Validation of the COPERT road emission inventory model with real-use data

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ABSTRACT

Portable Emissions Measurement Systems (PEMS) are a valuable source of real-world operation data to support the development and validation of vehicle emission factors. For the purposes of our research, a Euro 5 compliant diesel passenger car equipped with a particulate filter was fitted with a PEMS system and subsequently driven over predefined driving routes designed to include a variety of driving conditions. The exhaust flow and the concentration of exhaust pollutants at the tailpipe were recorded on a second-by-second basis. Engine speed, torque and other data readings provided by the ECU of the test vehicle were also recorded, along with GPS position and vehicle-mounted weather station data. The resulting data logs were run through a Matlab-based model (CEMOD) that performs a correction of the signal from the PEMS analyzers to account for instrument time lag and response characteristics. These synchronized emission data are then used to develop engine emission maps. The use of these maps within a vehicle simulation tool (ADVISOR) allowed for the prediction of emissions produced over different cycles and driving conditions, including a simulation of the predefined routes. For validation purposes, results were compared to the emission factors provided by the COPERT emission model. Emissions of CO_2, HC and CO correlated well with COPERT values, regardless of the distance split selected for average speed calculations. However, NO_X emission levels were consistently higher than the applicable emission standard and the COPERT emission factors.

INTRODUCTION

Road transport is the main source of air pollution in urban areas, where the combustion of hydrocarbon fuels in vehicles produces several pollutants. Of those, carbon dioxide (CO_2) is emitted in largest quantities and is the greenhouse gas contributing most to the anthropogenic radiative forcing and the related global climate change. In addition, nitrogen oxides (NO_X), uncombusted hydrocarbons (HC), carbon monoxide (CO) and particulate matter (PM) are the most important from a health perspective. Based on European Topic Centre for Air and Climate Change (ETC/ACC) data for 2005, road transport contributes to about 42% of total NO_X emissions, 47% of total CO emissions and 18.4% of total PM emissions at EU15 level.

Traffic emissions are characterized for a given vehicle type or class and estimated at large scales through the use of emission factors (EFs), which describe the emitted mass of a pollutant per driven distance or unit of fuel consumed. EFs can be derived for single vehicles, for a certain vehicle class or even for an entire fleet. These EFs depend on many variables such as size, type, cylinder capacity, fuel mode of the vehicle (gasoline or diesel), type of exhaust technology (with/without catalytic converter), driving style (acceleration and speed), road gradient and the maintenance of the vehicle. The large number of intervening factors means that an estimation of amounts of air pollutants due to traffic is a complex task.

Emission factors from road vehicles can be derived in a variety of ways. EFs of single vehicles can be measured by dynamometer tests[1,2,3] , by transient chassis dynamometers or engine emission measurements[4] . The most common approach to obtain emission factors of great resolution with regard to vehicle technology is to sample a range of cars of a given category and emission control technology (e.g. gasoline passenger car 1.4-2.0l, Euro 4), drive them according to pre-defined driving patterns (driving cycles) on a chassis dynamometer and record their emissions over such conditions. The total emissions produced divided by the total distance driven lead to a mean emission factor (typically expressed in g/km) which can be considered representative of the particular vehicle technology (provided that the vehicle sample is sufficient large) when driven under similar driving conditions as those covered by the driving cycle. The great majority of road transport emission inventories are based on emission factors derived in this way.

There are, however, a couple of issues related to the representativity and coverage of these emission factors. The first issue relates to the sample size: chassis dynamometer measurements are expensive and usually *only a small number of vehicles are used for the emission factor development* in order to reduce the total cost of the study. This may lead to emission factors which are not representative of the particular vehicle class. Another, even more important issue, is *whether the driving cycles utilized for testing are representative of real-world driving conditions*. It may for example occur that while a driving cycle representing urban conditions is used for the production of an urban emission factor, real-world urban driving conditions are much more transient and therefore the emission factor underestimates the actual emission performance.

