Discrepancies in Modelling Emissions of Mobile Air Conditionings

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Abstract

Mobile air conditioning systems (MACs) are the largest energy consumers in cars apart from driving itself. While different measurement series in hot ambient conditions are known, little data is available for lower temperatures. Moreover no data on diesel vehicles is available, despite these being quite common in various European countries. Further there are no models available that allow estimating extra fuel consumption and emissions for European car fleets and meteorological conditions. A test series with 12 vehicles (diesel and gasoline) was conducted to investigate for extra fuel consumption and CO_2 and pollutant emissions. These tests were run at different ambient temperatures, humidities and solar irradiation. Combining the results with the average meteorological year in Switzerland shows 5.4% rise of fuel consumption due to MACs. Different measures to lower this value are discussed.

Introduction

The impact of mobile air conditioning (MAC) systems on fuel consumption, CO_2 and pollutant emissions of vehicles is an issue that has been discussed for nearly two decades (Barbusse, 1996, Sand et al., 1996). With the increasing significance of global warming and the high market penetration of MACs, the CO_2 emissions of the latter are also highly relevant. In recent years, the main focus has been on improving the technical efficiency of MAC and on replacing refrigerants (Salim, 2010, Tian et al., 2009, Hager et al., 2006, Steven, 2005). Legislation stipulating maximum extra emissions for MACs and manufacturers developing more efficient technologies are both contributing to this process (Steven, 2005). However, despite MOBILE6 monitoring and modeling the real-world emissions of MACs in 2000, few studies have since been published on these extra emissions (Koupal, 2001, Hugrel and Joumard, 2004). Many modelers currently use MOBILE6 all over the world, including Europe (Hugrel and Joumard, 2004). It is also worth mentioning that the MAC sub-model of the new MOVES (Motor Vehicle Emission Simulator) of US EPA is based on MOBILE6 (EPA, 2010).

For Europe, with its different climates and varying vehicle technologies, most studies are based on data covering only a small temperature range or older vehicle technologies(Hovland, 2003). MOBILE6 is based only on measurements above 22°C, and assumes that MACs do not run at lower temperatures. The authors recorded that all systems in European cars, if left switched on, keep running except below 5°C to prevent freezing. In this range of 5°C-18°C, it is not necessary to cool incoming air to maintain a comfortable temperature. However, cooling to about 3°C dehumidifies the air for the rare case of windscreen misting. This load on the refrigerant circuit must be taken into account when calculating annual fleet emissions, which EEMAC is built for. Further, before this study, no data was available for diesel vehicles, where the power for the MACs is delivered with a different efficiency than for gasoline cars. In the project described here the behavior of MACs of gasoline and diesel cars was recorded over a wide temperature range and the EEMAC model was developed (Weilenmann et al., 2005, Weilenmann et al., 2010). Both EEMAC and MOBILE6 are applied to central European climatic conditions, with vast discrepancies in results.

Materials and Methods

In the context of mapping road traffic emissions for Europe, emissions were collected from tests on a chassis dynamometer in a climatic cell simulating different weather conditions. The variety of weather situations had to be restricted to four temperatures and three humidities for cost reasons. Six diesel and six gasoline passenger cars were measured.

Test Setup

To obtain representative results reflecting the situation on the roads of central Europe, the cars were chosen based on official Swiss sales statistics regarding engine size and manufacturer distribution (ref). The individual vehicles, with an average mileage of 67,000 km, were borrowed from consenting private owners.

Special lamps were installed to simulate solar radiation. Various sensors were installed to monitor the behavior of the MAC. Compressor activity (i.e. the compressor-on fraction of time for systems with a clutch) was monitored by collecting the clutch signal, where available. All of these signals plus exhaust emissions were recorded at 10 samples/s.

The values for extra emissions generated by MACs were determined as the difference between a test with the MAC off and one with the MAC on. The MAC was set such that the true temperature at the driver's head was 23°C.

The test cycle used was CADC, which originates from the EU - ARTEMIS project and represents real-world driving in Europe(Andre, 2004). It consists of three phases that depict urban, rural and motorway driving. These tests were run at ambient temperatures of 13°, 23°, 30° and 37°C. For the gasoline sample test were done with simulation of solar radiation on and off. For Diesels test were run with simulation of solar radiation on at relative humidities of 20%, 50% and 80%. For each situation also a test with MAC off was run as reference. The lowest test temperature of 13°C was intentionally chosen to study the situations where the MAC is only needed for windshield defogging.

