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Review

Road vehicle emission factors development: A review

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HIGHLIGHTS

► The accuracy of road emission models is directly linked to the quality of their emission factors.
► Road vehicles have a large natural variability in their emission profiles.
► Emission factors may have different resolution according to their intended use.
► Emission modellers should combine laboratory data with real-world measurements.

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ABSTRACT

Pollutant emissions need to be accurately estimated to ensure that air quality plans are designed and implemented appropriately. *Emission factors* (EFs) are empirical functional relations between pollutant emissions and the activity that causes them. In this review article, the techniques used to measure road vehicle emissions are examined in relation to the development of EFs found in *emission models* used to produce emission inventories. The emission measurement techniques covered include those most widely used for road vehicle emissions data collection, namely chassis and engine dynamometer measurements, remote sensing, road tunnel studies and portable emission measurements systems (PEMS). The main advantages and disadvantages of each method with regards to emissions modelling are presented. A review of the ways in which EFs may be derived from test data is also performed, with a clear distinction between data obtained under controlled conditions (engine and chassis dynamometer measurements using standard driving cycles) and measurements under real-world operation.

1. Introduction

Air pollution is a major risk to health and to the environment. Outdoor air pollution is estimated to cause 1.3 million annual deaths worldwide (WHO, 2011). Road transport often appears as the single most important source of urban pollutant emissions in source apportionment studies (Maykut et al., 2003; Querol et al., 2007). In the coming decades, road transport is likely to remain a large contributor to air pollution, especially in urban areas. For this reason, major efforts are being made for the reduction of polluting emissions from road transport. These include new powertrains and vehicle technology improvements, fuel refinements, optimization of urban traffic management and the implementation of tighter emission standards (EC, 2011a).

Road vehicle emissions depend on many parameters. *Emission models* are used to perform the calculations of road transport emissions. Smit et al. (2010) proposed a classification of these models in five major categories according to the input data required. These range from models which only require mean travelling speed to estimate emissions (*e.g.* COPERT, EMFAC) and models that need traffic situations (*i.e.*, qualitative assessments of driving conditions) to express emissions (*e.g.* HBEFA), to models which require second-by-second engine or vehicle state data (*e.g.* PHEM, MOVES) to derive emission information for the complete driving profile. Regardless of the specific implementation, each model aims to provide appropriate EFs.

Road vehicle EFs are functional relations that predict the quantity of a pollutant that is emitted per distance driven, energy consumed, or amount of fuel used. EFs are typically derived for

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vehicle categories (but they also exist for single vehicles, or even an entire fleet), and they depend on many parameters such as vehicle characteristics and emission control technology, fuel specifications, and ambient and operating conditions (cold-start, cruising, acceleration, etc.). The quality of the application of any road vehicle emission model largely depends on the *representativeness* of the EFs it contains. This refers to the accuracy with which the EF can describe the actual emission level of the particular vehicle type and driving condition it is applied to. For example, an EF based on the mean speed of vehicles may be representative for the estimation of emissions at a national level, but its representativeness will decrease when trying to assess the impacts of local traffic measures (*e.g.* a local traffic intervention with large impacts on the stop-and-go pattern of vehicles but not affecting their mean travelling speed).

EFs are usually developed on the basis of experimental data collected in vehicle emission measurement campaigns. The measurement technique selected, along with other specifics of each campaign – including the criteria for vehicle selection and the driving conditions imposed – all have an impact on the quality of the EFs later derived. The emission profiles of vehicles and their dependency on operating conditions can be measured under *controlled conditions* in laboratories (engine and chassis dynamometer studies) or *real-world conditions* (tunnel, remote sensing, on-road and on-board measurements).

This paper reviews the experimental approaches that have been used in practice for the measurement of vehicle emissions and the development of road vehicle EFs. An earlier, similar review was performed by Faiz et al. (1996). Strong points and limitations are presented for each method, together with literature examples of successful implementations. The aim of this paper is to provide guidance for the selection of methods that can be used for EF development or validation. The issue of validation is particularly important, as the widespread application of portable emission measurement systems (PEMS) has made the cross-check of model EFs with real-world data a very common exercise.

2. Emission measurements under controlled conditions

Road vehicle emissions can be measured *under controlled conditions* in laboratories. These measurements are performed either on *chassis or engine dynamometer* facilities. In these cases, test operators have control over the test cycle being followed, the environmental conditions and other parameters, thus contributing to the repeatability of results.

2.1. Chassis and engine dynamometer testing

A *chassis dynamometer* simulates the resistive power imposed on the wheels of a vehicle. It consists of a dynamometer that is coupled via gearboxes to drive lines that are directly connected to the wheel hubs of the vehicle, or to a set of rollers upon which the vehicle is placed, and which can be adjusted to simulate driving resistance.

During chassis dynamometer testing, the vehicle is tied down so that it remains stationary as a driver operates it according to a predetermined time–speed profile and gear change pattern shown on a monitor. A driver operates the vehicle to match the speed required at the different stages of the driving cycle (Nine et al., 1999). Chassis dynamometer test cycles are typically transient cycles (Yanowitz et al., 2000) and therefore the driver must anticipate and comply with changes in the required speed within a specified tolerance (Wang et al., 1997). Experienced drivers are able to closely match the established speed profile.

The load applied to the vehicle via the rollers can be controlled by the laboratory operators to simulate aerodynamic resistance for the vehicle under test, while the size of the rollers and the use of flywheels accounts for vehicle inertia. The exhaust flow rate is continuously monitored, and vehicle exhaust gas is collected in sample bags for later analysis, or processed by online chemical analysers attached to the sampling line, which may include dilution with ambient air (Fig. 1).

Because dynamometer facilities are designed to meet regulatory standards, their results are viewed as highly accurate as long as proper calibration and maintenance programs are established (Traver et al., 2002). Also, they may be enclosed in climatically controlled test cells to simulate driving under a wide range of temperatures, including sub-zero tests. A disadvantage of a chassis dynamometer testing is that it may not necessarily represent real-world emissions of individual vehicles. This is due to the limited range of test conditions (*e.g.* the set ambient temperatures and the preconditioning routines, the absence of road gradients) and to the fact that a dynamometer is implemented instead of actual driving. In particular, the driving resistance values that simulate road load are obtained from vehicle coast-down tests under artificially favourable conditions, thus frequently yielding lower consumption and emissions as compared to real-world results (Mellios et al., 2011). Moreover, chassis dynamometer test results may not be representative of the emissions of entire vehicle fleets, since typically only a few vehicles from each technology class are tested for modelling purposes.

An *engine dynamometer* is a device that simulates the resistive power directly in the engine power output. In an engine dynamometer test cell, the dynamometer shaft is directly connected to the engine shaft. Fully transient dynamometers may place or absorb any specified load (within limits) to the engine, even during load and speed change conditions. Engine test cells may also be climatically controlled. The use of an engine dynamometer for emission modelling requires removing the engine and the exhaust gas after treatment system from the vehicle (Oh and Cavendish, 1985; Artelt et al., 1999). The engine dynamometer measures power at the flywheel of the engine, where no transmission or driveline losses influence the results.