A new opportunity develops in the field of emission factor validation, through the use of measurements taken on board-vehicles with Portable Emission Measurement Systems (PEMS). PEMS are complete sets of analyzers carried on-board the vehicle which can accurately provide emission rates with a high temporal resolution (i.e. down to 1 Hz). The advantage of this method is that it can provide a long series of emission values of a particular well-known vehicle driven under varying driving conditions. Installation of PEMS setups on several vehicles of various categories can lead to a large database of emission values under different driving and environmental conditions and vehicle technologies. Also, linking this information with Portable Activity Measurement Systems (PAMS) can lead to complete emission-activity information. This means that with a PEMS-PAMS combination, emission rates can be correlated with driving speed, or acceleration/deceleration, or with engine-related parameters.

In this study, a comparison of EFs obtained with three different approaches is presented:

- EFs calculated directly from real-world emissions data obtained during a PEMS measurement campaign carried out on predefined routes.
- EFs calculated using the COPERT model.
- EFs calculated through pollutant engine maps, which were derived from the aforementioned PEMS measurements. The use of said engine maps within a vehicle simulation tool (ADVISOR) allows for the estimation of tailpipe emissions produced on a number of different cycles and driving conditions.

MATERIALS AND METHODS

Experimental setup

A stock DPF-equipped Euro 5 diesel passenger car (Fiat Bravo 1.6 JTD) was employed in the measurements. The vehicle was operated under various driving conditions and over different driving routes. The concentration of exhaust pollutants in the tailpipe and the exhaust flow were measured on-board the vehicle. The main unit containing the pumps, the electronic equipment and the analyzers was installed in the cabin of the vehicle in order to avoid contamination, excessive vibrations, overheating of the equipment, etc. The exhaust flowmeters were attached to the vehicle's tailpipe, while a GPS and a weather station were installed on the external area of the vehicle.

During the first phase of the program (carried out at the EC-Joint Research Centre), the vehicle was tested on local routes in the Lombardy region (Italy) designed to include a variety of urban, rural and highway conditions. During the second phase of the program, the following three routes were designed and used as test routes for all vehicles:

- Route 1: Ispra – Milan – Ispra, mix of rural and highway driving conditions;
- Route 2: Ispra – Varese – Ispra, mix of rural and urban driving conditions;
- Route 3: Ispra – Sacro Monte – Ispra, mix of rural driving and uphill-downhill conditions: this was designed to include a very demanding section (uphill from 400 to 1,200 meters of altitude) in terms of fuel consumption and emissions. Further characteristics of the aforementioned routes can be found in Table 1.

Table 1. Characteristics of PEMS test routes.

	Route 1			Route 2			Route 3		
Section Type	Rural	Mot.	TOTAL	Rural	City	TOTAL	Rural	Uphill	TOTAL
Distance [km]	35	100	135	51	10	61	50	10	60
Approx. aver. speed [km/h]	50	90	65	40	25	35	45	30	40

The gases and pollutants measured include O_2, HC, CO, CO_2 and NO using the following detection methods:

- HC, CO and CO_2 using non-dispersive infrared (NDIR). The accuracy for CO and CO_2 are excellent. The accuracy of the HC measurement depends on type of fuel used.
- NO measured using electrochemical cell. On most vehicles, NO_X can be inferred from NO. On diesel engines with continuous regenerating trap (CRT) particle filters, NO, NO_2, and NO_x can be inferred by simultaneous measurement of NO before and after the trap.

All pollutants were measured continuously, on a second-by-second basis. Although PM measurement capabilities have been recently added to some PEMS systems[5] they were excluded from the experimental setup because they were mutually exclusive with the measurement of other pollutants.

The vehicle exhaust gas was collected from the tailpipe using a repair-grade probe and sample line. Simultaneously, OBD data such as vehicle speed, engine rpm, intake air mass flow, coolant temperature, and other engine-operating parameters, were gathered. Using the intake air mass flow (or composition of intake air), measured composition of exhaust gas, and user-specified composition of fuel, a second-by-second exhaust mass flow was calculated from the on-board computer. Multiplying the exhaust mass flow by the concentrations of pollutants generates second-by-second emission data in grams[6], which are logged by the instruments.

