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## Accuracy of exhaust emissions measurements on vehicle bench - Artemis deliverable 2

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## **Accuracy of exhaust emissions measurements on vehicle bench**

(Artemis deliverable 2)

*Report n° LTE 0522*

*December 2006*

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13 Résumé 11 laboratoires européens se sont associés pour étudier l'influence d'un grand nombre de paramètres de la mesure des émissions des véhicules légers sur banc à rouleau, en vue d'améliorer la précision, la fiabilité et la représentativité des facteurs d'émissions : comportement de conduite (cycle, rapports de boîte, conducteur), paramètres véhicule (caractéristiques techniques, stabilité des émissions, dégradation, carburant, refroidissement et préconditionnement du véhicule), échantillonnage des véhicules (méthode, taille de l'échantillon), et paramètres laboratoire (température, humidité, calage du banc, rapport de dilution, température de la ligne chauffée, préconditionnement du filtre à particules, temps de réponse, air de dilution). À côté de synthèses bibliographiques, l'essentiel des résultats sont basés sur près de 2700 tests spécifiques (un véhicule, un cycle) sur 183 véhicules, et la réanalyse de plus de 900 tests sur 81 véhicules. Ces tests concernent les polluants réglementés et des véhicules de norme pré-Euro à Euro 4. 7 paramètres sont sans influence, et 7 autres n'ont qu'une influence qualitative. 6 paramètres ont une influence nette et quantifiable, ce qui nous permet de proposer des facteurs de correction pour 5 d'entre eux, pour homogénéiser les mesures d'émission : stratégie de changement de rapport, kilométrage, température, humidité, rapport de dilution. Le 6 <sup>e</sup> paramètre est le cycle de conduite, qui peut être plus important que le carburant ou la norme d'émission. Finalement les comportements de conduite européens peuvent être décrits par 15 comportements types. Ces résultats permettent de proposer de bonnes pratiques pour la mesure sur banc de facteurs d'émission. Un jeu de 3 cycles réels, dits cycles Artemis, sont mis au point pour représenter l'ensemble des usages européens. 3 modèles d'émission de haute fiabilité pour toute cinématique sont construits : un en fonction de la vitesse instantanée (après modélisation inverse du signal d'émission), un en fonction de la distribution croisée des vitesses et accélérations, et un dernier en fonction de 7 paramètres cinématiques.		
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# 1. Introduction

Transport activities contribute significantly to air pollutant emissions in Europe and the impact on emissions is a key element in the evaluation of any transport policy or plan. Calculation of emissions has therefore gained institutional importance in the European Community, particularly with the development of the CAFÉ (EC, 2005a) and ECCP (EC, 2005b) programmes. Reliable and credible emission estimates are a central prerequisite, but comparisons of the results from emission models such as COPERT (Ntziachristos & Samaras, 2000a), FOREMOVE (Samaras et al., 1993), TREMOVE (De Ceuster et al., 2005), RAINS (Amann et al., 2004), Handbook (Keller, 2004) and national models have shown substantial differences. This causes doubts about the credibility of the underlying data and methodologies and might mislead the political discussions.

The *Artemis* project "*Assessment and reliability of transport emission models and inventory systems*" proposes to combine the experience from different emission calculation models and ongoing research in order to arrive at a harmonised methodology for emission estimates at the national and international level. It addresses the Competitive and sustainable growth programme of the 5th framework programme of the European Commission, Key Action KA 2: Sustainable mobility and intermodality, Task 2.2: Infrastructures and their interfaces with transport means and systems, Sector 2.2.2: Environment, Sub-Task 2.2.2/2: Monitoring emissions from transport, including particulates. The project develops a harmonised emission model for all transport modes, which aims to provide consistent emission estimates at the national, international and regional level. This requires first of all additional basic research and a better understanding of the causes of the differences mainly with respect to emission factors.

The European MEET (Methodologies for Estimating air pollutant Emissions from Transport) project (Hickman et al., 1999) and the COST 319 action (Joumard, 1999) focused in particular on the production of emission factors and functions using most of the available measured data at this time in Europe. Despite the fact that the programme delivered usable results in terms of 'standardising' emission estimates, it also raised a main questions in relation to passenger car emissions, summarised as follows: large differences in measured emission levels occurred between the different laboratories in Europe; these differences appeared to be more pronounced for more recent (at this time) vehicle technologies (i.e. Euro 1). Other research programmes carried out in parallel to and, to a certain extent, in conjunction with MEET and COST 319 (e.g. the German/Swiss/Austrian Handbook exercise) have reached similar conclusions. Irrespective of the way the emissions modelling is conducted (i.e. average speed dependency approach, traffic situation approach) the above conclusion is clearly identified. The emission behaviour seems to be chaotic and therefore difficult to model via conventional methods.

In order to be able to produce accurate emission factors for current and near-future technology, taking into consideration the aforementioned observations for modern car categories, a two-fold strategy is proposed in the present project:

*Investigating and reducing the measurement differences between laboratories.*

Methods of emission measurement have already been partially standardised through the use of emission standards. However, emission standards relate mainly to new vehicles, and their objective is not to assess the emissions of the European vehicle fleet but to ensure that compliance can be established for new vehicles on an equal basis. Measurements have also been standardised in 'round-robin' tests performed by European laboratories. This has ensured that the measurements conducted in the different laboratories have been comparable. In addition, there has been some degree of standardisation in the limited number of studies that have examined the influence of various measurement parameters.

Many of the parameters influencing emission measurements are well known, but their actual impact on the results has not been well quantified. This is especially true for cars equipped with new technology engines or emission control systems. Emissions from these vehicles can be very low, but can also be very sensitive to changes in conditions.

Thus, the large variability of the emission levels of current catalyst-equipped vehicles undermines the production of accurate emission factors which could be used for the development of reliable emission inventories. Based on the findings of the European studies, future test programmes should at least fulfil the following points where a representative real-world emission database needs to be built:

- \* The test sample selection has to follow different rules. It is probable that specific makes and types of sample vehicles should be selected according to their contribution in the fleet population. Setting of macroscopic parameters as criteria for the selection of vehicles (e.g. engine capacity, power, etc.) does not seem relevant to the objectives of this task.
- \* The sampled vehicles need to be tested over a number of driving cycles to simulate different conditions and cover the large range of real-world engine operating conditions. It is why we develop here representative real-world driving cycles.
- \* Since mileage has a significant effect on the emission performance of catalyst-equipped vehicles, the emission levels of vehicles should be normalised according to their mileage. However, reliable mileage corrections can only be obtained by recording the emission level of the same vehicles at different mileage during their lives.
- \* In addition, the systematic errors between laboratories should also be investigated in detail. Available knowledge from round-robin tests indicates that the differences between laboratories may reach  $\pm 20\%$  when performing standard emission measurements. Nevertheless, on their own these errors cannot fully explain the scatter in the data discussed above.

*Investigating, understanding and modelling the emission differences among comparable vehicles.*

The differences in emission levels that were identified both in MEET (i.e. for average speed dependent emission factors) and for instantaneous emission modelling may, for short intervals of maybe tens of seconds, be as large as two orders of magnitude. This holds for passenger cars which comply with the same emission standard, have the same size, have more or less the same mileage, and are driven over similar driving cycles. These differences have been found to be much more pronounced for more recent (i.e. Euro 2) vehicles which, in general, have a lower absolute emission level than older car concepts. This is a clear indication that in the current (average speed dependent) modelling approach some very important parameters are overlooked.

The analyses and data from a number of investigations conducted so far indicate that the reasons for these differences can (in descending order of importance) be attributed to:

- lower level of emissions, close to the detection limit of the analysers;

- engine management and emission control concepts (effects such as rich and stoichiometric operation, spark advance, exhaust gas recirculation, etc.);
- driving cycles (effects such as average speed, average acceleration, relative engine load, idle time, urban/extra-urban/highway, etc.);
- mileage, age, and maintenance;
- other parameters such as test conditions, laboratory differences, etc.

The present project, whose final report is presented hereafter, corresponds to a part (task 31) of the comprehensive Artemis project, within the workpackage 3 "Improved methodology for emission factor building and application to passenger cars and light duty vehicles". The results of the corresponding evaluations should lead to a new methodological structure for estimating emissions factors. On the basis of the above the main objectives of the project can be summarised as follows:

- \* The first aim is to study the sensitivity of pollutant emissions to the key parameters identified above. These parameters may be split into four main categories:
  - Vehicle-related parameters, i.e. engine management and emission control concept, emission stability, mileage, age, maintenance, and fuel properties. These parameters may have a significant effect on real-world emissions. The way this effect has been dealt with so far is not adequate.
  - Driving cycle parameters. Evidently this is related to the bullet above, but it imposes additional constraints. A split between urban and extra-urban conditions can reveal the particularities of the overall management system.
  - Laboratory-related parameters. This should attempt to identify the systematic and random errors of the participating laboratories that are due to ambient test conditions, dynamometer settings, air cooling effects, analytical equipment, etc. It should also attempt to improve the understanding of the effects that these parameters may have on the measured emissions.
  - Vehicle sampling method. Due to the very large scatter of the emissions, the way the vehicles are chosen by each laboratory, and the number of vehicles tested in each category, can introduce an important bias which shall be statistically investigated.

Only some of these questions can be answered by a literature review or by the processing of existing emission data. In general, the research is not be theoretical, and in most cases specific laboratory measurements are required. The results has to be applicable to the European situation: the variation in each parameter must at least correspond to the actual measurement conditions met in the European laboratories and, most importantly, must correspond to the range of traffic conditions observed in Europe and the existing methods for modelling transport-derived pollution. In addition, it is necessary to study the sensitivity of emissions according to each measurement parameter, and where this sensitivity is significant the accuracy with which the parameter represents the real-world condition has to be maximised. This applies particularly to parameters such as the vehicle sample and the driving conditions.

- \* The second aim is to develop methods that allow the harmonisation of any European emission measurements. This will involve establishing 'standard' conditions in order to obtain comparable data, and building methods to extend the data to any European condition. This should allow us to improve considerably the accuracy of European methods and tools for road emission evaluation, and to greatly enlarge the range of application of these methods and tools.

This shall improve the comparability and the quality of the existing and future emission factors for passenger cars, as well as the design of a best practice for measuring emissions and its dissemination among the European laboratories.



## 2. Methodology

In order to investigate and reduce measurement differences among laboratories, to design a best practice guide for exhaust emission measurements, to investigate, understand and model the exhaust emission differences among comparable vehicles, the influence of all the potential parameters on the car exhaust emission level and accuracy is studied first with a literature review and then by laboratory tests on vehicles. The parameters studied, the vehicle tests and the specific methods are presented hereafter.

### 2.1. Parameters studied

To carry out the research, we consider the objectives of the emission measurement campaigns, i.e. the evaluation of emission factors of some atmospheric pollutants for the European passenger car fleet, and the measurement conditions potentially influencing these emissions.

#### 2.1.1. Pollutants considered

Regulated pollutants are considered: carbon monoxide CO and dioxide CO<sub>2</sub>, nitrogen oxides NO<sub>x</sub>, total hydrocarbons HC, particulate mass PM, and fuel consumption. The measurement of the pollutants was achieved in the different laboratories by means of usual analytical techniques (non-dispersive infrared for CO and CO<sub>2</sub>, chemiluminescence for NO<sub>x</sub>, flame ionisation detection for HC, and filter weighting for PM). Fuel consumption was calculated using the carbon balance method. Specific pollutant analytical methods are reported when necessary.

#### 2.1.2. Parameters of the measurement accuracy

Four types of parameters of the measurement conditions are studied:

- *Driving patterns*: To study and assess the effects of driving conditions on the pollutant emissions, tests are performed to compare real-world and standard driving cycles in terms of kinematics, representativeness of real driving behaviour, method of determination, emission level, looking at the influence of the road gradient and the vehicle load, of the gear choice behaviour on emissions. Emission modelling allows us to quantify the influence of number and quality of measurement cycles on emissions. In addition the actual driver performance must be investigated to minimise the additional error on emission factor estimation.
- *Vehicle related parameters*: Regarding absolute emissions (g/km), the new vehicles (complying with the more stringent emissions regulations) achieve much better results than the previously developed vehicles (less demanding emission regulation) even under the so-called real world driving conditions. Only the NO<sub>x</sub> emissions from diesel cars showed only small improvements in the last decade. Exhaust emission measurements of the same vehicle or a vehicle of the same model could differ significantly. As emission control systems that achieve actual and near future

emission limits have to be very efficient, they tend to be very sensitive to outside influences (as fuel properties). On the other hand, the reaction of different vehicle types to the same driving conditions could be very unlike, especially in situations that are not covered by homologation tests. The aim of this task is to identify and quantify vehicle sensitivities to test parameters regarding emissions taking into account measurement variations that occur even under normal conditions. Parameters investigated include fuel, preconditioning, cooling, age-mileage-maintenance. Furthermore various emission control systems are studied for their performance in different driving conditions and their long-term behaviour.

- *Vehicle sampling method*: Basically, an inquiry is done to describe accurately and compare the different vehicle sampling methods used by the labs.
- *Laboratory related parameters*: Ambient conditions (temperature, humidity, atmospheric pressure) have an influence both on the operation of a combustion engine and also on the emissions measurement. Here we address this as a source of inconsistency and give an estimate of the variability among representative emissions measurements made in different laboratories at different times under different ambient conditions. The work entails both literature review, as well as new tests, in ambient conditions within range of statistical significance in Europe. Apart from the ambient conditions, also the effect of parameters, related to the emission measurement hardware, are studied: dynamometer setting, dilution ratio, heated line sampling temperature, PM filter preconditioning, response time, including instantaneous versus bag value, and the dilution air conditions.

Each type concerns a number of parameters, which the list is given Table 1. Each parameter is presented in detail below.

Parallel to the study of the impact of different parameters on emissions, it is necessary to compare the roller test bench laboratories to each other by performing a *round robin test* with reference gases (CO, HC, NO<sub>x</sub> and CO<sub>2</sub>). This round robin test carried out on the common fuels basis completes the assessment of the accuracy of the laboratories with regard to the laboratory related parameters.

### ***Driving cycles***

The task was initially aimed at reviewing and comparing the existing driving cycles as regards their kinematics, representativeness and method of elaboration, and at analysing the sensitivity of the emissions as regards the test cycles. Initially based on a limited sample of emission measurements, these works were finally extended to the analysis of complementary dataset.

As far as the relation between emission and driving cycles was concerned, three complementary objectives were finally aimed at:

- the identification of kinematic parameters that would enable a detailed emission modelling
- the harmonisation and integration of the extremely heterogeneous dataset of passenger car emissions collected within the project and measured using a large range of driving cycles
- the setting-up of emission modelling principles, to assess the emissions at a "street level" i.e. within the so-called traffic situation approach.

### ***Gear choice behaviour***

The gear choice strategy could have an influence on the emission: for instance to shift gear at fixed speeds (as in the standard European NEDC cycle), as recorded on the road, by simulating the on-the-road gearshift strategy, or chosen by the driver...

Type of parameter	Parameter	Literature review, inquiry	Reprocessing of old data	New emission tests
Driving patterns	Driving cycles	X	X	X
	Gear choice behaviour			X
	Influence of the driver & cycle following		X	
Vehicle related parameters	Technical characteristics of the vehicles	X		X
	Emission stability			X
	Emission degradation	X		X
	Fuel properties	X		X
	Vehicle cooling			X
	Vehicle preconditioning			X
Vehicle sampling method	Method of vehicle sampling	X		
	Number of vehicles	X	X	
Laboratory related parameters	Ambient temperature			X
	Ambient humidity			X
	Dynamometer setting			X
	Dilution ratio			X
	Heated line sampling temperature			X
	PM filter preconditioning			X
	Response time, instantaneous vs. bag value	X		X
	Dilution air conditions			X
Round robin test				X

Table 1: Parameters studied, with indication if the study is based mainly on a literature review or inquiries, on reprocessing of existing emission data, and/or new vehicle emission tests.

### ***Influence of the driver and of the cycle following***

The driver is aiming at reproducing the vehicle speed and the gearshifts as they are described in the driving cycle. Nevertheless the reproduction is never perfect, which could influence the emission level to a certain extent. The goal is here to identify the influence of the driver choice on the accuracy of emission factor estimation, and to propose guidelines which allow to minimise the additional error on emission factor estimation.

### ***Technical characteristics of the vehicles***

We analyze engine technologies and emission control systems with respect to their influence on the emission behavior of the vehicles. If differences in the emission behavior measured at different cars could be attributed to special emission control technologies, the introduction of “technology classes” could improve the structure of emission inventory models and emission factor data bases (complementary to the existing structure according to propulsion system, certification level and engine capacity classes). Such an additional vehicle category would be useful, if it could explain the



huge differences found in the emissions measured in some real world driving cycles for cars within the same type approval level

The technical descriptions of this task are largely based on the Concawe report (Kwon et al., 1999). The analysis was further expanded via an extensive literature review on the currently available emission reduction technologies. The technical characteristics of the vehicles potentially influencing the emissions are presented in Annex 2.

Existing data for Euro 1 vehicles is reprocessed based on the findings of the review. Euro 2 and Euro 3 vehicles were tested on the chassis dynamometer to assess the behaviour of new vehicle technology and to define a classification of engine technologies of current and near future cars.

### ***Short term emission stability***

The measurement of hot vehicle emissions can occur at different moments in a measuring day. The emission stability for a vehicle is not obvious. Then we looked at the repeatability for each lab of emission measurements.

### ***Long term emission degradation***

The influence of the vehicle age or mileage, of the maintenance including on-board diagnostic (OBD) on the emissions is studied by a literature review and an existing data reprocessing. Additionally, the follow up of the emission and fuel consumption evolution of some vehicles should provide a clear picture of the influence of mileage and maintenance on emissions and fuel consumption, in relation to the vehicle and engine technology.

### ***Fuel properties***

The aim is to verify the influence of fuel specifications throughout the Europe on emissions, by analysing the local fuels used by the tested vehicles and calculating their impact on the emissions on the regulatory emission cycle using EPEFE formulae. Therefore we investigated the influence of average and extreme fuels.

### ***Vehicle cooling***

The influence of the cooling fan type, height from the ground, modulation of the air speed (with or without roller speed dependence), the opening of the engine bonnet (closed or open) is studied here. Cooling conditions are differentiated via using either small, normative fan or a much larger one with the modulation of the cooling air speed.

### ***Vehicle preconditioning***

Different preconditioning (warm up) cycles are studied to establish unified start conditions (thermal conditions of the engine, its exhaust system, catalyst, gearbox, test bench), by controlling the thermal conditions (temperature of the coolant and oil of the engine, oil of the gearbox, in the monolith of the catalysts, surface of the tyres). Various preconditioning types can be studied as idle, constant speed, NEDC, or full set of representative driving cycles.

### ***Method of vehicle sampling***

The different methods used by the different laboratories to select their vehicle samples are investigated by an inquiry: different types of random selections, as from rent car companies, private owners or car manufacturers...

***Number of vehicles (minimum size for a category)***

The influence of the sample size on the average emissions for the different vehicle types is studied, by a statistical investigation on existing data bases. Main outcome is the development of guidelines to determine the minimum vehicle type sample sizes for measurement programmes with respect to the highest possible accuracy of the resulting emission factors to be used for emission modelling.

***Ambient air temperature***

The ambient temperature influences both cold-start and hot-start emissions, but such influence is rarely studied with real-world driving cycles.

***Ambient air humidity***

The influence of the ambient humidity is known for NO<sub>x</sub>, where standard correction function is applied for all homologation measurements (see Annex 3). Although very commonly used, this influence was studied only for old vehicles. It is therefore necessary to up-to-date the function and to look on the other pollutants, by measuring emissions at different values of humidity, preferably also outside the homologation test range (between 5.5 and 12.2 g H<sub>2</sub>O/kg dry air), but within ranges of statistical significance in Europe.

***Dynamometer setting***

The results of emission and fuel consumption measurements of a vehicle strongly depend on engine load. Hence, the influence of a discrepancy of a dynamometer setting might be significant for the emission and fuel consumption measurement results. In this task the influence of altered dynamometer settings is determined under so called worst case conditions. This means that the input parameters for the chassis dynamometer will be based on the degrees of freedom 'permitted' by several methods used in Europe which are used to define the road load.

The different dynamometer setting methods used among the laboratories are presented in Annex 4.

***Exhaust gas dilution ratio***

The effect of the dilution ratio is investigated for both diesel and petrol vehicles. The dilution of the exhaust gases by non polluted air is the base of the constant volume sampling (CVS). It is a variable parameter according to the exhaust flow, but must vary in a limited range.

***Heated line sampling temperature***

For diesel vehicles, the sampling line must be hot (at 190°C) according to the standard procedure in order to avoid liquefaction of some hydrocarbons. We investigated the influence of a lower sampling line temperature.

***PM filter preconditioning***

The effect of the filter conditioning temperature and humidity for particulate matter PM of diesel vehicles on the emission results is investigated, especially for HC.

***Analyser and sampling response time, including instantaneous vs. bag value***

The delay of emission measurements caused by the CVS-system and the analysers is crucial for instantaneous measurements and second-by-second emission modelling, but also for standard HC-measurements of diesel engines. As delay times may vary due to different concentrations, temperatures and pressures, the gas flow through the CVS-system should be modelled to find a correction function of the recorded emissions.

### **Exhaust gas dilution air conditions**

The influence on the emissions of the ambient air, used to dilute the raw gas in the CVS, could be non negligible. For this aim, measurements with polluted ambient air can be compared to measurements with standard ambient air.

## **2.2. Building of the *Artemis* driving cycles**

To improve the representativeness of the tests and the comparability between the measurements made by different laboratories for different aims, we developed firstly a set of reference real-world driving cycles, to be used by all the partners during the *Artemis* exercise. Furthermore, these cycles were also used within several campaigns of pollutant emission measurements, ensuring then the compatibility and integration of all the resulting emission data in the European systems of emission inventory.

A compilation and synthesis of previous works has been considered to derive these cycles (passenger cars or light duty vehicles).

The development of real-world driving cycles was envisaged according to a four steps scheme: 1- observation of vehicle uses and operating conditions, 2- analysis of driving conditions, and 3- of vehicle trips, 4- development of representative driving cycles, reproducing trip structure and characteristics as well as driving conditions. These principles, which are briefly recapitulated hereafter, are described in (André, 2004a, b).

The works relied first on a European driving database resulting from the on-board monitoring of private cars in France, the UK, Germany and Greece (André et al., 1995; André, 1997). In all, 77 vehicles were monitored for, in total, 10 300 trips, 88 000 km travelled and 2 200 hours of driving, for which vehicle usage and operating conditions were known in detail (speed, acceleration, engine operation, trip information, etc.). This quite extensive database also offers the description of start and thermal conditions as well as gearbox use.

Complementary data have been used to validate the cycles thus obtained. These include the data recorded in Naples (Rapone et al., 1995), which cover highly congested conditions, and about 210 hours of driving corresponding to given and detailed categories of road conditions recorded in Switzerland (Keller et al., 1995).

A typology of the European driving conditions was derived from these data through the analysis of elementary segments described by their idling duration and 2-dimensional distribution of the instantaneous speeds and accelerations. To describe the high diversity of the driving conditions, twelve driving patterns contrasted in speed, acceleration and stop rates were then identified, ranging from the very congested urban driving to the motorway condition while opposing generally steady to unsteady driving (Figure 1). The computation of the Swiss data (recorded in known traffic situations) as regards these driving patterns showed good consistency and made it possible to establish a relationship between driving patterns and traffic conditions.

The analysis of trips as regards driving conditions encountered enables the characterization of urban trips, generally short and at low speed (3 km, 23 km/h) and with predominant urban driving conditions, rural-road trips (48 km/h) and motorway trips (long and at high speeds).

Three real-world driving cycles, so called *Artemis urban*, *Artemis rural*, and *Artemis motorway*, were then built up to reproduce urban, rural and motorway trip types according to driving conditions encountered as well as their heterogeneity and chronology within the trips (André,

2004a, b).

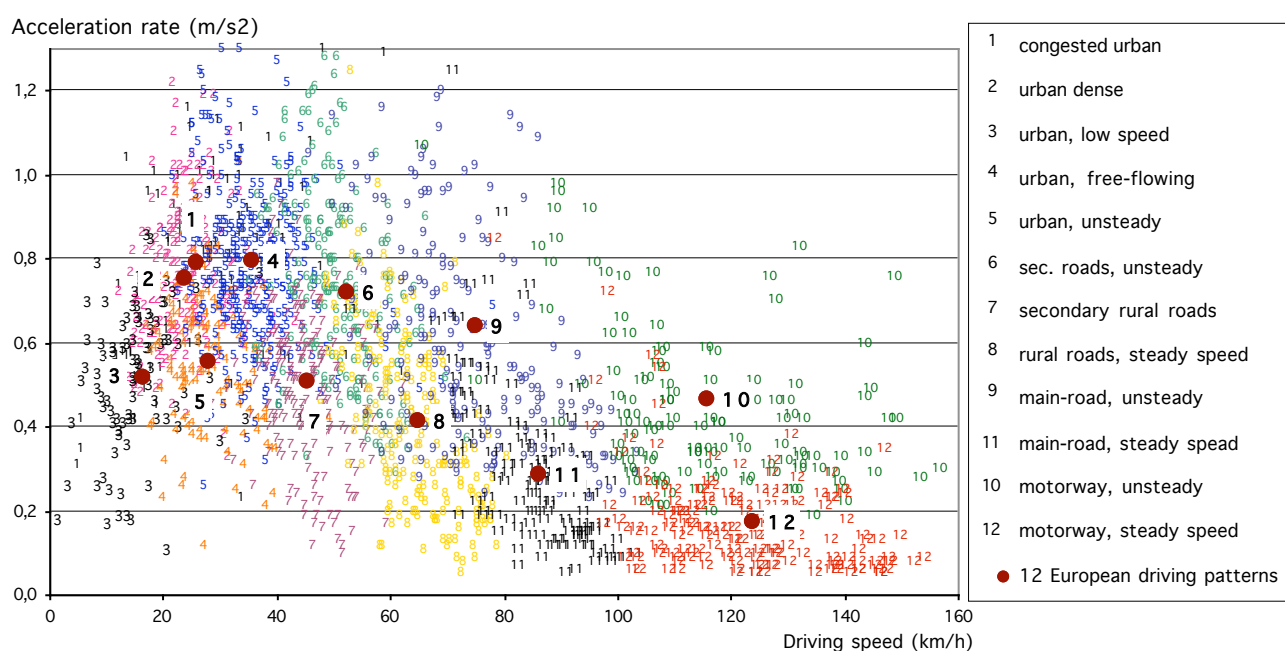


Figure 1: Variability of the European driving conditions and positioning of the 12 centres of the classes (amongst a sample of observations) derived by factorial analysis and cluster analysis of the speed profiles (André, 2004a, b).

The cycle structure was determined according to the composition of the actual trips considering the 12 typical driving conditions. In this way, a cycle is representative of one situation and an emission bag or measurement corresponds to an emission factor. A specific version of the motorway cycle, with speed limited to 130 km/h, was developed taking into account that some facilities are not capable of operating at speeds up to 130 km/h.

On the other hand, each of the three cycles includes various sub-cycles corresponding to the previously identified driving patterns, allowing a disaggregation of the emissions quantities at this level.

The cycles sometimes include a pre or post phase making it possible to measure the engine start and cold start emissions (urban cycle), and to reach the specific main-road or motorway driving (rural and motorway cycles). The Artemis cycles, including the sub-cycles are shown Figure 2 and described in Annex 1.

As the building-up of the driving cycles relies on a representative observation of the driving patterns, it is possible to establish the elements of weighing of the cycles and sub-cycles that would be necessary to assess an overall emission factor (i.e. including the different driving conditions). This weighing, given in (André, 2004a, b), is based on the observed statistics and share of the different driving patterns and trips categories.

Representative strategies of gearbox use were computed, allowing the driving cycles to be monitored in terms of technical performance of the vehicles and reproducing actual driver behaviours. The predetermination of 4 categories of vehicles for determining the gear shifting is given Table 2. Complementary simplified procedures (and in particular for the vehicles with 6 gear ratios) are also developed (André, 2004a, b).

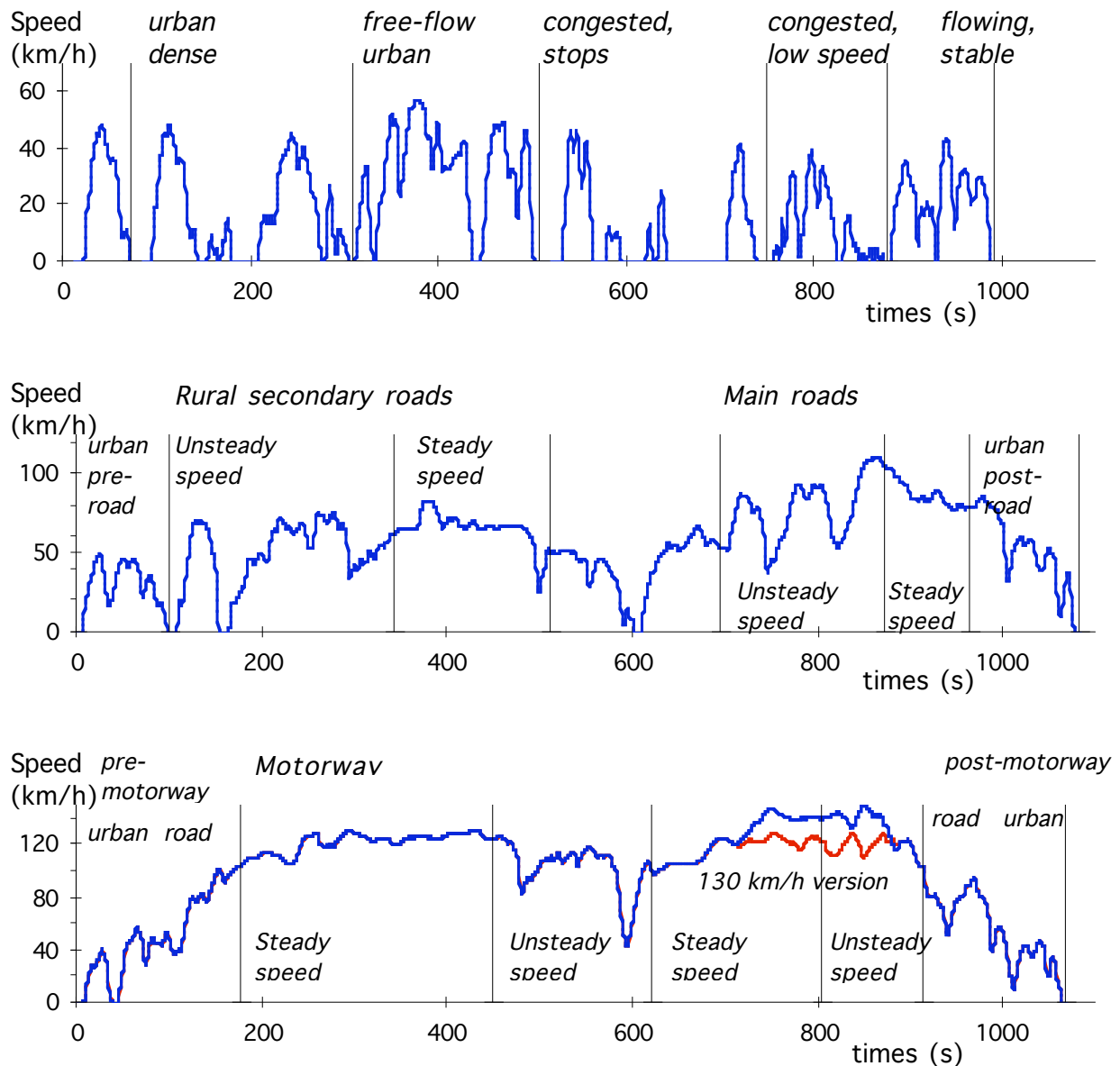


Figure 2: The Artemis urban, Artemis rural, and Artemis motorway driving cycles, including sub-cycles and starting conditions (André, 2004a, b).

The set of the *Artemis* real-world and reference driving cycles presents a real advantage as they are derived from a large database, using a methodology that was widely discussed and approved. Today they are widely used in the frame of European research projects and of national programmes for the measurement and modelling of the actual pollutant emissions. It should lead to the integration of a large amount of measurements into the European tools for estimating emissions.

In parallel to the construction of the *Artemis* driving cycles, 2 sets of specific driving cycles are derived, using the same principles and data, but build-up as a function of the technical characteristics of the vehicles, i.e. for low- and high-motorized vehicles (so-called *VP faible motorisation* and *VP forte motorisation*, or *Artemis.LowMot* and *Artemis.HighMot* in the *Artemis* database, see André, 2006).

Condition	Vehicle category:	1 – Diesel and heavy cars	2 – Low-motorised, long transmission ratio	3 – High-motorised	4 – Mean vehicles
if power to mass (W/kg)		< 60	< 76	> 76	Other cases
and if speed at the engine speed of maximum power in 3 <sup>rd</sup> gear ratio (km/h)		< 102	> 118	> 110	

Table 2: Categories of vehicles for determination of gear shifting during the Artemis driving cycles (André, 2004a, b), as regards the power-to-mass and the speed in 3<sup>rd</sup> gear at the engine speed of maximum power.

## 2.3. Description of the emission tests

A specific test programme was built-up for each parameter studied, excepted the vehicle running conditions and the method of vehicle sampling, where only literature review or inquiries were performed. In addition, as the tests are sometimes performed in several laboratories, the test programme could hardly differ between the laboratories for a same parameter studied.

### 2.3.1. List of driving cycles used

A large number of driving cycles are used for measuring emission factors, and especially within the formerly existing emission data base available to investigate the influence of parameters on emissions, and during the emission tests carried out specifically for this aim. An overview of the driving cycles tested is shown Table 3 per parameter and per laboratory.

Although a wide variety of driving cycles were tested for the whole study (65 cycles), most of them have been used either to look at the influence of the driving patterns, or when reprocessing existing data (case of the minimum size of a vehicle sample). For the influence of the vehicle and laboratory related parameters, the 3 Artemis driving cycles have been generally tested with hot start, but in a few cases without the rural or motorway cycles. In many cases cold and/or hot NEDC have been tested in addition.

All the tested driving cycles are described in details and analyzed in terms of driving patterns representativeness by André et al. (2006). Their main characteristics are given in Annex 5. With the exception of the NEDC and marginally the US Highway cycle, all the cycles are real-world ones, built from large driving behaviour records on the road.

### 2.3.2. Test sequences

The vehicles were tested at the participating laboratories on a DC chassis dynamometer equipped with one or two rollers. Vehicle cooling was ensured with air ventilation linked to the vehicle speed placed on the front of the grille; this was therefore very similar to real road conditions. The fuels used came from local petrol stations. Exhaust gases were sampled at constant flow using a constant volume sampler (CVS) with filtered ambient air as dilution air, with a bag or filter and also usually continuously. Specific sampling conditions are reported when necessary.

Parameter		lab.	N. veh.	NEDC (UDC+EUDC)		Artemis			Other cycles or families of cycles
				cold	hot	Urban	Rural	Mway <sup>a</sup>	
						hot	hot	hot	
Driving patterns	Driving cycle	Inrets	24			1	1	1	5 VP faible/forte m 3 Napoli, 1 modem, 1 PVU, 1 or 5 <sup>b</sup> VP fai/for m., 4 Handbook, 1 m. Hyzem
			6			1	1	1	
		IM	1			1	1	1	
		KTI	1			1	1	1	
	TNO	1			1	1	1		
	Gear choice	Inrets	9						3 VP faible/forte motorisation
			4			1	1		
KTI	2			1	1				
Driver	Empa	1		2				US Highway, 12 Handbook	
Vehicle parameters	Techn. char. veh.	LAT	15		2	1	1	1	
		Renault	7		2	1	1	1	
		TUG	21		2	1	1	1	
	Emission stability	all	12 <sup>c</sup>			1	1		
	Emis. degradation	LAT	2	2	1 <sup>d</sup>	1	1	1	
	Fuel properties	Renault	2	2		1	1	1	1 cold Artemis urban
	Vehicle cooling	VTT	6			1	1		
Vehicle precondition.	IM	2		2	1	1			
	KTI	3							
Veh. sample size	Inrets	80 <sup>e</sup>	2					modem, m. Hyzem, modem IM	
Laborat. related parameters	Ambient temp.	Empa	18			1	1	1	
		VTT	13			1	1		
	Ambient humidity	VTT	11			1	1		
	Dynamo. setting	TNO	5	2		1	1	1	
	Dilution ratio	KTI	2		2				
		IM	3	2		1	1	1	
		LAT	3	2		1	1	1	
	Heated line temp.	KTI	1		2				
	PM filter precondition.	TNO	1	2		1	1		
	Response time	Empa, TUG & LAT	5						specific tests
Dilution air cond.	IM	2	2		1				
Round robin test	most <sup>f</sup>	1	2	2	1	1			

a Artemis Mway means Artemis motorway or Artemis motorway 130 alternatively

b 5 for Inrets, 1 for other labs

c TUG: 3, IM: 2, Empa, Inrets, KTI, LAT, Renault, TNO, VTT: 1 each

d EUDC only

e all vehicles have not been tested with all driving cycles

f Empa, IM, Inrets, KTI, LAT, MTC, TNO, TUG, VTT

Table 3: Number of driving cycles tested per vehicle and per parameter studied, and number of vehicles tested by parameter and laboratory. The driving cycles and families of them are defined in Annex 5.

Parameter		lab.	N. veh.	N. driving cycles	Tested cases	N. bags
Driving patterns	Driving cycles	IM	1	14	Large range of driving conditions	14
		Inrets	24	8		192
			6	18		108
		KTI	1	14		14
		TNO	1	14		14
	Gear choice	Inrets	9	3	5 strategies	195
			4	2		
KTI	2	2				
<i>Driver</i>	<i>Empa</i>	<i>1</i>	<i>15</i>	<i>4 times 1 robot driver, 4 human drivers</i>	<i>120</i>	
Vehicle parameters	Techn. char. veh.	LAT, Renault & TUG	43	6	Tests repeated twice	516
	Emission stability	all	12 <sup>c</sup>	2	Tests repeated 5 times	120
	Emis. degradation	LAT	2	6	Test every 20 000 km, before and after maintenance; 1, 2 or 3 repetitions	174
	Fuel properties	Renault	2	6	4 fuels, tests repeated twice	96
	Vehicle cooling	VTT	6	2	A small fan at 2 heights, a large fan with 3 air speeds, with open air closed bonnet	108
	Vehicle precondition.	IM & KTI	5	4	4 preconditioning cycles, driving cycle repeated 4 times	320
	<i>Veh. sample size</i>	<i>Inrets</i>	<i>80<sup>e</sup></i>	<i>29<sup>e</sup></i>		<i>790</i>
Laborat. related parameters	Ambient temp.	Empa	18	3	3 ambient temperatures: -20, -7 and +23°C	240
		VTT	13	2		
	Ambient humidity	VTT	11	2	3 ambient humidity levels, tests repeated	131
	Dynamo. setting	TNO	5	5	3 settings for road load and inertia	75
	Dilution ratio	KTI	2	2	3 ratios for 1 veh., 5 ratios for the 2 <sup>nd</sup> one	91
		IM	3	5	3 dilution ratios	
		LAT	3	5	2 dilution factors	
	Heated line temp.	KTI	1	2	2 temperatures	4
	PM filter precondition.	TNO	1	4	3 temperatures and 3 humidity levels	20
	Response time	Empa, TUG & LAT	5	30	Specific tests	75
Dilution air cond.	IM	2	3	3 levels of polluted dilution levels, tests repeated twice	36	
Round robin test	most <sup>f</sup>	1	6	2 to 10 repetitions <sup>g</sup>	210	

c TUG: 3, IM: 2, Empa, Inrets, KTI, LAT, Renault, TNO, VTT: 1 each

e all vehicles have not been tested with all driving cycles

f Empa, IM, Inrets, KTI, LAT, MTC, TNO, TUG, VTT

g see Table 11

*Table 4: Description of the tests carried out, per parameter and laboratory. The bag number in italics and yellow corresponds to existing data, not measured within the project.*



The test sequences are described in detail in the detailed reports for each parameter studied. They are reported briefly hereafter and presented globally Table 4. Globally 2753 tests are carried out, i.e.:

- 537 tests to look at the influence of the driving patterns
- 1334 tests to look at the influence of the vehicle parameters
- 672 tests to look at the influence of the laboratory related parameters
- 210 tests are part of the round robin test.

