EVALUATION OF EUROPEAN ROAD TRANSPORT EMISSION MODELS AGAINST ON-ROAD EMISSION DATA AS MEASURED BY OPTICAL REMOTE SENSING

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ABSTRACT

A major on-road remote sensing emission measurement campaign was carried out in 2007 in Göteborg, Sweden, in order to provide on-road emission data for an evaluation of the three major road transport emission models in Europe, i.e. the COPERT 4 model, the Handbook of Emission Factors (HBEFA 2.1), and the recently developed ARTEMIS Road Model.

The University of Denver's latest generation remote sensing instrument, capable of measuring tailpipe concentrations of conventional remote sensing parameters CO, HC, NO and CO_2*, as well as new parameters* NO_2*,* NH_3 *and* SO_2*, was used at four different sites representing different driving pattern and fleet compositions.*

In all, the on-road measurements comprised more than 15,000 vehicles. From license plate recognition, the remote sensing data could be allocated to individual vehicles of known age, Euro-class, size, fuel type, power, etc. For each site, average on-road emission factors, expressed as grams pollutant emitted per liter fuel burned, by vehicle category (PC, LCV, HGV and buses), technology/fuel type (e.g. petrol, diesel) and Euro-class, were compared with corresponding outputs from the three emission models.

In this study the performance of the three pan-European emission models has been proven for several vehicle categories, traffic situations and pollutants, but some lacks in model performance have also been demonstrated in some cases, as for NO_X *for gasoline passenger cars at higher speeds and* NO_X *for diesel vehicles, both light- and heavy-duty, in which cases all models investigated tend to underpredict emissions, in particular for the more recent and stringent emission concepts.*

Keywords: *Road vehicles, road transport, emissions, emission models, on-road, real-world, remote sensing, FEAT, ARTEMIS, COPERT, Handbook of Emission Factors, HBEFA.*

1. INTRODUCTION

In 2005, road transport shares of the overall anthropogenic emissions within the EU-25 territory were around 40% for NO_X, 35% for CO, 20% for CO_2 and 15% for NMVOC [1, 2]. Thus, accurate road transport emission inventories are essential in any European policy addressing air pollution or climate change. Due to the diversity and complexity of the road transport sector in general and its emissions in particular, most national air emission inventories today are compiled by means of computerised emission models.

The oldest and presently most commonly used in Europe is the COPERT model, the initial version of which was used already for the CORINAIR 1985 emissions inventory [3], and was launched in a 4th version - COPERT 4 - in 2007 [4].

Another often used and cited European model is the “Handbook of Emission Factors for Road Transport”, or HBEFA [5], which was first published in 1995, and the most recent version (2.1) in 2004. A new update - version 3 - is expected in late 2008 or early 2009. For national air emission inventories, the main users of this model are Austria, Germany and Switzerland.

One of the prime deliverables from the recently concluded EU FP5-project ARTEMIS, “Assessment and Reliability of Transport Emissions Models and Inventory Systems” is the ARTEMIS Road Model, which is the most recent European model, and combines the best features of the COPERT and HBEFA models [6]. So far, this model has only been fully implemented for compiling national air emission inventories in one country (Sweden), however, it shares many similarities with the most recent versions of the COPERT and HBEFA models.

Despite the importance of the road transport sector for European air pollution and climate change policy, fairly few attempts have been made to check the validity and credibility of European emission models, e.g. by comparing model outputs with “real-world” or “on-road” emission data. Most validation work has been based on tunnel studies, in which real-world emission factors are derived from simultaneous measurements of the enrichment of air pollutant concentrations along the tunnel, the tunnel ventilation flux, and parameters describing the tunnel traffic (traffic flow, composition, speed, etc.) One of the more recent examples is from the ARTEMIS-project, which contained a dedicated workpackage for validation of the ARTEMIS Road Model by means of a series of tunnel measurements [7], but also the HBEFA model has been evaluated in a similar fashion [8]-[9].

