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Influence of Mobile Air-Conditioning on Vehicle Emissions and Fuel Consumption: A Model Approach for Modern Gasoline Cars Used in Europe

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The influence of air-conditioning activity on the emissions and fuel consumption of passenger cars is an important issue, since fleet penetration and use of these systems have reached a high level. Apart from the MOBILE6 study in the United States, little data is available on the impact of air-conditioning devices (A/Cs). Since weather conditions and A/C technologies both differ from those in the U. S., a test series was designed for the European setting. A fleet of six modern gasoline passenger cars was tested in different weather conditions. Separate test series were carried out for the initial cooldown and for the stationary situation of keeping the interior of the vehicle cool. As assumed, CO_2 emissions and fuel consumption rise with the thermal load. This also causes a notable rise in CO and hydrocarbons (HCs). Moreover, A/Cs do not stop automatically at low ambient temperatures; if necessary, they produce dry air to demist the windscreen. A model is proposed that shows a constant load for lower temperatures and a linear trend for higher temperatures. The initial cooldown tests highlight significant differences among cars but show that A/C operation for the initial cooling of an overheated passenger compartment does not result in any extra emissions for the fleet as a whole.

Introduction

The influence of air-conditioning 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 automatic systems that are common today are switched on most of the time. However, apart from studies involving MOBILE6 in the United States (*1*) and other U. S. studies (*2*−*5*), air-conditioning activity in relation to meteorological conditions has not been thoroughly investigated. For the European situation, with its different climatic conditions and different vehicle air-conditioning (A/C) technologies, most available studies are based on simulations, on measurements covering only a small temperature range or older vehicle technologies (*6*−*8*), or else they deal with particular questions (*9*).

In central Europe, typical summer temperatures range from 15 to 35 °C, humidity varies in a narrower range than in the United States, usually being between 50% and 80% relative humidity, and even at hot temperatures the percentage of time with clouds, and therefore no direct solar radiation, has to be considered.

Technically, the European car fleet consists of smaller cars with smaller engines, smaller passenger compartments, and thus smaller A/C devices than the U. S. fleet (*1*). A high percentage of the A/C systems are automatic or semiautomatic; i.e., the driver only has to set the desired temperature or has to set both the desired temperature and the fan speed. In addition, more and more vehicles are equipped with A/C systems that modulate the stroke of their compressor or have other modulation capabilities (*8*). It is therefore not possible to relate compressor activity data from real-world studies to chassis dynamometer tests where the A/C systems are off or at full load.

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 had to be restricted to four temperatures and two irradiation scenarios. Originally, it had been planned to run different humidity scenarios as well, but this was not possible for cost reasons.

Six gasoline passenger cars certified to the Euro-3 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.

Two test series were run to differentiate the situation of cooling an overheated passenger compartment, which occurs after parking in the sun, and that of keeping the interior climate stable at the desired comfort temperature.

Materials and Methods

General Setup. With the goal of obtaining representative results for the real-world situation on the roads of central Europe, six gasoline cars were chosen out of the official Swiss sales statistics to give a representative distribution of engine sizes and manufacturers. All of the cars comply with Euro-3 emission levels. The individual vehicles were borrowed from volunteer private owners. They had an average mileage of 48 000 km. The use of diesel vehicles is planned for a subsequent study.

To preserve maximum representativeness, the cars were taken to the test bench without maintenance. However, correct operation of the car was checked, and one car had to be replaced owing to a malfunction of the A/C system. As in homologation tests, the vehicles were given a simulated load of 100 kg. The detailed vehicle description is given in the Supporting Information.

The climatic test cell used here permits temperatures between −20 and 50 °C. It keeps the desired temperature within a tolerance of 1 °C. Relative humidity can be set between 5% and 95% (and to within 5% accuracy). A value of 50% was chosen for these tests since this is appropriate for regulated measurements and is in the range of typical meteorological conditions in Europe.

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 lights 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 so that the sun was allowed to shine only from the front, where,

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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 (the standard design value for solar panels in Switzerland).

It must be stressed here that the A/C systems of many modern cars are equipped with irradiation sensors whose signals are used to control the temperature management. Since these sensors are usually installed inside the passenger compartment, their signals are related to the reflection quality of the windows of the car. That is why the authors consider it quite inaccurate to simulate solar irradiation with a higher ambient temperature or with heaters installed in the passenger compartment.

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 in the ventilation ducts leading to the interior as well as 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 did give qualitative information on the operation of the cooling system. Compressor activity was monitored by collecting the clutch signal, where available.

All of these signals were recorded at a 10 Hz sampling rate.

Accurate measurements of both emission concentration and exhaust mass flow are required for the calculation of emission values and fuel consumption in g/s or g/km. For the regulative bag measurements, the exhaust gas is diluted first with fresh air in the constant volume sampler (CVS) system so that it can be cooled to room temperature without condensation of water. Since the flow within the CVS system is constant, the absolute values of the exhaust pollutants are proportional to their concentrations. A small proportion of the diluted exhaust gas is collected in Tedlar bags during the tests and analyzed for CO, CO_2, HC, and NO_x at the end.

Instantaneous emission measurements were also performed by collecting some exhaust gas directly at the tailpipe and leading it to analyzers measuring 10 samples per second (10 Hz). These measurements were used here for backup and to look for special events as the end of the warmup phase.

Test Description. For the "keep-cool" test series, extra emission values are sought in different driving scenarios such as urban, rural, and highway driving while the A/C 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 air conditioners, a good setting was sought before the test and the knobs for 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 it", 30−50% 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/Cs that are running and at what temperature.

The engine was completely warmed at test start (oil temperature >80 °C).

The test cycle used is CADC, which originates from the ARTEMIS project under the EU Fifth Framework Program and represents real-world driving in Europe (*10*−*13*). It consists of three phases that describe urban, rural, and highway situations; the exhaust gas of each phase is measured separately. This test was repeated with each car at ambient temperatures of 13, 23, 30, and 37 °C. 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.

FIGURE 1. Test bench with sun simulation.

At each temperature, one reference test was run with A/C off, one with A/C on and no solar radiation (shade), and one with A/C on and solar radiation on (sun).

The "initial cooldown" tests simulate the situation where the car starts after being parked in the sun. In reality, the passenger compartment and its surfaces may heat up to 70 °C, depending on the solar radiation and the reflective quality of the windows and interior surfaces. For these tests it was decided to condition the car with the solar lamps on and to heat up the passenger compartment 20 °C above the ambient temperature using electric heaters. The latter are switched off at test start.

These tests were run using a cycle called IUFC15 (inrets urbain fluide court), which originates from the same real-world driving behavior study as CADC and represents an urban journey (*10*). This journey of 189 s is repeated 15 times to guarantee complete warmup of the engine and complete stabilization of the temperature inside the car. These 15 repetitions are grouped into 3 phases of 5 each; the exhaust gas of each phase is measured in one bag. For a test without A/C activity, the transient part of the test describes the warming up of the engine. By establishment of the difference in the emissions between the transient part and the stabilized part, the extra emissions for a cold start are calculated. For the situation involving an overheated passenger compartment and the A/C on, the transient part describes engine warmup and interior cooldown at the same time. By establishment of the difference between the emissions of the transient part and that of the stabilized part, the extra emissions of the combined engine warmup and interior cooldown are generated. To judge the influence of the A/C, these extra emissions need to be compared with those without A/C activity.