Data models

This paper aims to demonstrate how the instantaneous data values from PEMS equipment may be used to develop engine emission maps which are subsequently used as input to a vehicle simulation model (ADVISOR). Additionally, the results are compared to the corresponding emission factors (based on average speed figures) from a comprehensive vehicle emission model (COPERT). The aforementioned models are briefly introduced in the paragraphs below.

ADVISOR

Advanced Vehicle Simulator (ADVISOR) is an analysis package for advanced vehicle modeling written in the Matlab/Simulink environment and developed by the National Renewable Energy Laboratory within the US Department of Energy. This tool may be used to predict the fuel economy and the emissions of vehicles equipped with combustion engines, and also those that use alternative technologies including fuel cells, electric motors, and internal combustion engines in hybrid (i.e. multiple power sources) configurations.

ADVISOR is fairly easy-to-use tool that relies on fundamental principles of vehicle dynamics and user-provided data regarding vehicle characteristics and engine performance to provide a backbone for detailed vehicle simulations. For the purposes of this research, *engine pollutant maps* were derived from PEMS data using software developed to that avail. This allows for the simulation and comparison of tailpipe emissions produced under a wide range of conditions (e.g. different regulated test cycles or user-created speed vs. time traces, including road gradient characteristics).

COPERT 4

COPERT 4 is a software program developed and maintained by the Laboratory of Applied Thermodynamics (LAT) at Aristotle University of Thessaloniki (Greece) which is aimed at the calculation of air pollutant emissions from road transport. It estimates emissions of all regulated air pollutants (CO, NO_X, VOC, PM) produced by different vehicle categories, and CO_2 emissions based on fuel consumption. COPERT is part of the EMEP/CORINAIR Atmospheric Emissions Inventory Guidebook[7] (AEIG), and it is used by several European member states (over twenty) in their official reporting of national emission inventories for road transport. Further details about the application of the COPERT methodology to the creation of traffic emission inventories can be found in the AEIG. In this study, only the hot-emission part of COPERT was used in the calculations, thus the cold-start effect of the vehicle at each trip was excluded.

Data analysis (CEMOD and INCERT tools)

Due to the difficulty of dealing with the large amount of data gathered during the experimental PEMS campaigns, the development of calculation tools to collect, screen and analyze the measured data was required. In line with this, two Matlab–based software applications and their corresponding graphical user interfaces (GUIs) were developed at LAT. The first one, 'CEMOD' (Creation of Engine Maps Using Optimized Data) is intended for the creation of engine pollutant maps using PEMS measurement data. The engine pollutant maps created are subsequently used as an input to ADVISOR. The second one, 'INCERT' (Interface for the Comparison of Emissions from Road Transport) was created for the comparison between the emission factors derived within COPERT and those from real-world operation data (PEMS). Both calculation tools were fed with experimental data collected from the experimental campaign conducted by the EC–Joint Research Centre (JRC), and relevant EFs were produced.

Creation of engine pollutants maps

The CEMOD software tool was developed for the creation of pollutant engine maps using the PEMS data provided by the JRC. A graphical user interface (GUI) guides the user through the process of creating pollutant engine maps to be subsequently used as input in ADVISOR, a Simulink–based application for vehicle simulation under various driving conditions.

