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Emission factors for passenger cars: application of instantaneous emission modeling

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Abstract

This paper discusses the use of 'instantaneous' high-resolution (1 Hz) emission data for the estimation of passenger car emissions during real-world driving. Extensive measurements of 20 EURO-I gasoline passenger cars have been used to predict emission factors for standard (i.e. legislative) as well as non-standard (i.e. real-world) driving patterns. It is shown that emission level predictions based upon chassis dynamometer tests over standard driving cycles significantly underestimate emission levels during real-world driving. The emission characteristics of modern passenger cars equipped with a three-way catalytic converter are a low, basic emission level on the one hand, and frequent emission 'peaks' on the other. For real-world driving, up to one-half of the entire emission can be emitted during these short-lasting peaks. Their frequency depends on various factors, including the level of 'dynamics' (speed variation) of the driving pattern. Because of this, the use of average speed as the only parameter to characterize emissions over a specific driving pattern is not sufficient. The instantaneous emissions approach uses an additional parameter representing engine load in order to resolve the differences between driving patterns with comparable average speeds but different levels of 'dynamics'. The paper includes an investigation of different statistical indicators and discusses methods to further improve the prediction capability of the instantaneous emission approach. The fundamental differences in emission-reduction strategies between different car manufacturers make the task of constructing a model valid for all catalyst passenger cars seemingly impossible, if the model is required to predict both fleet-averaged emission levels and emission factors for driving patterns of short duration for individual vehicles simultaneously.

Keywords: Emission factors; Real-world driving behavior; Instantaneous emissions; Standard driving cycles; Catalyst cars; Modal modeling

1. Introduction

Most of the emission factors used in models depend upon the average travel speed (e.g. Eggleston et al., 1992; Samaras et al., 1998). However, recent studies show a difference between emission factors derived from chassis dynamometer measurements with standard driving cycles, compared to dynamometer test of driving conditions originating from on-road measurements (e.g. Joumard et al., 1995; Sturm et al., 1997). Such differences appear to occur when the amount of fluctuation of the instantaneous speed with respect to the average travel speed differs. For example, Hansen et al. (1995) allow for the fact that speed fluctuation is very important for determining vehicle emissions by introducing the ratio of the official speed limit to the effective travel speed as an additional model parameter.

Standard (legislative) driving cycles like the new European driving cycle (NEDC) consist of an artificially created driving speed time series with very few speed fluctuations. It should be investigated whether such standard driving cycles are representative for real-world driving behavior and, hence, emission level. It is not clear a priori whether any emission model, including instantaneous emission models, could predict real-world

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emission levels based on NEDC measurements only. Possibly, the amount of speed fluctuations (i.e. driving 'dynamics') influences the resulting emission levels in a way that is difficult to model explicitly. This would mean that real-world driving cycles should be measured on the test-bench directly.

The influence of speed fluctuation on emission levels is particularly important for micro-scale applications of emission models. For national emission estimates, one could try to use applied correction factors to take such effects into account. Emission modeling applied to the level of single streets, however, should be able to properly resolve this effect with high temporal resolution in order to address questions like how traffic calming or speed limits affect the emission level of passenger cars.

This paper deals with the issue of real-world emission level forecasting for gasoline passenger cars using instantaneous emission models. The focus is on vehicles equipped with three-way catalytic converters. Extensive measurements of 20 EURO-I gasoline vehicles with catalytic converters were available, with several hours of 1 Hz measurement data per vehicle for most standard (i.e. legislative) driving cycles and a wide range of real-world cycles. Section 2 presents a short overview over current research on instantaneous emission modeling. The emission characteristics of EURO-I gasoline passenger cars, which significantly differ from cars without closed-loop catalytic converter, are briefly discussed in Section 3.

Sections 4 and 5 address the differences in emission level between standard driving cycles and real-world driving patterns and show that using measured real-world emission data significantly improves the prediction capability of instantaneous emission models. The apparently chaotic emission behavior of modern gasoline passenger cars (together with the fact that the amount of speed fluctuations influences the emission factor) calls for the development of instantaneous emission models specific for each individual vehicle, if the aim of the emission model is to predict the emissions on a second-by-second basis. This is further discussed in Section 6.

2. Instantaneous emissions approach ('modal modeling')

Currently, several approaches aim at refining emission models for road traffic by including additional parameters. The terms 'modal', 'on-line', 'instantaneous' and 'continuous' emission modeling are often used as synonyms. The classical 'modal modeling' approach distinguishes between single 'modes' typical for traffic regimes. For example, Cernushi et al. (1995) distinguish the operational modes idle, constant speed, acceleration, and deceleration. Pela and Yotter (1995) use the variables 'power', 'positive kinetic energy', 'acceleration' and 'idle' to identify different operating modes of vehicles. Washington et al. (1998) discuss a method to forecast joint distributions of modal activity, i.e. of speed and acceleration, needed as input to such modal models. Emission data from chassis dynamometer tests are then subdivided into discrete acceleration ranges and analyzed in terms of their dependence on speed.

