EUROPEAN COMMISSION
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Joint Research Centre

Institute for Environment and Sustainability

Mobile Measurement of Pollutant Emissions and Fuel Consumption of Road Vehicles In Real-World Driving Situations Using Portable Emission Measurement Systems (PEMS)

ADMINISTRATIVE ARRANGEMENT # N° 070501/2005/413194/MAR/C1

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FINAL REPORT

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1 Introduction

The objective of this Administrative Arrangement was four-fold:

- To help identify any further action required for the regulation of vehicle emissions in view of real-world emissions;
- To contribute to the establishment of a knowledge and data base on the nature and frequency of different driving situations of road vehicles encountered in real-world driving in the EU, the associated emission levels of pollutants and the associated fuel consumption. Emphasis should be given to LDV and small trucks to generate complementary data sets to the ongoing European HDV- PEMS programme;
- To contribute to the development of criteria for the testing of motor vehicles other than HDV using PEMS;
- To help building up an independent, permanent mobile emission measurement capacity at the JRC.

2 Design of the study

The activities conducted within the Administrative Arrangement were developed in two main phases:

- The first phase of on-road PEMS testing of vehicles ('Testing Phase 1', first half of 2007);
- The second phase of on-road PEMS testing of vehicles ('Testing Phase 2', second half of 2007).

The first phase of the experiments was designed:

- To develop the general 'recommendations' to install the equipment and to collect the data on board of light-duty vehicles;
- To design test routes that encompass the basic set of conditions (city, rural, highway, slope, etc…) that may be encountered by the vehicles;
- To evaluate available data processing methods that can potentially be used to either analyse the on-road emissions data or to provide pass-fail information in a type-approval context.

The second phase of the experiments was designed:

- To test several vehicles of different technologies on the same reference test routes (city, rural, highway, uphill);
- To study the test-to-test repeatability for a given vehicle-route combination, as each vehicle-route combination was tested three times;
- To further develop the statistical analysis of on-road emissions data after developing a PEMS data processing method \at the end of phase 1;
- To identify potential emissions 'problems' arising when vehicles with different vehicle technologies are driven under real-world conditions.

The list of tasks to be conducted and items to be addressed are shown in Table 1 that also indicates which sections of the report deal with the proposed work items.

<table>
<tr><th>TASKS
(Technical Annex of the Administrative Arrangement)</th><th>RESULTS AND DELIVERABLES
(With references to the sections of the present report)</th></tr>
<tr><td colspan="2">Task 1: Support the Commission in identifying any further action required in the regulation of vehicle emissions in the EU in view of real-world emissions, both for use within the EU and with a view to international developments</td></tr>
<tr><td>Item 1.1. Develop the scientific basis for further developments in the European type approval regulatory approach by extracting and listing the main strengths and weaknesses of current type approval testing. Provide a list of potential improvements and alternatives to the current type approval testing.</td><td>The scientific basis for further developments <u>based on PEMS</u> in the EU type approval approach comprise two basic elements:
- The test methods (or performance evaluation strategy) which include the base specifications of the instruments and the test protocol (how to use the instruments and to collect the data);
- The data evaluation methods (or pass-fail methods).
The work conducted under Tasks 2 and 3 provides the elements that were needed for the development of the above two items.

Links in the document:
<u>Chapter 3: Potential developments of PEMS in the legislation</u></td></tr>
<tr><td>Item 1.2: Provide scientific advice on the EU position regarding the work in the UN-ECE WP.29 GRPE OCE working group based on the expertise gained in the European PEMS programme with particular emphasis on the Not-To-Exceed (NTE) concept.</td><td>The potential application of PEMS in a regulation is introduced in the following way:
- List of the main strengths and weaknesses of current European type approval testing
- Review of PEMS application in the regulatory context including:
1. The on-going Heavy-Duty (and probably NRMM) EU developments based on PEMS (EU-PEMS programme);
2. The work in the UN-ECE Off-Cycle Emissions and its potential interaction with Point 1 above;
3. An overview of the United States efforts and strategy.

Links in the document:
<u>Chapter 3: Potential developments of PEMS in the legislation</u></td></tr>
</table>

Task 2: Investigation of road trip variability and the associated pollutant emission levels and fuel consumption	
Item 2.1: Establish a classification of driving situations in terms of appropriate parameters (city/highway driving, relative traffic density, vehicle speed, acceleration, road situation such as slope, environmental parameters such as altitude, temperature, humidity, etc).	The definitions of 'driving situations' is provided with the selection of the test routes used for the Phase 2 testing program. The definition of 'Phase 2 test routes' tried to reproduce the basic set of conditions (city, rural, highway, slope) that may be encountered by the vehicles. The effect of the relative traffic density upon the vehicle operating conditions cannot directly be 'measured'. It is tentatively introduced in the Phase 2 of the programme by testing a given vehicle on a given route at different times of the day, looking at the average operating speed for some sections of the routes (in particular in the city). *Links in the document:* Chapter 4: Test program Chapter 6: Results Phase 1
Item 2.2: Analysis of road measurement data available at JRC for a first assessment of driving conditions that will contribute to major differences between road test emissions and dynamometer test emissions.	This item was developed by comparing the on-road emissions measured with PEMS to the emissions of vehicles on standard laboratory test cycles *Links in the document:* Chapter 6: Results Phase 1 Chapter 7: 7 Results Phase 2
Item 2.3. Provide a small fleet of test vehicles for mobile testing, including passenger cars and small trucks/transporters. Final fleet size and composition shall be defined on the basis of the experience made during the first tests with vehicles selected from the JRC service vehicles fleet.	Phase 1: 2 Class II diesel vehicles (Euro 3 and Euro 4) Phase 2: 4 Euro 4 vehicles (1 Hybrid, 2 Gasoline, 1 Diesel) *Links in the document:* Chapter 4.3: Test vehicles
Item 2.4. Perform mobile and laboratory emissions testing as needed for item 5.	*Links in the document:* Chapter 4: Test program Chapter 6: Results Phase 1 Chapter 7: 7 Results Phase 2

Item 2.5. Establish a database of driving situations encountered as classified under point 1, recording relevant parameters including the relative frequency of these situations and their associated levels of pollutant emission and fuel consumption.	The emissions and fuel consumption results for the vehicles tested during Phase 2 have been presented: - As average emissions integrated over selected sections of the test routes (representing the different driving situations like city, rural, highway); - As average emissions using the CO_2 based averaging window data processing method; these emissions are presented versus the average vehicle speed of each window. *Links in the present document:* Chapter 7: 7 Results Phase 2
Item 2.6. Perform a statistical analysis of the data established under item 2.5.	Two elements are provided: - The basic characteristics (average and average deviations) from series of three tests conducted for one vehicle on the same test route; Chapter 7: 7 Results Phase 2 Section 7.3: 7.3 CO2 averaging window method
Item 2.7. Determine PM emissions under real-world driving conditions in an indirect way. A real-world driving profile will be registered and introduced as test cycle to the laboratory test bench (full vehicle dynamometer). This test cycle will be run under the same average temperature encountered during the outdoor test, and should result in similar emissions of gaseous pollutants and PM. The latter one will be measured as integrated value of the particulate mass over test cycle sequences, as well as on-line value of the particle number by means of a CPC. Further to that, the effect of temperature and humidity on PM emissions will be studied in the test cell using the same real-world driving pattern.	Chapter 6: Results Phase 1

Task 3: Investigation of possible criteria for mobile measurement of pollutants in connection with type approval and in-use compliance checks	
Item 3.1. On basis of the task 2 results the design of a measurement procedure for LDV emission testing with PEMS shall be developed. The main elements that should be included are a description of instrumentation's minimum requirements, such as resolution and detection limit and a description of general rules to follow for the equipment's installation in a vehicle and data collection.	Following the first phase of the testing program, some recommendations have been formalised in a guidance document that includes: - The PEMS Instrumentation minimum requirements; - The general 'recommendations' to install the equipment and to collect the data on board of light-duty vehicles. The 'Phase 2' experiments were conducted by the elements developed during Phase 1, in particular for the test protocol and data processing methods.
Item 3.2. The minimum criteria for the driving situations that need to be covered shall be defined and included in item 1 of Task 3	For the purpose of a legislative measure there should not be requirements for 'the driving situations that need to be covered' as the vehicles should be tested during their real operation, preferably by the user himself (real 'in-use testing) to provide the necessary random character in the testing. The only point to discuss would be the definition of exemptions (could be on minimum average operating speed, altitude, aggressiveness of driving, or any situation that does not correspond to the 'normal use' defined in the regulations).
Item 3.3. The assessment criteria regarding the results of the measurements undertaken shall be defined and included in item 1 of Task 3.	The selection of the assessment criteria for the results of the measurements was done using the conclusions of the HDV work on the pass-fail methods. The most appropriate method is an averaging window method based on a CO_2 mass, for the reasons exposed in section 5.3 (All operation included in the evaluation, possibility to check the emissions levels for durations that are close to the one of the reference test cycles).

Table 1 List of tasks, tasks items and corresponding deliverables

3 Potential developments of PEMS in the legislation

3.1 Strengths and weaknesses of current type approval testing

3.1.1 Overview

Within Europe, two systems of type approval have been in existence for over 20 years. One is based around EC Directives and provides for the approval of whole vehicles, vehicle systems, and separate components. The other is based around ECE (United Nations) Regulations and provides for approval of vehicle systems and separate components, but not whole vehicles.

Put simply, type approval is the confirmation that production samples of a design will meet specified performance standards. The specification of the product is recorded and only that specification is approved.
Automotive EC Directives and ECE Regulations require third party approval - testing, certification and production conformity assessment by an independent body. Each Member State is required to appoint an Approval Authority to issue the approvals and a Technical Service to carry out the testing to the Directives and Regulations. An approval issued by one Authority will be accepted in all the Member States.
(Note: automotive Directives are "old approach" in terms of requiring third party testing and approval. "New approach" Directives follow a different format and place more obligations on the manufacturer to make sure that the product meets appropriate requirements. EU Member States have agreed that the new approach is not appropriate for road vehicles.)

EC approval of most road vehicles is based around a "Whole Vehicle" framework Directive 70/156/EEC (as last amended by 2001/116/EC) and this specifies the range of aspects of the vehicle that must be approved to separate technical Directives. Hence, in order to gain EC whole vehicle approval, a vehicle first will have to be approved for e.g. brakes, emissions, noise, etc - up to 48 different standards for a typical car. The issuing of the whole vehicle approval does not in itself involve testing, but a production sample of the complete vehicle is inspected to check that its specification matches the specifications contained in all the separate Directive approvals.

The three ways in which vehicles can be approved for entry on the European market:
European type approval – cars have to meet requirements set out in 56 EU Directives. Among these, cars up to 2.5 t gross vehicle weight (i.e. weight of the vehicle plus the maximum weight a vehicle can carry as determined by the vehicle manufacturer) must meet European crash standards (frontal and side impact) under Directives 96/79/EC and 96/27/EC.

- Small series type approval – under Directive 70/156/ EEC cars do not need to meet European crash standards when produced in a limited number (maximum of 500 units per year per Member State). This is intended to save small manufacturers from disproportionate costs.
- Individual vehicle approval – via nationally operated approval systems cars do not need to meet European crash standards. However they must

satisfy (milder) national safety and environmental checks. Although each individual vehicle unit has to be separately approved there is no limitation on the number of vehicles an individual may have approved. Once approved and registered by one Member State, thanks to mutual recognition other Member States are obliged to accept such vehicles on their roads.

Evidently, type-approval testing for the emission behaviour has to strike a balance between an understanding of the emission behaviour under real world conditions and a very high degree of repeatability and reproducibility. This is indispensable, as a high reliability for equality for the type approval process by different authorities is desired throughout Europe.
Unfortunately, current test cycles for new vehicles do not reflect how cars are used under real driving conditions and so underestimate their actual emissions. "This may help to explain why urban air quality is not improving as fast as vehicle data suggest it should" [R1]. [R2] states that "NOx emissions at 160km/h can be three times of those determined with the standard test procedure".

3.1.2 LDV Test cycles

Currently type approval testing of Light-Duty Vehicles (LDVs) is done under controlled environmental conditions using a reference driving cycle (New European Drive Cycle, NEDC). For LDV certification testing, the boundary conditions are well known and consequently there might be a risk for a specific engine development tailored for passing emission tests when running under type approval conditions. There are examples where engines are being optimised for NOx emissions in one range of operation and for fuel consumption in another. This is not per se negative, but has to be seen in the light of real world use of LDVs: the operation points in type approval tests are limited. Therefore, they cannot reflect the ones from real world conditions. As a consequence the real world emissions and fuel consumption of LDV can differ from those measured during the laboratory test 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 0.

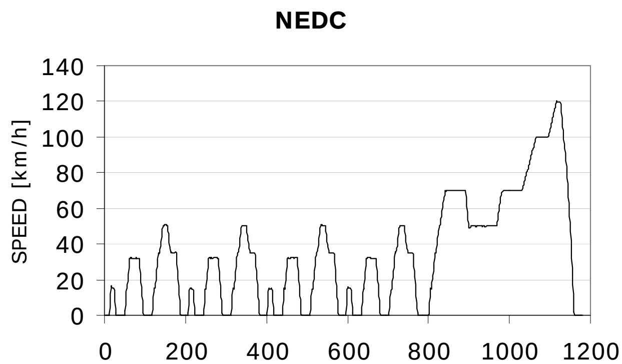


Figure 1 New European Driving Cycle (NEDC).

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 CVS and the total emissions are expressed in g/km for each of the regulated pollutants.
Several critical studies of the NEDC cycle have already been published. The main weakness of the NEDC, according to [R3], is due to its very smooth acceleration profile. The engine is used only in a very small area of its operating range and to fulfil the emission test engine manufactures have to focus only on this area [R4]. This very smooth acceleration is reflected in a low relative positive acceleration value (RPA) where RPA is a speed-related average of acceleration of the vehicle. It is directly related to the average acceleration power of a vehicle; it is defined as [R5]:

Equation 1 $$RPA = \frac{\int_0^T (v_i * a^+{}_i)dt}{x}$$

Where T is the total cycle time (s); *x* is the total distance (m); v_i is the instantaneous speed (m/s); a_i is the instantaneous acceleration (m/s^2) and $^+$ indicates only positive values.

Therefore, the NEDC underestimates the vehicle load compared to real traffic, which has a direct effect on its operating range. Similar RPA was found for ECE and FTP75 as reported in [R6], while a higher value was found for the Artemis and MOL cycles; a comparison of NEDC, MOL and Artemis in terms of tailpipe emissions and RPA is also reported in [R6,R7]; it turned out that a model year 2000 vehicle (Euro 3) might reach CO and NOx emissions that may be up to 10 times higher in real traffic compared to the NEDC. In addition, fuel consumption and CO_2 are generally underestimated by 10-20% in the NEDC.

Characteristic of real traffic operation is low speed/high torque operation, which is hardly used in the standard NEDC cycle. Generally the trend in emissions is to have high NOx /low CO values in real traffic for diesel LDV and high CO /low NOx in motorway traffic. 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 context [R7] and to demonstrate their strong influence on pollutant emissions [R8,R9]. Different cycles have been proposed in the literature as more suitable substitutes to the NEDC from the Artemis [R10] to the MOL cycle [R11]. Table 1 illustrates the 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≤30 km/h (s)	545	747	403	708
30<v≤50 km/h (s)	382	715	40	256
50<v≤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 1 Characteristics of different legislative tailpipe emission type approval tests: ECE, NEDC, US FTP-75, Japanese JTC and ARTEMIS urban.

Regarding the emissions performance of LDV on the standard test procedures, the work by Hausberger et al. [R14] provide a good illustration of one of the main NEDC limitations. As shown in 0, the reduction of NOx emissions is only effective on the NEDC cycle. The authors explain that these effects are due to:

- the trade off between Fuel consumption and NOx emissions;
- the NEDC controls a much smaller area of the engine load conditions than driven in the Artemis (CADC) cycle.

They also suggest that, “to achieve higher reduction rates for NOx in CADC like real world driving will need further efforts in the design of the type approval procedures and in R&D”.

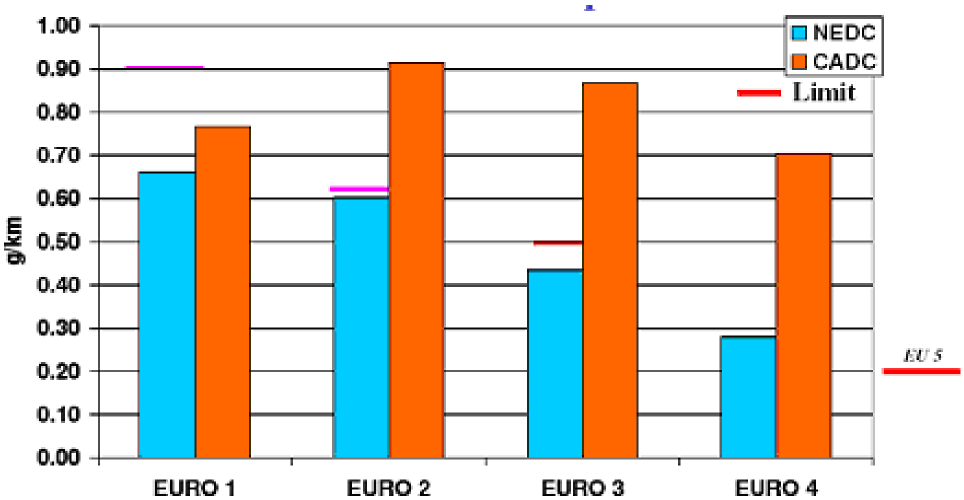


Figure 2 Average distance specific emissions of EURO 1 to EURO 4 diesel passenger cars on the NEDC and CADC (Artemis) cycles [R25].

3.2 "Off-cycle" developments in the legislation

In the current EU Heavy-Duty legislation [R16, R17], only the NOx random points (from EURO IV) provide a procedure that introduces some randomness into the type-approval testing of Heavy-Duty engines and therefore attempts to prevent the optimisation of the emissions control strategies for the standard test cycles (ETC, ESC). Such a procedure does not address the true question, i.e. to provide a quantifiable control of the emissions during the real operation of the vehicles-engines.

The developments of the EU-PEMS project address the developments of PEMS based methods to address ISC in the future EU heavy-duty emissions legislation. The objective of the ISC provisions proposed for heavy-duty vehicles are similar to the ones already existing for light-duty vehicles, i.e. to check the conformity of vehicles during their useful life. In the case of light-duty vehicles, the ISC is simply conducted by sampling in-service vehicles (directly from their users) and by testing them on the standard homologation test cycle. For heavy-duty vehicles, the extraction of engines from the vehicles, testing them on the engine dynamometer and rebuilding them into the vehicles was judged impractical and not cost-effective. The PEMS on-vehicle emission testing was developed to overcome these difficulties.

For the future regulations, there is also a recognised need to implement measures that will ensure that the emissions are appropriately controlled outside the conditions of the standard test cycles and during the real vehicle operation. Depending on the context, these ideas are underlying behind generic terminologies such as "off-cycle emissions" or "in-use emissions".

During the T&E conference (Milan, March 2007), the representatives of the European Association of heavy-duty manufacturers proposed the following definitions:

“For ISC, with reference to emission type-approval, the manufacturer will have to confirm the functionality of the emission control devices during the useful life of an engine installed in a vehicle (Directive 2006/55/EC Annex III)
For IUC, the demand on the manufacturer is to keep the emission level of vehicles in use below a certain level under all normal ambient and geographic conditions and usage pattern. The details of the IUC implementation are currently being discussed as one the elements of the future European legislation.”

Such definitions, though not yet used in working documents highlight the potential developments of PEMS in the future EU regulations, as PEMS are the only means to check the vehicle emissions during the real operation of the vehicle (i.e. “in-use”).