Heavy-duty vehicle (HDV) engines can be coupled to many different chassis and body types. Because it would be impractical to type-approve all the possible combinations, engine dynamometer testing is the regulated method for type-approval tests of heavy-duty engines. Emissions of the complete vehicle are not reflected in engine testing, although modern engine test benches can be made to run any real-world engine load test cycle by simulating the vehicle to get torque and engine speed curves, either offline or as hardware-in-the-loop simulation (HILS; *cf.* Lee, 2003). In the past few years, the increasing technological sophistication of engine and aftertreatment control systems of newer technology HDVs has

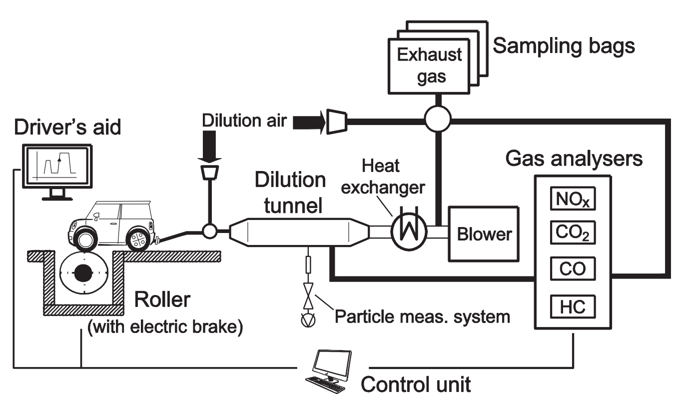

Fig. 1. Schematic representation of a chassis dynamometer emissions test facility.

made it cumbersome to perform engine dynamometer tests independently of manufacturers, which in turn continue to use this technique in engine and aftertreatment device development, both for heavy-duty and light-duty vehicles (LDVs). Chassis dynamometer testing thus became the primary source of emissions data for EF development purposes for recent-technology HDVs.

2.1.1. Test cycles

An emissions *test cycle* (or *driving schedule*) is a predefined driving profile that the vehicle or engine under test has to follow. They last for several minutes, and often comprise several parts (or sub-cycles) that represent different driving conditions (*e.g.* urban or highway driving). Test cycles are an integral part of all chassis and engine dynamometer tests, and their representativeness and completeness (*i.e.*, their ability to statistically represent the driving conditions under study) are essential to the quality of testing results (André and Rapone, 2009). The number of engine and vehicle dynamometer test cycles used worldwide for emission and fuel consumption measurements is continuously expanding to cover regulatory needs, while also trying to simulate real-world driving conditions (André et al., 2006).

Two categories of test cycles may be used in chassis or engine dynamometer tests, namely *steady-state* (or *modal*) and *transient* cycles. Steady-state test cycles involve running the engine or vehicle under a number of modes, each featuring constant engine speed and load. For each mode, the engine or vehicle is operated for a sufficient amount of time to produce relatively stabilized emission rates. When two or more modes are included in the test cycle, the emissions measurements from each mode are typically combined using a weighted averaging scheme, with specific definitions of each mode, and weighting schemes differing from one test cycle to another (Artelt et al., 1999). On the other hand, transient test cycles include variations in the operating conditions as part of the test procedure, and they are regarded as more representative of real-world operation because they can be designed to account for real-world situations such as idling, acceleration, and deceleration. Detailed technical information on the most commonly used standardized driving cycles can be found in the literature (CONCAWE, 2006a, 2006b; Barlow et al., 2009).

Chassis dynamometer test cycles are predominantly transient. This is the case of *type-approval cycles* such as the FTP and SFTP (Federal Test Procedure and Supplemental Federal Test Procedure, used for emission certification of LDVs in the US) and the NEDC (New European Driving Cycle, used for emission testing and certification of all Euro 3 and later LDV models in Europe). The latter has often been criticized for being too smooth and underloaded for typical vehicle operation, as it covers only a small area of the engine operating range (Kågeson, 1998; Mellios et al. 2011; Weiss et al., 2011a). In general, type-approval cycles underestimate real-world emissions because they exhibit low speed dynamics, and also because manufacturers are able to optimize emissions performance for specific operating points (Ntziachristos and Samaras, 2000). In order to address some of the shortcomings of current type-approval test cycles, a new transient chassis dynamometer test cycle (Worldwide Harmonized Light-duty driving Test Cycle, WLTC) is being developed within the framework of a larger project set to produce a global technical regulation for harmonized testing of LDVs (UNECE, 2012)

Besides standardized driving cycles used for regulatory purposes, there are many others that characterize the driving in specific areas (Esteves-Booth et al., 2001) or a particular technology (Rapone et al., 2000). From the EF development perspective, the so-called *real-world cycles* provide the most valuable emissions data thanks to a wider coverage of engine operating points in comparison to type-approval cycles. Examples of these are the test cycles for LDVs and HDVs included in the default database of MOVES (USEPA, 2012), the ARTEMIS suite of LDV cycles (André, 2004) and the recently developed ERMES test cycle (Knörr et al., 2011), which was specifically designed for emission modelling purposes (see Fig. 2). The short duration of the ERMES cycle is an advantage in terms of testing schedule flexibility and costs of individual test runs.

Engine dynamometer tests are predominantly modal. Some of the main *modal test cycles* used around the world for the type-approval of current-technology heavy-duty engines include the European Stationary Cycle (ESC; applicable in Europe, and comprising 13 modes) and the Supplemental Emissions Test (USA, 13-mode). Some *transient test cycles* are also in use, such as the European Transient Cycle (ETC) and the US heavy-duty engine Federal Test Procedure (FTP). For newer technology engines (EURO VI and beyond), the World Harmonised Stationary Cycle (WHSC) and its transient counterpart (WHTC) have been proposed by the UNECE GRPE group in an effort to create global cycles that reproduce typical driving conditions in the EU, USA, Japan and Australia (Steven, 2001).

2.2. Emission factor development

Chassis dynamometer testing is arguably the most proven technology for vehicle emissions measurements, having achieved a high degree of standardization. In order to obtain *robust* EFs (*i.e.*, ones that are unlikely to change within the accepted uncertainty if there was repetition of the original measurement programme or modelling activity; IPCC-EFDBEB, 2003), a sufficiently large number of vehicles should be tested repeatedly under different driving cycles. Engine dynamometer testing is somewhat less useful for EF development because it produces results in units of quantity of pollutant emitted per unit of engine energy output (such as g kWh^{-1}), which are not directly relevant to real-world activity patterns. To estimate total emissions using this type of EF, one needs to estimate or calculate the engine power profile over a trip travelled and apply a relevant EF.

A straightforward approach to EF development is to plot the aggregated – or 'bag' – results of various driving cycles with respect to the mean speed or another aggregated kinematic parameter (*e.g.* mean acceleration or relative positive acceleration) of the specific cycle and then fit a polynomial trend line to the experimental data using mathematical regression. The resulting formula of the trend line is the EF that expresses vehicle emissions as a function of the parameter selected. Such an approach may not adequately capture the impact of different driving cycles on emission performance. An illustration of this is provided in Fig. 3, where

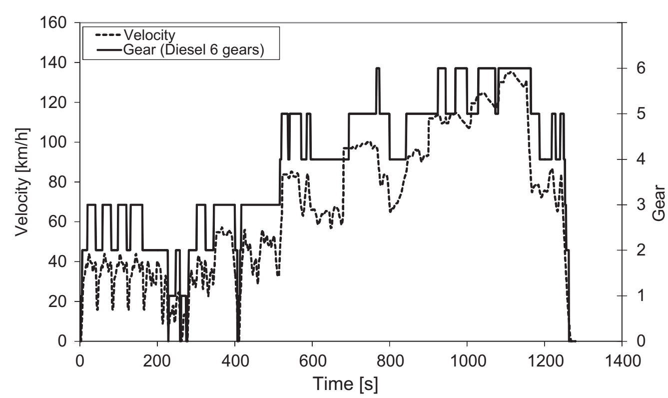

Fig. 2. Time–velocity profile of the ERMES chassis dynamometer test cycle.

