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Application and Quality Assessment of an Instantaneous Vehicle Emission Model at Fleet Level

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Abstract A developed instantaneous emission model is applied to predict emission factors for small vehicle fleets for quality assessment. Extensive vehicle measurements of pre-Euro-1 gasoline, Euro-3 gasoline, and Euro-2 diesel vehicles are available. The data were used to develop individual vehicle emission models for each car. The prediction quality for each vehicle category was determined by averaging the results obtained from the individual vehicle models. The results show that the prediction quality is improved in comparison with the individual vehicles, even with a small number of vehicles in a specific category. This indicates that the errors in the individual models are mainly random and that prediction quality, when applied to fleets of cars, is exceptionally high.

Keywords Instantaneous emission model · Pollutants · Vehicle fleet · Emission factors

1 Introduction

For more than a decade, attempts have been made to store or map emission measurements from tests on chassis dynamometer or engine test benches in a neutral manner, so that emissions of other driving conditions can be calculated from them. In this paper, a new model is presented, focusing in particular on its prediction quality for small fleets of cars.

The number of vehicle emission models has increased significantly in recent years. There are a variety of emissions and fuel consumption models derived for different spatial and temporal scales. These models can be roughly categorized into two main groups of increasing level of complexity: (a) bag emission models [7, 10–12, 14, 17, 19] and (b) instantaneous emission models [1, 3–6, 9, 13, 15, 18], some are combinations [8, 20]. Emission models are used to derive international, national, and regional emission inventories using measurements performed in emission laboratories and to predict the impact of different traffic-related measures.

Bag measurements represent the statutory method of determining the mass of emissions (CO, CO_2, THC total hydrocarbons, NO_x) generated over a statutory cycle. This procedure consists of drawing the entire content of the tailpipe exhaust into a constant volume sampling system, where it is diluted with fresh air, and a representative sample is afterwards put into bags. The analysis of the bags provides a single overall figure for each emission, representing the total mass of emissions produced over the driving cycle.

In instantaneous (modal) vehicle emission measurements, the emissions and other vehicle-related data (vehicle speed, engine speed, etc.) are collected at high time resolution (1 to 10 samples/s). When integrated over a driving cycle, the instantaneous emissions data should be equivalent to the bag results.

Emission models based on bag values provide results for traffic situations similar to that used to fill the bag. If driving behavior changes, new measurements involving similar patterns have to be performed. Moreover, the effect of contributory aspects such as load, slope, or gearshift strategy is modeled using correction functions. Due to cost reasons,