4 Test program

4.1 PEMS Instruments

The PEMS evaluated was a Semtech DS from Sensors Inc., able to measure the exhaust gas concentrations of the regulated pollutants and the exhaust mass flow. To measure the exhaust flow, the Semtech uses exhaust mass flow meters (EFMs) equipped with differential pressure devices and thermocouples to obtain the exhaust temperature. The relationship between the pressure, temperature and the exhaust mass flow is based on 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 [R20, R22]. For this LD vehicle a 2 inches (51 mm) flow tube diameter was used; the EFM accuracy over a typical test cycle is better than ±3.0%, with a resolution of 0.003 m^3/min and an exhaust temperature range that goes from ambient to 550 ºC.

Table 2 summarizes the main characteristics of the Semtech DS in terms of measurement technique, ranges and accuracy for the different analysers.

	Method	Range	Accuracy
CO_2	NDIR	0-20%	±0.1% or ±3% of reading
CO	NDIR	0-8%	50 ppm / ±3% of reading
THC	HFID	0-100 ppm	5 ppm / ±2% of reading
		0-1000 ppm	5 ppm / ±2% of reading
		0-10000ppm	25 ppm / ±2% of reading
NO	NDUV	0-2500 ppm	15 ppm / ±3% of reading
NO_2	NDUV	0-500 ppm	10 ppm / ±3% of reading

Table 2 Characteristics of SEMTECH DS analyzers [R26].

4.2 Test protocol

The test protocol for exhaust gas emission measurements is adapted from the one developed for heavy-duty vehicles [R21]. The only major difference is that all the emissions are measured from cold start and that the vehicle conditioning (temperature) has to be monitored throughout the test.

4.2.1 Installation of PEMS

The main components of the PEMS were installed as such:

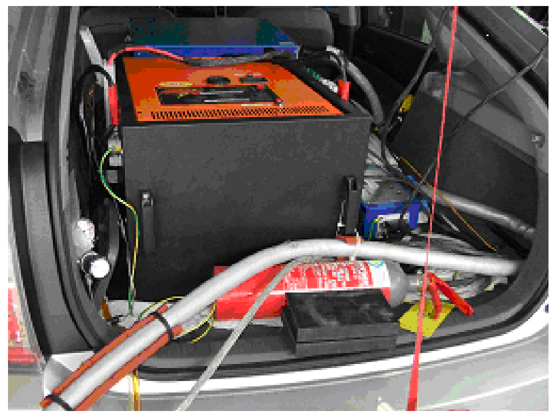
- The main unit containing the pumps, the electronic equipment and the analysers are installed in the ‘cabin’ of the vehicle which represents a “semi-protected” environment, to avoid contamination, excessive vibrations, heating of the equipment or shocks;
- The exhaust flow-meters are attached to the vehicle’s tailpipe;
- GPS and weather station are installed outside.

A few examples of installations on some test vehicles are shown in Figure 3 below, such as EFM on Ford CMax (a), installation on Toyota Prius (b), PEMS main unit (Semtech DS) (c) and battery pack (d).

(a) EFM on Ford CMax

(b) Installation of Toyota Prius

(c) PEMS Main Unit



(d) Battery pack

<u>Figure 3</u> A few examples of PEMS installations on some LDV test vehicles.

4.2.2 Test operation

The test vehicles started from the base and returned to the base after the test trips for the normal checks, calibration and data download. Therefore, the vehicles were away from the base for a maximum of 3 hours. Even though PEMS unit are capable of operating longer times, the challenge of having test durations longer than 2 hours, or to make tests far away from the base (and therefore the calibration and verification devices) is problematic. In particular for the following issues:

- The calibration and/or audit of the system (gas bottles needed);
- The power supply (PEMS equipment cannot be run on batteries for durations exceeding about 4 hours).

The list of basic operations carried out when testing a light-duty vehicle with PEMS are the following:

- Check zero air

- Zero-span the analysers
- Archive zero-span data
- Purge exhaust flow meter
- Leak check exhaust flow meter
- Check GPS signal
- Verify that all operation parameter controllers regarding system status are set at the correct operating values
- Launch the data acquisition
- Start the engine.

And after the test:

- Turn off the emissions sampling system and all measurement devices.
- Audit gas analysers
- Zero exhaust flow-meter
- Save and Back up test data.

The two major differences with the heavy-duty test protocol [R21] are:

1. The impossibility or the difficulty to record ECU data from the vehicle network, due to the absence of standardised communication protocols;
2. The absence of checks with a running engine as the emissions are measured from engine start.

4.2.3 Overview of test parameters

The table below (Table 3) lists the basic set of parameters that were measured during a road test and for each parameter the available corresponding measurement techniques used. The parameters have been categorised into 3 families, namely:

- Exhaust gas;
- Vehicle;
- Ambient conditions.

Parameter	**Measurement technique**
THC Concentration	Analyzer
CO Concentration	Analyzer
CO2 Concentration	Analyzer
NOx Concentration	Analyzer
Exhaust Flow Rate	EFM
Exhaust temperature	EFM Temperature Sensor
Vehicle speed	GPS
Vehicle position and altitude	GPS
Acceleration	GPS
Distance traveled	GPS
Elevation	GPS
Ambient humidity	Humidity Sensor
Ambient temperature	Temperature Sensor
Ambient pressure	Pressure sensor

Table 3 - Test parameters

4.3 Test vehicles

The main characteristics and specifications of the vehicles tested during the program phases 1 and 2 are reported respectively in Table 4 for phase 1 and in Table 5 for phase 2.

	Diesel	
Vehicle brand and type	Fiat Scudo JTD	VW T5 TDI
Engine capacity [litre]	2.0	2.5
After-treatment system	Oxidation catalyst only – No DPF	Oxidation catalyst only – No DPF
Emissions standards	EURO 3 Class II	EURO 4 Class II

Table 4 – Test vehicles (Phase 1).

	Hybrid	Diesel	Gasoline	
Vehicle brand and type	Toyota Prius	Renault Clio	Ford CMAX	Renault Clio
Engine capacity [litre]	1.8	1.5	1.8	1.2
After-treatment system		Oxidation catalyst only – No DPF		
Emissions standards	EURO 4	EURO 4	EURO 3	EURO 4

Table 5 – Test vehicles (Phase 2).

4.4 Test routes

During the first phase of the program, the vehicles were tested randomly on local routes including a variety of urban, rural and highway conditions. During the second phase of the program, the following three routes were designed and used as test routes for all vehicles:

- Route 1: Ispra-Milan-Ispra, mix of rural and highway driving conditions;
- Route 2: Ispra-Varese-Ispra, mix of rural and urban driving conditions;
- Route 3: Ispra- Sacro Monte - Ispra, mix of rural driving and uphill-downhill conditions: this was designed to include a very demanding section (uphill from 400 to 1200 m altitude) in terms of fuel consumption and emissions.

The main characteristics of the routes and their sub-sections are reported in Table 6 whereas their altitude profiles are shown in Figure 4.

	ROUTE 1			**ROUTE 2**			**ROUTE 3**		
Section	Rural	Mot.	**TOTAL**	Rural	City	**TOTAL**	Rural	Uphill	**TOTAL**
Distance [km]	35	100	**135**	51	10	**61**	50	10	**60**
Approx. Aver. Speed [km/h]	50	90	**65**	40	25	**35**	45	30	**40**

Table 6 Characteristics of phase 2 test routes

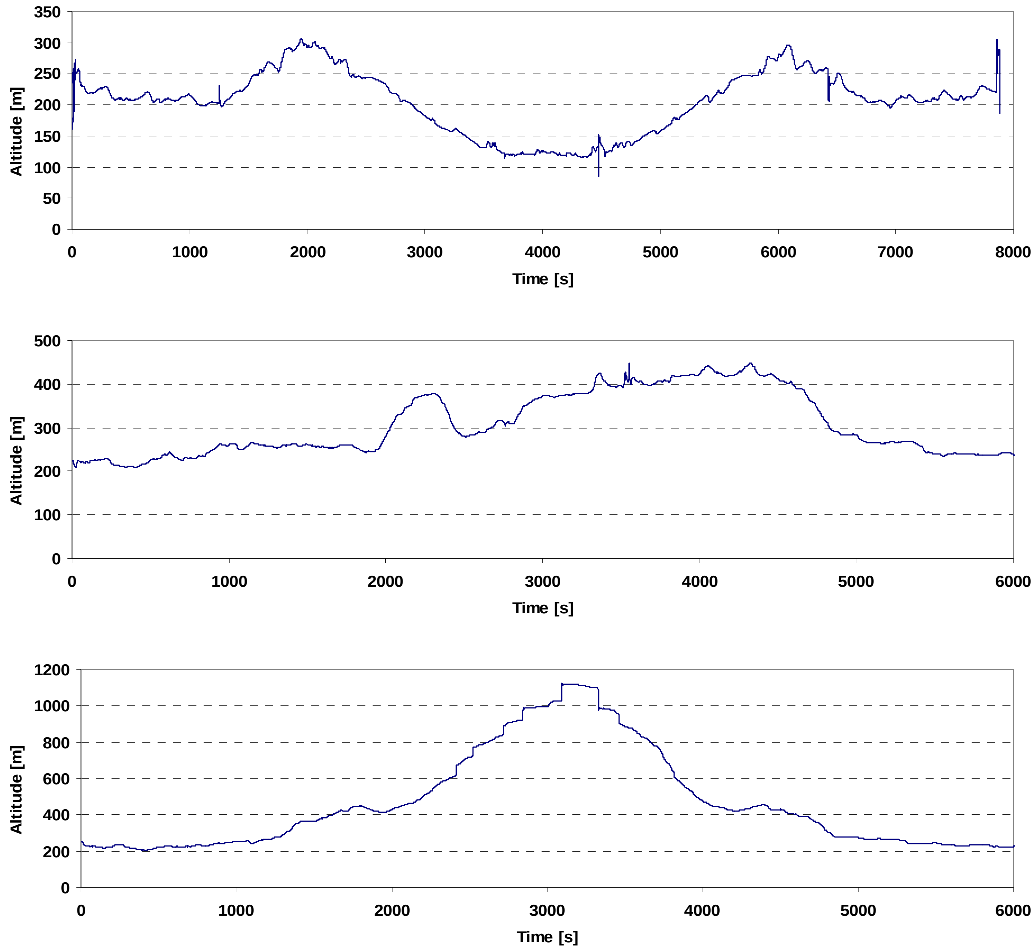


Figure 4 Altitude profile of test routes: (a) Route 1, (b) Route 2, (c) Route 3.

5 Methodological aspects of on-road emissions analysis

5.1 Introduction

The traditional method of measuring emissions during chassis dynamometer tests, which results in a single integrated or averaged value per pollutant, is not sufficient to characterise the variability of the vehicle emissions on the road. Many of the faster emission characteristics are not visible in the one-value result, even though they can contribute significantly to the overall emission. Critical areas of the engine map, which are linked to specific operation pattern, cannot be identified either. It is not feasible or realistic to evaluate instantaneous second-by-second emissions data: averaging of selected sub-sets of the data needs to be implemented. Furthermore, the expected variability of on-road emissions (changes in the vehicle speed, the road conditions, the environmental conditions and the vehicle load) should also be considered.

Evaluating the techniques that could potentially be applied for the control of heavy-duty vehicle emissions during their operation and using PEMS, two families of methods were considered [R22]:

- Control Area type (US-NTE, official US method);
- Averaging window method

5.2 Methods for Heavy-Duty Testing [R22]

The present section introduces the two types of methods that were considered for the heavy-duty in-service emissions testing based on PEMS:

- The "control-area / data reduction methods" that use only a part of the data, depending whether the operation points considered are part of a control area and belong to a sequence of consecutive points within this control area. The US-NTE (Not To Exceed) method - already established as an official tool in the United States - falls into this category but variations of the methods can be envisaged (with another control area for instance).
- The "averaging window methods", based on work or CO_2 mass that uses the complete data set.

5.2.1 Control Area method: Principle

For heavy-duty engines, the engine "operating points" are defined as pairs of engine speed and torque values, typically read from the vehicle ECU when testing with PEMS. The in-service brake-specific emissions are calculated when the engine operating points belong to the control area for a minimum duration, also known as the "minimum sampling rule". An "event" can be defined as a sequence of data whose operating points belong to the control area for at least the duration of the minimum sampling rule (at least 30 consecutive seconds in the US-NTE). For each event, a brake-specific emissions value is calculated, dividing the mass emissions by the event work.

Different control areas may be used, as illustrated in [R22, R19]. For the present document and in order to explain the principles of the method, the US NTE Zone is shown in 0. In the case of the US-NTE area, the minimum sampling rule is set to a duration of 30 seconds. The speed boundaries of the control area (filled in with a yellow color in Figure 5), are obtained from the engine speeds n_{low} and n_{high}, whereas the power boundary is set to 30% of maximum engine power and the torque boundary to 30% of maximum torque, where:

- n_{high} is determined by calculating 70 % of the declared maximum net power. The highest engine speed where this power value occurs on the power curve is defined as n_{high}.
- n_{low} is determined by calculating 50 % of the declared maximum net power. The lowest engine speed where this power value occurs on the power curve is defined as n_{low}.

The control area low speed boundary is obtained from:

Equation 2 $$NTE_{low} = n_{low} + 0.15(n_{high} - n_{low})$$

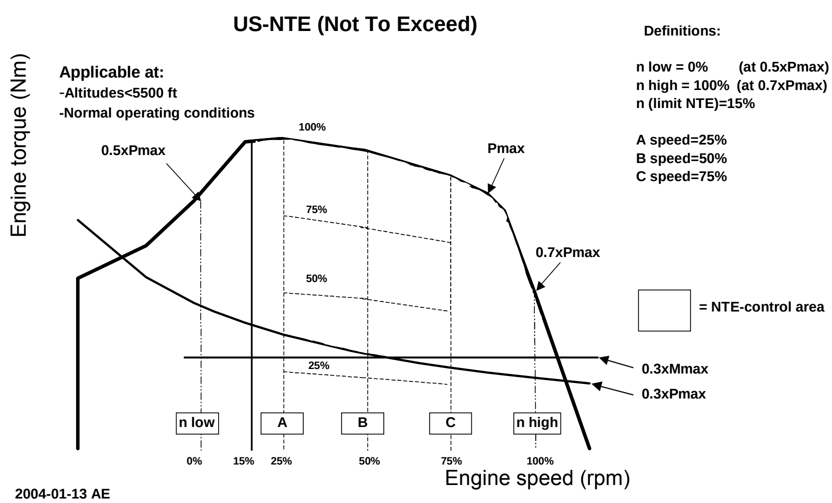


Figure 5 Definition of the US-NTE area.

An engine operating point is retained for the calculation when it fulfils the following criteria:
- Rule1: Engine speed ≥ NTE_{low}
- Rule 2: Engine power ≥ 30% of Engine maximum power
- Rule 3: Engine torque ≥ 30% of Engine maximum torque
- Rule 4: The operating point is part of a set of at least 30 seconds of data which lay always in the control area (minimum sampling rule).

In the United States official rules (Code of Federal Regulations CFR 40; Part 86. Paragraphs 007-21 and 1370-2007) define further carve-outs from the control area. Such criteria are not applied in this study: as the test vehicles were not equipped with after-treatment systems, the influence of the engine and after-treatment conditions upon the emissions was not taken into account.

5.2.2 Averaging Window method: Principle

For the methods discussed in the previous section, only a limited fraction of the in-service data is considered for the calculations. To overcome this limitation and to increase the amount of data analysed (and therefore be able to study any kind of engine operating conditions), "averaging window methods" based either on work (work window) or CO_2 (CO_2 window) can be introduced. The calculation principle is as follows for the work windows: Starting from a reference work value in kWh, (this work value can be selected for example to be the work needed to perform a chosen transient homologation cycle with this engine under investigation) one selects sub-sets in the data set from any time t1 until the time t2 in the data set such as:

Trip Work (t2) – Trip Work (t1) = Reference work

A principle example is given in 0: the lower the engine operating power is, the longer the duration of the work window will be. This method is therefore an averaging method, whose averaging times are variable and dependent upon the reference work chosen for the calculation.

A reference CO_2 mass can be used instead of a reference work. In that case, one selects sub-sets in the data set from any time t1 until the time t2 in the data set such as:

CO2 Mass (t2) – CO2 Mass (t1) = Reference CO2 Mass

The principle is illustrated in 0 for the work based window. Note that for representation purposes, the first point of the calculated brake-specific NOx trace (in orange) is aligned with the last calculation point for its window, i.e. all the data used for calculating its value is plotted upstream.

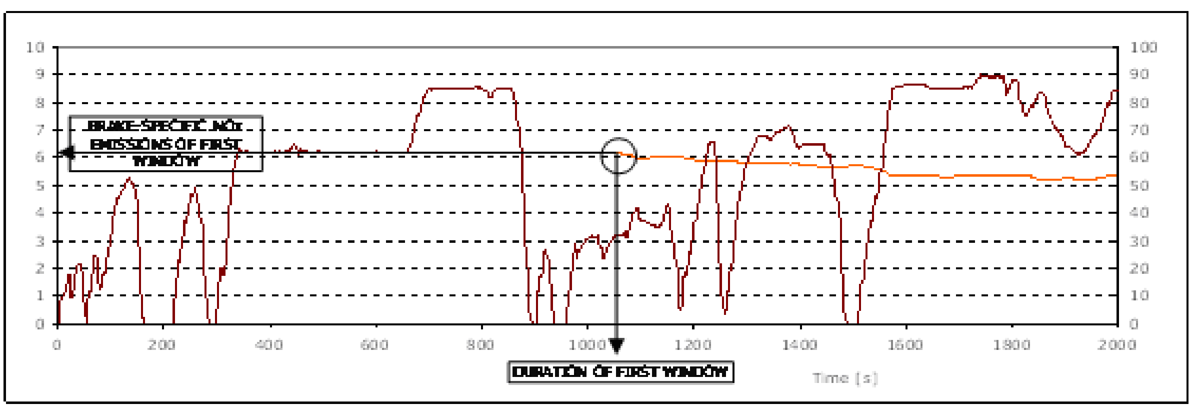


Figure 6 Principle of the work-based window method:
(Left Y-axis: Brake-specific emissions, Right Y-axis: Vehicle speed or Window Duration)

5.2.3 Suitability of the methods for PEMS-based in-service testing

5.2.3.1 Data reduction with control area methods

The major difference between the two methods introduced in 5.2.2 is their ability to 'capture' data. This difference is illustrated for a small truck tested on a trip including a significant share of city driving and a small part of the motorway (15 km out of 40). This vehicle and its test route could therefore be qualified as "small delivery truck operating in a city". With the default calculation settings (the US-NTE control area), the share of operation points in the control area is 38%. With the application of the minimum sampling rule (30 seconds), the data available for a control area calculation drops down to 6%. These calculations are illustrated in 0 and 0:

These figures also show that the main effect of the NTE sampling rule is to remove most of the dynamic operation of the vehicles: especially under city driving conditions where accelerations and decelerations have short durations because of the traffic.