An interesting alternative approach to tunnel studies for model validation exercises is offered by optical remote sensing, more commonly known as FEAT (Fuel Efficiency Automobile Test), and originally developed in the late 1980's for e.g. CO gross-emitter identification [10]. Being capable of measuring individual vehicle raw exhaust concentrations of CO, HC and more recently also NO_X, remote sensing enables a much higher degree of disaggregation with regard to providing emissions/emission factors by vehicle category, in contrast to tunnel measurements, which normally only enables a disaggregation of the measured emissions into light- and heavy-duty vehicles, respectively. In two recent studies, both the COPERT III model and the ARTEMIS Road Model were evaluated against the same set of on-road optical remote sensing emission data collected in 2001 and 2002 [11]-[12].

In the present study, a major dedicated optical remote sensing on-road emission measurement campaign was conducted in Göteborg, Sweden, in 2007, with the main aim to collect data to evaluate the three most predominant European emission models COPERT (version 4), HBEFA (version 2.1) and ARTEMIS Road Model (version 0.4d). A significant improvement compared with the remote sensing dataset collected in the same city in 2001 and 2002, and the associated model evaluation exercises, was that the 2007 remote sensing measurements involved - from improved instrument capability - for the first time NO_2 (and thus overall NO_X) and also NH_3.

2. EXPERIMENTAL

2.1. Remote sensing measurements

All measurements were carried out by means of the most recent remote sensing (FEAT) technology developed by the University of Denver, capable of measuring individual vehicle raw exhaust concentrations of NO_2, NH_3 and SO_2, in addition to the “traditional” remote sensing parameters CO_2, CO, HC and NO [13]. The remote sensing instrument used provided also speed and acceleration measurements on individual light-duty vehicles. The measurements followed the normal procedures for remote sensing operation with regard to instrument calibration, vehicle license plate recognition, etc., that have been described in detail in earlier work [11], with the only difference being that now also NO_2, NH_3 and SO_2 were included in the measurements.

Four different sites were included in the measurements, all of which exhibited a weak to moderate inclination:

Site 1: A sharply curved city freeway interchange ramp with speed limit 30 km/h.

Site 2: A slightly curved city freeway off-ramp with speed limit 70 km/h.

Site 3: A straight single-lane city freeway with speed limit 70 km/h.

Site 4: A single-lane access road in the city restricted for busses only.

By default the remote sensor provides emission data as volume-% in the undiluted (raw) exhaust. However, from the definition of the remote sensing measurement principle, the volume-% emissions may also be converted to corresponding fuel-specific emissions, expressed as grams of pollutant emitted per liter or kg of fuel burnt. One advantage with this, as referenced [11], is that it has been shown from tunnel studies that fuel-specific emission factors, in contrast to emission factors expressed in g/km, are more or less independent of roadway grade [15]. In this study the conversion of the remote sensing emission data in volume-% to g/kg fuel burnt was done in accordance with the formulas and methods as described in detail in [11]. Cold start enrichment operation was considered negligible for all sites, thus it was assumed that the remote sensing data represent hot emissions only.

2.2. Emission modelling

As already mentioned in the introduction the models investigated were ARTEMIS 0.4d, HBEFA 2.1 and COPERT 4. These models share many similarities, for instance the input emission factor data relies for all three models to a large extent on the emission factor database compiled within the ARTEMIS- and COST 346-projects [14]. However, there is a fundamental difference between the ARTEMIS and the HBEFA model on the one hand, and the COPERT model on the other hand, in the way which raw (input) emission factors are converted to operational (output) emission factors. ARTEMIS and HBEFA both utilise a traffic situation (kinematics) approach, whereas the COPERT model applies an average speed approach.

3. RESULTS AND DISCUSSION

3.1. Remote sensing data

The number of vehicles measured by the remote sensor, and the effective (measured) average speed for light-duty vehicles at each site are presented in Table 1.

Table 1: No. of vehicles measured by the remote sensor and measured average speed per site

	No. of vehicles measured[1]	No. of passengers cars measured	Measured average speed (km/h)
Site 1	5745	5560	29
Site 2	6250	5870	46
Site 3	3345	3120	58
Site 4 (buses only)	250	-	37
All sites	15590	14550	40

[1]Refers to the number vehicles with valid NO_X-readings in the remote sensing measurements. The numbers of vehicles with valid CO- and HC-readings were generally higher.