Joumard et al. (1995) also use 'modal' parameters (average travel speed, and average value of the product of the instantaneous values of speed and acceleration), but the underlying measurements are 1 Hz data. Jost et al. (1992) present this approach, where the emission prediction on a second-to-second basis is derived from the instantaneous speed and the rate of acceleration (which in turn is derived directly from the instantaneous speed). Total emissions for any driving pattern are obtained by summation of the values for each second.

Sturm et al. (1997) also introduce the acceleration as second parameter along with the instantaneous speed. All recorded emission data is put into bins, i.e. intervals of instantaneous speed and instantaneous acceleration. Each two-dimensional bin constitutes a cell of a so-called emission matrix. For emission forecasting, the appropriate cell of the emission matrix is determined for every second-by-second combination of speed and acceleration during the driving pattern in question. The total emission again is the sum of the cell values for each second. Sturm et al. (1998) compare the use of acceleration alone as the second parameter against using the product of acceleration and speed, and also assess the effect of different sizes of the cells of the emission matrix.

The so-called Handbook on emission factors for road transport (abbr. HBEFA; SAEFL, 1995) presents emission factors for all current vehicle categories for a wide variety of traffic situations for many different pollutants. The underlying model used to compute these emission factors (Jost et al., 1992) parameterizes the instantaneous emission with its speed and the variable speed × acceleration. The emission data originating from dynamometer measurements are grouped into emission matrices, where the individual cells of the matrix stand for speed and speed × acceleration intervals of $10\,\mathrm{km\,h^{-1}}$ and $5\,\mathrm{m^2\,s^{-3}}$, respectively.

All the approaches listed above introduce a new parameter in addition to the average travel speed. For older passenger cars (without catalytic converters, or with open-loop catalysts), the emission level is, roughly speaking, a function of the engine load, which can, in turn, adequatly be parameterized by the average speed. So for vehicle fleets with a low share of three-way catalyst cars, the average speed approach works more or less (see, e.g., Jensen (1995) who concludes that for a study conducted 1989 the average travel speed proved to be a good parameter in statistically describing emissions).

This paper argues that for modern catalyst gasoline cars, this does not hold true. The argument is based on an analysis of emission data with a high time resolution from vehicles measured within the HBEFA framework.

Emissions were sampled over time intervals of 0.2 s, the average of five subsequent intervals was used to obtain 1 s averages of the emission level (see, EMPA (1997) for more details). For every second of the emission measurements, the travel speed and the acceleration were determined (computationally derived from the speed). The emissions from 12 different real-world driving patterns from the EMPA (1997, 1998) studies are reported here. These driving patterns were derived from on-road recordings of real-world driving. These recordings were made within the SAEFL (1995) framework, and are described into more detail in EMPA (1997).

3. Emission behavior of gasoline catalyst cars

This section outlines the fundamental differences between modern EURO-I vehicles equipped with three-way catalytic converters and older vehicle concepts (without converter, or with simple open-loop catalysts). Diesel vehicles are not considered. The analysis is based on the extensive measurements of 20 EURO-I vehicles as described in EMPA (1997). The measurements show that catalytic converter cars are entirely different from older vehicles; some 50% of all emissions are emitted during very short episodes. These emission 'peaks' occur during gear changing and high power intervals, they also often appear to happen without any cause. Fig. 1 shows an example for a single vehicle which is representative for all 20 vehicles for which measurements are available.

The strategies of tailpipe exhaust gas after-treatment differ among car manufacturers. EURO-I emission legislation requires the presence of a three-way catalytic converter in combination with a lambda sensor. By means of an electronic feedback mechanism based on the measured lambda ratio, the injection of fuel is regulated. Due to the different response times of the lambda sensor, the catalytic converter, and the electronic unit of the vehicle, the system as a whole shows adaptation time delays up to several seconds after sudden changes in the driving condition. The different concepts used show up when comparing exactly the same real-world driving pattern for different vehicles. The example depicted in Fig. 2 shows four vehicles out of the EMPA (1998) ensemble for a part of a real-world driving pattern. Large discrepancies between different vehicles can be observed. This can be considered trivial, since vehicles from different manufacturers with different exhaust gas after-treatment systems have been measured. But these discrepancies are not trivial to instantaneous emission modeling: The different instantaneous emission values of these vehicles coincide with the same speed and acceleration; hence the differently behaving emission time series of Fig. 2 will, second by second, be put into the same cells of the emission matrix.