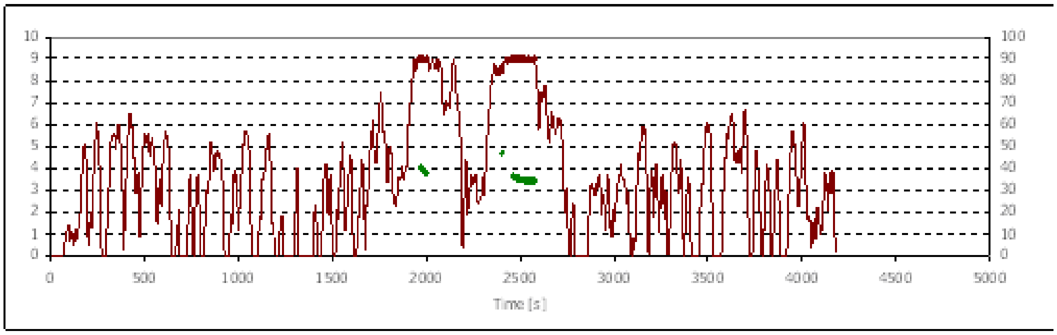


Figure 7 –Example 3: Vehicle speed trace and control area events (Settings 30% Max.Power and 30 Seconds) (Left Y-axis: Brake-specific emissions, Right Y-axis: Vehicle speed)

Modifying the control area calculation settings as such:
- Rule 2: Engine power ≥ 10%
- Rule 4: 15 seconds

	Initial settings	Modified settings
Number of events	3	12
Operation captured (*)	6%	16%
Average event duration [s]	82 s	53 s
Average rated power (**)	63 %	65 %
Average of all events (g/kWh)	3.68	4.33
Maximum of all events (g/kWh)	4.70	5.63
(*) of total trip time (**) of all the operation in the control area		

Results for vehicle case 3

Table 7 Characteristics of the example given in Figure 7

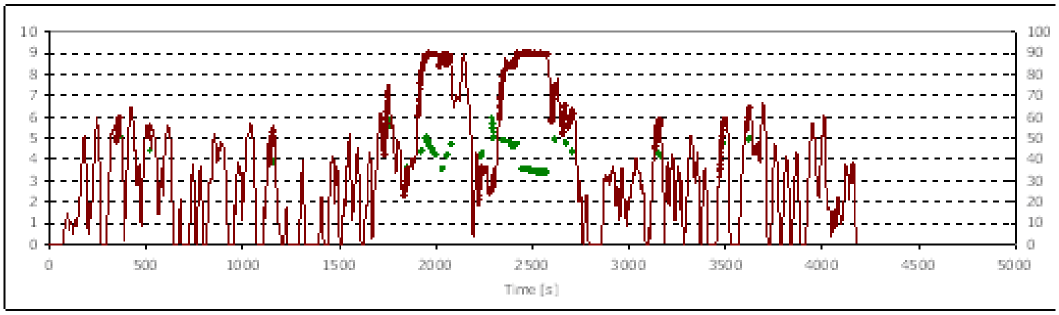


Figure 8 Example 3: Vehicle speed trace and control area events
(Settings 10% Max. Power and 15 Seconds)
(Left Y-axis: Brake-specific emissions, Right Y-axis: Vehicle speed)

5.2.3.2 Suitability for PEMS based testing

The differences between the data evaluation methods *in terms of PEMS testing* are summarised in the table below.

Method	**Engine information**	**On-board Data**	**Degree of complexity for PEMS approach**
1. Control Area	- Maximum power curve	- All (1)	Gaseous emissions: ++ PM: +++
2. Averaging window (Work based)	- None	- All (1)	Gaseous emissions: ++ PM: +
3. Averaging window (CO2 based)	- None	- All but Engine torque and speed	Gaseous emissions: + PM: +

(1) Real-time (at least second by second) CO, CO2, THC, NOx concentrations, Total PM, Exhaust Mass Flow, Engine Speed and Torque

Table 8

Using a CO_2 mass instead of work as reference leads to substantial simplifications in the PEMS test procedure as engine torque and speed obtained from the vehicle Engine Control Unit are no longer needed.

The averaging window methods – with settings (work, duration and average window power) close to the ones of the homologation cycle - represent the only valid alternative to the control area methods in the sense that:
NOT CLEAR

- The "averaging principle" that they also applied for the type approval test over both the stationary and the transient cycles, as the emissions data are also averaged over the cycle and specific to the cycle work;
- Testing engines on vehicles under real-world conditions and analyzing the collected data through a moving average window is similar to submitting them to a large number of random dynamic test cycles;
- The link between the above mentioned random test cycles and the type approval cycle is derived from its basic characteristics: cycle work (or CO_2 mass for the CO_2 window), duration and average power.

5.3 Averaging CO_2 window method for Light-Duty PEMS data

The proposed method's principle is similar to the one used to analyze on-road heavy-duty emissions data as introduced in 5.2.2. The target is to define a parameter, which allows a better comparison of driving results, as real world driving will happen in all sorts of diverse conditions. This is similar to what has been introduced for the heavy-duty engines, where the length of these sub-sets is determined by the engine work needed to run the laboratory reference cycle (for example ETC) [R20,R21]. In the present study, the chosen reference quantity for light-duty vehicles is the CO_2 mass measured on the European reference cycle (NEDC).

The emissions are then calculated not for the total trip, but for sub-sets of the on-road data. The length of every sub set (T) is selected so that its total (accumulated) CO_2 mass is equal to the reference value (M_{CO2}) over the NEDC standard cycle:

Equation 3 $$\int_{t=0}^{T} m_{CO_2}(t_{i+\tau}) - m_{CO_2}(t_i) = M_{CO_2,REF}$$

Where the CO_2 masses are calculated according to the ISO mass calculation formula as follows:

Equation 4 $$m_{gas}(t) = \sum_{t=0}^{i=f \cdot T} u_{gas} c_{gas,i} q_{raw,i} \frac{1}{f}$$

An example of such a calculation for one sub-set only is given in Figure 9. The example illustrates the first window, with its duration on the X-axis and its NOx mass on the left Y-axis. Starting from time zero, all the measurements points are included into the sub-set until the accumulated CO_2 mass over this temporal window reaches the reference quantity (CO_2 mass over the NEDC). Therefore, each point of the curve represents a calculated temporal window to which corresponds a NOx mass value (left Y-axis); the vehicle speed for this analysed set of data is provided on the right Y-axis.

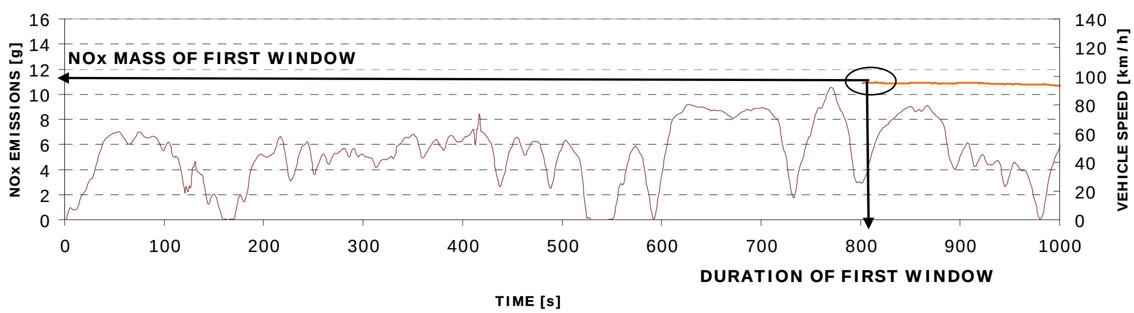


Figure 9 Illustration of the CO_2 window principle for the Fiat Scudo data over a city route.

The method is based on an averaging calculation window, whose averaging time is variable and dependent upon the reference CO_2 mass chosen for the calculation and the driving conditions. The output of the calculation is not a single value but a set of average values. Each calculated point in the set of results represents the average emissions over a CO_2 averaging window; the lower the vehicle CO_2 mass emissions is, the longer the duration of the window will be.

With such an approach, testing vehicle emissions under real-world conditions becomes equivalent to submitting the vehicle to a large number of random and consecutive driving cycles whose common denominator is - in this study - the reference CO_2 mass emitted by the vehicle. The main advantage is that the results from different sub-trips and different vehicles become comparable between each other.

The method can be applied to any data set provided that their size is sufficient, i.e. provided that the CO_2 mass emitted during the road test exceeds the CO_2 mass from the NEDC. As a matter of fact, when designing the trips to cover a wide range of operating conditions (including city, rural and highway driving conditions), there is a good probability to exceed by far the characteristics of the NEDC in terms of distance or CO_2 mass generated during the cycle.

To estimate the variability of on-road emissions with respect to laboratory test cycles a Deviation Ratio (DR) may also be introduced and defined as:

Equation 5 $$DR_{NO_x} = \frac{m_{NO_x,ROAD} / m_{CO_2,ROAD}}{m_{NO_x,NEDC} / m_{CO_2,NEDC}}$$

With:

Equation 6 $$m_{CO_2,ROAD} = m_{CO_2,NEDC}$$

Follows:

Equation 7 $$DR_{NO_x} = \frac{m_{NO_x,ROAD}}{m_{NO_x,NEDC}}$$

The deviation ratio is a good measure of the difference between the real world emissions and the lab measured emissions, and it also indicates the real world diversity relative to one single result from the lab. It allows characterizing real world emissions relative to the standard test without requiring new limit values. This is the case for NOx, but similarly, ratios could be introduced for CO (DR_{CO}) and THC (DR_{THC}). Further details may be found in [R23, R24]. An example of such a calculation as function of DR_{NOX} is given in Figure 10 for the Fiat Scudo case.

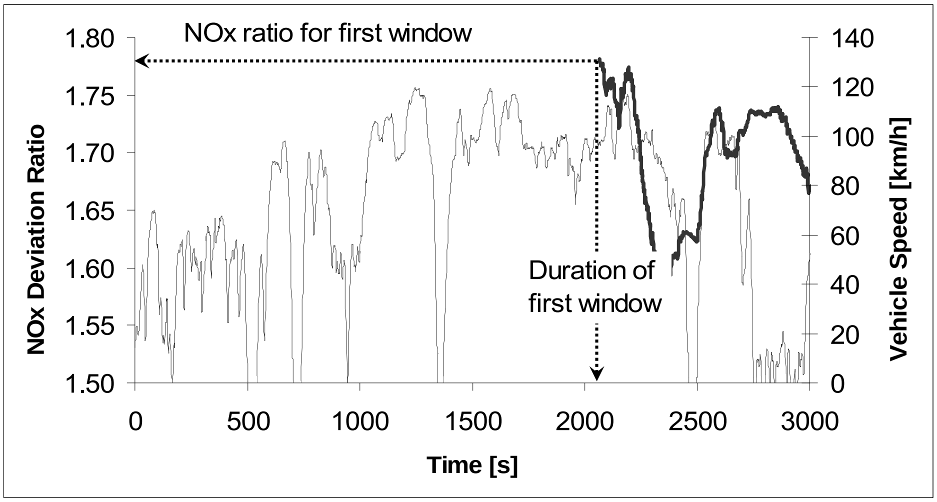


Figure 10 Illustration of the CO_2 window principle and the deviation ratio – highway test route – Fiat Scudo (chased car)

Where the CO_2 masses are calculated according to the ISO mass calculation formula as follows [R25]:

Equation 8 $$m_{gas}(t) = \sum_{t=0}^{i=f \cdot T} u_{gas} c_{gas,i} q_{raw,i} \frac{1}{f}$$

Examples of calculations with the method above are given in Sections 6.2, 6.3 and 7.3.

6 Results Phase 1

6.1 Evaluation of PEMS measurement performance versus laboratory instruments

The laboratory systems were used in parallel to the PEMS instruments. The tests were conducted on a 48 inches chassis dynamometer (MAHA, max power 150 kW, max velocity 200 km/h, inertia 454-4500 kg) over standards cycles (NEDC) and over the newly developed Milan urban “real world” cycles. A Horiba MEXA-7400HTR-LE was used for CO, HC, NOx and CO_2 measurements. Total hydrocarbons emissions were measured by heated flame ionization detector (FID), CO and CO_2 were determined by non-dispersive infra-red analyses and Nitrogen Oxides were measured using a chemiluminescence analyser (CLA). The CVS flow rate was set to 6m3/min for all vehicle tests.

Additionally to the inter-comparison of PEMS with the laboratory instruments, PM was collected with the standard gravimetric method (PTS) using Teflon coated glass fibre filters (PallflexEMFABTX40HI20) weighted on a microbalance according to the European standards in force for filter weighting, conditioning and handling. Vehicle testing was carried out over the NEDC (three tests) and the Milan City Cycle (three tests). The gaseous emissions were measured during all the tests according to the current European official type-approval protocol. Figure 3 in section 4.2 showed the instrument installation on board and the exhaust flow-meters (EFM) with 2” diameter attached to the vehicle tailpipe.

6.1.1 Results on NEDC Cycle

Using the instantaneous data measured either with PEMS or with the laboratory instruments, the total cycle emissions where calculated according to ISO standard method [R25]:

Equation 9 $$m_{gas}(t) = \sum_{t=0}^{i=f \cdot T} u_{gas} c_{gas,i} q_{raw,i} \frac{1}{f}$$

Where: u_{gas} is the ratio between the density of the component (CO, THC, CO_2, NOx) and the density of the exhaust gas; c_{gas} is the instantaneous concentration of the component in the raw exhaust gas in ppm; $q_{raw,I}$ is the instantaneous exhaust mass flow in kg/h; *f* is the data sampling rate (equal to 1 Hz for the present measurements).

Good agreement was found between the reference test cell analyzers (Horiba) and the PEMS analyzers as shown in Figure 11 over the NEDC cycle for CO_2 (a), THC (b), CO (c), NOx (d) emissions (ppm) and measured exhaust mass flow (e) (kg/h) for the first 600 sec of the cycle; system 1 refers to the Horiba analyzers while system 2 to the Semtech DS.

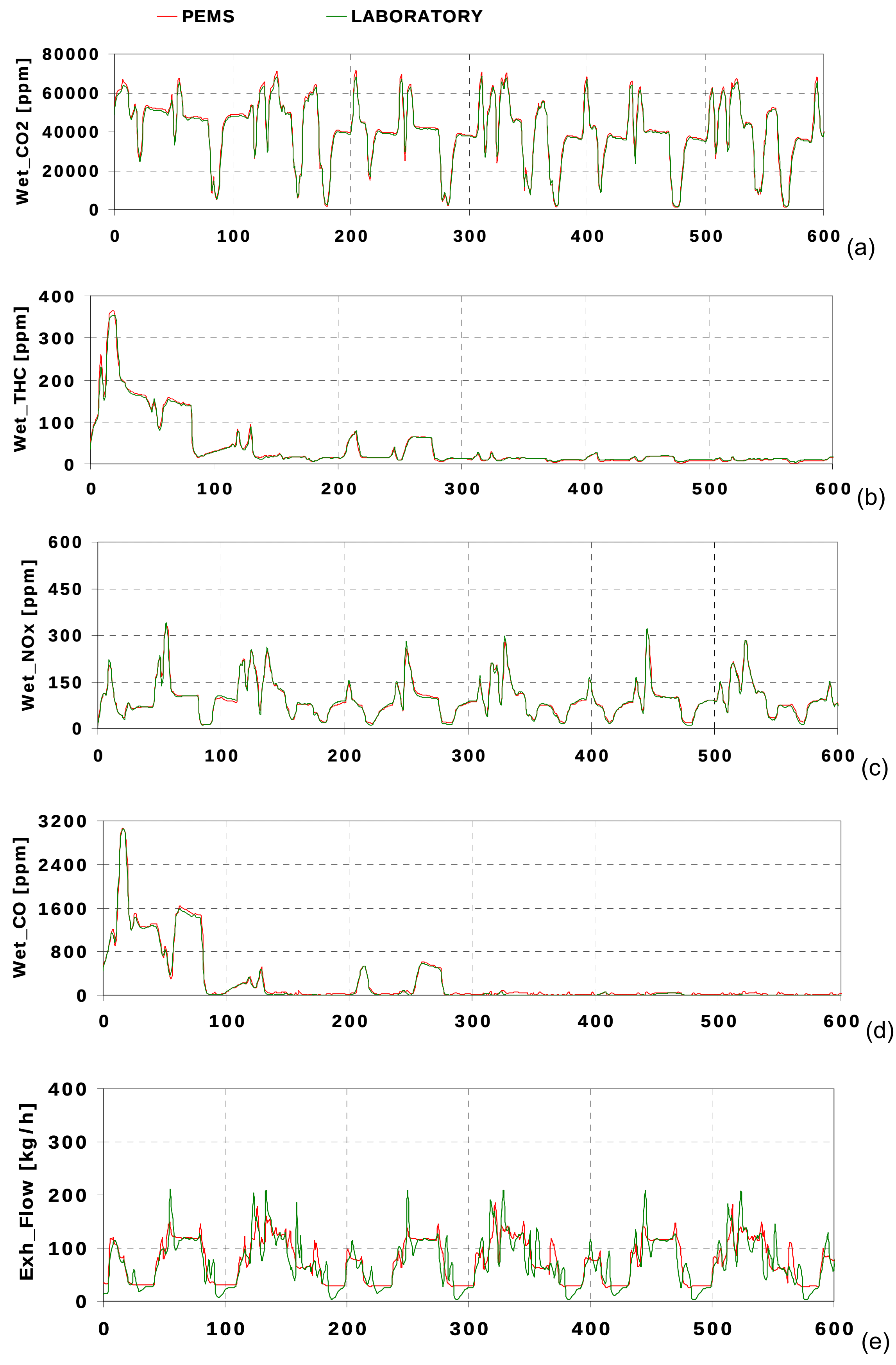
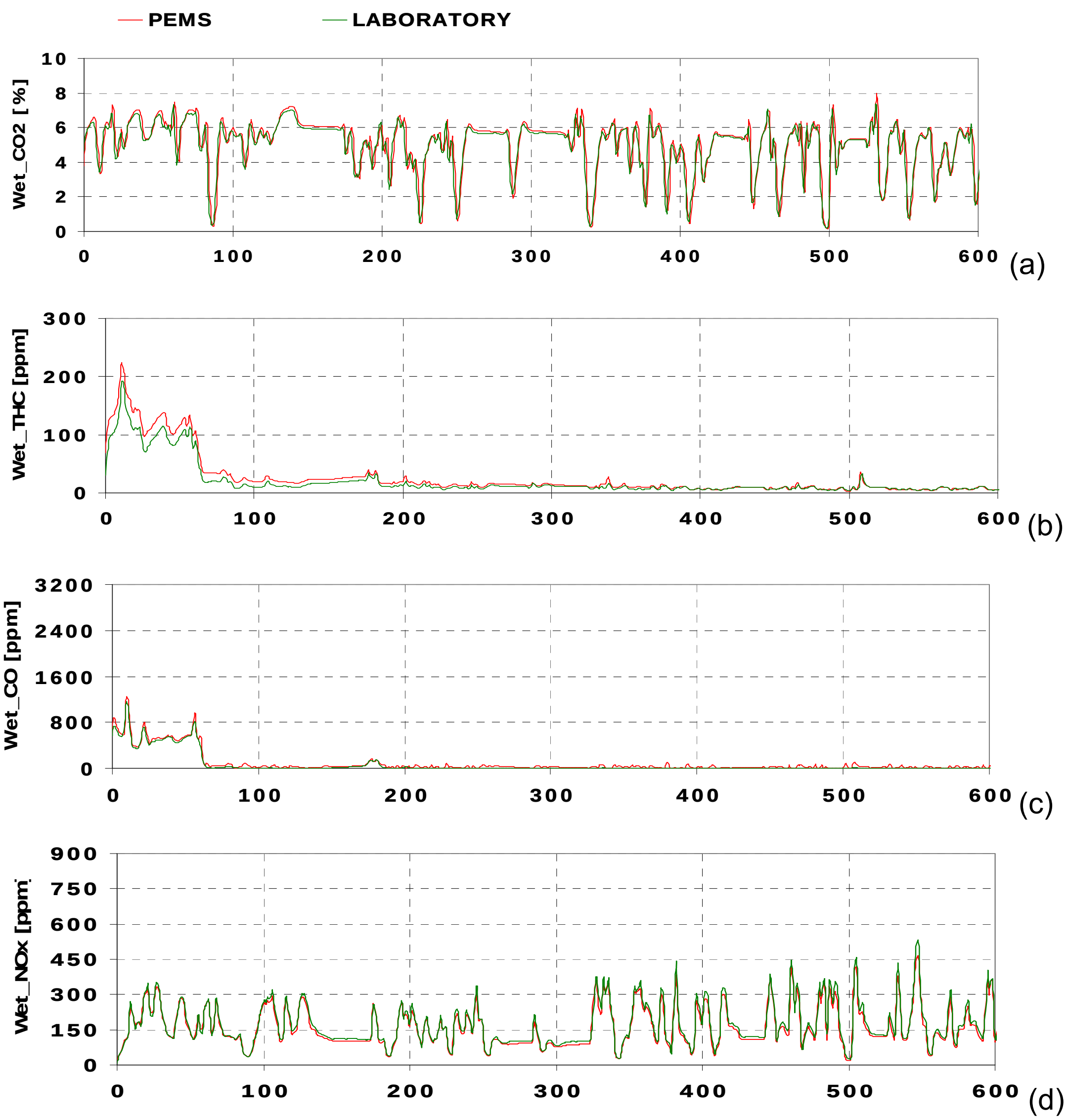
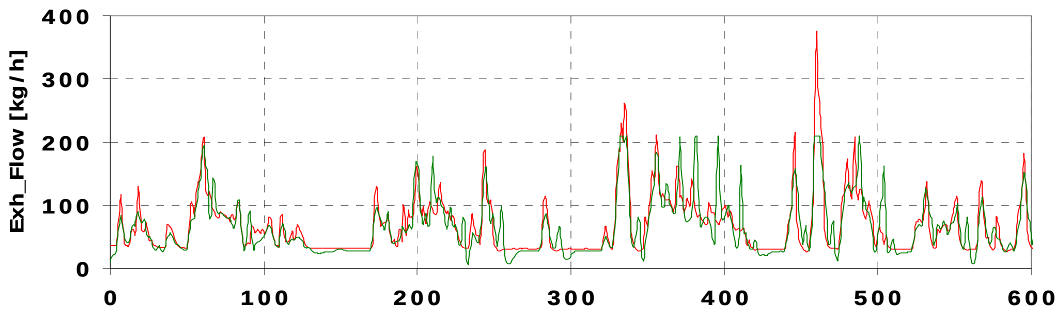