Test Results

All emission values obtained in the tests are listed in (Weilenmann et al., 2010). Figure 1 shows the average extra emissions of the gasoline vehicles for different temperatures at 50% humidity. As the differences from the shady to the sunny situation are small, the diesel vehicles were measured only with sun simulation on.

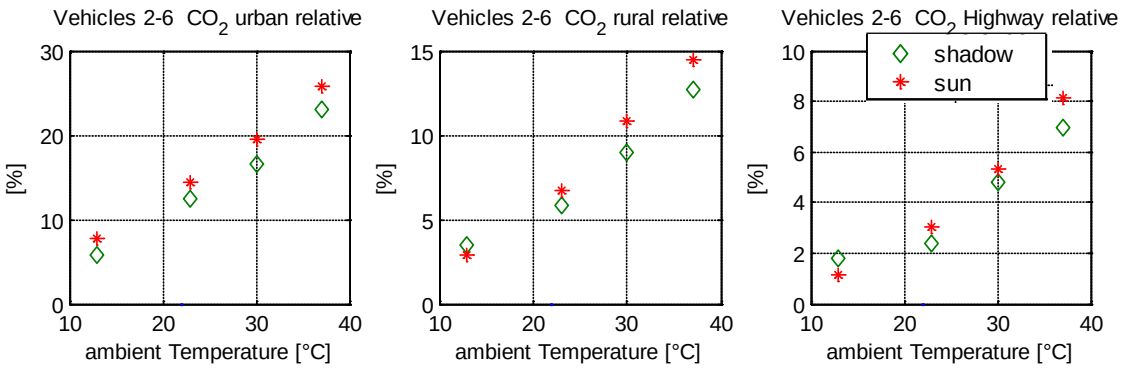

Figure 1: Average relative CO_2 emissions of MACs of gasoline vehicles 2-6 for different ambient conditions. Humidity is set to 50% rh. Vehicle 1 was excluded as it did not reach the desired comfortable temperature in the passenger compartment at 30 and 37 °C.

Figure 2 shows the average CO_2 emissions of the diesel test sample at different temperatures and humidities. Again, the relative difference in the tests with MAC on and off is shown. The following observations can be derived from both figures 1 and 2: 1) It is observed that the extra CO_2, at 13° C is not zero but 8%, 4% and 2% for gasoline vehicles and 4%, 2.5% and 1% for diesels, for urban, rural and motorway driving, respectively. It is known that this demisting activity keeps running down to about 4°C, where MACs switch off to avoid internal freezing. 2) The values clearly rise with temperature and humidity. They are highest in urban and lowest in motorway driving as it takes longer to cover one kilometer in cities. 3) The extra CO_2 emissions rise in a roughly linear manner from 23 - 37°C.

The Empa Emission model for Mobile Air Conditioning systems EEMAC

Out of this data a simple model was derived in two steps: The rise in CO_2 over temperature is suggested as a straight line interpolating the data points at 23°, 30° and 37° for the temperature

range where the interior really needs to be cooled, and adding a horizontal line through the data point at 13° (Figure 3, left) for the range where the MAC only runs for demisting purposes. The lower end of this horizontal line is put conservatively at 5°C, as most MACs have a set point of 3°C. Intuitively, it would appear to make more sense if, at lower temperatures, this line were also to rise with temperature. However, the emission values at 23° are not much higher than those at 13°, thus the gradient of that line would be rather small (Figure 2), and the cooling circuit runs at part load with reduced efficiency (Ratts and Brown, 2000). Nevertheless, a sensitivity analysis was performed with different gradients for this line at lower temperatures, which yielded little impact on the final results (Weilenmann et al., 2010).