For automatic A/Cs, the reference values were again set to the comfort temperature of 23 °C. For manual systems, the A/C was set to full cool and full ventilation at the start. As soon as the desired temperature was reached, the A/C was turned to settings to keep it as in the "keep-cool" tests. In this way an attempt was made to simulate normal behavior in a systematic way.

The test was run at 23 and 30 °C ambient temperature with the sun simulation on. At 23 °C a reference test was additionally run with the A/C off.

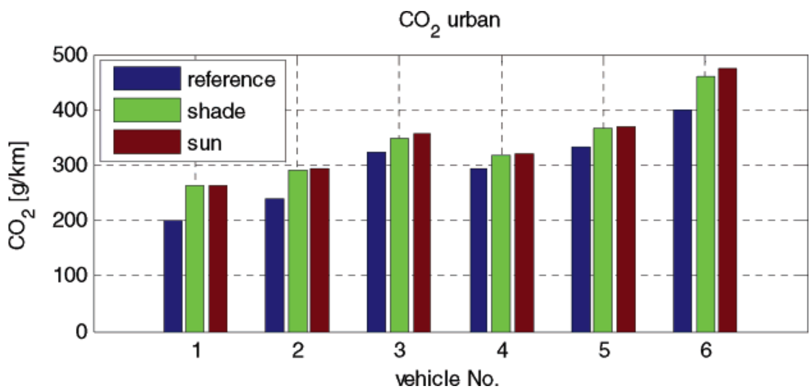

FIGURE 2. CO_2 emissions in urban part of CADC at 23 °C for different A/C settings.

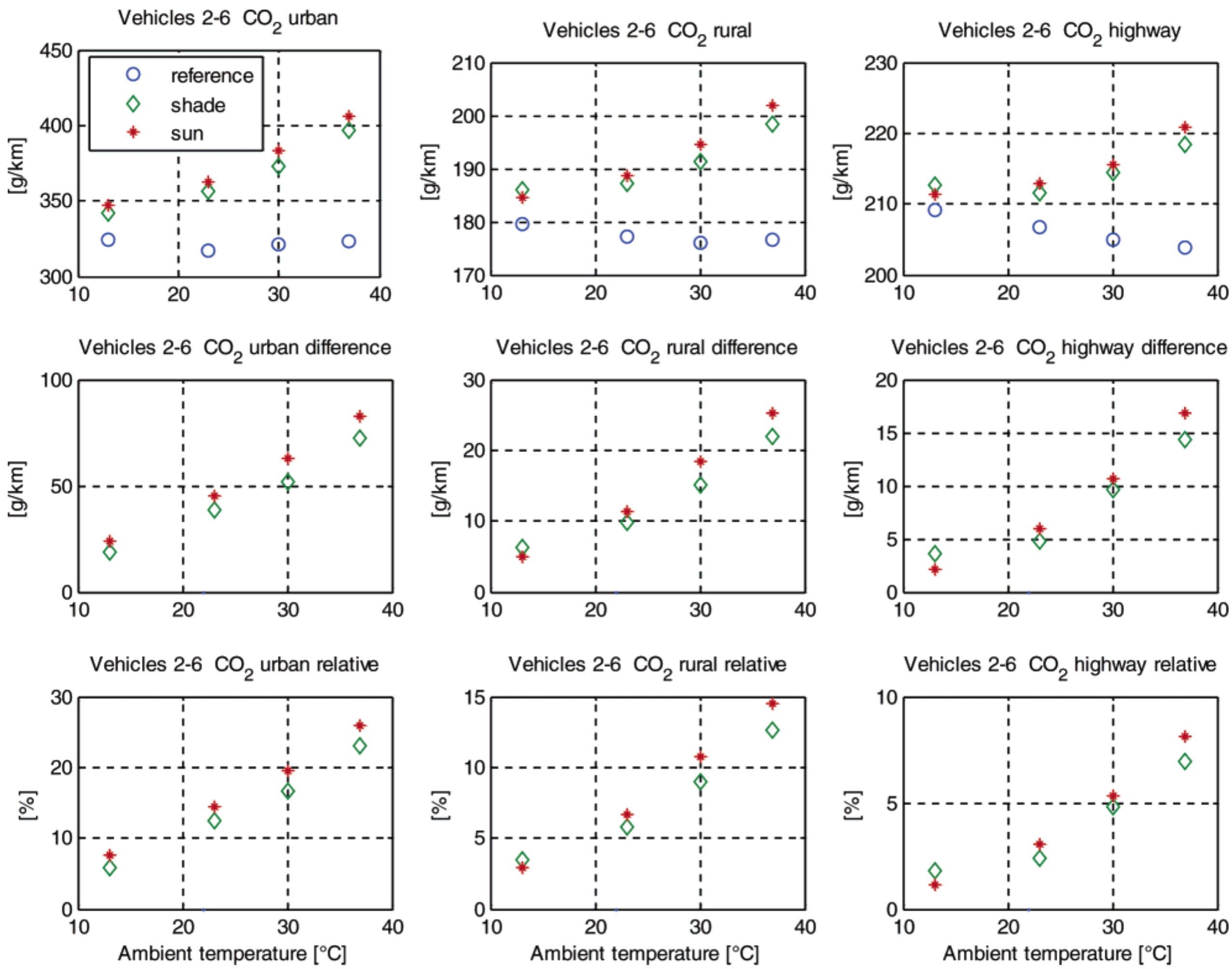

FIGURE 3. Average CO_2 emissions of vehicles 2−6 in CADC at different temperatures and in different irradiation scenarios for different A/C settings.

Results and Model Approach

All emission values of the tests are listed in the Supporting Information.

"Keep-Cool" Test Series. Some important details:

• Vehicle 1 was already unable to maintain the desired interior temperature at an ambient temperature of 30 °C; it was not tested at 37 °C.

• During the measurements on vehicle 2, the test bench showed some malfunctions, and the data set is therefore not complete.

• At 37 °C and with the A/C switched off, the compressor of vehicle 5 is switched on automatically for 8−16% of the time. It is assumed that this is done to prevent the engine control unit from overheating, since an air duct of the A/C system leads to it. Thus these measurements cannot be considered as 0% A/C activity. The 0% activity curves were linearly extrapolated from the data points at lower temperatures for this car.

• Within the MOBILE6 studies (*1*), it was recognized that the compressor activities at idle are different from those when the cars are moving. Some vehicles switch the A/C off to prevent the engine from stalling, while others run the A/C compressor permanently since its efficiency is low at idle. Here, no such effect was observed, and idle is not treated separately.