PEMS
LABORATORY
Wet_CO2 [ppm]
80000
60000
40000
20000
0
0
100
200
300
400
500
600
(a)
Wet_THC [ppm]
400
300
200
100
0
0
100
200
300
400
500
600
(b)
Wet_NOx [ppm]
600
450
300
150
0
0
100
200
300
400
500
600
(c)
Wet_CO [ppm]
3200
2400
1600
800
0
0
100
200
300
400
500
600
(d)
Exh_Flow [kg/h]
400
300
200
100
0
0
100
200
300
400
500
600
(e)

Figure 11- Comparison between reference laboratory instruments (Horiba) and Semtech DS over the NEDC cycle for CO_2 (a), THC (b), NOx (c), CO (d) and exhaust gas flow (e); red refers to the Horiba analyzers while green to Semtech DS.

6.1.2 Results on Milan City cycle

Similarly to the NEDC instrument comparison, good agreement was found on the Milan City cycle. Comparison between reference laboratory instruments (Horiba) and Semtech DS over the Milan City cycle for CO_2 (a), THC (b), CO (c), NOx (d) exhaust gas emissions (ppm) and measured exhaust mass flow (e) (kg/h) is reported in Figure 12 for the first 600 sec of the cycle; system 1 refers to the Horiba analyzers while system 2 to the Semtech DS. Characteristics of the Milan City Cycle may be found in [R23].





(e)

Figure 12 - Comparison between reference laboratory instruments (Horiba) and Semtech DS over the Milan PEMS cycle for CO_2 (a) , THC (b), CO (c), NOx (d) exhaust gas emissions (ppm) and measured exhaust mass flow (e) (kg/h) vs. time (s); laboratory (red) PEMS (green.)

Mass emissions have been recalculated according to the ISO standard [R25] for both test cell (Horiba) and PEMS instrumentation and are presented as mass emissions in g/km. Data are reported as average over the three cycles for both NEDC and Milan City cycle in Figure 13 for CO_2 (g/km) and in Figure 14 for CO, THC, and NOx (g/km), distinguishing between test cell analyzers (Horiba) and PEMS (Semtech DS).

Good agreement was found on both cycles between test cell instrumentation and PEMS. However, much higher exhaust gas emissions are observed over the Milan City compared to the NEDC cycle, especially for CO_2 and NOx with almost double emission values while similar emissions are reported for THC. PM emissions are also higher for the Milan City cycle as shown in Figure 15 with average values of over the three tests of 0.03 g/km for the NEDC and 0.07 g/km for the Milan City.

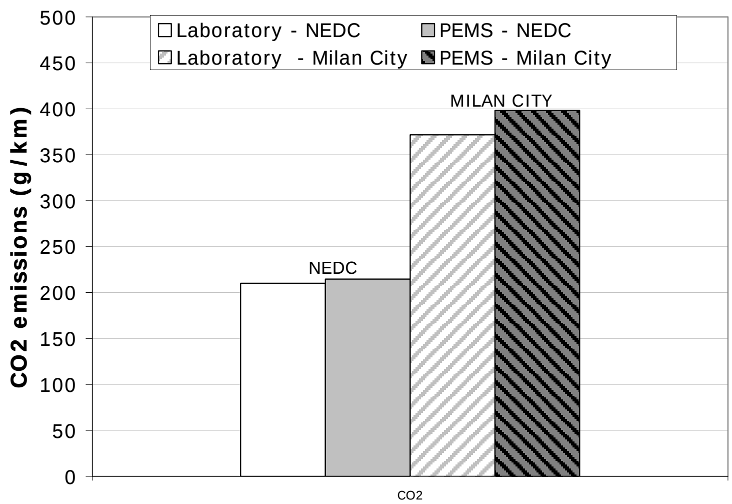


Figure 13 CO2 exhaust gas emission (g/km) as average over three cycles for both NEDC and PEMS cycle, distinguishing between laboratory (Horiba) and PEMS instrumentation.

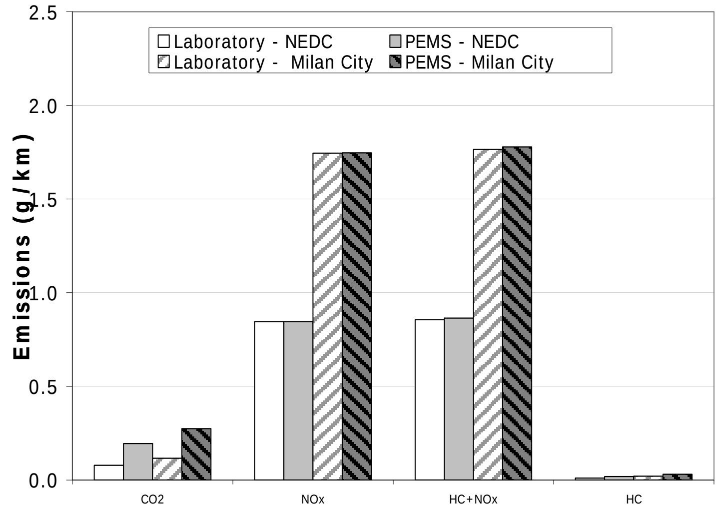


Figure 14 CO, THC, and NOx exhaust gas emissions (g/km) as average over the three cycles for both NEDC and Milan City cycle; laboratory (Horiba) versus PEMS instrumentation.

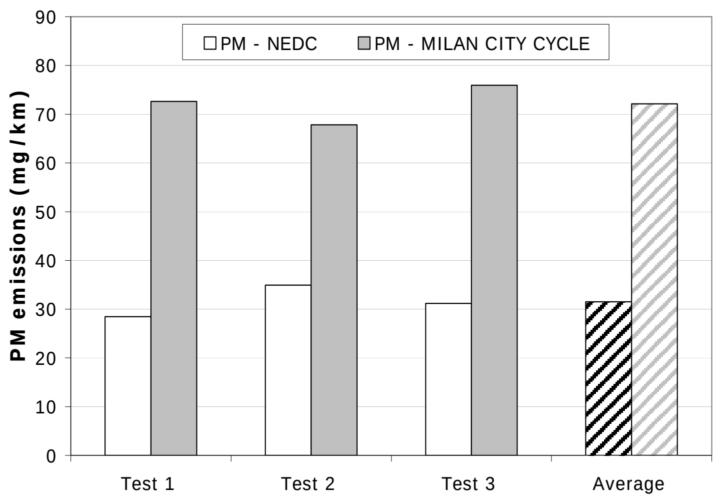


Figure 15 PM emissions (mg/km) over the three NEDC and PEMS cycles and average values.

6.2 On-road emissions variability [R23]

This section presents the results obtained for a Fiat Scudo 1.9 Diesel (EURO 3). The vehicle was tested on test routes including a variety of conditions:

- Route 1 whose speed profile is illustrated in Figure 16 is a city drive for which the vehicle speed does not exceed 60 km/h. This test was conducted in the area where most of the data was collected which was used to develop the MILAN City cycle.

- Route 2 is a different type of route including different types of driving conditions like rural driving in villages as well as motorway driving for which the velocity of the vehicle reaches up to 120 km/h. It also includes city driving and contains a short portion with a traffic jam at the end of the test. This data is presented here to illustrate how the CO_2 method characterizes on-road data different from the city driving conditions .

Using the CO_2 based averaging window method introduced in section 5.3, the on-road emissions are compared for the same vehicle to the ones measured on two laboratory test cycles: the standard NEDC and a custom MILAN CITY CYCLE developed to represent the driving patterns in the city of Milan.

The variability of the deviation ratios (and therefore the variability of the on-road emissions calculated from the CO_2 windows) is illustrated in 0 and 0, where the NOx deviation ratios are plotted against the average vehicle speed, i.e. each single data points represents the result obtained for a single CO_2 based calculation window. The results for the laboratory test cycles are reported in the same plots as markers: square for the NEDC and triangle for the MILAN CITY cycle.

From Figure 18 (a), the similarity between the average speeds for the MILAN City cycle and the on-road data analyzed with the CO_2 window may be observed. One can also see that the method brings a significant level of information on the variability of the on-road emissions when compared to a conventional laboratory cycle such as the NEDC; further details can be observed in Figure 18 (b), which shows the statistical distribution of the NOx deviation ratios. For instance, Figure 18 (b) shows that – most often - the on-road emissions calculated with the CO2 based method represent 1.2 to 1.3 times the mass emissions of the NEDC cycle.

Similarly to Figure 18, results for route 1+2 are shown in Figure 19, which further illustrates the potential of the calculation method and compares the data of the NEDC with some on-road results. Figure 19 (a) shows the cycle emissions versus the vehicle average speed for route 1+2, the NEDC and the MILAN City cycle. It is evident that – for the present vehicle - it was possible to measure emissions on the road that get sometimes close to the ones of a representative cycle in the case of the ideal MILAN City cycle, but not for the NEDC, whose emissions measured in the laboratory are far from any on-road data (even at similar average speeds).
This tends to confirm that the traditional test cycles, and the NEDC in particular, cannot ideally model the range of driving conditions found on the road, nor give a good estimate of the vehicle true emissions. The results also show that it becomes possible to get closer to the real operating conditions when developing a custom cycle such as the MILAN City cycle. It is clear that this reference cycle is only really representative for the data base it was developed from. This is indeed a shortcoming of transient cycles as they are limited to represent the pool of vehicles/engines used to develop the data base. The single number emissions results obtained for such cycles cannot provide the detail of information given by on-road measurements.
Such comparison is possible using the CO_2 window calculation method, which provides a fair comparison of emissions results averaged over cycles, whose common characteristic is a reference CO_2 mass.

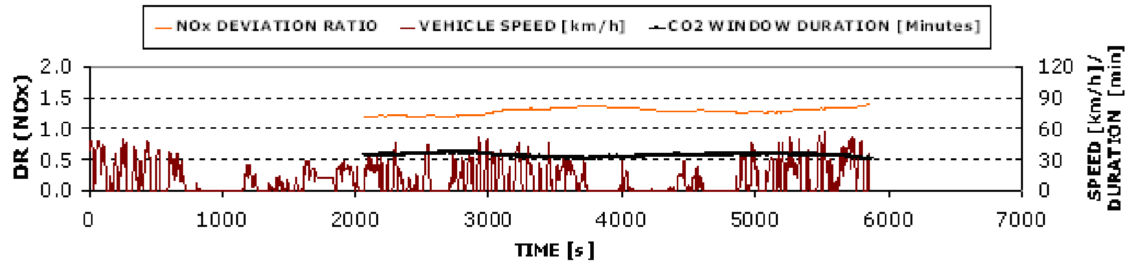


Figure 16 NOx deviation ratio (dimensionless) vs. time over test route 1.

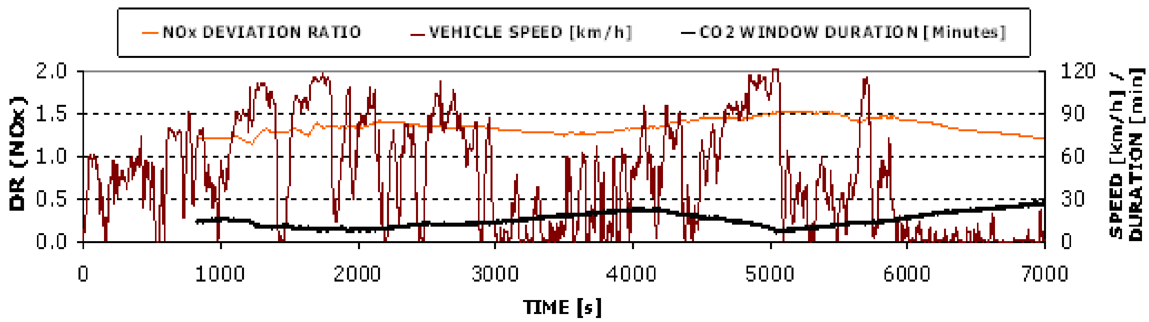


Figure 17 NOx deviation ratio (dimensionless) vs. time over test route 2.

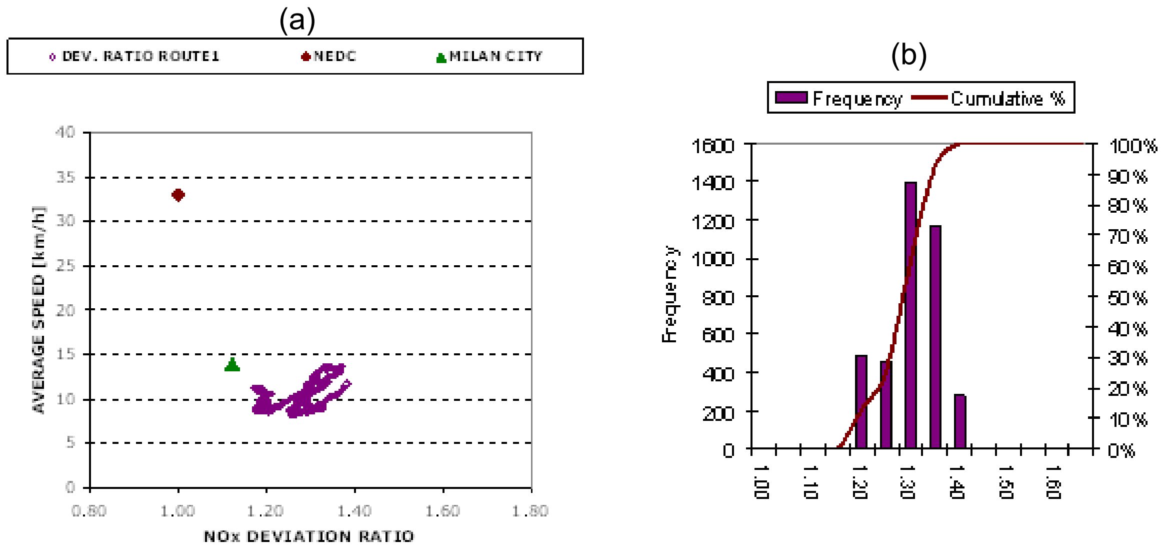


Figure 18 *NOx deviation ratio versus CO_2 window average speed for route 1 (urban). Brown marker square: NEDC, green marker triangle: Milan City cycle (a). Histogram of NOx deviation ratios for route 1 (b).*

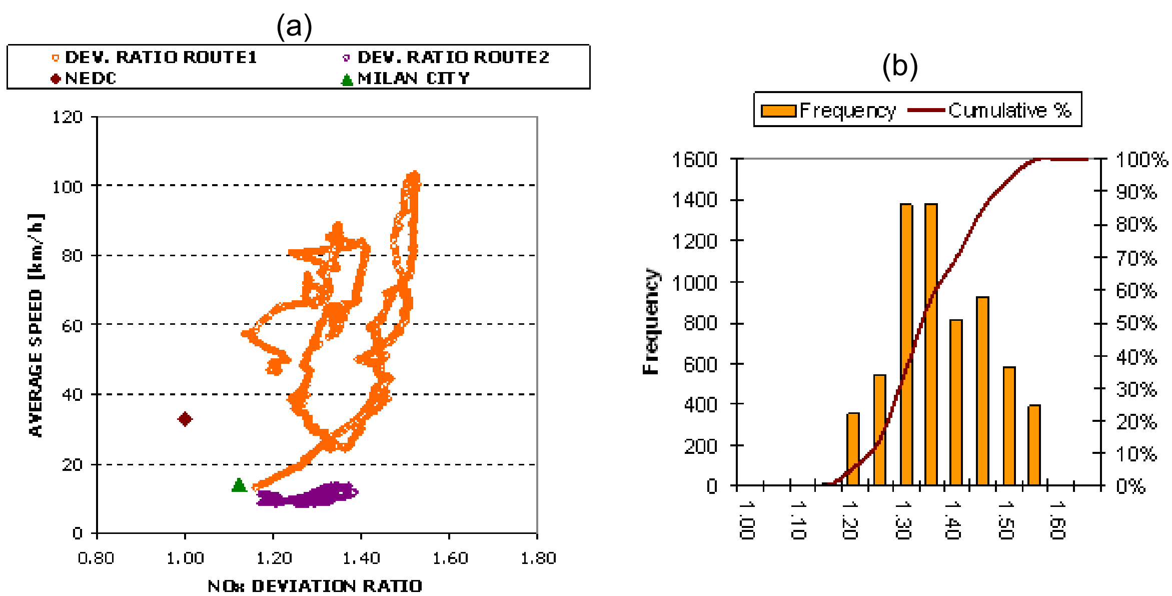
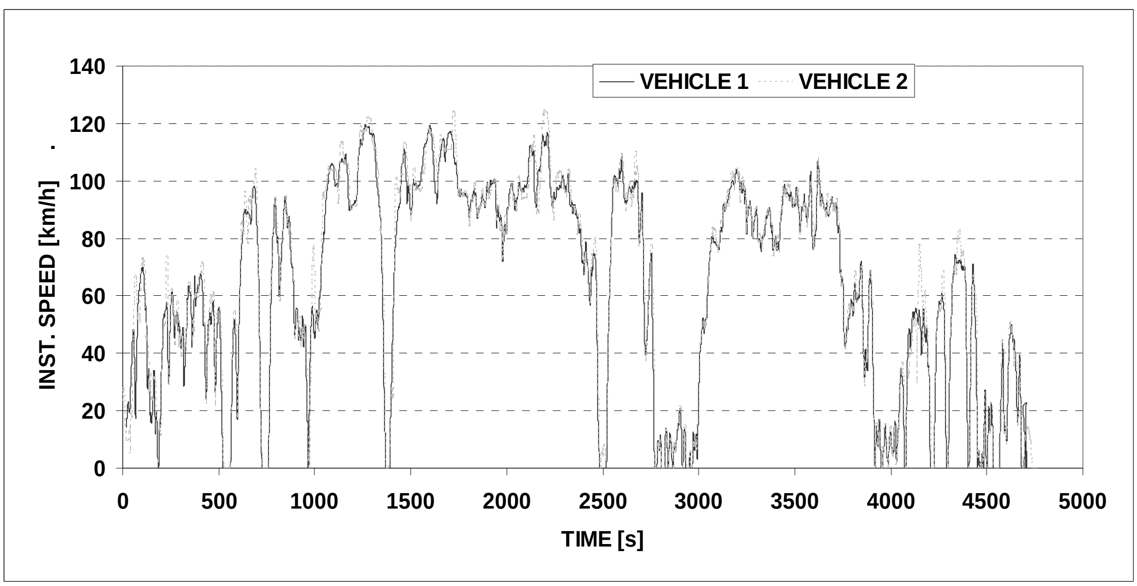


Figure 19 NOx deviation ratio versus CO_2 window average speed for route 1 (urban) and 2 (extra-urban and highway). Brown marker square: NEDC, green marker triangle: Milan City cycle (a). Histogram of NOx deviation ratios for Route 2 (b).

