MOBILE AIR-CONDITIONING SYSTEMS: IMPACT OF AMBIENT TEMPERATURE AND HUMIDITY ON VEHICLE EMISSIONS AND FUEL CONSUMPTION

Jean-Yves Favez, Martin Weilenmann, Robert Alvarez

Empa, Swiss Federal Laboratories for Materials Testing and Research, Laboratory for Internal Combustion Engines; Ueberlandstrasse 129, CH-8600 Duebendorf, Switzerland.

ABSTRACT

The impact of mobile air-conditioning (A/C) systems on the emissions and fuel consumption of passenger cars is a significant issue since such systems belong more and more to the standard equipment of a car and thus are used at higher rate. Apart two major studies, both dealing with gasoline cars, only sparse data is available concerning this topic. The first study, MOBILE 6, was conducted in the United States and a second study was conducted at EMPA (Switzerland) in order to gain knowledge regarding the European situation. Both studies primarily focus on the impact of A/C systems on emissions as a function of ambient temperature providing specific models.

The present work investigates the impact of A/C systems of diesel passenger car models of present Euro-4 certification. Results are provided derived from emission measurements at different ambient temperatures of 13, 23, 30 and 37 °C and at different ambient relative humidities of 20%, 50% and 80%.

Tthe main novel contribution focuses on the aspect of ambient humidity. In general, the function of an A/C system is to cool down the air to a fixed temperature (e.g. 1-10°C) and to subsequently reheat it by passing through a heat exchanger with engine cooling water. Due to the fact that the cooled air temperature is kept fixed, the A/C system needs more effort to cool down humid air since more water has to be condensed. Therefore, A/C activity may increase as a function of increasing humidity. The results presented in this work confirm this assumption. It turns out that the extra fuel consumption due to A/C activities decreases and increases about 40% at relative humidities of 20% and 80%, respectively, compared to assessments at the standard humidity of 50%.

Keywords: *Air-conditioning system, passenger cars, emissions, fuel consumption, real-world, ambient temperature, ambient humidity.*

1. INTRODUCTION

The influence of air-conditioning (A/C) activity on the emissions and fuel consumption of passenger cars is an important issue since fleet penetration has reached a high level and, in particular, the commonly used automatic A/C systems are switched on most of the time.

Apart two major studies, both dealing with gasoline cars, there is in general only sparse data available concerning this topic. The first study, MOBILE 6 (Koupal, 2001), was conducted in the United States, and a second study was conducted at EMPA (Switzerland) (Weilenmann et al., 2005) in order to gain knowledge regarding the European situation. Both studies primarily focus and provide models on the impact of A/C systems on emissions as a function of ambient temperature.

The EMPA study was conducted in the context of mapping road traffic emissions for central Europe. It was decided to run tests on a chassis dynamometer in a climatic cell and directly simulate different weather conditions. The variety of weather situations was restricted to four temperatures and two irradiation scenarios. In the framework of this project, a raw estimation of the influence of humidity presented in (Weilenmann et al., 2005) suggests that the extra fuel consumption due to A/C activities could decrease and increase about 50% at relative humidities of 20% and 80%, respectively, compared to a standard humidity of 50%.

In order to verify this indication, the present work focuses on the aspect of ambient humidity. Six diesel passenger cars certified to the Euro-4 standards were measured. In addition to the exhaust emissions (CO_2, CO, HC and NO_x), many signals from the A/C systems and from the passenger compartment were recorded to obtain a greater insight into the behavior of these devices.

2. EXPERIMENTAL PROGRAM

2.1. General setup

With the goal of obtaining representative results for the real-world situation on the roads of central Europe, six diesel cars of certification category Euro-4 (PD4) were chosen out of the official Swiss sales statistics to give a representative distribution of engine size, chassis type and manufacturer at the time of selection (***Table 1***). Three vehicles were equipped with original equipment manufacturer (OEM) particle filters. The individual vehicles were borrowed from volunteer private owners and have not been serviced before the test runs. They had an average mileage of 67000 km.

Table 1: Main characteristics of the Diesel Euro-4 vehicle sample. displ.: displacement, m: manual, aut: automatic

	make model	empty mass [kg]	displ. [cm3]	power [kW]	mileage [km]	gearbox type	particulate filter
PD4-1	VW Passat	1649	1968	100	87533	m6	yes
PD4-2	Toyota Avensis	1570	1995	85	74970	m5	no
PD4-3	BMW 525d	1750	2497	130	44332	m6	yes
PD4-4	Skoda Octavia	1530	1896	77	62083	aut	no
PD4-5	VW Touran	1652	1896	74	106745	m6	no
PD4-6	Audi A4	1620	1968	103	25633	m6	yes

The air-conditioned test cell used here allows the temperature to be controlled between -20 and 40 °C. Relative humidity can be set between 20% and 90%. Temperature and humidity are kept at reference values (adjustable by the operator) using a closed-loop control system, for which sensors located in front of the vehicle provide the actual temperature and humidity.