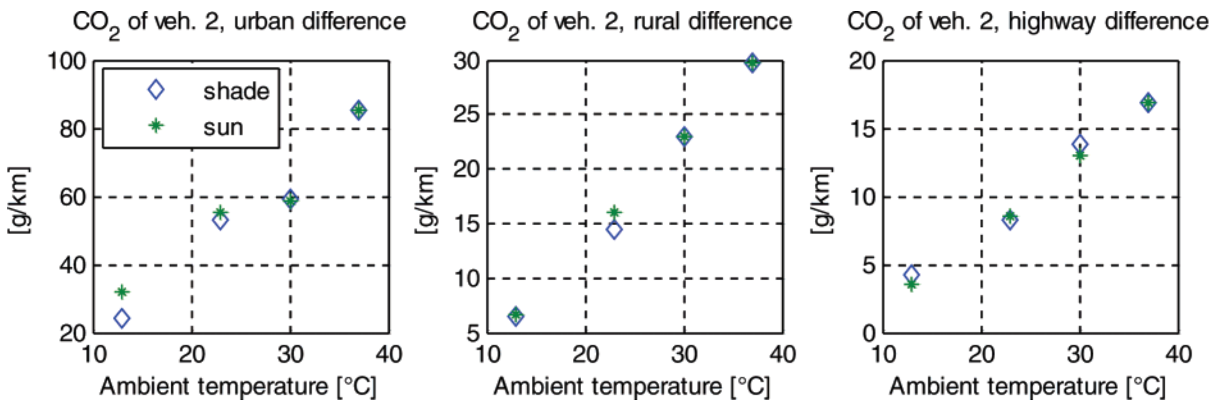

FIGURE 4. CO_2 emission differences of vehicle 2 in CADC at different temperatures and in different irradiation scenarios.

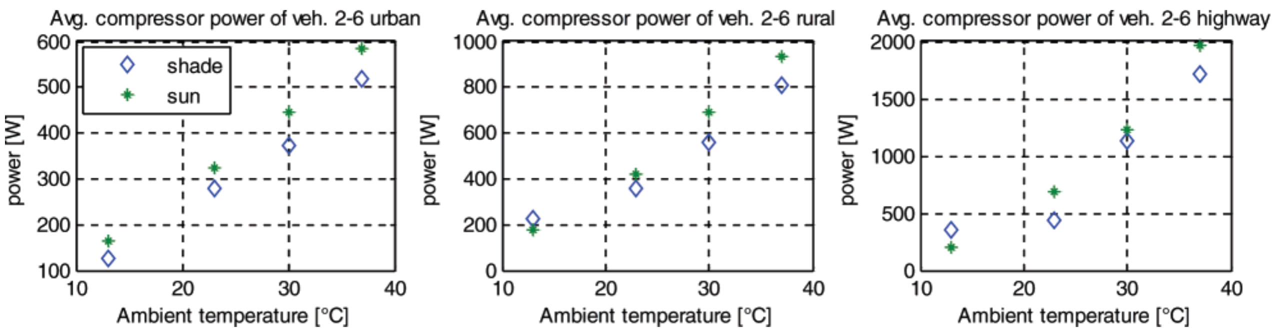

FIGURE 5. Stationary keep-cool test of the passenger compartment, average of estimated mechanical compressor power for A/C activity.

CO_2 and Fuel Consumption. For the tests at 23 °C, the difference between vehicles is highlighted in Figure 2. 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. While cars 1, 2, and 6 need a large quantity of extra fuel to keep the interior cool, vehicles 3−5 do this significantly more efficiently. It should be noted that for the following simplified discussion fuel consumption (FC) and CO_2 emission are considered to be proportional since CO and HC emissions are quite low (0.3148 g fuel ↔ 1 g CO_2), and CO_2 and FC are treated as synonymous in relative comparisons. The fuel consumption is correctly calculated as

$$m_{FC} = 13.85\left(\frac{m_{CO_2}}{44} + \frac{m_{CO}}{28} + \frac{m_{HC}}{13.85}\right)$$

Figure 3 shows the average CO_2 emissions of cars 2−6 for all temperatures and test settings. In the top row, the absolute values are shown, in the center the difference between A/C on and off is displayed, and in the bottom row the relative difference is given. Observations are:

• For the reference test of rural and highway driving, CO_2 emissions are lower at higher temperatures. This statistically relevant trend, already observed for tests at low ambient temperatures (−20, −7, and 23 °C) (*13*) may be due to the fact that warm air has a lower density, with the result that the engine is throttled less to give the same power and is thus running more efficiently. It is assumed that this trend also holds for urban driving, but it seems to be affected by measurement variations. Parameters for the linear trend are given in the Supporting Information. On the basis of this trend, it appears to be misleading if the CO_2 and fuel consumption depending on A/Cs are calculated as the difference between tests at 23° with the A/C off and tests

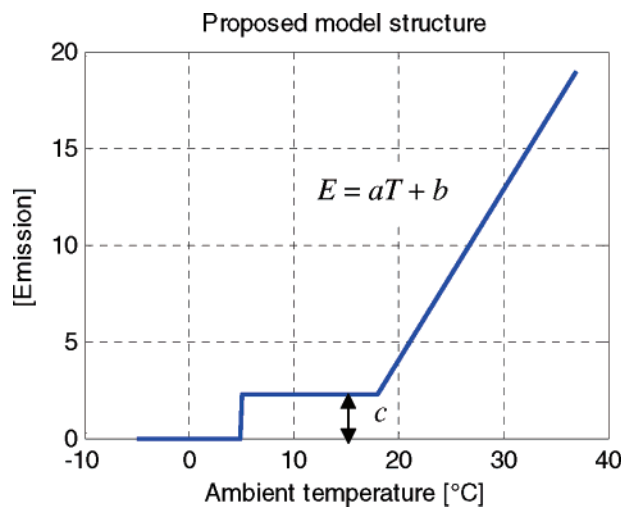

FIGURE 6. Suggested model structure for the extra emission due to the A/C activity for the keep-cool case.

with full A/C activity at high temperatures, as is done by other laboratories.

• In stark contrast to ref *1*, where no A/C activity is assumed below 20 °C, it is observed that the extra CO_2 and thus fuel consumption at 13 °C is not zero but 7%, 3%, and 1.5% for urban, rural, and highway driving, respectively. It was checked for these cases that the temperature in the ventilation ducts was above the ambient temperature so that the A/C was not needed to cool the interior. It was only running to prepare dry air in the event of a misting windscreen. Without proof, it is assumed that this demisting activity is active down to about 4 °C, where the A/Cs have to switch off to avoid internal freezing.

• The difference between A/C on and off clearly increases with temperature and is significantly higher with simulated solar irradiation. Expressed in g/km this extra CO_2 is highest

TABLE 1. Parameters for Proposed CO_2 and Fuel Consumption (FC) Model

CO_2		shade			sun		
parameter	unit	urban	rural	highway	urban	rural	highway
a	g/(km/°C)	2.4422	0.8522	0.6842	2.6889	0.9863	0.7778
b	g/km	−18.7718	−9.9298	−10.9286	−17.1977	−11.2158	−12.1216
c	g/km	18.4666	6.2840	3.6224	23.7000	5.0084	2.1753
FC		**shade**			**sun**		
parameter	unit	urban	rural	highway	urban	rural	highway
a	g/(km/°C)	0.7804	0.2847	0.2793	0.8488	0.3231	0.2790
b	g/km	−6.0888	−3.5017	−5.0211	−5.3366	−3.7406	−4.3917
c	g/km	5.7801	2.0163	1.1428	7.4062	1.5853	0.6512

in urban (81 g/km at 37 °C sun) and lowest in highway driving (17 g/km at 37 °C sun). This is due to the slow urban speed and thus the long time it takes to cover 1 km. However, as shown below, the efficiency of generating cool air is highest at low engine speeds, thus urban driving.