It must be noted that, as some common tests are used for several purposes, these figures are a little overestimated. In addition at least 910 tests from the data base but not carried out within the project are processed.

### **2.3.2.1. Driving cycles**

In order to assess the influence of the driving cycles and kinematic parameters on the emissions, emissions measurements were envisaged using a limited selection of cycles with the following constraints:

- to maximize the between-cycle differences in terms of kinematics
- possibly to enlarge the coverage of the emissions tests to driving conditions that were not well covered by the Artemis cycles (typically: the ultra-congested such as Napoli driving patterns, the Handbook stop & go, or the motorway driving in the range of 100 km/h)

In a first step, a large range of driving cycles was collected and reviewed, i.e. 213 standard and mainly representative driving cycles or sub-cycles (André et al., 2006). The driving cycles for light duty vehicles (light vans and vans) were not used for selection as the corresponding driving patterns would not have been appropriated for passenger cars. They were however considered in the analyses for their positioning as regards the other cycles.

In a second step, our purpose was to select a limited number of contrasted cycles (about 14), used later for emissions measurements and analyses. The approach used to characterize and select driving cycles is based on the analysis of the kinematical content of the cycles, through the two-dimensional distribution of the instantaneous speed and acceleration. An automatic classification enables establishing a typology of the test cycles, this typology being then used to select contrasted cycles, while preserving the representativeness of the initial dataset. This approach is indeed very efficient for such purpose and to identify easily similarities and contrasts between observations. It offers also criteria of ranking and representativeness of the cycles.

The heterogeneity of the driving conditions is too high between urban and motorway cycles to enable a direct analysis of the whole range (otherwise, we obtain trivial results such as: low speed means high dynamic and high speed means low dynamic). Therefore we attempt a first classification of the 213 cycles into groups of cycles.

This identification identified 4 categories of cycles: urban, suburban/rural, main roads and motorway. These 2 last categories (high speed cycles) were however analysed together due to their low number of cycles and quite satisfying similarity. As it will be shown later, the contrasted emission behaviour between these different driving conditions confirms also the pertinence of an analysis by driving type.

For each of the 3 resulting cycle categories, a further classification was done, enabling then the identification of 8 well contrasted groups of cycles per driving type (as well as the identification of exceptional cycles). From these 3x8 cases, one particular case was abandoned (the NEDC identified as a particular class). To cover the 23 other cases, a total of 43 sub-cycles was selected to offer the best representativeness and contrast. To simplify the experimental procedure, entire sets of sub-cycles (entire cycle) and entire sets of cycles (entire family) were privileged, when possible. The

Artemis cycles were obviously part of this selection.

Several modem sub-cycles and several Neapolitan speed curves were also identified as potential candidates for the selection (i.e. to represent sub-classes of the urban cycles). Then, we have composed 4 new cycles, one based on the selected modem sub-cycles and 3 based on the selected Neapolitan curves. With the other cycles, that results in a set of 14 driving cycles as follows:

1. "Artemis urban" (Artemis.urban" in the Artemis database)
2. "Artemis rural" ("Artemis.rural")
3. "Artemis motorway" ("Artemis.motorway\_150"), and alternatively "Artemis motorway 130" ("Artemis.motorway\_130")
4. "VP faible motorisation autoroute" (known also as "Artemis low motorization motorway" or "Artemis.LowMot\_motorway")
5. "PVU commerciale grand routier" (known also as "LDV-PVU commercial cars motorway" or "LDV-PVU.CommercialCars.motorway\_1")
6. "modem-HyZem pure road" ("modem-HyZem.road")
7. an urban modem cycle based on the modem cycles 5, 7 and 13, identified as "modem 5+7+13" or "modem.urban5713"
8. "Handbook R1" ("Handbook.R1")
9. "Handbook R2" ("Handbook.R2")
10. "Handbook R3" ("Handbook.R3")
11. "Handbook R4" ("Handbook.R4")
12. a Neapolitan cycle based on driving patterns number 6 and 17, identified as "Napoli.6\_17"
13. a Neapolitan cycle based on driving patterns 15, 18, 21, modified in "Napoli.15\_18\_21"
14. a Neapolitan cycle based on driving patterns 10, 23, modified in "Napoli.10\_23"

The characteristics of these 14 cycles are given in Annex 5, and their coverage is highlighted Figure 3, together with the one of their sub-cycles. These cycles have been tested on a sample of 9 passenger cars.

In addition, in the frame of the so-called "PNR-Ademe" study associated to the Artemis one, 6 among these 9 cars and 24 other cars are tested with the following driving cycles:

1. "Artemis urban", as above
2. "Artemis rural", as above
3. "Artemis motorway" (alternatively "Artemis motorway 130"), as above
4. "VP faible motorisation urbain dense" ("Artemis.LowMot\_urbdense") - alternatively "VP forte motorisation autoroute" ("Artemis.HighMot\_urbdense")
5. "VP faible motorisation urbain" ("Artemis.LowMot\_urban") - alternatively "VP forte motorisation urbain" ("Artemis.HighMot\_urban")
6. "VP faible motorisation urbain fluide" ("Artemis.LowMot\_freeurban") - alternatively "VP forte motorisation urbain fluide" ("Artemis.HighMot\_freeurban")
7. "VP faible motorisation route" ("Artemis.LowMot\_rural") - alternatively "VP forte motorisation route" ("Artemis.HighMot\_rural")
8. "VP faible motorisation autoroute" ("Artemis.LowMot\_motorway") - alternatively "VP forte motorisation autoroute" ("Artemis.HighMot\_motorway"), as above



cycles were thus derived using the same database and principles than for the Artemis cycles, but considering distinctly two classes of vehicles (André, 2006) according to their power-to-mass ratio (the low-powered cars with 61 W/kg or less, the high-powered cars with higher rates). Although they were similar in terms of structure, these cycles reproduce the statistics of car use and driving conditions observed for each car class. These cycles offered a good contrast with respect to dynamics, as shown in Figure 4.

The third set of emission data, considered to analyse the cycle influence, is the whole Artemis emission database. In that case, the data is the compilation of most of the existing datasets in Europe. The vehicle list is very long and does not really follow representativeness rules. These vehicles were tested using a very large range of different cycles (André et al., 2006).

The results are presented in section 3.1.1.

### 2.3.2.2. Gear choice behaviour

Five gearshift strategies are compared, i.e. five methods of gear shifting. The 5 strategies are tested for each among the 2 or 3 hot real-world driving cycles (2 Artemis cycles, or 3 VP faible/forte motorisation cycles, according to the vehicle sample) (André et al., 2003).

Two strategies depend on the vehicle characteristics:

- The so-called 'cycle' strategy is included in the design of the corresponding driving cycles (Artemis and VP faible/forte motorisation ones, see section 2.2). 4 gearshift behaviours are predetermined according to vehicle characteristics (vehicle power-to-mass ratio and 3<sup>rd</sup> gear ratio, see Table 2). For each of the 4 vehicle classes, the gearshifts reproduce the observed ones, according to the initial gear ratio, the instantaneous speed and acceleration (see André, 2004).
- The so-called 'RPM' strategy depends on the gear ratios, as the gearshift is foreseen at absolute engine speeds.

Two other strategies impose given gearshifts independently of the vehicle characteristics:

- The so-called 'NEDC' strategy imposes gearshift for given vehicle speeds, as foreseen in the NEDC driving cycle.
- The so-called 'record' strategy imposes the gearshifts recorded on the road during the driving behaviour data collection.

The last strategy, so-called 'free', is up to the laboratory driver.

The 5 gear choice strategies are briefly described in Table 5 and the results are presented in section 3.1.2.

Strategy	Description
cycle	Foreseen in the corresponding cycle, depends on vehicle power-to-mass ratio and 3 <sup>rd</sup> gear ratio
RPM	Foreseen at given engine speeds
NEDC	Foreseen at given vehicle speeds, as foreseen in the NEDC cycle
record	As recorded on the road during the driving behaviour data collection
free	Up to the laboratory driver

Table 5: Description of the 5 gear choice strategies tested.

### 2.3.2.3. Influence of the driver and of the cycle following

15 driving cycles (3 standard ones and 12 representative for the Swiss driving behaviour) were measured formerly, and each of them was accomplished four times by a robot driver Horiba ADS-

1100 and by four different human drivers, resulting in 120 bags (Devaux & Weilenmann, 2002). The actual vehicle speed is recorded at 1 Hz. The results are presented in section 3.1.3.

#### **2.3.2.4. Technical characteristics of the vehicles**

A quite large sample of cars were measured with the NEDC (with hot start) and the 3 Artemis driving cycles. The cars differ by their emission control technology, described in details in (Samaras et al., 2005):

- Gasoline vehicles: palladium containing three-way catalyst, formulation and loading of three-way catalyst, close coupled three-way catalyst, catalyst physical design, exhaust gas recirculation, advanced engine management strategies as rich start and secondary air injection, cold start spark retard and enleanment, transient adaptive learning;
- Diesel vehicles: oxidation catalyst, exhaust gas recirculation, engine design, engine management.

Each test was repeated twice. Since the engine load in the NEDC is quite different compared to the Artemis cycles, the test program should show up potentially different responses of different emission control technologies to cycles with different dynamics, engine speed levels and power demand (Samaras et al., 2005).

The results are presented in section 3.2.1.

#### **2.3.2.5. Short term emission stability**

After a preconditioning with the NEDC, repeatability tests were performed for each vehicle in each of the 9 participating laboratories by repeating the Artemis urban driving cycle 5 times. Each Artemis cycle was preceded by a 20 minutes break necessary to analyze the bags and to prepare the test bed for the next test. Since the Artemis cycles include a preconditioning part in his speed profile (see section 2.2.1), the engine should have been in comparable hot running conditions in each repetition.

Here is the first part of the test sequence:

- preconditioning with the NEDC
- 20 minutes break
- Artemis urban
- 20 minutes break
- Artemis urban
- 20 minutes break
- Artemis urban
- 20 minutes break
- Artemis urban
- 20 minutes break
- Artemis urban

The second part of the test sequence is a similar sequence but performed with the Artemis rural driving cycle (Cornelis et al., 2005).

The method of data processing is presented in section 2.4.1 and the results in section 3.2.2.

#### **2.3.2.6. Long term emission degradation**

The maintenance interval defined by the manufacturer for both tested vehicles is 10 000 km. The measurements were scheduled at mileage intervals of 20 000 km thus at every second maintenance point. Measurements were performed both before and after the maintenance. In the case of the second vehicle it was possible to get a reference measurement at 0 km. The scheduled

measurements of the first vehicle were completed at 110 000 km while for second one at 50 000 km. The measurement schedule is presented in Table 6. As seen in this table, some measurements were not performed due to technical difficulties (weather conditions, unavailability of vehicles etc).

Mileage [km]	Before / after maintenance	Vehicle 1	Vehicle 2
0			3
10 000			
20 000	before	3	2
	after	3	2
30 000			
40 000	before	2	
	after	1	
50 000	after		2
60 000	before	2	
	after	2	
70 000			
80 000	before	2	
	after	2	
90 000			
100 000			
110 000	before	1	
	after	2	

Table 6: Measurement schedule for the emission degradation along the mileage. One test corresponds to 6 bags.

The test protocol started with an NEDC (cold start) sampled in two bags followed by a one-bag EUDC. After the analysis of the samples, two repetitions of EUDC were executed in order to achieve engine warm-up, without any measurement. The three Artemis cycles were then performed and sampled in one bag each. All together 6 driving cycles or bags were performed per test (Geivanidis & Samaras, 2004).

The results are presented in section 3.2.3.

### 2.3.2.7. Fuel properties

In order to evaluate the influence of fuel specifications throughout Europe on vehicle emissions, the 9 laboratories involved supplied both one petrol and one diesel commercial fuels Euro 3. These 9+9 fuels have been analyzed, and their impact on emissions according to the SG1-EPEFE formulae (Acea and Eurovia, 1996) were assessed: see section 2.4.2.

This allowed to select over the sample of fuels provided by the laboratories, 3 petrol and 3 diesel fuels, which are supposed to give minimum, average, and maximum emissions. In addition, reference Euro 4 fuels were provided, one petrol and one diesel fuel. All together 4 petrol and 4 diesel fuels are tested.

Each fuel is tested with 1 vehicle, with the following protocol:

- lubricant change in order to avoid any carry-over effect
- a preconditioning phase: a cold EUDC (followed by a EUDC for diesel fuel)

- a cold start NEDC sampled in two bags
- a cold Artemis urban
- the 3 Artemis cycles

All the emission tests were performed twice for repeatability purposes.

While replacing one fuel to another the car was driven for a distance between 150 and 200 km, to remove any carry-over effect of the previous fuel (learning procedure, canister purge, oil dilution...).

The tests conditions were monitored and complied with the standard procedure: ambient temperature between 20°C and 30°C, controlled hygrometry, constant blower speed set up at a value simulating a vehicle driven at 50 km/h in the case of the NEDC cycle, and a blower with a speed evolving according to the vehicle speed for the Artemis cycles (Renault & Altran, 2002).

The tests conditions were monitored and complied with the standard procedure: ambient temperature between 20°C and 30°C, controlled hygrometry, constant blower speed set up at a value simulating a vehicle driven at 50 km/h in the case of the NEDC cycle, and a blower with a speed evolving according to the vehicle speed for the Artemis cycles. The exhaust gas temperatures (upstream and downstream from the catalytic converter and at the core of it) were also measured.

The results are presented in section 3.2.4.

### 2.3.2.8. Vehicle cooling

The cooling arrangement was varied by using small blower, confirming with the provisions of standardised emissions test protocols, set at the distance of 30 cm from the face of the car, and used either in normal, “stand-up” position directed towards the face of the vehicle front end, or in a “flat-on-the-floor” position, directed more below the engine.

In addition, a large blower with a 1.2 m x 1.2 m cross-section area and regulated air speed was employed. It was used either with fixed air speeds (30 or 60 km/h corresponding resp. to 50 % and 100 % of the average speed of the cycle, roughly), or relative to roller speed representing the driving speed of the car (i.e. following the cycle speed).

Apart from the blower arrangement, the opening of the bonnet of the car was altered between open (up) and closed (down) positions. Table 7 explains the basic matrix of different combinations tested.

Fan type	Air fan		Vehicle bonnet
	Air speed	Height	
<i>Small blower</i>	<i>25 km/h</i>	Low	Open / up
			Closed / down
		High	Open / up
			Closed / down
Large blower	30 km/h		Open / up
	60 km/h		Open / up
			Closed / down
	modulated		Open / up
			Closed / down
			Closed / down

Table 7: Test matrix for the effect of vehicle cooling. The normative method is in italics.

In all testing, ambient temperature at the start of the test run was usually targeted at +23 °C. However, in case of exhaustive and repeated hot start tests, ambient temperature in the test cell was sometimes raised to rather high values, even if not violating yet the upper limit of the normative

range, designated between +20 and +30 °C, but high enough to cause heating of the fuel and resulting an increase in evaporation, thus loading the active carbon canister of some of the cars up to a point, when purging occurred. This could be detected, as sometimes the continuous measurement of HC emissions showed very high, but quite short peaks during idle periods (Laurikko, 2005a).

Local commercial quality, unleaded petrol (RON95) and diesel (low sulphur) form a well-known quality supplier (Fortum/Neste). Single batch of both fuels was used for all testing at VTT.

The results are presented in section 3.2.5.

#### **2.3.2.9. Vehicle preconditioning**

The test protocol is the following:

- a cold NEDC as preconditioning cycle
- 10 minutes delay with stopped engine
- the preconditioning test
- the measurement driving cycle, performed 4 times.

This test was made for 4 preconditioning tests and 4 measurement cycles.

The four preconditioning tests are:

- 10 minutes idling
- 10 minutes at constant 80 km/h speed
- NEDC
- Artemis urban cycle

The measurements were conducted at normal ambient temperature - which is kept between +20 and +25°C - in conditioned laboratory. Local, commercial grade fuels were used (Olàh, 2005).

The results are presented in section 3.2.6.

#### **2.3.2.10. Minimum vehicle sample size**

The data base used to look at the influence of the vehicle number on the stability of the emission function was made with three measurement campaigns carried out formerly in the same laboratory. Per vehicle category, the vehicle number is 25 to 30, and the cycle or bag number varies between 17 and 31. All together data from 160 cold start cycles and 630 hot start cycles were used (Lacour & Joumard, 2001). The method used is described in section 2.4.4 and the results in section 3.3.2.

#### **2.3.2.11. Ambient temperature**

The tests for this task were performed in series with the test runs carried out to determine cold-start excess emissions (see Joumard et al., 2007). At first, a cold-start test was done, and when the engine was fully warmed-up, a hot-start test run was performed to assess the effect of ambient temperature on the hot emissions.

The tested ambient temperatures were approximately -20, -7 and +23°C (Laurikko, 2005b).

For all tests at VTT, single-quality (and batch) of both fuels from a supplier was used. According to the specifications of the supplier, petrol was unleaded, RON95, and diesel fuel had sulphur contents maximum of 10 ppm. For tests at Empa, two types of petrol and one quality of diesel fuel was used. A first petrol was unleaded, RON 98, and contained 0.6 % (vol) benzene and 27.5 % (vol) aromatics, whereas the second petrol was unleaded, RON 95, and contained 3.0 % (vol) benzene, 39.4% (vol) aromatics. Furthermore, diesel fuel had 18.8 % (mass) monoaromatics, 3.3 % (mass) diaromatics, and 0.5 %(mass) triaromatics.



The results are presented in section 3.4.1.

#### **2.3.2.12. Ambient humidity**

The tests for ambient humidity were performed with a test cell equipped with humidification system to keep the level within a range, close to the target value of 60 % relative humidity. However, to be able to assess the effect even beyond the range that is deemed acceptable by the emission measurement standards (5.5 to 12.2 g/H<sub>2</sub>O in kg dry air), the ambient humidity was varied by running the tests in wintertime, when ambient air was for natural reasons very dry, well below the lower limit of the statutory test protocol. Additional humidity was then added into air to reach normal and above-normal conditions, when the content of water in the air was higher than 12.2 g H<sub>2</sub>O/kg dry air, which is the upper acceptable limit. A special spray humidifier was employed, when necessary. 3 levels of humidity were tested (Laurikko, 2005c). Tests were repeated basically under the same ambient conditions during the day in order to assess general repeatability of the test and increase quality of the data.

The results are presented in section 3.4.2.

#### **2.3.2.13. Dynamometer setting**

An inquiry was held amongst the partners within the Artemis project in order to gather all information on the methods for the definition of the chassis dynamometer settings used by the Artemis partners, assuming that the most commonly used methods will than be covered. The outcome of the inquiry showed that most partners within Artemis use either road load information derived from the coast down method performed by themselves or performed by the manufacturer of a vehicle, or road load figures from the look up table in EC 70/220. The reference mass is determined either by weighing, or by using information from the car license papers.

The two methods have been analyzed on their degrees of freedom of the road load. Two worst case chassis dynamometer settings (minimum and maximum) and one average setting for static road load and vehicle inertia were derived (see Annex 4). These three sets of settings were used to perform emission tests (Vermeulen, 2005).

The results are presented in section 3.4.3.

#### **2.3.2.14. Dilution ratio**

2 to 5 dilution ratios were tested per vehicle (Geivanidis et al., 2004):

- At LAT, the high dilution ratio was the one normally used for emission measurements. The low dilution ratios were determined according to the vehicle, under the limitations set by the temperature limit of 52°C at the PM sampling point.
- At IM, at least three dilution factors were used: the usually used plus a lower and a higher, varying as a function of car and cycle.
- At KTI, a diesel vehicle was tested with 3 dilutions ratios, a petrol vehicle with 5 dilution ratios.

The results are presented in section 3.4.4.

#### **2.3.2.15. Heated line temperature**

A diesel vehicle was tested using two different temperature settings for the HC sampling line: at low temperature (160°C) and at normal temperature (190°C) (Geivanidis et al., 2004). The results are presented in section 3.4.5.

### 2.3.2.16. *PM filter preconditioning*

The procedure consisted of reference tests with conditioning and weighing of the particle filters at an average temperature and humidity in the filter conditioning room, and of tests with a defined minimum and maximum value for these conditions. The minimum and maximum values were defined by the capability of the climate control system to adjust a certain range of temperature and humidity. Therefore 3 room temperatures and 3 room humidity levels were tested, all together 5 test conditions (Geivanidis et al., 2004). The results are presented in section 3.4.6.

### 2.3.2.17. *Response time, including instantaneous vs. bag value*

The tests are very specific, as the method is mainly based on model building. The method is described in section 2.4.5 and the results in section 3.4.7.

### 2.3.2.18. *Dilution air conditions*

Measurements with polluted dilution air have been compared to measurements with standard ambient air. Two different levels of pollution of dilution air have been studied and compared to standard condition: a low level and a maximum level. Values considered as standard condition are common to all participating laboratories to Artemis project (except of HC and NO<sub>x</sub> measured by TUG). The low level of polluted dilution air is representative of the highest concentrations measured in Artemis labs. The high level of polluted dilution air, instead, represents a improbable air condition, which could be reached because of an incident as gas or fuel leaks.

The 3 levels of pollution are shown in Table 8. In both cases, dilution air pollution has been obtained by inoculating a specific quantity of CO, HC and NO<sub>x</sub> upstream dilution tunnel. For each of the three pollution levels, two repetitions of each cycle have been performed (Prati & Costagliola, 2004).

The results are presented in section 3.4.8.

	standard	low	high
CO	0.4	2-3	11-12
HC	3-4	11-12	20-21
NO <sub>x</sub>	0.1-0.2	1-1.2	5.5-6

Table 8: Concentrations of CO, HC and NO<sub>x</sub> in the three dilution airs (ppmv).

### 2.3.3 Vehicle sample

183 vehicles have been specifically tested for the study and data from 81 previously tested vehicles have been used for two parameters. The samples per task are described in terms of fuel and emission standard in Table 9 and in terms of average cubic capacity, maximum power, weight and mileage per fuel in Annex 6. The detailed characteristics of all the vehicles are given in Annex 7.

Some specificities of the samples are given hereafter for some parameters studied.

#### *Driving cycles*

The distribution of the vehicles tested is provided in Table 10. 6 out of the 9 cars tested specifically within Artemis for this task were also tested in the PNR-Ademe study. These cars have then been tested using the 2 cycles sets. The samples per vehicle category (fuel x emission regulation) are quite limited. The most significant samples concern the Euro 2 and diesel vehicles. Obviously these limited sample sizes limit the extent of the conclusions.

Parameter	total.	Petrol						Diesel						
		PreE1	E1	E2	E3	E4	total	PreE1	E1	E2	E3	E4	total	
Driv.	Driving cycles	33		3	7	6		16	2	3	10	2		17
	<i>sub-sample 14 DC</i>	9				4		4		2	2	1		5
	Gear choice	15		3	3	2		8		2	4	1		7
	Driver	1		1				1						0
Vehicle par.	Techn. char. veh.	43			3	23 <sup>a</sup>	6 <sup>a</sup>	32 <sup>b</sup>			2	9		11
	<i>"" detailed analysis</i>	13				5	3	8				5		5
	Emission stability	12		1	3	6		10				2		2
	Emis. degradation	2				2		2						0
	Fuel properties	2				1		1				1		1
	Vehicle cooling	6			4			4			1	1		2
	Vehicle precond.	5			2	1		3			2			2
Veh. sample size	80	34	18	3			55	11	9	5			25	
Laboratory par.	Ambient temp.	31	6		7	7	2	22			8	1		9
	Ambient humidity	11			4	5		9			2			2
	Dynamo. setting	5			3			3			2			2
	Dilution ratio	8			2	1		3			3	2		5
	Heated line temp.	1						0			1			1
	PM filter precond.	1						0				1		1
	Response time	5	1	1	1			3			1	1		2
	Dilution air cond.	2			1		1	2						0
Round robin test	1				1		1						0	
Total	183	7	8	40	55	9	119	2	5	37	20	0	64	

a including 1 CNG vehicle

b including 2 CNG vehicles

Table 9: Description of the vehicle samples per parameter studied in terms of fuel and emission standard (pre-Euro 1, Euro 1 to Euro 4). Vehicles in italics were not tested specifically for the study, but within a former research, or are a sub-sample for a more detailed analysis.

Emission standard	PNR-Ademe		Artemis		Total
	Diesel	Petrol	Diesel	Petrol	
Pre-Euro	2				2
Euro 1	3 (1)	3	2		8
Euro 2	10 (2)	6	2 (1)	1 (1)	19
Euro 3	2	4 (1)	1	3 (1)	10
Total	17	13	5	4	39

Table 10: Recapitulation of the vehicles tested in the 2 experimentations (in brackets, cases of high emitting vehicles).

Amongst these vehicles, several were quite early identified through the analyses as "abnormal" emitters (for one or the other pollutant, the figure exceeds 50 % to 100 % the average emission of the vehicle category: fuel x emission standard). It appeared that they could perturb considerably later analyses (attempt to model the emissions as regards the kinematic parameters, etc.). For these reasons, we have identified these 5 cars as "High emitters" and analysed specifically their behaviour (André et al., 2006).

*Influence of the driver and of the cycle following*

A review and statistical analysis of older data (Schweizer, 1998) is used.

*Emission degradation*

Two petrol vehicles representative of the middle and small engine displacement market segments were chosen for the measurements. Both vehicles belonged to a car rental company and were leased to specific customers with high mileage accumulation. This way it was assured that use and maintenance conditions were well controlled (the latter according to manufacturer's specifications) and that both vehicles would reach the target mileage within programme schedule.

*Number of vehicles (minimum size for a category)*

This study was based on the Inspection Maintenance measurement campaigns of 1994 (Samaras et al., 2001), and Hyzem or Hyzem-Ademe campaigns of 1997 (Joumard et al., 2000), for the parts carried out at INRETS. The selected samples are representative of the French vehicle fleet at a three-year time interval. They are split into 3 vehicle categories: non catalyst petrol, catalyst petrol, non catalyst diesel, with resp. 25, 25 and 30 vehicles.

The equivalence of the IM and Hyzem sets was checked using variance analysis and mean comparison tests over common EUDC and ECE15 cycles for the three vehicle categories. The comparison of the results shows that the measurements do not significantly differ between the two samples, whatever the pollutant and the category studied. Therefore the vehicles of both campaigns can be grouped in a same set (Lacour & Joumard, 2001).

## 2.4. Specific methods and methods of data processing

Instead or before the emission tests, other methods have been used to look at the influence of given parameters. It is the case to select the fuel to test in the laboratory, for the study of the vehicle sampling methods, and to determine the minimum number of vehicles in a sample.

### 2.4.1. Short term emission stability

The short term emission stability (see the test description in sections 2.3.1 and 2.3.2.5) was assessed by use of the standard deviation and relative standard deviation (s. d. rated by the average). Different standard deviations are used, for a given driving cycle and a given vehicle class (fuel, emission standard):

- For a given vehicle tested, the s. d.  $s_v$  between the repeated driving cycles, i.e. over the 5 repetitions.
- The quadratic average of the s. d.  $s_v$ , so-called  $s_r$  because it refers globally to the repeatability.
- The s. d. between the emissions averaged per vehicle. This standard deviation  $s_s$  shows the differences between vehicles and refers to the sample.

$s_r$  and  $s_s$  allow us (Cornelis et al., 2005) to decompose the measurement uncertainty of all measurements in the uncertainty due to differences between vehicles (sample standard deviation -  $s_s$ ) and the uncertainty due to a spread in test results for one vehicle (repeatability standard deviation -  $s_r$ ). The results are presented in section 3.2.2.

### 2.4.2. Selection of the fuels tested

The equations derived from Auto/Oil 1 programme were used to determine what fuels would give the minimum, the maximum and the average amount of emissions, both for petrol and for diesel

fuel (Renault and Altran, 2002, see the test description in sections 2.3.1 and 2.3.2.7). The AutoOil / EPEFE programme, designed to quantify the reduction in road traffic emissions that can be achieved by combining advanced fuels with the vehicle or engine technologies under development for the year 2000, provides linear model equations for average light duty petrol and diesel vehicle to determine the exhaust emissions from both vehicle types, according to several fuel parameters such as:

- For petrol, the aromatics content, the olefin content, the evaporated fraction of the fuel at 100°C and also at 150°C, the sulphur content and the oxygen content
- For diesel fuel, the density, the polyaromatic hydrocarbon content, the cetane number, the temperature at which 95 % of the fuel has evaporated and the sulphur content

The coefficients of these equations are specific to each pollutant and are given in Annex 8.

In order to be as representative as possible of the wide range of quality available for fuels across Europe, each participating laboratory was asked to sample in its region / country both unleaded petrol and diesel fuels at a filling station. Then the analysis of each kind of fuels was performed by the SGS Redwood France Company (see the results in Annex 8). These results show that all fuels sampled do comply with the European Directive specifications (EN228:1999 and EN590:1999, resp. for petrol and diesel ones). Nevertheless the aromatic content of one petrol fuel is at the maximum limit of the specification (42 % m/m), and the olefin content of another petrol fuel is very low (10 times lower than the maximum limit). In addition, all PAH contents of diesel fuels are very low.

Using the above data and the EPEFE formulae, the emissions over the NEDC cycle were assessed for each fuel. It is essential to underline that the emissions calculated in absolute g/km represent the emissions of the EPEFE vehicle distribution that would have been produced by using the fuels instead of the EPEFE fuel matrix. This explains why the absolute emissions are between Euro 2 and Euro 3 emission limits, which correspond to the EPEFE vehicle distribution. The results are listed in Annex 8.

From these results, the maximum amplitude is obtained for the petrol fuels for the NO<sub>x</sub> emissions (7 %). Therefore, it is inferred that NO<sub>x</sub> emission factor is the most influenced by the quality of these fuels, and therefore this pollutant is the criteria chosen to determine which petrol fuels will be tested. The petrol provided by TUG has the lowest emission factor and the one from Renault has the highest emission factor. The petrol provided by LAT gives the median of the emission. Therefore these 3 fuels are chosen to be tested.

For the diesel fuels, as it is important to improve PM emission factors and as, except NO<sub>x</sub>, the amplitude in percentage is more or less the same between HC, CO and PM (resp. 11, 10 and 8 %), PM is chosen as the driver to select the fuels. The origin laboratories are VTT, INRETS and IM, resp. for the maximum, minimum and medium PM emissions.

In addition the European IV market fuels, both petrol RON 95 and diesel fuel, are tested.

The results are presented in section 3.2.4.

### **2.4.3. Methods of vehicle sampling**

In order to assess the influence of the vehicle sampling method on the emission factor level, it is necessary firstly to know the different methods used by the measurement laboratories. For this aim, two inquiries were carried out by email in direction of 10 laboratories (André, 2002): Empa, IM-

CNR, INRETS, KTI, LAT, MTC<sup>1</sup>, Renault, TNO, TUG and VTT. The first inquiry underlined the terms used by the laboratories to characterise their sampling methods. It aimed especially to know the meaning of the word "sample" and to describe the ways and the difficulties to obtain the vehicles. The 10 laboratories answered.

The second inquiry went more in depth and looked also on the minimum number of cars below which the laboratories do not analyze the data. 7 laboratories among 10 did answer (IM, LAT and VTT did not).

The results are presented in section 3.3.1.

#### 2.4.4. Minimum vehicle sample size

Considering the high emission dispersion from one vehicle to another, it is important to determine how many vehicles are required to be able to consider the obtained emission factors as representative of the average of in-operation vehicles (Lacour and Joumard, 2001; see the test description in sections 2.3.1 and 2.3.2.10). It depends on the emission factor shape, i.e. the shape of the emission model. We choose here the MEET methodology for building-up the emission factors (Joumard, 1999): An emission factor corresponds to a model in which emission is related to the average trip speed.

Then for a given vehicle sample and a given pollutant, two conditions are required:

- In order to compare the models directly over model-related parameters, all the emission models must have the same structure
- For meaningful comparisons, these models should also be representative enough of the measurements performed

The first step was aimed at finding out an algebraic form of the models that would be the most appropriate to meet both requirements. Emission variables were thus transformed in order to maximise model quality. The general form used is written as follows:

$$G(EF) = a(\text{category, pollutant}) \cdot F(V) + b(\text{category, pollutant})$$

with:

EF = emission factor

V = trip speed

G and F are functions

a and b are category and pollutant-related constants

We used the following algebraical formulae for emission models, giving good results for individual vehicle and vehicle sample modeling, for any vehicle category:

- For CO and HC:  $\text{Ln } EF_{\text{pol}} \text{ (g/km)} = a \cdot \text{Ln } (V \text{ (km/h)}) + b$
- For NO<sub>x</sub> and CO<sub>2</sub>:  $EF_{\text{pol}} \text{ (g/h)} = a \cdot V \text{ (km/h)} + b$

Models are built for each vehicle of the vehicle sample, then for each of the three vehicle samples defined in section 2.3.3, and then for a large number of sub-samples with different sizes. In each case the model validity was checked twice, the model being considered valid if both following criteria were met:

- The Fisher test was used to check that the relationship between EF and V does occur by chance
- The Student test was used to check that each parameter a and b has a real role in the model

Therefore, in a second step, we assess the number of vehicles for which an individual vehicle model

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is valid.

In a third step, we verify that the models for the whole samples (i.e. for each of the 3 sub-samples of 25, 25 and 30 vehicles) are valid. The whole samples are assumed to be representative of the studied population.

Then we considered all intermediate vehicle sample sizes between one and the size of the whole sample. For a prescribed size  $i$ ,  $i$  vehicles were sampled among the whole sample available, building a restricted random sampling. For each driving cycle, an average emission was calculated and an emission model was built-up from these averages. The model thus calculated is called a "restricted" model since it is defined with a limited number of measurements as compared to the whole model. Each restricted model was tested using the same criteria as previously defined in order to check its validity (Fisher and Student tests).

For a prescribed sample size, 20 sampling operations were performed, i.e. 20 models were tested per size. Therefore, the proportion of non-valid restricted models was determined for each size. This means that the minimum size of a sample was determined so as to guarantee emission modelling availability whatever the sampling result. This minimum size is directly related to the percentage of vehicles with aberrant behaviours.

As the number of vehicles in sub-samples is increased, average emissions get stabilised and converge to mean values of the whole sample. The aim was thus to determine the number of vehicles required to build-up a model which would describe the average behaviour of the vehicles satisfactorily, i.e. to study the capacity of restricted models to predict average emissions of the whole sample. Therefore the consistency and the accuracy of the restricted models (B) as compared to the whole sample (A), considered as the best sample, were tested. If the sub-sample B is of same nature than the sample A, the model B can be used to predict emissions from the sample A. We considered the sum of squared residues over the sample:

$$rSS_B^* = \sum_{N_A} (y_{A,i} - \hat{y}_{B,i})^2$$

where  $y_{A,i}$  is the average emission of trip  $i$  assessed over Sample A

and  $\hat{y}_{B,i}$  is the predicted emission with Model B.

$rSS_B^*$  is proportional to the residual variance of the model B with respect to the sample A. This term enables to evaluate the pseudo index of fit for model B with respect to sample A, which thus enabled us to determine the Fisher value of the model B over the sample A:

$$F_B = \frac{r_B^{*2}}{1 - r_B^{*2}} \quad \text{where} \quad r_B^{*2} = 1 - \frac{rSS_B^*}{\sigma_y^2 (N_A - 1)}$$

The Fisher test enabled us to check the validity of model B over sample A, i.e. whether the measurement values for sample A and the predicted values for model B were related in a significant manner. This test (with a 5 % margin of error) was performed over all the models corresponding to a prescribed size and we checked that 100 % of the models were valid.

But  $rSS_B^*$  is also a model quality index since this quantity is proportional to the squared mean of the distances of measurement values to the line. This distance is minimum for model A. Therefore, the quality of model B is assessed with respect to that of model A using the following criterion:

$$\Delta_{B/A} = \frac{rSS_B^{*2} - rSS_A^{*2}}{rSS_A^{*2}} \leq 0.75$$

$$\Leftrightarrow \Delta_{B/A} = \frac{r_A^2 - r_B^2}{1 - r_A^2} \leq 0.75$$

Thus, this amounts to accepting model B provided that the squared distance between the two models is lower than the squared distance between the measurements and the model by at least 25 %. This criterion is more stringent than the Fisher test, but it is a requisite to guarantee that the emissions predicted by the model for a prescribed speed are in good agreement between the various models studied. It allows us to calculate the required number of vehicles to obtain a quality of emission model equivalent to that of the whole model.

The results are presented in section 3.3.2.

#### 2.4.5. Response time, including instantaneous vs. bag value

There are several potential systematic problems associated to the instantaneous emission measurement. The emissions recorded from the analyzers are delayed and smoothed compared to the emission events at the location of formation due to

1. The transport of the exhaust gas to the analysers
2. The mixing of exhaust gas especially in the silencer and the CVS tunnel
3. The response time of the analysers

The transport time of the exhaust gas to the analyser is determined by the velocity in the exhaust system of the vehicle and by the velocity in the CVS tunnel and in the related connection pipes. Especially the velocity of the undiluted exhaust gas is highly variable over time since it depends on the exhaust gas volume flow. The volume flow mainly depends on the engine speed and on the engine load. All together, the varying transport times and the analyzers response time can shift the signal of the analyzer from approx. 1 to 10 seconds (depending on the engine, the exhaust system, the CVS system, the analyzer used and certainly the engine load). Mixing effects during the gas transport and the analyzers response behavior add a smoothing effect on the signals of the exhaust gas concentration levels.

These inaccuracies are usually compensated over the complete test cycle, such that the integral of the instantaneous measurement is in line with the bag value.

In most of the instantaneous emission models, the mapping of emissions is performed by statically relating the emission signals to causative variables, such as vehicle speed, acceleration, engine speed, etc. As a result of this static approach, the emission values can be correlated to the correct engine state of the car only if they are at the correct location on the time scale. Thus instantaneous models are heavily affected by inaccurate time alignments. Thus, improvements in the instantaneous emission modelling need improved instantaneous measurement data as a first step.

In order to minimize the errors resulting from inaccurate time alignments, Empa and TU-Graz developed methods to compensate the delay and the smoothing of instantaneous emission measurement. Specially calibrated for the own test bed, both methods are based on (Le Anh et al., 2005):

1. Explaining the change of the emission value from their location of formation to the analyser signal by formulas
2. Inverting these formulas to gain equations which transform the analyser signal into the engine out (or catalyst-out) emission value

The main difference in the models of TUG and EMPA is, that the EMPA model is more detailed



but needs modal measured data on the exhaust gas volume flow and information on the volume of the exhaust gas system of the tested cars. The TUG model has a simpler approach, which basically can be applied with the data recorded usually at roller tests.

As example for the model quality achieved, Figure 5 shows the oxygen signal at the catalyst outlet reconstructed from the analyzer signal. The time quality of this overall reconstruction is about 0.8 seconds, when raw gas measurements are used.

Moreover, the integral value (i.e. the sum) of the reconstructed emission data has been compared to the integral value of the measured emissions at the catalyst outlet and a deviation of less than 1.5 % has been found, which is considered to be very good for the emission inventories.

Using signals from the diluted measurements, the quality of the reconstructed signals shows maximal time errors of 2.5 seconds, which is significantly better than using the original signal with up to 25 seconds uncertainty, but which is notably worse than using the raw line.

From Figure 5 it is clear that using uncorrected signals from modal measurements leads to huge errors in the allocation of emissions to the corresponding engine operation conditions. Since the transport time of the undiluted part of the sample system depends on the exhaust gas volume flow and thus on the engine load conditions, the misalignment between engine load and emission signal is highly variable over a test cycle. Thus, the constant time shift of measured signals used in previous models does not lead to a satisfactory result but to distorted vehicle emission maps.

The conclusion is presented in section 3.4.7.

