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Influence of passenger car auxiliaries on pollutant emission factors within the Artemis model

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Abstract

The impact of the auxiliaries and particularly Air Conditioning on emissions (CO₂, CO, HC, NO_x, and particles) is investigated. To this aim, various data from European laboratories are used and analysed. Parameters linked to technology and to climatic conditions are investigated. The main distinction is made between gasoline and diesel vehicles. A physical model is proposed to extrapolate the excess emissions at low temperature (below 28°C) and with solar radiation, together with a statistical model.

Keys-words: Air Conditioning, auxiliary, emission, atmospheric pollutants, passenger car, climatic condition.

Résumé

Les effets des auxiliaires et plus particulièrement de la climatisation sur les émissions (CO₂, CO, HC, NO_x et particules) sont étudiés. Pour cela, des données expérimentales de plusieurs laboratoires européens ont été rassemblées et analysées. Les paramètres liés à la technologie et aux conditions météorologiques sont évalués. La principale distinction est opérée par le type de carburant : essence ou diesel. Un modèle physique a été développé pour déterminer les émissions pour des faibles températures (inférieures à 28°C) et selon le rayonnement solaire, ainsi qu'un modèle statistique.

Mots-clef : climatisation, auxiliaire, émission, polluants atmosphériques, véhicule particulier, condition climatique.

Introduction

The Artemis (Assessment and Reliability of Transport Emission Models and Inventory Systems) study is aiming at developing a harmonised emission model for road, rail, air and ship transport to provide consistent emission estimates at the national, international and regional level. A workpackage is aiming at improving the exhaust emission factors for the passenger cars and light duty vehicles, by enlarging the emission factor database, especially for effects of auxiliaries.

A European Climate Change Programme working group estimated that the usage of air conditioning (AC) systems under average European conditions causes an increase of fuel consumption between 4 and 8 % in 2020 (ECCP, 2003). A recent study valued an increase of fuel consumption in 2025 below 1 % (Hugrel & Joumard, 2004). That is why it is proposed to undertake a state-of-the-art review of this area, to include fleet characteristics and a collection of data on auxiliaries (Roujol, 2005). Studies about air conditioning have been done in Europe focussed on the evaluation of individual passenger car emission due to AC (Barbusse et al., 1998; Gense, 2000; Pelkmans et al., 2003; Weilenmann et al., 2004), or on the improvement of AC (Benouali et al., 2003). A major study about AC impact has been carried out in the framework of Mobile 6 by the USEPA, focussed

on the real use of AC in real conditions (Koupal, 2001) and on the effect of air conditioning running at full load on regulated pollutants (Koupal & Kremer, 2001).

1 –Excess fuel consumption and CO₂ emission data analysis

Air conditioning database is made up of experimental data from 3 European laboratories (Utac and Cenerg in France, Vito in Belgium), i.e. 27 vehicles and 146 tests. Driving cycle, number of vehicle tests, type of vehicle, experimental objectives vary with experimentation. The choice of vehicles covers the main types of vehicle (small and large vehicles), different propulsion systems (gasoline and diesel) and the emission standards (mainly Euro 1, but also Euro 3 and 4). The climatic conditions are specific to each laboratory, but have been chosen in order to represent severe climatic conditions. The small size of the database allows us to perform a simple statistical analysis. According to Mobile 6, emitter classes, vehicle type, driving cycle, emission AC off and mean speed have to be distinguished to estimate effect of AC. At this short list, we can add, as proposed by Benouali et al. (2003), the regulation type and the compressor technology type.

The excess emission of pollutants due to air conditioning is the difference of emission with and without air conditioning running in the same condition. We have first to decide the type of unit to express the excess fuel consumption due to AC: in volume per distance unit or in volume per time unit. For physical reason (no strong relation between cooling demand and vehicle speed), it seems that volume per time (l/h for instance) is better.

The mean speed has little impact on excess fuel consumption, but variance test indicates that the relation is statistically significant. The relationship is mainly influenced by the data at 90 and 120 km/h constant speed. It seems due to the engine efficiency, which varies with load and engine speed. The effect of AC on fuel consumption is partially hidden by the improvement of engine efficiency, but not at high speed or load. A similar conclusion is given in a recent experimental study on two vehicles in real driving conditions (Roumégoux et al., 2004). The effect of speed is explained by the fact that the engine load for EUDC cycle is particularly low. For real driving cycle, engine load is slightly higher, and fuel consumption due to AC should be quite independent of the speed or type of driving cycle.