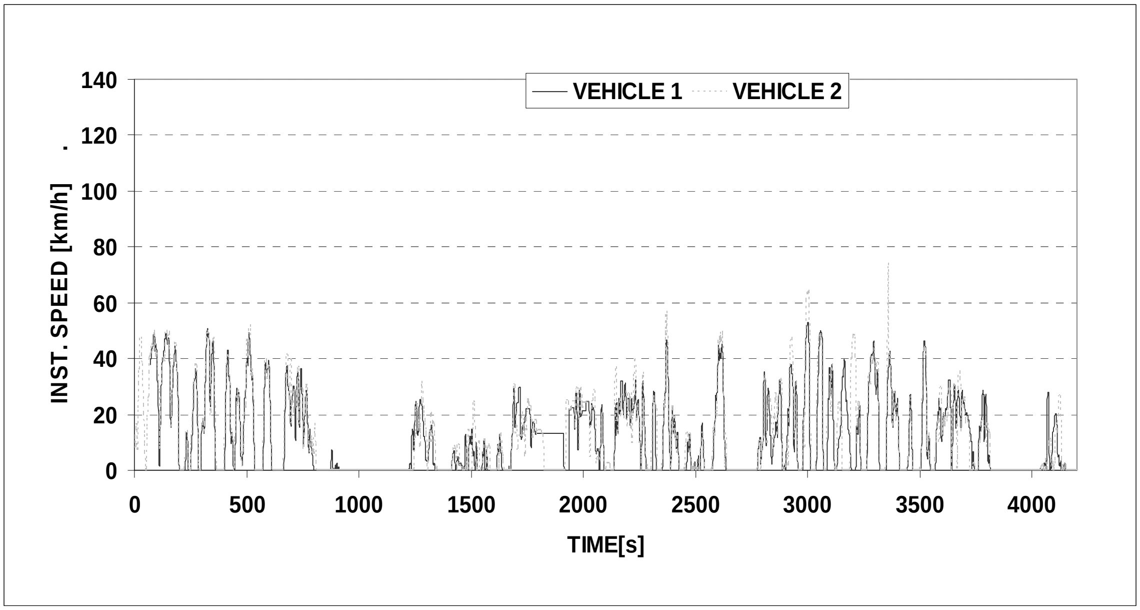
6.3 Chase Testing experiments [R24]

6.3.1 Introduction

For the experiments presented in this section, 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. PEMS emissions measurements are reported distinguishing between highway and rural and urban routes. Figure 20 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 20 (a, b) are presented respectively in Figure 21 (a, b). The calculated slopes (1.0 for the rural-highway section, 0.9 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 expected, a good chase is more difficult to achieve in the city, where, with traffic being intense, the driver of the chasing vehicle has difficulties to maintain the constant distance between the two test vehicles.



(a)



(b)

Figure 20 Velocity profile for both vehicles: Fiat Scudo (vehicle 1) and VW T5 van (vehicle 2) over the rural-highway route Ispra-Milan (a) and city route downtown Milan (b).

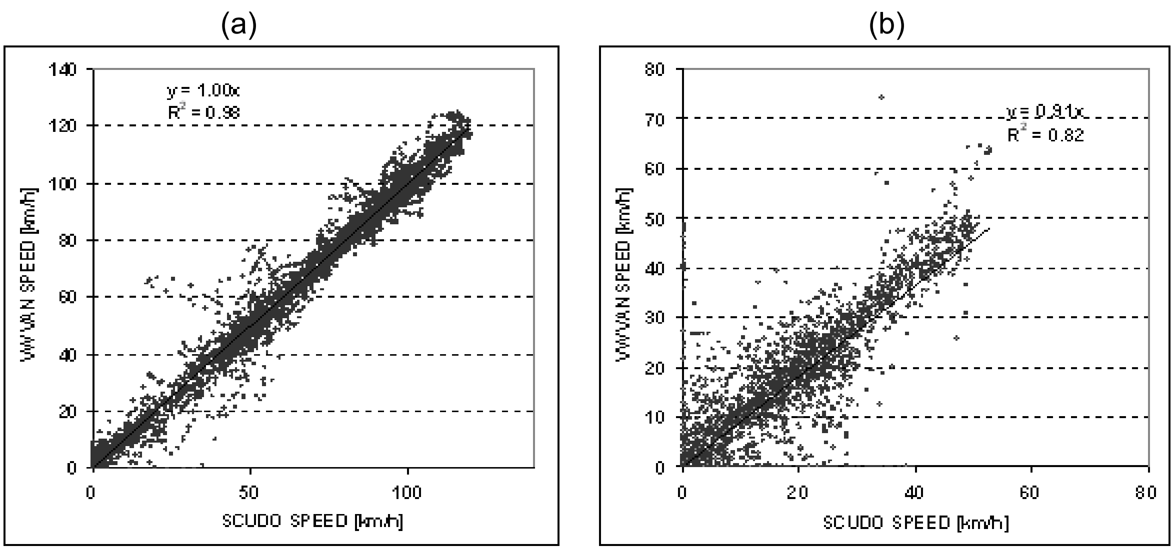
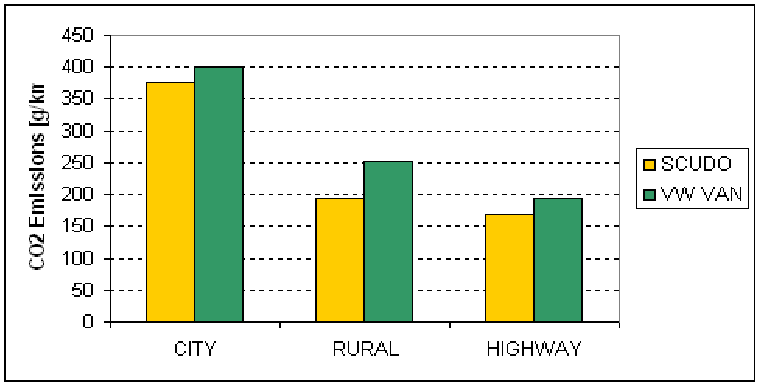


Figure 21 VW van speed vs. Fiat Scudo speed over the rural + highway route (Ispra-Milan); R2 = 0.98 (a) and city route - R2 0.82 (b) during chase testing.

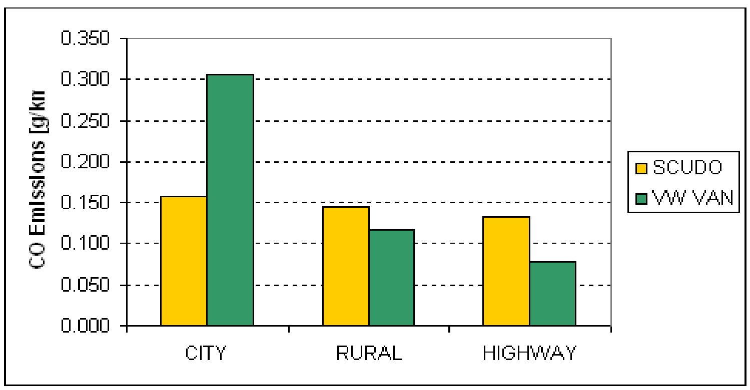
6.3.2 Comparison of integrated emissions

The comparison of PEMS emissions measurements for all routes (city, highway and rural) for both vehicles is shown in Figure 22, distinguishing among CO_2 (a) CO (b), NOx(c) and fuel consumption (d). Fuel consumption values for the two vehicles are reported as well in Figure 22 (d). As expected (because of the higher engine power and vehicle mass), the emissions as well as fuel consumption is generally higher for the VW T5. However the VW T5 van is Euro 4 type while the Fiat Scudo is a Euro 3 type. CO, CO_2 emissions are higher for the VW van over the urban route (city) while NOx is slightly higher (about 20%)

for the Fiat Scudo over the same urban route, . Higher NOx emissions are measured for the VW van over the rural and highway routes. CO_2 emissions are similar for both vehicles for the urban case but generally higher over rural and highway route for the VW van case. CO is much higher for the VW van over the urban route (around 50%) but not over the highway route where the Fiat Scudo is emitting around 30% more. Fuel consumption is higher for the VW van around 6% over the urban, 20% over the rural and 13% over the highway route.



(a)



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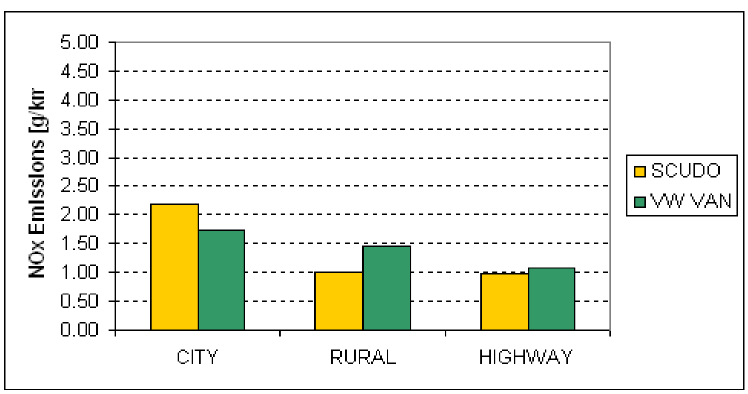
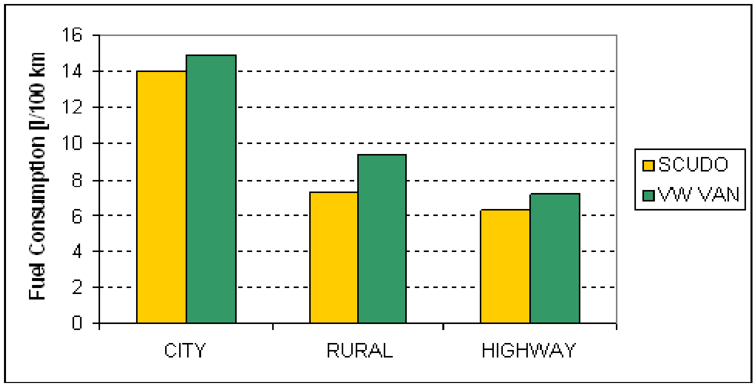


(c)

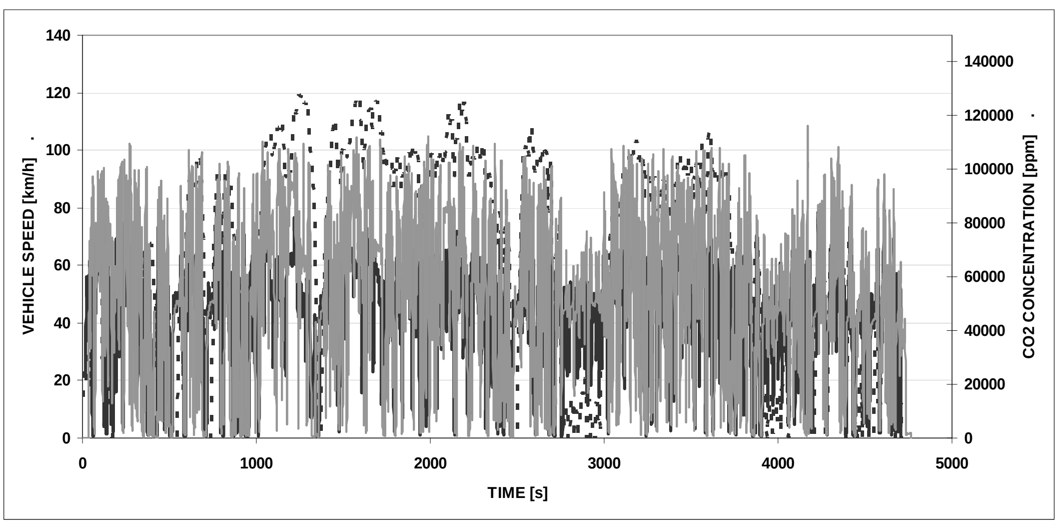


(d)

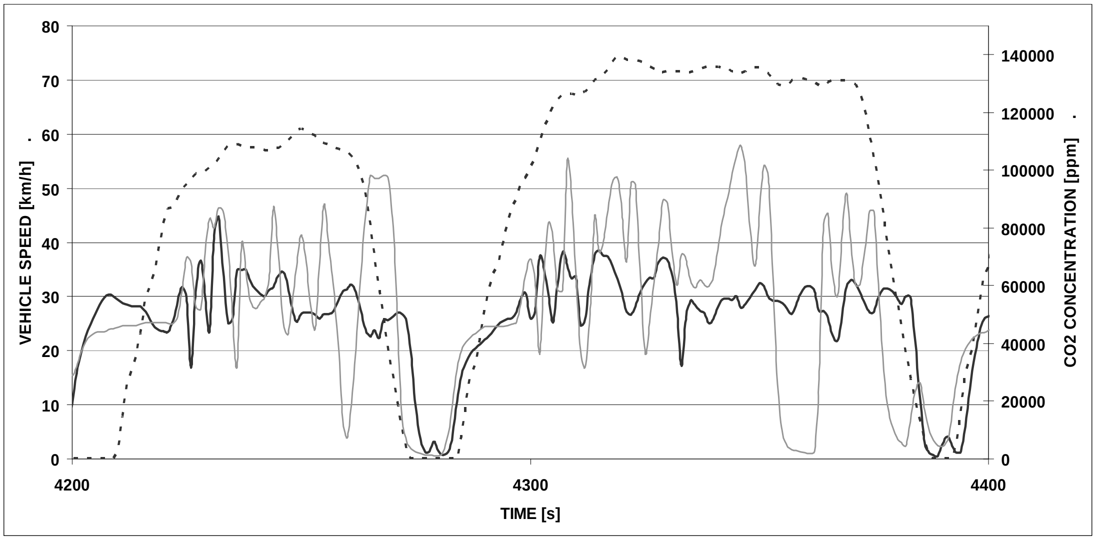
Figure 22 Comparison of exhaust emissions for the two vehicles over city, rural and highway route for CO2 (a), CO (b), NOx (c), and fuel consumption (d)

6.3.3 Chase testing effects

When looking for example at CO_2 emissions over the highway route for both vehicles (Figure 23), one can observe that the chaser (VW Van, grey line) exhibits a much wider range of CO2 concentrations during the test, up to 100000 ppm. Looking at the details in the same figure (See Figure 23b), one sees that one of the vehicles, at cruising speed exhibits a smooth CO_2 concentration trace whereas the chaser (VW van, grey line) reveals bigger variations .



(a)



(b)

Figure 23 *CO_2 emissions concentrations for the two vehicles over the highway route Ispra-Milan (a) and zooming into the same figure between 4200 s and 4400 s (b); chaser (grey line) chased (black line), vehicle speed (dotted line).*

Such a difference can be attributed to a ‘chase testing effect’: when the driver of the vehicle in front (chased) can cruise at a relatively stable speed, the driver of the second vehicle is constantly regulating the distance between the two vehicles using the accelerator pedal. The bigger variations observed in the CO_2 concentrations of the second vehicle (VW van) are clearly a result of this behaviour.

As result of the analysis of comparing the positive acceleration (i.e. when the engine has to work) between the two vehicles over the highway route Ispra-Milan, the chaser vehicle (VW Van T5) has 12.4 % more of positive acceleration elements. Thus the chaser has to be considerable more dynamic than the chased .

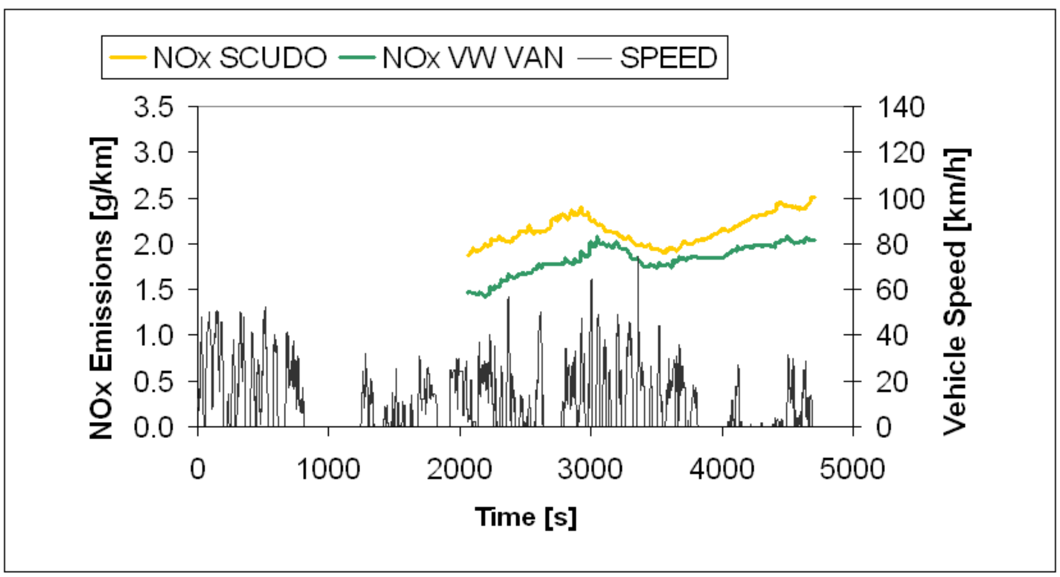
The more in positive acceleration means more work and thus higher fuel consumption and more emissions. This may effect significantly the emissions even tough of course other elements will play also an important role. In this particular case NOx and CO_2 emissions are increased by 15 - 19 % in the VW van case (Figure 22). The results of this type of chase are only of limited value for the comparison of the respective emission behaviour. This observation on the emissions is important as the very good R2 of 0.98 would suggest that the chase is indeed successful.