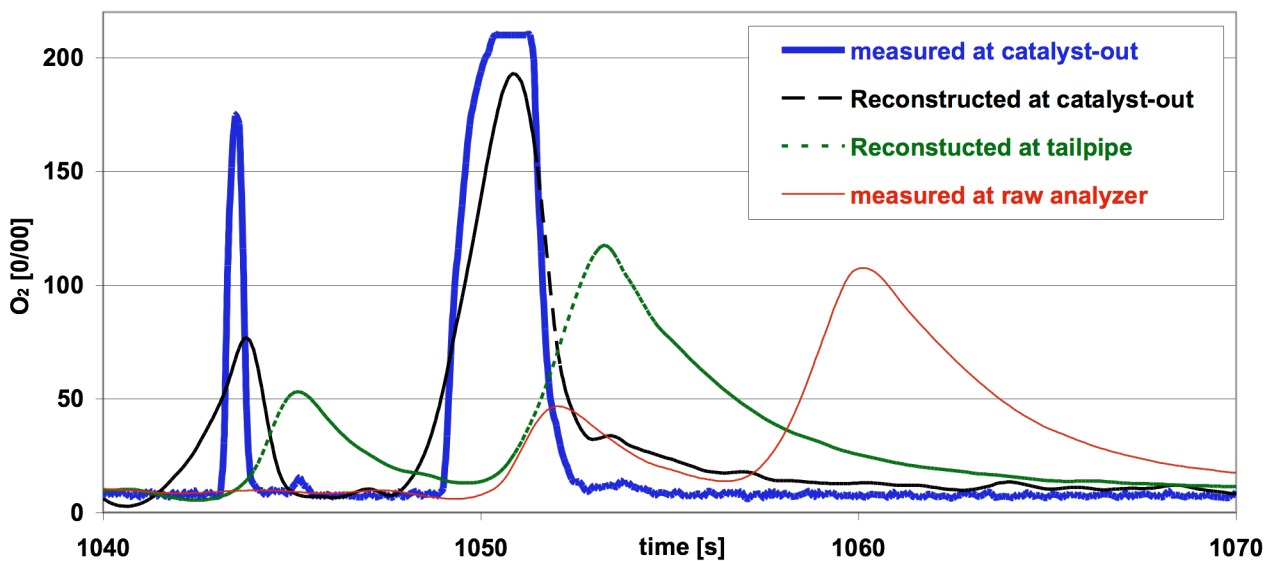


Figure 5: Overall inversion of the instantaneous concentration measured by gas analyser, using the Empa model. The blue thick line is measured by a fast oxygen analyser in situ at catalyst out location, the red thin solid line is measured by a standard oxygen analyser attached to a raw gas line of some 10 m connected to the tailpipe of the car. The green dotted line is reconstructed out of the red signal compensating the transport dynamics of the sampling line. The black dashed line is reconstructed out of the green line compensating the time varying transport in the exhaust system of the car.

### 2.4.6. Round robin test

A petrol vehicle, rented through a rental company in France, was used as round robin vehicle. It was a Euro 3 vehicle (see its characteristics in Annex 7). It was tested successively at INRETS, IM, TUG, KTI, Empa, TNO, MTC, VTT, LAT and finally again at INRETS. The successive order, presented Table 11, was based on their geographical position as well as their availability. As it can be seen, the exercise spanned itself over nearly 8 months. The vehicle started the tour with nearly full fuel load, and that fuel was continuously used in the successive tests by the next laboratories, until the fuel level became low (usually below 20 %), and then the vehicle was refuelled with normal commercial fuel available at that laboratory (Table 11).

The testing protocol determined the vehicle road load for setting up the dynamometer using either the coefficients of the basic road-load formula or the so-called coast-down times, i.e. time intervals between two determined speeds on a free-rolling (no-gear engaged) coast-down on the chassis dynamometer (see Annex 4 for a detailed description of the dynamometer settings). As a further reference, net power absorption (in kW) at two speeds was also included.

The test sequence (see Table 3 and Table 4) is a cold NEDC, a hot NEDC, a hot Artemis urban and a hot Artemis rural, i.e. 6 bags all together, in normal ambient temperature conditions. At INRETS this complete protocol was executed 10 times at the begin to look at the stability of the vehicle emissions, between 2 and 4 times for the eight next participating laboratories (2 times for 5 labs, 3 times for 2 labs, 4 times for one lab), and finally 5 times at INRETS at the end of the round robin test (see Table 11). Apart from the temperature, humidity and barometric pressure data were also collected to improve the analysis and assessment of the spread among the testing conditions.

Exhaust pollutant measurements included regulated gaseous emissions. Some laboratories determined also particulates (PM), even if those are not regulated in case of a petrol-fuelled car. The vehicle exhaust emission test was augmented with stand-alone standard gas concentration measurements using a set of calibration gas samples that travelled with the vehicle. The results of the analysis of those gas samples were also collected as part of the effort making it somewhat possible to relate separately also the accuracy of the emissions analysis benches separate from the total test installation, including the set-up and conduct of the full protocol.

The results are presented in section 3.5.

lab	location	country	test period	fuel	n ex.
INRETS	Bron	F	27-07-2004 to 07-09-2004	unleaded 95 RON	10
IM-CNR	Napoli	I	02-11-2004 to 04-11-2004	same as Inrets	3
TUG	Graz	A	16-11-2004 to 18-11-2004	same as Inrets	2
KTI	Budapest	H	02-12-2004 to 07-12-2004	same as Inrets	2
Empa	Duebendorf	CH	13-12-2004 to 20-12-2004	unleaded 95 RON (Migrol)	4
TNO	Delft	NL	28-12-2004 to 29-12-2004	petrol RON 95, S<50ppm	2
MTC	Haninge	S	18-01-2005 to 19-01-2005	blend 95, RVP 63	2
VTT	Espoo	FIN	27-01-2005 to 28-01-2005	same as MTC	2
LAT	Thessaloniki	GR	18-02-2005 to 24-02.2005	unleaded 95 RON	3
INRETS	Bron	F	07-03-2005 to 11-03-2005	unleaded 95 RON	5

Table 11: Laboratory order, timing and fuels used during the Round-robin exercise, and number of execution of full protocol (6 bags).



## 3. Detailed results

Following the methodology described in section 2, a huge amount of emission data is integrated in the Artemis database and then processed, parameter per parameter. The parameters concern the driving patterns, the vehicle related parameters, the vehicle sampling method, the laboratory related parameters, and finally the round robin test.

### 3.1. Driving patterns

The driving patterns include the driving cycles, the gear choice behaviour and the way the driving cycle is followed in the laboratory. As the driving cycle is the main way to represent the driving behaviour, we look in depth at its influence, in order to go further than the current taking into account of the average speed.

#### 3.1.1. Driving cycles

To highlight and understand the influence of the driving cycles on the pollutant emissions, we use two experimental datasets: 9 cars measured within the task of the Artemis project dealing with the influence of the driving cycles (DC), by using a selection of well-contrasted driving cycles, and 30 cars tested within the PNR-Ademe campaign using the Artemis driving cycles on one side and specific driving cycles, which were built-up with the same principles and data than the Artemis cycles, but considering separately the high and low motorized vehicles (André, 2006; see sections 2.3.1, 2.3.2.1 and 2.3.3). We have done also several analyses from a third dataset (the whole Artemis database collected amongst the European laboratories and covered measurements from 1980 up to now – see André, 2005), but its heterogeneity as regards laboratories, vehicles samples, etc. (none data was recorded with the same vehicles and all the cycles, by one laboratory, etc.) did not allow usable conclusions up to now.

We attempt first to identify and rank the factors influencing the pollutant emissions. We analyse then the influence of the driving cycles and of their kinematic parameters on the pollutant emissions. We examine then the influence of using a common set of driving cycles (which is the current way of testing) rather than considering specific cycles according to the characteristics of the vehicles (here the motorization or the power-to-mass rate).

Finally, a Partial Least Square regression approach is applied on the Artemis emission database (Artemis cycles only), considering two sets of kinematic parameters to attempt analysing their effect and modelling the hot emissions (André et al., 2006).

##### 3.1.1.1. Emissions parameters

Although the two datasets present slightly different kinematic characteristics (the PNR-Ademe emissions were measured at about 52 km/h, with 15 % of stops, with 0.8 stop per km, while the Artemis emissions were measured at 58 km/h, 11 % of stops, 0.6 stop per km) we observe a good

agreement in the emissions for the vehicles tested using the two different protocols. This allows considering together the two datasets for the analyses.

We perform first a characterization analysis, in which pollutant emission is analysed as a function of factors (fuel, driving cycles, etc.) and as a function of kinematic parameters. The statistics relies on a F Fisher test, for variance analysis. Such an analysis has two aims: First, to identify the level of disaggregation of the dataset at which analyses can be conducted, and secondly to assess the relative influence of these factors and parameters.

Considering the whole dataset, the fuel type (petrol, diesel), the emission standard, the driving type (i.e. urban, rural, motorway/main roads), the driving cycle, and the vehicle (variability between vehicles) were identified as significant and preponderant factors.

However, the variation induced by the driving type or cycle as above was more significant than the variation induced by the fuel type (for HC, CO<sub>2</sub>), or by the emission standard (NO<sub>x</sub>, CO<sub>2</sub>), or even between the vehicles (CO<sub>2</sub>). This highlights well the importance of the driving conditions on the emission.

Considering petrol and diesel separately, it appears that driving type, driving cycle as above and vehicle are the preponderant factors for diesel cars, while vehicle and emission standard are preponderant for petrol cars. The emitter status (high/normal) is almost always significant. This demonstrates the necessity to analyse the data by vehicle category (fuel, emission standard) and driving type. The similarity between Euro 2 and Euro 3 enables however associating these two categories to get sufficient samples. The results demonstrate also that:

- for the diesel cars, the urban driving leads systematically to higher emissions, while the rural and motorway driving leads to low emissions
- for the petrol cars, the urban implies higher CO<sub>2</sub>, HC and NO<sub>x</sub> emissions, while CO emission is rather associated with the motorway driving, and the rural driving leads systematically to lower emission.

### ***3.1.1.2. Influence of the driving cycles and kinematic parameters***

In a first step, five vehicles were identified as abnormal emitters (for one pollutant, the figure exceeded 100 % of the average emission of the vehicle category, i.e. for a fuel and an emission standard). Although such gaps are quite usual in emission measurements (high variability between vehicles), their strong incidence on the following analyses led us to exclude these high emitters in several cases. These data were however used at a later stage to compute actual emissions.

The analysis of the Euro 2 and Euro 3 normal emitters demonstrates that the urban congested driving with a lot of stops (Artemis.urban\_3 sub-cycle and similar ones) produces high CO<sub>2</sub> (petrol and diesel) and NO<sub>x</sub> diesel. On motorway, the very high speeds (Artemis.motorway\_150\_3 and similar) generate high CO<sub>2</sub>, while the unstable high speeds (Artemis.motorway\_150\_4 and similar) increase the NO<sub>x</sub> diesel and CO petrol emissions.

For diesel cars in urban driving, we observe that:

- all the pollutants increase with the stop frequency and the relative stop duration
- all except CO decrease when the speed increases, while the CO emission is sensitive to high speeds (60-100 km/h)
- NO<sub>x</sub> and CO<sub>2</sub> are sensitive to the frequency of accelerations and of strong accelerations.

On motorway and main roads,

- NO<sub>x</sub> and CO<sub>2</sub> are sensitive to the high speeds (120-140 km/h) and also to the variability of these speeds (standard deviation of the speed); they decrease at intermediate speeds (60-100 km/h)

- CO increases with the occurrence of intermediate or low speeds, of stops and of accelerations, and is low at high speed.

On rural roads,

- all the pollutants increase with the stop frequency and the relative stop duration
- all the pollutants decrease when the speed increases, and are sensitive to low speeds (20-40 km/h or less) and to the accelerations (average positive acceleration, standard dev. accelerations frequency). The CO emission seems however rather sensitive to the strongest acceleration / deceleration.

For petrol cars in urban driving, we observe that:

- all the pollutants are sensitive to acceleration parameters (frequency of accelerations and strong accelerations, average acceleration, time spent at high acceleration)
- CO and HC emission is sensitive to high speeds (60-100 km/h) and strong acceleration
- CO<sub>2</sub> and HC increase with the stops, CO<sub>2</sub> decreases when the speed increases.

On motorway and main roads, all the petrol pollutants are sensitive to accelerations occurring at high speeds. CO<sub>2</sub> and CO are furthermore high at high speeds (120-140 km/h and above) and low at intermediate speeds (60-100 km/h)

On rural roads, as for urban, all the pollutants are strongly sensitive to acceleration parameters (frequency of accelerations and strong accelerations, average acceleration, time spent at high acceleration):

- CO<sub>2</sub>, HC and NO<sub>x</sub> increase with the stops (duration or frequency)
- CO<sub>2</sub> and NO<sub>x</sub> decrease when the speed increases.

We observe then quite contrasted behaviour between diesel (rather sensitive to speed and stop parameters) and petrol cars (rather sensitive to accelerations). There is also a certain similarity between urban and rural driving for both the categories of vehicles.

These conclusions were established for Euro 2 and Euro 3 vehicles only. Nothing supports their validity for Euro 4 and later vehicles.

### **3.1.1.3. Sensitivity of the emissions to the test protocol**

In the previous analysis, we have also observed that the vehicle class (high or low motorized vehicle) was systematically a significant emission factor for the petrol cars. In fact, this factor measures the difference in emissions between 2 car categories but also the difference between two different sets of driving cycles, adapted to each vehicle category. It was then not possible to conclude directly that the vehicle class influences the emissions. A specific analysis was conducted to highlight rather the sensitivity of the emission to the test protocol: i.e. common cycles versus dedicated cycles.

We consider here the aggregated emissions values (i.e. emissions factors measured on the urban, rural and motorway driving cycles, weighed in distance by the corresponding coefficients), i.e. aggregated emission factors for the whole driving behaviour. We compare the emission measured on the 3 Artemis cycles on one side (level 100, not depending on the vehicle) and the emissions measured on the 3 low or high-powered cycles (depending on the vehicle). Relative ranges of variation are provided according to the standard deviation of the relative emissions (Table 12).

Except for CO<sub>2</sub> emissions, large and significant discrepancies can be observed for the most recent vehicles (less pollutant). These gaps can easily reach 20 or 50 % in both ways, i.e. the usual test procedure with a single set of cycles can lead to an overestimation (petrol vehicles Euro2, CO diesel) or to an underestimation (HC of the Euro 3 petrol, of the Euro 2 and 3 diesel cars, and diesel particulates).

Driving cycles	Pollutant	Petrol vehicles			Diesel vehicles			
		Euro 1	Euro 2	Euro 3	ECE 1504	Euro 1	Euro 2	Euro 3
Number of vehicles		3	6	4	2	3	10	2
Artemis cycles (reference)		100	100	100	100	100	100	100
Specific cycles for High- and Low- powered cars	CO	103 ±23	92 ±42	<b>175 ±18</b>	95 ±5	113 ±24	85 ±22	42 ±8
	HC	100 ±18	80 ±25	<b>141 ±22</b>	92 ±6	108 ±15	<b>120 ±20</b>	<b>155 ±5</b>
	NOx	112 ±10	94 ±18	87 ±10	108 ±4	114 ±6	99 ±3	92 ±1
	CO <sub>2</sub>	97 ±2	96 ±3	97 ±2	100 ±6	102 ±5	100 ±3	98 ±1
	PM				72 ±10	40	<b>139 ±56</b>	

Table 12: Comparison of pollutant emissions measured through a unique set of cycles (Artemis, 100 basis) or using vehicle-specific cycles (relative emissions and interval of variation corresponding to their standard deviation).

We conclude that, for the recent vehicles (Euro 2 and 3), the use of one unique set of driving cycles (as the Artemis cycles) leads to a significant underestimation (by 15 to 20 %) of the CO (petrol) and of the HC and particulates (diesel), and to an overestimation of the diesel CO (by 20 %).

Furthermore, these gaps depend on the driving type, and the test procedure can then affect “local” pollutant estimations. Indeed, the usual testing procedure (i.e. a unique set of cycles) leads to a significant overestimation of urban emissions (6-10 % for NOx and CO<sub>2</sub>, 15-20 % for CO and HC) whilst rural and motorway emissions were slightly underestimated. These trends should be reinforced when considering recent cars, and also consequently in the future when these vehicles will become predominant.

Finally, we observe that low-powered cars are penalized by a common procedure as their CO<sub>2</sub> emission and fuel consumption are higher (by 11 %) when measured using a common set of cycles, than when measured using appropriate cycles. The usual procedure led also to an underestimation of CO and HC emissions from the small cars (by 4-13 %) and to a slight overestimation of HC and NOx from the most powerful cars (10 %).

The previous analysis demonstrates that the usual test procedure with one common set of cycles for all the cars could led to strongly different emissions estimations, particularly for the most recent vehicle categories. These gaps induced by the test procedure, and the differences observed as regards vehicle uses and driving conditions should justify the possible use of specific driving cycles to measure actual pollutant emissions more accurately.

Although the increase of complexity induced by such a refinement, the taking into account of the vehicles performances and of their specific uses should become important in a short term, to improve the quality of the emissions estimations, and also as the recent cars - more sensitive to the testing conditions - will become predominant.

#### 3.1.1.4. Hierarchical model combining Partial Least Square regression approach to assess the emission

The Artemis emissions data (using the Artemis cycles) were analysed by fuel type, emission regulation and engine size. Taking into account the test number per category, we considered 3 diesel cases (Euro 1, 2, 3, Figure 6) and 7 gasoline cases (Euro 1, Euro 2 1.1-1.4 l, Euro 2 > 1.4 l, Euro 3 1.1-1.4 l, Euro 3 1.4-2.0 l, Euro 3 > 2.0 l, Euro 4).

A hierarchical model was built-up to explain the logarithm of the total emission per cycle, as a function of the cycle characteristics. The logarithm is justified by the fact that emissions are close to

zero with large coefficient of variation, and because emission results are generally distributed according to a log-normal distribution. In fact, this high-level model combines two individual Partial Least Square regression models based on the different sets of kinematic parameters (low-levels models).

The first low-level model is based on 7 dynamic related parameters, i.e: average speed, square and cubic speed, idling and total running times, average of the speed x acceleration product (positive), plus the inverse of the cycle distance. The second low-level model considers the 2-dimensionnal distribution of the instantaneous speed and acceleration (in 42 cells). Both models are based on principal components regression (i.e. analysing the correlations between the initial variables, and building-up then orthonormal (normative) factors that can be easily analysed).

These low and high-level models are compared to a traditional polynomial regression model as regards the average speed and to the data. The results demonstrate again that the driving cycle is a predominant factor as regards most emissions. The engine size is significant for CO<sub>2</sub> (petrol cars).

Considering the low-level models, most often, the best fit between the observed and predicted emissions is obtained using the model based on the distribution of the instantaneous speed and acceleration. The dynamic related model is satisfying for CO<sub>2</sub> Euro 1 diesel while a speed x acceleration model better explains the emissions in general. The high level model (combining the 2 previous ones) enhances slightly the prediction. The average speed model (through a parabolic trend) is unable to predict the "tooth-shaped trend" emissions determined by the effect of critical driving cycles (acceleration factor at different speeds, see the observed data Figure 6) and leads in some cases to a significant emission increase at high speed whereas there isn't.

However, the model fit is generally good for CO<sub>2</sub> but less or not satisfying for the other pollutants due to a large variability between the vehicles, and in particular to a low number of "high emitting" cars in the gasoline cases. Further investigations should be conducted in that direction.

### **3.1.1.5. Dataset correction as regards the driving cycles**

The significant influence of the driving conditions on the emissions implies a necessary correction of this heterogeneous dataset as regards the driving cycle. Various approaches have been envisaged of which:

- the building-up of a relation between emissions and kinematic parameters – the previous analyses have however demonstrated the difficulty to establish a clear dependency
- the building-up of a direct relation between emissions and cycles, that would have needed at least several paired tests (same vehicles for different sets of cycles).

Instead, an approach based on the kinematic similarities was developed, considering that cycles which would be similar, could be considered as different measurements of the same driving conditions (analogy with a sample of vehicles). The approach consists in 3 main steps:

- 1 Classification of the cycles as regards their kinematic contents, and building-up of a typology of test patterns
- 2 Selection of pertinent cycles to represent each pattern
- 3 Selection of the cycles to be considered in each pattern and possible corrections, for the building-up of reference emissions.

Then these reference emissions should be used for the computation of the emissions factors and the elaboration of modelling approaches.

#### **3.1.1.5.1. Cartography of the driving cycles**

As none dataset would have enabled covering all vehicles categories and all driving cycles (or detailed driving conditions), it is necessary to aggregate data that are similar as regards test cycles,



in order to compute emissions factors.

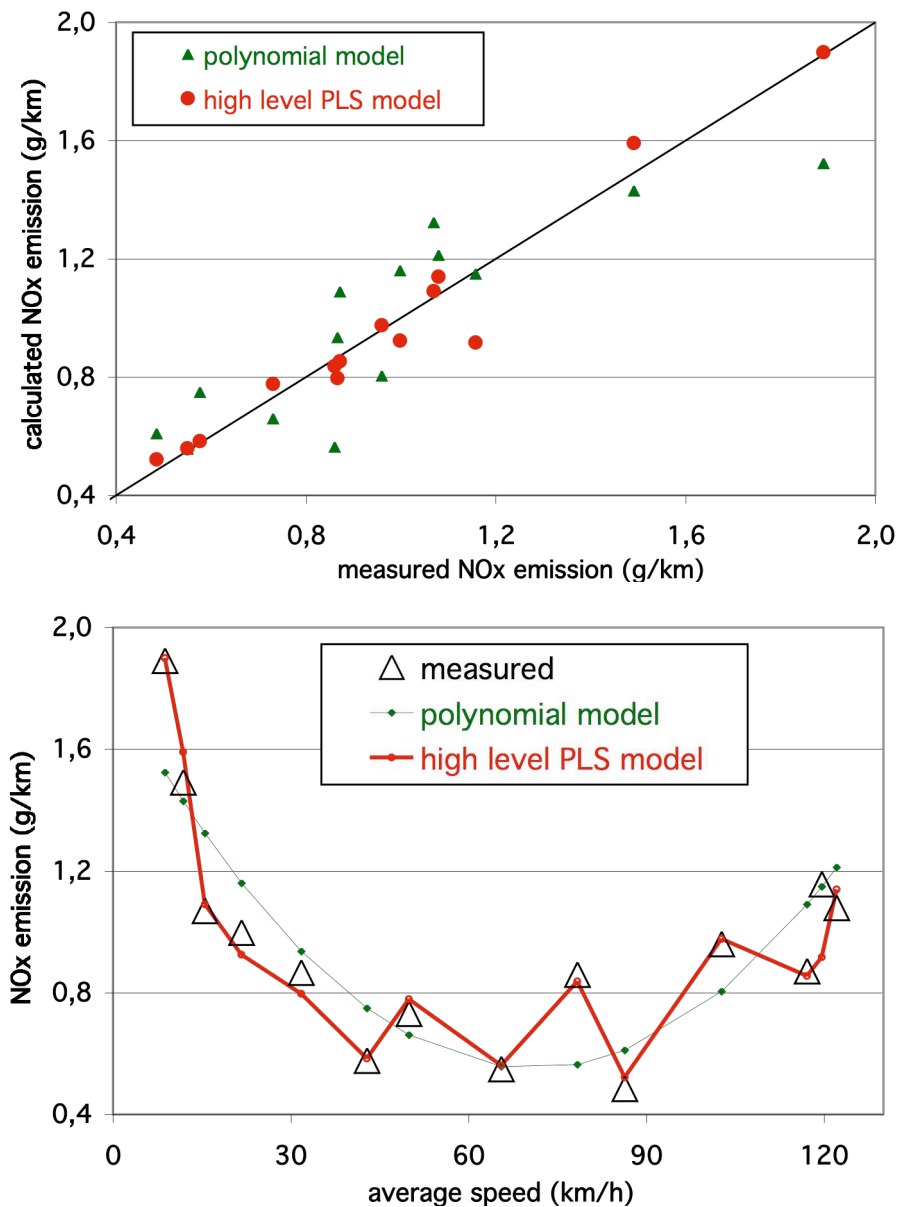


Figure 6: *NOx emissions of diesel Euro 2 vehicles as measured on the Artemis driving cycles and calculated with the polynomial and high level Partial Least Square models.*

More than 800 cycles/sub-cycles were recorded in the Artemis database, of which 824 were analysable and 375 pertinent, i.e. after eliminating transition and pre-conditioning phases, artificial cycles such as constant speed, constant accelerations, cycles with a gradient, cycles without representativity, cycles for vans, etc. The driving cycles, but not the sub-cycles, are briefly described in Annex 5. The most significant driving cycles, i.e. 98 cycles or sub-cycles representing the actual driving conditions and for which there are a significant number of emission data, were used to develop a typology of the test cycles. The other pertinent cycles do not contribute to the construction of the typology but are also classified according to this typology.

In this aim, we consider the 2-dimensional distribution of the instant speed and acceleration to describe the cycles. We apply then a Binary Correspondence Analysis (factorial or multidimensional analysis) and an automatic clustering. The typology into classes maximizes then

the cycles homogeneity within the classes and the contrast between classes. These 15 classes or Reference Test Patterns (RTP) include then a sub-set of homogeneous driving cycles (as regards kinematic conditions), which can be combined together at a later stage to compute emissions (Figure 7).

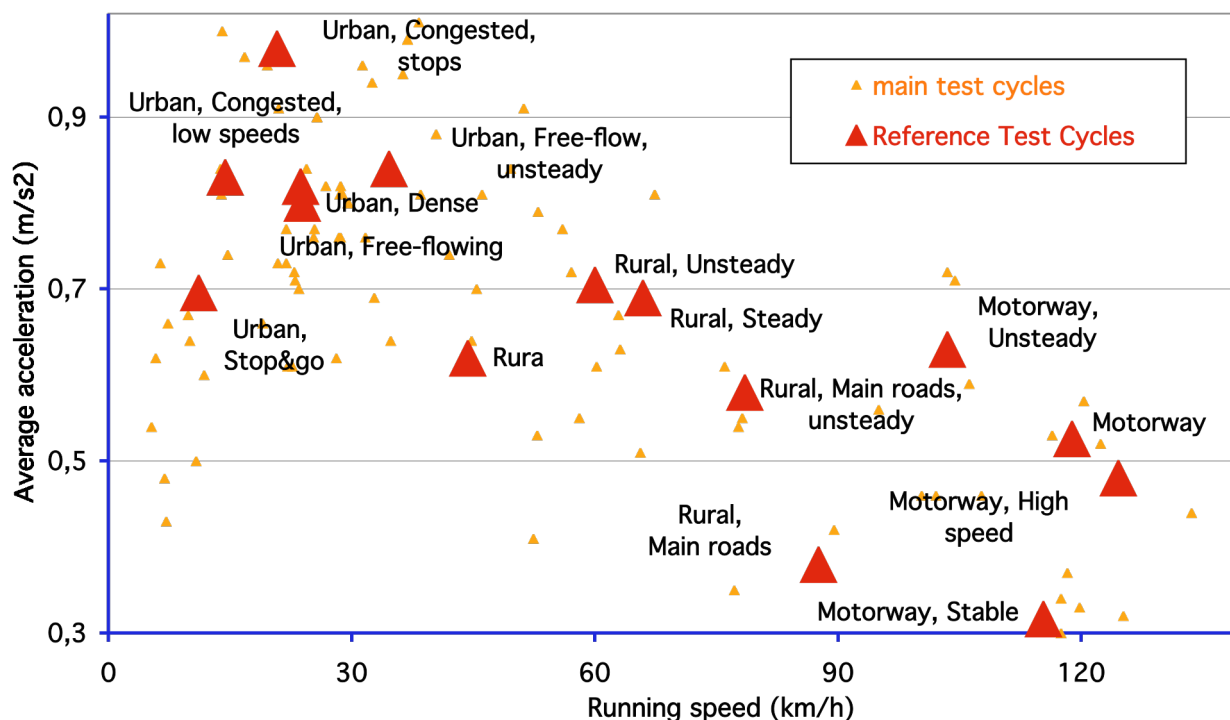


Figure 7: Cartography of the main test cycles and reference test cycles representative of each class of the reference test patterns.

#### 3.1.1.5.2. Selection of reference cycles and emissions

For each test pattern, one or several Reference Test Cycles (RTC) are selected amongst the most significant (in term of representativeness and of number of associated emission data). 13 of these cycles are combination of Artemis cycles and sub-cycles. The 2 complementary cases represent the very congested driving and the stabilized motorway driving in the range of 100 km/h (Table 13).

At this stage, we intend to set-up a definitive list of cycles for each test / driving pattern, to compute then their reference emissions. This implies the analysis of the variability and coherency of the emission data within each class and for each vehicle category (the emission standard is considered) and fuel. The coherency throughout the vehicle categories is also examined.

Out of 27 700 data (hot emission, vehicle x test, passenger cars only), about 20 000 were analysed. The variability within a test pattern can be very high: the relative emission (around a reference value of 1) can indeed range from 0.2 to 10 (for NO<sub>x</sub>, CO), from 0.4 to 2 (CO<sub>2</sub>).

We consider then the average emission values observed for the reference test pattern (i.e. the whole class) and for the reference test cycles on one side, and the individual figures for each of the cycles belonging to the class on the other side.

Reference test pattern (RTP) number and characteristics			Reference test cycles (RTC)	Average speed (km/h)	Average Positive acceleration (m/s <sup>2</sup> )	Stop duration (%)	Stop/km
7	Urban	Stop&go	OSCAR.H1, OSCAR.H2, OSCAR.H3, TRL.WSL_CongestedTraffic	7	0.70	35	16.3
3	Urban	Congested, stops	Artemis.urban_3	9	0.98	58	10.2
2	Urban	Congested, low speeds	Artemis.urban_4	12	0.83	19	16.7
1	Urban	Dense	Artemis.urban, Artemis.urban_1	17	0.82	29	5.2
4	Urban	Free-flowing	Artemis.urban_5	22	0.80	10	4.3
5	Urban	Free-flow, unsteady	Artemis.urban_2	32	0.84	9	2.3
6	Rural		Artemis.rural_3	43	0.62	3	0.5
11	Rural	Unsteady	Artemis.rural, Artemis.rural_1	58	0.71	3	0.3
9	Rural	Steady	Artemis.rural_2	66	0.69	0	0.0
10	Rural	Main roads, unsteady	Artemis.rural_4	79	0.58	0	0.0
8	Rural	Main roads	Artemis.rural_5	88	0.38	0	0.0
14	Motorway	Unsteady	Artemis.motorway_150_2	104	0.63	0	0.0
15	Motorway	Stable	EMPA.BAB, modemHyzem.motorway, TRL.MotorwayM113	115	0.32	0	0.0
13	Motorway		Artemis.motorway_130, Artemis.motorway_150_1	119	0.53	0	0.0
12	Motorway	High speed	Artemis.motorway_150, Artemis.motorway_150_3, Artemis.motorway_150_4	125	0.48	0	0.0

Table 13: Cartography of the cycles: definition and characteristics of the reference test patterns RTP and reference test cycles RTC.

The analyses showed that in most cases, the orders of magnitude of the RTP and RTC emissions are very comparable, and the variability for the most important cycles is generally low. In that case, considering all the data does not affect significantly the results. Some deviating cycles show however quasi-systematic under- or over-estimation. They are generally far away from the RTC in term of kinematic. When they do not represent a high quantity of tests, the corresponding data are cancelled. When the difference is not at all systematic or understandable, the cancellation of the related data is unavoidable. The relative evolution observed between pre-Euro, Euro 1, 2, 3 and 4 was also examined, as it should be - theoretically - consistent for different cycles.

From the 20 000 initial data, about 11 000 coherent data are retained (after exclusion of the non pertinent cycles; 3 100 diesel and 7 700 petrol), and enable the computation of the emission for diesel and petrol cars, from pre-Euro to Euro 4 passenger cars. Several cases were however insufficiently covered (Table 14). Mechanisms have then been implemented to cover them, through:

- the extrapolation of the rate Euro4/Euro3 (resp. Euro 3/Euro 2, etc.) observed on a similar test pattern (urban, rural or motorway)
- the equivalence between close vehicle categories (i.e. Euro 4 and Euro 3, etc.) when they were too few data (case of the particulates).

We should note that, weighing factors – as initially envisaged and according to the quality of the cycles and to the number of data - were implicitly (but not rigorously) implemented through the above cycle selection process.

Reference test pattern RTP number and characteristics			Average speed (km/h)	pre-Euro 1	Euro 1	Euro 2	Euro 3	Euro 4
7	Urban	Stop&go	7	3,884	1,551	1,583	1,620	0,633
3	Urban	Congested, stops	9	1,669	1,506	1,892	1,750	0,618
2	Urban	Congested, low speeds	12	1,644	1,124	1,458	1,455	0,665
1	Urban	Dense	17	0,862	1,049	1,143	0,991	0,566
4	Urban	Free-flowing	22	1,938	0,877	0,981	1,009	0,339
5	Urban	Free-flow, unsteady	32	1,076	0,807	0,854	0,939	0,441
6	Rural		43	0,691	0,550	0,568	0,644	<i>0,386</i>
11	Rural	Unsteady	58	0,963	0,612	0,703	0,670	0,401
9	Rural	Steady	66	0,629	0,519	0,554	0,608	<i>0,364</i>
10	Rural	Main roads, unsteady	79	0,781	0,654	0,942	1,105	<i>0,662</i>
8	Rural	Main roads	88	1,098	0,732	0,521	0,609	<i>0,365</i>
14	Motorway	Unsteady	104	0,772	0,689	0,977	1,077	<i>1,015</i>
15	Motorway	Stable	115	1,398	1,053	0,790	0,973	<i>0,917</i>
13	Motorway		119	1,013	0,825	1,049	0,785	0,740
12	Motorway	High speed	125	1,038	0,872	1,316	1,248	<i>1,176</i>

Table 14: Reference NO<sub>x</sub> emissions for the diesel cars (in italics and blue, extrapolated cases).

### 3.1.1.6. Implications as regards the emissions modelling and estimation

The previous process (cartography of cycles and computation of the emission per driving pattern) can be considered to several aspects as a robust approach: indeed, prior to any interpolation, computation, it realizes a certain equilibrium between the different and contrasted driving conditions, considering the different cycles according to their quality. It seems then pertinent to build-up emissions functions (in particular the emission versus average speed functions) while starting from this basis.

Furthermore, the cartography of the driving cycles constitutes a good mapping of the driving conditions as regards the average speed level but also as regards the acceleration dimension, i.e. the dynamic of the traffic conditions. Indeed, we clearly identify two classes of driving along the speed scale, i.e. the stable driving with low acceleration and stop frequencies on one side, and the unsteady driving on the opposite.

Considering this distinction could enable a more accurate analysis of the traffic dynamic at a later stage. Indeed, for certain pollutants (NO<sub>x</sub> and CO<sub>2</sub>) and vehicle categories, the influence of this dynamic dimension appears clearly as shown in Figure 8.

### 3.1.1.7. Implication as regards the emissions estimation at a street level

The previous concepts and results have been implemented to build-up a method for the estimation of the emissions at the street level (the so-called "traffic situation approach", Fantozzi et al., 2005). In that aim, a traffic situation scheme has been defined, considering the existing road types and a declination of the traffic conditions (from free-flow to stop-and-go).

Driving data have been collected throughout Europe to get representative speed curves for each of the traffic situations. For the cars, the 2-dimensionnal distribution of the speed and acceleration is computed for these speed curves. They can then be processed as the driving cycles, and projected into the multidimensional or factorial space, which was the result of the factorial analysis of the driving cycles. This enables measuring distances from one given traffic situation, to each of the 15 previously defined reference test cycles, and then to compute its emission as regards the reference

emissions and their proximity to 1 to 5 reference cycles (Figure 9). This is a purely interpolation approach.

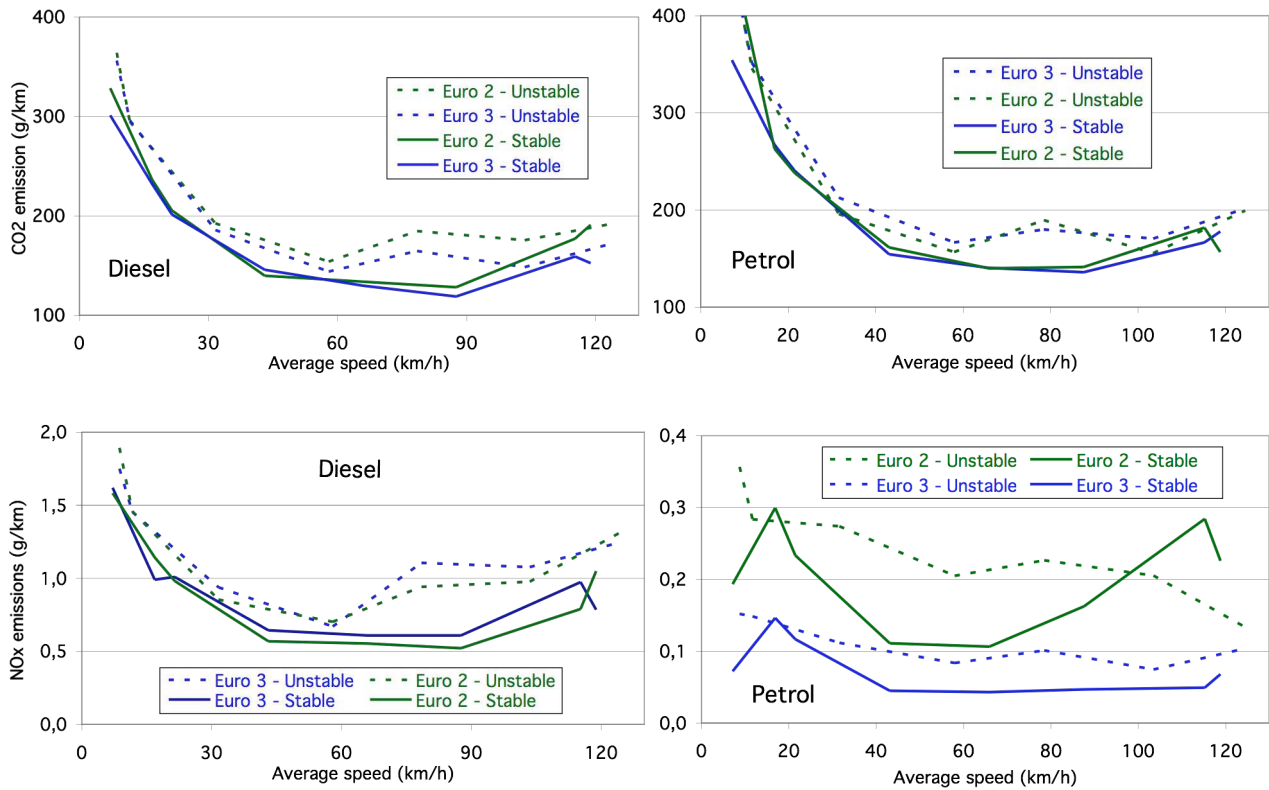


Figure 8: Dynamic influence on the CO<sub>2</sub> and NO<sub>x</sub> pollutant emissions, between high (unstable) and low (stable) dynamics.

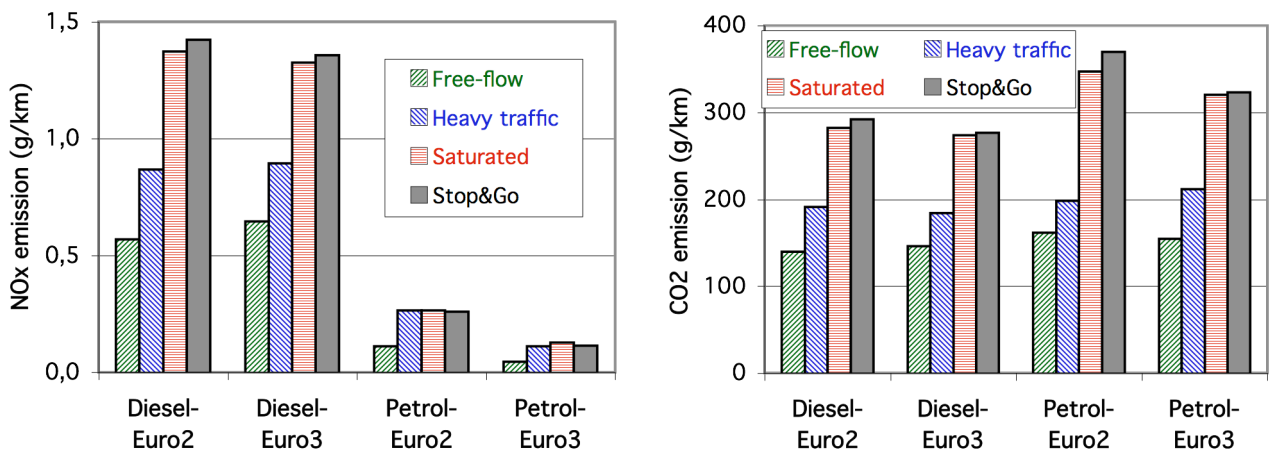


Figure 9: Traffic situation approach illustration: NO<sub>x</sub> and CO<sub>2</sub> emissions of cars have been estimated for an urban trunk road (speed limit: 50 km/h), at different traffic conditions, according to dedicated speed curves.