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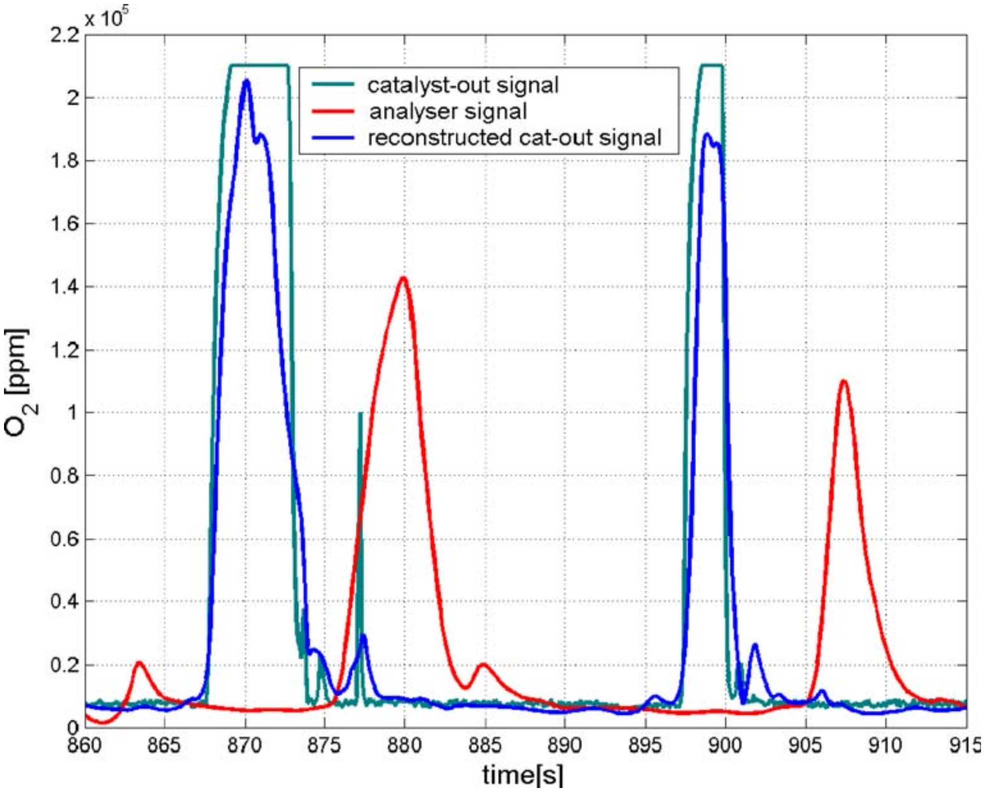
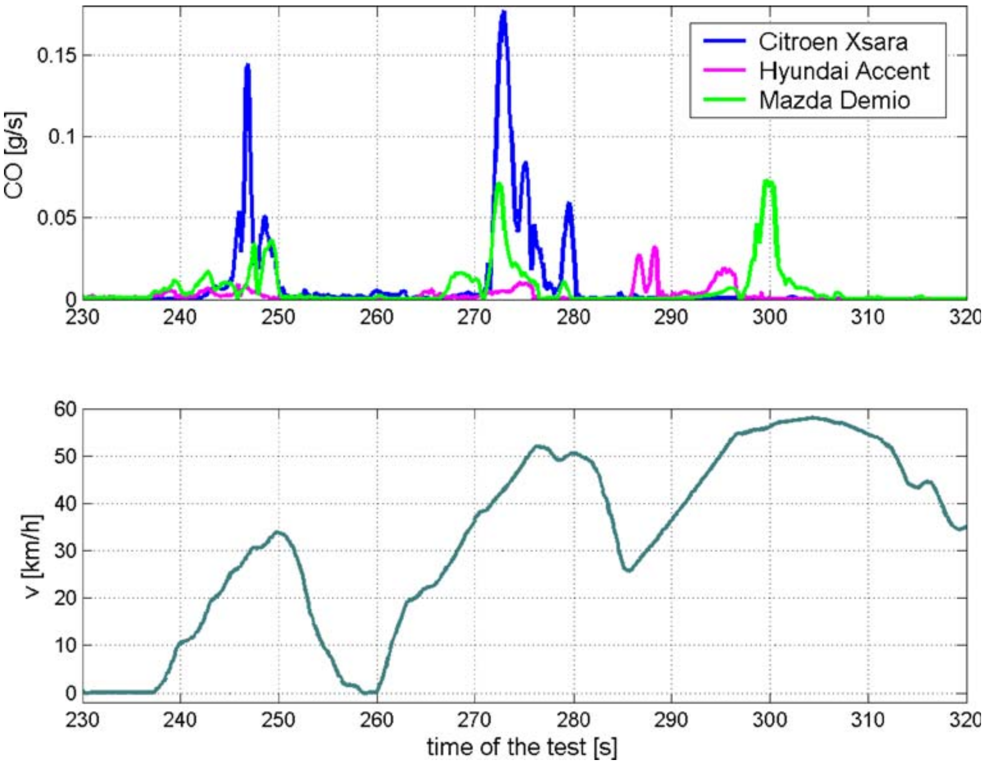
Fig. 1 Inversion from the analyzer to the catalyst-out



however, these correction functions are usually based on a small number of measurements with a small number of vehicles, which may not be representative of emission behavior, and the results may therefore be misleading.