Adequate illumination was installed to simulate solar radiation. At latitudes around 47° in central Europe, the sun shines on average at an inclination of around 45° (inclinations of below 20° are assumed to be irrelevant owing to atmospheric absorption and obstacles). This angle was therefore chosen for the illumination in the laboratory. In reality, the sun may shine from any side of the car, imposing different thermal loads on the passenger compartment. This was simplified to only frontal irradiation, where typically the largest window is located. Since the test bench used here is not located in a wind tunnel that would cool the whole vehicle surface, it was decided not to irradiate the roof of the vehicle, just the windscreen. The lamps with an optimized solar frequency spectrum cover a surface area of 1.7 m^2 with radiation of 800 W m^{-2}, which corresponds to the standard design value for solar panels in Switzerland.

Various sensors were installed to monitor the behavior of the A/C systems of the cars. The main gauge was mounted at the driver's headrest and was used for the main internal temperature information. Further temperature gauges were installed at the front seat passenger position, at the rear seats and at the steering wheel. Depending on the car's architecture and thus accessibility, temperature sensors were installed at the pipes of the cooling system. Being simply attached to the pipes, the latter sensors obviously did not measure the true temperature of the cooling fluid, but they gave qualitative information on the operation of the cooling system. For car PD4-1 a temperature sensor was installed in the ventilation ducts at the outlet of the evaporator (cooled-down air) as well as at the inlet pipe of the evaporator. Compressor activity was monitored by collecting the power modulation or the clutch signal, where available. All these signals were recorded at a 10 Hz sampling rate.

The exhaust gas composition, i.e. CO, CO_2, HC and NO_x, is determined in two different ways. Firstly, the gas is analysed in accordance with European Council Directive 70/220/EEC for passenger cars (European Council Directive 70/220/EEC), insofar as included. Under this procedure the exhaust gas has to be diluted with a Constant Volume Sampling (CVS) system and gas samples of the diluted exhaust and the ambient air are collected in bags for each section of the measured driving cycle. The contents of these bags are analysed after finishing the test run and the pollutant emissions are determined by taking the difference between the measured pollutant concentrations in the exhaust gas and the ambient air. Secondly, undiluted (raw) online gas analysis measurements are carried out at the tailpipe at 10 samples per second. These measurements were used here for backup reasons.

2.2. Test description

Extra emission values are sought in different driving scenarios such as urban, rural and highway driving while the A/C system of the car is running to keep the interior at the desired comfort temperature of 23°C. For automatic systems, the desired temperature was chosen so that the true temperature at the driver's head was 23°C. For manual and semi-automatic air conditioners, a good setting was sought before the test. The knobs for temperature, cooling and ventilation were readjusted if the temperature drifted more than 1°C. The ventilation was set on a common-sense basis, "as drivers usually do": 30 to 50% fan speed, e.g. position 2 of 4. In this way, the "normal" behavior of people who run their air conditioning systems was simulated. However, fleet statistics are needed to give figures on the number of A/C types that are running, and at what temperature.

The test cycle used is the warm started (oil temperature > 80°C) cycle CADC, which originates from the ARTEMIS project under the EU Fifth Framework Program and represents real-world driving in Europe (ARTEMIS, André (2001), André (2004)). It consists of three sections which describe urban, rural and highway driving situations; the exhaust gas of each section is measured separately. This test was repeated with each car at ambient temperatures of 13°, 23°, 30° and 37°C and at ambient relative humidities of 20%, 50% and 80%. The lowest temperature was intentionally chosen to obtain information on the situation where the A/C is not needed to cool the passenger compartment but just to create dry air in the event of windscreen misting. At each temperature, one reference test at 50% relative humidity was run with A/C off and no solar radiation.

Note that measurements with all 16 combinations of ambient conditions were only conducted for vehicle PD4-1, while for the other vehicles only 13 tests were carried out (***Table 2***).

Table 2: Test run ambient conditions; only 13 (marked with X) out of 16 tests were carried out for vehicles PD4-2 to PD4-6

		ambient temperature			
		13°C	23°C	30°C	37°C
ambient relative humidity	80%	X		X	X
	50%	X	X	X	X
	20%	X		X	
	reference, 50%	X	X	X	X

3. RESULTS

3.1. CO_2 and fuel consumption

For the tests at 23°C, the difference between vehicles is highlighted in ***Figure 1***. The reference tests show the variation in fuel consumption since vehicles with different engine size and vehicle mass are used intentionally. The differences between the reference tests and the tests with the A/C on highlight the different efficiencies of the A/C systems. In order to keep the interior cool, vehicles 1, 3 and 5 consume about twice the extra fuel compared to vehicles 2, 4 and 6.