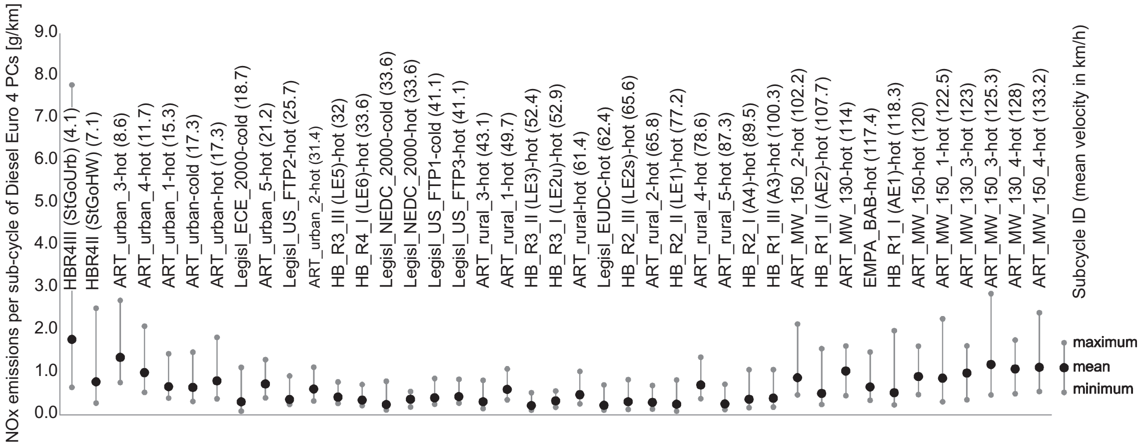

Fig. 3. Illustration of the variability of emission test results. Source: Artemis 300 database.

the NO_x emissions over 41 different driving cycles and sub-cycles for fifteen different Diesel Euro 4 passenger cars of similar engine capacity are summarised as a function of mean cycle velocity. Fig. 3 shows the mean, maximum, and minimum recorded value for each cycle to illustrate the variability of the emission levels within a given vehicle class and also the variability of average emission levels from different test cycles with similar average velocities. The variability is much higher for CO and HC and lower for CO_2 and fuel consumption than it is for NO_x (Boulter and McCrae, 2007; Zallinger, 2010), and is generally higher at lower mean velocities (Choi and Frey, 2009, 2010). In any case, the development of robust EFs requires the measurement on a sufficient number of vehicles and an adequate selection of driving cycles that are representative of the driving conditions being modelled.

Whenever instantaneous data from online analysers (typically with a sampling frequency of 1 Hz or higher) are available in addition to aggregated (or 'bag') values, other, more elaborate approaches to EF development may be considered. In such cases, measured emission values can be related to recorded instantaneous kinematic parameters or engine covariates. This is done in the MOVES model, which uses the metric of vehicle-specific power (VSP) and instantaneous velocity to bin instantaneous data and estimate EFs, and in PHEM (Passenger car and Heavy duty vehicle Emission Model), which uses modal chassis and engine dynamometer test data to produce *emission maps* that predict pollutant mass emissions as a function instantaneous engine speed and engine power, normalised by their maximum rated values (see Fig. 4).

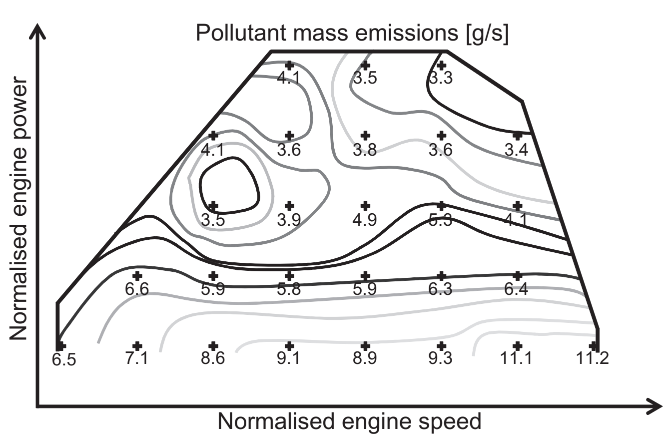

Fig. 4. Example of 'engine emission map' (adapted from Kousoulidou et al., 2010a).

An advantage of EFs derived from instantaneous emissions data is that they allow for the simulation of fuel consumption and emissions for any driving pattern and vehicle configuration (Kousoulidou, 2011). For such applications the instantaneous mass emissions for a non-measured driving pattern can be interpolated from measured data. However, the creation of *engine map* EFs requires additional data post-processing efforts to fine-tune the results. For example, maps derived from modal data may have to incorporate correction factors to account for the excess emissions typical of transient states, or be calibrated with 'bag' results (Hausberger et al., 2009). Additional complications arise if *transient data* are used to develop the instantaneous EFs. In this case, the fine allocation of instantaneous mass emissions to engine state data poses a technical challenge because pollutant concentrations are affected by a number of distortions including mixing of the exhaust gas, variable transport delays, and dispersion due to the finite dynamic response characteristics of gas analysers. All of these result in measured emission signals which are smoothed, dynamically delayed instances of the 'true' signal at the catalyst-out point. A number of methodological proposals have been made to address this issue through data post-processing [see, for example, the work of Weilenmann et al. (2003), Ajtay and Weilenmann (2004) and Geivanidis and Samaras (2008)], but they are not applied in routine measurements.

2.3. Applications

Chassis dynamometer measurements are routinely used for the type-approval of road vehicles and engines. Scientific studies involving chassis dynamometer measurements are also conducted for several purposes, including the investigation of the emission characteristics of specific types of vehicles or pollutants, the assessment of emission control technologies or the analysis of the emissions performance of different types of fuels.

Chassis dynamometer testing can cover a wide range of pollutants depending on the type of analysers used to analyse vehicle exhaust. As far as the type of vehicles tested is concerned, chassis dynamometer tests are more commonly used for motorcycles, passenger cars and light commercial vehicles (Pelkmans and Debal, 2006; Fontaras et al., 2007, 2008; Chiang et al., 2008), than for HDVs (Wang et al., 1997; Morawska et al., 1998; Whitfield and Harris, 1998; Ramamurthy and Clark, 1999; Clark et al., 2002), because only the more costly HDV chassis dynamometer laboratories can accommodate these larger vehicles.

Chassis dynamometer studies have been used to investigate the *emission profiles of several pollutants* from different types of vehicles under various conditions. For instance, Yanowitz et al. (1999) reported the emissions of regulated pollutants from twenty-one in-use Diesel HDVs as measured on a chassis dynamometer for three different standard driving cycles. Mohr et al. (2000) carried out an experimental study on particulate emissions of gasoline vehicles with three passenger cars at a chassis dynamometer. Durbin et al. (2002) investigated the variation of ammonia emissions across different driving cycles. Soltic and Weilenmann (2003) studied the total amount and the partitioning of the NO_x over different test cycles for sixteen Euro 2 light-duty vehicles. Heeb et al. (2003) reported the emissions of methane, benzene and the alkyl benzene class compounds for gasoline passenger cars from Euro 0 to Euro 3 technology class over the US urban driving cycle (FTP), measured by chemical ionization mass spectrometry (CI-MS) under cold and hot engine conditions. In order to assess the influence of cold engine start upon emissions, Weilenmann et al. (2005) measured and analysed benzene and toluene emissions at various ambient temperatures for Euro 3 gasoline cars, Euro 2 Diesel cars and pre-Euro 1 gasoline cars over a repetitive urban real-world test cycle. More recently, Livingston et al. (2009) used a chassis dynamometer equipped with Fourier Transform Infrared Spectroscopy (FTIR) analysers to measure tailpipe ammonia emissions from a random sample of light and medium-duty vehicles, while Adam et al. (2011) investigated the time-resolved emissions of several hydrocarbons and other unregulated pollutants of a medium-sized truck using state-of-the-art spectrometers.