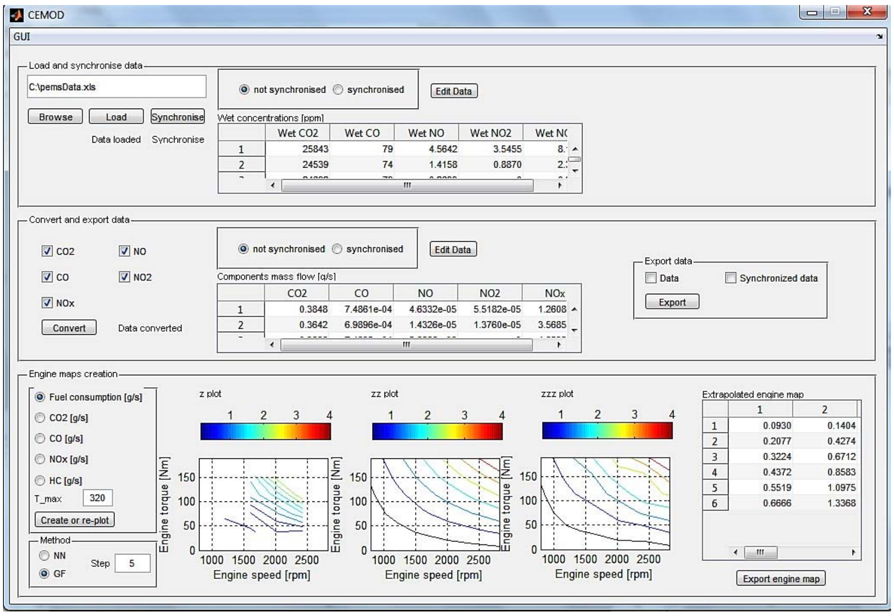
As a case study, a Fiat Bravo 1.6 JTD Euro 5–compliant diesel passenger car was employed, using the PEMS measurement datasheet obtained for the Ispra–Milano route. As mentioned earlier, this route is a mix of rural and highway conditions. The engine speed (in rpm), the actual engine torque and the friction torque of the vehicle, as well as the instantaneous pollutant emission, fuel consumption and vehicle speed values were recorded for the entire trip, on a second–by–second basis.

Because the actual emission signal measured by PEMS (or any other similar system) is distorted due to physical limitations of the measurement setup (e.g. the delay of transfer due to the length of the sampling line, mixing phenomena along the flow to the analyzer system, or the response times of the emission analyzers due to both their internal flow characteristics and electronics), the raw measured data had to be processed based on the algorithm previously created and validated by LAT. In particular, the algorithm performs a correction of the analyzers' signal to account for time lag and response[8]. This procedure ensures that the instantaneous emission values measured were corrected to their original values and time– aligned to the engine speed, as recorded by the vehicle's on–board diagnostics system (OBD).

Synchronized data for each pollutant measured (CO, HC, NO_X and CO_2) were then converted from ppm to grams per second in order to be used as input for the creation of the engine maps. A datasheet with the engine speed, the torque and each pollutant expressed in g/km was prepared, in which the highly transient operating modes were filtered out. Several attempts were made before reaching the optimal filtering of the data.

These 'optimized' data were then used as an input in Matlab, where a mesh was created through extrapolation of the available data points for engine speed, torque and the emission data calculated for each one of the pollutants measured. The pollutant engine map thus extrapolated (plot labeled as 'z_plot') is the first step of the creation of the engine map, which needs to be improved at those (usually several) points were the initial code fails to extrapolate. To solve this, a calculation approach based on a neural network calculation was taken, which extrapolates the proper values (zz_plot) based on the original engine map. Finally, CEMOD calculates the 'zzz_plot' (and its associated data points in tabular form), which is a combination of the 'z plot' and the 'zz_plot'. In ADVISOR, the user uses the 'zzz_plot' given by CEMOD as the input. Figure 1 presents an example of a fuel consumption engine map created using CEMOD.

Figure 1. CEMOD tool screenshot (FC engine map shown at the bottom).



The pollutant engine maps were used as an input in ADVISOR, along with all the relevant vehicle and route data (speed vs. time trace and road gradient as derived from GPS altitude measurements). Finally, the simulation of the trip (Ispra – Milano – Ispra route) was performed in ADVISOR, and the mean emission results were compared to those calculated from the original PEMS data. Moreover, the emission factors calculated for the trip using the INCERT tool (for which three different distance splits of 1, 5 and 10 km were considered) were compared side by side with those provided by COPERT for an equivalent trip.