Emission models based on bag data are often used for medium- and large-scale emission estimates (i.e., countries, regions, etc.). This type of approach has the distinct advantage of being simple and easy to apply in emission estimations.

Fig. 2 Comparison of CO emissions from three Euro-3 gasoline vehicles for the same speed profile



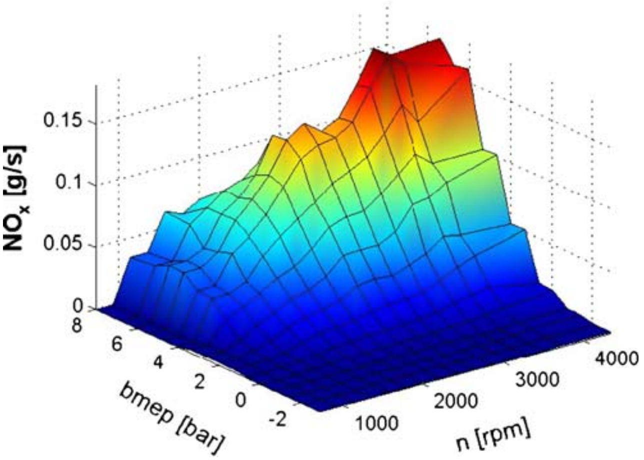


Fig. 3 NO_x emission map for a pre-Euro-1 gasoline vehicle

However, bag-based data are often inadequate to assess the emissions impact of various transportation management schemes, transportation control strategies, or inspection/ maintenance programs contained in most air quality management plans. What is needed alongside these macroscale models is an emission model that takes into account the instantaneous operating conditions of the vehicles (i.e., emissions that relate directly to vehicle operating situations such as idle, acceleration, deceleration, etc.).

Instantaneous emission modeling maps the emissions at a given time to their generating "engine state," such as vehicle speed, engine speed, torque, etc. This makes it possible to integrate new, unmeasured patterns over the model and to calculate their emission factors without further measurements. Emission factors for a large number of driving situations can therefore be determined from a small number of measurements. Moreover, contributory aspects such as vehicle load, slope, or different gearshift strategies can be included without introducing ambiguous correction functions as in the case of bag-based models.

Most of both bag-based and instantaneous emission models average measured emission values from groups (fleets) of cars as a first step and afterwards create the mathematical model (i.e., maps, functions) that links input variables to emission values for that average car. However, as these mathematical connections are strongly nonlinear and each vehicle behaves differently (Fig. 2), higher accuracy is reached when each vehicle is modeled individually, and only the model output is averaged to generate fleet emission values [3].

In the present paper, the accuracy of a developed instantaneous emission model [3] is identified for fleets of vehicles. As this model is based on individual models for each vehicle, it has to be verified whether the error of averaged results is similar to the errors of the individual models (the worst case, as modeling errors would be systematic) or whether the errors are reduced when averaging individual results (the best case, as accuracy will increase with higher numbers of available cars). Section 2 presents details of the measurement program and the methodology. Using the developed instantaneous emission model, the prediction quality of the emission factors for each vehicle category is analyzed in Section 3. The results show that the individual errors are random and that the error at fleet level is smaller than for the individual cars.

2 Methodology

In most instantaneous emission models, the emission signals and all other information from the tests are collected at a rate of 1 to 10 samples/s, and the mapping of emissions is performed by relating them to causative variables such as speed, acceleration, torque, engine power, etc. [1, 3–6, 9, 13, 15, 18].

It has been shown [8] that due to the frequency content of both emission signals and engine-related signals (torque, manifold pressure, etc.), the sampling frequency of the measurements should be 10 Hz or faster.