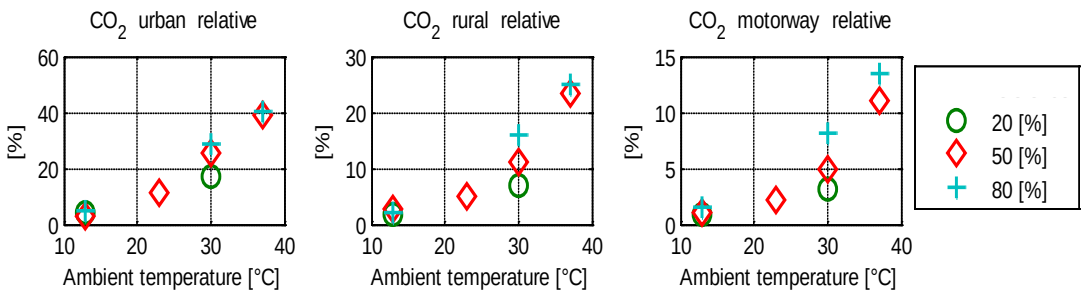

Figure 2: Average extra CO_2 emissions from MACs of the diesel test sample in the CADC cycle at different temperatures and humidities with suns simulation on. Values are given in % of CO_2 released for driving.

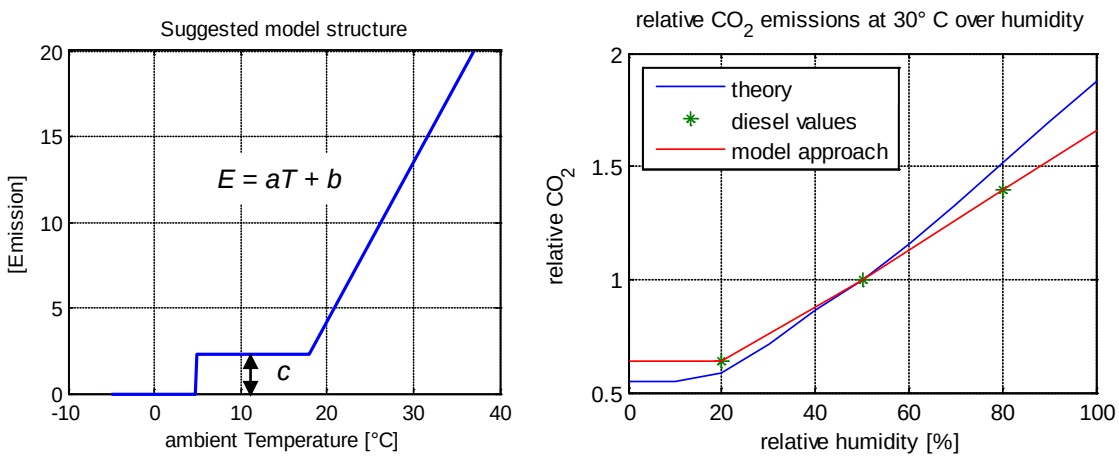

Figure 3: Left: Proposed model structure of EEMAC for extra emissions (relative, in %) due to MAC activity as a function of temperature. Right: Theoretical relationship between relative CO_2 emissions and humidity at 30° (blue line), measurement data from diesel cars (asterisk) and proposed model (red line). Note: data is scaled to 50% humidity.

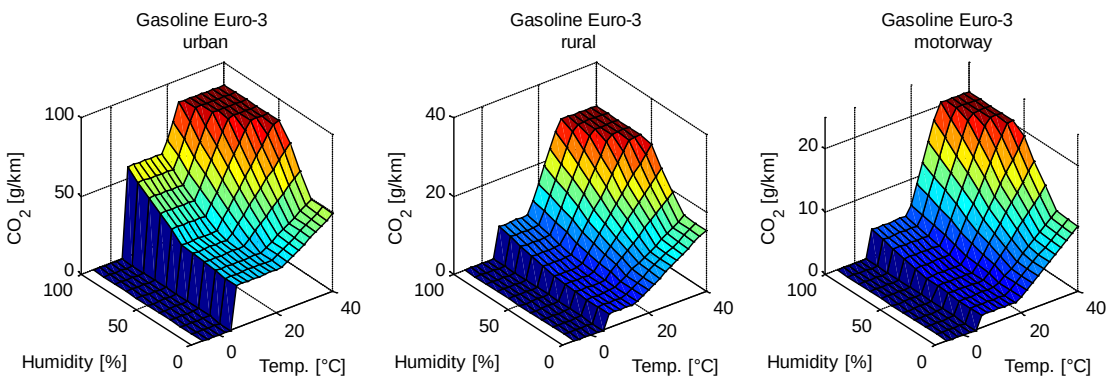

Figure 4: EEMAC for CO_2 extra emissions caused by MAC activity.