6.3.4 CO_2 window emissions

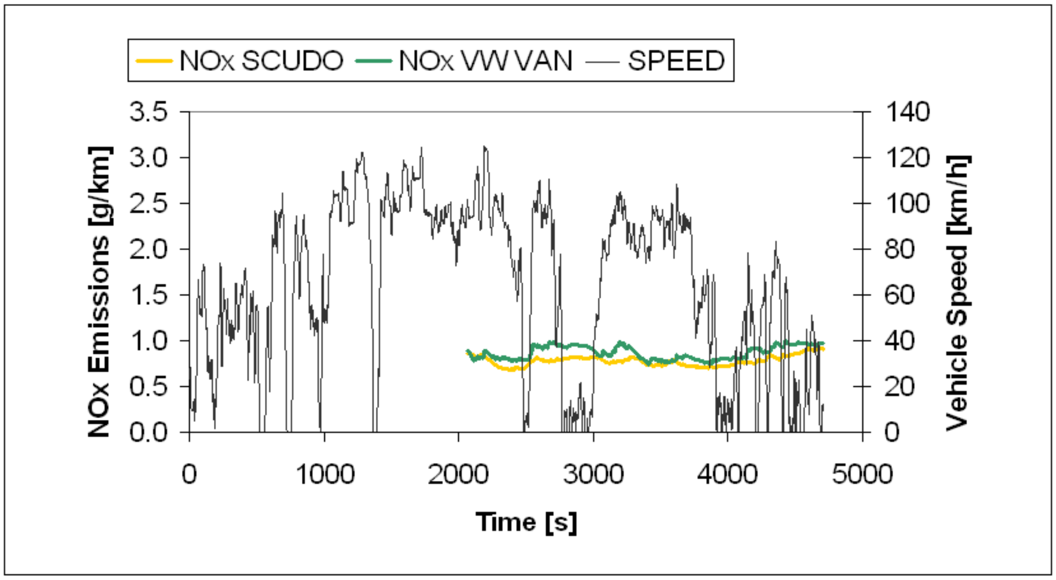
Figure 24 presents NOx emissions measurements as g/km versus time for the chaser (VW T5 van), in green, and chased vehicle (Fiat Scudo), in yellow, respectively for the urban (a) and rural-motorway (b) routes. Figure 25 presents the NOX deviation ratio values (DR_{NOx}) for the two vehicles over the rural (a) and rural-motorway route (b) as in Figure 24; the light grey points represent the VW T5 van whereas the dark grey ones show the results for the Fiat Scudo (chased).

Figure 26 shows instead the NOx deviation ratios for the two vehicles versus the window average speeds, where the window average speed corresponds to the average speed of each subset considered for the CO_2 method. Euro3 and Euro4 NOx limits are reported for the NEDC only in Figure 25; these correspond to a DR_{NOx} value respectively of 0.5 and 1 .
What clearly appears from Figure 24 and Figure 25 is the difference in the NOx emissions mainly over the urban routes (Figure 24 a) and the difference in the NOx deviation ratios between the two vehicles in the average speed range from 10 to 50 km/h: the VW Van (Euro 4) exhibits ratios between 1.2 and 1.6 while the Scudo (Euro 3) has ratios between 1.7 and 2.0 (Figure 25). The Euro3 and Euro4 limit values reported are calculated considering the EURO3 Class II limit over the NEDC cycle, i.e. 7.15 g (0.65 g/km multiplied by the length of the cycle in km) for the chased vehicle (Fiat Scudo); therefore the Euro3 limit for NOx equals 1 for the chased and the Euro4 equals 0.5 for the chaser vehicle.

As the average vehicle speed increases, the difference between the ratios of the two vehicles gets smaller (see Figure 25). For average speeds above 50 km/h, the ratios for both vehicles fall in the same range (1.5 to 2 times the NEDC NOx emissions), which means that their on-road emissions performance is nearly identical in the high speed range. Similar findings were already reported in [R15], where NOx emissions of different generations of light-duty vehicles tested on two laboratory driving cycles (NEDC and Artemis) were reduced only over the standard NEDC.

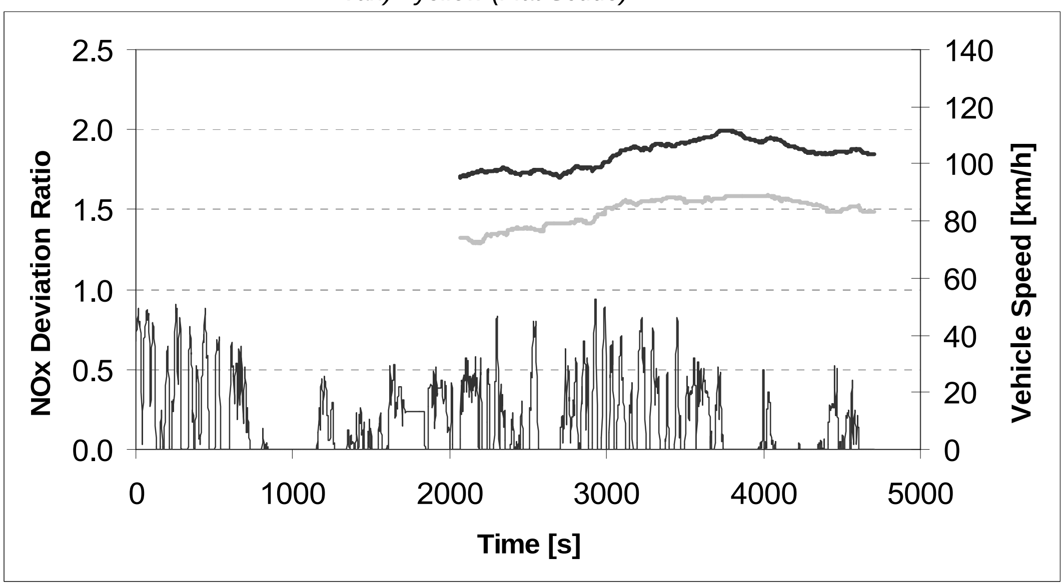


(a)

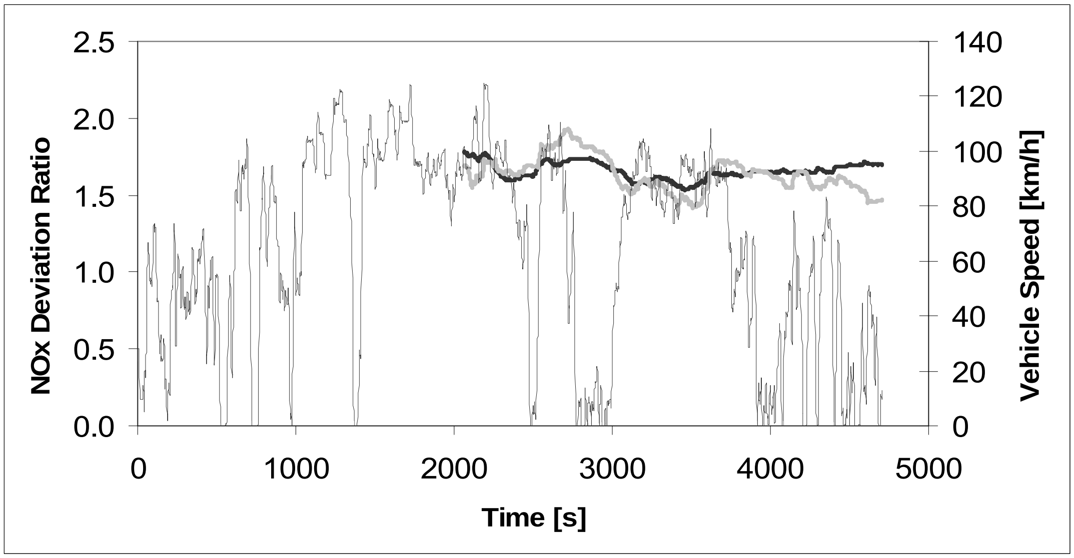


(b)

Figure 24 Illustration of the CO2 window principle and NOx emissions measurements (g/km) over the urban (a) and highway test route (b) for both vehicles. – green (VW T5 van) - yellow (Fiat Scudo)



(a)



(b)

Figure 25 Illustration of the CO2 window principle and NOx deviation ratio over the urban (a) and highway test route (b) for both vehicles; light grey (chaser), dark grey (chased)

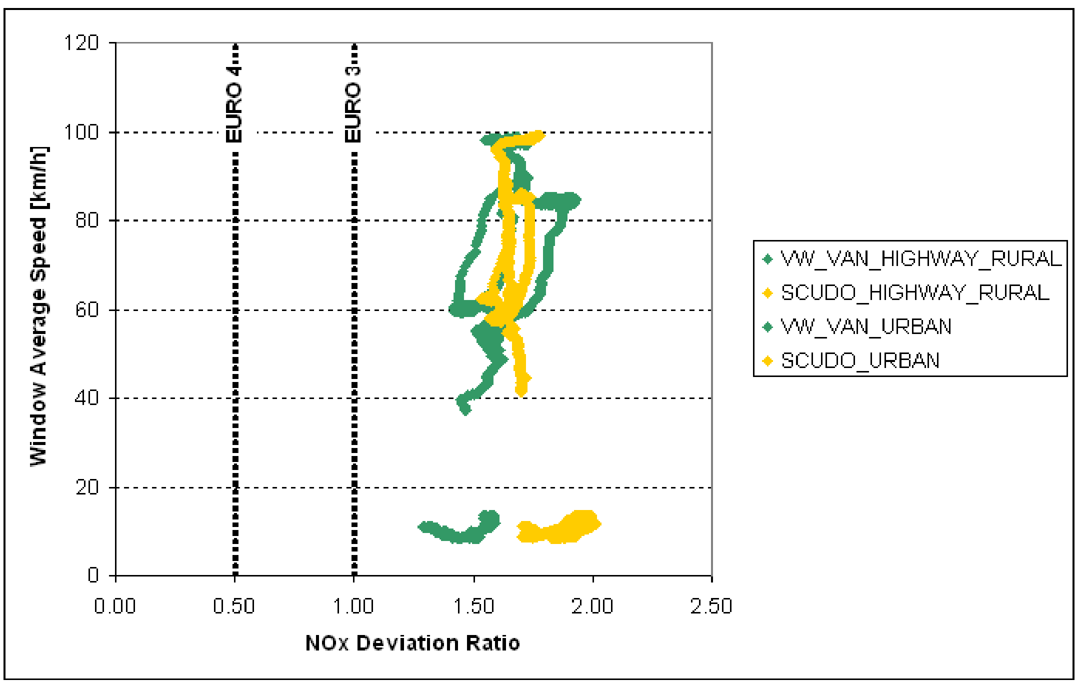


Figure 26 Window average speed versus NOx deviation ratios for the two vehicles during chasing experiments over both urban and highway routes – green (VW T5 van) - yellow (Fiat Scudo)

NOx emissions for the two vehicles during chasing experiments over both urban and highway routes (Figure 26) show how far away from "real world driving" conditions the current limits over the standard NEDC are. The VW van is performing better then the Fiat Scudo but only in urban driving conditions. This is a more compact way to look at the PEMS data pinpointing the differences between the two vehicles and differences compared to the emissions on standard cycles like the NEDC.

6.4 Conclusions Phase 1

From the evaluation of on-road emissions variability (Section 6.2):

The results from the standardized procedures cannot be reliably representative for the fuel consumption and emission in real world operation of the vehicle. The development of representative test cycles from real world data sets, which has become a typical approach to address special driving situations, results less efficient because of the effort needed for the development and the poor representativeness of the results beyond the underlying data.

From the chase testing experiments (Section 6.3):

Chase testing was used to compare the relative emissions and fuel consumption performance of the two LDVs under nearly identical testing operating conditions (i.e. operating speed and ambient conditions). The approach was judged as feasible even though it was observed that the "chase experiment" itself may have an impact on emissions as the chaser vehicle has higher positive acceleration than the chased.

This study confirms how difficult and inefficient the traditional approach based on ideally representative test cycles is when it comes to evaluate the real vehicle emissions and their variability on the road. The analysis of the on-road emissions through the CO_2 averaging window shows where differences in emissions are between the two vehicles. The proposed approach is very promising to study the on-road emissions and fuel consumption measurements from LDVs using PEMS as it provides an indication for any vehicle tested on the road with PEMS of its emissions performance relative to the conventional laboratory test cycles. The analysis clearly shows that the most recent vehicle emits less NOx, but only in the low speed range (below 50 km/h) under urban driving conditions.

In general:

Analysing PEMS data with an adequate methodology gives a detailed insight into the on-road emissions behaviour of the vehicles with respect to their behaviour on 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.

7 Results Phase 2

7.1 Introduction

Using the methodology (test protocol and data processing methods) developed during the first phase of the program, the main objective of phase 2 was to evaluate potential emissions ‘problems’ arising when vehicles are driven under real-world conditions. The investigations were therefore carried out on a larger sample of vehicles, including various engine technologies (hybrid, gasoline and diesel engines). The tests were repeated over the same reference routes (introduced in section 4.4) and several times for the test vehicles, to allow for a statistical analysis of the emissions variability caused by traffic changes at different times or even different days on the same route.

7.2 Average Emissions

The data presented in Figure 27, Figure 28, Figure 29 and Figure 30 are the emissions results obtained respectively for THC, CO, NOx and CO_2 on the three reference test routes (Route1, 2 and 3) and some of their sub-sections (motorway and city).

Note that:

- The results for the phase 1 vehicles are only shown for the motorway and city sections, as these vehicles were not tested on the reference routes proposed for phase 2;
- Each bar is an the average of 2 or (most often) three tests;
- The diesel vehicles do not have to meet any THC limit as such, as they have to meet a (THC + NOx) limit instead: their THC emissions are illustrated only for comparative purposes with the gasoline vehicles.
- For all the vehicles and all the test routes, the results are expressed as a percentage of the applicable limit: for example, 200% will be calculated for a vehicle that should meet a 0.25g/km limit on the NEDC cycle and exhibiting 0.5g/km on the road.
- The results are no longer presented as “Deviation Ratio” DR (as in the previous section), but as a percentage of the target (the limit, as explained above) or the declared performance on the NEDC in the case of CO_2.

The following observations could be made for the distance specific emissions integrated over the complete test routes:

- All THC and CO vehicles emissions are far below the applicable limits;
- The diesel vehicles exhibit NOx emissions well above the applicable limits (200% to 400% of the limit), and this observation is independent of the test route;
- Only one of the gasoline vehicles was found on the road to exceed the NEDC NOx limit: this was observed for the most demanding route (Route 3, uphill).

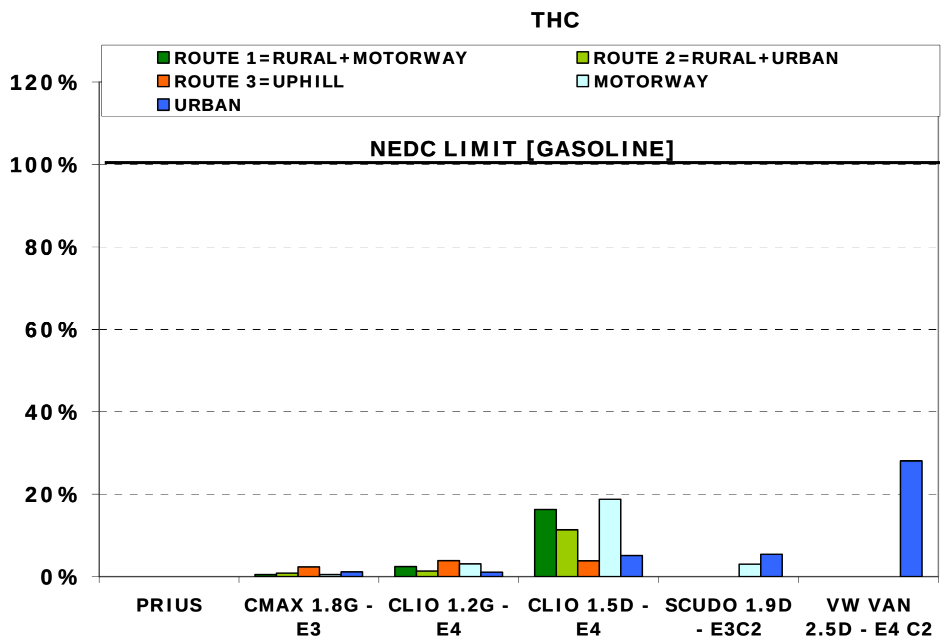


Figure 27Total Hydrocarbons: On-road distance specific emissions versus applicable limit on NEDC cycle.

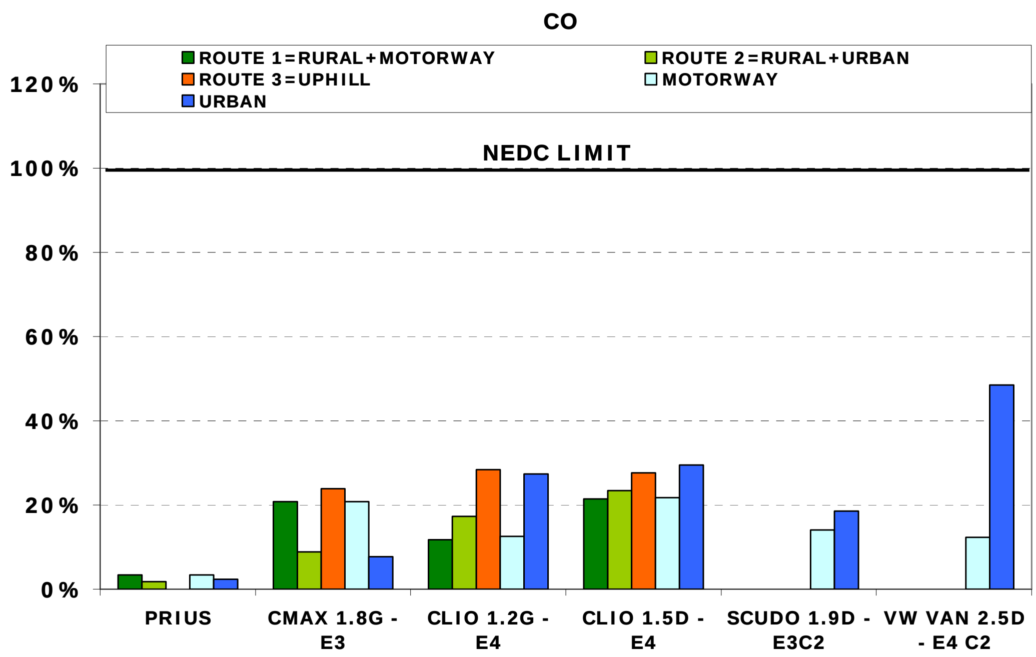


Figure 28 Carbon Monoxide: On-road distance specific emissions versus applicable limit on NEDC cycle.

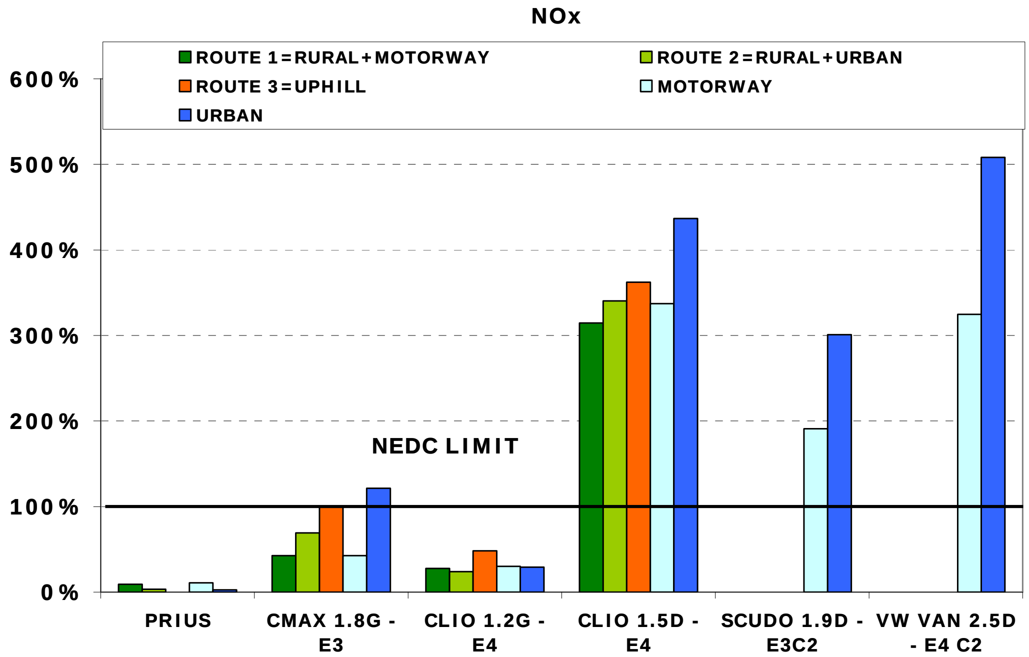


Figure 29 Nitrogen Oxides: On-road distance specific emissions versus applicable limit on NEDC cycle.