Technological parameters analysed are parameters connected to the vehicle engine, to the AC system and to the body shape of the vehicle. The data are displayed according to the engine size, the fuel type, the vehicle size, the type of compressor and the type of regulation. In order to get enough data per class, only 4 types of vehicles are distinguished (see Table 1). The results show that the fuel consumptions are quite close with large standard deviations. Therefore we assume that the fuel consumption of AC does not depend on technical parameters.

vehicle type			fuel consumption		
	fuel	AC regulation	nber veh.-tests	average	st. dev.
Small, Medium 1	Gasoline	manual	38	0.7	0.2
	Diesel		55	0.68	0.22
Medium 2, Large, SUV	Gasoline	automatic	25	0.75	0.34
	Diesel		28	0.85	0.35

Table 1: Average fuel consumption due to air conditioning (l/h) for the 4 vehicle types.

The climatic conditions and set temperature have certainly a huge influence on AC running, and then on pollutants emissions. No experimentation is performed according to the solar radiation, although, according to Barbusse et al. (1998), solar load represents 45 % of the total load of the air conditioning. According to Figure 1, the variation of excess fuel consumption with the outside temperature is lower than expected: although the uncertainty of the measurements, the outside temperature at which there is no cooling or heating, obtained by linear extrapolation, seems to be below 0°C. Theoretically, the relation between fuel consumption and outside temperature is quite

linear because of convective heat gains linearly linked with the difference between outside and inside temperatures. That seems to demonstrate that AC is running quite close to full load for outside temperature higher than 28°C. An extrapolation of these data is therefore non applicable. As the experiments do not allow us to take into account temperature below 28°C and solar heat radiation, a physical model is therefore developed.

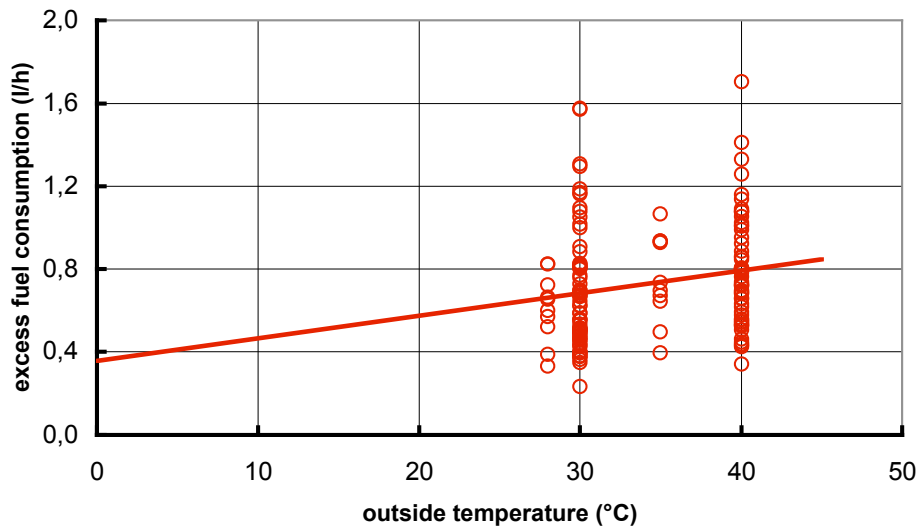


Figure 1: Excess fuel consumption (l/h) due to AC versus outside temperature (°C), with linear regression.

2 - Air conditioning physical modelling

The physical phenomena taken into account are the heat exchanges of the cabin with outdoor, the heat exchange on evaporator of air conditioner, the air conditioner and the engine running.

The passenger compartment modelling is based on a description of heat exchange as it is usually done in mono-zone thermal building modelling (Bolher et al., 2000). Air temperature and humidity in the cabin is assumed to be uniform. Heat exchanges governing temperature of cabin are due to the global heat exchange coefficient, UA ($W.m^{-2}.K^{-1}$), the untreated air flow rate due to permeability, m_p ($kg.s^{-1}$), the internal heat gains due to occupants and electrical equipments, A_{int} (W), the solar gains, A_{sol} (W), and the treated air flow, m_t ($kg.s^{-1}$).