As second step an analogue approach was used to deal with humidity. Straight lines are also chosen here in order to keep the model simple and as close to measured data as possible.

For weather with high temperature and humidity the MAC's run maximally, no longer being able to keep the passenger compartment cool. This limit was estimated by analysing online data.

Finally, the EEMAC appears as in Figure 4. As the measurement data for the pollutants is much more scattered than for CO_2, as these emissions are several orders of magnitude smaller, it was decided to model the extra emissions of the following pollutants only as a function of ambient temperature and not humidity: CO and HC for gasoline vehicles, NO_x for all diesels, PM and PN for diesels without DPF, see details in (Weilenmann et al., 2010).

Results and model comparison

Model characteristics

EEMAC was compared to MOBILE6. To make this comparison meaningful, MOBILE6 was adapted to the two vehicle fleets discussed here (Weilenmann et al., 2010).

The model maps for the MOBILE6 “Morning-Afternoon” case are compared with the EEMAC in Figure 5. For motorway driving, the two models agree closely except for the 20% humidity (rare in Europe). For rural driving, the models agree well for temperatures above 25°C. However, for 20-25°C, EEMAC provides higher values. This discrepancy is even greater in urban driving.

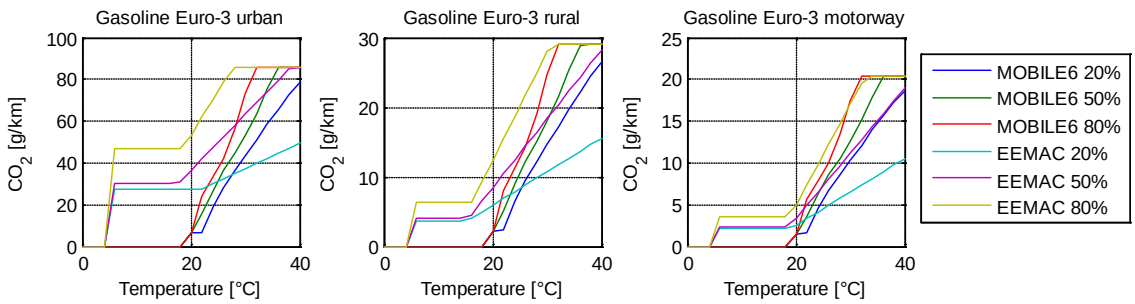

Figure 5: MOBILE6 “morning-afternoon case” and EEMAC MAC models at three different humidities.

This difference may be explained as follows: EEMAC data shows that at 23°C, the average compressor-on fractions are 70%, 56% and 45% for urban, rural and motorway situations respectively (with average velocities of 17, 60 and 120 km/h). The refrigerant circuit is thus less effective when the engine is running at a lower rpm, and the engine runs less efficiently. In MOBILE6, the measured trend of compressor-on fraction over average speed coincides very well with the aforementioned percentages but was considered insignificant for the final model.

Both models thus show comparable CO_2 emissions in the temperature range that formed the main focus of MOBILE6 (above 30°C). However, at intermediate temperatures down to 20°C, the discrepancies rise to a factor of two. Below 20°C, EEMAC describes notable emissions, while in MOBILE6 activity is assumed to be zero.

Application to climate and traffic data of central Europe

Both models were then applied to the following reference case: the Design Reference Year (DRY), EN ISO 15927-4:2005 of the Swiss Association of Engineers and Architects for the city of Berne, which consists of hourly values for humidity and temperature. For a substantial number of hours (95%), the ambient temperatures are below 20°C and humidities are around 80%. This data was combined with the average diurnal traffic activity for Switzerland (Keller et al., 2009).

While MOBILE6 was applied as described above, EEMAC was applied twice: “EEMAC full” assumes that everyone with a MAC leaves it running for the whole year. This is quite realistic for automatic systems, as they provide a comfortable environment in both cold and hot weather with the same setting, and the driver therefore sees no reason to change the settings. Furthermore, unbeknownst to the driver, many systems automatically turn the MAC on at ignition under all ambient conditions. “EEMAC reduced” assumes that the driver turns the MAC off as soon as temperatures drop below 18°. Not using the MAC in this case does not cause

any higher risk of tiredness or discomfort. The small number of cases when the MAC needs to be turned on below 18°C due to windscreen misting is neglected, as this is fairly seldom and lasts for only a short period of the trip.