From the combined remote sensing data of site 1-3, average on-road emissions (expressed in g/kg fuel) of NO_X and NO_2 per Euro-class, are presented for gasoline and diesel passenger cars, respectively, in Figure 1. Few older gasoline vehicles lacking effective emission control appeared in the remote sensing measurements, as did diesel passenger cars older than Euro 2. The latter is due to that diesels have been very rare in Sweden until the last couple of years, when sales have increased strongly. Figure 1 reveals a couple of interesting observations:

- For gasoline passenger cars: the strong and continuous reduction in on-road NO_X-emissions along with the tightening of the European emission standard, corresponding to approximately a 96% reduction from pre-Euro to Euro 4, and the low NO_2/NO_X-share (2-5%) , independent of the emission standard.
- For diesel passenger cars: the continuous reduction in on-road NO_X-emissions from Euro 2 and onwards, corresponding to approximately a 30% reduction from Euro 2 to Euro 4, while simultaneously the NO_2/NO_X-share increases from approximately 14% for Euro 2 (or 10% for Euro 1 - not shown in Figure 1 due to few data) to above 50% for Euro 4. The latter observation is very much in line with observations in recent chassis dynamometer studies [16]. The Euro 3 and 4 vehicles in Figure 1 represent a mix of vehicles with and without CPF (catalytic particle filter), yet to be determined.

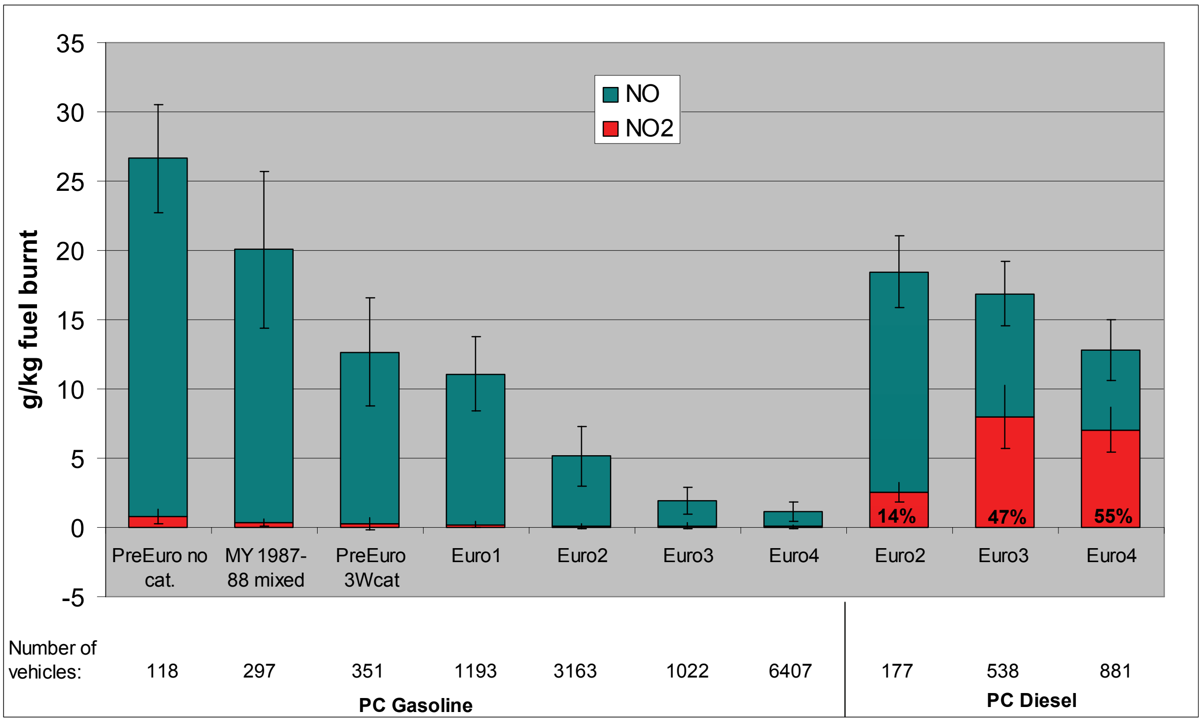

Figure 1: Average NO_X and NO_2 emissions in g/kg fuel per Euro-class for gasoline and diesel passenger cars according to the remote sensing measurements. Data from site 1-3 combined

According to Figure 2, CO and HC emissions from gasoline passenger cars show a similar pattern to NO_X, with a reduction in on-road emissions from pre-Euro vehicles to Euro 4 vehicles of around 95%. However, the pattern for NH_3 is quite different, with emissions reaching a maximum for Euro 1 vehicles, followed by a steady decrease with increasing Euro-class, with Euro 4 vehicles reaching the same (low) emission level as pre-Euro vehicles.