### 3.1.2. Gear choice behaviour

Five gearshift strategies are compared. They are tested for each among 2 or 3 hot real-world driving cycles and all together with 15 vehicles (see sections 2.3.1, 2.3.2.2 and 2.3.3). The tests show that the different gearshift strategies used (see Table 5) influence firstly the conditions of the shifts and secondly the emissions (André et al., 2003).

#### 3.1.2.1. Gearshift conditions

The comparison of the number of gearshifts or of their engine speeds according to the gearshift strategies<sup>2</sup> described in section 2.3.2.2 on page 27 shows:

- For the NEDC strategy, the gearshifts are performed at rather low speeds, but are nearly 50 % more frequent than for the other strategies: resp. 181 and 130 shifts during the Artemis cycles, and resp. 214 and 130 shifts during the VP faible/forte motorisation cycles.
- The RPM strategy induces upgearshifts at very high speeds as compared to the other strategies. But for downshifting the gearshift engine speeds are extremely low for the 5 to 4 and 4 to 3 shifts and very high for the 2 to 1 shift. This demonstrates that, in the real world, gearshifting under deceleration conditions is not performed according to the engine speed, but according to the vehicle speed.
- Both NEDC and RPM strategies using set values count a great number of gearshifts of the 3 to 2 and 2 to 1 types, as compared to the other strategies. This can be explained by the lack of anticipation: under real-world conditions, the driver often anticipates vehicle stopping by shifting from 3 to 0 or 2 to 0, which does not occur in the RPM and NEDC strategies.

No anticipation can be made with a strategy including set values. The main advantage of a strategy based on gearshifting statistics is to enable to take into account such cases as a function of their frequency of occurrence. In addition, the strategies adapted to the vehicle characteristics produce gearshifts quite different from a vehicle to another, with differences of gearshift vehicle speed often of 10-15 km/h.

When considering the relative engine speed, i.e. the real engine speed rated by the engine speed at maximum power, for each real-world driving cycle, but averaged over the whole cycle and all the vehicles tested, it increases from urban to rural and finally to motorway conditions (Table 15).

Gearshift strategy	cycle			NEDC			RPM			record	
	Urban	Rural	Mot.	Urban	Rural	Mot.	Urban	Rural	Mot.	Urban	Rural
Artemis	20	43		21	43		27	51		20	43
VP faible/forte m.	20	45	64	23	41	63	33	59	71		

Table 15: Average relative engine speed according to the gearshift strategy (in % of the maximum engine speed), for the different driving cycles tested. The gearshift strategies are described in Table 5.

<sup>2</sup> The engine speed recorded on the chassis dynamometer is not accurate enough to determine the time when gearshifts are operated, due to a frequent slipping of the clutch and thus an erratic engine speed when releasing the clutch. Only theoretical data for gearshifting can be used. Therefore, the conditions of the "free" strategy, which does not include theoretical changes, cannot be analyzed here.

Pollutant	Driving cycle		Strategy A	Strategy B	difference A-B (%)
CO <sub>2</sub>	Artemis	urban	RPM	Cycle	12
				NEDC	15
		Free		11	
		Record		11	
	rural	cycle	RPM	NEDC	5
				Cycle	9
		Free		11	
		NEDC		13	
CO <sub>2</sub>	VP faible/forte motorisation	urbain	free	NEDC	6
			Cycle		4
			RPM		4
		route	free	NEDC	5
			cycle		10
		autotoute	cycle	RPM	8
			NEDC	2	
	HC	urbain	cycle	NEDC	27
	CO		route	NEDC	Free
					RPM

Table 16: Statistically significant differences, in %, between gearshift strategies, using T-test with a probability of 95 %. The strategy A is more polluting than the strategy B.

### 3.1.2.2. Strategy impact on the emissions

We use the t-test (at 5 %) to look at the statistical significance of the emission differences between strategies, for a same vehicle sample (see Table 16). So CO<sub>2</sub> is the pollutant the most sensitive to the strategy, with a systematic emission variation between strategies, going from 2 to 15 %. The other pollutants show sometimes significant differences. For CO, significant differences (25 - 39 %) are between the fixed speed strategy 'NEDC' from one side, and the fixed engine speed 'RPM' and 'free' strategies from other side. For HC the significant difference appears between the fixed speed 'NEDC' and the 'cycle (VP motorisation)' strategies (27 %). NO<sub>x</sub> is never influenced by the gearshift strategy.

It is therefore possible to classify the gearshift strategies according to their CO<sub>2</sub> emission (the only pollutant always influenced by the strategy), for the different data sets: for the VP faible/forte motorisation driving cycles, the most polluting strategy is the 'cycle' strategy in rural and motorway situation and the 'free' strategy on urban situation. For the Artemis driving cycles, the most polluting strategy is the fixed engine speed 'RPM' whatever the situation. For the two data sets the less polluting strategy seems to be the fixed speed (so-called 'NEDC') one.

Such a classification is not possible for the other pollutants. A first reason is the too low size of the vehicle sample, as the sample size is a higher significant parameter than the gearshift strategy. A second reason is the emission level, which is often near to the detection limit of the analysers.

The strategy impact remains nevertheless relatively low as soon as realistic patterns are selected.

### 3.1.3. Influence of the driver and of the cycle following

15 driving cycles were accomplished four times by a robot driver and by four different human drivers, for one car (see the methodology followed in sections 2.3.1, 2.3.2.3 and 2.3.3). We compare

firstly the robot and human drivers from dynamic and emission point of view, then we compare the different human drivers, before looking at the tolerance of the different participating laboratories (Devaux & Weilenmann, 2002).

### 3.1.3.1. Comparison between robot and human drivers

The goal here is to compare the driving parameters and the emissions of the group of four drivers on one side and the four repetitions of the robot on the other side. For this purpose we consider four dynamic parameters based on the difference between the reference and the actual speed signals (Figure 10), which first should correlate to the emissions and second should show a clear difference between robot and humans: the mean standard deviation of the speed error (between the actual and the reference speeds), the mean absolute error of the actual speed, the autocorrelation of the speed error, the regression coefficient between actual and reference speeds.

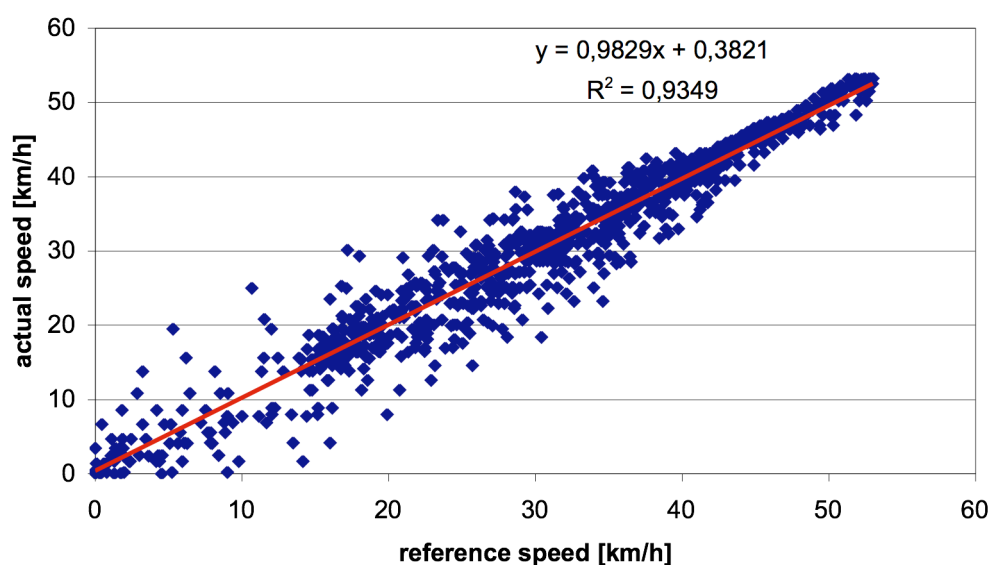


Figure 10: Illustrative example of the link between the actual and reference speeds for the driving cycle Handbook LE5F and the driver 2.

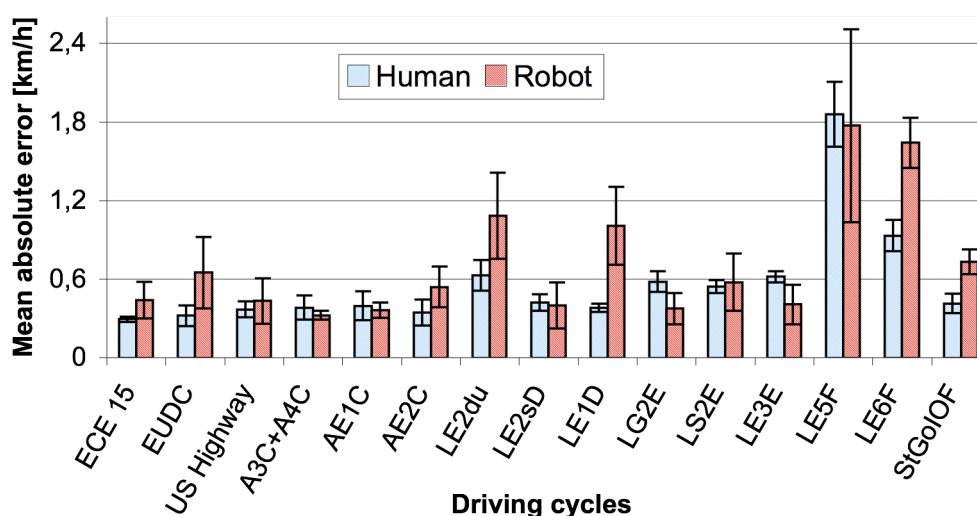


Figure 11: Mean absolute error of each driving cycle (defined in Annex 5) for human and robot driver.



The speed error, i.e. the difference between the actual and reference speeds, was built for every second. The mean value of the absolute error can be used to determine how faithfully a driver followed a given driving cycle. It can be seen in Figure 11 that the robot behaves not better than the humans. In addition the absolute error does not correlate to the emissions neither.

The standard deviation allows us to assess the repeatability of the driving. The robot showed a slightly better repeatability than the human drivers, but this is not significant. Some driving cycles showed to be too aggressive for the robot, which affected its repeatability. It can be seen also that the emission values do not correlate to the standard deviation.

The autocorrelation of a signal gives an information like “how similar” is a value at time  $t$  to a value at time  $t + dt$ . The autocorrelation value of the difference between the actual and reference speeds was computed at a lag of one second for this comparison. The results highlight again that the autocorrelation values of the robot differ not systematically from the values of the human drivers.

The regression coefficient between the two sets of data (Figure 10) shows one more time that this parameter does not correlate to big emissions and in addition the robot is not better than the humans.

Therefore it has been shown that no dynamic parameter shows any trend against emissions or between robot and humans. Except for CO<sub>2</sub> no significant difference was found between emissions of robot or human driven tests. But the CO<sub>2</sub> emissions of the human drivers is in average ~4% higher than for the robot. Thus the humans must drive somewhat different than the robot, but this difference is not explicable with the existing data set. We assume that motions of the gas pedal with frequencies above 0.5 Hz, thus undetectable in the 1 Hz data set, may be responsible for that fact.

Out of this, it can be concluded that the initial goal to separate the variance of the emissions caused by the driver from the variance of the car, test bench and analysers cannot be reached. The results even indicate that the driver influence is maximally of the same order of magnitude as the combination of the variance of the car, test bench and analysers.

### **3.1.3.2. *Statistical analysis of human data***

The typical relative emission standard deviation of 4 human drivers over 15 driving cycles is 25 % for CO, 2 % for CO<sub>2</sub>, 27 % for HC, and 36 % for NO<sub>x</sub>.

The goal here is to verify if this emission variability among the human drivers depends on the test cycle. Six parameters calculated from the reference speed signal have been investigated: Average positive acceleration, average speed, relative positive acceleration (RPA), positive energy, number of zero crossovers of acceleration, number of gear shifts. These parameters do not show any correlation to the variations of the emissions.

### **3.1.3.3. *Cycle curve following***

The goal of this chapter is to collect the various tolerance values and fail criteria applied by each participating laboratory to the reference cycle curves and to derive recommendations how the tolerance band should be defined and what fail criteria should be used if driver errors occur. Six laboratories answered the questionnaire on this topic: Empa, INRETS, MTC, Renault, TNO and TUG. The collected information contains the tolerance values, fail and grace criteria, which definition is presented in Annex 9.

It can be noted that all labs use the same time tolerance of 1 second, but they have different speed tolerances, ranging from 1 to 3 km/h. There are great differences for the fail and grace criteria among the labs. Some do accept every cycle, whereas other require a perfect following of the cycle. In-between, one may find every possible combination of the fail and grace criteria. Most accepted is

the fact that some vehicles are not able to achieve the nominal speed curve. Also accepted is when the speed tolerance violation occurs due to a vehicle which decelerates more than prescribed by the reference speed curve and the driver is not allowed to touch the power pedal. There are also some differences in how the measures are treated. Sometimes the paper datasheets are marked, but the database doesn't contain a remark for any applied fail or grace criteria.

The tests used for the analysis of the robot and human drivers have been executed with a tolerance band of  $\pm 2$  km/h and  $\pm 1$  s. When looking at the number of violation seconds, it can be concluded, that in general it is possible for a trained test bench driver to follow a real-world driving cycle with a tolerance band of  $\pm 2$  km/h and  $\pm 1$  s in a quality, such that he violates the tolerance band less than 1 % of the test duration. A tolerance band of  $\pm 1$  km/h and  $\pm 1$  s would lead to violation percentages of up to 50 %, however, thus it would be too tight. Certainly, longer violation times arise:

- if the car has not enough power to follow the curve of the cycle
- if wheel slip occurs during decelerations
- in tests where it is not allowed to touch the power pedal during decelerations and the engine decelerates in idle more than the reference curve does (NEDC)
- if the car has a very “difficult” gearbox, resulting in time consuming gear-shift manoeuvres
- The engine may stall or it does not activate at the first turn of the key in tests including engine start

The analysis of the error distance of each test shows, that the real distance driven in chassis dynamometer tests differs from the reference distance usually less than 1 %. Bigger differences occur in tests of stop and go cycles as the Handbook StGoIOF cycle. Beside the difficult cycle following in such cycles, the relative measurement error of the speed and distance measurements is significantly bigger than for other cycles.

Meaningful fail criteria should be such that they are accomplishable in praxis, thus not reached for most of the tests, but they should not be too loose to avoid an unnecessary emission variation.

## 3.2. Vehicle related parameters

The vehicle related parameters cover the technical characteristics of the vehicle, but also the short term (one hour) and long term (some years) stability, the fuel parameters, the vehicle cooling and the vehicle preconditioning. The short term stability, the vehicle cooling and preconditioning are at the same time related to the laboratory, as these parameters depend on laboratory choices.

### 3.2.1. Technical characteristics of the vehicles

43 cars were measured with NEDC and Artemis driving cycles. A basic analysis of technology effects on the emission behavior of the cars tested did not end in useful results (Samaras et al., 2005, see the methodology used and the technologies studied in sections 2.3.1 and 2.3.2.4). The statistical analysis showed only that the type approval level (Euro 2, 3 or 4) and the propulsion system (petrol or diesel) have a significant influence on the emission level. These parameters are used already for the vehicle classification.

Since differences in the emission measurements at different labs on one hand and the incomplete information on the technology employed in the tested vehicles on the other hand may have influenced the analysis, a more detailed attempt was made with thirteen vehicles tested at TUG. These cars represent different typical technologies of Euro 3 and Euro 4 where most information on the emission control technologies employed was available (see Table 27 in Annex 7). The technology differs by the injection system, the number and type of lambda sensors for gasoline

vehicles, and for diesel ones by the fuel injection system.

Clear influences of the vehicle size and of the rated engine power (i.e. the engine power at maximum power) on CO<sub>2</sub> and on the fuel consumption can be seen, but other dependencies were not found on [g/km] basis: Different time shares at idling and different acceleration and deceleration values influence the emissions in [g/km] very much. This effect may overlap the technology.

Since all cars met the Euro 3 limits, a technology dependency may be found if the emission level in the NEDC cycle is compared with the emission levels in the real-world Artemis urban, rural and motorway cycles. Since the analysis of the emission data in [g/km] for all 43 cars in this task did not show any dependencies, the unit [g/kWh] was selected for the detailed analysis on influences from different technologies in different cycles. The engine work [kWh] here is the integral of the seconds with positive engine power over the cycle.

Concerning the petrol cars, for the fuel consumption a clear trend can be seen, where the cars with the lowest ratio of engine power demand to rated engine power have the highest specific fuel consumption values since they are driven in ranges of poorer engine efficiency. For NO<sub>x</sub> one of the 2 cars with 2 two point sensors showed the lowest emission values, the second rather high ones. Since the Artemis urban cycle has the most dynamic driving style of the four test cycles, we may assume that a better lambda control technology should result in a smaller emission increase from the NEDC to the Artemis urban cycle. For NO<sub>x</sub> the two cars equipped with the broadband lambda sensor showed rather high increases in the emissions from NEDC to Artemis urban cycle within the tested Euro 3 cars. Concerning the make of the injection system and the engine control unit no systematical influence on the emission behavior for any exhaust gas component is visible. Similarly for HC and CO also no influence of the emission control technology is visible for the cars tested here.

Concerning the diesel cars, the only obvious difference between the cars tested was the injection system where 2 vehicles among 5 had unit injectors. One of these vehicles is a “3 Liter car” using a start stop automatic (mainly improving the fuel efficiency in the Artemis urban cycle compared to the other cars) and other technologies to reduce the fuel consumption. Systematic effects of the “3-Liter” technologies or of the different injection systems on the emissions of NO<sub>x</sub>, PM, HC and CO are not visible, neither in the absolute levels nor in the ratios of the emissions in the different test cycles.

Even with this detailed survey no correlation between emission behavior and emission control technologies were found as long as the cars belong to the same type approval category. The additional introduction of technological characteristics won't improve the accuracy of emission data bases of conventional cars up to Euro 4. Most likely within cars of the same type approval level, the application of the engine control system by the engineers has much more influence on the exhaust gas emission behavior than the hardware used for the emission control. This result does not concern the diesel particulate filter, not studied here, which can have a huge impact on the emission levels (see Coroller and Plassat, 2002 for instance).

### **3.2.2. Short term emission stability**

After a preconditioning with the NEDC, repeatability tests were performed in each of the 9 participating laboratories by repeating the Artemis urban and rural driving cycles 5 times. All together 12 vehicles were tested (see the methodology in sections 2.3.1, 2.3.2.5, 2.3.3 and 2.4.1). The results show that the different standard deviations calculated vary a lot according to the pollutant and the vehicle class (Cornelis et al., 2005). The repeatability standard deviation  $s_r$  is the lowest for CO<sub>2</sub>, where most vehicles are below a variation of 1 % within the 5 repetitions. For this pollutant, it is higher in the urban cycle than in the rural cycle which is easier to follow on a

dynamometer by the driver.

The relative repeatability standard deviations for the HC and CO measurement repetitions are for most cars high (from 0 to 71 %, 15 % in average) but the absolute standard deviation in g/km is small. Since especially the Euro 3 cars showed a low absolute emission level, small absolute differences in the measurement result lead to high relative standard deviations.

As expected, NO<sub>x</sub> from diesel cars proved to be a very well repeatable exhaust gas component with variations in the same range as for CO<sub>2</sub>.

The relative repeatability standard deviations for CO, HC and NO<sub>x</sub> are similar for Euro 2 and for Euro 3 petrol cars resulting in much lower standard deviations for the Euro 3 cars.

Additional influences were found from the settings of the analyzers. Especially using high concentration ranges at the analyzers with high concentration calibration gases to measure low exhaust gas concentrations (as it is the case for the most recent vehicles) increases the standard deviation between the repeated tests, because the measured concentrations are within the accuracy range of the analyzer used. Analyzers with auto-range function (switch between different concentration ranges according to the actual exhaust gas concentration) do have a clear advantage in this respect.

In order to get a better view on the spread in test results, we plot the relative repeatability standard deviation according to the relative sample standard deviation per pollutant, each point corresponding to specific emission standard, fuel and driving cycle (Figure 12 and Annex 10). The sample standard deviation  $s_s$  is always much higher than the repeatability standard deviation  $s_r$ . The ratio goes from 1 to 21 with a mean value of 7.5; The highest and lowest values correspond both to the Artemis rural cycle but resp. to CO<sub>2</sub> emission factors for petrol cars and NO<sub>x</sub> emission factors for diesel Euro 3 vehicles.

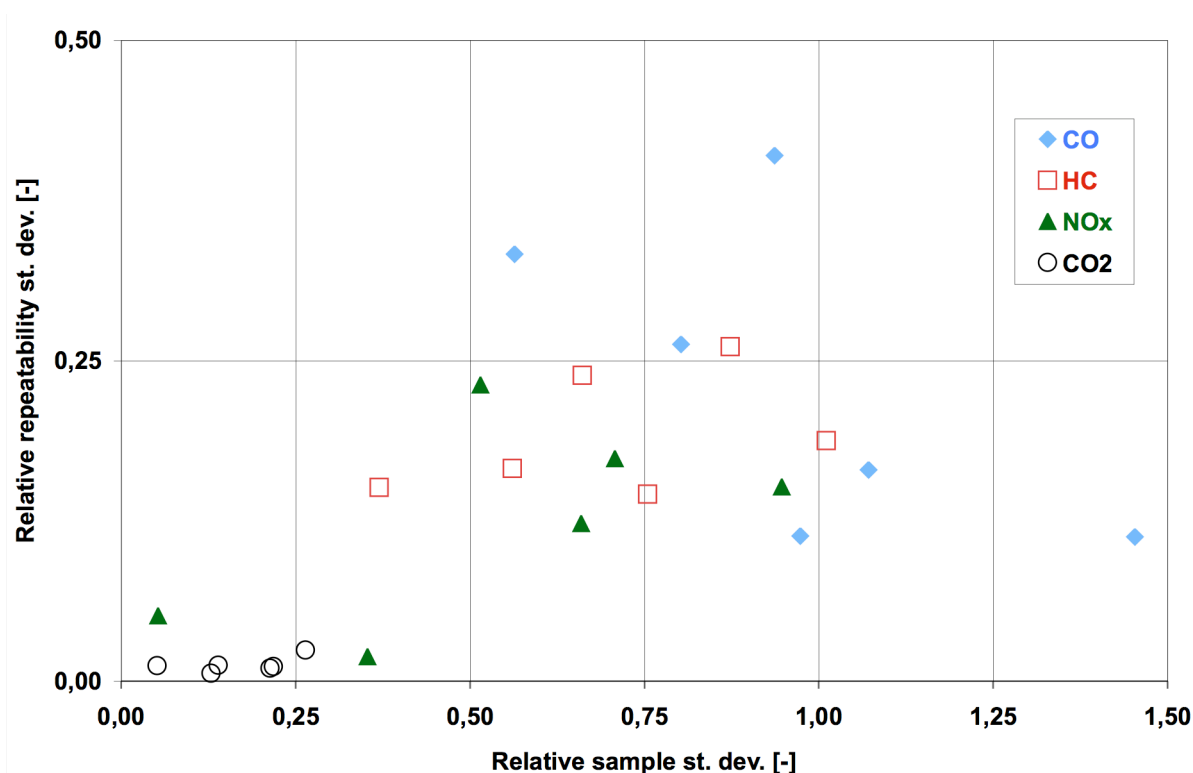


Figure 12: Repeatability according to sample relative standard deviations for the different vehicle classes and pollutant tested (data in Annex 10).

This indicates that the differences between the test results of several vehicles are larger than the differences one might expect when testing the same vehicle a couple of times. It is hence recommended to take rather more cars and to carry out a small number of repetitions for each tests cycle on these cars to derive emission factors instead of taking a small vehicle sample with a high number of test repetitions.

### **3.2.3. Long term emission degradation**

2 vehicles were tested according to NEDC and Artemis driving cycles at mileage intervals of 20 000 km, before and after maintenance (see sections 2.3.1, 2.3.2.6 and 2.3.3). It allowed us to design a long term degradation scheme (Geivanidis & Samaras, 2004).

#### **3.2.3.1. Degradation scheme**

The correction factor by which the basic emission factor should be multiplied in order to take into account the degradation of emissions due to mileage which was kept in-line to the MEET / COPERT III methodology (Ntziachristos & Samaras, 2000a) is given by the equation:

$$MC_{C,i} = a_M \times M_{\text{mean}} + b_M$$

where:

- $M_{\text{mean}}$ : the mean fleet mileage of vehicles for which correction is applied
- $MC_{C,i}$ : the mileage correction for a given mileage ( $M_{\text{av}}$ ), pollutant  $i$  and a specific cycle
- $a_M$ : the degradation of the emission performance per kilometre
- $b_M$ : the emission level of a fleet of brand new vehicles

$b_M$  is lower than 1 because the correction factors are determined using vehicle fleets with mileages ranging from 16 000 to 50 000 km. Therefore, brand new vehicles are expected to emit less than the sample vehicles.

By lack of data, it is assumed that emissions do not further degrade above 120 000 km for Euro 1 and 2 vehicles and 160 000 km for Euro 3 and 4 vehicles.

The effect of average speed on emission degradation is taken into account by combining the observed degradation lines over the two driving modes (urban, rural). It is assumed that for speeds outside the region defined by the average speed of urban driving (19 km/h) and rural driving (63 km/h), the degradation is independent of speed. Linear interpolation between the two values provides the emission degradation in the intermediate speed region. Table 31 in Annex 11 presents the methodology parameters and the application of the scheme that are being discussed later.

As regards Euro 1 and Euro 2 vehicles, MEET data are proposed to be used as the majority of data covering these vehicle categories contained in the Artemis database originated from the same dataset used for the MEET estimations.

In order to estimate the degradation of modern Euro 3 and Euro 4 vehicles, an analysis was performed on the data derived from the Artemis database (version 1/12/2004). The mileage effect on CO, HC and NO<sub>x</sub> emissions was examined as CO<sub>2</sub> emissions have been proven to be unaffected by mileage (Samaras & Ntziachristos, 1998; Ntziachristos & Samaras, 2000b, 2001): The analysis was performed in two driving mode regions: urban and rural. In order to increase the number of data and to achieve a more realistic result, UDC (hot start) and Artemis urban measurements were combined to produce the urban driving mode data while EUDC and Artemis rural measurements were combined to produce the rural driving mode data. Due to the low number of data as well as low mileage of Euro 4 vehicles, they were considered in the same category as Euro 3 vehicles and the hypothesis that both Euro 3 and 4 vehicles are expected to have the same degradation behaviour was accepted. The emissions of all vehicles were plotted against their mileage. Linear regression

lines were produced as representative of the mileage degradation for three engine capacity ranges: <1.4 l, 1.4-2.0 l, >2.0 l. An example of results of this approach is presented in Figure 13. Table 31 in Annex 11 summarizes the results of the regressions, together with the average mileage and the size of the part of the fleet that was used for each subset of data.

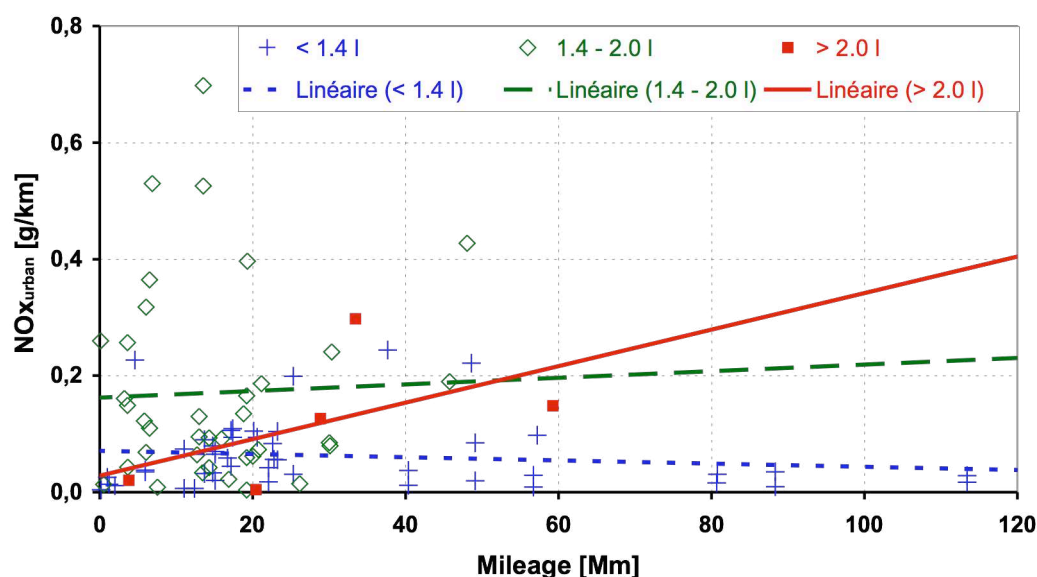


Figure 13:  $NO_x$  degradation in urban driving behaviour for petrol vehicles.

Then we decided the vehicles with engine capacity >2 l not to be considered as an individual class due to the small size of the sub sample. We propose:

- For CO in urban condition, a degradation is proposed for each driving mode and for 2 engine capacity categories.
- For CO in rural condition, a degradation is proposed for vehicles  $\leq 1.4$  l while no degradation is proposed for vehicles with engine capacity above 1.4 l.
- For HC in urban and rural condition, a considerable degradation is observed only in the case of vehicles  $\leq 1.4$  l in urban driving mode.
- For NO in urban and rural condition, a considerable degradation is observed only in the case of vehicles >1.4 l in urban driving mode.

In order to apply a degradation scheme, the above estimated regression lines should be dimensionless. This can be achieved by normalizing the equations given that the correction factor MC should not modify the average emission factor of the sample when applied to the average mileage of the sample (Samaras & Ntziachristos, 1998; Ntziachristos & Samaras, 2000b, 2001). The initial regression lines have the form:

$$emission [g/km] = a \times mileage + b$$

The mileage correction factor (MC) should yield 1 for the average mileage of the sample (av.samp.mil) thus the normalization parameter (norm\_par) is given as follows:

$$MC(av.samp.mil) = \frac{a \times av.samp.mil + b}{norm\_par} = 1 \Rightarrow$$

$$\Rightarrow norm\_par = a \times av.samp.mil + b$$

Following the above the proposed parameters for Euro 3 and Euro 4 vehicle are presented in Table 22 on page 85. They can be applied according to the Copert methodology presented above using the

Equation 1 on page 84. The stabilization mileage was assumed to be 160 000 km. The Copert III/MEET values for the speeds defining the urban and rural regions were not changed for consistency reasons as they are very close to the average speed of the new cycles used (legislative and Artemis).

In average the emissions of CO, HC and NO<sub>x</sub> are multiplied by a factor 3.6 from 0 to 100 000 km for Euro 1 and 2 cars, and increase by 18 % for Euro 3 and 4 vehicles. For Euro 1 and 2 vehicles, NO<sub>x</sub> is more influenced by the mileage than CO and HC (multiplied resp. by 5.3, 2.9 and 2.7), but no influenced for Euro 3 and 4 cars.

### 3.2.3.2. Validation of the degradation scheme

A set of measurements on two specific vehicles was performed in order to get an image of the influence of mileage and regular maintenance on emissions (see section 2.3.3). No effect of maintenance was observed on the level of emissions neither as a consistent before-after maintenance improvement nor as a function of mileage. The same methodology that was applied to produce the mileage correction factor from the Artemis database was applied on the two vehicle measurements as well in order to validate the proposed degradation scheme.

The in-use durability requirements of EU for Euro 3 and Euro 4 petrol vehicles allow a deterioration factor of up to 1.2 for all emission components at 80 000 km. Although this factor refers to cold start NEDC emissions it has also been included in the validation of the degradation scheme under the assumption that it is an indication of the general trend of emissions. Figure 14 present an example of the correction factor as a function of mileage for Euro 3 and Euro 4 vehicles as it is proposed by the new Artemis scheme compared to the MEET approach as well as the measurements of the two specific vehicles, and the EU in-use durability requirements.

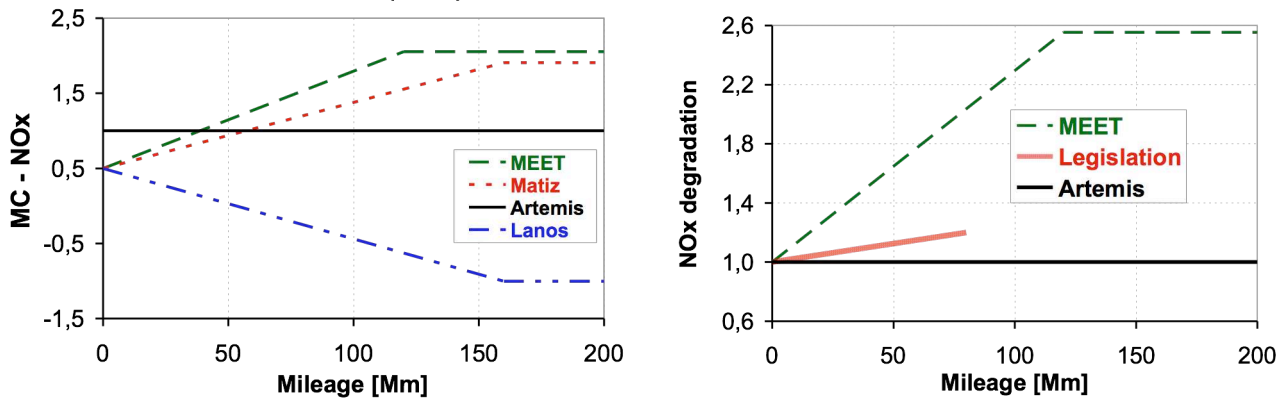


Figure 14: NO<sub>x</sub> correction factor comparison (MEET, Artemis, 2 tested vehicles: left), and relative to 0 km (right) with in-use legislative requirements.

The new Artemis degradation scheme predicts lower emission degradation with mileage than MEET. This lays closer to the EU in-use emission durability requirements in most cases. MEET predicts higher degradation (significantly higher in most cases) than the in-use durability factor requires.

As regards CO, Lanos seems to be closer to the MEET approach thus showing higher degradation than the EU limits while Matiz shows contradictory performance between urban and rural driving mode. In the case of NO<sub>x</sub>, Lanos shows an improvement of emissions with mileage which lies under even the lowest of all Artemis prediction. Matiz performance is close to the MEET scheme. HC emission performance of both Lanos and Matiz seems to deteriorate higher than any of the rest prediction scenarios under urban driving conditions. The improvement of Matiz emissions under

rural driving conditions can only be attributed to the low number of mileage intervals it was measured under and the high influence of the last measurement.

Both vehicles that were examined during their mileage evolution showed no obvious malfunction that could lead to higher emission levels. Their operation though seems to have been affected by the harsh use conditions they were both driven under as both cars accumulated mileage as part of a car rental fleet. The initial top mileage limit after which these cars were scheduled to be withdrawn from the car rental company fleet was exceeded especially in the case of Lanos in order to be able to obtain measurements at higher mileage points. This top limit is determined by the certain company in cooperation with the manufacturer as the point where the operation of the vehicle is significantly deteriorating under the specific use. The above along with the fact that Matiz was a low engine capacity vehicle with bad emission performance position both vehicles at an extreme position compared to the average European fleet as regards both their emission level and emission durability performance.

### 3.2.4. Fuel properties

After a selection of petrol and diesel fuels giving theoretically minimum, average, and maximum emissions, a petrol and a diesel car are tested with these fuels and a reference Euro 4 fuel, for cold and hot driving cycles (see the methodology in sections 2.3.1, 2.3.2.7, 2.3.3 and 2.4.2). It shows different results for petrol and diesel fuels (Renault & Altran, 2002).

#### 3.2.4.1. Petrol fuels

For the petrol fuels, the results (see Table 32 in Annex 12) show:

- The results from the tests performed with the Austrian petrol fuel show higher levels for CO emission factor than the 3 other fuels, but only on the cold Artemis urban driving cycle. The aromatic content of this fuel is the highest for this fuels (42 compared with 35 %vol maximum). Knowing that CO emissions are mainly produced at the start of the engine, before the optimum temperature of the catalytic converter has been reached, this explains why the CO emission factor is so high for a cold start urban cycle. This influence of the aromatic content is offset with the other Artemis cycles done under hot start conditions.
- For HC, the petrol composition should have a clear influence on the emissions: if the aromatics (for example) content of the petrol is high, the proportion of such compounds in the HC emissions will rise, and in cold start conditions the temperature in the after-treatment system will not be sufficient to post-oxidized these heavy compounds. It will be also true for other organic compound such as olefins. We are hardly able to observe the influence of the petrol composition on HC emissions since their level are very low in particular with the Artemis cycles. Nevertheless, and despite of what was forecasted with the EPEFE formulae, it is obvious that the composition of the fuel has an influence on the HC emissions. Therefore as for CO, the Austrian fuel with the highest aromatic content has the highest emissions for the cold Artemis cycle.
- For NO<sub>x</sub>, the influence of the aromatic content is similar than for CO and HC. The trend and level forecasted by the EPEFE formulae (see Annex 8), has been confirmed on the different hot Artemis cycles and on the NEDC cycle. But for the cold start Artemis urban cycle, we can't see any real trend for the different fuels. Even if it is not possible to describe a real trend for its influence, nor to describe what kind of specifications may explain the results, the fuel composition is a key parameter for the evaluation of the NO<sub>x</sub> emission factors. Indeed, the NO<sub>x</sub> emission factor for the 2005 petrol fuel is always lower than for the other petrol fuels.
- For CO<sub>2</sub>, no global trend or conclusions can be found.

Although the EPEFE equations have been confirmed on the test bench with NEDC for NO<sub>x</sub> emissions, it is clearly not the same situation with the other emissions components (CO and HC)



and more important with the Artemis cycles. Indeed, the EPEFE formulae have been designed to evaluate the emissions using the NEDC cycle and not other driving cycles. The standard deviation for the Artemis cycles is often too high to allow clear comparison.

From the measurements themselves, the fuel parameters has an important influence on the emissions factors and has to be considered as a key parameter to study them. Indeed, the NOx emission factors, which was chosen as the indicator for the petrol tests, has clearly shown that the composition of the fuel may alter or increase the emissions by changing even a little some chemical characteristics. Even physical characteristics such as the volatility (increase because of the oxygen content) may cause serious change into the behaviour of the engine and therefore change the emission factors, in particular with different start conditions.

As a matter of fact, the Euro 4 petrol fuel always gives the lowest levels for each emission factors considered. Indeed, its chemical and physical characteristics are well defined and even complied with narrower range than the ones allowed for the Euro 3 petrol fuel, even though the Finnish fuel used is already a high standard quality petrol fuel according to the analysis.

### 3.2.4.2. Diesel fuels

For the diesel fuels, the results (see Table 33 in Annex 12) show:

- Over hot driving cycles, CO emissions are very low and it is very difficult to find any significant difference between the fuels. Over cold cycles, significant differences between fuels can be found, for instance by a factor 2. These results are quite unexpected and cannot be explained by the state of the art on fuel effects. Therefore no conclusion can be drawn. The results are similar for HC.
- For NOx, no real significant influence of fuel can be found.
- For PM (see Figure 15), significant differences are found between fuels, but the repeatability is sometimes very poor.
- For CO<sub>2</sub>, the fuel compositions have a marginal influence on the emissions.

Therefore, in spite of some significant fuel impacts, it seems difficult to propose any correction for taking into account the fuel influence on emissions, due to poor repeatability and with only one car tested.