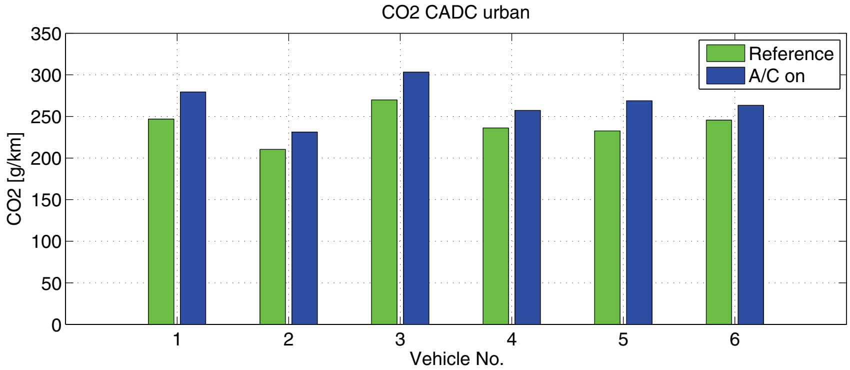

Figure 1: CO_2 emissions in the urban part of the cycle CADC at 23 °C and 50% humidity for A/C off (reference) and on

Note that in the following, fuel consumption (FC) and CO_2 emission are considered to be proportional since CO and HC emissions are quite low and CO_2 and FC are treated as synonymous in relative comparisons.

Figure 2 shows the average CO_2 emissions of the test sample at different temperatures and humidities (only 13 test settings available, see ***Table 2***). The top row depicts the absolute values, the middle row the difference between A/C on and off and the bottom row the relative difference. Similar results as in (Weilenmann et al., 2005) can be derived:

- In contrast to (Koupal, 2001), where no A/C activity is assumed below 20°C, it is observed that the extra CO_2, and thus extra fuel consumption, at 13° is not zero but 4%, 2.5% and 1% for urban, rural and highway driving, respectively. In this context, the A/Cs are only running to prepare dry air in case of a misting windscreen. It is assumed that this demisting activity is active down to about 4°C, where A/Cs switch off to avoid internal freezing.
- The difference between A/C on and off clearly rises with temperature. This extra CO_2 is highest in urban and lowest in highway driving. This finding is due to the slow urban speed and thus the long time it takes to cover one kilometer.
- The extra CO_2 emissions and thus engine load rises in a roughly linear manner from 23 to 37°C.

By assuming a constant ambient humidity, the same model for CO_2 and FC as proposed in (Weilenmann et al., 2005) can be derived, see ***Figure 3***. It consists of no A/C activity for temperatures below 5°C and a constant A/C load, and thus CO_2 emissions and FC, for temperatures above 5°C for demisting. Its values are given by the test runs at 13°C. Then a linear trend is assumed for the temperature range where cooling takes place. The corresponding line is the linear regression through the measured points at 23, 30 and 37°C. This model is to be individually applied to urban, rural and highway driving situations.

