

In-Use Emissions Testing with Portable Emissions Measurement Systems (PEMS) in the Current and Future European Vehicle Emissions Legislation: Overview, Underlying Principles and Expected Benefits

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ABSTRACT

In-use testing with Portable Emissions Measurement Systems (PEMS) has received attention by policy makers and industry as an effective and cost-efficient means to verify emissions of a wide range of vehicles. We provide an overview of the state-of-the-art PEMS in-use emissions testing in the current and future European emissions legislation for light-duty and heavy-duty vehicles as well as non-road mobile machinery.

For obtaining type approval in European Union (EU), light-duty vehicles have to comply with Euro 6 emission standards from January 2014 onward. In parallel, a new test procedure will complement standard emissions testing in the laboratory to control gaseous and particulate emissions over a wide range of real-world driving conditions. Two candidate procedures are developed at present, i.e., random cycle testing and on-road emissions testing with PEMS. Currently, key challenges are the definition of test conditions and design of a suitable method for data evaluation.

For heavy-duty vehicles, in-use testing with PEMS is already enforced in the European Union since 2009. The revision of European requirements will be completed in 2014 and shifts the focus from engine conformity checking towards the assessment of emissions under real-world driving conditions. The feasibility of PEMS for measuring particle mass is currently investigated by an industry-run pilot program. Moreover, the application of PEMS to Stage IV and V engines of non-road mobile machinery is currently under discussion.

We conclude that in-use testing with PEMS will play an important role in the future European vehicle emissions legislation. The application of PEMS can effectively control vehicle emissions, may accelerate the adoption of novel emission abatement technologies and thereby contribute to air quality improvements throughout Europe.

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2. INTRODUCTION

Transport is the backbone of the European Union's economy, accounting in 2010 for 5% of each, the gross domestic product and the total employment [1]. In 2011, European private households spent roughly 13% of their total consumption on transport-related items (replacing old vehicles, expenditures for transport services and equipment), while 83% of total passenger transport activities were covered by road transport including passenger cars, buses, trolley-buses and coaches. Road and intra-European Union maritime transport represented the most used means for goods transport covering shares up to 45% and 37% of the total freight transport

respectively [1]. However, oil dependency and environmental pollution represent two of the major challenges that European transport sector faces today.

European transport relies strongly on fossil fuels causing thereby substantial greenhouse gases (GHG) emissions. In 2011, transport consumed 364 Mtoe (21.5% of the gross inland consumption) of which only 4.6% was attributed to biofuels [1]. Transport thereby accounted for 24% of the energy-related GHG emissions of the European Union. In more detail, among all forms of transport, road transport of passengers and goods accounts for the largest share, i.e., 72% of both transport-related energy use and GHG emissions [1] and represents the most important anthropogenic source of nitrogen oxides (NO_x).

Road transport contributes 16% to particulate matter (PM_{2.5}) emissions in EU and 26% to the economy-wide carbon monoxide (CO) and is responsible for the 40% of EU's total NO_x emissions [2,3]. Therefore road transport is partly responsible for the deterioration of European air quality [4] and the increased exposure of European citizens at carcinogenic agents [5].

In this context, the European Union's policy on transport aims at:

- decreasing the GHG emissions and thereby the absolute consumption of fossil fuels by 20% below 2008 levels by 2030 and by 60% below 1990 levels by 2050 [6] via e.g., increasing fuel efficiency, shifting to alternative fuels, supporting the electrification of transport, and adopting alternative and intelligent means of transportation;
- decreasing the emissions of gaseous and particulate pollutants, e.g., by adopting more stringent emission limits, applying more comprehensive emission test procedures, and supporting the introduction of innovative after-treatment technologies.

To meet these objectives, the European Union regulates energy consumption and emissions of road transport with a comprehensive legislative framework that has been developed over the past 40 years. Emissions legislation for light-duty vehicles (LDV), heavy-duty vehicles (HDV), and non-road mobile machinery (NRMM) consists of elements that establish performance and design requirements as well as responsibilities for manufacturers and users throughout the entire life cycle of engines and vehicles. As far as emissions are concerned, the three main legislative elements are (Table 1):

- the type approval;
- the conformity of production;
- the in-service conformity (ISC) and durability requirements.