Chassis dynamometer studies have been used to study the performance characteristics of different *emission control technologies*. For example, Huai et al. (2004) measured N_2O emissions from different vehicle technologies ranging from non-catalyst to super-ultra-low-emission vehicles (SULEV) over the FTP and other, more aggressive cycles. Heeb et al. (2006a, 2006b) studied the efficiency of catalytic reduction of nitrogen monoxide (NO) and the selectivity towards NH_3, and analysed the parameters with impact on the NH_3 output of a three-way catalyst equipped gasoline LDV during real-world driving. Olfert et al. (2007) studied the modal particle emissions of a passenger car equipped with a Diesel oxidation catalyst (DOC). Bergmann et al. (2009) evaluated the efficiency of a passenger car Diesel particulate filter (DPF) over NEDC and a custom acceleration–deceleration chassis dynamometer cycle, while Biswas et al. (2008, 2009) studied the particulate emissions of Diesel HDVs retrofitted with recent-technology aftertreatment systems (DPF and selective catalyst reduction, SCR) over steady-state and transient cycles.

Repeated chassis dynamometer testing is an excellent way to assess the influence of *different fuels* on vehicle emissions because the repeatable conditions allow even small emission and consumption differences to be observed. Chao et al. (2000) used chassis dynamometer measurements to study the effect of an additive containing methanol on the emission of carbonyl compounds from a HDV Diesel engine. Some chassis dynamometer studies (Wang et al., 2000; Fanick and Williamson, 2002; USEPA, 2002) compared exhaust emissions from in-use heavy-duty trucks fuelled with biodiesel blends with those from trucks fuelled with Diesel fuel. The impact on both particle and carbon dioxide emissions of alternative fuels such as liquefied petroleum gas (LPG) and unleaded gasoline was analysed by Ristovski et al. (2005). Peng et al. (2008) examined the effect of biodiesel blend fuel on aldehyde chemical emissions form Diesel exhaust in comparison with those from Diesel fuel. Aslam et al. (2006) studied the performance of compressed natural gas in comparison with gasoline. Nelson et al. (2008) reported the emissions of a range of toxic compounds from twelve in-use vehicles which were tested using urban driving cycles developed for Australian conditions and Diesel fuels with varying sulphur contents. More recently, Kousoulidou et al. (2010b) studied the impact of biodiesel on regulated pollutant emissions and fuel consumption of a modern passenger car, and Fontaras et al. (2012) assessed the on-road emissions of four Euro V Diesel and CNG waste collection trucks. A study by Kousoulidou et al. (2012) used chassis dynamometer test data to provide correction factors for pollutant emissions when biodiesel is used on passenger cars at different blending ratios.

Chassis dynamometer measurement data have also been used as an input to specific *emission models*. For example, the study of Kear and Niemeier (2006) used chassis dynamometer test data to derive a model to develop operational correction factors that correct distance-based HDV Diesel particle emission rates measured on standard test cycles for real-world conditions. The study of Fontaras et al. (2007) presented the application of a tool for predicting CO_2 emissions of vehicles as measured on a chassis dynamometer under different operating conditions, and these results were directly used to represent hybrid EFs in COPERT. In the context of the DECADE project – carried out under the 5th Framework Programme of the European Commission – a software package was developed to predict vehicle fuel consumption and emissions for a given distance–speed profile. Specific LDVs were subjected to measurements on engine dynamometers in order to give input to the model (Pelkmans and Debal, 2006). Engine dynamometer test data have been found to be especially accurate for the simulation of instantaneous fuel consumption. Moreover, the upcoming HDV CO_2 monitoring regulation is expected to rely on a combination of component measurements and vehicle simulation (Hausberger et al., 2012).

Newer powertrain configurations such as Hybrid Electric Vehicles (HEVs) and full-electric vehicles (EVs) need modified test benches to evaluate the electric power flows among the driveline components. UNECE Regulation 101 (UNECE, 2005) defines standard test procedures for the measurement of fuel consumption and CO_2 emissions from passenger cars and LDVs, including HEVs and plug-in hybrid vehicles (PHEVs). It also proposes a method to measure the electric range of EVs and PHEVs. Silva et al. (2009) proposed a methodology based on the SAE J1711 standard to produce dynamometer-based EFs for PHEVs, including life cycle assessment considerations to make comparisons fair among different vehicle technologies. In general terms, chassis dynamometers (coupled with some degree of hardware simulation) capture the emissions of newer powertrain configurations better than engine dynamometers (ICCT, 2012).

3. Emission measurements under real-world conditions

Measuring emissions under real-world conditions – be it in tunnel, remote sensing, on-road or on-board measurements – yields valuable data regarding the actual emissions behaviour of road vehicles as they operate outside the boundaries of the emissions laboratory. The results of real-world techniques are typically less precise and repeatable than those of engine and chassis dynamometer studies, due to the absence of a standard test cycle and the presence of additional sources of variability such as environmental or traffic conditions, driver behaviour or highly transient operation. Moreover, real-world techniques exhibit other technical shortcomings that limit their applicability to EF development. Still, the data produced by these measurements can play an important role towards the identification of gaps in emission models and the establishment of model development priorities. Real-world emission measurements are essential towards the validation of EFs gained from laboratory testing.

3.1. Remote sensing

In remote sensing (also called 'roadside measurement'), instantaneous ratios of pollutant concentrations are determined as vehicles pass by a measurement station on the roadway (Bishop et al., 1989). Remote sensing equipment is able to take several readings of the ratios of concentrations for each exhaust plume analysed, correct for background levels and report a mean value for each passing vehicle. Infrared and ultraviolet light of specific wavelengths from a source passes through the exhaust plume to a detector wherein the amount of light absorbed is proportional to the concentration of CO, CO_2, or THC (measured in the IR band) and NO_x (measured in the UV band; Bishop and Stedman, 1996). Remote sensing can be used to determine the molar ratios of pollutants, offering a quick and effective method of monitoring exhaust emissions from in-use vehicles under real-world driving operation.

The major advantage of remote sensing is that it enables the monitoring of the emissions of large numbers of vehicles (up to thousands per day). It also offers the necessary resolution to identify emission levels of single vehicles – whose emission technology may be determined by video recording licence plates and cross-referencing with vehicle registration databases – and not just the average fleet-wide emission level. This has made this technique especially valuable for the *identification of high emitters* (Jimenez et al., 2000; Chan et al., 2004; Ko and Cho, 2006). On the other hand, remote sensing only gives an uncertain instantaneous estimate of emissions at a specific location, is a rather 'fair weather' technology (Frey and Eichenberger, 1997), and cannot be used across multiple lanes of heavy traffic. In most cases, approximately half of the data collected are valid. Moreover, measurements of exhaust emissions by remote sensing are influenced by many factors, such as the physical characteristics of sampling sites, sampling times, and operating mode of the vehicles (Sjödin and Lenner, 1995; Sadler et al., 1996), and even the visible presence of the measurement instruments on the roadside may have an influence on the behaviour of some drivers as they approach the measurement site. Thus, the uncertainty of emissions factors derived from remote sensing studies is large, and their resolution is limited as this technique can only provide a snapshot of vehicle emissions and does not provide insight regarding how emissions vary at different points of a trip.

3.1.1. Emission factor development

In remote sensing measurements, exhaust plumes are immediately diluted with ambient air, and so the actual concentrations of pollutants at the tailpipe cannot be directly measured. However, assuming that dilution is turbulent and happens instantaneously, the *ratios of pollutant concentrations* for a given plume should be preserved (Bishop and Stedman, 1996), and it is these that are measured and reported by remote sensing equipment (*e.g.* N_2O to CO_2; *cf.* Jimenez et al., 2000). By assuming *stoichiometric combustion conditions* and mean fuel characteristics (carbon mass fraction and ratio of H to C), one can calculate an expected concentration of CO_2 at the tailpipe (Heywood, 1988), and thus the *tailpipe concentration* of a generic pollutant P can be estimated by means of the following equation (Jiménez, 1999):

$$[\mathrm{P}]_{\mathrm{tailpipe}} = \left(\frac{([\mathrm{P}]/[\mathrm{CO_2}])_{\mathrm{remote}}}{1+([\mathrm{CO}]/[\mathrm{CO_2}])_{\mathrm{remote}}}\right)\cdot[\mathrm{CO_2}]_{\mathrm{stoich}} \quad (1)$$

where $[CO_2]_{stoich}$ is the stoichiometric concentration of CO_2 for the fuel considered and the ratios of pollutant concentrations to CO_2 with the *remote* subscript are measured by the remote sensing instrument. The assumption of stoichiometric combustion is correct for properly functioning gasoline vehicles, but in Diesel vehicles (and frequently in gasoline direct injection vehicles) lean-burn mixtures are used. In these cases, CO_2 does not perform well as a reference gas to estimate tailpipe pollutant concentrations.