The modelling of solar gains (Fraisse & Virgone, 2001) depends on the direct and diffuse solar radiation, the position of the sun in sky and the geometric and physical properties of the vehicle window. Temperature and flow rate of treated air flow are regulated in order to maintain cabin air temperature to set temperature.

The thermal mass of the vehicle's interior has an effect in dynamic behaviour, increasing cooling demands during cool down for instance, but has no effect during steady state cooling and is therefore neglected. Weilenmann et al. (2004) have studied initial cool down, by combining the effect of initial cool down of the overheated passenger compartment and the effect of cold start. Two counteracting effects occur: Because of thermal mass, AC running involves more power than at steady state, and AC running involves that engine compartment is heated much faster than without AC running. These two effects compensate each other, and excess emission due to initial cool down in comparison to steady state emission is in the same order of magnitude than the cold start excess emission in the same temperature conditions.

With the internal temperature T_{int} , the temperature of treated air T_t , and the outside temperature T_{ext} , the conservative equation of energy is:

$$(m_t + m_p) \cdot T_{int} - (m_t \cdot T_t + m_p \cdot T_{ext}) = A_{int} + UA \cdot (T_{ext} - T_{int}) + A_{sol}$$

The internal temperature is chosen according to the thermal comfort theory (Fanger, 1972). The conditions of thermal comfort are a combination of skin temperature and body's core temperature providing a sensation of thermal neutrality and the fulfilment of body's energy balance. From ASHRAE standard 55 (1992) and Charles (2003), 23°C is chosen as default value. The sensible heat exchange P_{sens} at evaporator to maintain internal temperature at the comfort temperature can be deduced, and, if air treated rate m_t is known, air treated temperature T_t can be calculated:

$$P_{sens} = m_t \cdot (T_{ext} - T_t) = (m_t + m_p + UA) (T_{ext} - T_{int}) + A_{sol} + A_{int}$$

Heat exchange at the evaporator can cause dehumidification of air treated. The average surface temperature humidity of air treated across AC evaporator depends on the heat transfer coefficients of evaporator and the temperature of coolant. With the air side heat exchange efficiency, it allows us to calculate the average surface temperature and humidity of outlet air. With assumption on a minimum air flow rate of 300 m³/h and a minimum average surface temperature of 0°C, the air treated temperature can be calculated. We assumed that the efficiencies of AC and engine are constant. For energy efficiency of the engine, experimental data show that running conditions of the engine have a small effect on CO₂ emissions due to air conditioning. According to Park et al. (1999), the main parameters on AC efficiency are the temperature conditions, but the effects of temperature on energy efficiency are lower than on cooling demands.

The model is applied to all experimental conditions either presented in section 1, or by Weilenmann et al. (2004), with temperature range resp. of 28-40°C and 13-37°C. The results of the model are compared to the experimental results (see Figure 2). They are quite close for temperature higher than 30°C. From 20°C to 30°C, the model underestimates the fuel consumption; And below 20°C, hourly fuel consumption from model are null, but experimental excess fuel consumption can be linked to the electrical consumption of ventilation to avoid windscreen fogging.