The mapping of instantaneous emissions is mostly performed by statically relating the emission signals for each time span to their causative variables, such as vehicle speed, torque, engine speed, etc. [16, 22]. As a result of this static approach, the emission values can be correlated to the correct engine state of the car only if they are at the correct location on the timescale. However, the original signals measured in a test are delayed in relation to their site of formation, due to transport from the engine to the analyzers. If these dynamic aspects of exhaust transport are disregarded, disregarded, the emission events are correlated to "the wrong second," resulting in incorrect engine status in emission modeling.

The transport dynamics from the engine to the analyzers must therefore be compensated by time-varying approaches.

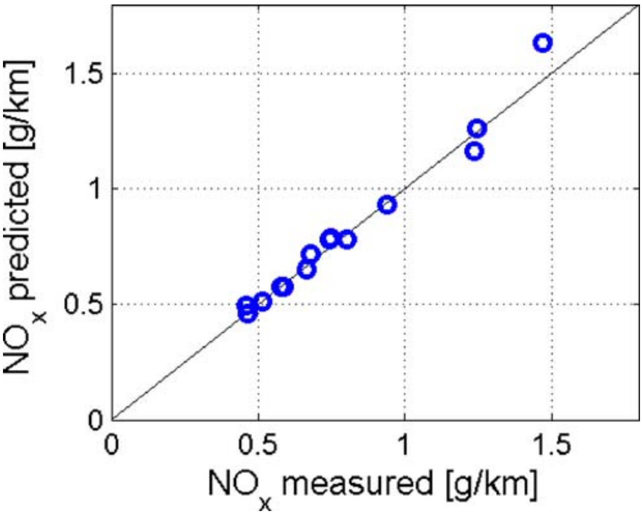


Fig. 4 Validation chart for a diesel car of Euro-2 level. Model output compared to measurements

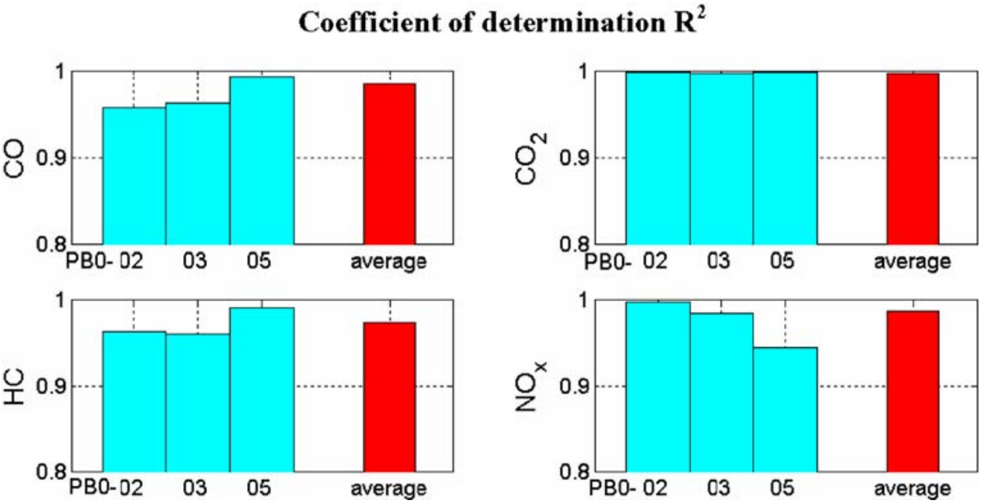


Fig. 5 Coefficient of determination (R^2) for the pre-Euro-1 gasoline vehicles (*blue*) and for the group of pre-Euro-1 gasoline cars (*red*)

Using a method presented elsewhere [2, 21], the signals at their site of formation (catalyst-out or engine-out) can be reconstructed using the signal recorded at the analyzer with a time quality of about 0.8 s (Fig. 1).

Additionally, because emissions show scattered and nonlinear behavior from vehicle to vehicle (Fig. 2), the emission maps should be developed at individual vehicle level, and the resultant emission factors for the driving pattern considered should afterwards be averaged for each vehicle class.