• The compressor activity of vehicle 2 was above 99% for both tests at 30 and 37 °C. The interior temperature was slightly too high at 30 °C and significantly above comfort at 37 °C. It can thus be concluded that the A/C of this car was running at full load from 30 °C up. However, it is surprising to note that the CO_2 emissions are far higher at 37 °C than those at 30 °C (Figure 4). The authors conclude that the load of the compressor on the engine is not constant but varies significantly with the thermal load of the A/C.

It should be noted that, even though the extra fuel per kilometer decreases from urban to highway driving, the estimated power consumed by the A/C system increases sharply (Figure 5). Since the thermal load of the A/C system does not increase, this highlights the inefficient operation of A/C systems at higher engine speeds. Consequently, it may be assumed that most A/C systems are designed to work well at idle and low rpm's (urban) but that they are oversized and thus inefficient at higher engine speeds (highway). A significant fuel savings could be achieved by using electrically instead of mechanically powered compressors.

As observed above, in cars 3−6 the A/Cs are able to keep the passenger compartment comfortable up to 37 °C ambient temperature, and the extra CO_2 and thus engine load rises in a roughly linear manner from 23 to 37 °C. For car 2, the extra CO_2 also increases linearly, even though the A/C is already running full at 30 °C. On this basis, a model with the basic shape shown in Figure 6 is proposed. It consists of no A/C activity for temperatures below 5 °C and a constant A/C load (thus CO_2 and FC) for temperatures above 5 °C for demisting. Its value is given by the tests 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 applied individually to both sunny and shady scenarios and to urban, rural, and highway driving situations.

The question arises as to whether it is to be applied to the absolute difference in emissions in g/km or to the relative emissions in percentages. For CO_2 and FC it could be argued that it is meaningful to use the relative emissions since cars with larger engines usually also have larger passenger compartments and thus need more cooling power than small vehicles. However, the relative standard deviations of the absolute and relative extra emissions are comparable and do not show either approach to be superior. For the pollutant emissions (CO, HC, and NO_x) no purpose is served by considering the relative emissions for the model since the basic values are quite low and thus uncertain. On this basis, it is proposed that the model be applied to the absolute extra emissions in g/km.

For CO_2 and fuel consumption (FC) the average parameters *c* and the parameters *a* and *b* derived by least-squares regressions are given in Table 1.

The intersection of the two straight lines is not fixed; it is defined as:

If $T > 5$ °C, then (if $c > aT + b$, then emission $= c$, else emission $= aT + b$) else emission $= 0$.

Pollutant Emissions Results. The relation between A/C activity and CO, HC, and NO_x for the "keep-cool" situations is given in Figures 7−9 . Since the absolute values of these pollutants are significantly lower than the CO_2 emissions, the scatter of the data is greater. Nevertheless, a certain trend for the pollutants to increase with higher A/C activity is observed.

For CO, the emissions at 37 °C with sun simulation are roughly 2.5 times higher than those at 23 °C and with the A/C off.

Figure 8 shows the HC extra emissions from A/C activity. The increase from 23 °C "clean" to high A/C loads is up to 100% but somewhat scattered by test uncertainties.

The NO_x values given in this report are the measured values without the humidity correction that must be applied to legally required measurements. This is done for two reasons. First, the real NO_x emission factors are of interest here. Second, the empirical formula used for legally required measurements is applied there only for measurements between 20 and 30 °C and might thus be misleading for other temperatures. All measurements were performed at a relative humidity of 50%.

The NO_x values without A/C activity show a notable trend over temperature. Its linear approximation is given in the Supporting Information.

The NO_x extra emissions caused by the A/C activity are in the range of 50% of the basic values, and the data is scattered significantly.

Even though the CO, HC, and NO_x data are quite widely spread and, owing to the small test fleet, the trends are not statistically significant, the increases in CO and HC roughly by a factor of 2 seem to be relevant for fleet modeling.

Hence, the parameters for the same model approach as for CO_2 (Figure 6) are also given in the Supporting Information.

How To Deal with Humidity. The model approach of MOBILE 6 (*1*) is based on the heat index instead of the pure temperature. The heat index is a calculation to "mix" humidity and temperature into one figure based on comfort, i.e., the human body's capacity for thermal regulation by sweating.

However, most air-conditioning systems cool the exterior air to temperatures significantly below 23 °C (i.e., 5−10 °C). Water is condensed, and thus the air fed to the passenger compartment is fairly dry (100% relative humidity at 10 °C gives 45% relative humidity at 23 °C). The ambient humidity therefore has no effect on the people inside the car, and since they do not feel it, they do not manipulate the A/C differently.

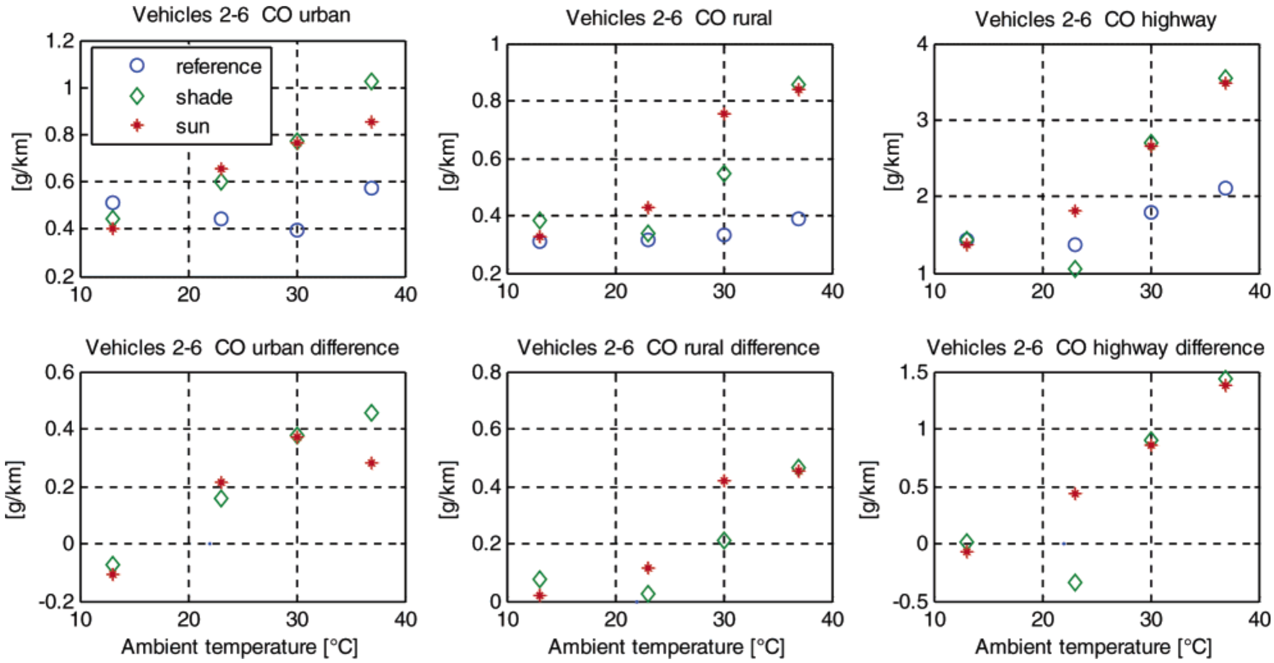

FIGURE 7. Average CO emissions of vehicles 2−6 in CADC at different temperatures and in different irradiation scenarios for different A/C settings.