These two extreme approaches are chosen to stress the possible savings of fuel and emissions.

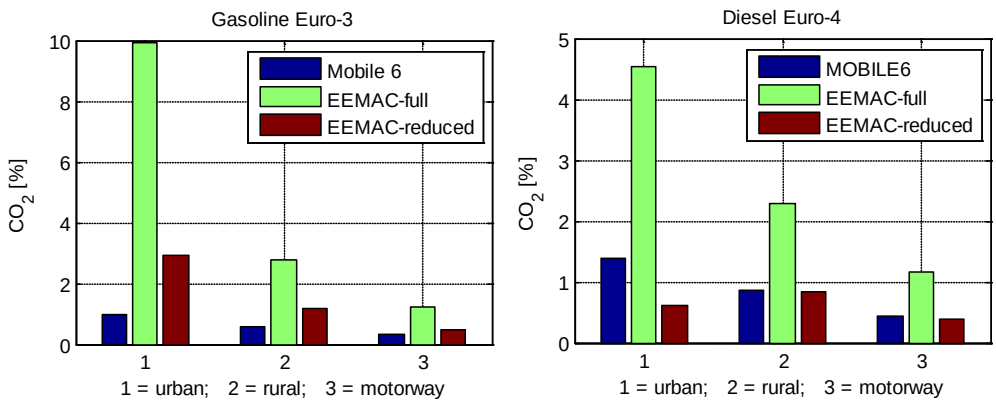

Figure 6: Annual average CO_2 extra emissions for the different models applied to the region of Bern.

The results are shown in Figure 6. Huge discrepancies are evident between the results of the two models for the gasoline vehicles, owing to the differences between the two models in the mid-to-low ambient temperature range common in Central Europe. The application of MOBILE6 to European gasoline fleets therefore leads to a clear underestimation of extra emissions caused by MAC. There is also a discrepancy when comparing the EEMAC-reduced approach with MOBILE6, which is mainly due to MOBILE6 neglecting the fact that the extra emissions caused by a MAC depend on the vehicle's average velocity.

For the driver, however, the main message of this finding is that two thirds of CO_2 and fuel consumption from MAC activity could be saved without discomfort by switching off the MAC below 18°C. The saving would be 7, 1.5 and 0.75% of overall fuel consumption for urban, rural and motorway driving respectively. For diesel vehicles, MAC emissions are also clearly underestimated by MOBILE6. Here 3.9, 1.5 and 0.8% of fuel could be saved by switching off the MAC below 18°C.

Discussion

New data on the impact of mobile air conditioning activity on CO_2 and fuel consumption are presented in this paper. A simple model has been derived to calculate extra emissions and fuel consumption resulting from MAC activity as a function of ambient temperature and humidity. When the present EEMAC model for gasoline cars is applied to activity and meteorological data for Central Europe, annual average extra emissions of 9.9, 2.8 and 1.25% of CO_2 result for urban, rural and motorway driving respectively. Moreover, up to two thirds of these emissions are caused by operating the MAC at temperatures below 18°C, where mere ventilation is sufficient, and the MAC could thus be switched off without any discomfort to the vehicle occupants. When the MOBILE6 model is applied, the resulting extra emissions are lower by a factor of 3 to 10, and thus greatly underestimate the European situation.

The authors suggest that these findings are used to inform the public such that they turn off MACs completely if no cooling is needed and turn on only when the windscreen mists. Legislation could also support this process. As technical measures the authors suggest the following: The "turning off below 18°C" could be realized through the automated control of the MAC system. By installing a humidity sensor in the interior, the need of drying incoming air could be controlled appropriately. Further, the set point (the lowest temperature in the cooling circuit) does not need to be at 3 °C all the time. It could be set higher according to the actual conditions of temperature and humidity. Moreover, online date shows clearly that compressor efficiency varies strongly with engine speed. Thus, using electrically driven compressors would improve efficiency even more.

Acknowledgements

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