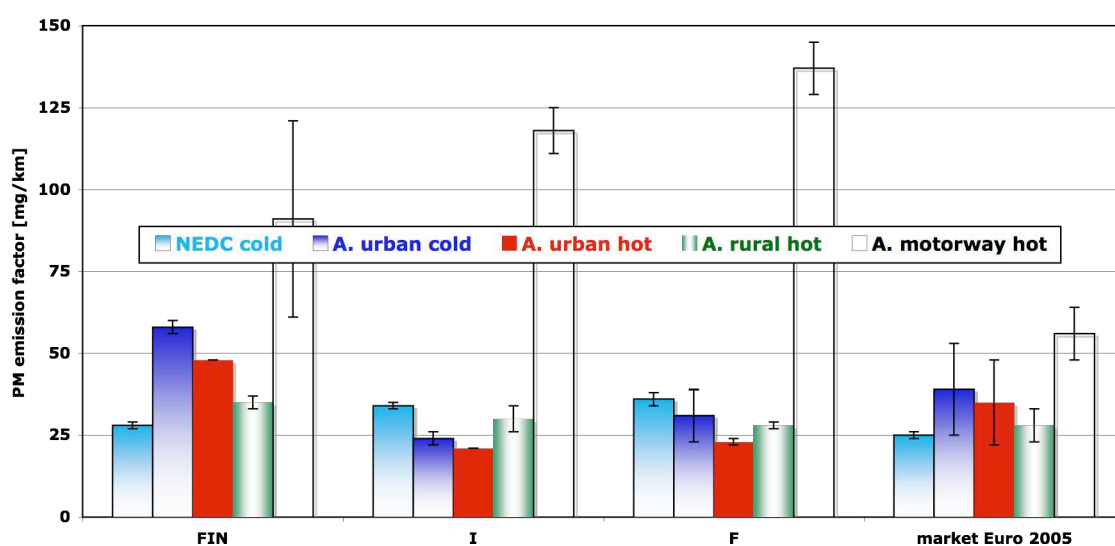


Figure 15: PM emission factors as measured for one vehicle fuelled with fuels from four origins, following five driving cycles, cold or hot.

### 3.2.4.3. Conclusion on fuel influence

The results confirm the influence of fuel on the exhaust emissions. But in spite of observing significant differences, especially for PM emissions with diesel vehicle, it was not possible to propose an explanation based on the today knowledge of fuel effect.

In addition, over the Artemis cycles, the repeatability was poor, even very bad, especially for diesel PM emissions on motorway. This leads to a real difficulty to propose any correction factor to take into account the fuel effect on Artemis data, especially with one vehicle tested per fuel.

### 3.2.5. Vehicle cooling

Different types of cooling were tested with 6 passenger cars and both Artemis urban and rural driving cycles (see sections 2.3.1, 2.3.2.8 and 2.3.3). All cars showed only small deviations (-3 to +2 %) in CO<sub>2</sub> emission, indicating good basic reproducibility of the test. However, we were able to observe that on average the other exhaust components did not show such clear trends that could be attributed to e.g. certification level of the car, or engine/fuel combination (Laurikko, 2005a).

Also it was found that some petrol cars performed “purge” when tested hot, resulting in gross hydrocarbon gas release into the intake, yielding to high CO emissions. However, we deemed such tests as “anomalies”, and did not take those results into account when assessing the data, as in those cases the level in CO emissions was usually elevated almost by an order of magnitude. Thus those tests were easily differentiated from the rest of the pool. An example of that kind of performance is presented in Annex 13, giving good indications of the magnitude of this phenomenon. Overall assessment of the pollutants indicated that only one car (Ford Mondeo) showed marked sensitivity to modifications in cooling arrangement in terms of CO and HC. Regarding NO<sub>x</sub>, two more cars (VW Polo & Opel Corsa) seemed to be somewhat affected.

The trends that we observed were:

- Overall no trend between the open and close bonnet, suggesting that this parameter is of secondary importance. An average over both cases is a valid representative for that type of cooling arrangement.
- No significant influence of the height of the small blower.
- For the petrol cars, a slight decrease in CO and NO<sub>x</sub>, when using larger cooling fan and more air speed compared to the small normative fan (see Figure 16). However, one car (Nissan Almera) did not follow this trend on NO<sub>x</sub>, but presented results in the opposite direction.
- Regarding HC emissions of the petrol cars, a slight overall increase was observed with increased cooling power, but the results of one car (Ford Mondeo) were strongly opposing the rest.
- Among the petrol cars, an overall assessment of the pollutants indicated that two cars (Ford Mondeo and Opel Corsa) showed marked sensitivity to changes in cooling arrangement in terms of CO and HC. Regarding NO<sub>x</sub>, also one more car (VW Polo, in addition to both vehicles above) seemed to be somewhat affected, but in relative terms less than for CO and HC.
- Between the technology options, the two diesel cars tested seemed to be somewhat less sensitive to the cooling arrangement than the group of petrol-fuelled test cars.

Given the small number of cars tested, and the ambiguous nature of the results and observed trends, we must conclude that the collected data were, unfortunately, too inconclusive to develop any correction factors for the effect of vehicle cooling arrangement. However, a number of observations of the possible direction of the effects were collected, and those can serve as indicators in the overall evaluation of the sources for the disparity between the results obtained in different laboratories, and assessment their magnitudes.

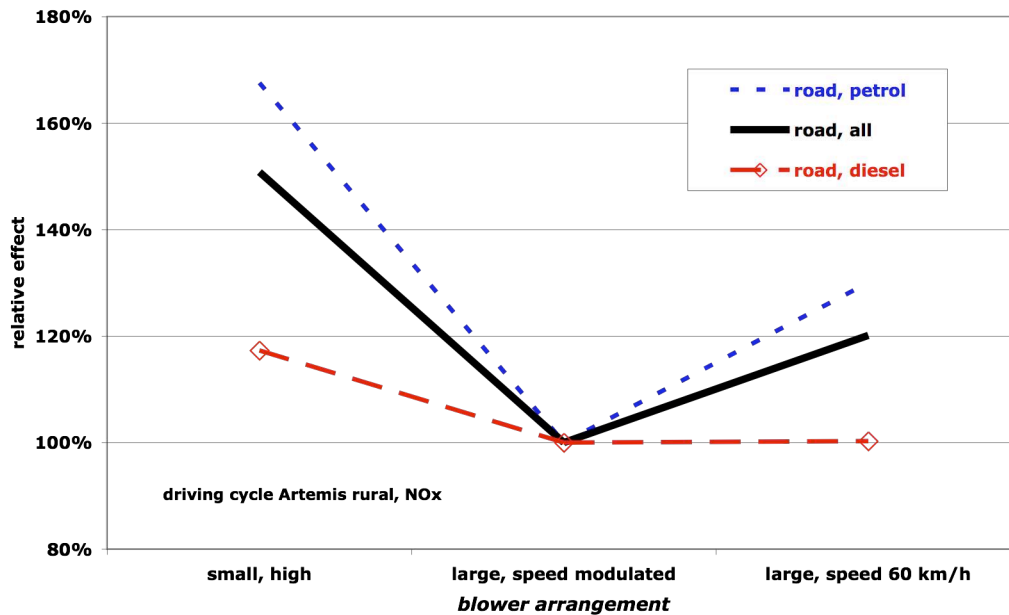


Figure 16: Relative change in NOx emission over the Artemis rural driving cycle due to some altered cooling arrangements per vehicle class.

### 3.2.6. Vehicle preconditioning

The preconditioning has to stabilize the thermal condition (operating temperature) of the engine, exhaust gas aftertreatment device, power transmission, tyres, bearing of test bench.

Four preconditioning conditions are tested with 5 vehicles and hot driving cycles (NEDC, Artemis urban and rural). The methodology followed (see sections 2.3.1, 2.3.2.9 and 2.3.3) shows that the 10 minutes idling is suitable in the slightest degree to precondition the driving cycle measurements. It resulted in the biggest emission values for all measurement cycles among all the preconditioning cycles (Oláh, 2005).

The emission test results of the Artemis rural measurement driving cycle are influenced to a lesser degree by preconditioning than that of the emission results of the Artemis urban measurement driving cycle.

The emission test results of diesel cars are influenced to a lesser degree by preconditioning than those of the petrol vehicles.

The emission test results of Artemis urban driving cycle as measurement cycle is influenced to the highest degree by preconditioning in particular by Artemis urban as preconditioning cycle. This influence depends a lot from the pollutant considered.

The EUDC cycle as measurement cycle (second part of the NEDC cycle) is less influenced by the preconditioning than the other cycles. It is partly due to the fact that the first part of the NEDC cycle can be considered as a kind of preconditioning.

The 10 minutes cycle at a constant speed of 80 km/h can be considered as the most suitable preconditioning cycle. It resulted in the lowest emission levels and the lowest standard deviation for the majority of the measurements.

The method of preconditioning has not significant influence on the modern closed loop controlled vehicles with catalyst: After the operating temperature is reached, the preconditioning caused just a

little difference in the exhaust emissions.

We propose as preconditioning cycle a constant speed cycle with a reasonable vehicle speed level. This is a well reproducible and simple driving cycle. The length of the preconditioning can be modified without changing the cycle characteristic. The average engine load, temperatures and tyre temperature can be modified and adjusted by changing the constant speed level.

### 3.3. Vehicle sampling method

In order to design emission factors for the European vehicle fleet, rather than for some particular vehicles, the representativeness of the vehicle sample is of course important. The size of the sample is the main parameter, but as the vehicles cannot be chosen randomly in the fleet, the method of vehicle sampling could also be important.

#### 3.3.1. Method of vehicle sampling

In order to assess the influence of the vehicle sampling method on the emission factor level, two inquiries were carried out by email in direction of 10 laboratories (see section 2.4.3). Both inquiries shows us the methods used by the different laboratories to design a vehicle sample to be tested on a vehicle bench (André, 2002).

The average number of vehicles per measurement campaign is situated between 10 and 25. The choice of the number of vehicles is determined firstly by the financial means (cost of instrumentation, workforce, rent of vehicles...). The second criterion is the representativeness of the sample. This one is compared, according to the subject of the measurement campaign, with national or European statistics (sales, fleet composition, traffic: see below). The third criterion is the availability of the bench.

The minimum number of vehicles below which laboratories do not analyse the obtained results or at least are not confident on their viability, i.e. think that the conclusions are not representative, is situated between 3 and 10 vehicles (and sometimes 20 for one laboratory). This number is in most of the cases very close to the minimum number of vehicles per sample.

The representativeness of the sample is assessed according to the following parameters by decreasing importance:

- Fuel type (petrol, diesel...)
- Emission standard (Euro 1, 2...) and engine technology (catalyst...)
- Engine capacity and age
- Mileage, model and make

6 laboratories among 10 use statistical databases for assessing the representativeness of their sample according to these characteristics. These bases used by 5 laboratories contain the technical characteristics of the vehicles registered in the year. The database used by the 6<sup>th</sup> lab is created with a model of the number of vehicles on the road, based on the number of sold vehicles per year and per category.

The main way to obtain given vehicles to test is trough rental agencies, garages, concessionaires, or by signing a contract with a company: 9 labs among 10 use such method, and only this one in 2 cases. But the rented vehicles are not driven as the other vehicles and it could impact the emissions. The second way of obtaining a vehicle is to choose this one in a owners' list. This list can be an official one or a local one:

- Only Empa uses an official list from the Swiss government. This list contains all the characteristics of the sold vehicles and the coordinates of the owner. The laboratory sends a letter to all the owners of the wished vehicle (at least 100 letters to be sure to have a sufficient number of positive answers). If the owner agrees to lend his car for the tests, he receive a 100 € a week compensation.
- 7 laboratories are using a list created in the laboratory. The owners' coordinates and the technical characteristics of the vehicle are obtained by advertising in the staff of the laboratory company and of the surrounding companies. A disadvantage is that the laboratory staff is aware of vehicles pollution problems and has certainly a behaviour a little bit different from the average one. The owner can get till 150 € a week as compensation, plus a rental vehicle.

When the category of the vehicle is chosen, it is often possible to choose among several vehicles. The secondary criteria to choose the vehicle to test (after the first criteria determining its category) are, by decreasing importance, the engine technology, fuel type, emission standard, engine capacity, make, model, age, maintenance, gearbox type, mileage, manufacturer country, normal use of the vehicle, owner, engine power, equipment, and comfort level. Of course the representativeness parameters (primary parameters) are among the first choice parameters. (or secondary parameters).

3 laboratories never test vehicles before making the definitive tests, while all other laboratories make it sometimes and always for one laboratory. All the laboratories reject vehicles with grave defects as broken exhaust pipe, lack of the basic equipments...

Finally the laboratories record a lot of parameters of the vehicles tested. A non exhaustive and non systematic list is given in Annex 14.

	Vehicle type		
	Non catalyst petrol	Catalyst petrol	non-catalyst diesel
CO	<i>20 (23)</i>	17 (23)	12 (24)
HC	7 (13)	10 (18)	<i>9 (10)</i>
NOx	<i>18 (21)</i>	16 (25)	12 (24)
CO <sub>2</sub>	13 (22)	10 (20)	11 (23)

Table 17: Required number of vehicles to obtain a quality of emission model equivalent to that of the whole model – In brackets: maximum size studied; in italic pink: uncertain conclusion.

### 3.3.2. Minimum vehicle sample size

From a given emission data base with 80 vehicles, we build different emission models corresponding to different vehicle samples (see sections 2.3.1, 2.3.2.10, 2.3.3 and 2.4.4). The methodology followed allows to determine the minimum number of vehicles, or minimum sample size, necessary to get the same quality of an emission model according to the average cycle speed than with the maximum size of the sample studied (Lacour & Joumard, 2001). These results are given Table 17. They are explained more in detail and illustrated in two cases in Figure 29 and Figure 30 in Annex 15.

It can be observed that the required number of vehicles to build-up a representative model of average emissions usually exceeds 10. The results covering conventional petrol vehicles for CO and NOx and diesel vehicles for HC are affected by uncertainty since the minimum size required is very close to the maximum size observed. This means that when adding one vehicle to the sample the average emissions per trip vary significantly. It should be then considered that when increasing the

whole sample size by one vehicle, the averages recorded would vary significantly. In this case, there is a convergence to the whole sample, but the mean of the whole sample does not necessarily converge to a steady value.

### 3.4. Laboratory related parameters

The laboratory related parameters concern at least the ambient air temperature and humidity, the dynamometer setting, the exhaust gas dilution ratio, the heated line temperature, the PM filter preconditioning, the response time of the whole analysing line, and the dilution air condition.

#### 3.4.1. Ambient air temperature

31 passenger cars are tested with hot Artemis driving cycles but for 3 ambient air temperatures (-20, -7, and +23°C). The methodology followed (see sections 2.3.1, 2.3.2.11 and 2.3.3) shows that the lowering of the ambient temperature increases generally the emissions of CO, HC, NO<sub>x</sub> and CO<sub>2</sub> (Laurikko, 2005b). However, in some cases a decrease in CO was detected, most notably in case of CO for petrol-fuelled cars in rural and motorway driving.

On average over all tested driving cycles, the ratio between emissions at -10°C and at +20°C was for all tested petrol-fuelled cars (Euro 2, Euro 3 and Euro 4) 0.96, 1.54, 1.11 and 1.05 respectively for CO, HC, NO<sub>x</sub> and CO<sub>2</sub>, and for diesel Euro 2 cars the ratios were respectively 2.14, 1.73, 1.04, 1.04 and 1 for PM. Therefore in most of the cases, emission is a decreasing function of the ambient temperature.

On average, these ratios do not depend much on the emission standard of the vehicle, as almost equal responses were observed. However, in urban type of driving (i.e. low speed and low thermal load in the engine) the hydrocarbon emissions showed increasing sensitivity to low ambient temperature with the advance in Euro standards, i.e. Euro 4 cars were the most sensitive ones, and the Euro 0 cars were least affected. In terms of CO, the responses were most scattered regarding the influence of the driving type (urban, rural, motorway), whereas regarding CO<sub>2</sub>, the response was most uniform, i.e. less dependence on the road type.

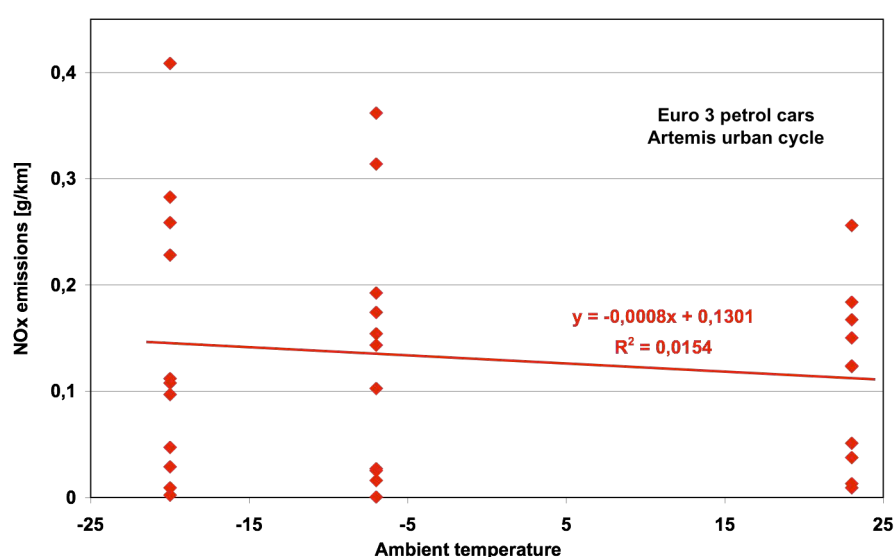


Figure 17: Influence of the ambient temperature on the NO<sub>x</sub> emissions of Euro 3 petrol cars over the Artemis urban driving cycle.

The influence of the ambient temperature on the emissions was in most cases linear (see an example Figure 17), but in a few cases (urban HC for petrol Euro 4, and motorway HC for diesel Euro 2), exponential type of function gave better match. In a few cases we could not set any trend, as ambient temperature did not seem to have any effect.

### 3.4.2. Ambient air humidity

11 vehicles are tested with hot Artemis urban and rural driving cycles, but for 3 ambient air humidity levels. The methodology followed (see sections 2.3.1, 2.3.2.12 and 2.3.3) allows us to plot the emissions as measured for both Artemis urban and rural driving cycles according to the ambient humidity. An example is given in Figure 18; Results are grouped for Euro 2 and Euro 3 petrol cars, and for diesel vehicles including both Euro levels. Plotted are individual test results, average values (arithmetic means) for each group in low, medium and high humidity conditions, as well as linear regression models based on the test results.

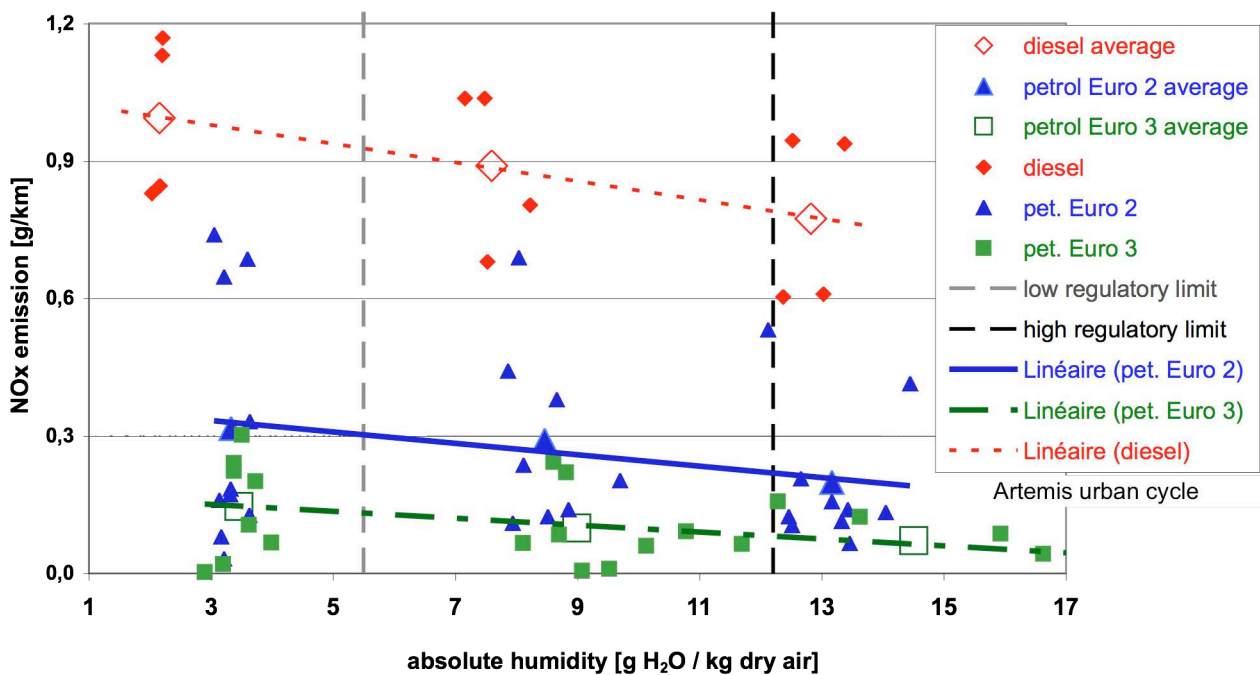


Figure 18: NOx emissions (uncorrected) in Artemis urban driving cycle as a function of the ambient humidity, for petrol cars separately for Euro 2 and Euro 3, and diesel cars (only Euro 2). Low and high regulatory limits designate the humidity range allowed in regulatory test protocols, such as EU directive 70/220/EEC.

Vehicle type	≠ veh.	Driving conditions	CO	HC	NOx
Petrol Euro 2	4	urban	<i>-0.13</i>	<i>-0.10</i>	-0.25
		rural	<i>0.04</i>	<i>0.01</i>	-0.17
Petrol Euro 3	5	urban	<i>0.13</i>	0.16	-0.29
		rural	<i>0.11</i>	0.21	-0.04
Diesel Euro 2	2	urban	0.73	0.28	-0.49
		rural	0.60	0.41	-0.87

Table 18: Correlation factors  $R^2$  between the absolute humidity and the pollutant emissions. Results in italics correspond to the lowest correction factors.



The correlation factors given Table 18 suggest that hardly any correlation between petrol CO, petrol Euro 2 HC emissions and the ambient humidity exists, because  $R^2$  were below  $\pm 0.2$  in these cases.

The effect of the humidity can be normalised according to a reference point, chosen as for the existing correction factor (see an example in Figure 19): It corresponds to a present correction factor  $kH$  equal to 1, i.e.  $10.71 \text{ gH}_2\text{O/kg dry air}$ , corresponding to 61 % relative humidity at  $+23^\circ\text{C}$  and  $101.3 \text{ kPa}$  pressure, which are often referred as “standard” test conditions.

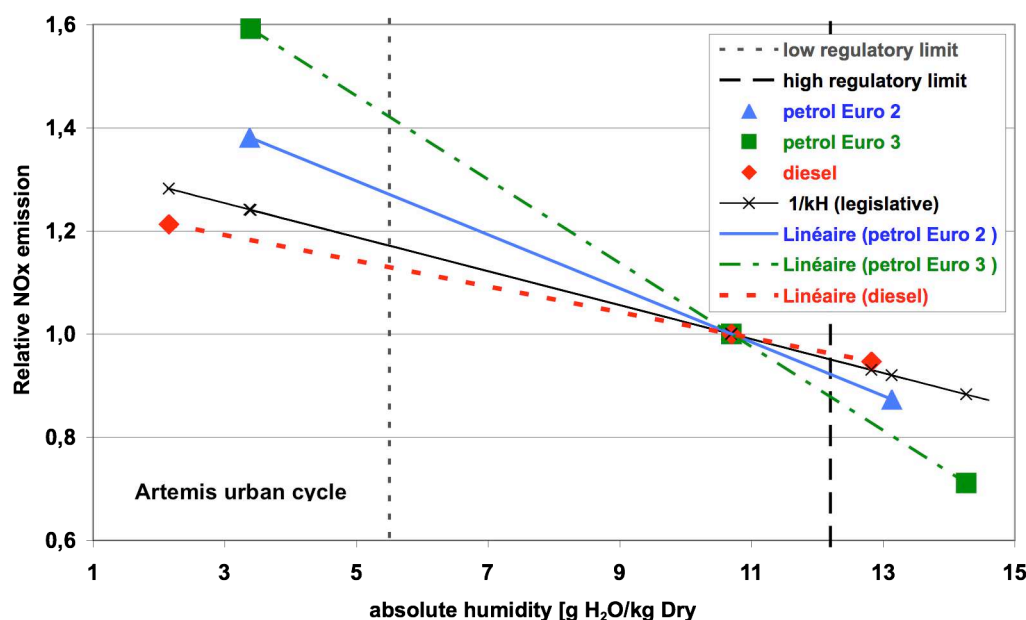


Figure 19: Linear models of (uncorrected) NO<sub>x</sub> emissions measured in Artemis urban driving cycle, fitted in average values for high, medium and low humidity, and correction factor according to legislative test protocol (as  $1/kH$ ).

The results show that an increase in ambient humidity lowers the NO<sub>x</sub> emissions (Laurikko, 2005c), which is also the expected general trend according to the humidity correction established in legislative testing (see Annex 3). Figure 19 shows that in urban test cycle the standard correction is nearly valid for diesel cars with less than 5 % deviation from the now-established model (i.e. trendline). However, both groups of petrol cars would need much stronger correction, as the relative change over the allowed humidity range is about 35 % for the Euro 2 to and over 55 % for the Euro 3 test fleet, and the normative factor corrects only by some 20 % within the same range of humidity. Therefore, the normalisation provided by the standard correction factor is insufficient. However, according to Figure 20, the case is very different when rural driving cycle is employed. All linear correction models developed here lie almost on top of each other, and the necessary correction is less than 20 %, even somewhat less than provided by the standard method. So, using the standard correction factor here actually leads to a slight “overcorrection”. We must take note though, that for some reason the standard deviations in all the pooled results for the urban cycle were two to three times higher than for the results from the rural cycle. Therefore, the validity of the analysis is better for the rural case.

For CO and HC, in case of diesel vehicles, CO correlates to the absolute humidity by 0.60 (rural) to 0.73 (urban), and HC to humidity by 0.28 (urban) and 0.41 (rural). The plotting of the relative influence of the humidity in Figure 21 and Figure 22 shows a clear influence of the humidity in the following cases:

- CO for diesel cars



- CO for petrol Euro 2 vehicles in urban situation
- HC for diesel cars and for petrol Euro 2 cars
- HC for petrol Euro 3 cars in urban situation

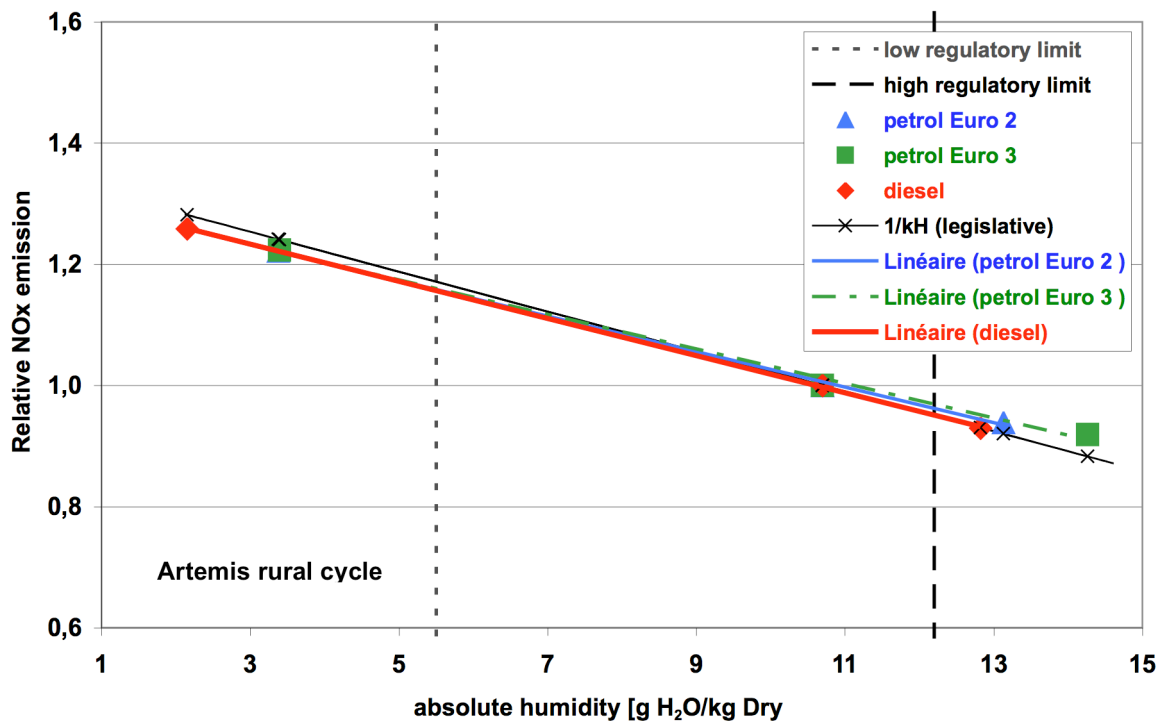


Figure 20: Linear models of (uncorrected) NOx emissions measured in Artemis rural driving cycle, fitted in average values for high, medium and low humidity, and correction factor according to legislative test protocol (as 1/kH).

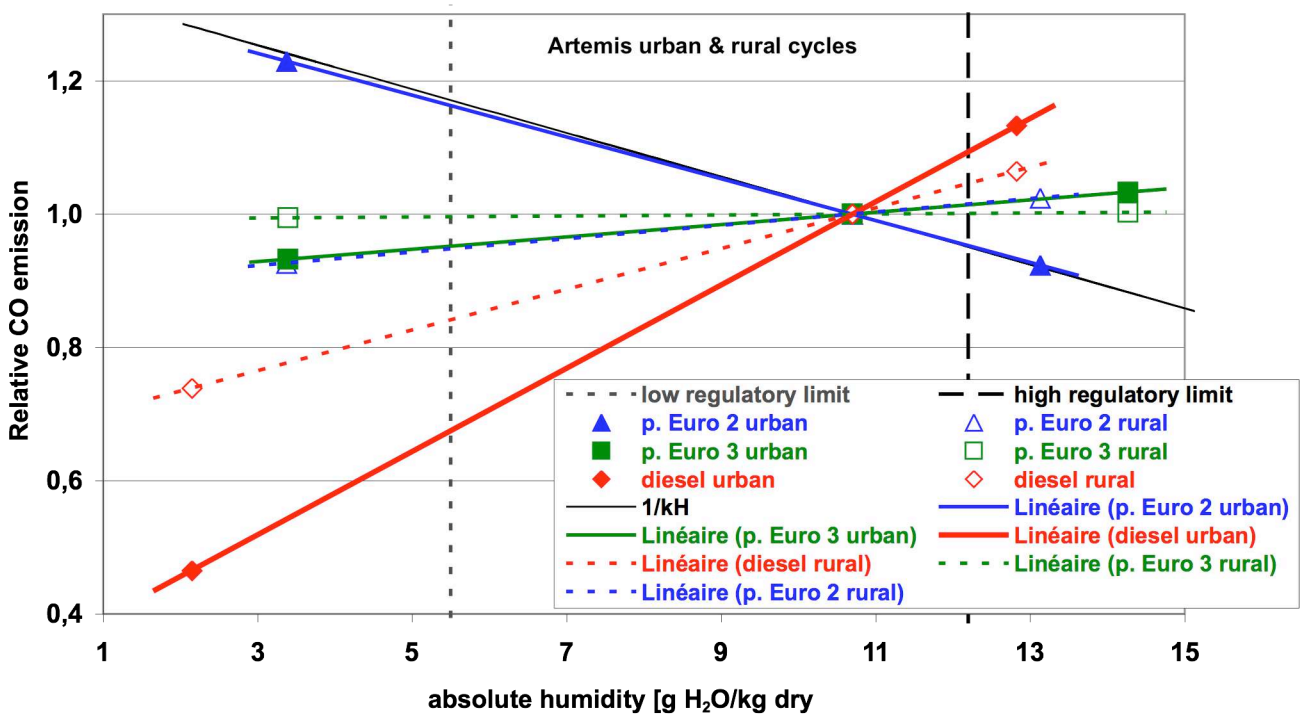


Figure 21: Average relative variations of CO emissions according to the absolute humidity.

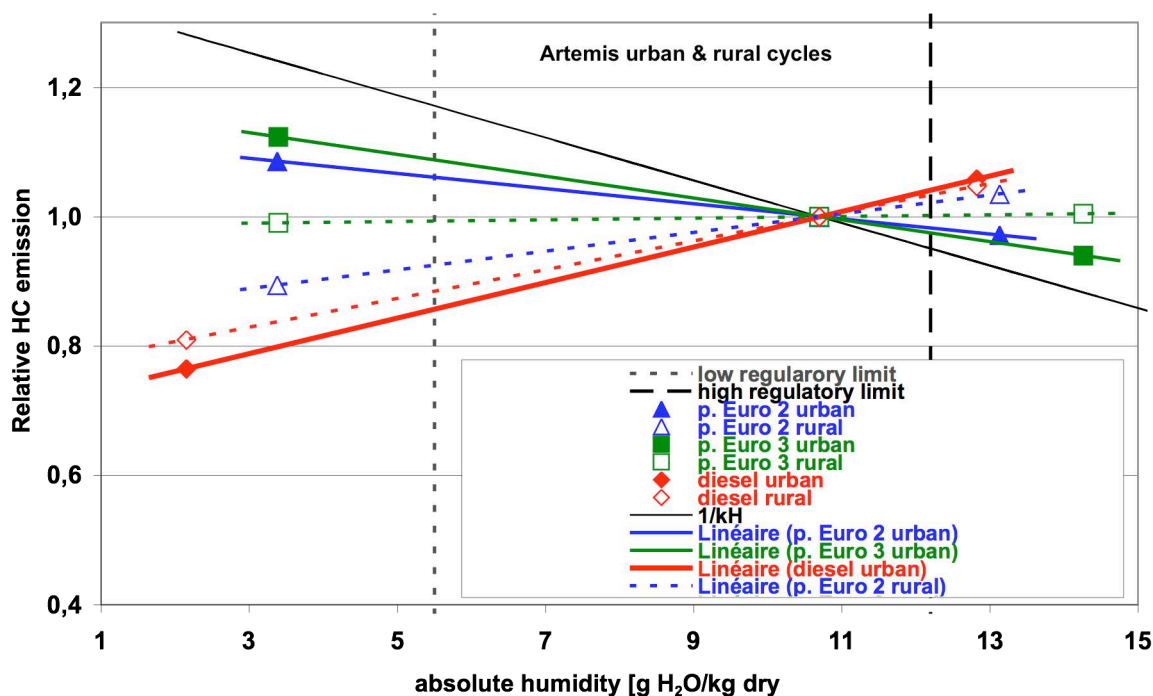


Figure 22: Average relative variations of HC emissions according to the absolute humidity.

	setting	NEDC				Artemis cycles					
		UDC		EUDC		Urban		Rural		Motorway	
		Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
CO	Petrol	5	5	-45	60	-3	-14	12	190	-42	<b>260</b>
	diesel	1	-6	13	-25	-4	-16	25	-25	-25	0
CO <sub>2</sub>	Petrol	<b>-7</b>	<b>-1</b>	<b>-10</b>	<b>12</b>	<b>-7</b>	<b>2</b>	<b>-10</b>	<b>8</b>	<b>-10</b>	<b>24</b>
	diesel	<b>-4</b>	<b>5</b>	<b>-12</b>	<b>13</b>	<b>-6</b>	<b>2</b>	<b>-9</b>	<b>9</b>	<b>-11</b>	<b>25</b>
HC	Petrol	10	9	inf	inf	14	-29	-50	150	-43	86
	diesel	-65	-19	-33	-17	-56	-28	-14	-14	25	-25
NO <sub>x</sub>	Petrol	4	17	-14	43	-13	-12	-17	7	-6	59
	diesel	-3	5	<b>-17</b>	<b>36</b>	<b>-11</b>	<b>13</b>	<b>-11</b>	<b>21</b>	<b>-24</b>	<b>70</b>
PM	diesel	-9	0	-18	1	-22	-8	-19	-4	-11	51
FC	Petrol	<b>-6</b>	<b>0</b>	<b>-10</b>	<b>12</b>	<b>-9</b>	<b>2</b>	<b>-9</b>	<b>9</b>	<b>-11</b>	<b>28</b>
	diesel	<b>-4</b>	<b>5</b>	<b>-12</b>	<b>13</b>	<b>-6</b>	<b>2</b>	<b>-9</b>	<b>9</b>	<b>-11</b>	<b>25</b>

Table 19: Average difference (%) of emissions measured with minimum, resp. maximum, vehicle bench settings, compared to average settings, for petrol and diesel vehicles. statistically significant differences are in **red bold**, possible significant differences in **red italics**.

### 3.4.3. Dynamometer setting

3 settings for road load and inertia are compared on 5 vehicles tested with cold NEDC and the set of three hot Artemis driving cycles (see the methodology in sections 2.3.1, 2.3.2.13 and 2.3.3). It

shows a statistically significant influence of the dynamometer settings for the CO<sub>2</sub> emission and fuel consumption (Vermeulen, 2005; see Table 19). With a higher road load, CO<sub>2</sub> and fuel consumption increase. Deviations of -12 to -4 % have been observed for the results of the minimum settings compared to the average settings. Deviations of +2 to +25 % have been observed for the results of the maximum settings compared to the average settings. This applies for both petrol and diesel fuelled passenger cars.

For Fuel Consumption and CO<sub>2</sub> emission the amount of influence by the altered chassis dynamometer settings varies with the driving cycle that is applied. The reason is that the relative alteration of the vehicles static load curve and the vehicles inertia is not responsible for an alteration in FC and CO<sub>2</sub> emission directly. The efficiency of the complete drive line interferes at this point. Higher loads may cause higher drive line efficiency for example. On the other hand the cycle characteristics determine the share of static and dynamic situations during the driving cycle. Because the relation of the chassis dynamometer settings at different driving cycles with FC and CO<sub>2</sub> is not proportional, it is recommended to use the results as a range of uncertainty caused by worst case chassis dynamometer settings.

For the regulated components CO, NO<sub>x</sub>, PM and HC there were no statistically significant influences found. However a clear trend was observed for the NO<sub>x</sub> emission of the diesel fuelled passenger cars. The higher the road load settings the more NO<sub>x</sub> the tested diesel vehicles emit. This is according to expectation, as diesel engines commonly produce more NO<sub>x</sub> when they operate at higher thermal loads.

For the CO emission of the petrol fuelled vehicles a raise was noticed at the Artemis rural and motorway cycles using high road load settings, but again this effect was not significant. From the theory, however, it can be expected that the CO and HC emission increase at very high engine loads.

From the results of this investigation there are no clear indications that altered chassis dynamometer settings explicitly influence the emissions of CO, HC, NO<sub>x</sub> and PM, although from the theory it might be expected that a change in engine load will affect these emissions to some extent. The very small size of the vehicle samples (3 petrol, 2 diesel fuelled cars) does not allow a clearer conclusion.

In this investigation it was found that chassis dynamometer settings may vary depending on the method chosen to determine the settings, the accuracy of the determination and the variation of ambient conditions. Because for CO<sub>2</sub> (and fuel consumption) the effects of altered settings are significant, it is recommended to investigate whether the methods used for determination of the chassis dynamometer settings (road load) have systematical errors for which the CO<sub>2</sub> model needs to be compensated.

#### **3.4.4. Exhaust gas dilution ratio**

Between 2 and 5 dilution ratios are compared on 8 vehicles, using cold and hot driving cycles. The methodology followed (see sections 2.3.1, 2.3.2.14 and 2.3.3) shows that, when the emission measurement results are presented as % deviation from the reference value which is the dilution ratio that would be normally selected for the respective measurement and the emission result of the measurement under the certain dilution ratio, it is rather the measurement scatter that is observed than any trend attributed to the effect of dilution ratio (Geivanidis et al., 2004).

The only visible exception is that of diesel PM emissions (see Figure 23): there is a trend of getting higher PM results with the increase of the the dilution ratio. This can be combined with the opposite trend of lower HC emissions with higher dilution ratios. The decrease of HC emissions may be

attributed to higher condensation of particles which is measured as an increase in PM emissions.