Type approval test procedure, conducted on a single engine or vehicle (independently of its family and type), ensures that emissions of regulated pollutants meet the applicable limits when measured in standardized test procedures. Conformity of production ensures that all products of a type are in conformity with type-approval specifications. Finally, in-service conformity test guarantees that vehicles are compliant with legislation during their use phase. It is the manufacturers' duty to obtain type approval under the scrutiny of type-approval authority, and to ensure conformity of production for their vehicles and engines. By contrast, in-service conformity and durability requirements are under the responsibility of both the manufacturers and the vehicle users.

Type-approval testing has to ensure reproducibility of emission measurements and should capture the emissions behavior of engines and vehicles as under normal operating conditions. Although standard type-approval testing proved to be effective in controlling emissions of gasoline vehicles, specifically the on-road NO_x emissions of light-duty diesel vehicles appear to

deviate substantially from the established type-approval values [7, 8, 9, 10, 11, 12]. Figure 1 depicts average NO_x on-road and laboratory emissions for different Euro standards compliant vehicles. In summary, PEMS results indicate that the increasing stringency of Euro 3 to Euro 5 emission limits did not lead to a substantial decline in the off-cycle on-road NO_x emissions of light duty diesel vehicles. On-road NO_x emissions of current Euro 5 light-duty diesel vehicles might exceed emission limits by up to a factor of four, depending on driving conditions. It should be noticed that Euro 6 vehicles present a significant reduction of NO_x emissions respect to older vehicles, mainly thank to technological improvements in engine management and the introduction of novel after-treatment systems. Nevertheless, emissions remain beyond regulation objectives expressed by limit values (see white columns). One reason for this situation is the current practice of conducting compliance testing in laboratory under standardized conditions and excluding, until recently, actual on-road driving of light-duty and heavy-duty vehicles or the normal use of non-road mobile machinery. Laboratory tests allow obtaining comparable and reproducible emission measurements based on the application of relatively large stationary test equipment but cover a limited range of operating and environmental conditions.

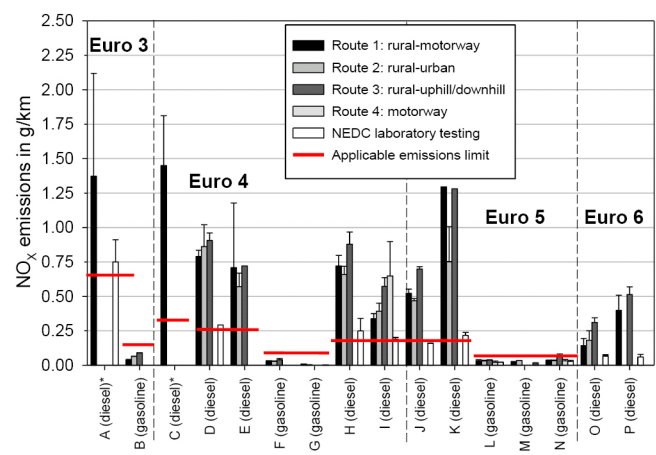


Figure 1. Average NO_x emissions on the PEMS test routes and during new European driving cycle (NEDC) testing in the laboratory; uncertainty intervals indicate the maximum average emissions for each test and vehicle

European Commission acknowledges the limitations by shifting the main focus of the new emissions legislation toward the testing of emissions during normal vehicle use. PEMS expands the ability for controlling emissions under a wide range of normal operating conditions of increasingly heterogeneous and technologically diverse transport equipment. Although requiring further technological developments, PEMS offer a breakthrough in two areas of emissions control because they:

- enable to accurately quantify emissions during the actual use of a large range of vehicles and technologies, both at type approval and for in-service conformity testing;
- allow deriving more reliable emission factors for modeling air quality and pollution, as well as data on transport-related energy use and GHG emissions.

In the following sections, we present PEMS testing underlying principles, background information and an overview of approaches in the current legislation of vehicle emissions as well as key findings of the research conducted worldwide with PEMS for each vehicle category separately. In the last part, we provide an outlook to the future developments and we draw principle conclusions.

3. PEMS TESTING - UNDERLYING PRINCIPLES

The usage of PEMS as a possible mean for regulating emissions implies the development of specific in-use emissions test procedures which should define the protocols for testing vehicles under real world random conditions.