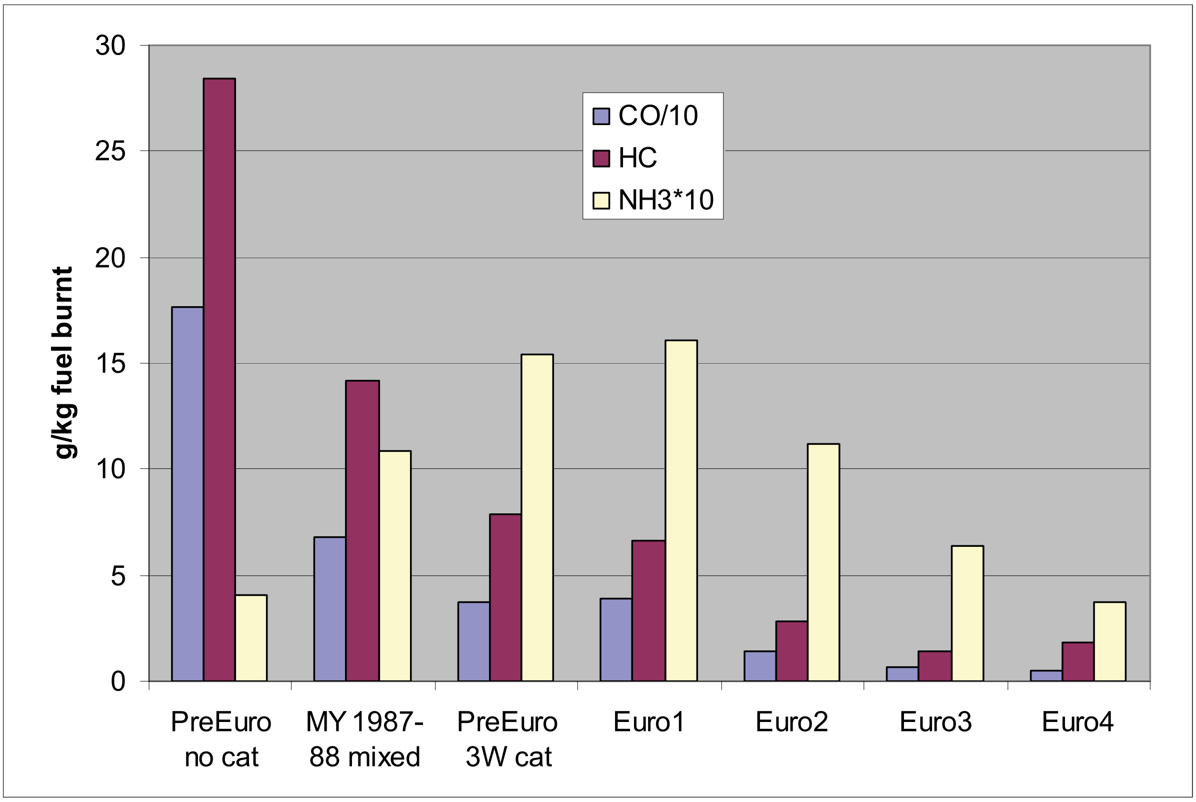

Figure 2: Average CO, HC and NH_3 emissions in g/kg fuel per Euro-class for gasoline passenger cars, according to the remote sensing measurements. Data from site 1-3 combined

