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Review

Road vehicle emission factors development: A review

Vicente Franco [a], Marina Kousoulidou [a], Marilena Muntean [a], Leonidas Ntziachristos [b], Stefan Hausberger [c], Panagiota Dilara [a,*]

[a] European Commission Joint Research Centre, Institute for Energy and Transport, Via Enrico Fermi 2749, I-21027 Ispra, VA, Italy
[b] Laboratory of Applied Thermodynamics, Aristotle University, P.O. Box 458, GR-54124 Thessaloniki, Greece
[c] Institute for Internal Combustion Engines and Thermodynamics, Graz University of Technology, Inffeldgasse 21A, A-8010 Graz, Austria

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

* Corresponding author. Tel.: +39 0332 78 9207; fax: +39 0332 78 5236.
E-mail address: panagiota.dilara@jrc.ec.europa.eu (P. Dilara).

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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

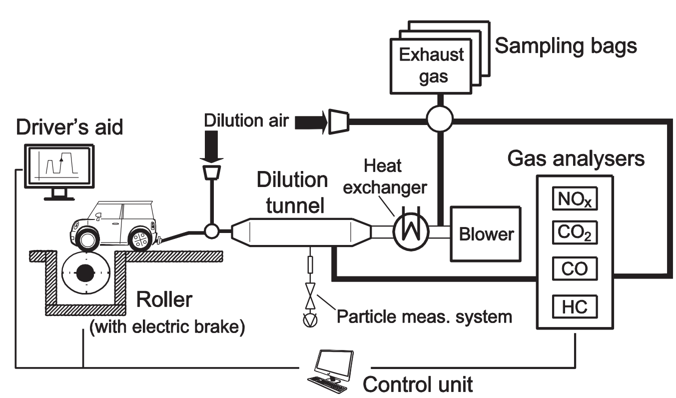

Fig. 1. Schematic representation of a chassis dynamometer emissions test facility.