Figs. 3 and 4 show data taken from a special test program (EMPA, 1994) in which driving cycles with constant speed were reproduced on a dynamometer. Although travel speed was constant and no accelerations occurred, the emission behavior was very unsteady. Some of the vehicles in question showed pronounced NO_x fluctuations on time scales of roughly 10 s. Fig. 3 depicts the fluctuation of NO_x emissions on time-scales of roughly 10 s for a constant high driving speed of 115 km h^{-1}. This behavior is possibly caused by internal response and adjustment times of the exhaust gas after-treatment system, and not by the instantaneous speed and/or acceleration. Such fluctuations can be observed not only for NO_x. Other vehicles showed periodical fluctuations in the CO and HC pollutants, with NO_x showing minor fluctuations on a low level only. Fig. 4 shows fluctuating CO and HC emissions, again for a constant high driving speed of 110 km h^{-1}.

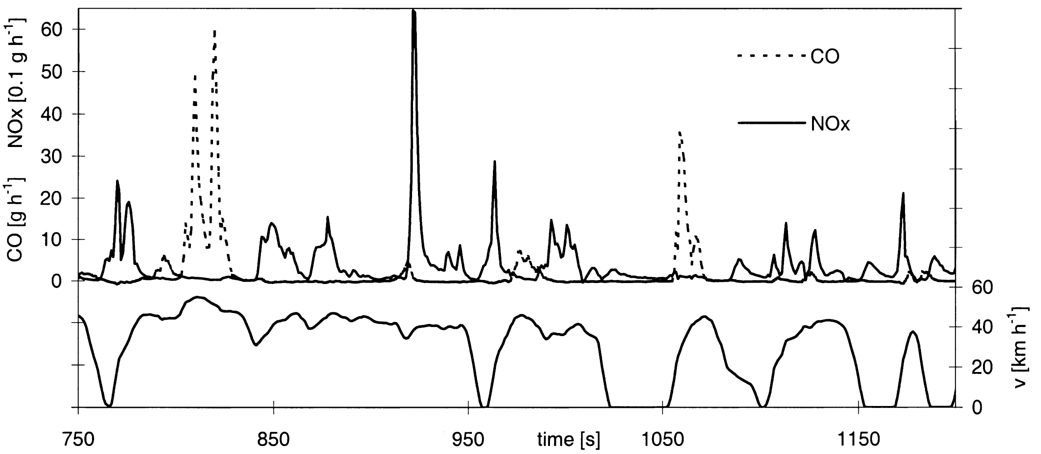

Fig. 1. Emission peaks of a gasoline catalyst car. Example depicted: BMW 318i. The corresponding speed time series is shown in the lower part of the graph and taken from the warm part of the FTP-75 driving cycle.

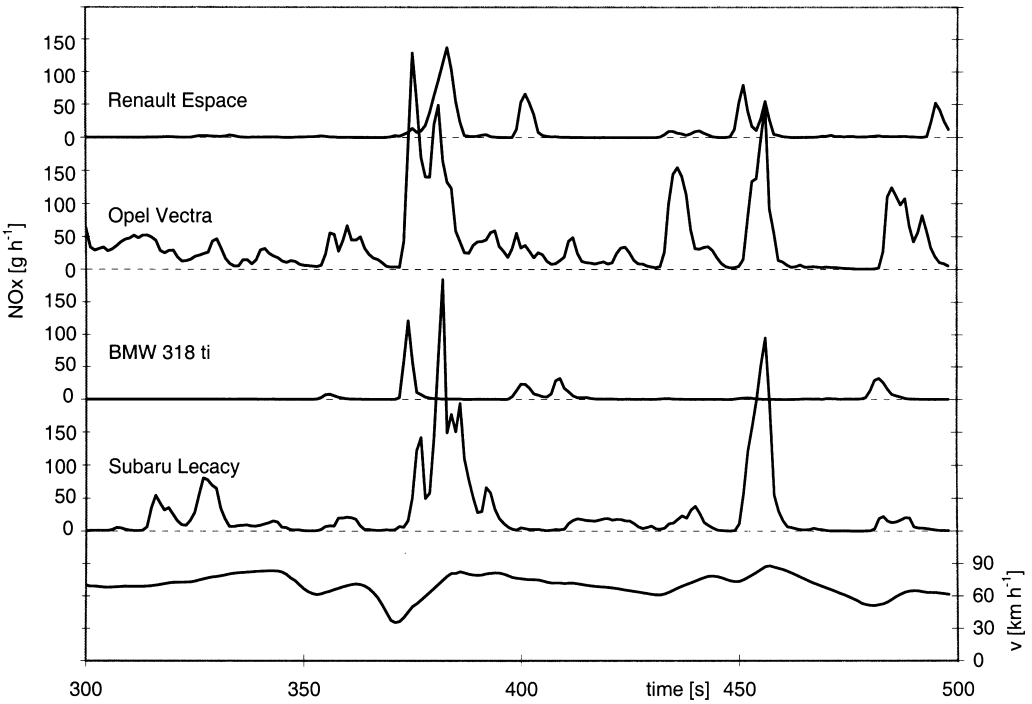

Fig. 2. Comparison of NO_x emissions from four EURO-I vehicles for the speed time series shown in the lower part of the graph.