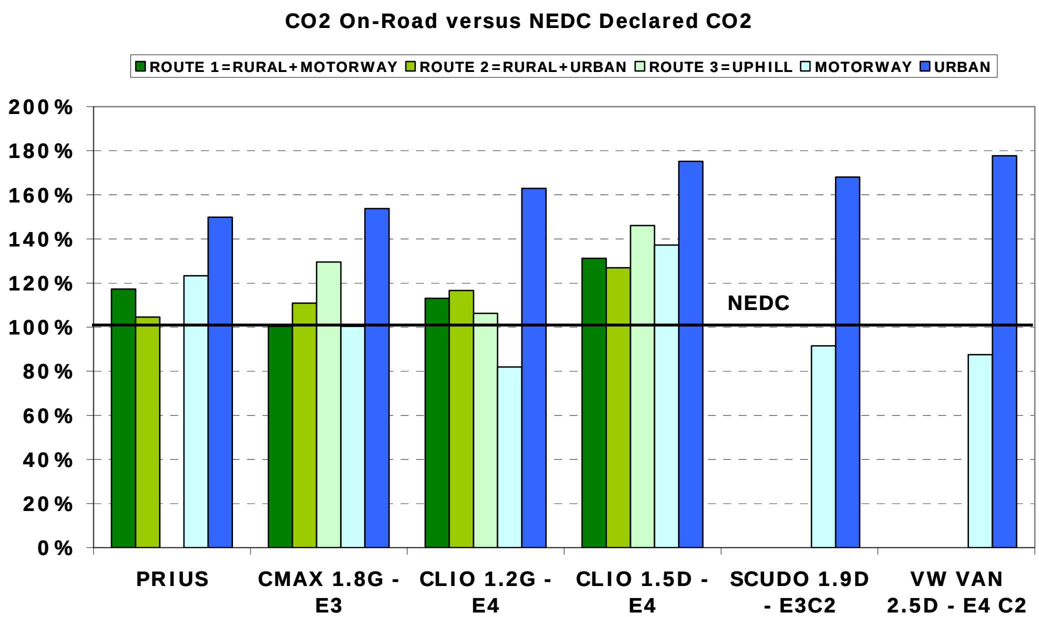


Figure 30 CO2 - On-road distance specific emissions versus declared value on NEDC cycle.

7.3 CO_2 averaging window method

The results presented in Figure 31, Figure 32, Figure 33 and Figure 34 are the emissions calculated with the CO_2 averaging window method respectively for the Prius, CMax, Clio Diesel and Clio Gasoline on the three reference test routes (Route1, 2 and 3).

Note that:

- The results for each route is represented with a different colour: orange for Route1 (Motorway), brown for route 2 (City), rural and red for Route 3 (Uphill);
- All the test repeats conducted for one test route are plotted;
- The X-axis represents the emissions as a percentage of the applicable limit for each pollutant; similar to the previous section, the diesel vehicles do not have to meet any THC limit as such, as they have to meet a (THC + NOx) limit instead: their THC emissions are illustrated only for comparative purposes with the gasoline vehicles.

These results confirm the observations made from the integrated results in the previous paragraph. As the advantage of the CO_2 averaging window method is to show the variability of the on-road emissions with respect to the emissions on a standard test cycle, some basic statistics calculations were carried out and are presented in Figure 35 and Figure 36 respectively for NOx and CO_2. These figures show the minimum, maximum and average (at the boundary of the two colours) of the values calculated with the method. The charts show which that Route 3 (as expected because it is the most demanding) gives the largest scatter of results for all the vehicles whereas Route2 (motorway) exhibits the smallest scatter.
It is important to remark that the scale of the x-axis in Figure 35 a, b and d is different from the one in Figure 35 c, as the values corresponding to that vehicle (Clio Diesel) were exceeding by far (up to 1200 %) the standard 300% chosen as upper limit for all the charts.

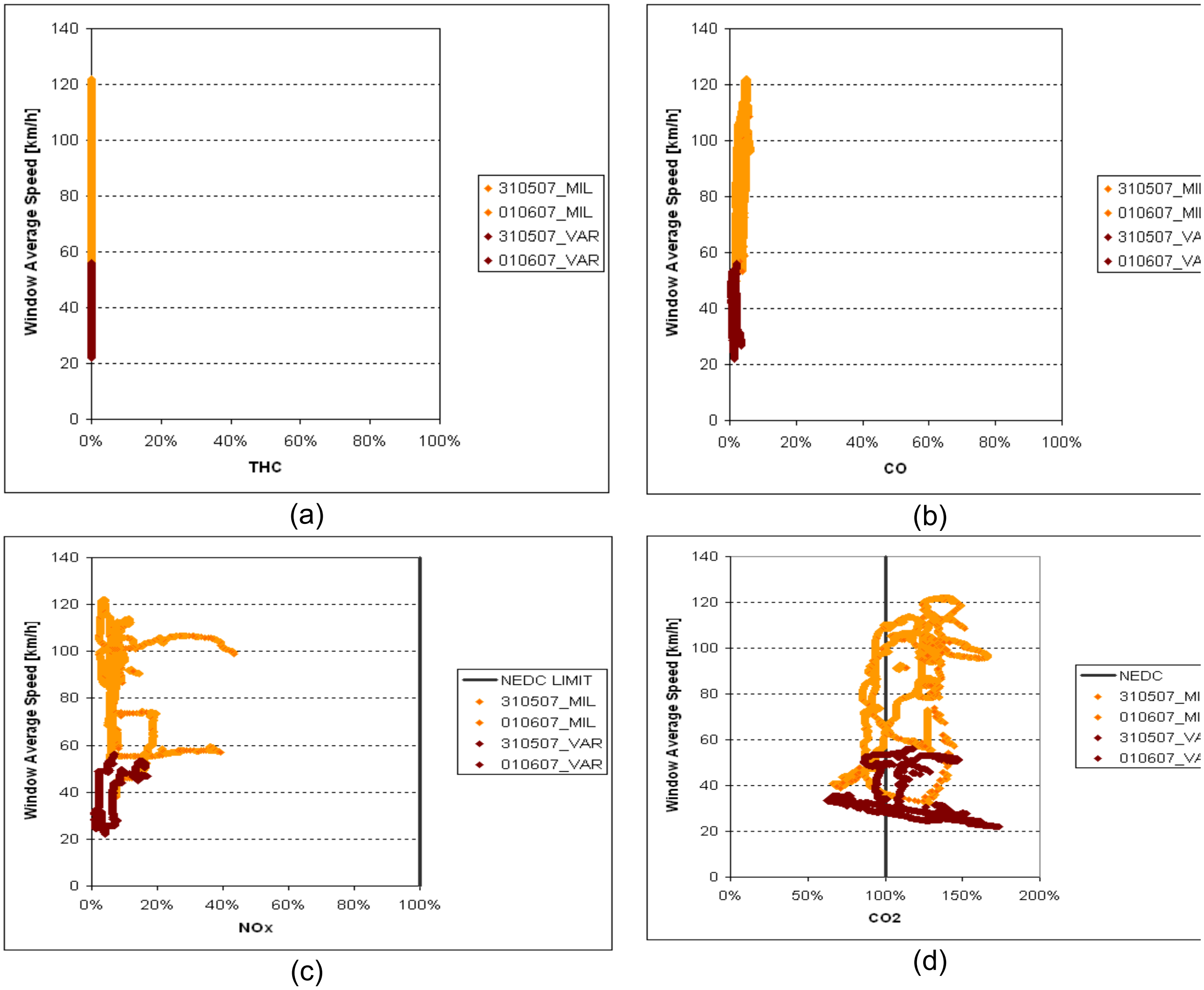
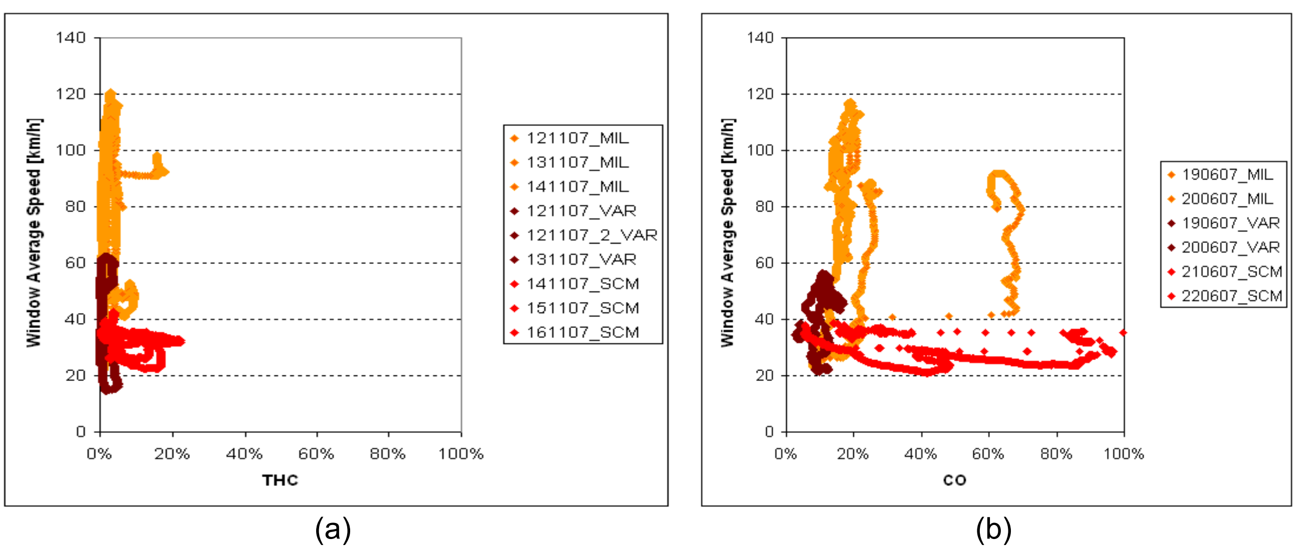
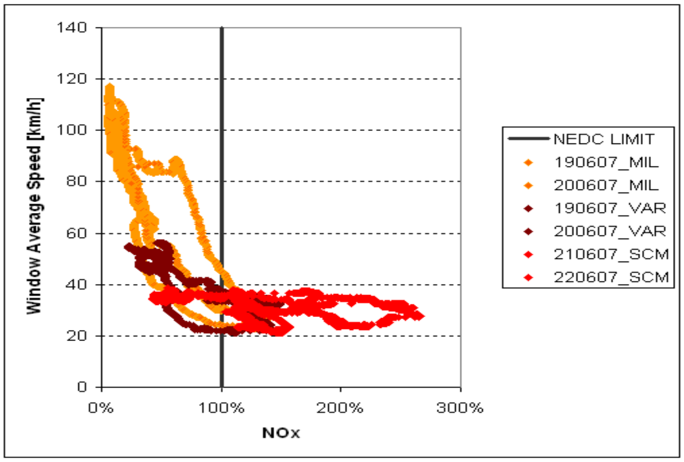
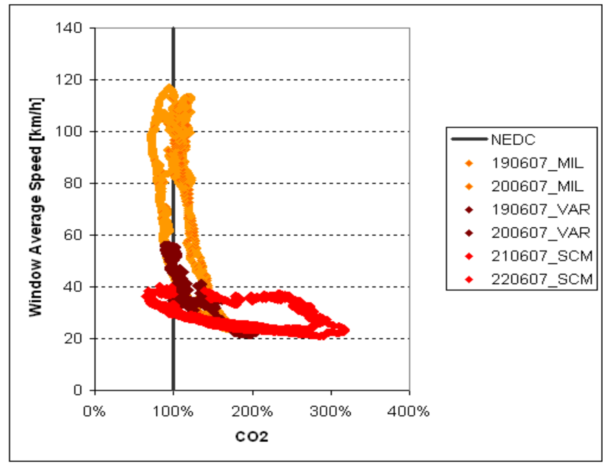


Figure 31 Emissions calculated with the CO2 window method versus average speed (a) THC (b) CO (c) NOx (d) CO2 – Vehicle: Prius



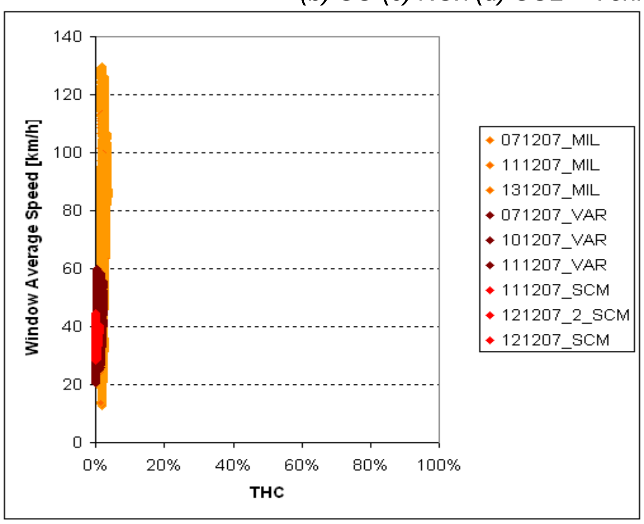


(c)

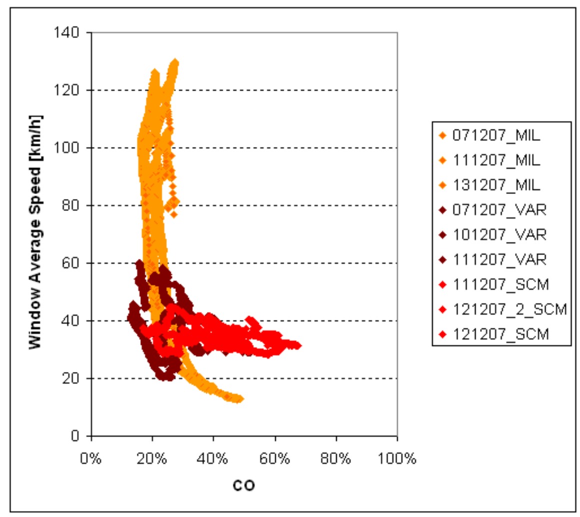


(d)

Figure 32 Emissions calculated with the CO2 window method versus average speed (a) THC (b) CO (c) NOx (d) CO2 – Vehicle: CMax.



(a)



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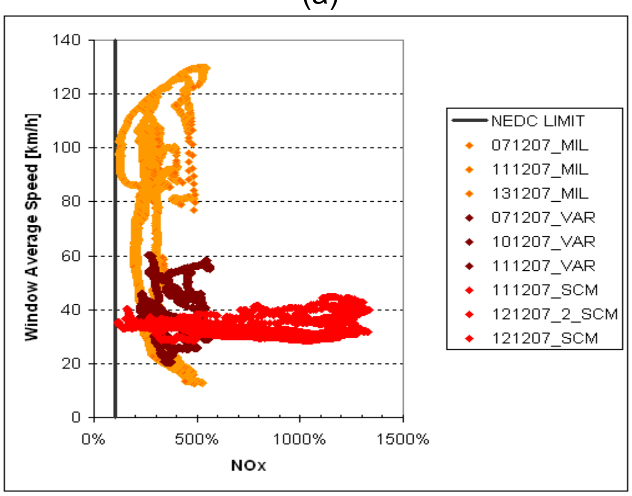

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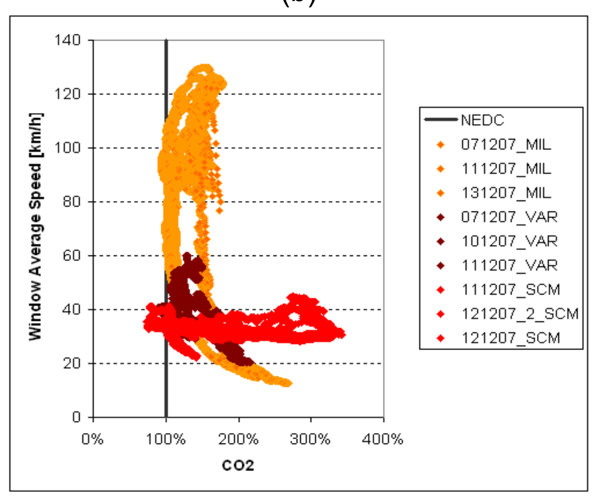


(d)

Figure 33 Emissions calculated with the CO2 window method versus average speed (a) THC (b) CO (c) NOx (d) CO2 – Vehicle: Clio Diesel.