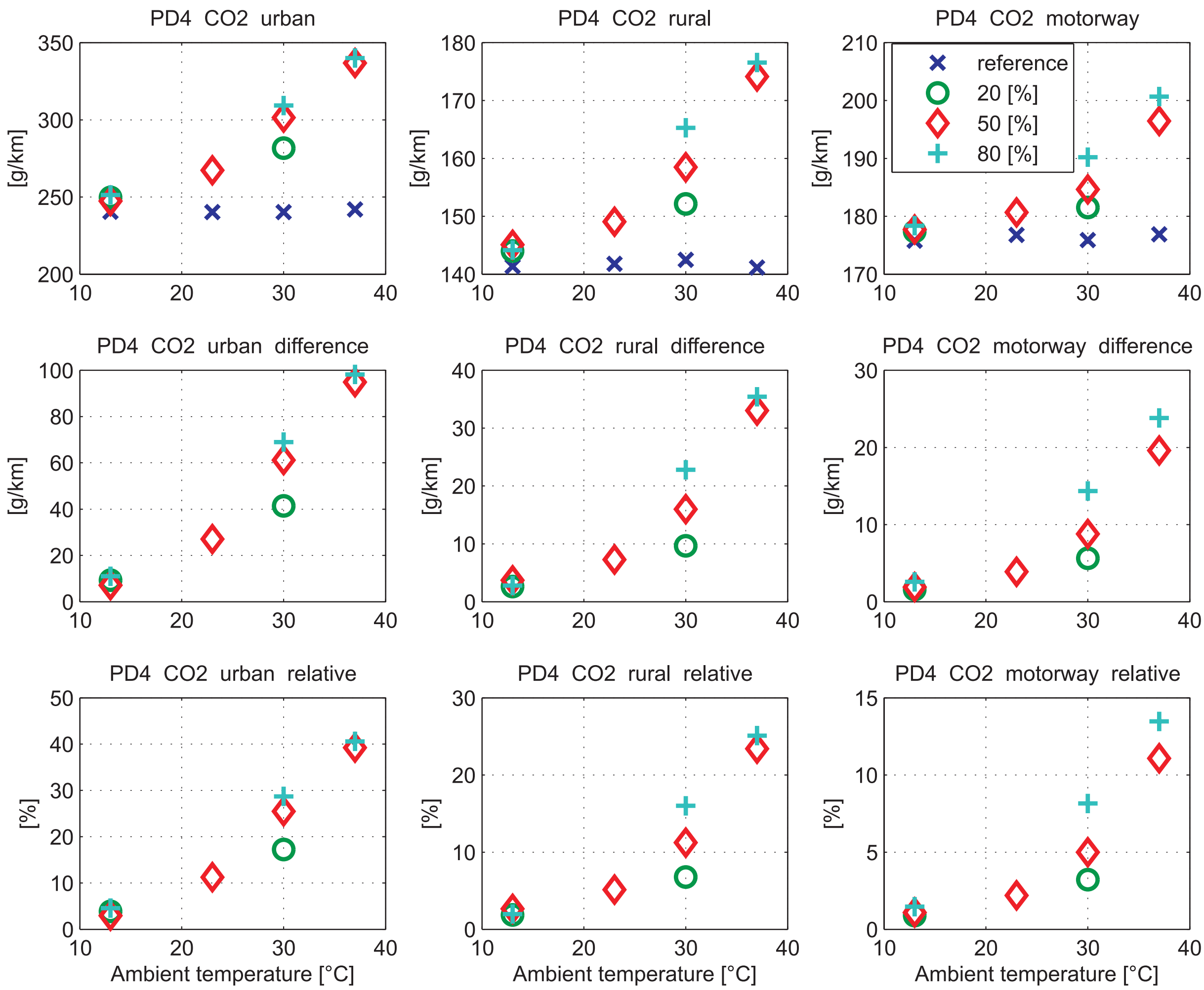

Figure 2: Average CO2 emissions of the test sample in the cycle CADC at different temperatures and relative humidities (only 13 test settings available)