RESULTS AND DISCUSSION

Results indicate a remarkable correspondence between EFs derived from PEMS data and those provided by the simulation of the corresponding route within ADVISOR, with excellent agreement for fuel consumption (FC). Adequate correspondence in the EFs is observed for HC and NOx, whereas CO exhibits the largest deviation. A summary of the comparison of the emission factors derived from PEMS data and those from the simulation within ADVISOR is provided in Table 2.

Table 2. Comparison of EFs derived from PEMS and ADVISOR.

	PEMS	ADVISOR	Deviation
FC	5.37 [l/100km]	5.4 [l/100km]	–1%
CO	0.169 [g/km]	0.129 [g/km]	24%
HC	0.0033 [g/km]	0.003 [g/km]	9%
NO	0.704 [g/km]	0.81 [g/km]	–9%

The pollutant engine map created was also validated using data from a different trip (Ispra–Varese–Ispra; a mix of urban and rural driving conditions). Results indicated a very good agreement between PEMS data and the simulation within ADVISOR, exhibiting very similar deviations to those found for the trip to Milano (in the order of –2%, 21%, 9% and –9% for FC, CO, HC and NOx, respectively).

Table 3 presents the mean values for the EFs calculated from PEMS data (using three different distance splits in INCERT) and those provided by COPERT for the corresponding mean speeds, along with the deviations found among them.

Table 3. Mean values for PEMS and COPERT EFs

	CO [g/km]			NO_x [g/km]		
	PEMS	COPERT	Deviation	PEMS	COPERT	Deviation
10–km split	0.150071	0.046143	225%	0.674771	0.375064	80%
5–km split	0.154252	0.046511	232%	0.697248	0.402322	73%
1–km split	0.154485	0.046629	231%	0.69461	0.430735	61%

	HC [g/km]			FC [g/km]		
	PEMS	COPERT	Deviation	PEMS	COPERT	Deviation
10–km split	0.003251	0.004821	–33%	43.66594	46.23593	–6%
5–km split	0.003367	0.00497	–32%	45.08184	47.11497	–4%
1–km split	0.003341	0.005203	–36%	44.95022	48.34256	–7%

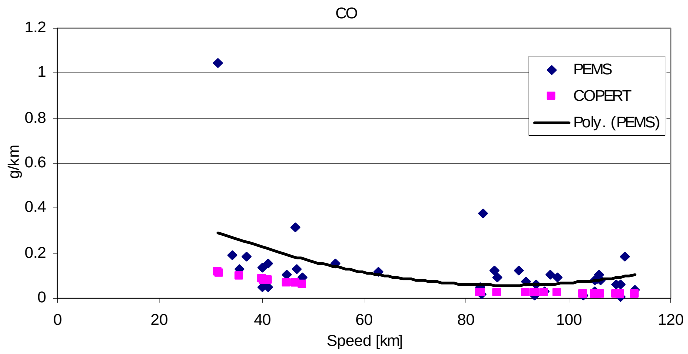
Concerning *CO emission* levels (Figure 2), both COPERT and PEMS EFs present similar trends (e.g., they decrease as mean speed increases). Vehicle emissions measured using PEMS are in this case higher than those predicted by COPERT, with deviations reaching levels beyond 200%. However, the corresponding emission standard for Euro 5 diesel vehicles is in the order of 0.5 g/km, which is well above the CO emission levels measured for the vehicle. It should be noted that the1600cc engine of the PEMS diesel vehicle is of relatively low capacity compared to the engines of the vehicles that were used for deriving the average emission factors for COPERT.

The *HC emission* levels (Figure 3) remain low during low, medium and high average speed conditions. However, some emission events were recorded in which emission levels approached the value of 0.1 g/km. On the other hand, the values provided by COPERT suggest that HC emission levels under urban driving are higher than those under rural driving. Furthermore, the deviation between COPERT values and the measured data remains practically constant in the 60–100 km/h speed range.