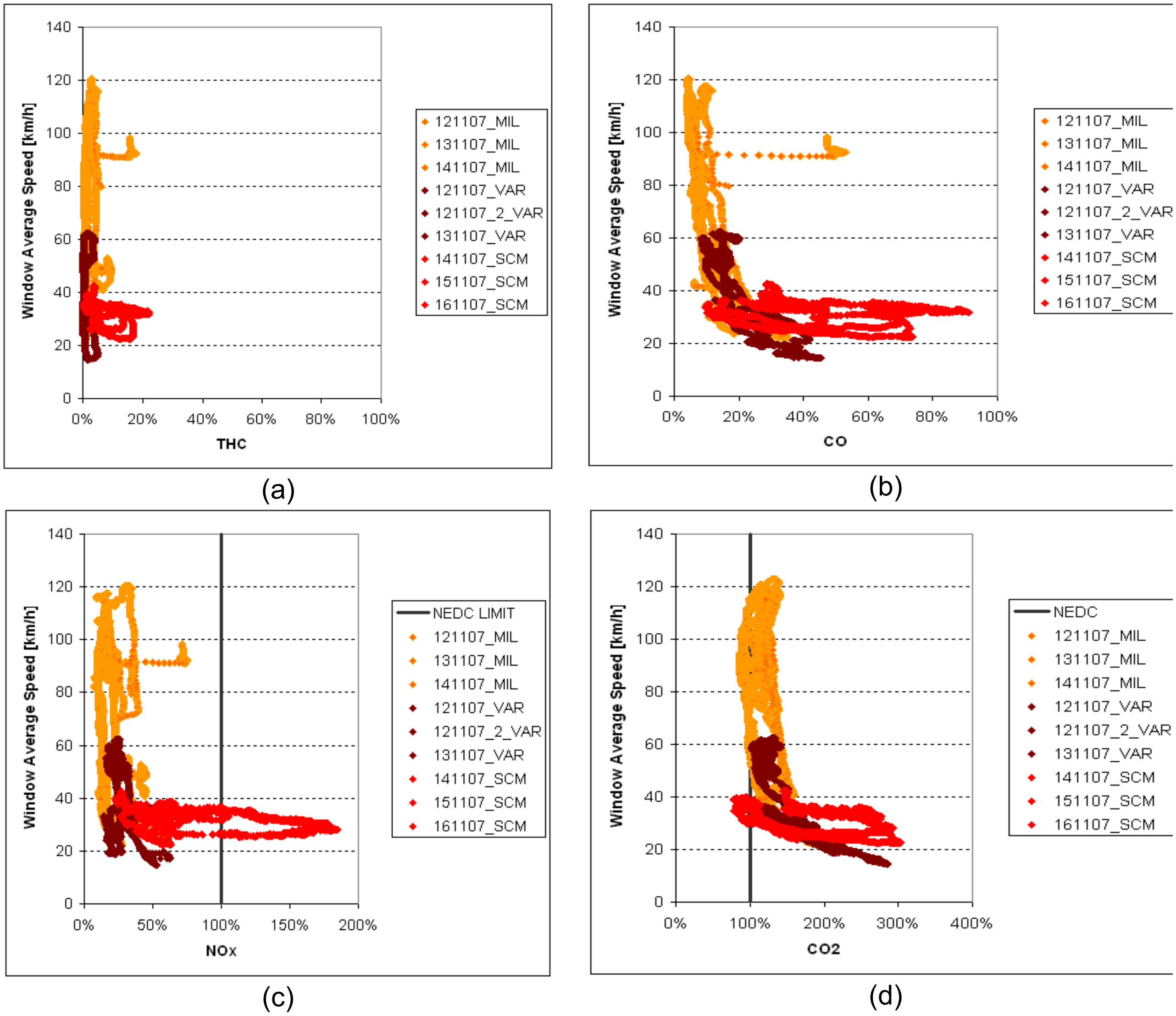
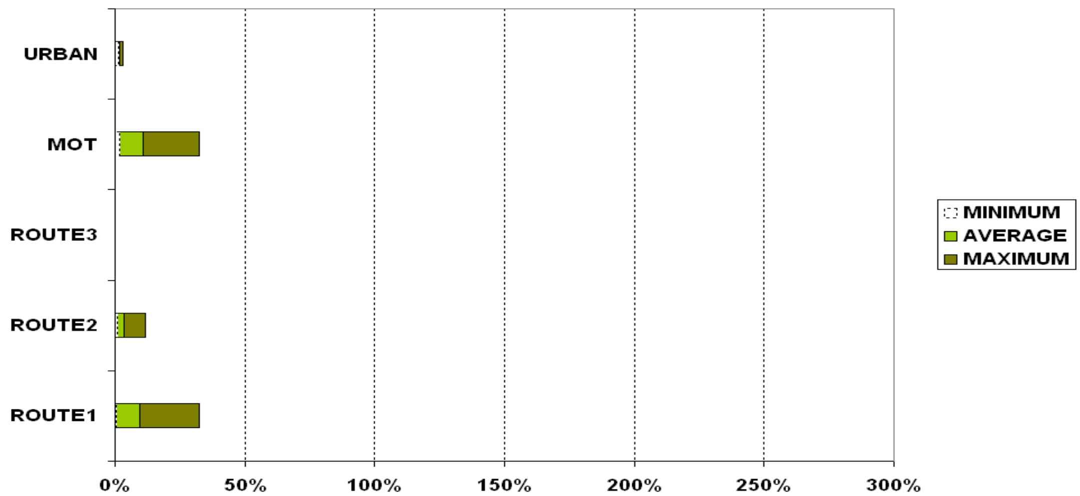


Figure 34 Emissions calculated with the CO2 window method versus average speed (a) THC (b) CO (c) NOx (d) CO2 – Vehicle: Clio Gasoline.


URBAN
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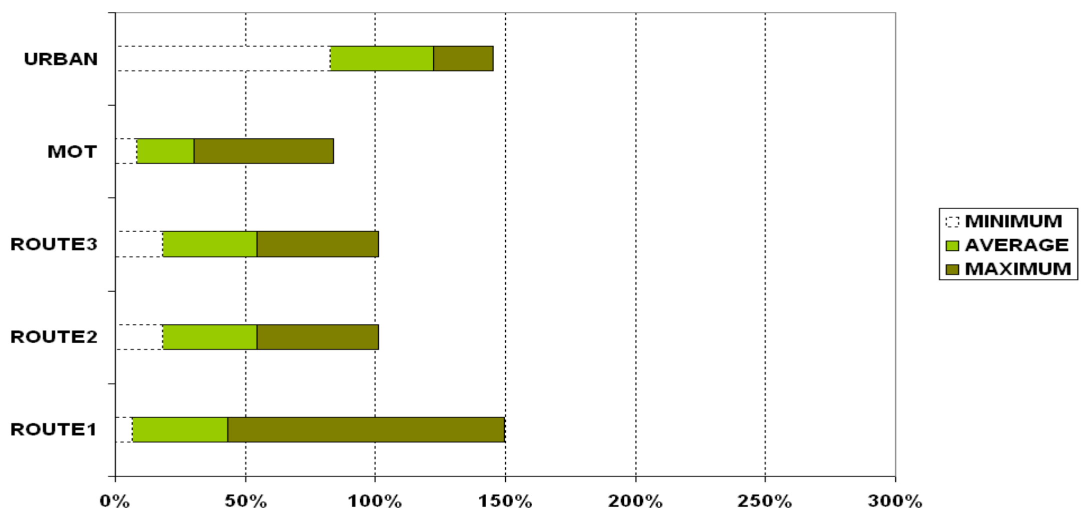
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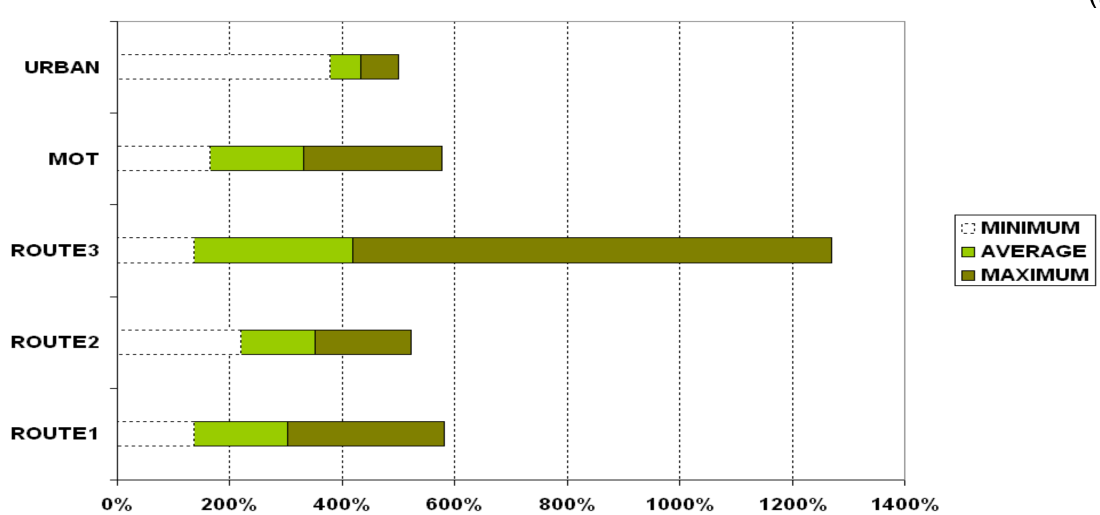
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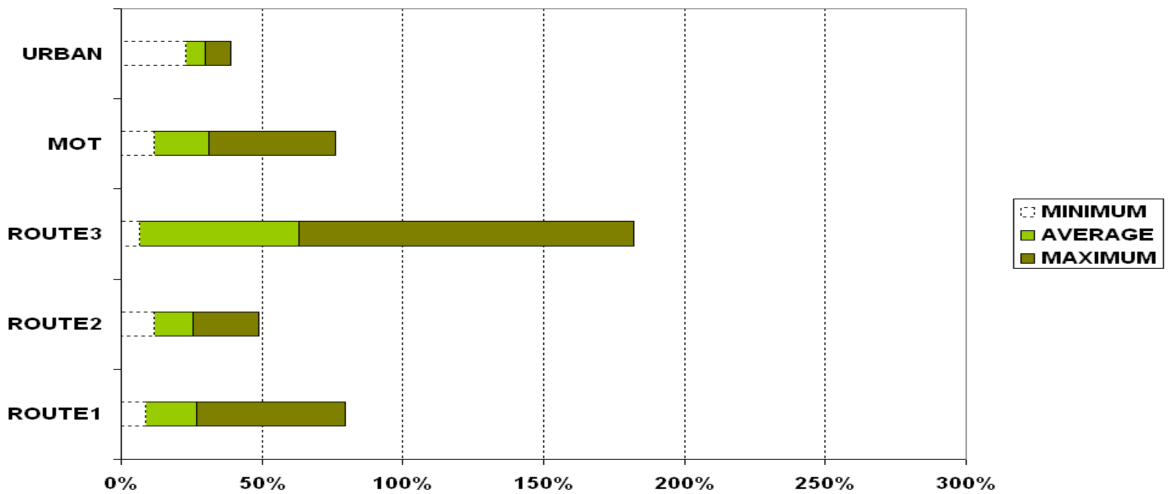
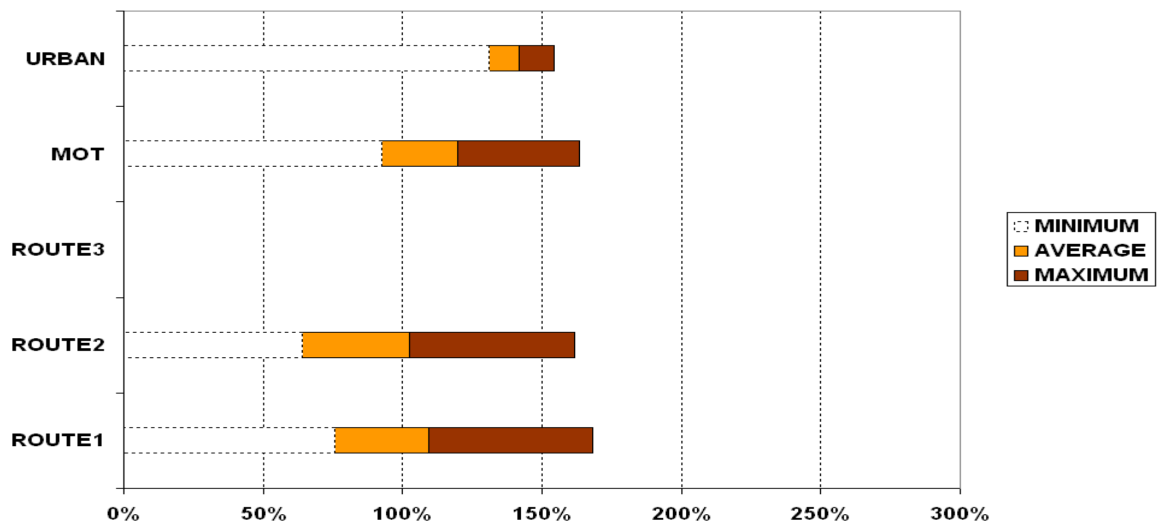
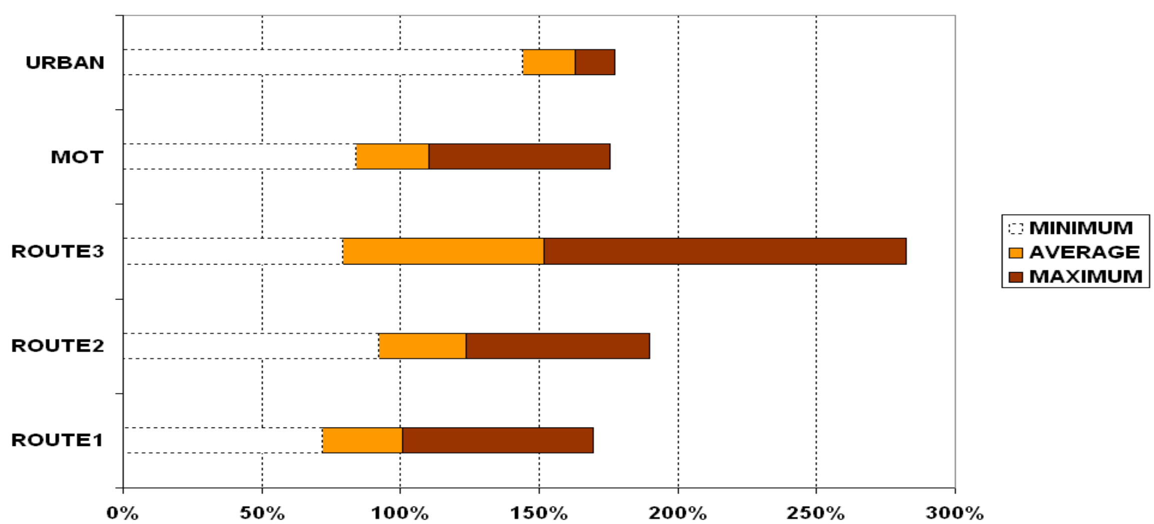
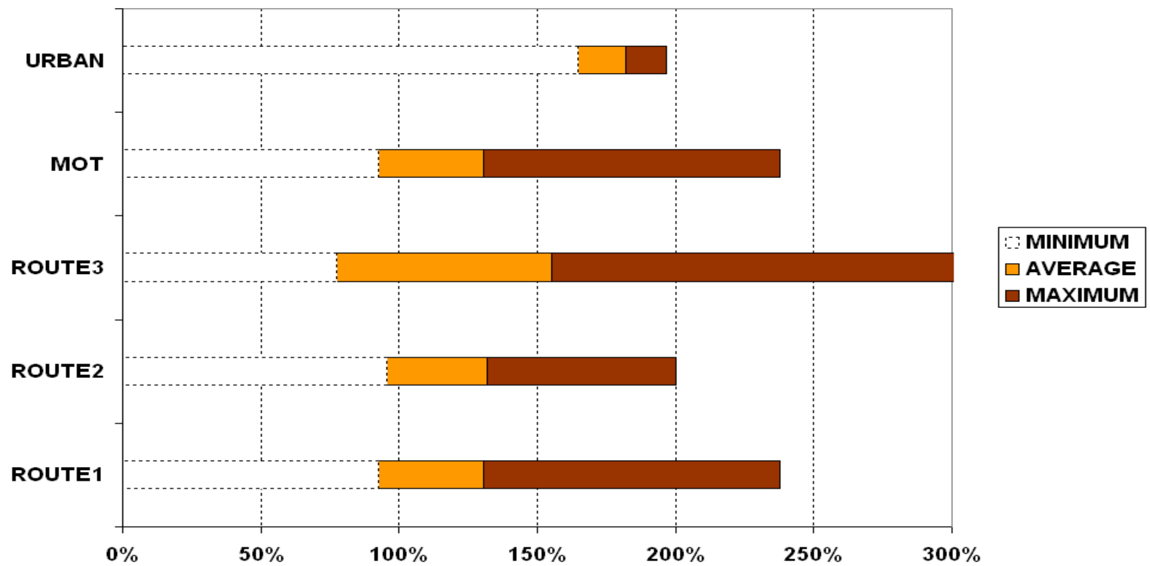


Figure 35 Scatter of NOx emissions calculated with the CO2 window method (a) Prius (b) CMax (c) Clio Diesel (d) Clio Gasoline.







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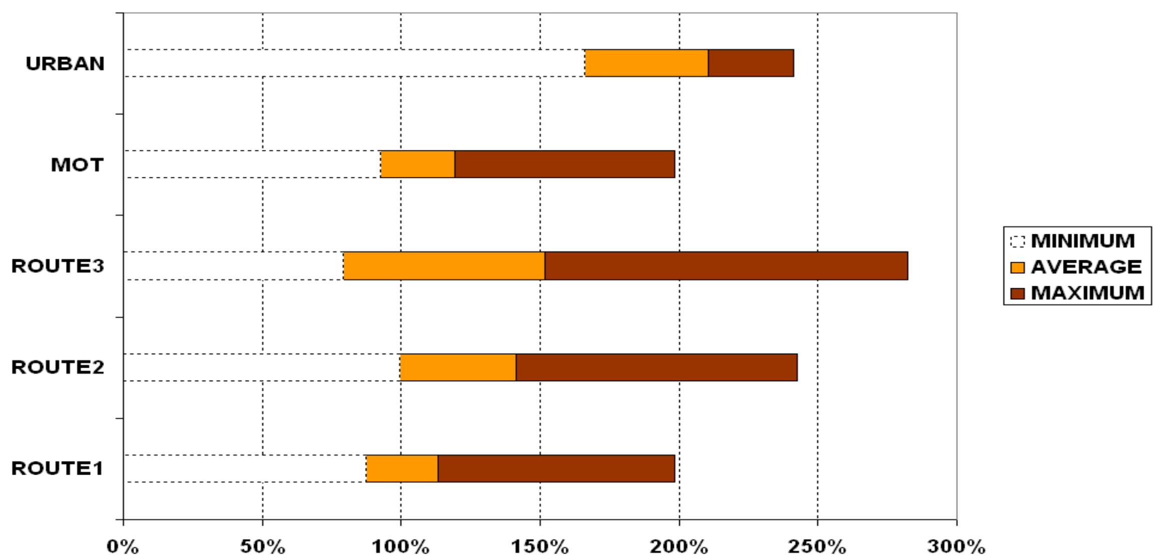

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Figure 36 Scatter of CO2 emissions calculated with the CO2 window method for Prius (a) CMax (b) Clio Diesel (c) and Clio Gasoline (d)

8 Final conclusions and recommendations

1. From the results presented in section 6.2 and 6.3 in particular, one can conclude that any test cycle – and the NEDC in particular - can only poorly represent the vehicle emissions during a real use. The poor emissions performance of the vehicles tested on the road with respect to the NEDC confirm the critical assessment made on the NEDC itself by several authors (See Section 3.1.2).

2. The poor NEDC engine map coverage, associated with the absence of provisions to control the emissions and the fuel consumption outside the conditions of the test cycle only have resulted in:

- High 'on-road' NOx emissions for diesel vehicles: this was observed for Euro 3 and Euro 4 diesel vehicles of different classes, where the NOx on-road distance specific emissions can represent 200% to 400% of the applicable NEDC limit.
- On-road CO_2 emissions quite different from the ones declared on the standard NEDC (10% to 50% higher, depending on the driving conditions).

3. PEMS associated with the appropriate data processing methods represent a solid base to develop a regulatory tool, following the example currently developed for the heavy-duty case. as they offer the possibility to test the vehicle emissions "in-use" and therefore to introduce some randomness in an emissions testing scheme.
As far as the practical feasibility of PEMS is concerned and even though the first conclusions form the LDVs testing sound positive,, further evaluation should be carried out to evaluate the applicability of PEMS to a large range of vehicle categories and technologies.

4. The development of a new or additional test cycle is an alternative or additional option to overcome the off-cycle emissions problems. However, some vehicle operating conditions, such as the high speed motorways can only be covered with PEMS, as vehicles cannot reliably be tested several minutes on chassis dynamometers at elevated speeds.

9 List of acronyms

A/F	Air-Fuel ratio
CH4:	Methane gas
CO:	Carbon monoxide gas
CO2:	Carbon dioxide gas
ECU:	Engine Control Unit
EFM:	Exhaust Flow Meter
ESC:	European Steady state Cycle
ETC:	European Transient Cycle
FID:	Flame Ionisation Detector analyser
FS:	Full Scale
GPS:	Global Positioning System
I/O:	Input / Output
ISC:	In Service Conformity
ISO	International Standards Organisation
IUC:	In Use Compliance
NDIR:	Non-Dispersive Infrared analyser
NDUV:	Non-Dispersive Ultraviolet analyser
NEDC:	New European Driving Cycle
NO:	Nitric oxide gas
NO2:	Nitric dioxide gas
NOx:	Nitric oxides gases
NTE:	Not To Exceed
O2:	Oxygen gas
PEMS:	Portable Emission Measurement System
PM:	Particulate Matter
PFS	Partial Flow Sampling
PID:	Vehicle data Parameter IDentifier
QCM	Quartz Cristal Microbalance
SAE:	Society of Automotive Engineers
STP	Custom Step Cycle
TEOM	Tapered Element Oscillating Microbalance
THC:	Total Hydrocarbons

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