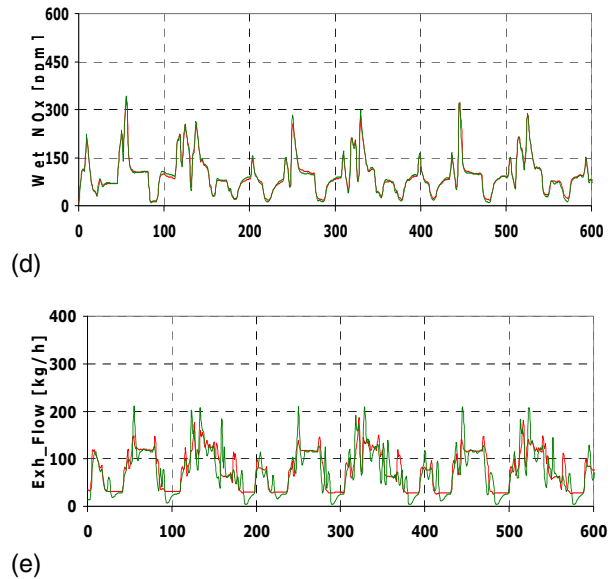
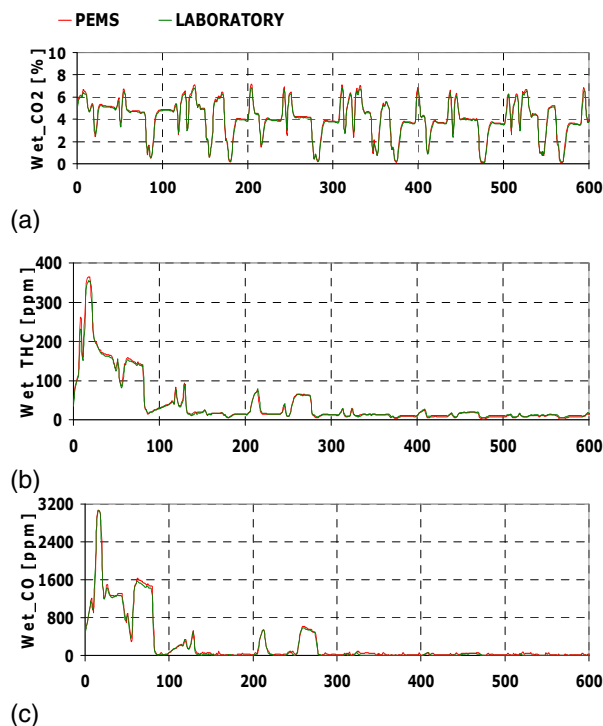


Figure 2: Comparison between reference laboratory instruments (Horiba) and Semtech DS over the NEDC cycle for CO₂ (a), THC (b), CO (c), NOx (d) and measured exhaust mass flow (e) (kg/h); system 1 (red) refers to the Horiba analysers while system 2 (green) to the Semtech DS.

Figure 3 shows the instrument installation on board and the exhaust flow-meters (EFM) with 2 inches diameter attached to the vehicle tailpipe for the Fiat Scudo; the same set-up was used for chassis dynamometer testing in the test cell. Figure 4 shows the instrument installation for the VW van. Power supply and backup batteries were used to conduct on road measurements; no vehicle power was needed during measurements.



Figure 3: Picture of PEMS installation on board of the 2 litre Fiat Scudo Diesel; the same set-up was used for chassis dynamometer testing in the test cell.



Figure 4: Picture of PEMS installation on board of the VW T5, 2.5 litre van for on road measurements.

Vehicle testing was carried out with a similar instrument set up for both the Fiat Scudo (Figure 3) and the VW T5 van (Figure 4). Chasing experiments were conducted on highway, rural and urban routes downtown Milan. A picture of two vehicles (Fiat Scudo e VW T5 van) downtown Milan during a chasing experiment is shown in Figure 5.



Figure 5: Picture of the PEMS equipped Fiat Scudo and VW T5 van during the chasing experiments downtown Milan.

Test protocol

The test protocol for exhaust gas emission measurements is adapted from the one developed for heavy-duty vehicles [5, 6], the only major difference being that all the emissions are measured from cold start and that the vehicle exhaust temperature is monitored continuously throughout the test. The two PEMS were calibrated with the same gas mixture.

Test routes

The test route was selected to include a variety of conditions, i.e. city, rural and highway driving. Its main characteristics are reported in Table 5. The city route was based on the daily activity of a food delivery company downtown Milan. The reported average speed is the one observed for the chased

vehicle (Fiat Scudo). Note that the results for the rural and highway routes are reported together in the following sections of the paper.

Table 5: Characteristics of the test routes.

Section	City	Rural	Highway
Distance [km]	17	13	35
Average speed [km/h]	11	49	94
Average altitude [m]	120	241	275
Average temperature [°C]	18	10	11

Values presented are the average for the two vehicles.

The calculation of integrated emissions for the different parts of the complete route is conducted using sub-trips. Each sub-trip is defined as the route between two checkpoints, which are identified from the PEMS GPS data.

ON-ROAD VEHICLE CHASE TESTING WITH PEMS

For the experiments presented in this paper, chase testing is defined as “two vehicles (the chased and the chaser) equipped with similar portable emissions measurement systems (PEMS) that follow each other at a quasi-constant time interval in order to obtain the same operating speed profiles for both vehicles”. To judge upon the “quality of the testing strategy”, i.e. the ability to obtain similar speed patterns for both vehicles, some indicators were developed in the following section of the paper.

PEMS emissions measurements are reported distinguishing between highway and rural and urban routes. Figure 6 reports the velocity profiles for both Fiat Scudo and VW T5 van during the chase experiment over the highway route Ispra-Milan (a) and over the city route (b) as GPS vehicle speed versus time.

To understand how the vehicle speed profiles compared and therefore to estimate how well the vehicles were tested under the same velocity conditions, several kinds of indicators were developed: the average speed of each vehicle, the speed difference between the vehicles, the slope and correlation coefficients of a simple scatter plot using the respective speeds. The scatter plots corresponding to Figure 6 (a, b) are presented respectively in Figures 7 (a, b). The calculated slopes (1.0 for the rural-highway section, 0.91 for the city section) as well as the values obtained for the correlation coefficients (0.98 for the rural-highway section, 0.82 for the city section) show the level of correlation that can be achieved. As evidenced by the correlation coefficient in Figure 7 (b), a good chase is more difficult to achieve in the city, where traffic is intense, the presence of traffic lights high and the driver of the chasing vehicle has difficulties to maintain the constant time interval between the two test vehicles.