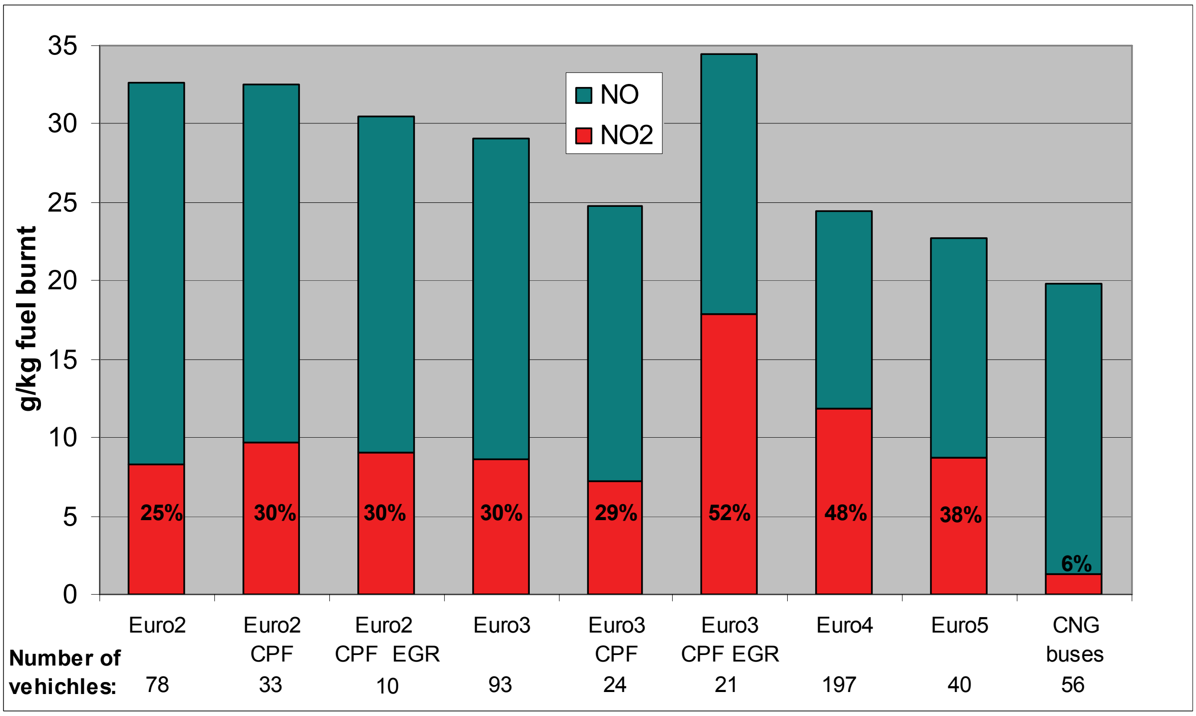

Figure 3: Average NO_X and NO_2 emissions in g/kg fuel per Euro-class for heavy duty buses according to the remote sensing measurements. Data from site 1-4 combined

From the combined remote sensing data of site 1-4, average on-road emissions of NO_X and NO_2 per Euro-class for heavy-duty buses are presented in Figure 3. The dataset comprised in total measurements on more than 500 buses. No buses older than Euro 2 appeared in the measurements, on the other hand some 40 buses corresponding to Euro 5 appeared, as well some 50 CNG buses. For Euro 2 and Euro 3, there was a mix of conventional buses, with CPF- and CPF plus EGR-equipped buses. From Figure 3 a general downward trend in NO_X emissions with increasing Euro-class can be observed for conventional buses, resulting in approximately a 30% reduction in NO_X emissions from Euro 2 to Euro 5. The lowest NO_X emissions were observed for CNG-buses, which were just slightly lower than Euro 5. NO_2/NO_X-fractions were generally high (25-50%), except for CNG-buses (6%). There was no clear trend in the NO_2/NO_X-fraction for the diesel-fuelled buses, however Euro 3 CPF- and EGR-equipped buses showed the highest fraction (52%), as well as the highest NO_X emission.