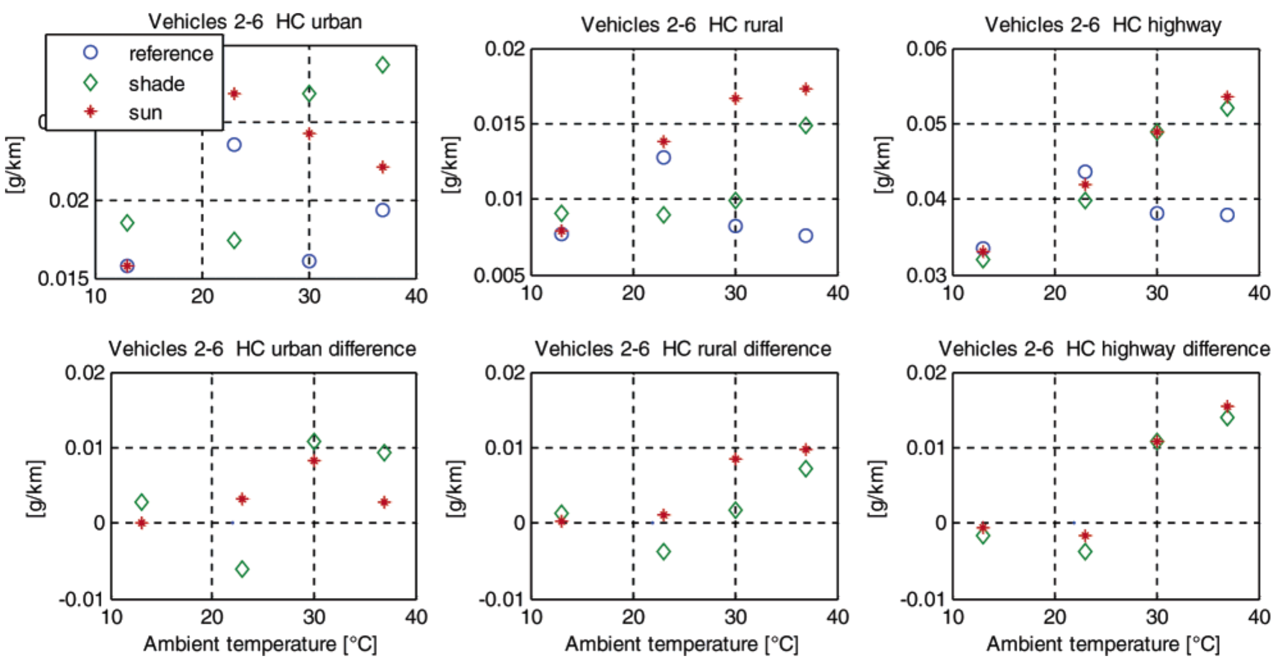

FIGURE 8. Average HC emissions of vehicles 2−6 in CADC at different temperatures and in different irradiation scenarios for different A/C settings.

It is not the goal of this paper to give statistics on how many A/Cs are switched on at what temperature/humidity; it will just give extra emissions in cases where the A/Cs are running. Nevertheless, some words on human manipulation of A/Cs. Since no official statistics are available for Switzerland, the authors concluded from a small sample of 121 Euro-3 vehicles that a majority (68%) of A/Cs are automatic systems. They automatically adjust fan speed and inlet temperature to regulate the interior temperature to the desired value. Since they do a good job, it seems reasonable to assume that most people leave the system on for the whole year or at least for the whole of the warm season. For manual A/Cs, it seems also to be rather common to run the system for the whole of the warm season and just to turn the temperature knob if the comfort temperature is not reached. In all of these situations, human manipulation is independent of ambient humidity. A/C activity depends on humidity and temperature, thus the heat index, only with people who do not run their A/C as long as they do not feel uncomfortably hot. This would need to be taken into account in fleet statistics.

Another aspect of humidity is more technical. If the logic of A/C is to cool the air to a fixed temperature (e.g., 5−10 °C) in all situations, then it needs more effort to cool humid air since more water has to be condensed. Thus A/C activity may nevertheless be a function of humidity, but for technical rather than for comfort reasons. An estimated calculation of this function is given here.

Without intervention by the driver, most air-conditioning systems have no air recirculation in steady-state conditions.