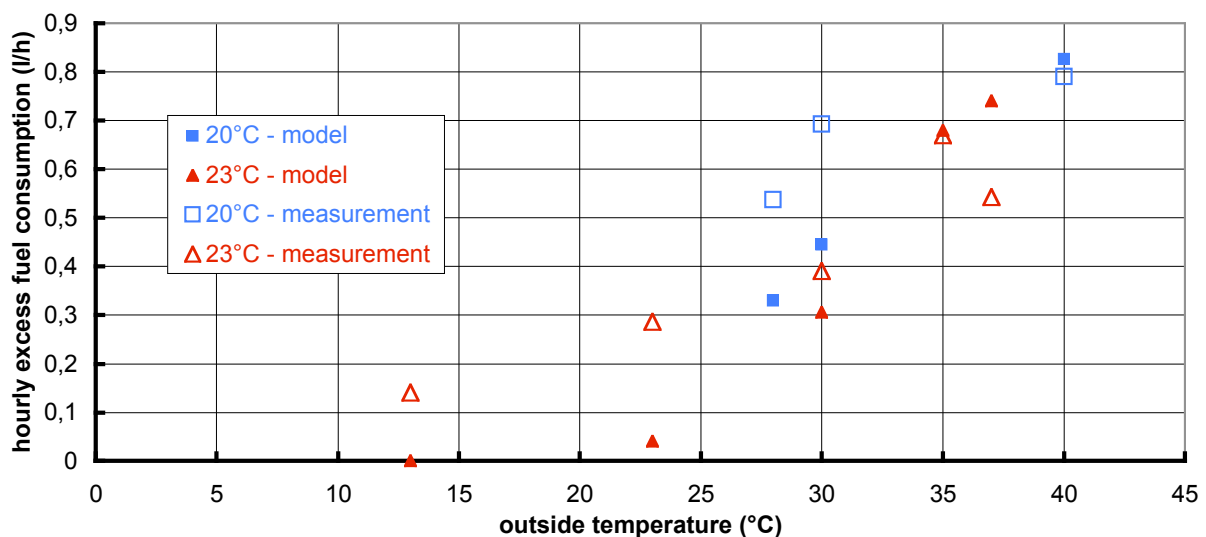


Figure 2: Comparison of the results from model and from experiments as a function of outside temperature for two internal temperatures (20 and 23°C).

A second comparison is done with the Mobile 6 model of demand factor based on experimental measurements. Demand factor is defined by Mobile 6 as the fraction of running time of AC, but can be also defined as the ratio of part load power consumption to the full load power consumption, estimated at 0.85 l/h. The Mobile 6 model and the proposed model are applied with hourly weather data of Seville in Spain, which has the closest climate in Europe to the climate of Denver where vehicle were followed in order to determine demand factor in Mobile 6. In order to take into account the solar loads, Mobile 6 distinguishes daytime and night, and our model calculates the solar loads for each climatic condition described in the weather data. As shown Figure 3, demand factors obtained by Mobile 6 and our model are quite close for temperature higher than 20°C.

Below 20°C, demand factor from Mobile 6 model is null but slightly above 0 for our model because of solar loads heating.

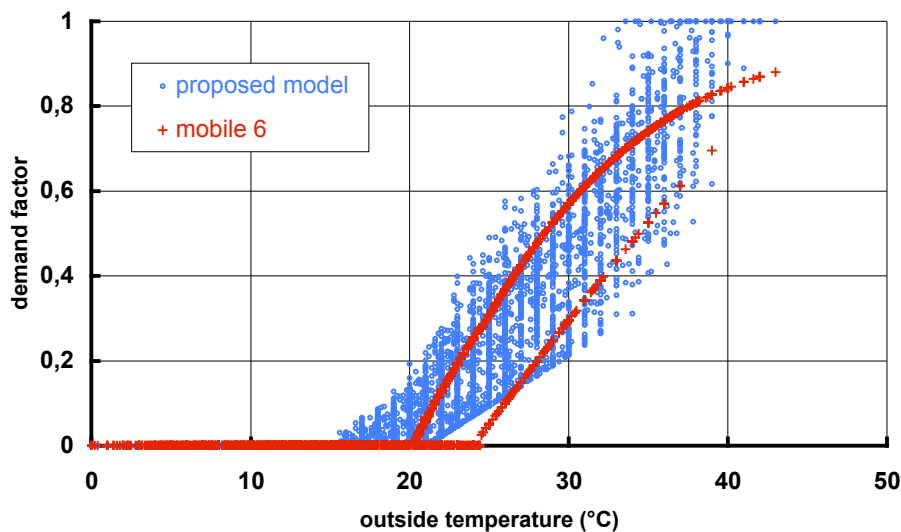


Figure 3: Comparison of the Mobile 6 model (upper curve for daytime and lower curve for night) with the proposed model (set temperature at 23°C).

We consider that the model satisfied our objective, which is to determine hourly fuel consumption in non-tested weather conditions. The differences between results from model and data from EMPA (Figure 2) at temperature below 20°C are not well understood and required additional experiments at these particular conditions.