In addition, the emissions requirements (not-to-exceed (NTE) limits) are to be met within the “boundary” conditions i.e. conditions under which the emissions cannot exceed a given threshold.

Finally the procedures must include a proper evaluation method to analyze the recorded emissions and vehicle an/or engine activity, ensuring at the same time that the entire tests or parts of the test fall within the said boundary conditions.

PEMS equipment should satisfy criteria regarding its measurement performance and size, the installation on vehicle and guarantee safety for users during operations. In more detail, PEMS measurement performance, in terms of accuracy and linearity, has to be in the order of the one of existing advanced laboratory equipment to be used for confirmatory testing [13, 14, 15], as has been attested by plethora of studies [16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27]. Instrumentation should be reasonably small and lightweight in order to facilitate installation and anchoring on vehicle, minimizing at the same time modifications to its mass and aerodynamic performance [17, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38]. Equipment should work with a low power consumption so that long tests can be run either with a small generator or a set of batteries, be ruggedized for frequent installations and removal, measure and record concentrations of NO_x , CO, CO_2 , THC gases and particulate matter (PM) in the engine exhaust, record operation parameters such as the engine data from the engine control unit (ECU), machine/vehicle position from the global positioning system (GPS) and ambient conditions. A schematic overview of PEMS and auxiliary components is shown in Figure 2, while Figure 3 illustrates typical installations of PEMS on LDV, HDD and NRMM.

Testing conditions must fulfill requirements in terms of trip duration, ambient conditions, altitude, vehicle payload, vehicle conditioning and composition of test routes. These requirements are given a priori, by means of an already prescribed list of testing conditions, e.g. urban, rural and motorway portions of route composition and checked a posteriori through a verification of the realized test using a

series of indicators. In any case a minimum coverage of the “prescribed” conditions should be achieved; otherwise tests should be repeated or complemented.

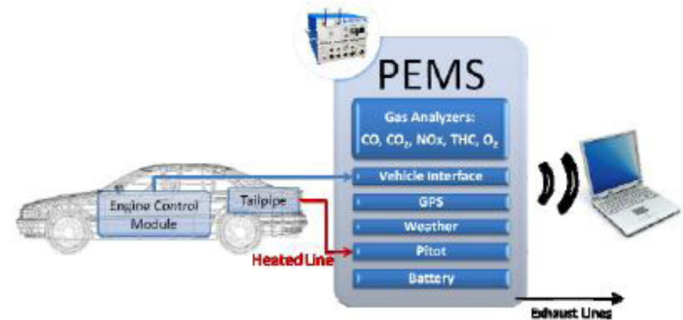


Figure 2. Schematic overview of PEMS and auxiliary components (courtesy Sensors Inc.) [26].



Figure 3. Demonstrating the installation of PEMS in a light-duty vehicle (top) [39], heavy-duty vehicle (middle) [40] and non-road mobile machinery (bottom) [39].



Figure 3. (cont.) Demonstrating the installation of PEMS in a light-duty vehicle (top) [39], heavy-duty vehicle (middle) [40] and non-road mobile machinery (bottom) [39].

Finally, depending on the regulatory purpose, the evaluation method should be able to assess the emissions performance. In the case of real driving emissions (RDE), the method and the associated testing requirements (route composition, coverage of engine operation) should also:

- exhibit a sufficient sensitivity to identify high emitters;
- have the ability to evaluate a posteriori the validity of the realized testing conditions;
- be robust against uncertainties of data acquisition and data evaluation;
- be applicable to a large range of vehicle and engine technologies (compressed or spark ignition engines, after-treatments, conventional or hybrid powertrains).

4. LIGHT-DUTY VEHICLES

4.1. Legislative Background

For type approval in European Union, light-duty vehicles, i.e. vehicles included in M1, M2, N1, and N2 categories with a mass lower than 2,610 kg and in special cases lower than 2840 kg, currently have to comply with Euro 5 emissions standards [41]. Compliance with the emissions standards is verified by the so-called Type I test that is used to measure tail-pipe emissions after cold start by following a standardized test procedure in the laboratory [42, 43, 44]. Following Regulation 715/2007 [41], light-duty vehicles have to comply with Euro 5 emission limits for NO_x , CO, THC, non-methane HC (NMHC), as well as for PM particles mass and number (Table 2). Carbon dioxide emissions are also measured and reported even if they are currently unrestricted at the level of individual vehicles [15].