From the combined remote sensing data of site 1-3, average on-road emissions of NO_X and NO_2 per Euro-class for heavy-duty goods vehicles (HGVs), all of them diesel-fuelled, are presented in Table 2. The dataset comprised in total measurements on more than 600 HGVs, both with and without trailer, the vast majority corresponding to the Euro 2 and Euro 3 standards, some 50 corresponding to Euro 4, but only a handful of vehicles before Euro 2, thus the latter were not represented in Table 2. It has been demonstrated earlier that real-world emissions of Euro 2 and Euro 3 heavy-duty truck engines do not differ as much as proposed by the standards, due to “cycle-beating” [6], thus the small difference in NO_X emissions between Euro 2 and Euro 3 HGVs according to the remote sensing data was expected. More surprising is the lack of reduction in NO_X emissions between Euro 3 and Euro 4 according to the remote sensing data. The explanation may be one or a combination of the following:

- The Euro 4 vehicles measured were too few (N=52) to form a representative average, and thus by coincidence the average may be biased high.
- The (induced) driving and engine operational behaviour at the sites, where the remote sensing measurements were carried out, is unfavourable in terms of NO_X emissions and NO_X emission reductions
- A significant fraction of the Euro 4 vehicles are Euro 3 (or even Euro 2) vehicles that have been retrofitted to qualify as Euro 4, the emission performance of which may not be as high as "original" Euro 4 vehicles.

Analysing the strengths and weaknesses of these explanations in more detail, will be the target for further work on the HGV remote sensing dataset in the near future.

Table 2: Traffic situations/road types/average speeds applied in the emission models to calculate emissions for the different sites

	NO_X emission (g/kg fuel)	NO_2/NO_X-fraction (%)	Number of vehicles measured
Euro 2	34.0	7.6	218
Euro 3	32.6	9.2	353
Euro 4	33.1	13.7	52

3.2. Comparison of on-road emissions vs. modelled emissions

Emission data according to the remote sensing measurements were compared with emission data according to the three models on a g/kg fuel basis. The comparison was made on a site-by-site basis for gasoline passenger cars only, whereas for all other vehicle categories - due to insufficient amounts of data - the comparison was made by combining all the remote sensing data from all three sites (four for buses). The road types, traffic situations, traffic conditions and average speeds applied in the three models to calculate emissions for the three sites, respectively, are presented in Table 3. Examples of observed (on-road) versus predicted (models) emissions (of NO_X) for various vehicle categories are presented in Figure 4.

Table 3: Road types/traffic situations/traffic conditions/speed limits/average speeds applied in the emission models to calculate emissions for the different sites

	ARTEMIS	HBEFA	COPERT (average speed km/h)
Site 1	Urban/Access road/40 kmh^{-1}/Freeflow	Urban_Main road2	29
Site 2	Urban/Distributor/50 kmh^{-1}/Freeflow	Urban_Main road>50_1	46
Site 3	Urban/MW-City/70 kmh^{-1}/Freeflow	Urban_Main road>50_1	58