Simplified model and weather data

A physical model of excess fuel consumption due to AC seems to be too complex to be implemented in an inventory software as Artemis. Therefore we computed the physical model with weather data of 91 regions all over Europe, and looked for a relationship by statistical regressions between hourly fuel consumption and the following explicative variables: ambient temperature, humidity, position of sun in the sky, and solar radiation, replaced by the hour in the day. The general form of the simplified model is:

$$hfc = a_{1,wf} + a_{2,wf} \cdot T_{ext,wf} + a_{3,wf} \cdot T_{int} + a_{4,wf} \cdot h + a_{5,wf} \cdot h^2 \quad \text{with } hfc \geq 0$$

with:

hfc : hourly excess fuel consumption (l/h)

$T_{ext,wf}$: external temperature provided by hourly, daily or monthly weather data (°C), which contain resp. 8760, 365 and 12 values

T_{int} : set temperature in the cabin; default value is 23°C

h : the hour (between 1 and 24)

$a_{1,...,5}$: coefficients depending on the location

The coefficients a_1 to a_5 are available for each location. But in addition, two other sets of coefficient a are provided: The first set is given according to 6 modified Köppen climate classification, based on the annual and monthly averages of temperature and precipitation (DOE, 2004), and the second set corresponds to an average.

The excess fuel consumption and CO₂ emission for a fleet is calculated by summing hfc according to the number of vehicles with AC running for a given road segment, expressed in number of vehicles per hour.

3 - Excess pollutants emissions analysis

Data available for pollutant emissions (CO, HC, NO_x, PM) due to AC are rare in comparison with data available for CO₂ emission, mainly because only 13 gasoline and diesel vehicles are tested.

As it was shown in section 1, AC system is running quite close to the full load at the test conditions (outside temperature $> 28^{\circ}\text{C}$), where pollutants emissions are assumed to be full load ones. An example of data is shown in Figure 4: NO_x emission and effect of AC are larger during the urban driving cycle ECE15 than during the extra-urban cycle EUDC. For each pollutant a relationship is proposed between excess emission and hot emission without AC (Figure 4). Results of gasoline vehicles are in accordance with the theoretical explanation proposed by Soltic & Weilenmann (2002): as long as the increased torque does not cause a air fuel mixture enrichment, an increase in the exhaust temperature, a slight reductions of HC and CO emissions, and an increase of NO_x emission are expected. If an increased torque level causes an increase of enrichment, CO and HC emissions will also increase.

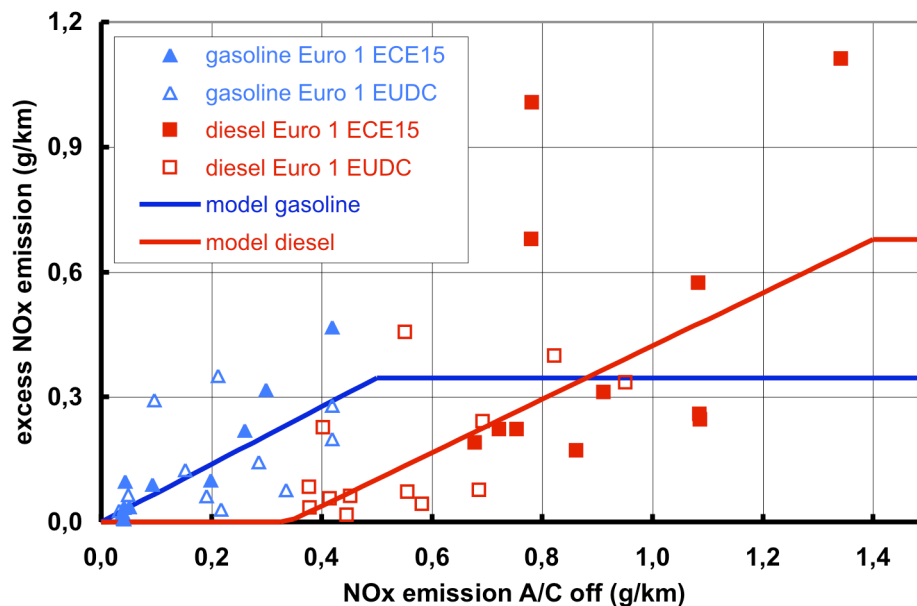


Figure 4: NO_x excess emission versus NO_x emission AC off according to the fuel and driving cycle for Euro 1 vehicles, for urban ECE15 and extra-urban EUDC driving cycles, with the corresponding modelling.