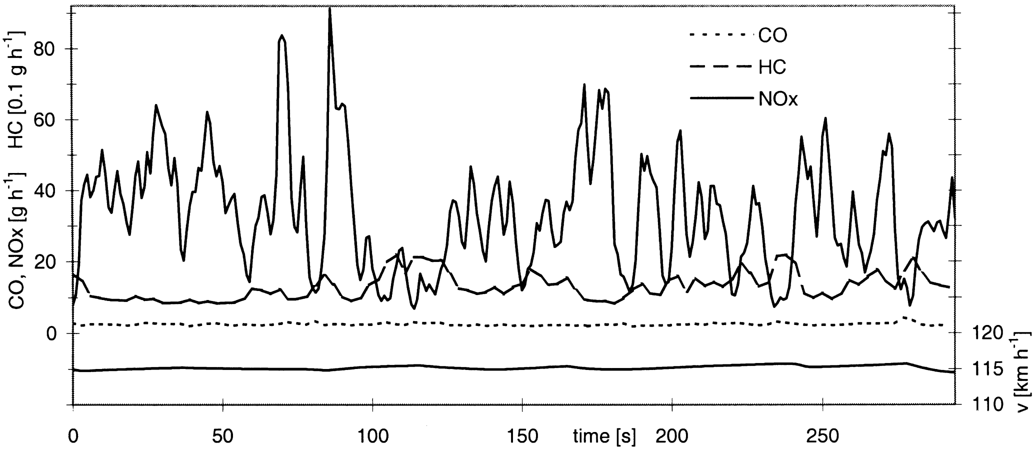

Fig. 3. Fluctuation of NO_x emissions for nearly constant driving speed. Example for Opel Omega 2.6i Caravan (constructed 1991, equipped with three-way catalytic converter) and driving pattern T115c from EMPA (1998).

The frequency spectrum of the fluctuations remains more or less constant, suggesting that this effect is indeed due to adaptation time and feedback mechanisms between lambda sensor and any change in fuel injection. A third group of vehicles showed no fluctuations of this magnitude for any pollutant. SfS-ETH and INFRAS (1999), for the EMPA (1998) ensemble of 20 vehicles, conclude that the system consisting of engine, catalytic converter, lambda sensor and electronic unit shows a chaotic (in a mathematical sense) behavior with respect to instantaneous exhaust emissions.

4. Real-world emissions and standard driving cycles

This section aims at showing that the emission level of real-world driving patterns is higher than for comparable standard (i.e. legislative) driving cycles, and that the

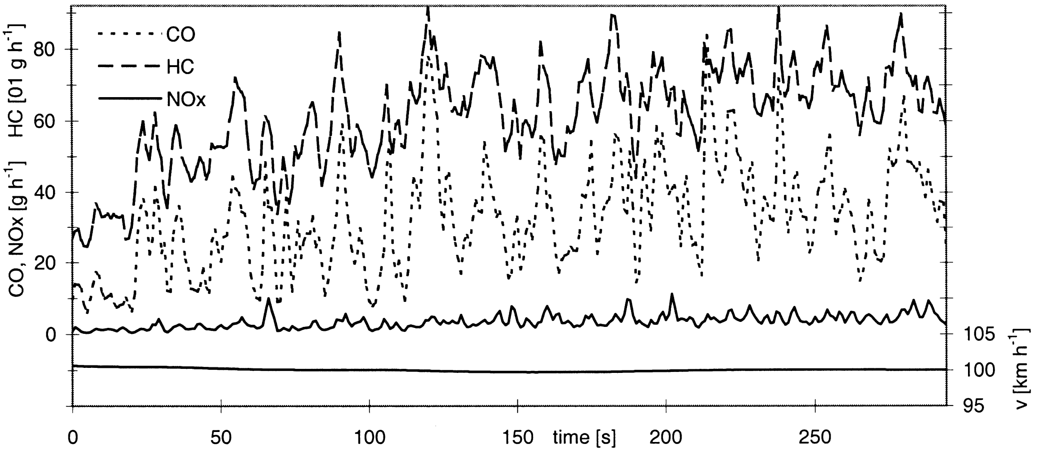

Fig. 4. Fluctuation of CO and HC emissions for nearly constant driving speed. Example for Ford Scorpio 2.9i (constructed 1991, equipped with three-way catalytic converter) and driving pattern T110c from EMPA (1998).