In the model considered here for diesel and carburetor vehicles, and presented in more detail in [8], the mapping variables are brake-mean-effective pressure (*bmep*) and engine speed (n). Brake-mean-effective pressure can be considered as "scaled" engine torque size because:

$$bmep = \frac{4\pi \cdot T_\mathrm{e}}{V_\mathrm{d}},$$

where V_d denotes the displacement volume of the engine, T_e is the engine torque, and 4 is the number of strokes per engine cycle. Brake-mean-effective pressure is thus equal for different engines when running at similar operating points (unlike torque) and is useful for the comparison of different cars.

For gasoline cars equipped with fuel injection and three-way catalysts, the engine model needs to be extended by considering as an additional variable the derivative of manifold pressure, $\dot{p}$. This variable, which is strongly correlated to the derivative of torque, is necessary, as high emissions occur mainly during transients for these vehicles. In this way, a three-dimensional emission matrix is developed for modern gasoline cars. This matrix provides the instantaneous emissions and fuel consumption for different combinations of instantaneous n, *bmep*, and $\dot{p}$.

For model development and validation, data from 3 classical gasoline vehicles of pre-Euro-1 level, 10 gasoline cars with three-way catalyst of Euro-3 level, and 7 Euro-2 diesel vehicles were available. Each car was measured using a program that includes 16 different real-world driving cycles. Each of the considered cycles accounts for

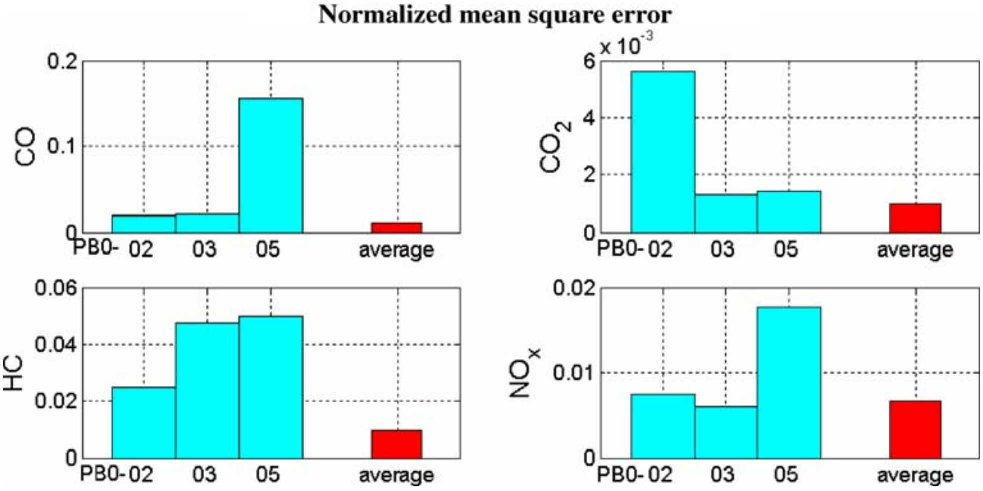


Fig. 6 Standard mean square error for pre-Euro-1 gasoline vehicles (*blue*) and for the group of pre-Euro-1 gasoline cars (*red*)