For the pollutants emissions modelling, we assume that pollutants emissions at part load are a fraction of pollutant emissions at full load, with a fraction equal to the demand factor.

Because of the lack of data, only a distinction between the gasoline and diesel vehicles is proposed. The model do not explicitly distinguish the age of vehicle, because we consider it has no influence on excess CO₂ emission. The effect of emission standard on pollutant emission is taken into account through the hot emission, which depends on standard emission.

For the future vehicles, some counteracting effects occur: Firstly, technological improvements of efficiency of AC system are expected:

- By reducing the thermal load of the vehicle (Türler et al., 2003; Farrington et al., 1998, 1999) through the use of advanced glazing which reduces the transmission of infrared solar radiation. The improvement of air cleaning allows reducing the amount of outside air, reducing by the way thermal load and power consumption of fan. Advanced regulation of ventilation allows ventilating parked vehicles reducing the peak cooling load.
- By increasing energy efficiency ratio of AC system (Benouali et al., 2002; Barbusse & Gagnepain, 2003). The first improvement will be due to the improvement of AC components as the external control of compressor, the electrical compressor, a high efficiency heat exchanger. At long term, alternative technologies are investigated as magnetic cooling, desiccant cooling, and absorption.

Secondly, the evolution in the vehicle design and in the leakage refrigerant standard will certainly increase the CO₂ emission due to the use of AC. The constraint against refrigerant leakage drives to

use alternative refrigerant with a lower Global Warming Potential as HFC 152a and CO₂. These alternative refrigerants have the drawback to reduce the efficiency of AC system because their lower thermodynamic properties. The use of alternative refrigerant as the CO₂ allows using AC system as a heat pump in order to warm passenger compartment, made more and more difficult by the development of high efficiency engine which could reduce the possibility to use the engine heat to warm the passenger compartment and which justify the development of reversible system.

At short time, we assume that these two effects compensate each other. No correction is proposed for future vehicles.

4 - Other auxiliaries

The excess fuel consumption due to other auxiliaries can be express in l/h as for AC. According to Soltic & Weilenmann (2002), we evaluated an average excess fuel consumption of 0.075 l/h for an electrical load of 160 W corresponding to dip headlight. We assume that excess fuel consumption is proportional to electrical load of each auxiliary. In order to be in accordance with excess pollutant emission due to AC, we proposed to use a similar way for excess emission due to auxiliaries. Excess pollutant emission due to AC at a given conditions is a fraction to excess pollutant emission at full load. This fraction is calculated as a ratio of excess fuel consumption at given condition to excess fuel consumption at full load. We proposed to use the same model by replacing the excess fuel consumption of AC by the excess fuel consumption of auxiliaries. For instance, in the case when headlights are use, the value of fraction is 0.075/0.85.

Conclusion

The different analyses show that the excess fuel consumption expressed in l/h is quite independent to the speed or to the traffic situation. No significant technological parameters are found. That does not mean that no relation exists between excess fuel consumption and technological parameters, but that the number of data is not sufficient to extract this type of relation or that the technological solutions are too close each other.

The excess fuel consumption due to air conditioning is well know in warm conditions because of the large number of experiments. It is quite different in usual climatic conditions with solar radiation, because of the reduced number of experiments. To approach the behaviour of AC system at these conditions, a physical model is proposed and compared to experimental data. According to the objective of the model, the results show a good agreement in warm conditions. At usual conditions, the model underestimates the excess fuel consumption without understanding the reason. Effect of AC in usual conditions is an important way of investigation because of the occurrence of these conditions in comparison to warm conditions. In the model, based on the usual comfort theory, we assume that the set temperature is 23°C for all the vehicles equipped with AC, but experiments on real world vehicles with air conditioning could improve the knowledge of user's behaviour.

The model proposed is a part of the new European emission inventorying model Artemis.

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