Remote sensing measurements can also be used to develop *fuel-based EFs* by measuring the ratios of concentrations of pollutants and carbon-containing species (CO_2, CO and HC) in the vehicle plumes and referring them to the amount of fuel consumed. Since the conversion efficiency of elemental carbon in fuel to CO_2 is roughly 99% for normal operation of both gasoline and Diesel vehicles, it is reasonable to assume that the carbon mass in the exhaust plume is mostly in the form of CO_2 and CO, and the measurement of other carbon-containing compounds can be omitted. Thus, it is possible to estimate an emission factor for pollutant P by means of Equation (2) (Singer and Harley, 1996):

$$E_{\mathrm{P}} = \frac{\text{Estimated mass emission of P}}{\text{Estimated fuel consumption}} = \frac{w_{\mathrm{c}}\cdot M_{\mathrm{P}}}{M_{\mathrm{c}}}\cdot\left(\frac{([\mathrm{P}]/[\mathrm{CO_2}])_{\mathrm{remote}}}{1+([\mathrm{CO}]/[\mathrm{CO_2}])_{\mathrm{remote}}}\right) \quad (2)$$

where E_P is given in kg of P per kg of fuel burned, w_c is the weight fraction of carbon in the fuel considered and M_P and M_C are the molecular/atomic masses (in g mol^{-1}) of P and elemental carbon, respectively. For the purposes of area-wide emissions estimation, a fuel-based approach may be adequate, but not enough for meso- or micro-scale emission inventories (Cadle and Stevens, 1994). It is not straightforward to associate roadside emission concentrations with the engine states that produce them, since the latter are not recorded. EFs can be expressed in qualitative terms of vehicle operation, such as emissions over 'acceleration', 'steady-speed', and the like (primarily based on the location of the remote-sensing equipment used) or linked to estimated kinematic parameters like vehicle-specific power (Frey et al., 2010). An estimation of instantaneous fuel economy is required to convert fuel-based emissions to distance- or time-based estimates.

The application of remote sensing to the derivation or validation of disaggregate EFs (*i.e.*, broken down by vehicle category) requires additional data for each passing vehicle to allocate measured EFs to the vehicle class (notably engine type and year of first registration, which may be determined later if licence plate recognition is implemented). The EFs estimated using a fuel-based approach become more uncertain for pollutants that are characterized by concentrations close to background levels (due to a low signal-to-noise ratio of the recorded concentrations), which in turn are affected by older, diluted exhaust plumes.

3.1.2. Applications

Remote sensing studies of road vehicle emissions abound in the literature: Singer and Harley (1996) built a large database of on-road vehicle emissions to estimate the fuel-based EFs of CO and HC using a remote sensing device. Yu (1998) developed the ONROAD emissions estimation model, which established a relationship between the emission rate and the instantaneous speed profile of a vehicle based on in-use CO and HC emissions data collected from five highway locations in the Houston area (TX, USA) using remote sensing. In one of their multiple applications of the technique, Stedman and Bishop (1997) used remote sensing to evaluate the effectiveness of a vehicle inspection and maintenance programme in the metropolitan area of Denver (CO, USA). A database of EFs vehicles based on remote sensing measurements of CO, HC and NO was developed in Hong Kong for both gasoline (Chan et al., 2004) and Diesel vehicles (Chan and Ning, 2005). In Mexico City – where the availability of data used in traditional on-road mobile source estimation methodologies is limited – the remote sensing technique was used within a scientific study by Schifter et al. (2005) as an alternative method to estimate motor vehicle emissions. Guo et al. (2007a) performed on-road remote sensing measurements on over 32,000 gasoline vehicles at five sites in Hangzhou, China, and derived average EFs for CO, HC and NO_x specific of model year, technology class and vehicle type. Westerdahl et al. (2009) conducted measurements in three different environments (on-road, roadside and ambient) in Beijing (China) and derived carbon monoxide, black carbon and ultrafine particle number fuel-based EFs for on-road LDVs and HDVs. Wehner et al. (2009) measured number size distributions of exhaust particles and thermodynamic parameters under real traffic conditions with roadside measurements using a Diesel and a gasoline passenger car driven under different conditions, and calculated distance-based EFs for primary emissions of particles.

Remote sensing has been employed in several *emission model comparison and validation processes*. Ekström et al. (2004) used on-road remote sensing measurements for gasoline and Diesel passenger cars and HDVs to evaluate the COPERT III model. Hueglin et al. (2006) found good agreement between the average real-world road traffic EFs obtained from long-term roadside air quality measurements at a monitoring site of the Swiss national air pollution monitoring network and the corresponding EFs from the HBEFA model. An evaluation of the International Vehicle Emission (IVE) model – which was developed by USEPA to estimate emissions from motor vehicles in developing countries – was performed by Guo et al. (2007b).

Remote sensing can also provide interesting results about *real-world driving conditions* that are difficult to replicate in the laboratory. For example, some studies were specifically targeted at the effects of *altitude* upon vehicle emissions (Bishop et al., 2001; Burgard et al., 2006). Akin to tunnel studies, remote sensing campaigns can also be used to assess *emission trends* and to evaluate the effects of emission control standards upon air quality (Schifter et al., 2008; Carslaw et al., 2011), or to support and orient air quality policies (Xie et al., 2005).

3.2. On-road (chase) measurements

During on-road (also *chase* or *plume chase*) measurements, individual vehicles are followed by a mobile laboratory – usually on board a van or trailer – that is instrumented with gas and aerosol measurement equipment (ideally instruments with fast time response and high sensitivity, such as laser spectrometers), plus meteorological and positioning instruments, and even video recording equipment to monitor traffic situations (Shorter et al., 2005). In a similar fashion as remote sensing studies, CO_2 is used as a tracer of combustion, and the results indicate the relative concentration of the pollutant of interest per CO_2 concentration value. These mobile laboratories are able to capture the exhaust plume of the vehicle being followed, thus providing real-world emissions data under a wide range of operating and environmental conditions. Mobile emission laboratories make it possible to study a statistically representative sample of vehicles for *fleet characterization*. One disadvantage is that such measurements are best conducted on a test track due to traffic safety considerations. Moreover, they are limited by a minimum distance of about ten metres between the laboratory and the vehicle being chased – unless the laboratory is mounted on a trailer; see (Morawska et al., 2007) – and a maximum chase speed of approximately 120 km per hour.

3.2.1. Emission factor development and applications

On-road measurements allow for the calculation of *fuel-based EFs*. The derivation of EFs is analogous to remote sensing applications discussed in Section 3.1.1. In some practical instances, mobile laboratories may sample within traffic without following a particular vehicle to get on-road average emission levels, or be parked at specific locations to perform roadside or background measurements (Pirjola et al., 2004).

Chase measurements are especially interesting for the study of *particulate emissions* (Kittelson et al. 2004, 2006; Canagaratna et al., 2004; Morawska et al., 2007) because they allow the study of secondary formation after the exhaust, and also due to the fact that they are not affected by artefact nucleation modes unlike measurements in dilution tunnels used in dynamometer studies (Maricq et al., 1999). This technique has also been used to investigate the influence of real-world driving on vehicle emissions of other pollutants. For example, Shorter et al. (2005) used this technique to study the NO and NO_2 emissions profile of the New York City Transit bus fleet, and a follow-up study by Herndon et al. (2005) included SO_2, H_2CO, and CH_4.