Currently, the New European Driving Cycle (NEDC) is used as test cycle. The NEDC is a modal driving cycle that consists of four repeated urban driving cycles (ECE-15 cycles, each lasting 195 s) and one extra-urban driving cycle (EUDC) of 400

seconds duration (Figure 4) [50]. The entire NEDC covers a distance of 11.007 km in 1180 s at an average speed of 34 km/h. Emissions sampling begins with the start of the engine; the final result is expressed as average over the entire cycle in g/km.

European emissions legislation includes additional provisions for a low-temperature emission test at -7°C of light-duty gasoline vehicles, which have to comply with limits of 15 g/km for CO and 1.8 g/km for THC, measured over the urban portion of NEDC.

Regulation 715/2007 defines in addition to the Euro 5 emissions standards also more stringent Euro 6 emissions standards to be enforced gradually from 2014 onward. Moreover, it contains provisions to ensure that the emissions standards are effective under normal vehicle operation and use [41]. In this context, NEDC has been criticized for its smooth acceleration profile that requires only a narrow range of possible engine operation points [45, 46]. Under the lead of UNECE, the currently applied NEDC will be replaced by the more transient world-wide harmonized light-duty test cycle (WLTC). Emissions testing in the laboratory based on a single driving cycle may, however, still fail to cover the wide range of ambient and driving conditions as they occur during normal vehicle use. Therefore, the European Commission by means of the real-driving emissions LDV working group (RDE-LDV working group) currently develops complementary test procedures which could verify emissions during a wide range of normal operating conditions. Initially, four procedures were investigated:

- complementary fixed driving cycles for emissions testing in the laboratory;
- emission modeling;
- random driving cycles for emission testing in laboratory;
- on-road emissions testing with PEMS.

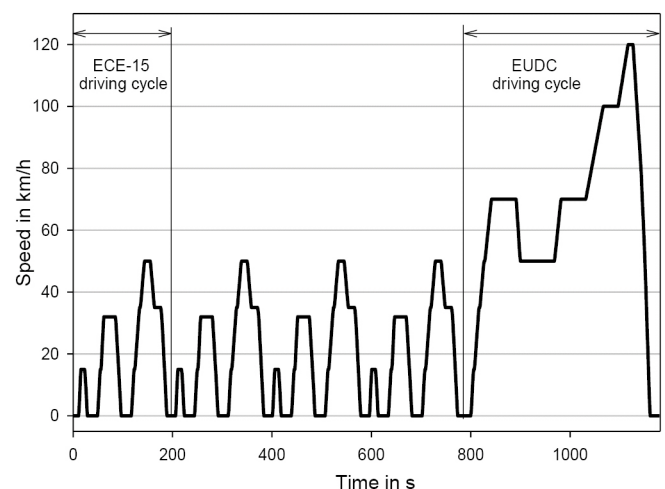


Figure 4. Speed profile of the New European Driving Cycle [55]

Up front, fixed driving cycles have been excluded because of concerns about the lack of randomness in test conditions and potentially insufficient coverage of driving conditions.

Predictability of driving cycles enables cycle-based emissions control technologies that may not function properly under normal vehicle use. Emissions' modeling has been excluded due to, the potentially, challenging model validation which may itself require substantial emissions testing in the laboratory and on the road. The RDE-LDV working group therefore focused between March 2011 and July 2012 on the technical assessment of random driving cycles and on-road emissions testing with PEMS. The aim was to identify whether the two procedures have fundamental weaknesses that would exclude them from further consideration.

4.2. Random Cycle Testing

When assessing the functionality and performance of the emissions control, it appears to be necessary to test vehicles under real conditions including a certain degree of randomness, while remaining within pre-defined boundary conditions. As an alternative to PEMS on-road testing, vehicles may be tested in the laboratory on the chassis dynamometer under conditions where the test temperature and the driving dynamics are randomized. A random cycle generator (RCG) based upon combining randomly selected "short trips" (i.e. driving events between two idling periods) contained in the data base of short trips used to develop the worldwide light-duty test procedure (WLTP) has been developed by the European automobile manufacturers' association (ACEA).