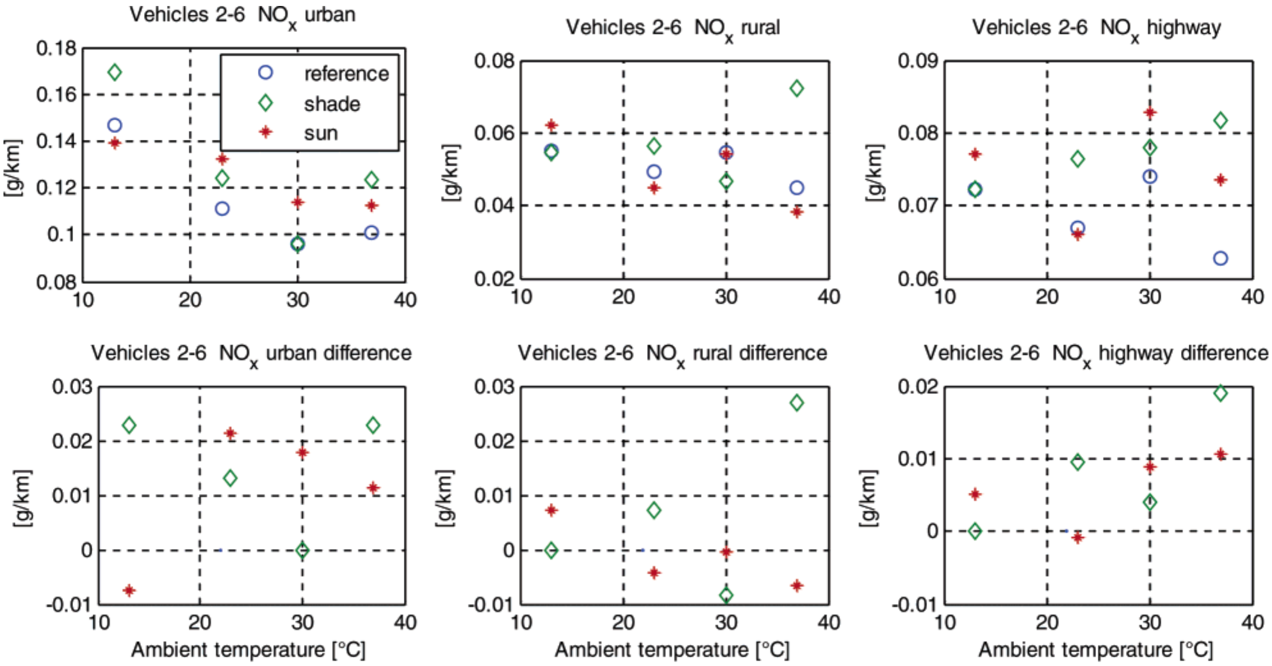

FIGURE 9. Average NO$_x$ emissions of vehicles 2−6 in CADC at different temperatures and in different irradiation scenarios for different A/C settings.

The ambient air is first fed through the evaporator of the cooling circuit. Most A/Cs regulate the outcoming air temperature so that no freezing occurs. This air is then reheated to a comfortable inlet temperature by being passed through a heat exchanger with engine cooling water (*14*). Given this scenario and with some temperatures measured online, the following procedure yields an estimate of the influence of humidity on A/C load:

• The measured temperatures of the cooling liquid in the evaporator range from −1 to 8 °C for the different cars and temperatures. The temperatures of the conditioned air range from 5 to 11 °C.

• By assuming the evaporator surface temperature on the air side to be 2 °C higher than the cooling liquid, the humidity of the outcoming air may be obtained from the Mollier diagram. The point of the incoming air (temperature and humidity known) is linked by a straight line with the point of the surface temperature and 100% relative humidity (*14*). The temperature of the outlet air on this line gives the humidity figure.

• With the enthalpy of air defined as $h_{air} = c_{p\ air}T + x(r_0 + c_{p\ vap}T)$, where $c_{p\ air}$ and $c_{p\ vap}$ are the heat capacities of air and vapor, r_0 is the evaporation heat, and x is the absolute humidity in grams of water per grams of dry air, the heat per gram of air can be calculated as $Q/m_{air} = h_{in} - h_{out} - c_w(x_{in} - x_{out})T_{out}$, where c_w is the heat capacity of water.

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. Thus the clutching compressors run with equal torque for a longer time, and the modulating compressors run at a higher stroke as the load increases. By neglecting a possible small increase in engine efficiency for the vehicles with modulating compressors, the extra heat rises in a linear correlation to fuel consumption and CO_2 emissions.

On this basis, the extra load as a function of ambient humidity can be calculated. Dividing the results by the values of the measured cases with 50% relative humidity produces a correction function as given in Figure 10.

For all temperatures the load roughly doubles for 100% humidity compared with the 50% case. At low temperatures and dry air, the drop is small (factor 0.9) while at higher temperatures the drop from 50% to 0% humidity results in a factor of 0.46. As a consequence, the influence of humidity has to be considered as an important factor.

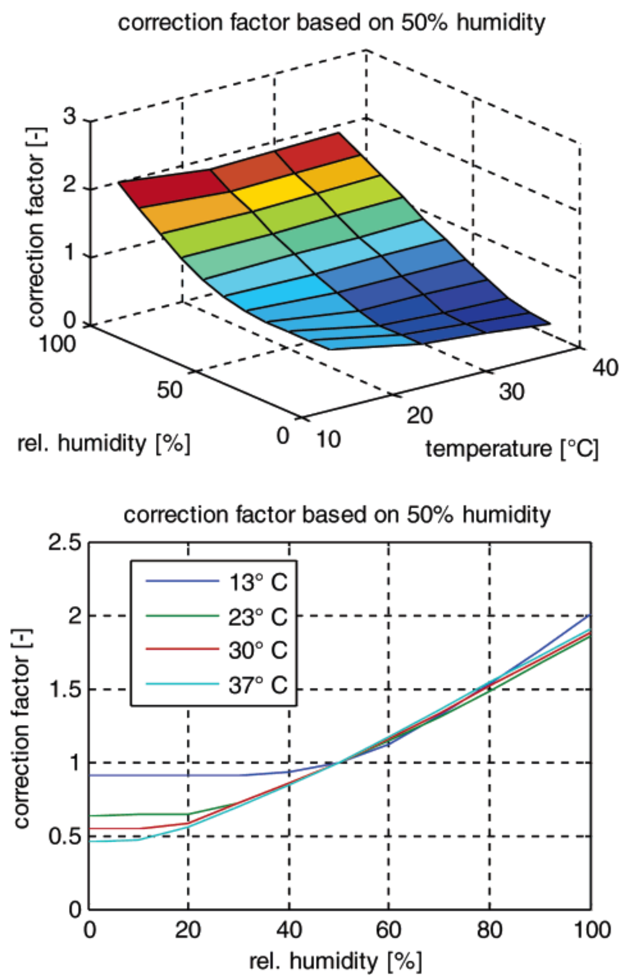

FIGURE 10. Correction function for different humidities.