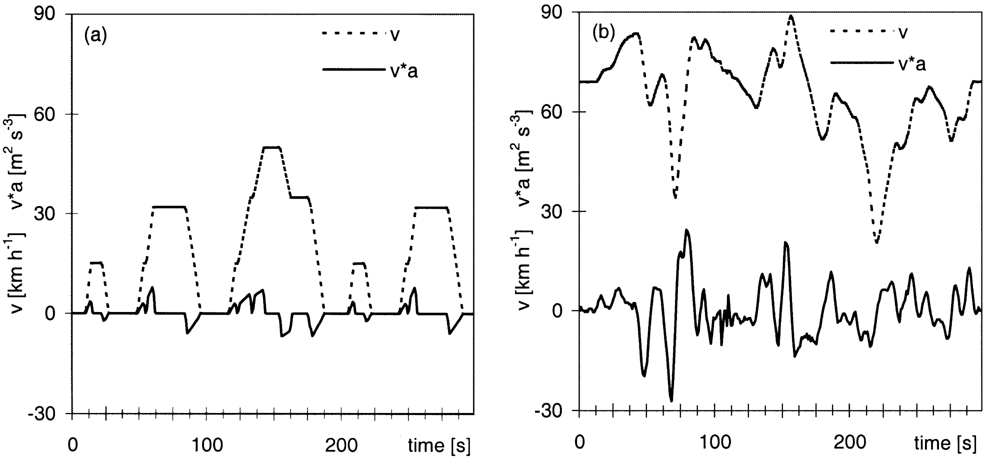

Fig. 5. Time series (first 300 s) of speed, v, and speed times acceleration, va, for (a) the legislative cycle NEDC and (b) the real-world 'LE2u' driving pattern (EMPA, 1997) characteristic for extra-urban non-steady traffic.

inclusion of such real-world driving patterns in dynamometer tests significantly increases the prediction capability of instantaneous emission models.

As an illustration, Fig. 5 depicts the first 300 s of standard and non-standard driving patterns, with identical scales. It illustrates the well-known fact that real-world driving has higher speed fluctuations than the driving behavior represented by legislative cycles. In Fig. 6 the emission matrices are presented. The emission level is clearly higher when the emission matrix is based on dynamometer tests with real-world driving patterns (right panel of Fig. 6), even though the emission matrix cells are parameterized by instantaneous speed and the product of acceleration and speed. These two parameters are not able to resolve all of the emission level difference between standard driving cycles and real-world driving patterns.

In the following, we assess the prediction capability of the instantaneous emission model as used in SAEFL (1995) to predict the emission level of real-world driving patterns. Instantaneous measurement data from 20 EURO-I gasoline passenger cars has been used to build the emission matrices. Three cases are distinguished:

1. Emission matrices based upon standard cycles only (for example, the NO_x matrix is depicted in Fig. 6a). Standard cycles used are FTP, and NEDC (warm part only), Highway and Bundesautobahn (BAB).
2. Emission matrices based only upon the EMPA (1998) dynamometer measurements of 12 real-world driving

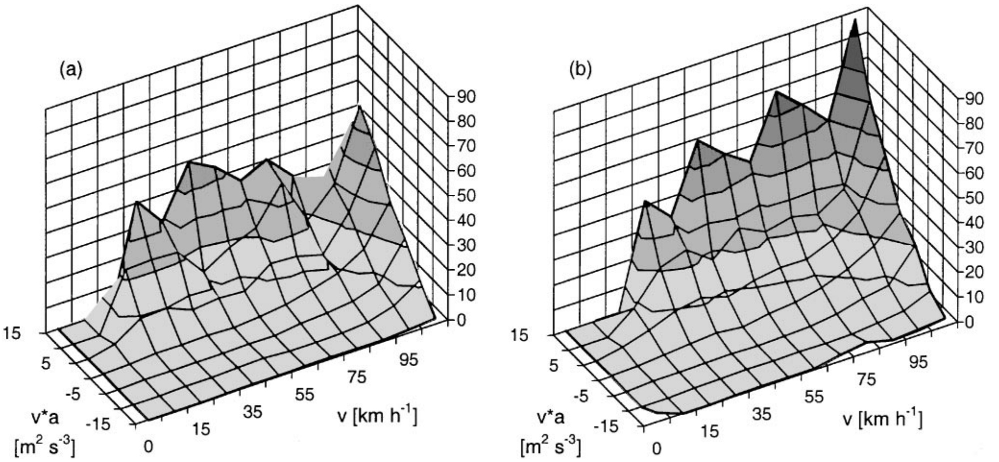

Fig. 6. NO_x emission matrices derived from (a) standard driving cycles and (b) real-world representative driving patterns. The vertical axes denote the NO_x emission in g km^{-1}. Standard driving cycles used are FTP, NEDC (both without cold start part), Highway and BAB. The real-world emission matrix is based on the twelve driving patterns from EMPA (1997).

patterns (for NO_x, the resulting matrix is depicted in Fig. 6b).