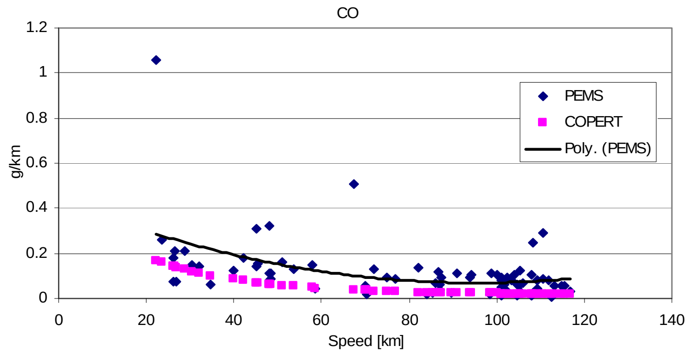
The evolution of measured NO_X *emissions* with speed follows a pattern that is similar to COPERT results (Figure 4). The emission levels recorded appear to be approximately 60% higher than COPERT values. This increase may be attributed to higher load operation (for example possible uphill driving, which is not accounted for in COPERT).

Fuel consumption was found to be lower compared to the COPERT values (Figure 5). Again, in this case this may be attributed to the fact the vehicle measured was of relatively low engine capacity, size and weight. Such vehicles are poorly represented within the emission factors provided by COPERT, which is based mainly on larger diesel vehicles. Engine downsizing and small capacity diesel engines are new features introduced in the European vehicle market in order to tackle CO_2 emissions. This indicates that new vehicle categories of lower engine capacity need to be included in COPERT.

Figure 2. Comparison between CO EFs derived from PEMS data and COPERT model results for a) 10 km, b) 5km and c) 1 km splits.



a)



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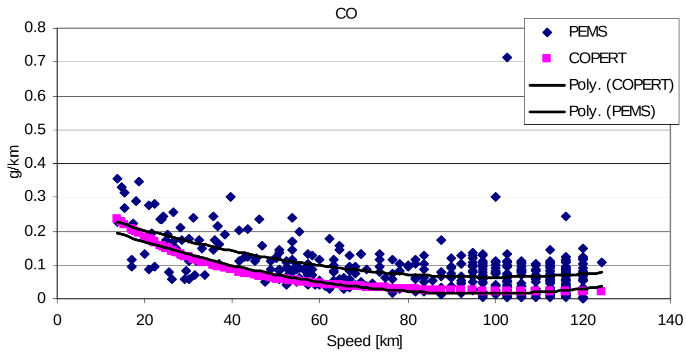

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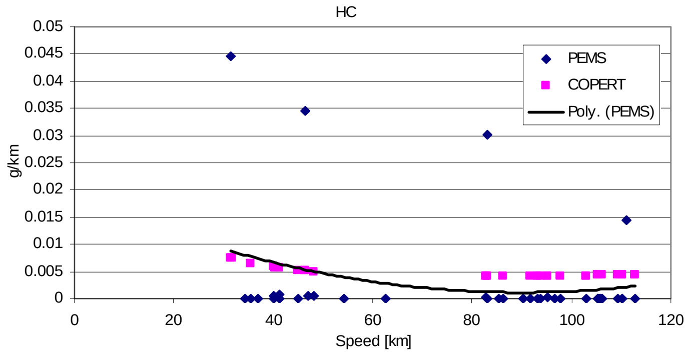
Figure 3. Comparison between HC EFs derived from PEMS data and COPERT model results for a) 10 km, b) 5 km and c) 1 km splits.



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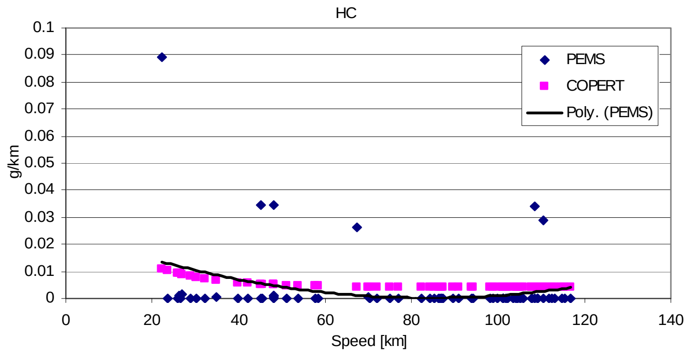