3.3. Tunnel studies

Tunnel studies involve measuring the total flux of pollutants from vehicles passing through a tunnel and correlating the pollutant flux to traffic flow (Jamriska et al., 2004; Hueglin et al., 2006). Pollutant measurements are typically performed at the entrance and exit of tunnels with separate bores for each direction. Total pollutant production may be calculated by estimating the airflow through the tunnel and multiplying it by the difference in pollutant concentrations between outlet and inlet. Wind speeds and through-traffic are also recorded.

An advantage of tunnel studies is that, contrary to roadside or chase experiments, the wind conditions in road tunnels are well defined, and so average absolute levels of emissions (rather than estimations based on CO_2) can be obtained. Tunnel studies are thus able to capture a cross-section of the on-road vehicle fleet and represent real-world operation conditions at the location of the tunnel. These, in turn, may not be typical of real-world urban driving, since tunnels are usually traversed at steady speeds (El-Fadel and Hashisho, 2000).

An additional benefit of tunnel studies is that they can cover not just tailpipe emissions, but also brake lining wear, tyre wear, and emissions of secondary particulate matter coming from chemical transformations within the tunnel. A notable disadvantage of tunnel studies is the difficulty to apportion emissions to specific vehicle classes unless different tunnel bores are dedicated to them (Geller et al., 2005). Furthermore, induced wind speed effects in the tunnel, due to the movement of large vehicles may affect the driving resistance -and therefore the emissions- of lighter cars (Corsmeier et al., 2005).

3.3.1. Emission factor development

Tunnel studies can be used to derive *aggregated real-world EFs*. These may be either distance- or fuel-specific (if a carbon balance can be assumed). The EFs from tunnel measurements may be calculated according to the method of Pierson (Pierson and Brachaczek, 1983; Pierson et al., 1996) (Equation (3)), where *EFveh* is the average EF in mg vehicle^{-1} km^{-1} travelled. C_{out} and C_{in} represent the pollutant mass concentrations (in mg m^{-3}) at the exit and entrance of the tunnel, respectively. A is the tunnel cross-sectional area in m^2, U is the wind speed (in m s^{-1}), t is the sampling duration (in seconds), N is the total number of vehicles during the sampling period and L is the distance between the two monitoring stations in kilometres. When using this equation, one assumes that the movement of air and vehicles causes uniform mixing and distribution of pollutants throughout the tunnel (El-Fadel and Hashisho, 2001).

$$EF_{veh} = \frac{C_{out} - C_{in}}{N \cdot L} A \cdot U \cdot t \tag{3}$$

In a similar fashion to remote sensing and chase experiments, *fuel-based EFs* can be calculated from road tunnel experiments using the carbon balance of the major carbon-containing exhaust constituents (Miguel et al., 1998; Kirchstetter et al., 1999; Kean et al., 2003).

3.3.2. Applications

Several tunnel studies have been conducted to measure and analyse gaseous and particulate pollutants emitted by vehicles. The majority of these studies were aimed at obtaining representative EFs using mass balance techniques (Ingalls, 1989; Sjödin and Lenner, 1995; Staehelin et al., 1997; Rogak et al., 1998; Sjödin et al., 1998; Tsai et al., 1998; Sturm et al., 2003). Allen et al. (2001) measured particulate matter emissions in a tunnel in the San Francisco Bay area and determined the chemical composition of sampled particulate, as well as separate EFs for HDVs and LDVs. Abu-Allaban et al. (2004) measured size distributions of particle emissions in a Pennsylvania highway tunnel using a scanning mobility particle sizer, and were able to determine EFs for LDVs and gasoline HDVs. Cheng et al. (2006) calculated a real-world EF for $PM_{2.5}$ in the Shing Mun tunnels (Hong Kong), while Ho et al. (2009) calculated vehicle EFs for seventeen gas and particulate polycyclic aromatic hydrocarbons (PAHs) at the same location. Sánchez-Ccoyllo et al. (2009) calculated EFs for fine particles, coarse particles, inhalable particulate matter and black carbon, as well as size distribution data for inhalable particulate matter from measurements at two different tunnels in São Paulo (Brazil).

Because the dispersion of pollutants is prevented by the confined space, tunnels offer a suitable microenvironment for model evaluations. Tunnel studies have thus been used to *validate EFs* found in road transport emission models by comparing the results of the measurements with the calculated pollutant concentrations based on the corresponding EFs for the mix of vehicles operating in the tunnel (Hsu et al., 2001; Hausberger et al., 2003; Colberg et al., 2005a; Singh and Sloan, 2006). One disadvantage of this approach is that it only provides a lump average of all vehicle categories operating through the tunnel, which are frequently heterogeneous.

Tunnel studies have also been used to *evaluate the impact of real-world sources of variability* that are difficult to reproduce on the test bed, such as the effect of road gradient (Kean et al., 2003; Colberg et al., 2005b; Chang et al., 2009), or diurnal and seasonal traffic emission variations (Grieshop et al., 2006). Also, repeated measurements in tunnels over long periods of time have been used to assess the impact of technological and legislative improvements on *emission trends* (Kean et al., 2002; Stemmler et al., 2005; Vollmer et al., 2007; Ban-Weiss et al., 2008; Kean et al., 2009).

3.4. On-board measurements (PEMS)

Portable emissions measurement systems (PEMS) are complete sets of emission measurement instruments that can be carried on-board the vehicle under study (Vojtisek-Lom and Cobb, 1997; Frey et al., 2003). Such systems can provide instantaneous emission rates of selected pollutants with satisfactory levels of accuracy. A PEMS unit is usually comprised of a set of gas analysers with heated sample lines directly connected to the tailpipe, plus an engine diagnostics scanner designed to connect with the OBD (on-board diagnostics) link of the vehicle and an on-board computer that provides data regarding emissions, fuel consumption, vehicle speed, engine speed and temperature, throttle position and other parameters. PEMS systems typically measure instantaneous raw exhaust emissions of NO_x, THC, CO_2 and CO. Portable *particle mass* analysers have become commercially available after extensive testing (Mamakos et al., 2011). Exhaust flow meters are attached to the tailpipe (alternatively, exhaust flow rate can be calculated from engine operating data, known engine and fuel properties, and measured CO_2 concentrations in the exhaust gas) while a GPS and a weather station are normally installed on the external area of the vehicle. In some cases, other instruments may be used, such as accelerometers to record instantaneous acceleration (Oprešnik et al., 2012), altimeters or video/photographic equipment to document traffic conditions during test runs.

In heavy-duty trucks, PEMS equipment is often mounted in the trailer (if present), while in the case of buses and LDVs the main unit is installed in the cabin of the vehicle to avoid contamination, excessive vibrations and overheating of the equipment (Fig. 5). The connections of the PEMS to the vehicle are typically reversible, and no further modifications are necessary in many cases.

In the past few years, PEMS systems have experienced a remarkable technological development, with significant reductions in size, weight, and piping and cabling complexity, improved gas measurement principles, reduced analyser response times and an overall performance similar to conventional fixed laboratory equipment. The main advantage of on-board methods is that they can provide long series of emission values of a particular well-known vehicle driven under a wide range of traffic conditions, operational/duty cycles and ambient conditions (Cicero-Fernández et al., 1997), including some that would otherwise be difficult to replicate in the laboratory (*e.g.* large road gradients). The installation of PEMS on several vehicles of various categories can lead to a large database of emission values from vehicles of different technologies driven under different driving and environmental conditions. PEMS are relatively simple and inexpensive, and can be installed on a wide variety of vehicles. They can be especially convenient for HDVs, considering that dynamometer test beds have limitations in terms of vehicle size and become expensive for high engine power applications. PEMS are thus becoming an important regulatory tool for HDVs. US authorities have introduced additional emissions requirements based on PEMS testing and the 'Not to Exceed' (NTE) concept, whereby emissions averaged over a time window must not exceed specified values for regulated pollutants while the engine is operating within a control area under the torque curve. The corresponding test procedures and the portable instrumentation performance requirements are laid down in (USEPA, 2005). In Europe, PEMS can be applied to verify the in-service conformity of EURO V and EURO VI heavy-duty engines with the applicable emissions standards (EC, 2011b, 2012).