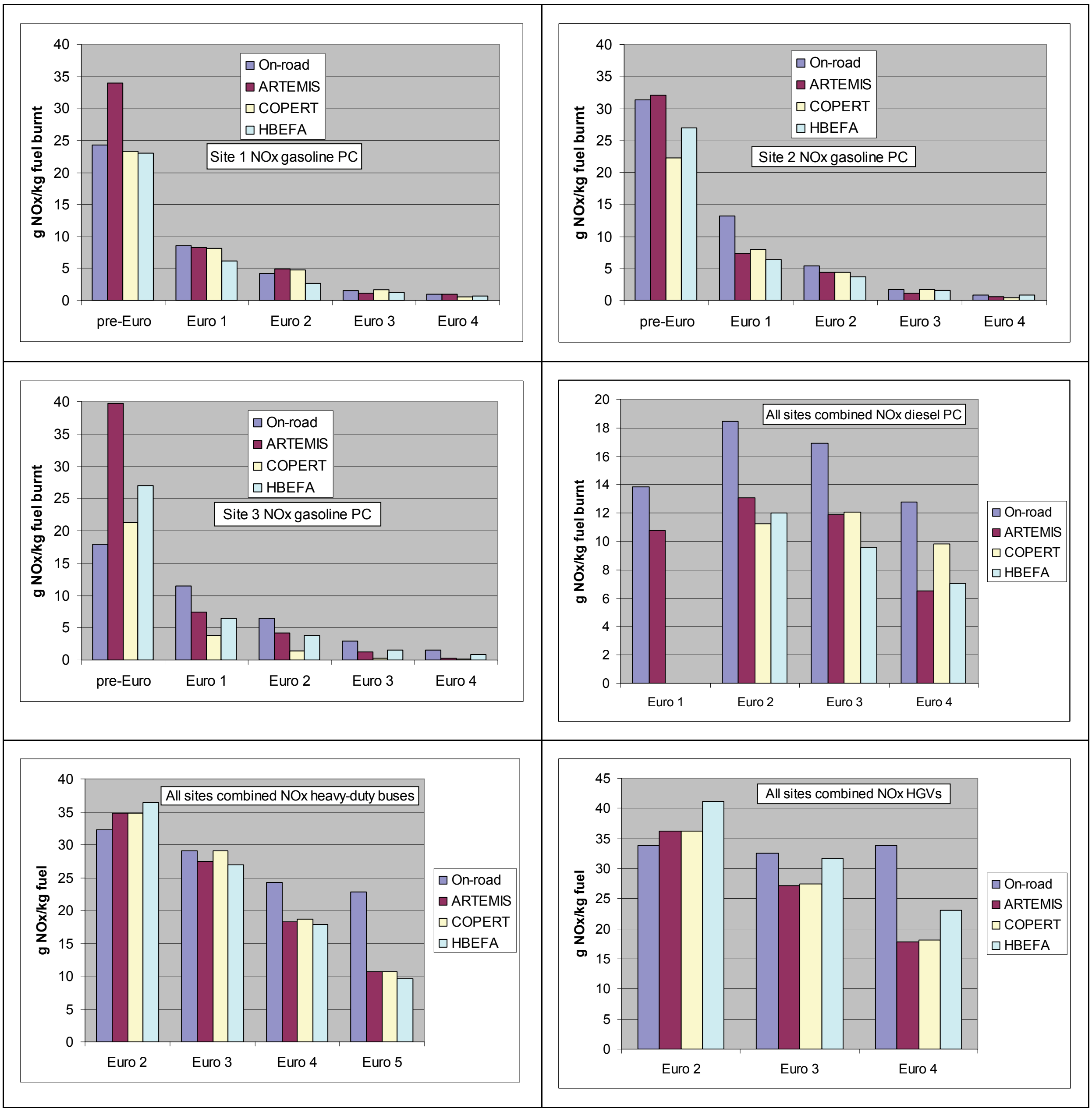

Figure 4: Comparison of observed (on-road) with predicted (modelled) emissions of NO_X for passenger cars, heavy-duty buses, and HGVs, respectively

Figure 4 exemplifies that there is occasionally a good agreement between modelled and measured emissions, as well as occasionally also major discrepancies.

In order to present a better overview, in Table 4 the ratios between predicted (modelled) and observed (on-road) emissions are presented for the various vehicle categories and pollutants investigated, by emission concept (Euro-class), and by site where applicable. Pollutants CO and HC for diesel vehicles were not included in this comparison, mainly because these are considered to be only significant for gasoline passenger cars. A ratio of 100% in Table 4 means a perfect agreement between modelled and measured emissions, whereas e.g. a ratio of 150% means that modelled emissions are 50% higher than measured emissions, and a ratio of 50% that modelled emissions are half of the measured emissions. Overpredictions above 50% are marked in red, whereas underpredictions below 50% are marked in blue in Table 4.

Table 4: Ratios (%) between predicted (modelled) and observed (on-road) emissions as a function of vehicle category, pollutant, emission concept (Euro-class) and site