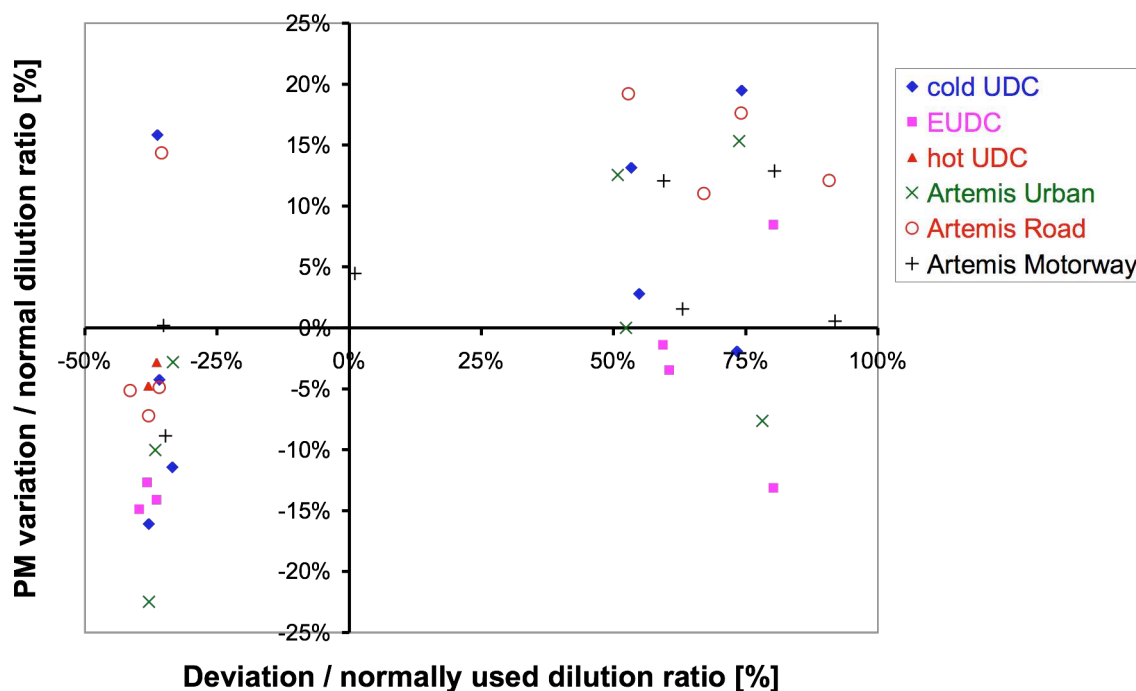


Figure 23: Dilution ratio effect on diesel vehicle PM emissions.

### 3.4.5. Heated line sampling temperature

The methodology followed (1 vehicle tested on hot NEDC with 2 temperatures: See sections 2.3.1, 2.3.2.15 and 2.3.3) shows that a lower heated line temperature resulted in higher HC emission values (Geivanidis et al., 2004). But this observation contradicts to what was expected as increased sampling line temperature aims to the opposite direction (increase the fraction of HC maintained in sample).

### 3.4.6. PM filter preconditioning

One passenger car was tested on cold and hot driving cycles, but by using PM filters preconditioned at 3 temperatures and 3 humidity levels (see sections 2.3.1, 2.3.2.16 and 2.3.3). The results show that no effect of the PM filter conditioning temperature and relative humidity was observed during the tests (Geivanidis et al., 2004): See Figure 24.

A higher value of PM emissions of the reference measurements is observed for UDC and subsequently for NEDC, in comparison of lower or higher filter conditioning temperature and relative humidity. This cannot be attributed to the sensitivity on the filter conditioning, but to an insufficient vehicle preconditioning before the start of the measurements. Considering the rest of the data, all variations are within the daily repeatability.

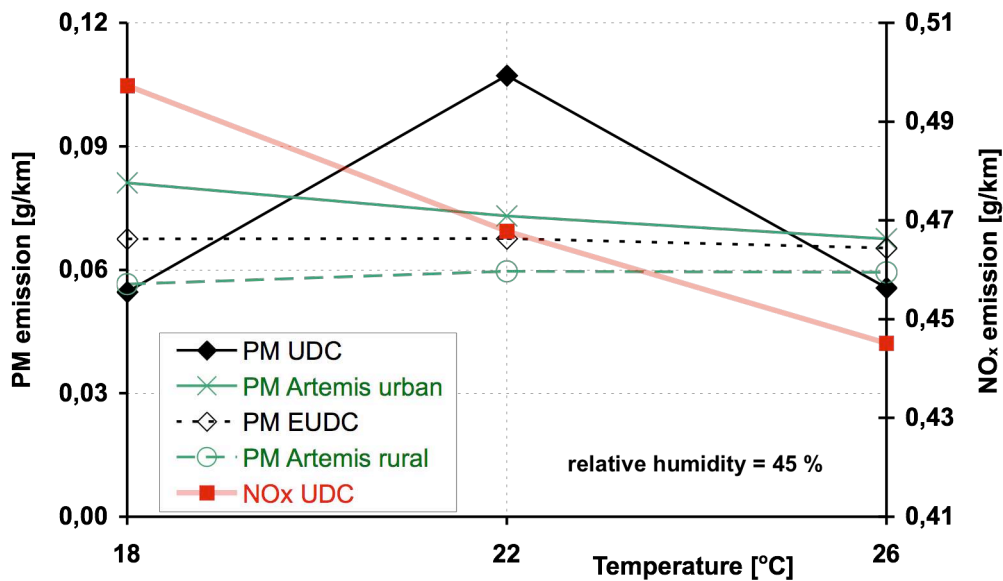


Figure 24: Influence of filter conditioning temperature on mass PM measurements.

### 3.4.7. Response time, including instantaneous vs. bag value

Two approaches, from Empa and TUG, were developed in parallel, in order to build the emission signal just after the catalyst from the emission signal measured after the CVS; They are different in some details with specific advantages (see the methodology in section 2.4.5). Both methods proved to improve the quality of instantaneous emission signals significantly and were both used for the instantaneous emission models successfully (Zallinger et al., 2005; Joumard et al., 2006).

Both, the methods from Empa and from TUG were specially calibrated for the own test bed. The method of TUG was applied to a CO<sub>2</sub>-measurement at the roller test bed of LAT also. Which method is preferable for a laboratory has to be selected mainly according to the parameters measured in their standard protocol and the parameters needed by the model (Le Anh et al., 2005).

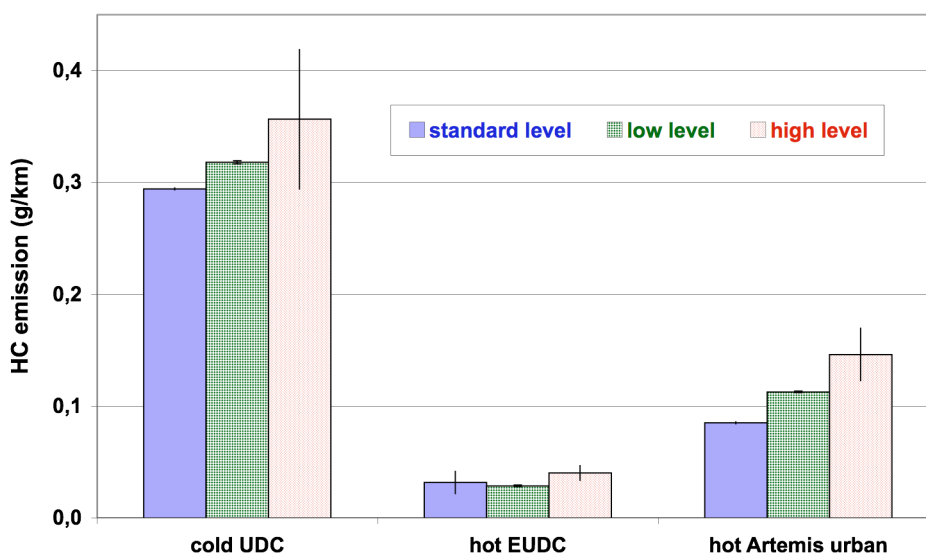


Figure 25: HC emissions for a petrol Euro 2 Fiat Punto according to 3 dilution air conditions (g/km).

### 3.4.8. Dilution air conditions

Two vehicles were tested on cold and hot driving cycles, but with 3 levels of polluted dilution air (see sections 2.3.1, 2.3.2.18 and 2.3.3). It allow us to investigate any significant differences amongst three dilution air pollution levels (see Figure 25), performing a one-way analysis of variance for CO, HC and NO<sub>x</sub> emissions expressed in g/km, using a F-test (Prati & Costagliola, 2004).

The results show that for the two cars tested and for the three chosen pollution levels of dilution air in all tested situations (with the exception of HC for Fiat Punto during the Artemis Urban cycle - see Figure 25) there is not a statistically significant difference between the mean emission factors from one level of pollution to another at the 95 % confidence level. Hence the quality of the dilution air has not a significant influence on emission measurements.

## 3.5. Round robin test

The results of the round-robin test conducted within 9 laboratories with a petrol passenger car show that assessing the variation between the results obtained in different laboratories is not an easy task. Even if we tried to develop and define a test protocol that should minimise procedural variations, and tests were performed according to that and to the best of the ability in each (see methodology in section 2.4.6), quite large spread amongst the results was recorded (Laurikko, 2005d). Two of the most influential factors were probably non-uniform fuel and variations in test cell ambient temperature. However, based on the results of the repeated tests pre and post-tour, we have reasons to believe that although the emissions level of the car was probably close to its legislative level, the operation of the car seemed not to be very stable and it had quite poor ability to produce repeatable emissions results. Therefore, part of the spread of results encountered in this exercise is probably resulting just from this variation, and not from the irregularities between laboratories.

The best accuracy (i.e. lowest spread in results) was encountered for CO<sub>2</sub>, where the average deviations (considering all six cycles) of each laboratory ranged between +7 and -10 %, and average coefficient of variation was around 5 %. Next best was CO, where the average spread was between +30 % and -50 %, and average coefficient of variation was around 40 %. For NO<sub>x</sub> the figures were somewhat larger, between +60 % and -35 %, and average coefficient of variation was below 40 %. The highest spread was by far recorded for HC, where the magnitude of average deviations was between +120 % and -50 % compared to the average result of the whole group, and average coefficient of variation was around 60 %.

When comparing these variations to those values calculated on the basis of the repeated tests at INRETS (depicted in Figure 26), we can conclude that the overall variability that was recorded for CO in the round robin test was roughly at the same order of magnitude than the “basic” repeatability combining the repeatability of the laboratory and fluctuations in the car performance. However, with HC the overall spread of results over the whole round robin test was higher, suggesting that some external factors, like the change in fuel quality, affected and lowered the repeatability. In terms of NO<sub>x</sub>, the overall round robin test variability was also somewhat higher than the basic value obtained from one laboratory alone, but we made no speculations over the probable reasons to this.

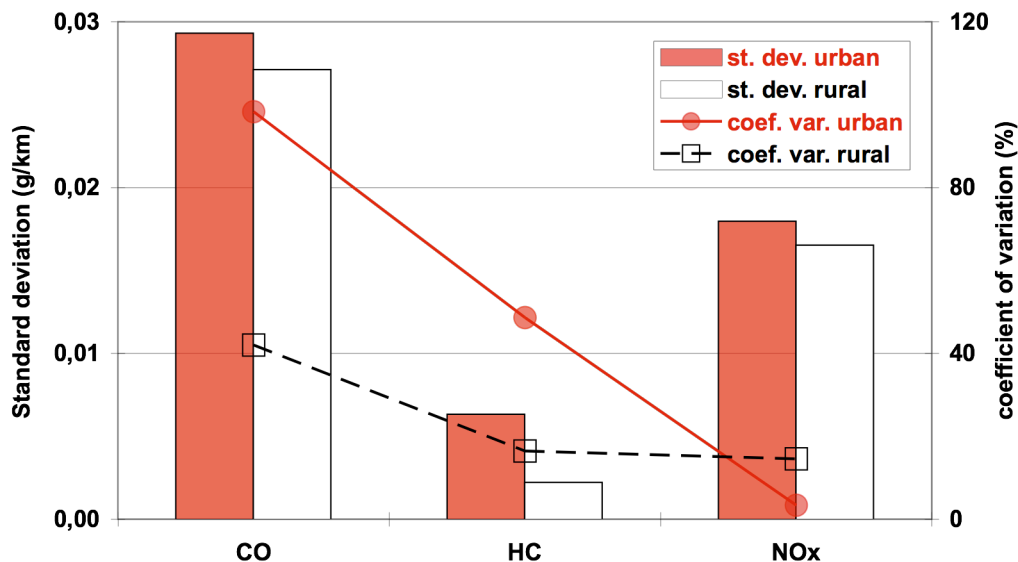


Figure 26: Standard deviation ( $s$ ) and coefficient of variation ( $cv\%$ ) of emissions measured in 3 sets of repetitions of hot Artemis urban and rural driving cycles at INRETS, for CO, HC and NOx. Each repetition is a sequence of 5 cycles whose emissions are averaged. Two sets of repetitions took place at the beginning, and the third set at the end of the round robin test.

Furthermore, closer assessment of the data reveals that it was not possible to develop any “correction factor” or “lab factor” that could be applied to the results provided by the laboratories to the pool of results collected in Artemis. This conclusion was mainly based on two facts. The first of these decisive factors was the quite long temporal span (over one year) between the round-robin exercise and the initial testing phase probably resulting in evolution of the measurement apparatus, and in one case even totally new set of main devices (CVS, analysers and chassis dynamometer were renewed at TUG). Therefore, it was probable that the results measured in this round robin exercise were different from those that would have been obtained, if the round robin test would have been executed parallel to the actual testing itself. However, the consortium had no provisions to perform that task, as round robin was part of the extension, and not part of the initial agreement, and the extension became heavily delayed due to the contractual dispute.

The second main fact that affected our conclusion not to develop any correction factor was that when different driving cycles were used, the spread of results became very random, i.e. none of the laboratories showed consistently higher or lower results compared to the average. Instead, laboratories could show results higher-than-average in one test case (driving cycle or component), and vice versa when another driving cycle or component was considered. Only if each of the pollutants was considered separately, a few cases could be found that results of a laboratory for that particular pollutant over all cycles tested could be consistently higher or lower than the average. This can be seen in Figure 27 that plots the average variation (all cycles and all components) for each laboratory, with high-low bars marking the largest deviations. Even in those laboratories that on average seem to lay above or below the average of the group, high or low bar ends extend to the other side of the 0-axis, indicating that the overestimation (or underestimation) was not consistent. Only perhaps LAT may be considered to show consistently lower results than the others, and KTI somewhat higher, but not in all cases.

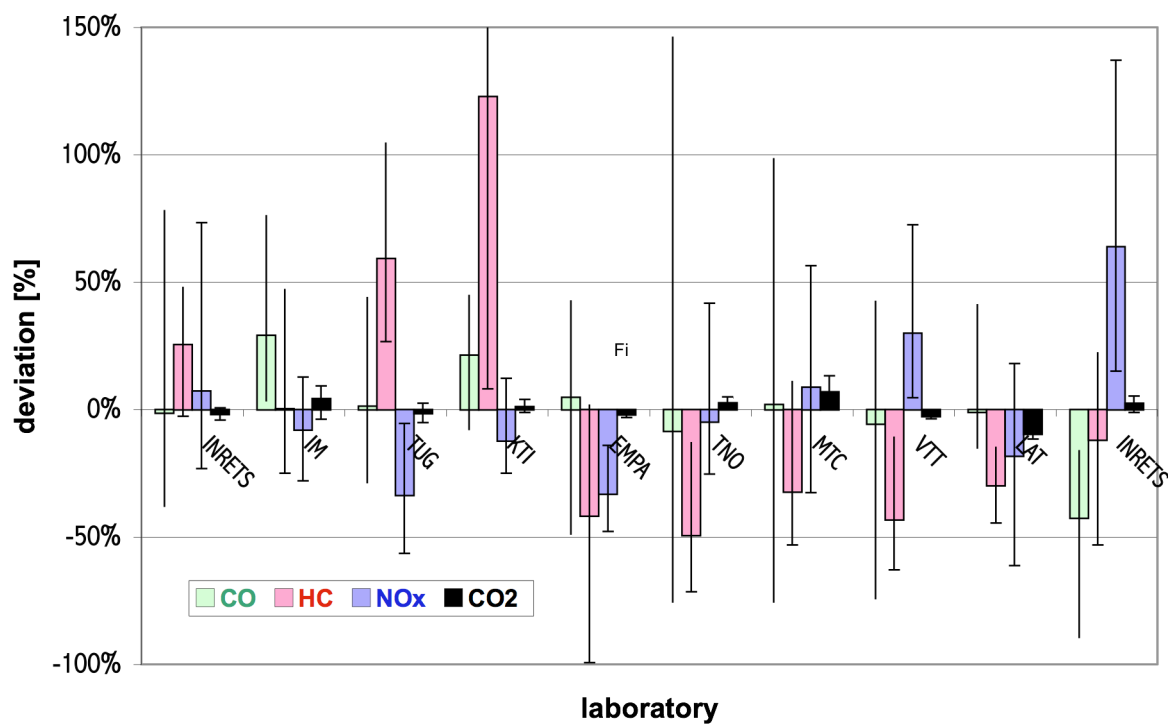


Figure 27: Relative emission deviation for each laboratory, in comparison with the average all laboratories considered (average for all cycles together for each component), as measured during the round robin test, with high-low bars marking the largest deviations.





## 4. Synthesis and correction factors

According to the outputs of the above studies and in the conditions of the tests, we did not find any influence of some parameters on the emission measurements. For some other parameters we showed a qualitative influence we are not able to quantify. Such result is nevertheless useful to design recommendations for the emission factor measurement method. Finally some parameters have a clear and quantifiable influence and can be used to normalise emission measurements when the level of these parameters during the experiment is known.

### 4.1. Not influencing parameters

According to the results presented above, we did not find any statistically significant influence on emission measurement for the following parameters:

#### *Vehicle related parameters*

- Short term emission stability or driving cycle repetition (see section 3.2.2). Nevertheless we recommend to test more than 10 cars per vehicle category to derive emission factors and in terms of limited budget to carry out only a limited number of repetition tests on these cars instead of taking a smaller sample tested many times.
- Inspection-maintenance (see section 3.2.3.2).
- Fuel properties (see section 3.2.4). The results confirm the influence of fuel on exhaust emissions, but in spite of observing significant differences, especially for PM emissions with diesel vehicle, it was not possible to propose an explanation based on the today knowledge of fuel effect.
- Vehicle cooling (see section 3.2.5). Although the cooling arrangement did affect the emissions, the results proved to be counteractive and too inconclusive.

#### *Laboratory related parameters*

- Heated line temperature (see section 3.4.5), because the observed emission change contradicts what is expected from the physico-chemical properties of the diluted emissions.
- PM filter conditions and (see section 3.4.6).
- Dilution air condition (see section 3.4.8).

It does not mean that these parameters have no influence on the emission measurements, but only that we cannot prove any influence, taking into account the small data sample or the contradictory results.

## **4.2. Parameters with qualitative influence**

Some parameters have a qualitative influence, as shown by our measurements. Therefore recommendations are made concerning these parameters:

### *Driving patterns*

- Driver (see section 3.1.3). Only the CO<sub>2</sub> emission was significantly higher with human driver than with a robot driver, but the difference cannot be explained by the driving characteristics.

We recommend that a cycle following should be in the following tolerance band:  $\pm 2$  km/h and  $\pm 1$  s. A test is accepted if it is within that band for more than 99 % of time and if the driven distance is within 1 % to the reference distance. A test is accepted with remark if it fails these values due to insufficient power, wheel slip, difficult gear box, in NEDC if deceleration is steeper than reference or if the engine stalls or does not activate immediately at test start. In all other cases a test should be rejected.

### *Vehicle related parameters*

- Vehicle classification (see section 3.2.1). The type approval category (Euro 1 to 4) and the fuel have a clear influence on the emissions, together with the engine capacity in some cases. But no correlation between emission behavior and emission control technologies were found as long as the cars belong to the same type approval category. Therefore the additional introduction of technological characteristics won't improve the accuracy of emission data bases of conventional cars up to Euro 4.
- Vehicle preconditioning (see section 3.2.6). The precondition conditions have an influence in some cases, but very few for modern close loop vehicles. A 10 minutes cycle at a constant speed of 80 km/h can be considered as the most suitable preconditioning cycle. It resulted in the lowest emission levels and the lowest standard deviation for the majority of the measurements.

### *Vehicle sampling method*

- Method of vehicle sampling (see section 3.3.1). The sample characteristics influence the emission levels, especially its size and of course the vehicle classes given above. If financial means allow it, a sampling method containing more than 10 vehicles, chosen the most possible in an official list (i.e. list created by an official body as government), would be that it will give results closest to the fleet representativeness. If an official list cannot be obtained, the list created in laboratories should be completed by vehicles owners, which the profession does not in relation with the pollution.
- Minimum size of vehicle sample (see section 3.3.2). Usually 10 to 15 vehicles are required for all the pollutants, in order to build-up an emission model which is representative of an average emission behaviour of a vehicle category. Below these prescribed numbers, the weight of the individual behaviour of some vehicles is too significant to obtain a mean, which is representative of an average behaviour.

### *Laboratory related parameters*

- Dynamometer settings (see section 3.4.3). The dynamometer setting has a clear influence on all emissions, but significant only on CO<sub>2</sub> and fuel consumption, and on NO<sub>x</sub> for diesel vehicles. It is recommended not to take into account emissions measured with altered chassis dynamometer settings.
- Response time including instantaneous versus bag value (see section 3.4.7). The measured instantaneous emission level must be corrected using specific functions, before building an instantaneous emission model.

### 4.3. Influencing parameters

Some parameters have a clear and statistically significant influence on the emissions measured. Quantitative correction factors are available (see section 4.4), in the following cases:

#### *Driving patterns*

- Driving cycle (see section 3.1.1). The analyses of the emissions as regards the driving cycles have demonstrated their significant influence (and often preponderant as regards other factors such as vehicle category or fuel). However, it was not possible at this stage to design a satisfying model or correction function that would enable a systematic correction. Indeed, the correlations are often weak and such corrections would be hazardous.

Taking into account the very high diversity of the emission data collected in the Artemis database – and the large range of the corresponding driving cycles – it was however not possible to elaborate emissions factors without managing this cycle influence. A harmonisation approach was then developed, based on the similarities between cycles from a kinematic point of view. This "cartography of the test cycles" enabled then the aggregation of the hot emission data in coherent groups. On this basis, emissions can be more reliably computed to elaborate hot emissions functions and factors.

- Gearshift strategy (see section 3.1.2.2). It is possible to classify the gearshift strategies according to their CO<sub>2</sub> emission (the only pollutant always influenced by the strategy). The most polluting strategy is the 'RPM' (at given engine speeds) whatever the cycle. The less polluting strategy seems to be the 'NEDC' one (at given vehicle speeds). The ratio between these two strategies is around 15 %. For urban cycle, the 'Artemis' strategy (depending on the vehicle power-to-mass ratio and on the 3<sup>rd</sup> gear ratio) pollutes as the 'NEDC' one. For rural cycle, the 'Artemis' strategy pollutes less than 'RPM' (9 %) one but more than the 'NEDC' (6%) one. Such a classification is not possible for the other pollutants.

#### *Vehicle related parameters*

- Mileage (see section 3.2.3.1). The influence of the mileage on petrol fuelled vehicle emissions depends on the pollutant, the type approval category (or emission standard) and the average speed. No influence of the mileage is considered for diesel vehicles.

#### *Laboratory related parameters*

- Ambient air temperature (see section 3.4.1). The influence of the ambient temperature is available for all pollutants and most of the vehicle classes. It is usually a linear function and sometimes an exponential one.
- Ambient air humidity (see section 3.4.2). The influence of the ambient humidity exists only for NO<sub>x</sub> and for some vehicle classes. It is a linear function.
- Exhaust gas dilution ratio (see section 3.4.4). A higher dilution ratio increases only the diesel PM emission measurement.

### 4.4. Correction factors

The influence of 5 parameters can be quantified. Correction factors are applicable in 4 of them to the Artemis emission data measurements:

- Gearshift strategy
- Vehicle mileage
- Ambient air temperature
- Ambient air humidity

- Exhaust gas dilution ratio (not applicable).

*Driving patterns*

- **Gearshift strategy** (see section 3.1.2.2). The correction factor CF (see Table 20) is used for CO<sub>2</sub> according to the formulae:

$$\frac{\text{emission } CO_2(\text{Artemis strategy})}{\text{emission } CO_2(\text{other strategy})} = CF$$

Strategy	driving behaviour	CF
Artemis	Urban	1
	Rural	1
	Motorway	1
	All	1
VP Motorisation	Urban	1
	Rural	1
	Motorway	1
NEDC	Urban	1
	Motorway	1.03
	Rural	1.08
Record	Urban	1
	Rural	1
	Motorway	1
Unknown	Unknown	1

Table 20: Correction factors CF to apply to the CO<sub>2</sub> emission factors, according to the gearshift strategy.

*Vehicle related parameters*

- **Vehicle mileage** (see section 3.2.3.1). The influence of the mileage M<sub>1</sub> or M<sub>2</sub> [km] is expressed by the formulae

$$\frac{\text{emission}(M_1)}{\text{emission}(M_2)} = \frac{y(M_1)}{y(M_2)}$$

y is available for Euro 1 and 2 petrol cars in Table 21, and for Euro 3 and 4 petrol cars in Table 22, in both cases for urban and rural situations, i.e. resp. for an average speed lower than 19 km/h and higher than 63 km/h. For an intermediate speed V, the following formulae has to be used:

Equation 1 
$$y(V) = y(\text{urban}) + \frac{(V - 19) \cdot (y(\text{rural}) - y(\text{urban}))}{44}$$

Petrol Euro 1 & 2		Capacity class [l]	Average mileage [km]	a	b	Value at ≥ 120 000 km
y(urban) for V≤19 km/h (urban situation)	CO	≤1.4	29 057	1.523E-05	0.557	2.39
		1.4-2.0	39 837	1.148E-05	0.543	1.92
		>2.0	47 028	9.243E-06	0.565	1.67
	HC	≤1.4	29 057	1.215E-05	0.647	2.10
		1.4-2.0	39 837	1.232E-05	0.509	1.99
		>2.0	47 028	1.208E-05	0.432	1.88
NOx	all	44 931	1.598E-05	0.282	2.20	
y(rural) for V≥63 km/h (rural situation)	CO	≤1.4	29 057	1.689E-05	0.509	2.54
		1.4-2.0	39 837	9.607E-06	0.617	1.77
		>2.0	47 028	2.704E-06	0.873	1.20
	HC	≤1.4	29 057	6.570E-06	0.809	1.60
		1.4-2.0	39 837	9.815E-06	0.609	1.79
		>2.0	47 028	6.224E-06	0.707	1.45
NOx	all	47 186	1.220E-05	0.424	1.89	

Table 21: Emission degradation correction factor  $y = a \times \text{Mileage} + b$ , for Euro 1 and Euro 2 petrol vehicles. Mileage expressed in km,  $y$  normalised for the corresponding average mileage.

Petrol Euro 3 & 4		Capacity class [l]	Average mileage [km]	a	b	Value at ≥ 160 000 km
y(urban) for V≤19 km/h (urban situation)	CO	≤1.4	32 407	7.129E-06	0.769	1.91
		>1.4	16 993	2.670E-06	0.955	1.38
	HC	≤1.4	31 972	3.419E-06	0.891	1.44
		>1.4	17 913	0	1	1
NOx	≤1.4	31 313	0	1	1	
	>1.4	16 993	3.986E-06	0.932	1.57	
y(rural) for V≥63 km/h (rural situation)	CO	≤1.4	30 123	1.502E-06	0.955	1.20
		>1.4	26 150	0	1	1
	HC	all	28 042	0	1	1
	NOx	all	26 150	0	1	1

Table 22: Emission degradation correction factor  $y = a \times \text{Mileage} + b$ , for Euro 3 and Euro 4 petrol vehicles. Mileage expressed in km,  $y$  normalised for the corresponding average mileage.

#### Laboratory related parameters

- **Ambient air temperature** (see section 3.4.1). The influence of the temperature  $T_1$  or  $T_2$  [°C] is expressed by the formulae

$$\frac{\text{emission}(T_1)}{\text{emission}(T_2)} = \frac{y(T_1)}{y(T_2)}$$

$y$  is available for urban, rural and motorway driving behaviour in Table 23.

			urban		rural		motorway	
			a	b	a	b	a	b
CO	petrol	Euro 0	0.0021	0.95	0.003	0.93	0.0054	0.88
		Euro 2	-0.0115	1.3	0.002	0.95	-	-
		Euro 3	-0.0087	1.2	0.0053	0.88	-0.0008	1.02
		Euro 4	No correction		0.017	0.61	-	-
	diesel	Euro 2	-0.034	1.784	-0.075	2.72	-0.024	1.56
HC	petrol	Euro 0	-0.001	1.02	-0.0027	1.066	No correction	
		Euro 2	-0.016	1.37	No correction		-	-
		Euro 3	-0.0525	2.21	-0.025	1.57	-0.001	1.02
		Euro 4	<i><b>3.4627</b></i>	<i><b>-0.0544</b></i>	0.0107	0.7442	-	-
		<i><b><math>y = a e^{bT}</math></b></i>				<i><b><math>y = a e^{bT}</math></b></i>		
diesel	Euro 2	-0.027	1.62	-0.032	1.75	<i><b>1.43</b></i>	<i><b>-0.015</b></i>	
NOx	petrol	Euro 0	-0.0075	1.17	-0.0063	1.14	-0.0035	1.08
		Euro 2	-0.0091	1.21	0.0045	0.895	-	-
		Euro 3	-0.0084	1.19	-0.0027	1.065	-0.002	1.05
		Euro 4	-0.01	1.23	0.0013	0.97	-	-
	diesel	Euro 2	-0.0015	1.05	-0.0015	1.05	-0.0006	1.016
CO <sub>2</sub>	petrol	Euro 0	-0.0038	1.09	-0.0038	1.09	-0.0033	1.08
		Euro 2	-0.0013	1.03	-0.0017	1.04	-	-
		Euro 3	-0.001	1.03	-0.0013	1.03	-0.0015	1.0342
		Euro 4	-0.0028	1.0619	-0.0016	1.0334	-	-
	diesel	Euro 2	-0.0015	1.03	-0.0017	1.04	-0.0009	1.0205
PM	diesel	Euro 2	0.005	0.88	No correction		-0.005	1.11

Table 23: Correction factor  $y = a \times \text{Temperature} + b$ , or  $y = a e^{b \times \text{Temperature}}$  when in blue italics bold, for urban, rural or motorway driving behaviour. Temperature in °C.  $y$  normalised at 23°C.

- **Ambient air humidity** (see section 3.4.2). The influence of the humidity on NOx emission is expressed by the formulae

$$\frac{\text{emission}(H_1)}{\text{emission}(H_2)} = \frac{y(H_1)}{y(H_2)}$$

$y$  is available for some vehicle classes and for urban and rural driving behaviour in Table 24. It is recommended to use the rural figures for motorway driving behaviour, and to use the petrol Euro 2 figures for petrol Euro 0 and 1, petrol Euro 3 figures for petrol Euro 4, and diesel Euro 2 figures for the other diesel cases. For other pollutants, no correction factors are proposed.

				urban		rural	
				a	b	a	b
Uncorrected emissions	NOx	petrol	Euro 2	-0.052	1.5592	-0.0293	1.31
			Euro 3	-0.081	1.8669	-0.0284	1.3
	diesel	Euro 2	-0.0249	1.2668	-0.0307	1.325	
Corrected emissions	NOx	petrol	Euro 2	-0.0182	1.1944	0.004	0.9571
			Euro 3	-0.0529	1.5654	-0.0093	1.0996
	diesel	Euro 2	0.0067	0.9281	0.0106	0.8869	

Table 24: Correction factor  $y = a \times \text{Humidity} + b$ , for NOx emissions corrected or not using the current method, and for urban or rural driving behaviour. Humidity in g H<sub>2</sub>O/kg dry air, y normalised at 10.71 g H<sub>2</sub>O/kg dry air.

- **Exhaust gas dilution ratio** (see section 3.4.4). A correction factor could be determined for PM, but it is not applicable to the common Artemis emission data, as the dilution ratio is usually unknown.





## 5. Guidelines

The knowledge of the sensitivity of vehicle pollutant emissions to the key parameters identified above allows us to design a best practice for measuring emissions of the European passenger car traffic. These guidelines can be displayed into four directions: Which cars to measure? In which conditions to test the cars? How to sample and analyse the pollutants? How to manage the data?

In order to look at the influence of any parameter on the emissions of the in-use fleet, or to contribute to an emission inventorying model, we do hereafter some recommendations.

### 5.1. Vehicle sampling

The fuel, the emission standard, the vehicle size and the engine power at the maximum power, and the vehicle mileage influence a lot the emissions. The size and power influence a lot the CO<sub>2</sub> emission and fuel consumption. In opposite way, the mileage has no influence on the CO<sub>2</sub> emission, but increases a lot CO, HC and NO<sub>x</sub> emissions of petrol cars: Between 0 and 100 000 km, these emissions increase by a factor 3.6 in average for Euro 1 & 2 vehicles, and by 15 % for Euro 3 & 4 vehicles.

We recommend therefore to take into account the distribution of the fuels, emission standard, vehicle size, maximum engine power, mileage in the traffic or running fleet, and to choose as far as possible a vehicle sample with similar distributions than the in-use fleet. At least the means or medians of the cubic capacity, maximum power and mileage should be similar in the traffic and the test vehicle sample.

The variability between vehicles is also identified as a significant and preponderant factor, together with the emitter status (high/ or normal emitter). It is not possible to know a priori the emitter status before measuring, but the high variability between vehicles of a same category obliges to choose the cars randomly within a category and to sample a minimum number of vehicles. The sample size depends often mainly on the means of the study, due to the high cost of each test. The desirable sample size depends on the number of parameters, according to which we want to express the results. Therefore we define here a minimum sample size per vehicle category, with the aim to calculate only an emission average per vehicle category. The minimum number of vehicles of a given category to get a quite stable emission average seems to be not less than 10 vehicles.

The vehicles to test can be chosen in many ways, but the best solution is to choose the vehicles randomly in an official owners' list when available, or in a list created by the laboratory, but not from the laboratory staff.

## 5.2. Usage conditions of the vehicles

The vehicle conditions in the measuring laboratory should correspond to the range of traffic conditions observed in Europe: It concerns not only the traffic parameters (driving patterns), but also the environmental conditions, the vehicle load, the fuel used... We look hereafter at the main usage conditions in order to recommend given conditions when they influence a lot the emissions.

### 5.2.1. Driving cycle

The driving type (i.e. urban, rural, motorway/main roads) and the driving cycle were also identified as significant and preponderant factors of the emissions. The variation induced by the driving type or cycle was more significant than the variation induced by the fuel type (for HC, CO<sub>2</sub>), or by the emission standard (NO<sub>x</sub>, CO<sub>2</sub>), or even between the vehicles (CO<sub>2</sub>). This highlights well the importance of the driving conditions on the emission. Considering petrol and diesel vehicles separately, it appears that the driving type, the driving cycle and the vehicle variability are the preponderant factors for diesel cars, while vehicle variability and emission standard are preponderant for petrol cars. Concerning the driving behaviour influence, we observe then quite contrasted behaviour between diesel (rather sensitive to speed and stop parameters) and petrol cars (rather sensitive to accelerations).

Therefore it is highly recommended to test the passenger cars with *real-world driving cycles*. A lot of such driving cycles are available in Europe, based on driving pattern records. We designed the so-called Artemis driving cycles from a large amount of driving records in Europe. The Artemis cycles are urban, rural and motorway cycles, with 14 sub-cycles all together representing different driving patterns (see Annex 1). They are now widely used in Europe to measure passenger cars emissions.

The Artemis cycles do not depend on the vehicle performances, but similar cycles are adapted to the vehicle performances. When we compare unique and *vehicle-adapted cycles*, for the recent vehicles (Euro 2 and 3), the use of one unique set of driving cycles leads to a significant underestimation (by 15 to 20 %) of the CO (petrol) and of the HC and particulates (diesel), and to an overestimation of the diesel CO (by 20 %). These gaps depend on the driving type (urban, rural, motorway). The low-powered cars are penalized by a common procedure as their CO<sub>2</sub> emission and fuel consumption are higher (by 11 %) when measured using a common set of cycles, than when measured using appropriate cycles. The usual procedure led also to an underestimation of CO and HC emissions from the small cars (by 4-13 %) and to a slight overestimation of HC and NO<sub>x</sub> from the most powerful cars (10 %). The usual test procedure with one common set of cycles for all the cars could led to strongly different emissions estimations, particularly for the most recent vehicle categories.

These gaps induced by the test procedure, and the differences observed as regards vehicle uses and driving conditions should justify the possible use of vehicle-specific driving cycles to measure actual pollutant emissions more accurately. Although the increase of complexity induced by such a refinement, the taking into account of the vehicles performances and of their specific uses should become important in a short term, to improve the quality of the emissions estimations, and also as the recent cars - more sensitive to the testing conditions - will become predominant.

### 5.2.2. Gearshift strategy

For given driving cycles, the gearshift strategy modifies the CO<sub>2</sub> emission by 2 to 15 %, and less significantly for CO and HC. The strategy impact remains nevertheless relatively low as soon as realistic patterns are selected. The gearshift strategy "cycle", i.e. foreseen in the Artemis and

vehicle-adapted driving cycles, depends on the vehicle power-to-mass ratio and the 3<sup>rd</sup> gear ratio. It seems to be the most appropriate.

### 5.2.3. Vehicle preconditioning

The petrol cars are more influenced by the preconditioning than the diesel ones. We propose as preconditioning cycle a constant speed cycle with a reasonable vehicle speed level. This is a well reproducible and simple driving cycle. The length of the preconditioning can be modified without changing the cycle characteristic. The 10 minutes cycle at a constant speed of 80 km/h can be considered as the most suitable preconditioning cycle.

### 5.2.4. Driver

The driver can be a human driver or a robot. The robot does not give more stable emissions and some driving cycles are too aggressive for it. In average, the robot decreases the CO<sub>2</sub> emission by +4 % compared to human drivers. Therefore it is no reason to prefer robot than a human driver.

It is possible for a trained test bench driver to follow a real-world driving cycle with a tolerance band of  $\pm 2$  km/h and  $\pm 1$  s in a quality, such that he violates the tolerance band less than 1 % of the test duration.

### 5.2.5. Fuel characteristics

Both diesel and petrol fuels influence a lot the emissions, but not CO<sub>2</sub>. Therefore it is recommended to use common fuels rather than laboratory fuels.

### 5.2.6. Ambient air temperature and humidity

The hot emissions decrease with increasing temperature for petrol and diesel cars, but mainly for diesel cars. Between 10 and 20°C, the CO and HC emissions varies by 15-20 %, the NO<sub>x</sub> and CO<sub>2</sub> emissions by 2 %, and PM is constant. It is therefore recommended to measure the emissions close to the average ambient temperature rather than at "standard" one when this one is far from the reality.

From the low to the high regulatory limit of humidity, i.e. 5.5 and 12.2 gH<sub>2</sub>O/kg dry air, NO<sub>x</sub> emission decreases for the petrol and diesel vehicles by resp. 30 and 15 %. This influence of the humidity is different from the legislative correction factor kH. Again it is therefore recommended when possible to perform the tests with an ambient air humidity close to the real-world average.

### 5.2.7. Vehicle cooling

The open and close bonnet, the height of a small blower have no influence on the emissions measured. The cooling power, i.e. the flow of the cooling air, has not a clear influence on the measured emissions. We recommend nevertheless to use a high power cooling system, in order to reproduce as far as possible the real-world cooling.

### 5.2.8. Dynamometer setting

The effect of altered dynamometer settings was found significant for CO<sub>2</sub> for both petrol and diesel cars and NO<sub>x</sub> for diesel cars only. For the other pollutants no effect was found. It can not be excluded, however, that altered settings might affect these other pollutants too. The sample size for this investigation was too small to draw strong conclusions or to establish correction factors.

Although only few effects were found significant, they still require an accurate simulation of the

actual road load; the chassis dynamometer settings should lead to a load applied to the driving wheels of a vehicle that is equivalent to the load experienced on the road at all speeds and accelerations. For the testing to be performed for the determination of real world emission factors, it is therefore primarily recommended to use;

- road load information derived from the coast down method performed by the laboratory and
- an inertia setting as close to the actual on road inertia as possible, which is also determined by the laboratory.

### **5.3. Sampling and analysing the pollutants**

The dilution ratio (between exhaust air and dilution air), the quality of the dilution air, the PM filter preconditioning seem not to have clear influence on the emissions. It could maybe due to the low sample size and to the widely standardised sampling and analysing conditions, respected by the participating laboratories.

Nevertheless, the pollutant analysing and sampling conditions seem far to be an important source of error, compared to the other parameters studied above.