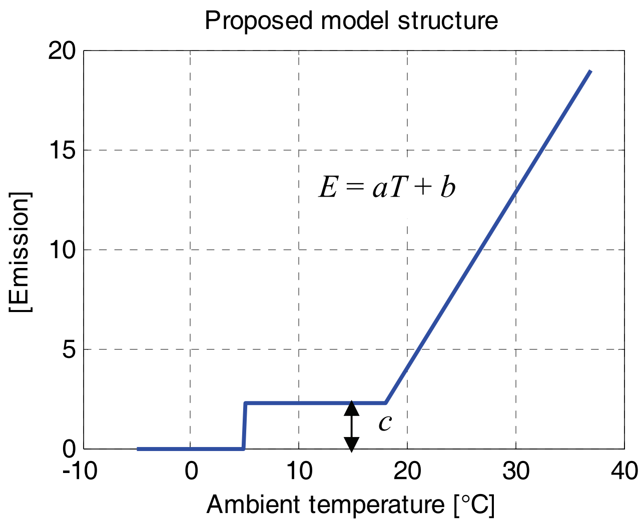

Figure 3: Proposed model structure for the extra emission caused by A/C activity

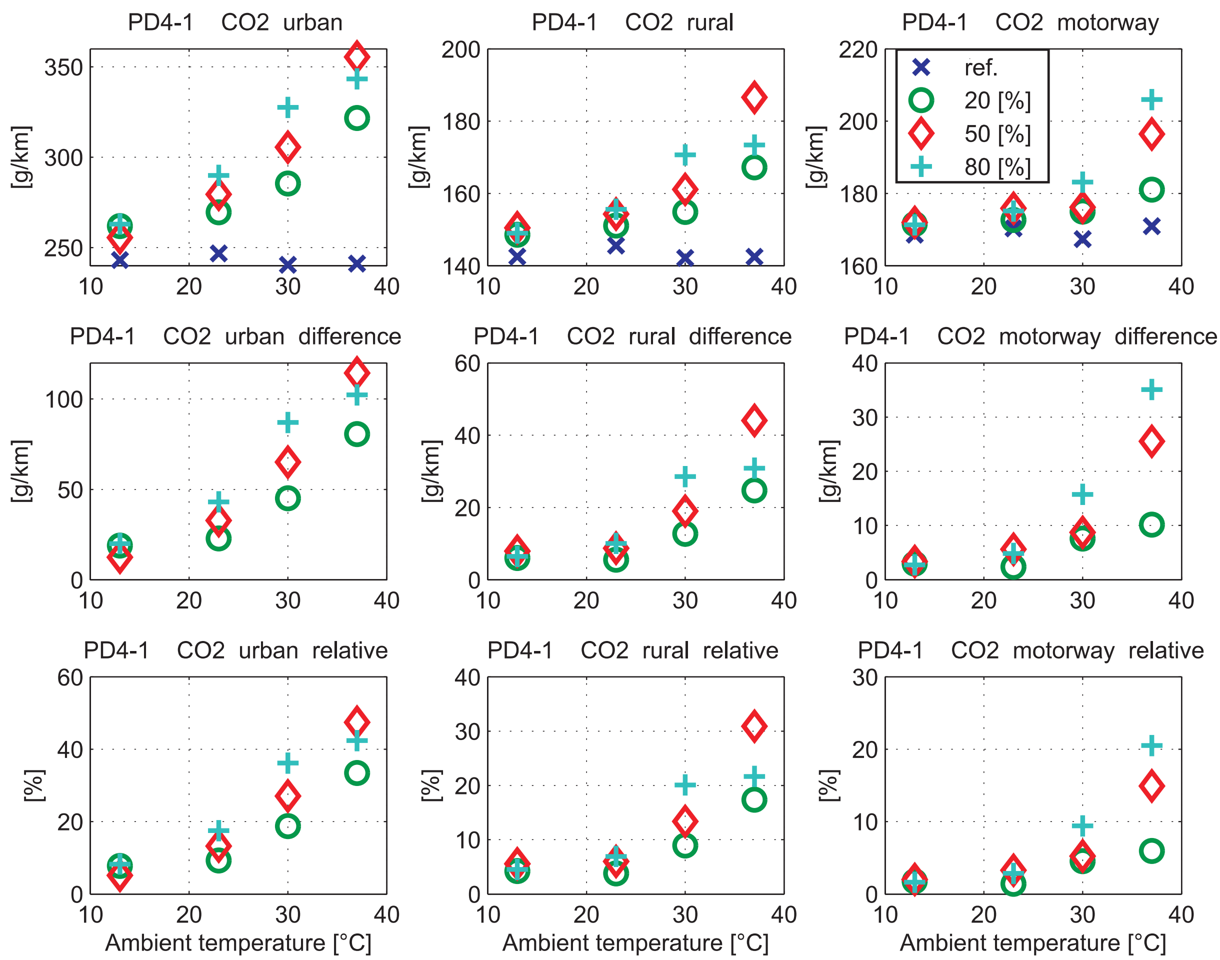

Figure 4: CO2 emissions of vehicle PD4-1 in the cycle CADC at different temperatures and relative humidities (all settings available)

3.2. The influence of ambient humidity

Figure 2 already indicates that at temperatures of 30 and 37°C, the extra fuel consumption is higher when humidity increases. The analysis of vehicle PD4-1 ***(Figure 4)*** provides a better insight concerning humidity since for this car all temperature and humidity settings are available. By analyzing the total CO_2 emissions of the reference tests, it turns out that i) the emissions do not vary as a function of temperature and ii) the variation from the lowest to the highest emissions is about 6 g km^{-1}. This provides a detection limit for determining trends as a function of humidity. At a temperature of 13°C the CO_2 variations as a function of humidity do not exceed the detection limit of 6 g km^{-1}. Thus, no trend can be deduced. The same finding can be stated at 23°C for the rural and motorway parts. In contrast, for the urban part and at higher temperatures, clear trends of higher fuel consumptions as a function of increasing humidity can be established since the variations are distinctly above the detection limit. The test conducted at 37°C and 80% relative humidity is an exception. For this test setting, the automatic A/C system was not able to maintain the internal temperature at 23°C. It turns out that the compressor was partly switched off during the test, which induces a considerable CO_2 reduction.
A model incorporating the influence of ambient humidity can be obtained by expanding the above proposed model with additional characteristic curves (***Figure 3***) at different humidities. Points located between or beyond the characteristic curves can be derived by linear interpolation and extrapolation.

Another approach consists in deriving a characteristic curve at a reference humidity, e.g. 50%, and correcting the influence of humidity by a correction factor. An estimated calculation of such a correction factor is proposed in (Weilenmann et al., 2005). It consists of computing the enthalpy of the moist air at the inlet of the A/C system's evaporator (at ambient temperature and humidity) and the enthalpy of the moist air and potential water at the outlet of the evaporator (at a constant temperature). The heat transferred to the cooling circuit is given by the difference of both enthalpies. Since the temperature of the evaporator is kept constant, the characteristics of the cooling circuit remain constant for a given temperature and so the thermal load caused by humidity correlates linearly with the compressor activity. Moreover, it is assumed that the compressor activity varies in a linear correlation to fuel consumption and CO_2 emissions. Dividing the results by the values of the measured cases with 50% relative humidity produces the estimated correction function. ***Figure 5*** illustrates the estimated correction factor (lines) and the effective correction factor derived from the measurements (marks) for vehicle PD4-1. As discussed above, no distinguishable trends can be deduced from the tests at 13°C, the rural and motorway tests at 23°C and the test at 37°C and 80% relative humidity. For all other tests, the measurement results coincide quite well with the calculated estimations.