3. Emission matrices where both data sets described above have been pooled into one single emission matrix.

Bag measurements are available for the same 20 vehicles for the 12 real-world driving patterns from EMPA (1998). The following statistical measures have been adopted to describe the performance of the instantaneous emission model, when the model tries to predict the bag measurements based on the three types of emission matrices introduced above:

The fraction of predictions within a factor of 2 from observations, FAC2,

the fractional bias, $\mathrm{FB} = (\bar{C}'_{\mathrm{obs.}} - \bar{C}'_{\mathrm{pred.}})/\{0.5(\bar{C}'_{\mathrm{obs.}} + \bar{C}'_{\mathrm{pred.}})\}$

the normalized mean square error, $\mathrm{NMSE} = \overline{(C'_{\mathrm{obs.}} - C'_{\mathrm{pred.}})^2}/(\bar{C}'_{\mathrm{obs.}}\bar{C}'_{\mathrm{pred.}})$

the correlation coefficient, $\mathrm{COR} = \overline{(C'_{\mathrm{obs.}} - C'_{\mathrm{obs.}})(\bar{C}'_{\mathrm{pred.}} - \bar{C}'_{\mathrm{pred.}})}/(\sigma_{\mathrm{obs.}}\sigma_{\mathrm{pred.}})$.

Here, $C'_{\mathrm{obs.}}$ is the 'observation', i.e. the measured bag value per driving pattern (arithmetic mean over 20 vehicles), and $C'_{\mathrm{pred.}}$ is the prediction from the instantaneous emission model (data from 20 vehicles has been put into one emission matrix, so there is one predicted value per driving pattern). The overbar denotes the ensemble average over all 12 real-world driving patterns. For the 12 observed and predicted values, $\sigma_{\mathrm{obs.}}$ and $\sigma_{\mathrm{pred.}}$ are the respective standard deviations.

Mean values are often dominated by a single value with a high leverage. To assess whether model performance is influenced by such outliers, confidence limits have been calculated using the bootstrap re-sampling method. This technique is frequently used if the type of the distribution of the variable to be investigated is not known. A good introduction can be found in Hanna (1989). In this study, 1000 samples from $C'_{\mathrm{obs.}} - C'_{\mathrm{pred.}}$ pairs are taken, and 95% confidence limits are based on the 2.5 and 97.5% quantiles of the distribution of statistics for the 1000 samples (so-called bootstrap-percentile confidence intervals).

Fig. 7 depicts the scatter plot of predicted emission factors for the EMPA (1997) real-world driving patterns in question. For CO, the inclusion of real-world data generally leads to an increase of the predicted emission factor. For NO_x, there is a strong influence of the individual driving pattern for which the emission factor has to be predicted. For some, inclusion of real-world data leads to a lowering of the emission factor.

The statistical measures corresponding to Fig. 6, FB (which is a measure for the systematical error, i.e. the bias), NMSE (which is a measure for the average error, i.e. the scatter), COR, and FAC2, are listed in Table 1. As can be seen, inclusion of real-world data always leads to a better prediction in the sense of lower scatter (smaller NMSE value) and a higher correlation coefficient. The changes in FAC2 are less pronounced. The FB values show that overall, the inclusion of real-world data leads to higher emission factor (a negative FB means overprediction). Whether the FB value improves (towards zero) or not depends on the 'dynamics' level of the driving patterns for which the emission factors are to be estimated. For highly dynamic driving, real-world data will

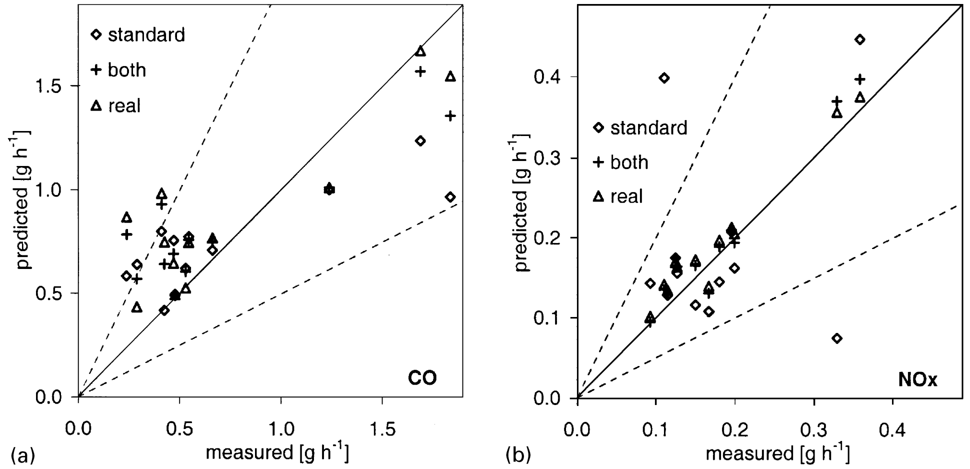

Fig. 7. Scatter plot of measured and predicted (three different emission matrices; see text) emission factors (CO: (a); NO_x: (b)) for 12 different real-world driving patterns. The upper and lower dashed lines indicate the range where predicted values are within a factor of two of the measurements.