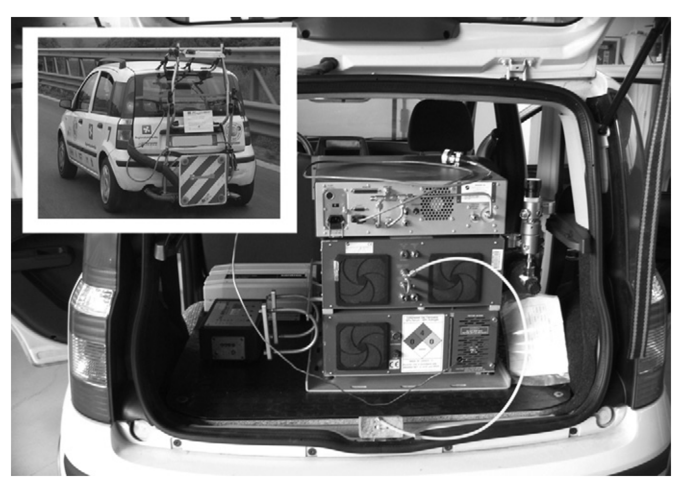

Fig. 5. Passenger car instrumented with PEMS.

Older PEMS systems were inferior to laboratory systems in terms of measurement accuracy but new systems have improved to a degree that distinctions from laboratory-grade systems are difficult to detect and negligible in terms of EF development. The main limitations of PEMS include the reduced range of measurable pollutants, the added mass (of approximately 30–70 kg) that may bias the measurement (especially for light-weight cars), and the reduced repeatability due to real-world sources of variability. Also, the range of pollutants that can be measured with PEMS is limited in comparison to laboratory measurements.

3.5. Emission factor development

The development of EFs from PEMS data is analogous to the procedure followed with chassis dynamometer data. Mean speed-based EFs may be derived by collecting bins of a large PEMS emissions dataset (which can be time- or distance-based) and plotting their corresponding mass emissions against the mean speed of the data bin, thus producing a cloud of data points to which a regression curve may be fitted. Rubino et al. (2007) and Weiss et al. (2011a, 2011b) used an 'averaging window' approach to derive distance-based EFs from PEMS datasets.

Alternatively, an instantaneous *engine map* model approach may be used, whereby pollutant engine maps are developed from the instantaneous PEMS data. A practical application of this principle was developed by Kousoulidou et al. (2010c) who developed a tool for the creation of pollutant engine maps from on-board data, which were then used as input to a vehicle simulation tool. As discussed in Section 2.2, the use of transient PEMS data for direct derivation of 'engine map' EFs is hindered by the difficulty to accurately allocate emissions to measured vehicle or engine states. Moreover, it is difficult to measure engine power or torque during PEMS testing (in contrast to chassis dynamometer testing). Readings from the OBD of vehicles can be quite inaccurate in absolute terms, and the application of torque measurement systems (such as resistance strain gauges) is complicated and difficult to calibrate on the road, while a calculation from the measured velocity signal is limited by the usually unknown road gradient. These problems can be overcome if the PEMS tests are planned properly and all relevant data (road gradient, vehicle mass and frontal area, etc.) are recorded. When done properly, PEMS are a good source for reliable real-world emissions data and an interesting tool for the validation of current EFs.

4. Applications

PEMS have been used to study the behaviour of exhaust emissions under real-world operation for EF derivation and validation, emission model improvement or investigation of the emissions performance of new powertrains or aftertreatment systems. Vojtisek-Lom and Cobb (1997) made an early demonstration of the feasibility of PEMS. A simple on-board measurement system was employed by Miyazaki et al. (2002) to evaluate the NO_x emissions of a medium-duty vehicle. Another version of these simple systems was implemented and tested by Hawirko and Checkel (2002) using a vehicle fuelled either with gasoline or natural gas under a wide range of driving conditions in the region of Edmonton, Canada. In these early applications of PEMS, the authors used an on-road setup to record ambient conditions, driving behaviour, vehicle operating parameters, fuel consumption and exhaust emissions results for a small set of repeated commuting trips to illustrate the capabilities of the in-use measurement approach.

The issue of the accuracy and repeatability of PEMS has been covered by a number or research studies that compare the performance of PEMS to fixed laboratory equipment (Daham et al., 2005; Dearth et al., 2005; Pelkmans and Debal, 2006; Gierczak et al., 2006; Durbin et al., 2007; Rubino et al., 2010; Liu et al., 2010) or to a reference mobile laboratory (Johnson et al., 2009a, 2009b). Moreover, (Zhang and Frey, 2008) evaluated the response time of a commercial PEMS system, and found that it lead to deviations which could be corrected by adequate data post-processing. Judging from the results of these studies, it can be concluded that PEMS are a robust tool to measure vehicle emissions that exhibits acceptable correlation with results from reference measurement instruments.

The technological development of PEMS is seeing advances that position it as an interesting alternative to conventional testing equipment. This is especially true when effects that typically cannot be captured under controlled laboratory conditions need to be investigated. Among those effects is the impact generated by so-called emission events, such as sudden accelerations. On-board systems have also been employed to evaluate the effect of ambient temperature on exhaust EFs; for instance, Hawirko and Checkel (2003) analysed a series of trips over a one year period with temperatures ranging from -25 to $+20$ °C. The influence of driver behaviour upon emissions was studied by Nam et al. (2003), who also derived a custom driver aggressiveness indicator calculated from instantaneous speed and acceleration based on PEMS data. Unal et al. (2003, 2004) used PEMS to evaluate the effects of traffic signal timing and coordination on emissions for arterial corridors, and to identify emission hotspots. Chen et al. (2007) studied the impact of speed and acceleration on fuel consumption and emissions of HDVs in an urban area in Shanghai (China) using PEMS, finding that congestion conditions – characterized by low-speed with frequent acceleration and deceleration – led to an increase in exhaust emissions of CO and THC. Frey et al. (2008) used PEMS data from ten different vehicles and three different routes to study the influence of routing on emissions, finding that total emissions of NO varied significantly from trip to trip and from route to route due to variations in mean speed and travel time.

PEMS have been used within studies aimed at evaluating the on-road performance of different emission control technologies and the emission performance of different blends of fuels. For example, Lenaers and Van Poppel (2005a) used an on-board measuring system capable of determining emissions of ammonia to evaluate the emissions performance of a city bus equipped with selective catalytic reduction (SCR). The same authors also investigated the real-world PM emissions reduction from a city bus retrofitted with a continuously regenerating trap using an on-board emission measurement system that performed measurements before and after the installation of the CRT (Lenaers and Van Poppel, 2005b). Tzirakis et al. (2006) investigated the vehicle emissions from a EURO IV vehicle fuelled by Diesel and Diesel/biodiesel blends using on-board emission measurements performed under real-world driving conditions that included also altitude differentiations. Lenaers and Van Poppel (2007) used PEMS to evaluate the real-world emissions performance of two Euro II buses retrofitted with two different combined solution systems for the simultaneous reduction of NO_x and PM. Frey et al. (2007) performed a comparison of fuel consumption and emission variations for Diesel and hydrogen fuel cell buses that operate on identical routes. Frey and Kim evaluated the impact of biodiesel on the real-world emissions of dump trucks (2006) and cement mixers (2009). Graver et al. (2011) evaluated the real-world energy use and emissions of a retrofitted PHEV using a combination of PEMS and a data logger for the hybrid system.