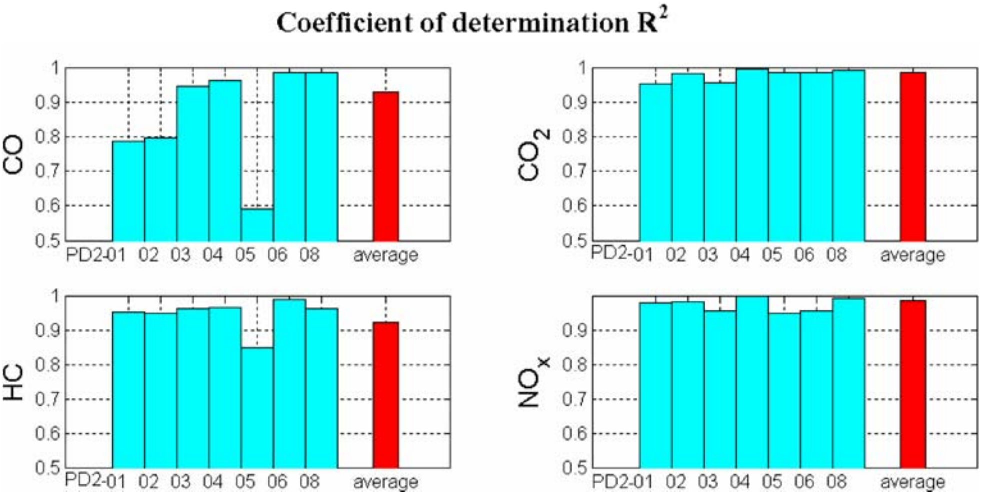


Fig. 7 Coefficient of determination (R^2) for Euro-2 diesel vehicles (*blue*) and for the group of Euro-2 diesel cars (*red*)

a different driving pattern, such as urban, rural, highway driving, combined with free-flow, dense, congested traffic, etc. Besides the exhaust emissions, all relevant parameters (e.g., vehicle speed, manifold pressure, engine speed, etc.) were recorded on a 10-Hz basis.

One of the advantages of mapping using dynamic real-world driving cycles is that this model is not restricted to pure steady-state emission maps and transient correction functions as in some other approaches. Emission events that are related to the transient operation of the vehicles can therefore be modeled more appropriately.

An *n-bmep* (or *n-bmep-*$\dot{p}$ or the Euro-3 cars) matrix was set up for each emission (Fig. 3). In each cell of this matrix, the emission or fuel consumption rates are averaged to give a mean value. Instantaneous emissions and fuel consumption are afterwards estimated by selecting values from the corresponding combination of *n* and *bmep* (and $\dot{p}$, where applicable).

Such maps were created for the fuel consumption and emissions of CO, CO_2, HC, and NO_x using the same time basis as for the input signals. The basic model outputs are the instantaneous fuel consumption and emissions at their sites of formation (catalyst-out or engine-out, depending on the vehicle category). Emission factors (in g/km) of the considered driving patterns are determined by integrating the instantaneous signals with respect to time and afterwards dividing by the distance driven.

3 Results and Discussion

A cross-validation method was used for model verification. A set of 15 of the measured cycles was used to develop the vehicle emission maps, and the 16th remaining cycle was used for verification of the model. Validation data were consequently not available for model parameterization. This

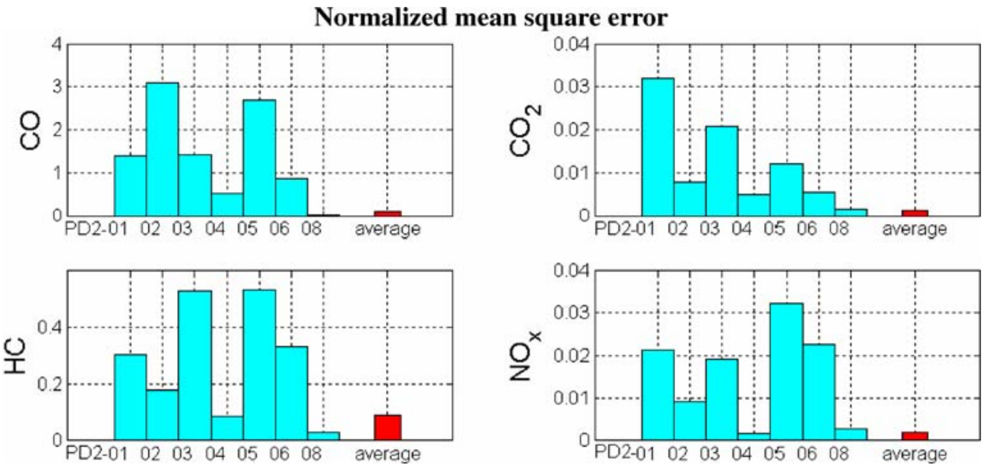


Fig. 8 Standard mean square error for Euro-2 diesel vehicles (*blue*) and for the group of Euro-2 diesel cars (*red*)