### **5.4. Data management**

The data management, i.e. the way to preprocess and record the data, is not the purpose of this study. It is studied in details in another report (Joumard et al., 2007). We can do nevertheless the following basic recommendations:

- Record precisely the vehicle characteristics, the usage conditions of the vehicle as pointed above (driving cycle characteristics, ambient air, cooling...), especially when these conditions are stable in the laboratory but also specific to the laboratory
- Do not apply any correction factor to the measured parameters, especially concerning the air humidity
- Enter if possible the data into the so-called European Artemis light vehicle emission measurement database (Artemis LVEMDB), in order to share the data with other users
- Do apply in a second step correction factors as proposed in the section 4.4, in order to harmonise the data, to obtain comparable data. But, if the standardisation reduces usually the standard deviation, it deletes at the same time the influence of the standardisation parameter: it must be applied with care, and always without replacing the hard data.

## 6. Conclusion

The study was designed to look at the influence of a lot of parameters of the measurement of light vehicle emission factors: driving patterns, vehicle related parameters, vehicle sampling method, and laboratory related parameters.

In the conditions of the tests, we did not find any influence of some parameters. For some other parameters we showed a qualitative influence we are not able to quantify. Finally some parameters have a clear and quantifiable influence and can be used to normalise emission measurements when the level of these parameters during the experiment is known, by using correction factors: Gearshift strategy, vehicle mileage, ambient air temperature and humidity, exhaust gas dilution ratio.

The results allow us to design recommendations or guidelines for the emission factor measurement method.

The driving conditions are one of the main emission parameters, more significant than the fuel type (for HC, CO<sub>2</sub>), or than the emission standard (NO<sub>x</sub>, CO<sub>2</sub>) for diesel vehicles. It is the reason why we designed a set of real-world driving cycles, the so-called *Artemis* driving cycles and two sets of specific driving cycles build-up as a function of the technical characteristics of the vehicles, i.e. for low- and high-motorized vehicles. The *Artemis* driving cycles were used firstly by all the partners within the study and then widely in Europe, either to measure the emissions on chassis dynamometer or to model vehicle performances. The cycles include specific gearshifts.

The processing of the emission data according to driving behaviour parameters allowed also to design two emission models: one according to the distribution of the instantaneous speed and acceleration, and a second according to 7 dynamic related parameters. Both models are able to reproduce at best the emission data for any driving behaviour.

In parallel, an inverse model was developed in order to build the instantaneous emission signal just after the engine or catalyst from the CVS signal. This tool allows us to build a third emission model for any driving behaviour, but based on the instantaneous speed.

At the same time, we showed that the European driving behaviour can be reduced to 15 reference test patterns, based on kinematic analysis. When processing the emissions representative of these patterns according to the average speed, we clearly identify two classes of driving along the speed scale, i.e. the stable driving with low acceleration and stop frequencies on one side, and the unsteady driving on the opposite. Any driving behaviour can be projected into the space of these 15 patterns, and its emissions can be calculated according to the emissions of the 15 patterns. It is especially the case of the traffic situations designed in the *Artemis* modelling.

All these outputs will be used to design the *Artemis* emission inventorying tools for light vehicles, on a better basis than the previous European models.

The outputs of this study are nevertheless not fully positive, mainly because of the too small number of tests performed to look at the influence of some parameters, which did not allow us to find any significant influence. Some parameters could therefore be studied again.



## Annex 1: Detailed characteristics of the Artemis driving cycles & sub-cycles

Driving cycle or sub-cycle	duration (s)	Distance (m)	average speed (km/h)	running speed (km/h)	stop duration (%)	Stop rate 1/km	average accel. (m/s <sup>2</sup> )	average decel. (m/s <sup>2</sup> )	St. dev. of accel. (m/s <sup>2</sup> )	stop duration (s)	stop number	Absolute weight (%)	relative weights (%)
<b>Artemis Urban cycle</b>	<b>920</b>	<b>4472</b>	<b>17.5</b>	<b>24.4</b>	<b>28.3</b>	<b>4.70</b>	<b>0.75</b>	<b>-0.75</b>	<b>0.68</b>	<b>260</b>	<b>21</b>	<b>29.2</b>	<b>100</b>
Start phase	72	398	19.9	29.2	31.9	5.03	0.78	-0.66	0.58	23	2	0.0	0.0
Sub-cycle urban 1	236	1016	15.5	22.0	29.7	4.92	0.67	-0.56	0.56	70	5	5.9	20.1
Sub-cycle urban 2	198	1748	31.8	34.8	8.6	1.72	0.75	-1.04	0.83	17	3	12.2	41.6
Sub-cycle urban 3	243	590	8.7	21.0	58.4	8.47	0.90	-0.87	0.63	142	5	3.7	12.6
Sub-cycle urban 4	128	420	11.8	14.5	18.8	14.29	0.68	-0.60	0.64	24	6	2.4	8.3
Sub-cycle urban 5	115	698	21.9	24.2	9.6	2.87	0.76	-0.77	0.77	11	2	5.1	17.3
<b>Artemis Rural cycle</b>	<b>1081</b>	<b>17272</b>	<b>57.5</b>	<b>59.3</b>	<b>3.1</b>	<b>0.29</b>	<b>0.58</b>	<b>-0.65</b>	<b>0.56</b>	<b>33</b>	<b>5</b>		
Pre-part	101	831	29.6	32.9	9.9	2.41	0.61	-0.69	0.64	10	2	0.0	0.0
Post-Part	118	1695	51.7	54.0	4.2	0.59	0.64	-0.85	0.77	5	1	0.0	0.0
<b>Rural part</b>	<b>862</b>	<b>14746</b>	<b>61.6</b>	<b>63.0</b>	<b>2.2</b>	<b>0.14</b>	<b>0.56</b>	<b>-0.59</b>	<b>0.51</b>	<b>19</b>	<b>2</b>	<b>44.9</b>	<b>100</b>
Sub-cycle rural 1	240	3346	50.2	53.3	5.8	0.30	0.60	-0.68	0.68	14	1	10.8	24.1
Sub-cycle rural 2	171	3126	65.8	65.8	0.0	0.00	0.59	-0.54	0.37	0	0	7.2	16.0
Sub-cycle rural 3	183	2190	43.1	44.3	2.7	0.46	0.52	-0.54	0.45	5	1	8.8	19.7
Sub-cycle rural 4	177	3880	78.9	78.9	0.0	0.00	0.54	-0.60	0.53	0	0	11.8	26.3
Sub-cycle rural 5	91	2204	87.2	87.2	0.0	0.00	0.34	-0.39	0.19	0	0	6.2	13.9
<b>Artemis Motorway cycle</b>	<b>1067</b>	<b>29545</b>	<b>99.7</b>	<b>101.2</b>	<b>1.5</b>	<b>0.10</b>	<b>0.52</b>	<b>-0.68</b>	<b>0.49</b>	<b>16</b>	<b>3</b>		
Pre-part	176	2598	53.1	56.7	6.3	0.77	0.63	-0.70	0.63	11	2	0.0	0.0
Post-Part	155	2344	54.4	56.3	3.2	0.43	0.64	-0.81	0.75	5	1	0.0	0.0
<b>Motorway part</b>	<b>736</b>	<b>24602</b>	<b>120.3</b>	<b>120.3</b>	<b>0.0</b>	<b>0.00</b>	<b>0.40</b>	<b>-0.58</b>	<b>0.35</b>	<b>0</b>	<b>0</b>	<b>25.9</b>	<b>100</b>
Sub-cycle motorway 1	272	9259	122.5	122.5	0.0	0.00	0.36	-0.33	0.16	0	0	9.3	36.0
Sub-cycle motorway 2	173	4959	103.2	103.2	0.0	0.00	0.49	-0.72	0.63	0	0	6.0	23.2
Sub-cycle motorway 3	182	6350	125.6	125.6	0.0	0.00	0.27	NA	0.12	0	0	6.2	24.0
Sub-cycle motorway 4	109	4035	133.3	133.3	0.0	0.00	0.36	-0.44	0.29	0	0	4.4	16.8
<b>Artemis Motorway130 cycle</b>	<b>1067</b>	<b>28736</b>	<b>97.0</b>	<b>98.4</b>	<b>1.5</b>	<b>0.10</b>	<b>0.52</b>	<b>-0.68</b>	<b>0.49</b>	<b>16</b>	<b>3</b>		
<b>Motorway 130 part</b>	<b>736</b>	<b>23793</b>	<b>116.4</b>	<b>116.4</b>	<b>0.0</b>	<b>0.00</b>	<b>0.40</b>	<b>-0.57</b>	<b>0.35</b>	<b>0</b>	<b>0</b>	<b>25.9</b>	<b>100</b>
Sub-cycle motorway 1	Idem above											9.5	36.6
Sub-cycle motorway 2	Idem above											6.3	24.4
Sub-cycle motorway130 3	182	5955	117.8	117.8	0.0	0.00	0.29	-0.25	0.14	0	0	6.1	23.4
Sub-cycle motorway130 4	109	3620	119.6	119.6	0.0	0.00	0.30	-0.46	0.30	0	0	4.0	15.6



## **Annex 2: Description of the technical characteristics of the vehicles**

We analyze engine technologies and emission control systems potentially influencing the emission behavior of the vehicles (Samaras et al., 2005). It is largely based on a Concawe report (Kwon et al., 1999), expanded via an extensive literature review on the currently available emission reduction technologies. The status of the tested vehicles according to the described characteristics is given when available.

The annex is divided in two parts: the first one refers to the technologies used in modern petrol-fueled vehicles, and the second refers to the technologies of diesel fueled vehicles.

### **A2.1. Petrol vehicle technologies**

This chapter provides a description of main emission control technologies from the petrol cars tested.

#### **A2.1.1. Palladium containing Three-Way Catalysts**

##### ***Description***

In such catalysts palladium is combined with either rhodium only or rhodium and platinum. The latter formulation is often referred to as a trimetal or trimetallic catalyst. Their operation is identical to the more common platinum/rhodium catalysts, which are designed to convert HC, CO and NO<sub>x</sub> emissions from a petrol vehicle designed to run stoichiometric. Recent advances in catalyst manufacture have resulted in improved durability of palladium containing catalysts and better sulphur tolerance over their earlier palladium containing counterparts or the more common platinum/rhodium catalysts.

##### ***Advantages / disadvantages***

Improved emissions are achieved for same precious metal cost compared to platinum containing catalysts: up to 28 % in THC, 30 % in CO and 22 % in NO<sub>x</sub> (Bjordal et al., 1996). Such systems have higher thermal stability enabling use as close-coupled catalysts achieving faster light off times.

Such catalysts not only have the same sulphur tolerance as platinum/rhodium catalysts over short-term operation (Benett, 1996) but they are possibly more sulphur tolerant over extended operation on high sulphur fuels.

##### ***Status***

For the cars measured it was not possible to obtain full information on the design of the catalysts.

#### **A2.1.2. Formulation and loading of Three-Way Catalysts**

##### ***Description***

Works as conventional three-way catalysts.

### ***Advantages / disadvantages***

Increased loading gives improved emissions conversion. For example, doubling the platinum group metal or PGM loading can result in emissions reduction of 13 % in both THC and CO and 8 % in NO<sub>x</sub> (Bjordal et al., 1996). Change in PGM loadings and formulation can result in large reductions in emissions. Catalyst formulations can be adapted to target particular emissions.

For example, increases in the rhodium content of the catalyst can give large reductions, up to 70 %, in NO<sub>x</sub> (Bates et al., 1996). On the other hand higher PGM loadings increase cost of catalysts. Doubling PGM loading will typically increase cost by US\$ 20 per application.

### ***Status***

For the cars measured it was not possible to obtain full information on the design of the catalysts.

#### **A2.1.3. Close coupled Three-Way Catalysts**

##### ***Description***

Operates in a similar fashion to conventional three-way catalysts but is positioned closer to the exhaust manifold. Catalysts are normally positioned under the body of the vehicle, often about a meter away from the exhaust manifold. During cold start a considerable amount of heat from the exhaust gases can be lost into and through the exhaust pipe. If the catalyst is moved closer then the exhaust gases enter the catalyst hotter. The catalyst therefore reaches light-off temperature quicker and the exhaust gases are converted earlier. Higher catalyst temperatures experienced during high vehicle speeds can accelerate the deactivation of the catalyst performance, which results in a lower catalyst durability. Palladium containing catalysts have a higher thermal stability than the more common platinum/rhodium catalysts, and thus are a more appropriate formulation to use in a close-coupled catalyst.

##### ***Advantages / disadvantages***

Faster catalyst light off is achieved and hence lower emissions, particularly HC. Positioning a catalyst close to the exhaust manifold can give emissions reductions of 60 % in THC, 9 % in CO and 10 % in NO<sub>x</sub> (Acea and Europa, 1996). On the other hand there might be lower catalyst durability in such systems. Lack of space in engine compartment for catalyst is a problem faced in these systems but insulation of the exhaust system can be an alternative.

##### ***Status***

All petrol cars measured in this task have a pre-cat close to the engine.

#### **A2.1.4. Catalyst physical design**

##### ***Description***

Decreases in catalyst wall thickness give a lower thermal capacity. The catalyst will therefore reach light-off temperature faster, resulting in lower exhaust emissions. Increases in catalyst cell density increase the surface area of the catalysts. These result in a more reactive catalyst, even with the same quantity of precious metal, and thus lower in emissions. High vehicle speeds and loads can lead to a breakthrough of emissions from the catalysts. Under such conditions exhaust volume flow rates are high, and residence time of the exhaust over the catalysts is therefore short. Catalysts conversion efficiency is limited by catalyst volume, and thus larger catalysts would give higher conversions.

### ***Advantages / disadvantages***

A simultaneous increase in cell density (400 to 900 cpsi, or 60 to 140 cells per cm<sup>2</sup>) and decrease in wall thickness (0.16 to 0.11 mm) can reduce THC and CO exhaust emissions by 25 % and NO<sub>x</sub> emissions by 12% (Umehara et al., 1996). Increased catalyst volume reduces emissions. In addition to this, larger catalysts may be less sensitive to sulphur (Benett et al., 1996). On the other hand such systems are probably less durable and there might be a small fuel consumption penalty due to higher back pressure in some cases.

### ***Status***

For the cars measured it was not possible to information on the cell density of the catalysts.

## **A2.1.5. Exhaust Gas Recirculation for petrol vehicles (EGR)**

### ***Description***

Exhaust gases are added to the fresh charge for the next cycle in order to reduce the peak combustion temperature. NO<sub>x</sub> emissions are related to peak combustion temperatures. A certain amount of "internal" EGR occurs in all engines due to the overlap in inlet and exhaust valve timings. On vehicles equipped with variable valve timing (VVT) it will be possible to control the amount of internal EGR. Most vehicles that operate with an EGR system use external EGR, which involves recirculating a controlled amount of the exhaust gas via a valve into the intake. This technology can be applied to both conventional and lean-burn petrol engines.

### ***Advantages / disadvantages***

Lower NO<sub>x</sub> emissions are achieved at up to 47% (Acea and Europa, 1996). Extra hardware (EGR valve) is need though to do this increasing cost. In addition to this, EGR valve can become blocked with exhaust gas deposits, resulting in either lower exhaust gas flows or in active valve. There is also increased fuel consumption and engine noise. Higher lubricant oil contamination along with increased engine wear are two more issues of concern.

### ***Status***

The cars measured in this task had no external EGR. The rates of internal EGR are not known for the tested cars.

## **A2.1.6. Advanced engine management strategies**

Modern petrol cars use complex engine management strategies to reach their low emission levels. For the conventional petrol vehicles the engine management strategies aim at a better control of the stoichiometric air to fuel ratio (1:1) at hot running conditions and at faster heat up of the catalytic converter during cold running conditions. Several different strategies are used for cars today but for most of the tested cars it was not possible to get information on the engine control strategies applied.

The following gives an overview on some main control strategies

### ***Advanced engine management strategies: Rich start and secondary air injection***

The vehicle runs rich during the cold start. Exhaust gases, containing HC, H<sub>2</sub> and CO, are mixed in the exhaust system with secondary air and react further producing heat. This increases the exhaust gas temperature at the catalyst inlet and accelerates catalyst light-off. The beneficial results of this technology are based on the faster catalyst light off that is achieved. Catalyst reached light-off after

about 30 s for a vehicle operating with the above strategy compared to about 65 s for a conventional vehicle tested over FTP. This results in lower cold start emissions. On the other hand it requires additional hardware (air pump) and hence will be more expensive than a vehicle using a conventional cold start strategy. A possible small fuel consumption penalty due to early rich operation should not be left out.

### ***Cold start spark retard and enleanment***

During cold start, the engine is operated slightly lean (up to 1.05) and the spark timing retarded by around 20°. This management strategy results in later combustion with significant heat release in the exhaust port and pipe. Thus, the exhaust gas entering the catalyst will be hotter than for a conventional cold start strategy. Cold start spark retard and enleanment may be used in conjunction with close coupled catalysts to achieve rapid catalyst light off. Faster catalyst light off resulting in lower cold start emissions needing no extra hardware is the great advantage of this technology. On the other hand, exhaust valves heat up more quickly, resulting in faster deposit formation. Valve stem expands more quickly than train and can sometime stick open. This technology can result in increased engine noise and poor idle stability.

### ***Transient adaptive learning***

A wide range lambda sensor can be used to monitor the duration and severity of a mixture strength excursion during a transient vehicle operation. A model based engine management system can use this information to adapt parameters with the model in order to minimize severity and duration of future excursions. Parameters in the model that are adapted are those that describe the fuel behavior in the inlet manifold (distillation) and those that determine the quantity of fuel required for stoichiometric operation. Reducing mixture strength excursions will reduce emissions. The only disadvantages are the development and extra hardware (wide range lambda sensor) costs.

For the cars tested in this task the number of lambda sensors as well as their principle was investigated. All cars had at least 2 lambda sensors and on-board diagnostic OBD.

## **A2.2. Diesel vehicle technologies**

This chapter provides a description of main emission control technologies from the diesel cars tested.

### **A2.2.1. Oxidation catalyst**

#### ***Description***

Oxidation catalysts consists of an under floor ceramic monolith catalyst with Pt as active noble metal on wash coat to oxidize CO, HC and PM (soluble organic fraction) under lean conditions. The carbon fraction of the PM remains rather unaffected. New version with improvement of interaction between support, stabilizers and promoters with the precious metal package led to high CO and HC activity, better thermal durability and better sulphur tolerance. Oxidation catalysts can be applied to all light and heavy duty engines as well as 2-stroke petrol engines.

#### ***Advantages / disadvantages***

A reduction of HC (up to 75 %), CO (up to 70 %), NO<sub>x</sub> (up to 15 %) and total particulate matter (up to 30 %) can be achieved for light duty vehicles. There is a general tendency to decreased

mutagenicity due to elimination of polyaromatic hydrocarbons PAHs and an improvement of diesel exhaust odor. Particularly for light duty cars catalyst light-off is difficult at cold start or urban conditions. The formation of N<sub>2</sub>O and aldehydes is possible and the share of NO<sub>2</sub> on the total NO<sub>x</sub> emissions (NO+NO<sub>2</sub>) increases. The formation of sulphate is also possible, thus there is an extra PM formation at high temperature due to SO<sub>2</sub> oxidation and sulphate storage. Much progress has been made to make the oxidation catalyst more sulphur tolerant (less sulphate formation). The sensitivity of vehicle emissions to fuel changes (density, cetane number) are reduced by the catalyst. The fuel consumption penalty due to a slightly increased exhaust gas backpressure is considered to be small.

### ***Status***

Almost all diesel cars fulfilling Euro 2 and Euro 3 and all cars tested in this task have an oxidation catalyst.

Since none of the cars tested in this task was equipped with a diesel particulate filter this technology is not described here.

### **A2.2.2. Exhaust Gas Recirculation (EGR)**

#### ***Description***

Exhaust gases are added to the fresh charge for the next cycle in order to reduce the peak combustion temperature. Maximum 30 to 40 % of the exhaust in diesel engines is recirculated to the fresh air inlet. NO<sub>x</sub> emissions are reduced due to charge air dilution (more CO<sub>2</sub> in exhaust and thus reduced O<sub>2</sub> for combustion) and lower combustion temperatures (CO<sub>2</sub> has a high heat capacity).

#### ***Advantages / disadvantages***

EGR is the most commonly used method for NO<sub>x</sub>-reduction at passenger cars until now. It has superb trade-off flexibility for NO<sub>x</sub>/PM in combination with high pressure Common Rail and/or with a DPF system. The PM emissions can increase, while there is also a small increase in fuel consumption. Increased lube oil contamination and potential engine wear as well as deposit formation into the intake are other possible disadvantages.

### ***Status***

All diesel cars tested in this task had cooled EGR.

### **A2.2.3. Engine design**

A number of improvements of the engine design applicable to all diesel vehicles have been introduced, such as high pressure injection, inlet swirl control by port de-activation, variable turbocharger geometry and charge air cooling.

### ***Status***

The injection types were registered for the diesel cars tested in this task. For other features of the engine design no complete information was obtained during the project.

### **A2.2.4. Engine management**

#### ***Description***

The new generation of fast, reliable and durable solenoids combined with powerful electronic

control unit (software/EPROM) enables the latest generation of fuel injection pumps (Unit injectors, High Pressure rotary pumps, Common Rail) to work fully integrated in the fuelling system. This "package" gives full flexibility, allowing individual cylinder temperature corrections, ignition delay feedback, boost pressure and temperature corrections.

Injection strategies are possible including maximum response (power/torque) strategy, smoke limiting strategy (limited fuelling response to pedal movement/position), boost limit strategy, model based strategy (low total emissions), low NO<sub>x</sub> strategy (EGR rate) etc. Pilot/post and rate shaped injection is also possible with Common Rail.

### ***Advantages / disadvantages***

The major disadvantages are the increased cost and complexity.

### ***Status***

All cars tested in this task had a modern engine control system. It was not possible to get detailed information on the engine management system for most of the tested cars.

### Annex 3: Standard correction factor for humidity

The present correction factors concern only NOx. The correction factor for NOx based on ambient humidity was established already in 1972 in the USA. It was based on the assumption that NOx emissions are affected by the humidity of the combustion (i.e. intake) air. Since then legislative test protocols have included a correction factor for ambient humidity (EEC, 1991).

In the current description of the European test method (EEC, 1991), the correction factor (kH) is expressed as:

$$kH = \frac{1}{1 - 0.0329 (H - 10.71)} \quad \text{where } H = \frac{6.211 \times R_a \times P_d}{P_B - P_d \times R_a \times 10^{-2}}$$

with

- H = absolute humidity, expressed in grams of water per kilogram of dry air
- R<sub>a</sub> = relative humidity of the ambient air, expressed as a percentage
- P<sub>d</sub> = saturation vapour pressure at ambient temperature, expressed in kPa
- P<sub>B</sub> = atmospheric pressure in the room, expressed in kPa

The value of this kH, and its inversion 1/kH, which is linear, are both depicted in Figure 28.

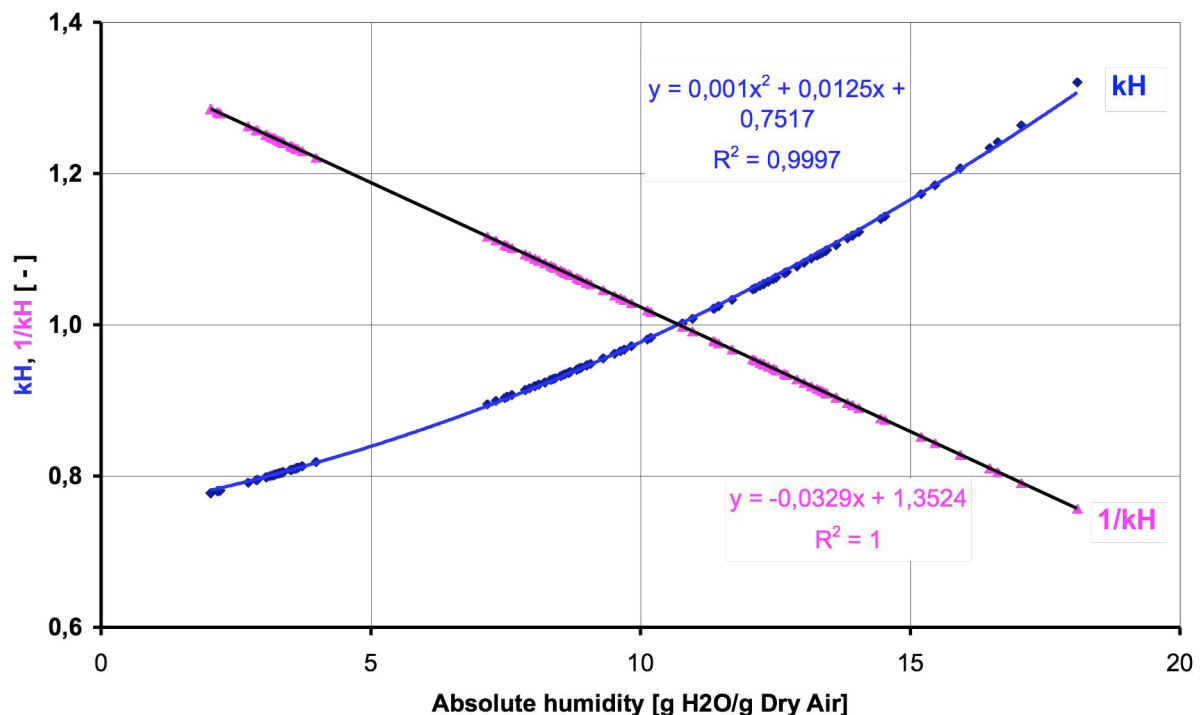


Figure 28: Humidity correction (kH) for NOx according to the legislative test descriptions (EEC, 1991).

## Annex 4: Dynamometer setting methods

### A4.1. Chassis dynamometer settings

#### A4.1.1. Determination of a vehicles road load

Several methods are available to define the road load of a vehicle. An inquiry was held amongst the partners within the Artemis project in order to gather all information on the methods for the definition of the chassis dynamometer settings used by the Artemis partners, assuming that the most commonly used methods will than be covered.

A vehicles static road load is mostly expressed in terms of a second degree polynomial:

$$A v^2 + B v + C$$

with

$A$  = the coefficient for driving resistance dependent on the squared speed

$B$  = the coefficient for driving resistance linearly dependent on speed

$C$  = the coefficient for driving resistance independent on speed

$v$  = the speed

This expression will be used to compare different methods of road load determination.

The outcome of the inquiry showed that most partners within Artemis use either road load information derived from the coast down method performed by themselves or performed by the manufacturer of a vehicle, or road load figures from the look up table in EEC 70/220 where the coefficients  $a$  and  $c$  of a polynomial for chassis dynamometer resistance are presented as a function of different reference mass classes. The reference mass is determined either by weighing, or by using information from the car license papers.

#### *Coastdown method 70/220EEC*

The coast down method is a commonly used method by manufacturers as well as by laboratories in order to define the road load of a vehicle. The procedure is described in EC regulation 70/220. The method is based on the equilibrium of vehicle inertia with vehicle drag and rolling resistance during deceleration with the gear positioned in neutral. Specific conditions are prescribed for this method in 70/220 in order to permit the least degrees of freedom as is reasonably possible for these kind of measurements on vehicles. Nevertheless there are some conditions that allow variances.

#### *Parameters derived from reference weight method 70/220EEC*

This method uses a predefined look up table (70/220EEC) where the coefficients  $a$  and  $c$  are given as a function of the reference mass of the vehicle.  $a$  and  $c$  in this method are respectively the coefficient for driving resistance dependent on the squared speed and the coefficient for resistance independent on speed. Looking at the way the parameters are determined it can already be pointed out that major errors on load adjustment can be made here, because the coefficients  $a$  and  $b$  solely depend on vehicle reference weight and not in any way on the real drag and rolling resistance of the vehicle. For instance two vehicles with the same reference weight can have totally different drag due to a different shape and accessories and a totally different rolling resistance due to a different



type and/or size of the tyres and due to a different construction of the drive train (wheel to gearbox, -> bearings, couplings, constant velocity joints etc..).

## **A4.2. Definition of the discrepancies**

The discrepancies of the coast down method and the reference weight method is described in this paragraph.

### ***Coastdown method***

For the coast down method variance is allowed for:

- measured vehicle speed: permitted error  $\pm 2$  %
- time: accuracy  $\pm 0.1$  s
- vehicle mass
- overall maximum repeatability of  $\pm 2$  % (at a 95 % confidence level) of (a minimum of) 4 x 2 = 8 coast down tests

Environmental conditions:

- slope of the road: maximum 1.5 %
- density of the air: maximum deviation from 1013 mbar and 293.2 K of  $\pm 7.5$  % (in the procedure a correction is applied)
- wind: maximum average speed 3 m/s, 5 m/s peak
- road surface

Vehicle conditions:

- tire pressure (in the procedure a correction is applied for the effect of temperature on tyre pressure)
- mechanical condition (bearings, constant velocity joints etc.)
- from a family the vehicle body variant with the highest drag should be chosen

the coast down is carried out starting at a speed of just above 120 km/h. The parameters for road load derived from the coast down curve are therefore only valid for vehicle speeds up to 120 km/h. Since vehicle speeds above 120 km/h at the chassis dynamometer are common for the Artemis driving cycle there is actually an underlying assumption that the load curve can be extrapolated or an acknowledgement that agrees with a possible large error. There is no evidence that for vehicle speeds up to 150 km/h as used in the Artemis driving cycle the extrapolation is valid within a certain range of a defined variance. This can even mean that a second degree polynomial fit is not sufficient to describe the vehicles road load from 0 to 150 km/h with a reasonable accuracy.

For the coast down method a few remarks have to be made, namely:

- for road gradient it is assumed that repetition in 2 directions will eliminate the influence of road gradient on driving resistance
- for wind and wind direction it is assumed that repetition in 2 directions will eliminate the influence of wind on driving resistance

For variations in road gradient during the coast down test (e.g. in one direction the road gradient at beginning of the coast down is  $-1$  %, in the other direction this is  $+1$  % at the end of the coast down) and wind speed variations can be said, that these are partly compensated when the coast down times for both directions are averaged and when these are included in the repeatability calculated from a minimum of 8 coast down tests. Road gradient and wind speed should never exceed the in 70/220EEC specified limits.

### **Reference mass look-up table**

As already pointed out, one major factor using this method is the independence of the vehicles load parameters a and b on the vehicles drag and rolling resistance. A look up table provides the load parameters as a function of reference mass. Furthermore a vehicle may come under a different load class if its reference weight is derived from the licence papers, because the vehicle mass printed on these papers may not correspond with the actual vehicle mass. Also in this method, it is assumed that adding the load from the chassis dynamometer and the wheels of the vehicle on the rolls up to the load derived from the polynomial function approximates the ‘true’ road load within a certain range. It is clear that variations in the chassis dynamometer set up (diameter of the rolls, number of rolls, surface of the rolls, bearings...) amongst laboratories might influence the amount of ‘base load’.

### **Chassis dynamometer**

The next source of discrepancies is the chassis dynamometer. An asynchronous motor, an eddy current dynamometer or a hydraulic dynamometer simulates road load (air resistance and rolling resistance). The vehicle mass is simulated mechanically by the inertia of the rotating components of the chassis dynamometer and partially by flywheels or by an asynchronous motor. A coast down test can be performed on the chassis dynamometer in order to validate the calculated vehicle parameters together with the chassis dynamometer characteristic parameters ( $av^2+bv+c$ ). For the chassis dynamometer the issues named in the following list may contribute to a discrepancy in simulated load:

- accuracy of mechanically simulated inertia:  $\pm 20$  kg
- accuracy of electrically simulated inertia:  $\pm 2$  % average and  $\pm 5$  % momentarily
- half the difference between two flywheel weight classes:  $\pm 60$  kg
- for chassis dynamometers with non adjustable absorbed power  $\pm 5$  % of the load at 80 km/h
- accuracy of the measured vehicle speed,  $\pm 1$  km/h at a speed  $> 10$  km/h
- coast down on the chassis dynamometer: tolerance of  $\pm 5$  % of the absorbed power at a speed  $> 20$  km/h and  $\pm 10$  % at a speed  $< 20$  km/h.
- accuracy and repeatability of the chassis dynamometer characteristic parameters: discrepancies may occur with temperature dependent resistance of components, for example bearings, drive belts and couplings, but also electrical components such as amplifiers, wiring etc.

During the coast down on the chassis dynamometer an error of 5 % of the absorbed power is allowed for vehicle speeds above 20 km/h. Below 20 km/h an error of 10 % is allowed. Within this error of 5 % and 10 % the error of the inertia influencing the equilibrium of inertia and load simulation during coast down on the chassis dynamometer is included. For the definition of the worst case chassis dynamometer settings a 5 % error will be applied only to the parameters A, B, and C (and not to the inertia).

The error in the inertia will directly influence transient load during the actual emission/fuel consumption tests. For the inertia of the rotating components of the chassis dynamometer including electrically simulated inertia an accuracy of 20 kg is required. Besides this error, a discrepancy occurs due to the resolution of the mechanically simulated inertia, if the ‘remaining’ inertia is not simulated in another way. Half the value of the inertia increment (resolution) can be pointed out as a maximum error. When both errors are combined, the total error for inertia approximates the inertia increment between two Inertia Weight Classes as prescribed in 70/220EEC. This error can be made at the reference mass method too. When the weight is derived from the vehicles license papers, the vehicle may come in a higher or lower inertia weight class than the weight class that is appropriate for the actual weight of the vehicle.

### A4.3. Definition of the altered chassis dynamometer settings

At first the variance of road load has to be determined. The altered settings will be defined by applying the two selected methods with their variance to the five vehicles which will be used to perform the tests.

For this investigation it is assumed that the polynomial approach of the road load determined from a coast down procedure is the best approximation of the ‘true’ road load. It will be clear that this function taken as an ‘average’ might already be a result of a worst case situation. The errors showed below this paragraph are used to approximate the worst case (combined) error of road load determination by performing a coast down procedure. These are the most important errors with a large potency on influencing the vehicles load. The remaining mainly small errors are not included in the calculation. Besides that, it can be assumed that all errors do not occur at the same time within the same procedure in the same (positive or negative) direction.

Vehicle speed:	$e_V = \pm 2 \%$
Repeatability:	$e_R = \pm 2 \%$
Load on chassis dynamometer:	$e_L = \pm 5 \%$

The combined error  $e_{COMB}$  is determined by the sum of the absolute errors, as given by the formula:

$$e_{COMB}(v) = \Delta RL_V(v) + \Delta RL_R(v) + \Delta RL_L(v)$$

The “reference mass” method should be compared directly to the average road load provided by coast down results because the road load from this method is already pre-determined as a function of reference mass. No chassis dynamometer adjustments have to be done but the input of the already named a and c coefficient. When the relative errors of the coast down procedure and the reference mass procedure from all vehicles are calculated as a function of vehicle speed it is possible to define two functions that cover all the errors at respectively the maximum load and at the minimum load. The Table 25 shows the minimum, average and maximum settings determined for the 5 vehicles tested.

	Make Type	VW Lupo 1.0	Ford Mondeo 1.8	Opel Omega 2.2	VW Golf 1.9TDi	Opel Omega 2.5TD
I <sub>-</sub>	minimum	910	1360	1590	1250	1590
I <sub>0</sub>	average	1020	1470	1700	1360	1700
I <sub>+</sub>	maximum	1130	1590	1810	1470	1810
A <sub>-</sub>	minimum	0.0266	0.0187	0.0352	0.0251	0.0289
A <sub>0</sub>	average	0.0307	0.0213	0.0407	0.0293	0.0324
A <sub>+</sub>	maximum	0.0526	0.0447	0.0661	0.0538	0.0578
B <sub>-</sub>	minimum	-0.7	1.11	-1.32	0.04	-0.57
B <sub>0</sub>	average	-0.7	1.35	-1.6	0.8	-0.85
B <sub>+</sub>	maximum	-1.7	0.49	-2.59	-0.95	-1.84
C <sub>-</sub>	minimum	0	-24	-2	-31	32
C <sub>0</sub>	average	37	24	77	16	110
C <sub>+</sub>	maximum	51	41	100	33	133

Table 25: Minimum (-), average (0) and maximum (+) chassis dynamometer settings of the vehicles used for the tests. A, B and C are defined in section A4.1.1.

## Annex 5: Characteristics of the driving cycles used

Within a family, the cycles are listed by increasing average speed. The cycles in italics and yellow are summation of cycles. The names of the driving cycle families and of the cycles within the families are original ones. The corresponding names within the Artemis database are given in the second table.