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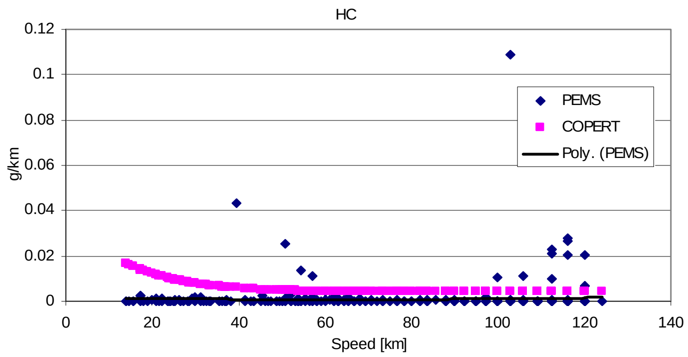
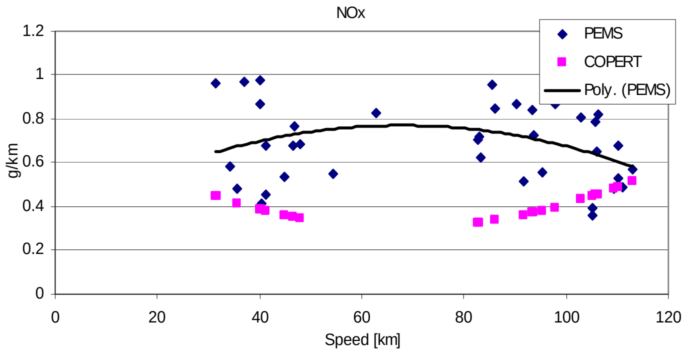


c)

Figure 4. Comparison between NO_x EFs derived from PEMS data and COPERT model results for a) 10 km, b) 5 km and c) 1 km splits.



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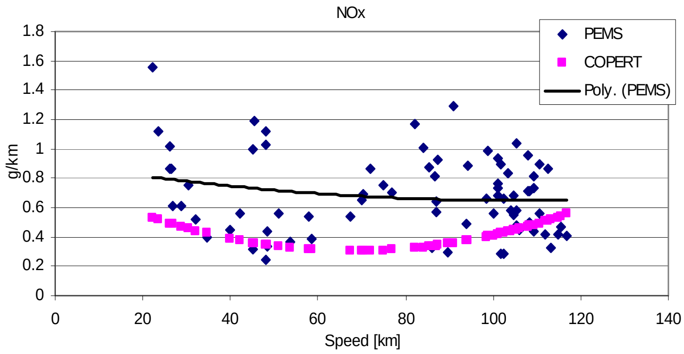