This examination indicates that the influence of humidity is independent of the cycle type (urban, rural, motorway) and increases linearly as a function of relative humidity. In general, the extra fuel consumption due to A/C activities decreases and increases about 40% at relative humidities of 20% and 80%, respectively, compared to a standard humidity of 50%.

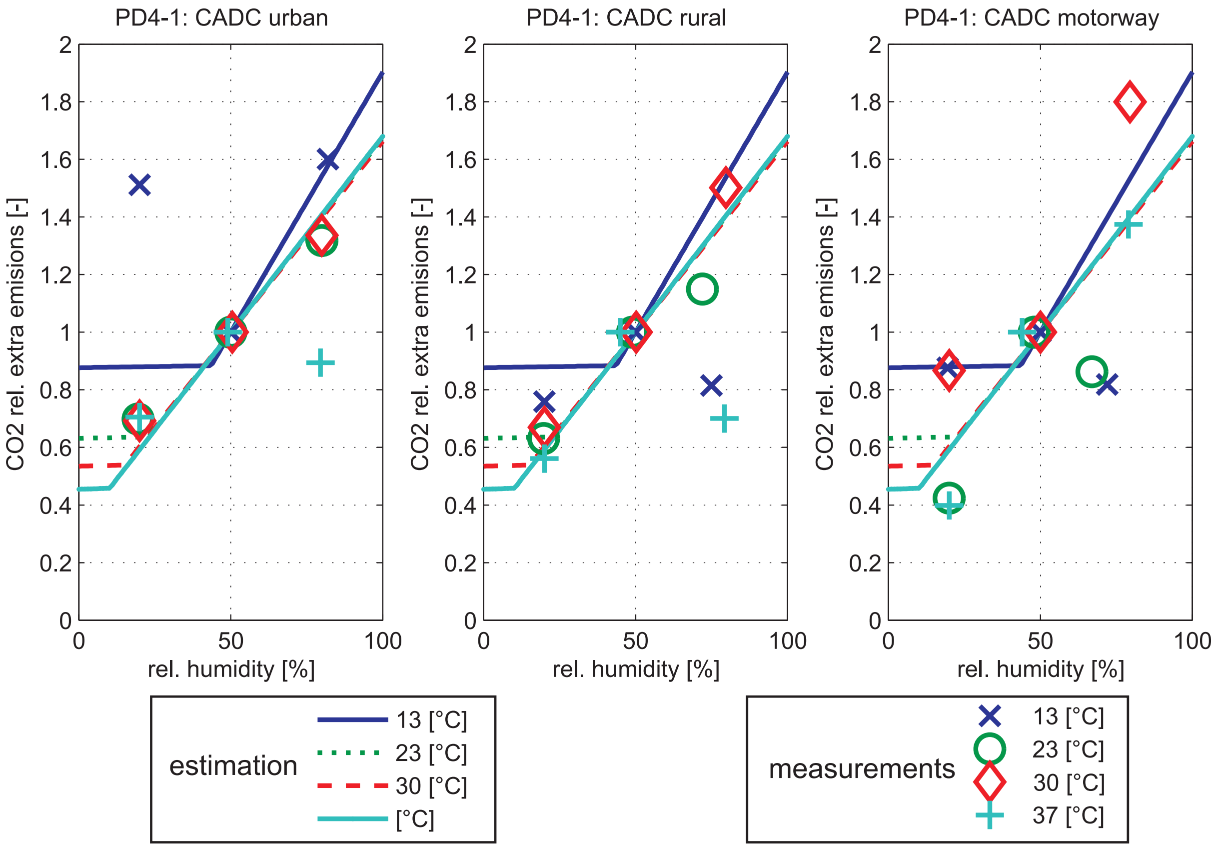

Figure 5: Correction factor at different humidities for vehicle PD4-1, lines: estimated calculation, marks: measurements

3.3. Regulated pollutants

The relation between A/C activity and CO, HC and NO_x is given in ***Figure 6*** to ***Figure 8***. Since the absolute values of these pollutants are significantly lower than the CO_2 emissions, the scatter of the data is considerably greater. Nevertheless, a certain trend for CO and NO_x to increase or decrease with higher A/C activity is observed, while for HC the scatter of the data is too large in order to detect any trends.

For CO, the emissions for urban and rural tests at 37°C are roughly 3 to 4 times higher than at 23°C, while no increase as a function of temperature can be detected for the motorway test. Concerning humidity, a potential increase of CO can be detected at 80% relative humidity for the rural and motorway test runs.