The RDE-LDV working group considers worthwhile that the RCG should ensure randomness in the choice of "short-trips" from the database while reproducing normal driving dynamics (e.g., with respect to acceleration, deceleration, idling, velocity) within pre-defined limits. The RCG presented by ACEA has been compared with PEMS on-road testing [47]. The assessment concluded that both candidate procedures are technically feasible, albeit displaying distinct strengths and weaknesses. The following section describes in more detail the main conclusion of the assessment.

4.3. Random Cycle versus PEMS On-Road Testing

Random-cycle testing in the laboratory presents advantages over on-road testing in that it allows:

- using established analytical equipment;
- repeating and reproducing individual emission tests under defined conditions;
- controlling the severity of the test through the driving dynamics and potentially adapting it to the vehicle power-to-mass ratio.

However, PEMS on-road testing can cover a wider range of driving conditions and be more effective in limiting the application of defeat strategies and the detection of emissions tests by vehicles.

The ability of the procedures to cover a wide range of driving conditions, thereby preventing the overly narrow optimization of emissions control technologies/strategies for a few operating conditions has been investigated in detail. A wide coverage of driving and ambient conditions is critical to address the limited coverage of real-world acceleration-speed patterns by the NEDC [46]. Both random cycle and PEMS on-road testing can reproduce transient real-world driving conditions (Figure 5); however, on-road emissions testing can cover longer distances and a wider range of operating conditions and may thus capture better potentially polluting urban and/or high-speed driving conditions. The severity of the test procedures with respect to driving conditions can be depicted in acceleration-speed plots (Figure 5). While NEDC covers only a limited range of the acceleration-speed spectrum, both random-cycle and on-road testing achieve a higher coverage of driving conditions. However, Figure 5 also suggests that random-cycle testing may not cover certain high acceleration events at low to medium speeds and low accelerations at high speeds, suggesting that on-road testing with PEMS may cover driving patterns more completely, and may hence be more robust in capturing emissions of light-duty vehicles, than random driving cycles. However, driver behavior remains a concern for PEMS testing: while driving patterns are *a priori* described for random cycles, this is not the case for PEMS on-road testing. Here, the freedom of the driver to limit on-road driving to a few acceleration-speed events of the engine map could be addressed by defining appropriate system boundaries or *a posteriori* by implementing suitable indicators to evaluate/weigh the severity of each on-road test. Covering changes in road gradients is feasible both with modern chassis dynamometers and on the road. However, the short trips available in the WLTP database contain no information on road gradients; the reproduction of variable road gradients by random-cycle testing is thus not feasible as long as short trips from the WLTP database are used for cycle generation. With regard to on-road testing, the geographical location of test facilities limits the degree to which uphill and downhill driving can be covered in practice.

In addition to covering a wide range of driving conditions, RDE-LDV procedure should also cover a wider range of ambient conditions than the current Type I type-approval testing, which is conducted at 20-30 °C. A wider coverage can indeed be achieved by both candidate procedures, although practical limitations exist. In the case of random cycles, testing and conditioning capacities may be limited. Data from original equipment manufacturers (OEMs) indicate that it may take up to 5 h to cool a test cell from 25°C to 10°C and then heat it up again to 25°C. The time required to perform one standard emissions test may increase for a test temperature of 10°C from 80 min to 320 min (other things being equal). Adjusting dynamometer settings, designing and implementing driving cycles, and running potential preconditioning cycles before each random cycle test will add considerably to the time, and hence the cost of random-cycle testing. As a result, covering a wide temperature range in the laboratory could be extremely costly and will likely require additional test facilities. Covering a

wide temperature range during on-road testing, on the other hand, is in practice limited by ambient conditions around test sites and the seasonal temperature variability.