			Predicted/observed emission		
Vehicle category	**Pollutant**	**Em. conc.**	**ARTEMIS**	**COPERT**	**HBEFA**
Gasoline PC	**NOx**		***Site 1***		
		pre-Euro	140%	96%	95%
		Euro 1	97%	95%	73%
		Euro 2	117%	113%	63%
		Euro 3	74%	108%	80%
		Euro 4	109%	54%	73%
			Site 2		
		pre-Euro	102%	71%	86%
		Euro 1	56%	60%	49%
		Euro 2	81%	83%	70%
		Euro 3	65%	106%	96%
		Euro 4	63%	52%	97%
			Site 3		
		pre-Euro	221%	53%	127%
		Euro 1	41%	9%	30%
		Euro 2	24%	4%	18%
		Euro 3	7%	1%	7%
		Euro 4	2%	0%	4%
Gasoline PC	**HC**		***Site 1***		
		pre-Euro	66%	70%	55%
		Euro 1	71%	127%	28%
		Euro 2	1293%	2300%	1148%
		Euro 3	-18%	-35%	-8%
		Euro 4	-9%	-12%	-7%
			Site 2		
		pre-Euro	133%	216%	114%
		Euro 1	79%	125%	30%
		Euro 2	223%	344%	259%
		Euro 3	-16%	-28%	-10%
		Euro 4	-39%	-36%	-20%
			Site 3		
		pre-Euro	60%	125%	54%
		Euro 1	40%	125%	16%
		Euro 2	105%	458%	131%
		Euro 3	-53%	-318%	-21%
		Euro 4	-35%	-97%	-20%

			Predicted/observed emission		
Vehicle category	**Pollutant**	**Em. conc.**	**ARTEMIS**	**COPERT**	**HBEFA**
Gasoline PC	**CO**		***Site 1***		
		pre-Euro	178%	142%	83%
		Euro 1	97%	130%	79%
		Euro 2	88%	113%	137%
		Euro 3	61%	119%	156%
		Euro 4	26%	32%	141%
			Site 2		
		pre-Euro	100%	81%	50%
		Euro 1	80%	105%	66%
		Euro 2	94%	128%	193%
		Euro 3	81%	210%	239%
		Euro 4	36%	54%	184%
			Site 3		
		pre-Euro	81%	70%	47%
		Euro 1	67%	85%	58%
		Euro 2	72%	93%	145%
		Euro 3	87%	127%	125%
		Euro 4	61%	44%	117%
Diesel PC	**NOx**		***All sites combined***		
		pre-Euro			
		Euro 1	78%		
		Euro 2	71%	61%	65%
		Euro 3	70%	71%	57%
		Euro 4	51%	77%	55%
Heavy-duty diesel buses	**NOx**		***All sites combined***		
		pre-Euro			
		Euro 1			
		Euro 2	108%	108%	113%
		Euro 3	94%	100%	93%
		Euro 4	75%	77%	74%
		Euro 5	47%	47%	42%
Heavy-duty diesel trucks	**NOx**		***All sites combined***		
		Euro 1			
		Euro 2	107%	107%	122%
		Euro 3	83%	84%	97%
		Euro 4	53%	54%	68%

The following observations can be made from Table 4:

- For NO_X from gasoline passenger cars, there is a reasonably good agreement between all three models and measured emissions, except for the high-speed site 3, where all three models predict much lower emissions for all emission concepts, except for the pre-Euro vehicles.
- In general, a fairly poor agreement between models and measurements is observed for HC from gasoline passenger cars. This is most likely due to the low emission levels from Euro 1 vehicles and onwards, in comparison to the detection limit/noise level of the remote sensor for HC measurements.

- With the exception of the lowest emitting vehicle categories, corresponding to Euro 3 and Euro 4, there is a reasonable agreement between all three models and on-road emissions for CO from gasoline passenger cars.
- In general, all three models tend to underpredict NO_X emissions from diesel passenger cars.
- For heavy-duty diesel vehicles, both buses and trucks, there is reasonably good agreement between predicted and observed NO_X emissions for the Euro 2 and Euro 3 categories, whereas for later categories (Euro 4, Euro 5 buses) the models tend to underpredict emissions.

4. CONCLUSIONS

This work has demonstrated that late-generation remote sensing technology, with e.g. NO_X-NO_2 and NH_3 measurement capability, offers many possibilities and a large potential to disseminate real-world emissions, and to evaluate the performance of road vehicle emission models. The performance of the three most prominent European emission models, i.e. COPERT, HBEFA and ARTEMIS, has been proven for several vehicle categories, traffic situations and pollutants, but some lacks in model performance have also been demonstrated in some cases, as for NO_X for gasoline passenger cars at higher speeds and NO_X for diesel vehicles, both light- and heavy-duty, in which cases all models investigated tend to underpredict emissions, in particular for the more recent and stringent emission concepts.

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