The NO_x values without A/C activity show a notable decreasing trend over temperature for the motorway test. The extra emissions caused by the A/C rise exponentially as a function of temperature. Moreover, there is a clear trend for lower NO_x emissions as humidity increases. For the motorway test, the emissions at 80% relative humidity are equivalent to the emissions without A/C activity. The reduction of NO_x as a function of increasing humidity is due to the fact that moist air has a higher specific heat capacity than dry air. This induces a lower engine temperature and thus less NO_x emissions are produced.

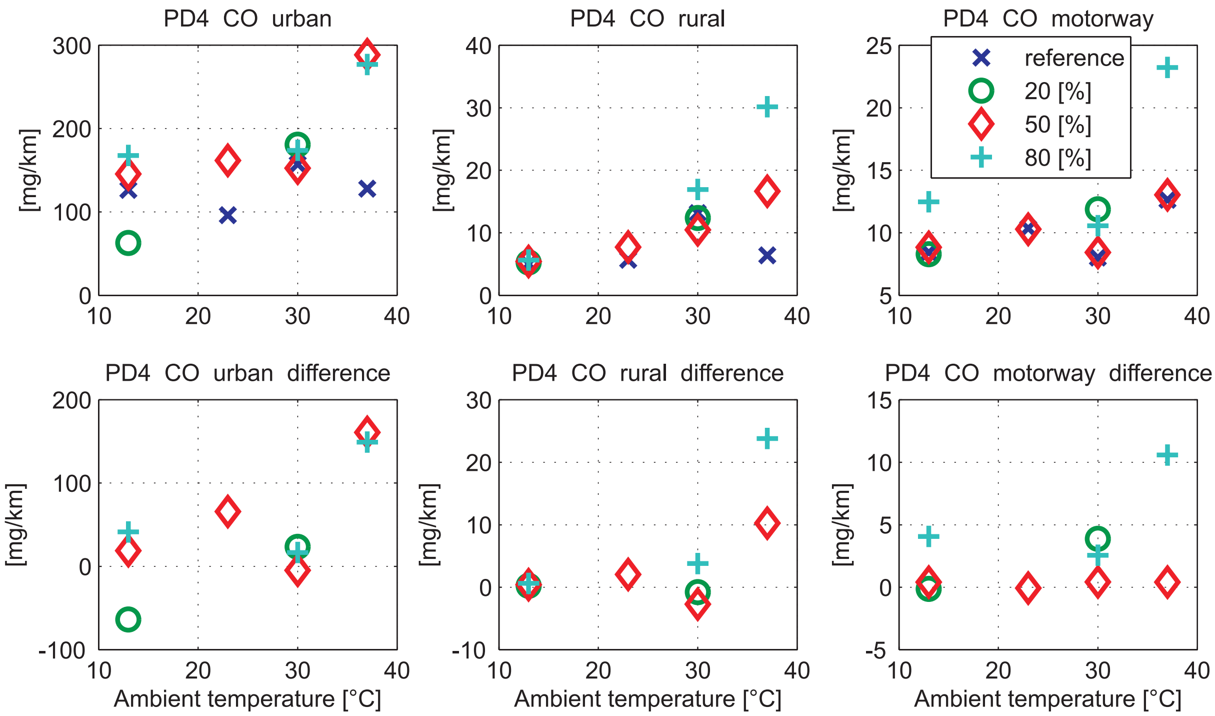

Figure 6: Average CO emissions of the test sample in in the cycle CADC at different temperatures and relative humidities (only 13 test settings available)