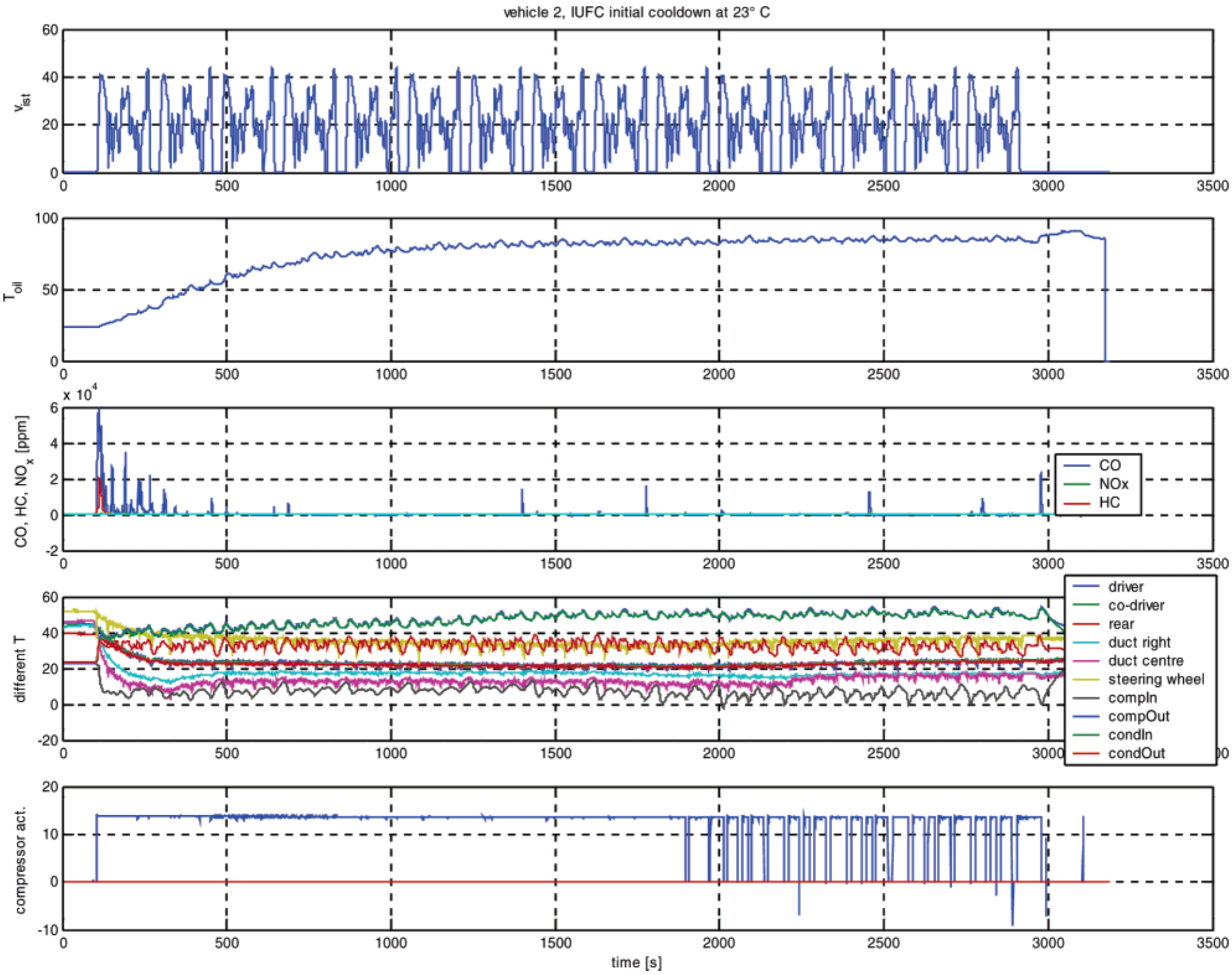

FIGURE 11. Example of online signals in an initial cooldown test.

Since this estimation of the influence of humidity on emissions is based on certain assumptions, it needs to be validated in future work.

Initial Cooldown Test Series. The bag values of all tests within the "initial cooldown" test series are given in the Supporting Information.

The basic goal of this particular test series is to determine the extra emissions due to the simultaneous engine warming up and initial cooling of the overheated passenger compartment. This extra emission is defined as the difference between the first part of a repetitive test in which all transients take place and the later parts of the tests where the engine is stably warm and the interior stably cool.

These tests are based on a cycle (speed diagram) with 15 repetitions. Five repetitions are always pooled, and the emissions are collected in one bag.

The differences between transient and stabilized emission are compared for the following three tests: reference at 23 °C (A/C off), 23 °C sun (A/C on), and 30 °C sun (A/C on). On the basis of the findings of the "keep-cool" tests above, the comparison between the reference tests at 23 °C and the tests at 30 °C is not totally correct. However, there was not sufficient time or funding to repeat these tests.

To calculate the difference between the transient phase and the stabilized phase, the end of the transient phase first has to be detected. This endpoint was determined on the basis of the signals collected online by first finding the end of the transient of each signal and then choosing the latest end time as the overall endpoint.

By way of example, the results of the initial cooldown test at 23 °C for vehicle 2 is given in Figure 11. It can be seen that the oil temperature stabilizes after 1500 s, while the catalytic converter seems to light off around 300 s (end of high CO and HC concentrations). The comfort temperature is also reached within around 250 s, while compressor activity is only reduced after 1800 s.

Some important details of the test results:

• Vehicle 1 was not able to reach the comfort temperature for the test at 30 °C. All other vehicles stabilize the interior temperature within 137−400 s for the test at 23 °C and within 353−557 s for the test at 30 °C, thus within the first third of the test.

• Catalytic converter light off takes place between a few tens of seconds and a maximum of 250 s.

• Oil temperature stabilizes typically between 900 and 1500 s, thus within the second third of the test.

• Both catalytic converter light off and stabilizing oil temperature occur earlier for tests with higher thermal load, i.e., A/C on and higher ambient temperature, as assumed.

• Owing to the higher loads, the emissions of HC and CO *before* catalytic converter light off are higher for the tests with A/C on.

• For the stabilized situation, the extra emissions due to A/C activity in this cycle (IUFC) are quite similar to those of the urban part of the CADC (keep-cool tests), and thus the two test series agree.

• The main results are shown in Figure 12. In the reference tests with no A/C activity, some extra CO_2 is produced during

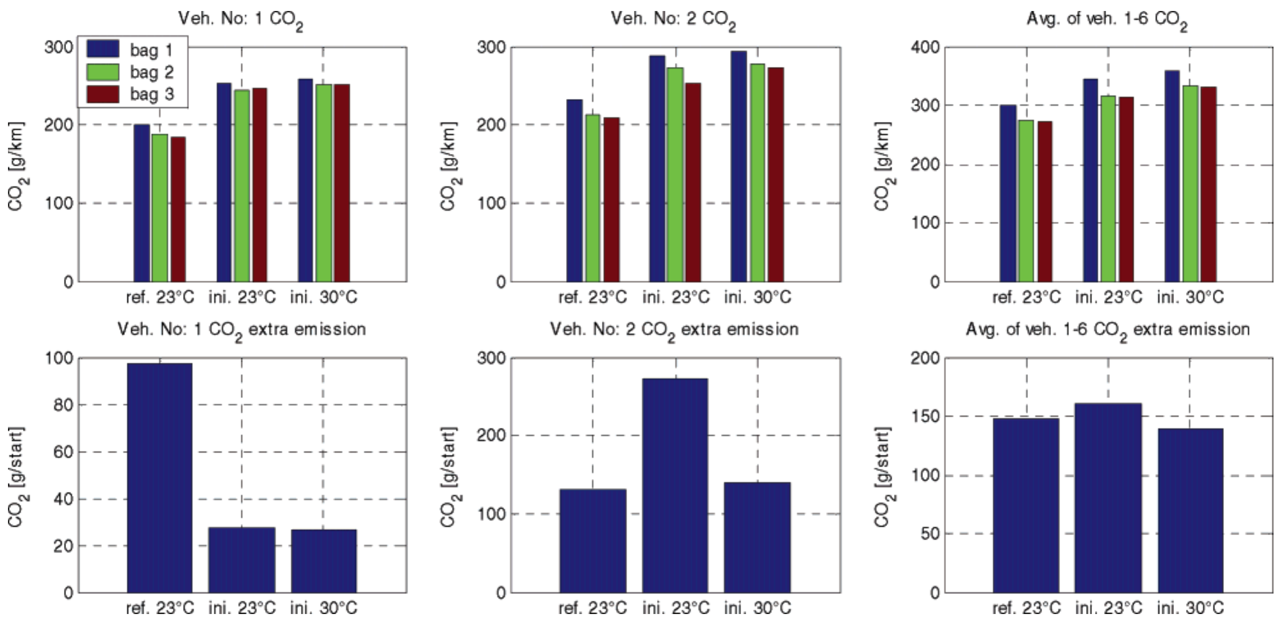

FIGURE 12. CO_2 results of "initial cooldown" test: top, absolute values; bottom, extra emissions compared with thermal steady-state conditions; ref., reference test; ini, initial cooldown tests.