Table 1
Statistical performance measures for three different emission matrices[a]

		FB	NMSE	COR	FAC2 (%)
	Measurements	0	0	1	100
NO_x	Standard cycles	– 0.051	0.418	0.261	83
	Both	– 0.086	0.021	0.973	100
	Real-world cycles	– 0.099	0.020	0.977	100
CO	Standard cycles	– 0.022	0.230	0.828	83
	Both	– 0.143	0.150	0.891	83
	Real-world cycles	– 0.170	0.140	0.874	83
HC	Standard cycles	0.071	0.360	0.928	92
	Both	0.010	0.200	0.960	92
	Real-world cycles	– 0.013	0.150	0.963	92

[a] For definitions of FB, NMSE, COR and FAC2, see text.

improve the prediction, for driving with low acceleration and few speed fluctuations, emission data from legislative cycles will be more representative and hence give a better prediction. This is in line with findings from INFRAS (1998). This means that the instantaneous emissions approach at present is not yet capable of resolving different levels of 'dynamics' of the driving patterns. Special care has to be taken which measurements are put into the emission matrix. The (resampled) confidence intervals belonging to Table 1 are given in Fig. 8.

5. Influence of driving dynamics on emission level

As discussed in the previous sections, the emission behavior of modern gasoline cars with three-way catalysts shows a low basic emission level together with emission 'events' (so-called 'peaks') of short duration but with an emission level 10–100 times higher. The overall effect is that around 50% of all emissions (except for pollutants which are directly related to the amount of fuel consumption, like CO_2 and SO_2) are emitted during 'peaks'.

Therefore, it is crucial to know how often, i.e. under which circumstances, these 'peaks' occur. The most logical explanation seems to be a relation between emission peaks and instantaneous acceleration, which is why this parameter has been selected in different instantaneous emission models in the first place (Section 2). Whether acceleration or the product of speed and acceleration is used, is of lesser importance. Sturm et al. (1997) show that only marginal differences in predicted emission factors result.

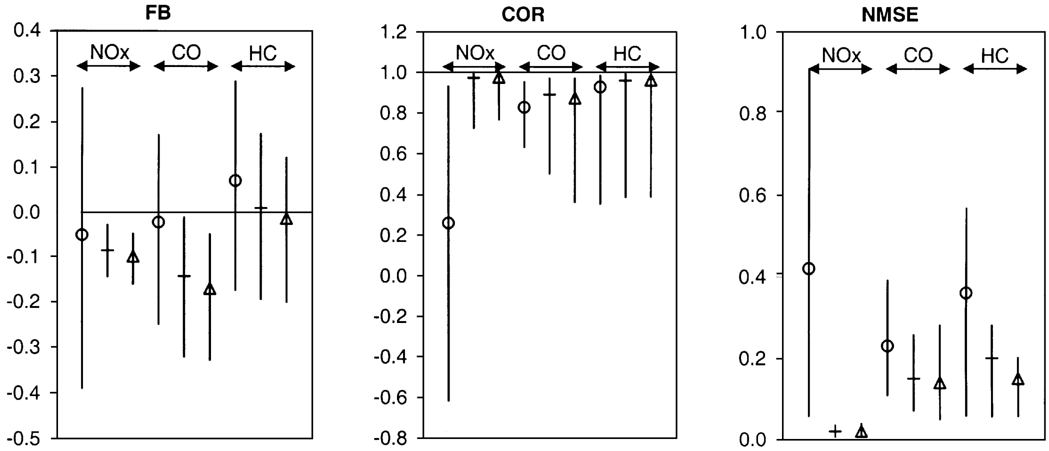

Fig. 8. Bootstrap confidence intervals for FB, COR and NMSE. Emission matrix based on standard driving cycles are depicted with circles (○), real-world with triangles (△), the combination of both with plus signs (+).

However, this will not be able to resolve all 'peaks' which actually occur. For example, Fig. 3 depicts the fluctuation of NO_x emissions on time-scales of roughly 10 s for a constant high driving speed of 115 km h^{-1}. This behavior is possibly caused by internal response and adjustment times of the exhaust gas after-treatment system, and not by the instantaneous speed and/or acceleration. Such fluctuations can be observed not only for NO_x. Fig. 4 shows the analogous behavior of fluctuating CO and HC emissions, again for a constant high driving speed of 110 km h^{-1}. The example of Fig. 2 also reveals significant differences. Differences can be observed regarding the height of emission 'peaks', but also regarding whether such a 'peak' is present at all or not.