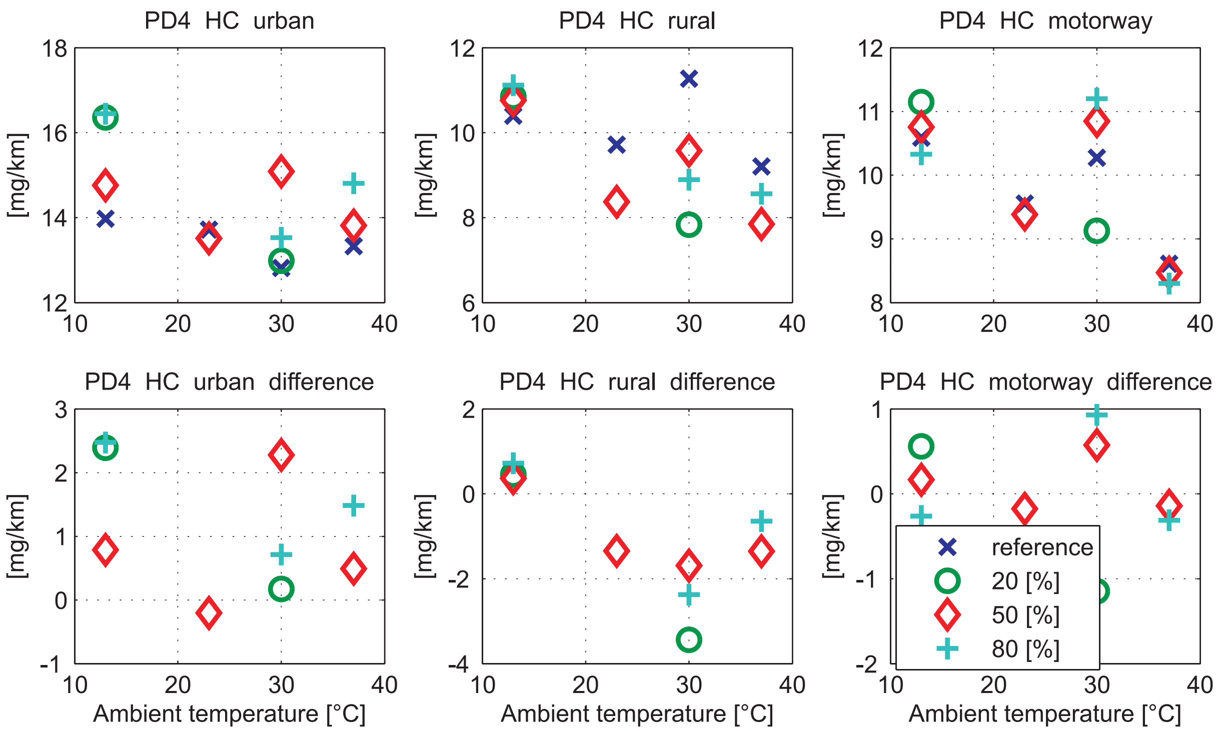

Figure 7: Average HC emissions of the test sample in in the cycle CADC at different temperatures and relative humidities (only 13 test settings available)

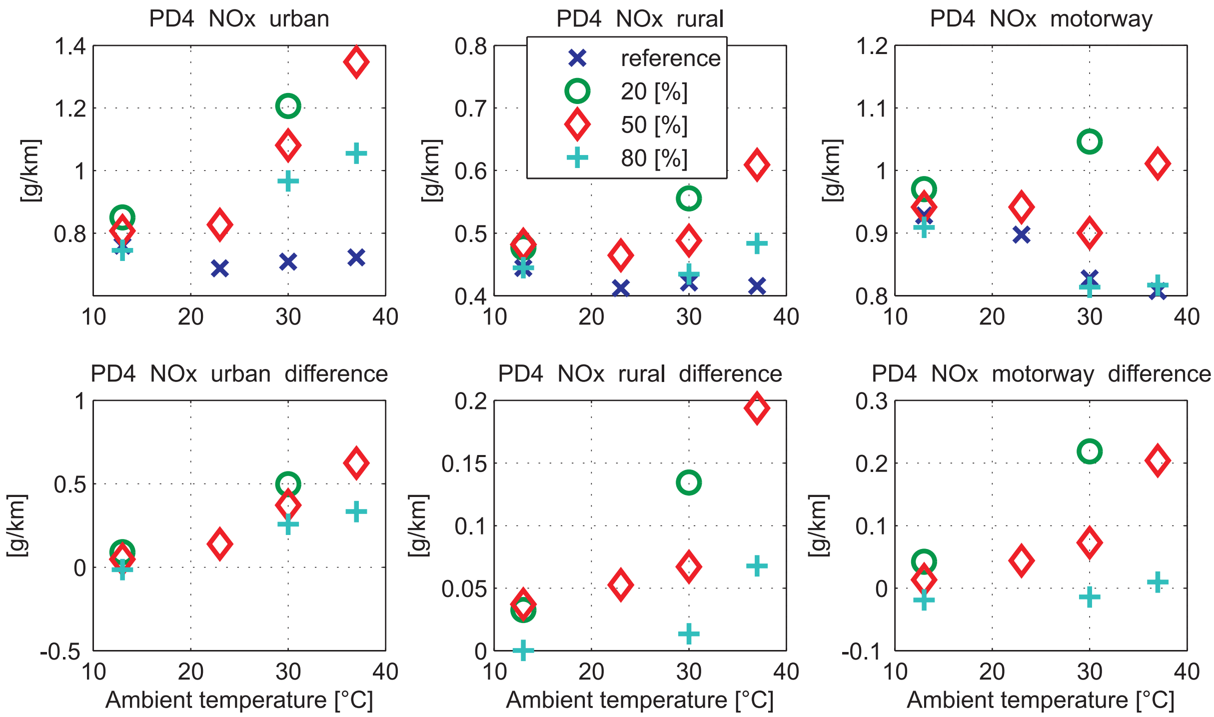

Figure 8: Average NOx emissions of the test sample in in the cycle CADC at different temperatures and relative humidities (only 13 test settings available)

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