Driving cycle family	Cycle name (within the family)	Distance (km)	Duration (s)	Aver. speed (km/h)	Max. speed (km/h)	St. dev. accel. (m/s <sup>2</sup> )	Max. accel. (m/s <sup>2</sup> )
Artemis	urban	4.472	921	17.48	57.70	0.79	2.86
	rural	14.724	862	61.49	111.50	0.58	2.36
	motorway 130	23.793	736	116.38	131.80	0.39	1.28
	motorway	24.602	736	120.34	150.40	0.39	1.28
Handbook	StGolOF	0.636	341	6.71			
	R4 = LE6+StGoAB+StGolO	6.117	1340	16.43	60.90	0.40	1.39
	LE6F	5.248	822	22.98			
	LE5F	8.393	1012	29.86			
	R3 = LE2u+LE3+LE5	14.140	1080	47.13	79.20	0.46	1.86
	LS2E	3.242	242	48.23			
	LE3E	3.720	276	48.52			
	LG2E	3.334	227	52.88			
	LE2du	15.831	885	64.40			
	LE2sD	4.318	235	66.15			
	R2 = A4+LE1+LE2s	22.342	1080	74.47	105.90	0.27	1.00
	LE1D	22.298	1076	74.60			
	A3C+A4C	12.110	476	91.59			
	R1 = AE1+AE2+AE3	41.157	1341	110.49	131.10	0.20	0.78
AE1C	16.029	516	111.83				
AE2C	36.045	1080	120.15				
modem	urban 1	3.447	635	19.54	60.00	0.70	2.14
	urban 2	0.879	168	18.84	60.00	0.71	2.89
	urban 3	1.082	282	13.81	39.10	0.67	2.42
	urban 4	0.405	132	11.05	31.00	0.70	1.81
	urban 5	6.333	1027	22.20	73.50	0.85	3.08
	urban 6	0.131	91	5.18	26.10	0.77	2.06
	urban 7	0.840	100	30.24	82.40	1.00	2.39
	urban 8	1.107	250	15.94	53.50	0.64	1.83
	urban 9	0.202	95	7.65	27.50	0.50	1.42
	urban 10	1.867	430	15.63	44.40	0.71	2.33
	urban 11	11.346	962	42.46	88.20	0.67	2.00
	urban 12	2.443	423	20.79	49.90	0.74	2.53
	urban 13	2.620	526	17.93	55.70	0.78	3.03
	urban 14	3.413	383	32.08	67.00	0.75	2.67
	<i>urban 5+7+13</i>	<i>9.193</i>	<i>1426</i>	<i>23.21</i>	<i>82.40</i>	<i>0.86</i>	<i>3.08</i>

Driving cycle family	Cycle name (within the family)	Distance (km)	Duration (s)	Aver. speed (km/h)	Max. speed (km/h)	St. dev. accel. (m/s <sup>2</sup> )	Max. accel. (m/s <sup>2</sup> )
modem Hyzem	pure urban 3	2.914	583	17.99	61.60	0.65	2.61
	pure urban 1	4.185	720	20.93	59.00	0.76	2.44
	pure urban	3.470	560	22.31	57.20	0.67	2.19
	pure road 1	6.957	584	42.89	71.70	0.71	2.72
	pure road	10.682	743	51.75	103.40	0.75	2.42
	pure road 2	23.107	1091	76.25	125.80	0.46	2.19
	pure motorway 2	36.939	1281	103.81	149.90	0.54	3.22
	pure motorway	42.902	1495	103.31	138.10	0.41	3.03
modem IM	urban slow	1.705	428	14.34	42.30	0.61	2.31
	urban free-flow	2.248	355	22.80	62.30	0.73	2.64
	short	2.246	255	31.71	69.70	1.35	1.89
	road	8.485	712	42.90	109.20	0.71	3.19
	motorway	12.683	452	101.02	128.70	0.49	2.14
Napoli	10-23	3.362	1081	11.20	49.96	0.52	1.90
	15-18-21	4.467	1070	15.03	52.00	0.57	1.80
	6-17	16.469	1038	57.12	105.51	0.54	2.09
PVU commerciale	grand routier	18.755	828	81.54	128.60	0.61	2.14
Standard	ECE 15 / Urban Driving Cycle UDC	4.052	780	18.70	50.00	0.47	1.06
	Extra Urban Driving Cycle EUDC	6.955	400	62.60	120.00	0.38	0.83
	<i>NEDC = UDC + EUDC</i>	<i>11.007</i>	<i>1180</i>	<i>33.58</i>	<i>120.00</i>	<i>0.44</i>	<i>1.06</i>
	US Highway	16.506	765	77.68	96.40	0.30	1.44
VP faible motorisation	urbain dense	2.935	711	14.86	55.20	0.67	2.44
	urbain	4.799	945	18.28	55.70	0.68	2.50
	urbain fluide	4.818	710	24.43	56.70	0.73	3.19
	route	13.149	821	57.66	111.50	0.57	2.19
	autoroute	24.090	729	118.97	150.70	0.39	1.28
VP forte motorisation	urbain dense	2.907	730	14.34	57.60	0.64	2.67
	urbain	4.924	918	19.31	57.60	0.71	2.39
	urbain fluide	4.780	710	24.23	61.30	0.76	2.14
	route	14.224	844	60.67	110.50	0.60	2.14
	autoroute	25.377	750	121.81	157.10	0.37	2.00

Driving cycle family	Cycle name (within the family)	Name in the Artemis database
Artemis	urban rural motorway 130 motorway	Artemis.urban Artemis.rural Artemis.motorway_130 Artemis.motorway_150
Handbook	StGoIOF R4 = LE6+StGoAB+StGoIO LE6F LE5F R3 = LE2u+LE3+LE5 LS2E LE3E LG2E LE2du LE2sD R2 = A4+LE1+LE2s LE1D A3C+A4C R1 = AE1+AE2+AE3 AE1C AE2C	EMPA.F3 Handbook.R4 EMPA.F2 EMPA.F1 Handbook.R3 EMPA.E2 EMPA.E3 EMPA.E1 EMPA.D1 EMPA.D2 Handbook.R2 EMPA.D3 EMPA.C1 Handbook.R1 EMPA.C2 EMPA.C3
modem	urban 1 urban 2 urban 3 urban 4 urban 5 urban 6 urban 7 urban 8 urban 9 urban 10 urban 11 urban 12 urban 13 urban 14 <i>urban 5+7+13</i>	modem.urban1 modem.urban2 modem.urban3 modem.urban4 modem.urban5 modem.urban6 modem.urban7 modem.urban8 modem.urban9 modem.urban10 modem.urban11 modem.urban12 modem.urban13 modem.urban14 modem.urban5713

Driving cycle family	Cycle name (within the family)	Name in the Artemis database
modem Hyzem	pure urban 3 pure urban 1 pure urban pure road 1 pure road pure road 2 pure motorway 2 <sup>a</sup> pure motorway	modemHyzem.urban3 modemHyzem.urban1 modemHyzem.urban modemHyzem.road1 modemHyzem.road modemHyzem.road2 modemHyzem.motorway1 <sup>b</sup> modemHyzem.motorway
modem IM	urban slow urban free-flow short road motorway	modemIM.Urban_Slow modemIM.Urban_Free_Flow modemIM.Short modemIM.Road modemIM.Motorway
Napoli	10-23 15-18-21 6-17	Napoli.10_23 Napoli.15_18_21 Napoli.6_17
PVU commerciale	grand routier	LDV_PVU.CommercialCars.motorway_1
Standard	ECE 15 / Urban Driving Cycle UDC Extra Urban Driving Cycle EUDC <i>NEDC = UDC + EUDC</i> US Highway	Legislative.ECE <i>or</i> Legislative.ECE_2000 Legislative.EUDC <i>Legislative.NEDC or Legislative.NEDC_2000</i> Legislative.US_HWAY
VP faible motorisation	urbain dense urbain urbain fluide route autoroute	Artemis.LowMot_urbdense Artemis.LowMot_urban Artemis.LowMot_freeurban Artemis.LowMot_rural Artemis.LowMot_motorway
VP forte motorisation	urbain dense urbain urbain fluide route autoroute	Artemis.HighMot_urbdense Artemis.HighMot_urban Artemis.HighMot_freeurban Artemis.HighMot_rural Artemis.HighMot_motorway

<sup>a</sup> original name as defined in (André, 1997)

<sup>b</sup> name given in the Artemis data base, but different than the original one, for the same driving cycle

## Annex 6: Average characteristics of the vehicle samples

Parameter		Sample size			Cubic capacity (cm <sup>3</sup> )			Power (kW)			Weight (kg)			Mileage (Mm)		
		Petrol	Diesel	total	Petrol	Diesel	total	Petrol	Diesel	total	Petrol	Diesel	total	Petrol	Diesel	total
Driv.	Driving cycles	17	16	33	1949	1406	1686	63	64	64	1213	1030	1124	77	35	56
	<i>(Subsamp. 14 DC)</i>	5	4	9	1889	1391	1667	59	65	61	1152	1079	1119	69	30	52
	Gear choice	8	7	15	1414	1867	1625	63	58	61	1021	1157	1084	47	57	51
	Driver	1	0	1	1800	-	1800	na	-	na	na	-	na	na	-	na
Vehicle par.	Techn. char. veh.	32	11	43	na	na	na	na	na	na	na	na	na	na	na	na
	<i>"" (detailed anal.)</i>	8	5	13	1765	1798	1778	90	83	87	1258	1288	1269	9	9	9
	Emission stability	10	2	12	1531	1905	1593	na	66	na	na	1229	na	na	5	na
	Emis. degradation	2	0	2	1073	-	1073	46	-	46	933	-	933	47	-	47
	Fuel properties	1	1	2	1600	1900	1750	na	na	na	na	na	na	na	na	na
	Vehicle cooling	4	2	6	1720	2030	1823	75	79	77	1200	1456	1285	45	45	45
	Vehicle precond.	3	2	5	1346	1832	1540	59	70	63	925	1300	1075	29	95	55
	Veh. sample size	55	25	80	1457	1832	1574	58	52	56	942	1071	982	55	59	56
Laboratory par.	Ambient temp.	22	9	31	1785	2001	1848	81	77	80	1215	1337	1251	53	71	58
	Ambient humidity	9	2	11	1572	1947	1640	76	73	76	1241	1375	1265	24	26	24
	Dynamo. setting	3	2	5	1664	2197	1877	76	89	81	1305	1478	1374	19	44	29
	Dilution ratio	3	5	8	1445	1868	1709	82	72	76	1004	1225	1142	10	68	46
	Heated line temp.	0	1	1	-	1753	1753	-	65	65	-	1345	1345	-	3	3
	PM filter precond.	0	1	1	-	2926	2926	-	142	142	-	1713	1713	-	17	17
	Response time	3	2	5	1681	1896	1767	na	81	na	na	na	na	na	na	na
	Dilution air cond.	2	0	2	1420	-	1420	66	-	66	1105	-	1105	5	-	5
	Round robin test	1	0	1	1598	-	1598	83	-	83	1200	-	1200	1	-	1



## Annex 7: Characteristics of the tested vehicles

Additional characteristics are given for some vehicles at the end of the annex (esp. in Table 27).

Lab.	Make	Model	Petrol / CNG / Diesel	Emis. standard	Year	Capacity (cm <sup>3</sup> )	Max. power (kW)	Weight (kg)	Mileage (Mm)	Driving cycle	Gear choice	Driver	Techn. char. veh.	Emission stability	Emis. degradation	Fuel properties	Vehicle cooling	Vehicle precond.	Veh. sample size	Ambient temp.	Ambient humidity	Dynamo. setting	Dilution ratio	Heated line temp.	PM filter precond.	Response time	Dilution air cond.	Round Robin test
all	Renault	Mégane 1.6 16V	P	E3	2004	1598	83	1200	1																			1
Em.	Alfa Romeo	156 2.4 JTD	D	E2	1998	2387	100	1410	71											T								
Em.	Ford	Focus 1.8 TD	D	E2	2000	1753	66	1273	36											T								
Em.	Opel	Zafira A 20 TD	D	E2	1999	1995	60	1430	69											T								
Em.	Peugeot	406 1.9 DT	D	E2	1997	1905	66	1365	94											T								
Em.	Seat	Ibiza GT TDI	D	E2	1999	1896	81	1105	31											T								
Em.	Volkswagen	Passat	D	E2	2001	1896	81	1375	103											T								
Em.	BMW	635CSI	P	preE1	1985	3430	160	1470	167											T								
Em.	Fiat	Uno 45	P	preE1	1986	999	33	795	110											T								
Em.	Honda	Accord 2.0l Auto	P	preE1	1985	1954	85	1155	117											T								
Em.	Opel	Kadett D 1.3	P	preE1	1984	1296	50	920	128											T								
Em.	Peugeot	505 GTI Auto	P	preE1	1984	2164	95,5	1235	58											T								
Em.	Volkswagen	Golf 19E	P	preE1	1984	1595	55	910	164											T								
Em.	BMW	318 TI	P	E1		1800					1														1			
Em.	Alfa Romeo	156 2.0 Twin Spark 16V	P	E2	1998	1970	114	1250	74				1												1			
Em.	BMW	323CI	P	E3	2000	2494	125	1370	28											T								
Em.	Ford	Focus 1.6 16V Auto	P	E3	2000	1596	74	1151	16											T								
Em.	Hyundai	Accent 1.3 GS	P	E3	2000	1341	62	990	22											T								
Em.	Mitsubishi	Galant 2.5 V6 Auto	P	E3	2000	2498	120	1445	33											T								
Em.	Nissan	Primera 2.0 CVT	P	E3	2000	1998	103	1325	30											T								
Em.	Toyota	Yaris 1.0	P	E3	2000	998	50	900	37											T								











*Accuracy of exhaust emissions measurements on vehicle bench*

VTT	Nissan	Almera Hatchback 1.8	P	E2	2000	1760	84	1300	26								1										
VTT	Opel	Astra Caravan 1.6-8V	P	E2	2001	1598	62	1235	13											T							
VTT	Opel	Corsa 1.2	P	E2	1999	1190	48	950	41								1										
VTT	Peugeot	306 1.6I Break 5D	P	E2	2000	1587	65	1195	23											T							
VTT	Peugeot	406 2.0I 4D Saloon	P	E2	1997	1998	97,4	1430	30												H						
VTT	Saab	95 Estate 2.0	P	E2	2001	1985	110	1680	17											T							
VTT	Toyota	Avensis 1.6	P	E2	1999	1598	81	1270	66												H						
VTT	Volkswagen	Golf 1.6 4D Auto	P	E2	1999	1595	74	1295	23												H						
VTT	Volkswagen	Golf Variant 1.6 5D	P	E2	2000	1598	77	1396	30											T							
VTT	Volkswagen	Polo Variant 1.4	P	E2	1998	1390	44	1105	23								1										
VTT	Volvo	S60 Saloon 2.4	P	E2	2001	2435	103	1548	59											T							
VTT	Citroen	C5 Break 2.0I	P	E3	2002	1997	100	1442	7												H						
VTT	Honda	CIVIC Hatchback 1.6 4D	P	E3	2001	1590	81	1210	21												H						
VTT	Peugeot	307 Hatchback 1.6 I 4D	P	E3	2001	1587	80	1268	19												H						
VTT	Renault	Clio Hatchback 1.2 2D	P	E3	2002	1149	43	955	2											T	H						
VTT	Renault	Mégane Break 1.4 16V	P	E3	2002	1390	70	1210	5						1							H					
VTT	Skoda	Octavia Hatchback 2.0-	P	E4	2002	1984	85	1310	2											T							
VTT	Toyota	Corolla Saloon 1.4	P	E4	2002	1398	71	1185	3											T							

<sup>a</sup> : subsample of 6 vehicles tested with 18 driving cycles

<sup>b</sup> : subsample described Table 27

<sup>c</sup> : directive 88/436

Table 26: Characteristics of the tested vehicles within the study of the accuracy of emission measurements, with the tasks per vehicle.

Lab.	Make	Model	St.	Injection system	Number of lambda sensors	Type of lambda sensor
TUG	Alfa Romeo	147 1.6 TS	P E3	Bosch	2	2 point
TUG	BMW	316I	P E3	Bosch ME 9.2	4	broadband
TUG	Chrysler	PT Cruiser	P E3	Siemens	2	broadband
TUG	Hyundai	Tiburon Coupe 2.7	P E3	Siemens	4	2 point
TUG	Saab	95 4D 2,3T	P E3	Bosch	2	2 point
TUG	Opel	Vectra C	P E4	Bosch	2	2 point
TUG	Skoda	Fabia	P E4	Magneti Marelli 4LV	1+1	2 point and broadband
TUG	Toyota	Yaris 5-Türig 1.0 VVTI	P E4	Bosch	2	2 point

## Petrol cars

Lab.	Make	Model	St.	Fuel injection	Variable turbine geometry	EGR
TUG	Alfa Romeo	156 Estate	D E3	common rail	yes	yes
TUG	Audi	A2 1.2 TDI	D E3	unit injector	yes	yes
TUG	BMW	320D Limousine E46	D E3	common rail	yes	yes
TUG	Ford	Mondeo Turnier TDCI	D E3	common rail	yes	yes
TUG	Volkswagen	Golf 1.9 PD TDI	D E3	unit injector	yes	yes

## Diesel cars

Table 27: *Main emission control technologies of the sub-sample used for a detailed analysis of the influence of the technical characteristics.*



## Annex 8: Determination of extreme and average fuels

More details are given in Renault and Altran, 2002.

### A8.1. AutoOil / EPEFE formulae

The EPEFE formulae allow us to calculate the emissions for average light duty petrol and diesel vehicles according to fuel properties (Acea and Eurovia, 1996).

*For petrol, the fuel effects are:*

$$FE(CO) = [2,459 - 0,05513 * (E100) + 0,0005343 * (E100)^2 + 0,009226 * (ARO) - 0,0003101 * (97-S)] * [1-0,037 * (O_2 - 1,75)] * [1 - 0,008 * (E150 - 90,2)]$$

$$FE(HC) = [0,1347 + 0,0005489 * (ARO) + 25,7 * (ARO) * e^{(-0,2642 * (E100))} - 0,0000406 * (97 - S)] * [1 - 0,004 * (OLEFIN - 4,97)] * [1 + 0,001 * (O_2 - 1,75)] * [1 + 0,008 * (E150 - 90,2)]$$

$$FE(NO_x) = [0,1884 - 0,001438 * (ARO) + 0,00001959 * (ARO) * (E100) - 0,00005302 * (97 - S)] * [1 + 0,004 * (OLEFIN - 4,97)] * [1 + 0,001 * (O_2 - 1,75)] * [1 + 0,008 * (E150 - 90,2)]$$

With:

- ARO = the aromatics content (weight percentage)
- OLEFIN = the olefin content (weight percentage)
- E100 = the evaporated fraction of the fuel at 100°C (volume percentage)
- E150 = the evaporated fraction of the fuel at 150°C (volume percentage)
- S = the sulphur content (ppm)
- oxygen = the oxygen content (weight percentage)

*For diesel fuel, the fuel effects are:*

$$FE(CO) = -1.3250726 + 0.003037 * DEN - 0.0025643 * PAH - 0.015856 * CN + 0.0001706 * T95$$

$$FE(HC) = -0.293192 + 0.0006759 * DEN - 0.0007306 * PAH - 0.0032733 * CN - 0.000038 * T95$$

$$FE(NO_x) = 1.0039726 - 0.0003113 * DEN + 0.0027263 * PAH - 0.0000883 * CN - 0.0005805 * T95$$

$$FE(PM) = (-0.3879873 + 0.0004677 * DEN + 0.0004488 * PAH + 0.0004098 * CN + 0.0000788 * T95) * (1 - 0.015 * (450 - S) / 100)$$

With:

- DEN = the density (kg/m<sup>3</sup>),
- PAH = the polyaromatic hydrocarbon content (weight percentage),
- CN = the cetane number (-)
- T95 = the temperature at which 95 % of the fuel has evaporated (°C)
- S = the sulphur content (ppm)

## A8.2. Emissions of the fuels tested

Parameter	Unit	Method	Laboratory origine of the fuel									Euro 4 fuel
			Empa	IM	INRETS	KTI	LAT	Renault	TNO	TUG	VTT	
ARO	% m/m	ASTM D1319-95	35.4	22.6	18.7	24.5	28.8	30.7	25.8	42.0	37.5	34.8
OLEFIN	% m/m	ASTM D1319-95	1.7	12.4	13	11.1	9	10.03	9.4	6.6	5.3	0.6
E100	% vol	ISO 3405-98	50.5	54	48	47.5	55.5	56.5	57	49.5	47.5	40.9
E150	% vol	ISO 3405-98	86.5	86	90.5	77	87.5	92.8	87.5	82	84	85.0
S	mg/kg	ISO 24260-94 ISO 8754-95 ISO 14596-98	30	61	79	41	101	118	66	19	71	1
oxygen	% m/m	EN 1601-97 PrEN 13132-98	0.3	0.6	1.1	0.2	0.9	0.15	1.5	0.7	1.9	0.15

Table 28: Analysis of the petrol fuels tested.

Parameter	Unit	Method	Laboratory origine of the fuel									Euro 4 fuel
			Empa	IM	INRETS	KTI	LAT	Renault	TNO	TUG	VTT	
DEN (15°C)	kg/m <sup>3</sup>	ISO 3675-95 ISO 12185-96	836.2	829.6	845	840.1	839.4	836.3	827.6	833.6	831	833
PAH	% m/m	IP 391-95	0.2	0.1	0.3	0.1	0.4	0.3	0.1	0.2	0.1	5.2
CN	-	ISO 5165-98	51.6	57.4	52.9	55.1	55.3	53.9	55.6	56.3	52	52
T95	°C	ISO 3405-98	336	356.5	358.5	357.5	356.5	342.4	344.5	353	318.5	350
S	mg/kg	ISO 24260-94 ISO 8754-95 ISO 14596-98	214	310	252	255	269	280	18	185	7	4

Table 29: Analysis of the diesel fuels tested.

Emission (g/km)		Empa	IM	INRETS	KTI	LAT	Renault	TNO	TUG	VTT	Mean	St. dev.	Rel. sd (%)
petrol	CO	1.46	1.33	1.24	1.47	1.38	1.39	1.32	1.55	1.44	1.40	0.09	6.7
	HC	0.150	0.137	0.141	0.129	0.145	0.152	0.142	0.145	0.150	0.144	0.007	5.1
	NO <sub>x</sub>	0.162	0.178	0.184	0.158	0.177	0.186	0.178	0.155	0.160	0.171	0.01	7.1
diesel	CO	0.45	0.34	0.46	0.41	0.41	0.42	0.36	0.37	0.43	0.41	0.040	9.7
	HC	0.090	0.066	0.091	0.081	0.079	0.082	0.071	0.072	0.086	0.080	0.009	10.9
	NO <sub>x</sub>	0.545	0.534	0.533	0.530	0.532	0.541	0.542	0.535	0.562	0.540	0.010	1.8
	HC+NO <sub>x</sub>	0.635	0.600	0.620	0.611	0.611	0.623	0.613	0.608	0.642	0.618	0.013	2.2
	PM	0.049	0.051	0.056	0.054	0.054	0.051	0.046	0.051	0.044	0.051	0.004	7.6

Table 30: Evaluation of the emissions of the selected fuels using EPEFE formulae. Minimum, medium and maximum emissions are indicated.

## Annex 9: Tolerances in driving cycle following

Here are described the various tolerance values and fail criteria applied usually by the emission laboratories to the reference driving cycle curves (Devaux & Weilenmann, 2002).

The **tolerance criteria** express the difference between the reference curve and the actually driven curve. The values may be expressed either as an upper and lower limit or relative to the reference. The criteria are:

- The *speed tolerance*, i.e. the upper and lower limits of vehicle speed with regard to the reference speed signal. The length of time during which the limit is violated is measured.
- The *time tolerance*, i.e. the time interval during which gearshifts and other tasks must be done.

The **fail criteria** represent the maximum allowable errors during a cycle. If any of these criteria is exceeded, the test has to be rejected from evaluation:

- The *speed tolerance violation*, i.e. the time limit during which the reference speed signal may be violated.
- The *distance violation*, i.e. the maximum difference between driven and reference distance.

In certain cases, such as a low powered vehicle, a driven cycle may be accepted although it violates certain tolerances. Regulation driving cycles are less likely to have such **grace criteria**:

- *Not enough power*: Some vehicles do not have enough power to reach the reference speed signal, nor to maintain it.
- *Motor stall*: On a cold start cycle, it may occur that the motor stalls.
- *Greater deceleration*: In the NEDC, it may happen that a vehicle has a greater deceleration than prescribed by the reference curve when taking the foot completely from the gas pedal, which is mandatory, thus violating the speed tolerance.
- *Wheel slip*: Certain combinations of rollers and tyres lead to wheel slip during decelerations
- *Difficult gearbox*: Certain cars have manual gearboxes, where the gearshift goes very hard and lasts significantly more than one second, thus leading to fall out of the tolerance band.

## Annex 10: Repeatability and sample standard deviations

Diesel cars are in red. Source: (Cornelis et al., 2005)

Artemis cycle	Fuel (Petrol/diesel)	emis. standard	CO			HC			NOx			CO <sub>2</sub>		
			Average	Sample	Repeatability	Average	Sample	Repeatability	Average	Sample	Repeatability	Average	Sample	Repeatability
Absolute standard deviations [g/km]														
urban	P	E2	1.41	1.51	.23	.083	.055	.020	0.22	0.11	0.05	253	67	6
urban	P	E3	0.47	0.26	.16	.031	.011	.005	0.19	0.18	0.03	277	38	3
urban	D	E3	0.02	0.01	.00	.029	.022	.004	1.05	0.37	0.02	249	13	3
rural	P	E2	1.13	1.65	.13	.027	.024	.007	0.12	0.09	0.02	152	33	2
rural	P	E3	0.66	0.64	.07	.016	.016	.003	0.06	0.04	0.01	166	21	1
rural	D	E3	0.01	0.01	.00	.012	.007	.002	0.76	0.04	0.04	157	34	2
Relative to average standard deviations [-], plotted Figure 12														
urban	P	E2		1.07	.16		0.66	.24		.51	.23		.26	.02
urban	P	E3		0.56	.33		0.37	.15		.95	.15		.14	.01
urban	D	E3		0.80	.26		0.75	.15		.35	.02		.05	.01
rural	P	E2		1.45	.11		0.87	.26		.71	.17		.21	.01
rural	P	E3		0.97	.11		1.01	.19		.66	.12		.13	.01
rural	D	E3		0.94	.41		0.56	.17		.05	.05		.22	.01

## Annex 11: Long term emission degradation correction factors

Source: (Geivanidis & Samaras, 2004).

		CO (urban)	CO (rural)	HC (urban)	HC (rural)	NOx (urban)	NOx (rural)
ALL	a	1.216E-05	-9.223E-07	4.966E-07	1.243E-08	-7.701E-07	-4.322E-07
	b	0.525	0.448	0.050	0.016	0.130	0.058
	av. mileage [Mm]	24.966	27.712	25.705	28.042	24.555	27.898
	no of data	87	145	83	142	89	144
<1.4	a	8.675E-06	9.182E-07	3.006E-07	-1.159E-08	-2.731E-07	-2.964E-07
	b	0.936	0.584	0.078	0.027	0.071	0.060
	av. mileage [Mm]	32.407	30.123	31.972	30.643	31.313	30.643
	no of data	45	57	46	56	47	56
1.4-2.0	a	5.260E-07	-7.435E-06	-7.929E-07	-7.416E-09	5.669E-07	-1.035E-06
	b	0.426	0.499	0.044	0.011	0.162	0.067
	av. mileage [Mm]	15.351	23.789	15.921	23.961	15.351	23.789
	no of data	37	74	34	72	37	74
>2.0	a	1.005E-05	3.174E-06	-2.140E-07	-5.052E-08	3.133E-06	3.740E-07
	b	-0.043	0.064	0.038	0.006	0.028	0.025
	av. mileage [Mm]	29.139	38.630	40.499	38.630	29.139	38.630
	no of data	5	14	3	14	5	14
>1.4	a	1.100E-06	-6.088E-06	-5.697E-07	-5.726E-08	6.573E-07	-7.390E-07
	b	0.393	0.460	0.041	0.011	0.154	0.062
	av. mileage [Mm]	16.993	26.150	17.913	26.349	16.993	26.150
	no of data	42	88	37	86	42	88

Table 31: Regression line factors of the influence of the mileage on emissions of petrol vehicles.  $a$  and  $b$  are the factors of the line that was produced by the regression in the form of  $y=ax+b$ . Values marked in blue correspond to negative degradation (decrease) of emissions with mileage.

## Annex 12: Results of fuel influence

Source: (Renault & Altran, 2002).

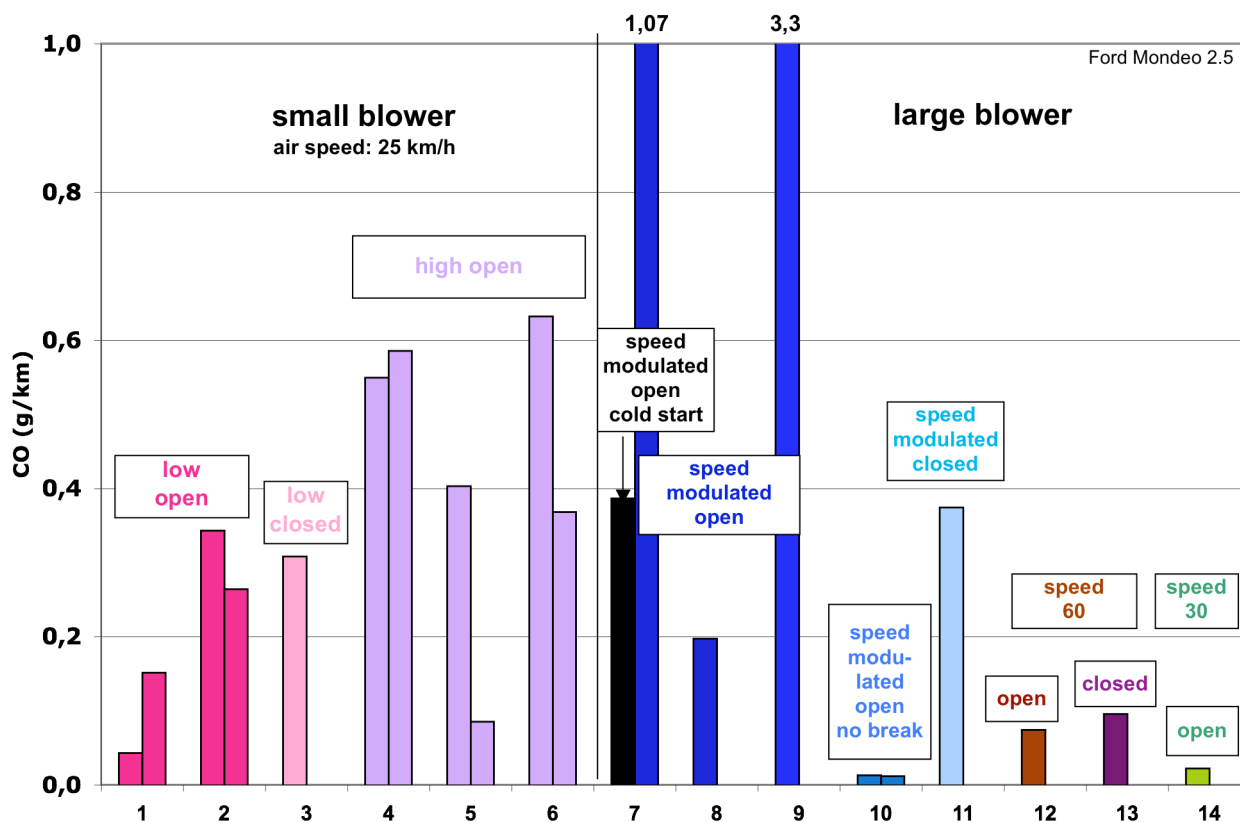
	cycle	fuel origine							
		Austria (TUG)		Greece (LAT)		France (Renault)		market Euro 05	
		mean	sd	mean	sd	mean	sd	mean	sd
CO	NEDC cold	850	64	730	119	816	51	836	21
CO	A. urban cold	2600	40	1385	125	1490	220	1169	40
CO	A. urban hot	171	55	210	87	348	108	69	14
CO	A. rural hot	312	6	285	25	427	181	297	90
CO	A. motorway hot	761	35	717	60	617	46	703	15
HC	NEDC cold	112	3	103	3	91	1	101	6
HC	A. urban cold	276	25	130	4	119	18	122	4
HC	A. urban hot	27	3	22	2	24	2	18	1
HC	A. rural hot	14	5	10	1	11	0	8	1
HC	A. motorway hot	18	3	19	2	17	0	9	1
NOx	NEDC cold	121	2	106	10	140	10	96	4
NOx	A. urban cold	416	40	303	28	362	3	254	5
NOx	A. urban hot	294	5	265	33	358	11	259	4
NOx	A. rural hot	98	15	109	4	140	1	93	2
NOx	A. motorway hot	47	6	51	5	66	0	39	3
CO <sub>2</sub>	NEDC cold	169811	260	168927	99	168083	503	169175	254
CO <sub>2</sub>	A. urban cold	303332	12759	292526	2466	284451	1312	290204	2281
CO <sub>2</sub>	A. urban hot	273563	906	272817	1118	260351	1872	269857	577
CO <sub>2</sub>	A. rural hot	150114	1186	147416	363	145766	325	148398	60
CO <sub>2</sub>	A. motorway hot	171629	1185	170437	472	167895	351	170670	394

Table 32: Emission factors for different fuels for the tested petrol Euro 3 vehicle, in mg/km.

	cycle	fuel origine							
		Finland (VTT)		Italy (IM)		France (Inrets)		market Euro 05	
		mean	sd	mean	sd	mean	sd	mean	sd
CO	NEDC cold	159	2	202	4	174	12	183	2
CO	A. urban cold	56	14	100	8	66	20	97	1
CO	A. urban hot	24	1	17	1	16	0	31	11
CO	A. rural hot	10	1	7	1	6	1	10	1
CO	A. motorway hot	9	1	6	1	7	1	9	0
HC	NEDC cold	16	0	21	1	16	2	17	0
HC	A. urban cold	21	2	28	1	23	1	26	1
HC	A. urban hot	10	1	11	0	6,5	2,5	14	1
HC	A. rural hot	7	1	7	0	7	1	14	1
HC	A. motorway hot	1	0	1	0	2	1	4	1
NOx	NEDC cold	400	4	382	7	366	7	412	2
NOx	A. urban cold	819	5	747	15	760	24	854	32
NOx	A. urban hot	792	15	789	19	791	1	805	36
NOx	A. rural hot	455	1	455	1	447	5	465	2
NOx	A. motorway hot	564	1	558	8	560	6	593	7
PM	NEDC cold	28	1	34	1	36	2	25	1
PM	A. urban cold	58	2	24	2	31	8	39	14
PM	A. urban hot	48	0	21	0	23	1	35	13
PM	A. rural hot	35	2	30	4	28	1	28	5
PM	A. motorway hot	91	30	118	7	137	8	56	8
CO2	NEDC cold	148633	582	150729	201	149472	225	150459	17
CO2	A. urban cold	254960	4060	248531	4807	261727	55	266885	1284
CO2	A. urban hot	226866	35	234709	5481	237422	525	229843	1231
CO2	A. rural hot	136504	1104	136885	352	141636	702	136967	1272
CO2	A. motorway hot	125355	1155	124811	474	126945	305	123447	683

Table 33: Emission factors of different fuels for the tested diesel Euro 3 vehicle, in mg/km.

## Annex 13: Example of initial results on the vehicle cooling influence



The figure shows initial test results for one petrol car (Ford Mondeo Euro II) on the Artemis urban driving cycle. It illustrates the variability among repeated tests. All bars that are in same colour are supposed to be replicates of the same basic set of parameters, and preferably should yield to similar results (Laurikko, 2005a).



## **Annex 14: Vehicle parameters usually recorded by the laboratories**

The parameters of the vehicle recorded during the measurements are the following ones. It is not an exhaustive list and all the parameters are not systematically recorded (André, 2002):

- Vehicles data:
  - Vehicles ID number
  - Make
  - Model
  - Registration number
  - Emission standard
  - Fuel characteristics
  - Mass
  - Mileage
  - Vehicle provenance
  - Service intervals
  - Construction year
  - Date of first registration
  - Drag coefficient
  - Cross-sectional area of vehicle
  - Tyres information
- Official emission level data
  - Standard emissions
  - Vehicle model standard emission and fuel consumption
- Engine data
  - Engine capacity
  - Cylinders number
  - Alignment of cylinders
  - Maximum power
  - Maximum torque
  - Engine power at maximum power
  - Maximum engine power
  - Compression ratio -  $\epsilon$
- Gearbox data
  - Gearbox type
  - Number of gears
  - Speeds at 1000 rpm
- Others
  - Number of catalysts
  - Catalyst(s) manufacturer
  - Catalyst type
  - Catalyst capacity
  - Number of  $\lambda$  sensors

## Annex 15: Emission models for different vehicle sample sizes

For each pollutant and each category of vehicle, model A was plotted for the whole vehicle sample, as well as all the extreme models obtained for the minimum sample size shown in Table 17. The measurements represented correspond to the whole Sample A. The number of vehicles included in the samples used to build-up the models is given in brackets.

The condition for accepting the minimum sample size is that the squared distance between the two models (with the whole vehicle sample and the minimum sample size) is lower than the squared distance between the measurements and the whole vehicle sample model by at least 25%. This criterion is more stringent than the Fisher test, but it is a requisite to guarantee that the emissions predicted by a model based on a limited sample size, for a prescribed speed, are in good agreement with the model based on the whole sample.

The minimum model (resp. the maximum) is defined as the model based on the minimum sample size with the lowest predicted emission value (resp. the highest) at a speed of 25 km/h. Figure 29 and Figure 30 give the results for NO<sub>x</sub> and CO<sub>2</sub> of petrol catalyst vehicles (Lacour & Joumard, 2001).

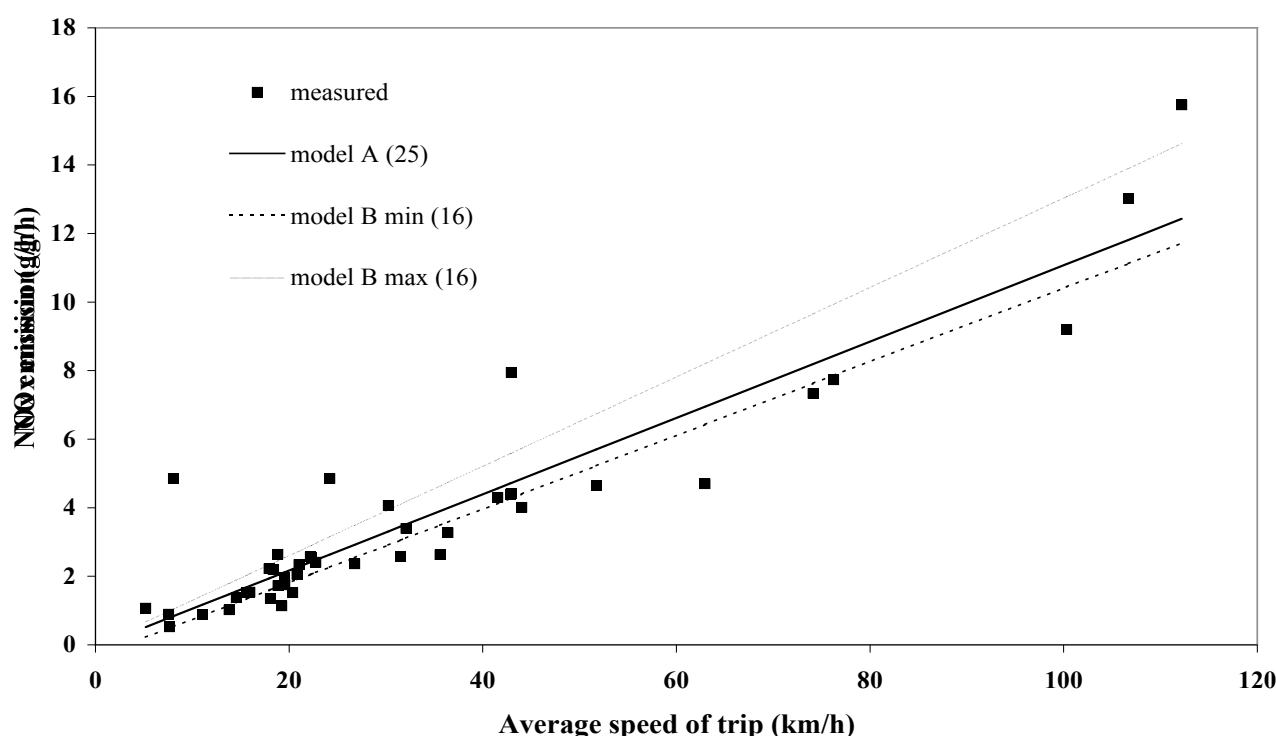


Figure 29: NO<sub>x</sub> emissions model for catalyst equipped petrol vehicles as a function of the average cycle speed, for the whole vehicle sample (A) and the minimum sample size B (minimum and maximum models).

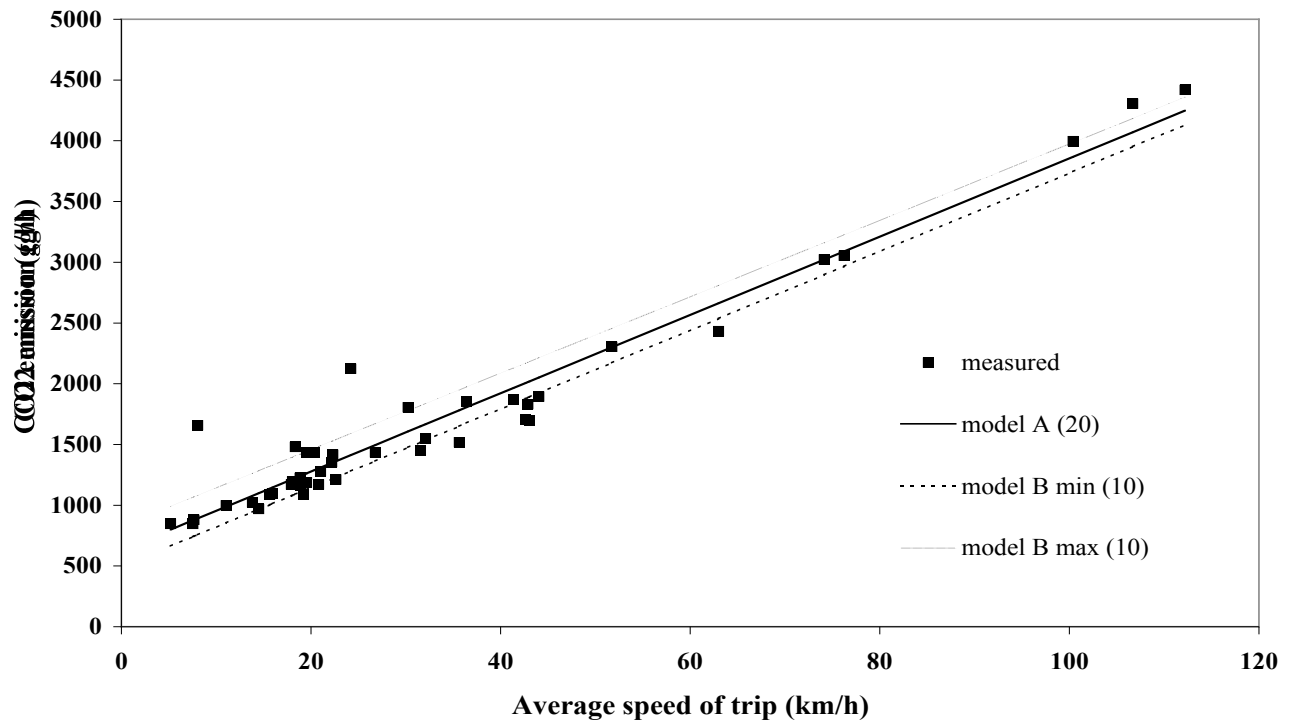


Figure 30: CO<sub>2</sub> emission model for catalyst equipped petrol vehicles as a function of the average cycle speed, for the whole vehicle sample (A) and the minimum sample size B (minimum and maximum models).

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