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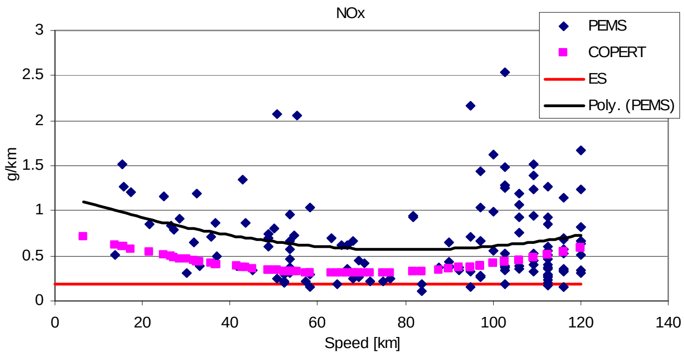
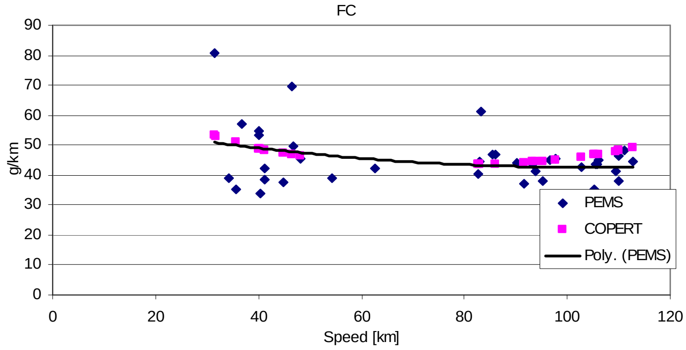
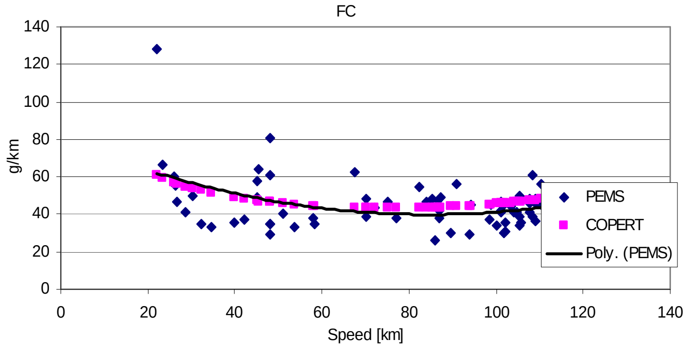


c)

Figure 5. Comparison between FC EFs derived from PEMS data and COPERT model results for a) 10 km, b) 5 km and c) 1 km splits.



a)



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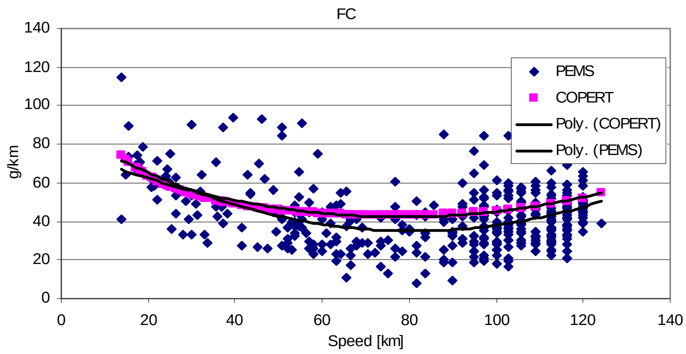

c)

CONCLUSIONS, RECOMMENDATIONS AND PERSPECTIVES

On–board PEMS instrumentation measurements are a valuable tool which can help characterize the emissions of regulated pollutants of light–duty vehicles over a full range of on–road driving states. With this type of setup, the emission and fuel consumption characteristics of vehicles can be tested during idling, cruising, accelerating and decelerating modes, on congested versus non–congested roads, and on uphill versus downhill roads. There is, however, some trade–off in that the PEMS measurement methods may not be as accurate or precise as those of the more complex and expensive equipment used in more permanent laboratory installations. These shortcomings can be reasonably expected to be overcome as PEMS measurement technology improves over time.

Due to the high costs involved, PEMS measurement campaigns are typically deployed on a small number of vehicles in any study, rendering them insufficient for the derivation of technology–specific emission factors as those found in COPERT. For this reason, PEMS measurements made during real–world vehicle operation are best used for validating existing emission factors or making relative comparisons of emissions.

In the comparison made in this study, a good agreement is found between PEMS and COPERT EF values. It is worth noting that, in the case of NO_X, both measured and simulated values are well above the applicable emission limit v (0.18 g/km) with 0.69 g/km (i.e. 3.8 times above the limit) for PEMS and 0.43 g/km (i.e. 2.4 times above the limit) for COPERT (average emission factors over 1 km distance splits). NO_X emission levels for this specific Euro 5 diesel vehicle were consistently higher (in urban, rural and highway driving) than the corresponding EF for Euro 1 diesel passenger cars. This raises a serious concern regarding the actual NO_X emissions of modern vehicles when driven outside type approval tests such as the New European Driving Cycle (NEDC).

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