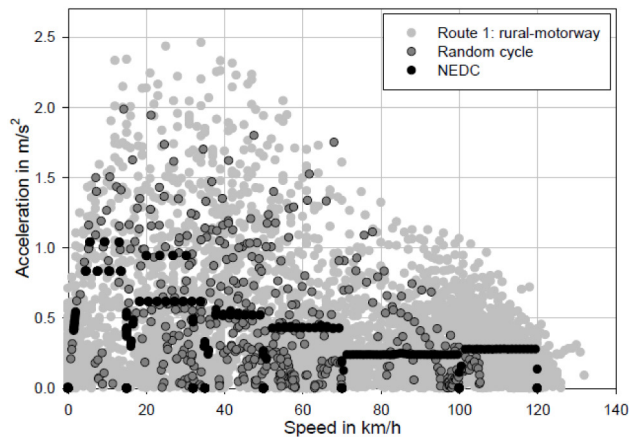


Figure 5. Acceleration-speed points of NEDC, one random cycle, and on-road driving with PEMS [47]

4.4. PEMS On-Road Testing

4.4.1. Review

PEMS for LDV applications have been introduced in the United States of America (USA) in 2001 at first, as part of US environmental protection agency's (EPA) pilot study of real-world emissions and fuel economy and subsequently EPA's in-use vehicle emissions compliance program. Tests performed on two 2001 model year LDVs showed that the laboratory and SEMTECH PEMS data were in good agreement for CO₂, CO, and NO_x, though the THC measurements were low by comparison. The study concluded that even if PEMS was able to capture emissions, improvements to its flow meters were needed [16]. In 2005, Ford Company performed an independent evaluation of a commercial PEMS as compared to chassis dynamometer testing. For investigation both compressed and spark ignition LDVs were tested [17,18]. The objective of the study was to evaluate the suitability of PEMS to measure transient emissions from LDVs. The study concluded that PEMS was both accurate and precise. Since 2007, European Commission's joint research center (JRC) in Ispra has been testing numerous light-duty vehicles. Results suggest that specifically the NO_x emissions of diesel vehicles exceed during on-road testing applicable emission limits. (Figure 1). Type-approval testing appears to fail to be representative of real-world driving conditions [21,7]. Furthermore, the influence of driving conditions and style on real-world emissions was highlighted by a study conducted in United Kingdom. The analysis showed that higher acceleration rates occurring during on-road testing and more aggressive driving behavior, could lead to higher fuel consumption and NO_x emissions under real-world driving conditions as compared to standard laboratory testing [8,48]. Recent research has also focused on evaluating the effects of biofuels on real-world emissions of both spark-ignition and

compressed-ignition LDVs [49, 50, 51]. Biofuels are found to increase NO_x emissions for both engines categories and to delay the light-off of after-treatment systems of diesel vehicles.

4.4.2. Data Evaluation Methods

PEMS on-road testing may cover a wide range of driving and ambient conditions and enables longer test durations than standard emissions testing in the laboratory. During tests, data provided by emissions analyzers, weather station, GPS, ECU and exhaust flow meter are recorded. Hence, suitable evaluation methods need to be developed to: (i) check, select, and aggregate data for further processing and (ii) to derive suitable emission averages for comparison with applicable emissions limits.

For a successful implementation within a type approval context an evaluation method should operate with reliable and traceable test data, present a working principle which is in line with the current emissions regulations and therefore show a minimum consistency with the main type approval emissions procedure. In addition the method should be able to identify high emitters and provide indicators to validate or invalidate parts of or an entire, realized test.

To date three evaluation methods are currently assessed within the RDE-LDV working group. The proposed evaluation methods are based on the following working principles:

- categorizing emissions data according to vehicle speed bins;
- weighing emissions data based on a pre-established vehicle power map;
- averaging emissions data using a the moving averaging windows principle.

In the following, we explain each method in more detail. The vehicle speed binning method categorizes emissions data that are averaged over 5 seconds in speed bins of 5 km/h. Sensitivity of emissions to driving conditions is addressed by defining wider bins representative of urban (<60 km/h), rural (>60,≤90 km/h) and motorway (≥90 km/h) driving. In a second step, the average pollutant and CO₂ emissions of each speed bin are calculated and the fractions of average pollutant emissions per average CO₂ emissions in g/kgCO₂ are calculated.

In the second method, first moving averages of pollutant and CO₂ emissions as well as vehicle speed and power at the wheels data are calculated over intervals of 3 seconds. Then, in order to eliminate misalignments between power and emission values in the second-by-second registered data, these are categorized in power bins. The averages of pollutant emissions for each power interval are weighed by multiplication with a weighting factor. This factor is obtained from the relative frequency distribution of power in a power distribution map obtained from the WLTP database. Finally the weighed distance-specific and CO₂ specific emissions overall power