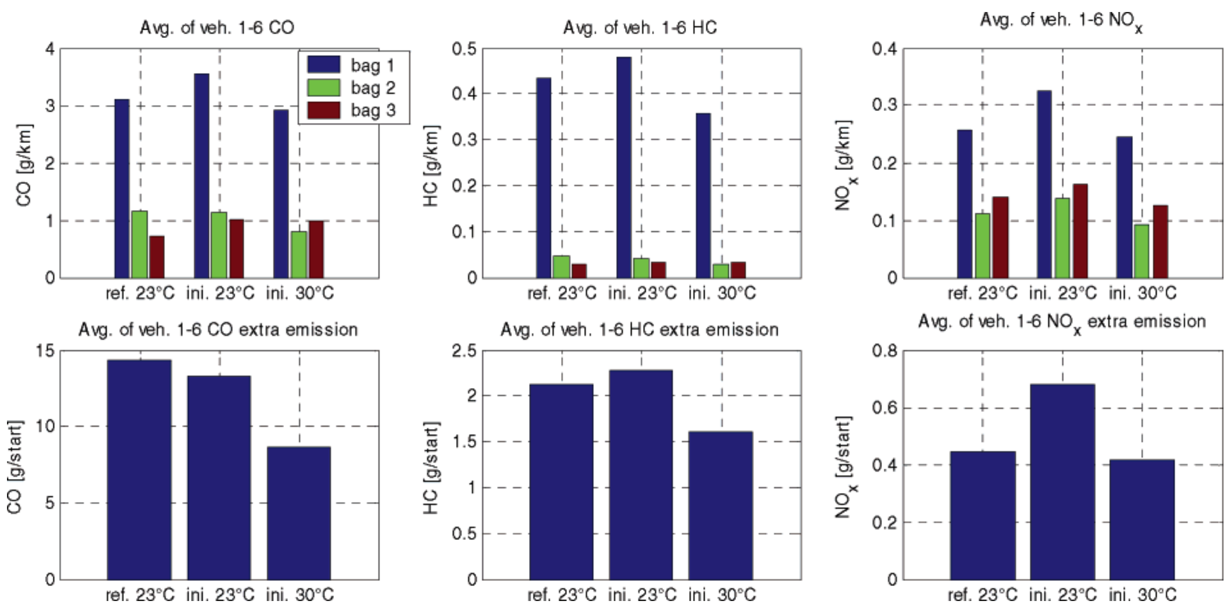

FIGURE 13. CO, HC, and NO_x results of "initial cooldown" test: top, absolute values; bottom, extra emissions compared with thermal steady-state conditions; ref., reference test; ini, initial cooldown tests.

a cold start. This extra fuel is used owing to inefficient combustion and higher friction in the engine during the warmup.

If the A/C is active, then two counteracting effects occur. First, the A/C has to cool the overheated interior and thus needs more power than to keep the interior temperature stable later. However, as already seen in Figure 1, some cars such as vehicle 1 need roughly the same energy for full and partial loads of the A/C. Second, the A/C running (at full load) has another effect. The energy released at the condenser is typically 3 times the energy given to the compressor. Consequently, more thermal energy is released, and the engine compartment heats considerably faster. This accelerated warming up reduces the extra fuel needed because of the friction in the cool engine.

As shown in Figure 12, for vehicle 1 the second effect dominates, and the amount of extra fuel (CO_2) for the transient phase of bag 1 is smaller with the A/C on than in the reference test. For vehicle 2 with significantly better partial load A/C efficiency, the first effect dominates. More extra CO_2 is produced for the transient phase with the A/C on at 23 °C. Since the steady-state load of the A/C at 30 °C is close to full load for this car, the first effect is weaker again, and the extra CO_2 is similar to that in the reference test.

For the average of six vehicles, these two effects cancel each other out, and the extra CO_2 emission is comparable for starts with and without A/C activity.

For the pollutants CO, HC, and NO_x the transient extra emissions are given in Figure 13. For CO it is observed that the extra emissions are reduced with higher A/C activity. However, for both HC and NO_x there is no clear trend.

Even though intuition suggests that the cooling of an overheated passenger compartment needs a large amount of energy, the extra emissions and fuel consumption of the transient phase are not higher than without A/C activity. Thus no extra model for the emissions in the initial cooldown situation is necessary; the well-established cold-start models may be used.

Discussion

The A/C systems of European cars are based on a variety of different technologies, so that it is not possible to link compressor activity data collected by tests on the road with emission results from A/C full-load tests on the chassis dynamometer. Fuel consumption and exhaust emissions have to be measured directly in tests where the cars are exposed to simulated weather conditions on the test bench.

Here, the meteorological situation was simulated with temperatures from 13 to 37 °C. The solar irradiation was simulated in front of the car with 800 W/m^2 on a surface area of 1.7 m^2 at an inclination of 45°.

A/Cs cause extra CO_2 emissions in g/km and thus fuel consumptions that increase:

- significantly with temperature
- sharply with solar irradiation
- significantly with lower vehicle speed, but A/C efficiency decreases significantly with higher vehicle speed

The maximum average extra CO_2 results in urban driving at 37 °C and with the sun shining. It amounts to 82.7 g/km (26%).

Extra CO_2 emissions are not zero but 2.4−18 g/km at 13 °C (1.5−7%), owing to demisting activity. This highlights the difference compared with the American situation described in ref *1*. For fleet statistics this finding will significantly increase the extra fuel consumption due to A/C activity. On the basis of specific temperatures in the A/C systems, the influence of humidity is estimated. This shows that for high humidities the load almost doubles and that for low humidities the load is reduced by some 10−50% in relation to the measured case of 50% relative humidity. CO and HC emissions show a relevant trend (factor 2 from 23 °C with the A/C off to 37 °C with the A/C on) over A/C activity. However, the vehicle sample is too small for a statistically reliable model. The trend in NO_x emissions is quite small.

For the stationary situation of keeping the interior cool, a model is suggested that shows a constant A/C load at low temperatures and a linearly increasing trend at higher temperatures. This model is to be individually applied to the sunny and shady situation as well as to urban, rural, and highway driving. For the emission model of CO, HC, and NO_x, more vehicles need to be measured to reach statistical significance.

For all of the emissions (CO_2, CO, HC, and NO_x) roughly no additional extra portions are emitted for the initial cooldown situation. No model is therefore necessary there.

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Supporting Information Available

Detailed vehicle descriptions, emission values and fuel consumption for the “keep-cool” test series, emission values and fuel consumption for the “initial cooldown” test series, model parameters for the CO_2 trend without A/C activity, model parameters for the NO_x trend without A/C activity, model parameters for the CO, HC, and NO_x extra emissions caused by A/C activity, and table for humidity correction. This material is available free of charge via the Internet at http://pubs.acs.org.

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