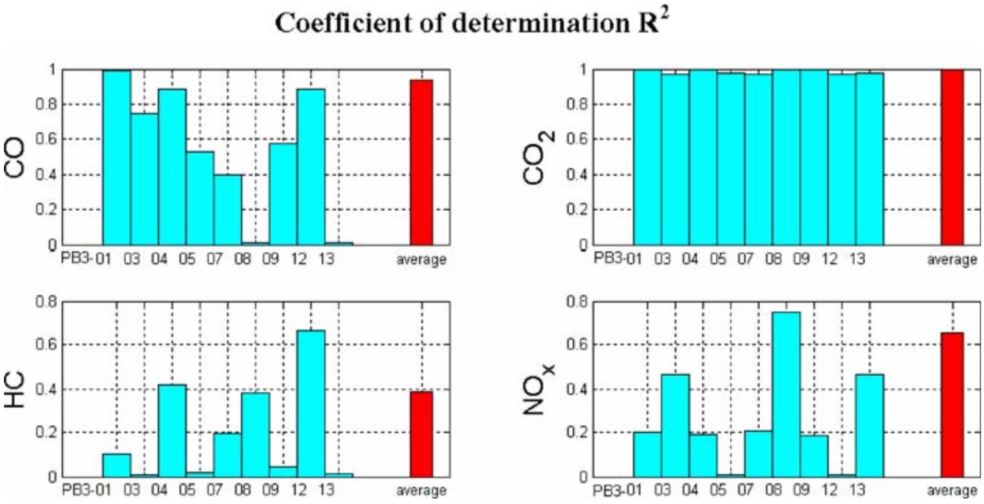


Fig. 9 Coefficient of determination (R^2) for the Euro-3 gasoline vehicles (*blue*) and for the group of Euro-3 vehicles (*red*)

was done for all the cars, choosing different cycles as verification cycles.

To compare the model output of all validation cycles to the measured values for each car, figures as in Fig. 4 are plotted for each pollutant. In a perfect model, the predictions would be identical to the measured values, and all the dots would therefore be on the 45° line. The vertical difference between the marks and the 45° line indicates the model error.

For application of the model to fleets of cars, i.e., to a vehicle class, the model output of all vehicle models of a certain vehicle category is averaged. These mean values may be compared to the mean measurement output in analog plots, as in Fig. 4. The main question to qualify the overall model quality (and thus its applicability) is whether the averaged values show less error than the values of the individual vehicle model. If so, the model errors for the different cars have a random element. Otherwise the model error would be systematic. This would mean, for example, that the emissions of "calm" cycles are overestimated and emissions of "aggressive" cycles are underestimated, as for older models. As a result, models would not be usable to compare the effect of traffic measures such as traffic light synchronization.

To quantify the error (or conversely, prediction quality) of the model, several statistical measures may be used for each vehicle and pollutant (i.e., for each of the plots as in Fig. 4):

- The normalized mean square error, $\mathrm{NMSE} = \overline{\left(E_\mathrm{m} - E_\mathrm{p}\right)^2} / \left(\overline{E}_\mathrm{m}\overline{E}_\mathrm{p}\right)$.
- The coefficient of determination, $R^2 = \overline{\left(E_\mathrm{m} - \overline{E}_\mathrm{m}\right) \cdot \left(E_\mathrm{p} - \overline{E}_\mathrm{p}\right)}^2 \Big/ \left(\sigma_\mathrm{m}\sigma_\mathrm{p}\right)^2$.