Portable instruments have also been employed in the validation of models based on dynamometer cycles. Silva et al. (2006) compared the outputs of three of these models – EcoGest, Comprehensive Modal Emission Model (CMEM) and Advanced VehIcle

SimulatOR (ADVISOR) – with fuel consumption and emissions data obtained using on-board instruments, concluding that models could be used with relatively high confidence to predict fuel consumption and CO_2 emissions. More recently, Kousoulidou (2011) used PEMS data for the calculation of EFs (which correlated well with the corresponding values provided by COPERT) and produced engine pollutant maps – initially developed from PEMS data and further enhanced through artificial neural network computing – that were then used to simulate the experimental PEMS runs under ADVISOR.

A different approach to on-board measurements (one that cannot be labelled as PEMS, since it is not a portable setup) was taken by a group of researchers at the Center for Environmental Research & Technology of the University of California Riverside (Cocker et al., 2004a, 2004b), who developed a complete emissions laboratory inside a heavy-duty trailer that acts as a load for the vehicle under test. This Mobile Emissions Laboratory (MEL) included a full-flow dilution tunnel, and was built to comply with legal requirements in the USA. Shah et al. (2004, 2006) used the MEL to illustrate the differences in exhaust emissions between cruising and congested traffic conditions, while Durbin et al. (2008) studied the NO_x, PM, THC and CO emissions of several HDVs under real-world operation.

5. Discussion

Road vehicles are operated under a wide range of conditions and exhibit a highly transient behaviour. Moreover, their emission profiles have a strong dependency on vehicle class, on operating and environmental conditions, and on the characteristics of the fuels used. Last but not least, road vehicle emission regulations are frequently updated, which drives constant technological changes in powertrains, fuels and aftertreatment devices. The production of high-quality EFs (*i.e.*, broken down by vehicle category and covering the relevant operating and environmental conditions) is thus a challenging task that requires intensive vehicle testing. On the other hand, vehicle emissions tests are costly experiments, and not every single vehicle model is tested for emissions modelling purposes. Therefore, the production of representative EFs must balance the demand for high-quality, high-resolution emission information with the limited availability of data from experimental tests. In this paper, the experimental techniques used to measure vehicle emissions and to develop EFs have been reviewed to provide some guidance for the selection of the appropriate methods depending on the application considered.

Vehicle emissions measurement techniques under controlled laboratory conditions – *i.e.*, on engine or chassis dynamometer test facilities – allow for the largest degree of control over measurement parameters and repeatability of results thanks to the elimination of real-world sources of variability. This is the reason why vehicle type-approval is performed in dynamometer laboratories worldwide. However, type-approval data are not optimal for EF modelling, as they often do not portray the real-world emissions of vehicles. Therefore, type-approval results are mostly used for the purposes of validation and verification of the accuracy of the measurement setup, and it is engine and chassis dynamometer test data derived from real-world cycles that lie at the core of EFs found in the leading road vehicle emission models such as COPERT, MOVES or HBEFA.

When representative real-world driving cycles are selected, dynamometer tests become ideal for EF development. This is because they allow for an independent control of input parameters. For example, if fuel effects on emissions need to be studied, then repeated test runs in which only the fuel used changes can be conducted. Similarly, if cold-start EFs are to be developed, a precise control of temperature will be required. This can be only achieved in the confined environment of a test cell. Hence, it is likely that dynamometer measurements will continue to be widely used for EF development in the future.

PEMS testing is an interesting alternative to laboratory testing, as it takes into account all real-world variables that may affect emissions. It can also be used over a wide range of driving/operating conditions that would otherwise be impractical to test in the laboratory. However, its reduced repeatability poses some limitations to its use as the core method for EF development. PEMS are currently used in the validation of EFs or as a mechanism for the identification of emission events that are not captured by laboratory testing (*e.g.* Diesel particle filter regeneration, sub-zero or altitude effects, etc.). The fact that PEMS are now approved or pending approval for certification purposes in some applications is an evidence of their technological progress and bright outlook.

Tunnel measurements have been frequently used in the past to validate model EFs. This technique is very useful to monitor the emission levels of hundreds or thousands of vehicles under semi-controlled, real-world conditions. Emissions can be calculated on an absolute scale (*e.g.* g km^{-1}) using the difference in the concentration between tunnel inlet and outlet, the air exchange rate and the vehicle flow through the tunnel. Tunnel studies can also provide ratios of pollutants (*e.g.* NO_x/CO), as these do not depend on the air flow rate through the tunnel. The limitations of the technique include the difficulty to distinguish emission levels between vehicle types or technologies and the fact that operation conditions in the tunnels refer mostly to moderate speed, free-flow traffic. Hence, only aggregate EFs can be reliably tested. Tunnels studies are best used to examine emission trends, *i.e.*, to monitor how vehicle emissions evolve over a period of several years, assuming that the mix of tunnel users has not changed over time. This can help validate not only EFs, but also how well the vehicle stock synthesis is incorporated in the emission models.

Remote sensing of vehicle emissions, akin to on-road measurements, has proven to be a valuable technique for EF validation. Its strong point is the ability to screen thousands of vehicles per measurement period. If combined with automatic licence plate recognition, remote sensing can be used to derive fuel – and technology-specific pollutant concentrations in the exhaust plume. This is a reliable measurement that can be used to derive emission trends over a significant sample of the vehicle stock. The main disadvantage of the technique is that only screenshots of the plume are taken, and so its results are specific to the operation instance of the engine (cruising, acceleration, fuel cut-off, etc.). Remote sensing should therefore be used within its limitations and not as a method to replace detailed model EFs.

A couple of issues have appeared recurrently throughout our review. One is the complex issue of *costs*. In general terms, engine and chassis dynamometer facilities require the highest initial capital investments. They also have higher operating costs than real-world techniques, and marginal costs (*i.e.*, the cost of testing one additional vehicle) similar to comparable PEMS test runs. The comparison to other real-world techniques becomes more complicated because they are not used for equivalent purposes (*e.g.* most real-world techniques are only used for scientific purposes, while dynamometer testing and PEMS are also used for vehicle type-approval). A second issue is the *accuracy and repeatability* of the measurement techniques, which are directly linked to the quality of the EFs derived from them. A large variability is often observed in reported laboratory results, even when identical test cycles and measurement equipment are used. Individual vehicles that comply with the same classification criteria may differ by orders of magnitude in their emission levels of certain pollutants. Fortunately, the EFs found in emission models are based on measurements of tens of vehicles of the same category, thus being robust estimations of average emission levels and trends. On the other hand, there is also a large variability in the emission profile of individual vehicles, especially if these are measured with real-world measurement techniques that bring about uncontrolled sources of variability (*e.g.* variable traffic situations, driver behaviour, environmental conditions and so forth). This implies that large quantities of real-world data from a sufficient number of vehicles should be used for the validation of EFs found in emission models, with careful attention to the influence of real-world factors like cold-start operation, fuel properties or vehicle mileage.

6. Conclusions

The development of accurate EFs found in road vehicle emission models is a joint enterprise among several parties that requires intensive testing to adequately cover all the relevant vehicle types and driving conditions, and substantial research and modelling efforts to keep up with technological advances and improve the methodologies to accurately reflect real-world emissions. All this needs to be accomplished with limited resources.

Chassis and engine dynamometer testing are mature technologies that can be expected to remain the major sources of experimental data underpinning vehicle emission models for the years to come. However, given their inherent inability to capture the full range of real-world driving parameters (even when real-world test cycles are used) these should not be the only data sources that emission modellers tap into. Indeed, the role of the technologically less mature real-world techniques (such as PEMS, remote sensing or tunnel studies) in EF development should not be downplayed, as they have often proved to be valuable resources of data for key aspects of emissions modelling such as EF validation, investigation of off-cycle emissions, characterisation of emission trends, identification of high emitters, assessment of alternative fuels and evaluation of the influence of real-world conditions upon the emission profile of vehicles and the formation of secondary pollutants. All of the above contribute to the quality of emission models, and to the achievement of long-term environmental goals.

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