The recent SfS-ETH and INFRAS (1999) research project investigated new instantaneous emission models. Certain improvements introducing new parameters, and new statistical models, could be made. For example, the instantaneous emission behavior of CO and HC can be better predicted when the past instantaneous speed is introduced as a new variable. For some vehicles, the speed 3 s ago was needed, for others, the speed 4, 5 or 8 s ago had to be introduced in order to enhance the R^2 of the statistical models in question (see SfS-ETH and INFRAS (1999) for details). In addition to the emission matrix method (Jost et al., 1992; SAEFL, 1995; Sturm et al., 1997), fundamentally different approaches were investigated: General additive models (GAM), neural networks, and projection pursuit regression. The validation of the new model approaches was done with cross-validation, and calculating bias and scatter of the predictions. It could be shown that whereas for most real-world driving patterns good estimations of the emission level can be obtained, there still are some situations where the new models do not resolve all relevant processes, and the prediction of the emission level remains difficult.

The conclusion of the project was that it is not possible to construct instantaneous emission models which are able to fully resolve the irregular ('peak') emission behavior of modern gasoline cars, when the same statistical model formulation for all vehicles has to be used. The differences between the vehicles are too pronounced. The only possibility would be to develop new statistical models for every vehicle coming to the market.

6. Fields of application of instantaneous emission models

6.1. Aggregated emission factors

The comparison of the emission level and characteristics between legislative and real-world cycles shows fundamental differences. This is due to the higher share of 'dynamic' driving conditions. For modern catalyst-equipped vehicles, emission data from legislative cycles should not be used as the only basis for the estimation of emission factors, even on aggregated levels. This conclusion stems from the analysis of the emission behavior of EURO-I gasoline passenger cars. For older vehicle concepts, for diesel engines, and for heavy duty vehicles, the difference between emission levels from standard test procedures and real-world driving probably are much less pronounced. Since even the more refined approach of instantaneous emission models cannot fully resolve the influence of driving 'dynamics' on the emission level, the 'dynamics' of the driving cycles for dynamometer measurements has to be representative for the traffic situation for which emission factors are to be forecasted.

6.2. Assessment of traffic calming measures

The topic of the present contribution is instantaneous emission modeling, and the identification of those fields where it can be applied. Within the area of local emission modeling, as needed for the assessment of measures like traffic calming, speed limit reduction, or the replacement of traffic lights by round-abouts, instantaneous emission modeling can in principle be applied when used together with specific dynamometer measurements. Any emission parameterization depending on the average speed as only parameter, of course, is not suitable for such assessments of emission levels on a local level, but for calculations on an aggregated level only.

Due to the fact that no general (i.e. valid for all gasoline EURO-I passenger cars) statistical model could be identified which completely resolves the influence of driving 'dynamics' on emission level, the only possible method to ensure that the underlying emission matrix is representative for the 'dynamics' level in question seems to be by conducting measurements. Again, however, the large differences between individual vehicles on the one hand, and very high sensitivity of the emission level of these vehicles to seemingly small changes in driving 'dynamics' on the other hand, prohibit any emission modeling for very small changes in 'dynamics'. If the two traffic situations to be compared are too closely related, significant results cannot be obtained due to the large confidence intervals, which stem from the variability among vehicles, and from the variability among emission level per driving pattern, and cannot be reduced by the refinement of the emission model used.

For measure assessment, we therefore suggest that two groups of similar driving patterns, each representative for the traffic situation 'before' and 'after' the traffic-calming measure, respectively, be constructed and measured on a chassis dynamometer. Differences in predicted emission level can only be considered to be significant if they exist for the large majority of possible pairings between 'before'- and 'after'-measure driving patterns. This would require a large number of tests.

6.3. Future research

No further refinement of emission models, and of instantaneous emission models in particular, can be expected in the future as long as the aim is to develop models that are valid for all vehicles. The differences between car builders, and between vehicles from the same car manufacturer, are too pronounced. Whether models can be developed on a brand basis, or whether even the differences between identical vehicles are too pronounced, has not yet been investigated. Any vehicle-dependent statistical model is likely to undergo changes as soon as slight modifications to the exhaust gas reduction system are performed by the car manufacturer.

Such an approach is not useful for the estimation of emission factors on an aggregated level. But it may prove useful to better understand the exhaust gas reduction strategies of the car manufacturers, thus being able to identify possible areas where the vehicles are likely to fail and high emission levels should be expected (e.g. traffic situations like stop-and-go).

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