Here, E_m and E_p represent the measured and predicted emission factors for all 16 cycles, $\overline{E}_\mathrm{m}$ and $\overline{E}_\mathrm{p}$ denote the mean values, and σ_m and σ_p are the corresponding standard

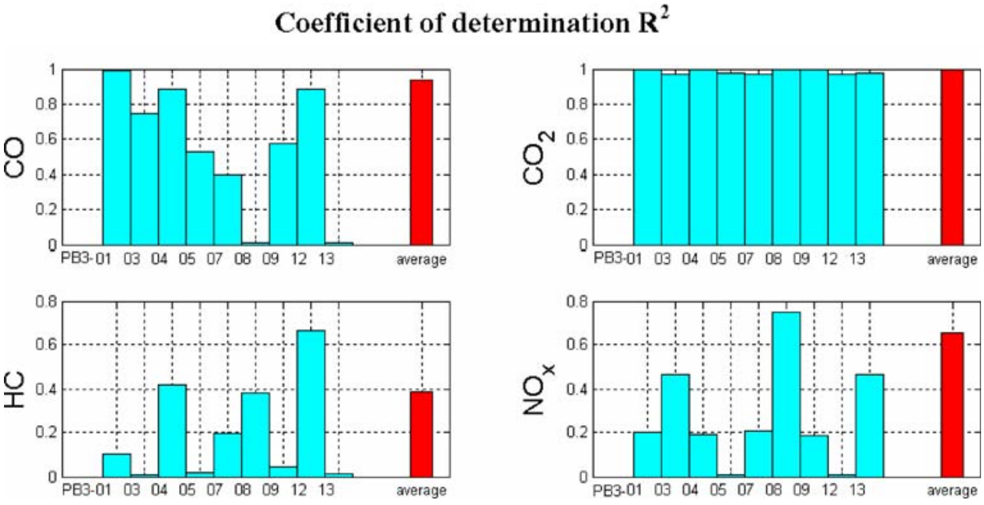


Fig. 10 Standard mean square error for Euro-3 gasoline vehicles (*blue*) and for the group of Euro-3 gasoline cars (*red*)

deviations of each vehicle. While NMSE should become small for an accurate model, R^2 has to tend to 1.

Figures 5, 6, 7, 8, 9, and 10 show these statistical measures for each individual vehicle and for each vehicle class. As they illustrate, prediction quality is excellent for CO_2 in the case of all vehicles (with an R^2 always higher than 0.90). For the other pollutants, prediction is still excellent in the case of pre-Euro-1 gasoline vehicles and Euro-2 diesel cars, for both individual and average vehicles. Although a more complex model has been considered for Euro-3 gasoline vehicles, the prediction quality is only satisfactory (R^2 for HC-prediction=0.4), which can be explained by the fact that catalytic behavior should be modeled separately for this category.

Nevertheless, as the figures show, the individual errors are reduced by averaging. For all vehicle classes, the error becomes smaller, in the sense of a lower average error (smaller NMSE value) and higher correlation (larger R^2), when compared to individual vehicles.

This analysis shows that the prediction of emissions for single cycles can be achieved with reasonable accuracy with this model. It thus appears possible to use this model for emission prediction at local levels such as for individual streets and districts, an issue that is becoming more and more important for local authorities dealing with “hot spots” where air quality limits are regularly exceeded. Obviously, when the results of different cycles are added together, it will also predict emissions at regional or national levels. With this ability to predict local emissions accurately, this model might be an important complement to the bag-based models that predict emissions for large areas only. As input to this accuracy at local level, the more complex online measurement has to be calculated.

As a comment on the above figures, it should be noted that the notation of vehicles follows EMPA rules on designating cars.

4 Conclusions

Considering fleets of vehicles, the accuracy of the instantaneous emission model improves when compared to the models for individual vehicles, even with a small number of vehicles at a specific category. This shows that the errors in the individual vehicle models are mainly random. The results emphasize that instantaneous emission models, although fairly complex to develop, can be used at both microscale and macroscale levels.

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