Influence of passenger car auxiliaries on pollutant emissions - Artemis 324 report

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Report n° LTE 0502
February 2005

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SUR LES TRANSPORTS ET LEUR SÉCURITÉ

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13 Summary The impact of the auxiliaries and particularly Air Conditioning on emissions (CO_2, CO, HC, NOx, 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.			
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13 Résumé Les effets des auxiliaires et plus particulierment de la climatisation sur les émissions (CO_2, CO, HC, NOx et particules) sont étudiées. Pour celà, des données expérimentales de plusieurs laboratoires européens ont été rassemblées et analysées. Les paramètres liés à la technologie et aux conditions meterologiques sont évalués. La principal 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 avec le rayonnement solaire.			
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Content

1. 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.

The workpackage 300 entitled "Improved methodology for emission factor building and application to passenger cars and light duty vehicles" is aiming at improving the exhaust emission factors for the passenger cars and light duty vehicles, by investigating the accuracy of the emission measurements, by enlarging the emission factor data base especially for effects of auxiliaries, and by building emission factors according to the different purposes of Artemis.

In 2000, a voluntary agreement has been signed between the European Car Manufacturer Association (ACEA) and the European Commission for the limitation of CO_2 emissions. This limitation does not take into account the use of auxiliaries (lights, electric system, air-conditioning and heating systems).

Existing research has indicated the significant impact on emissions and fuel consumption of auxiliary usage. Different evaluations of the effect of Air Conditioning on CO_2 emissions have been purposed. The ECCP Working Group estimated that the usage of air conditioning systems under average European conditions causes an increase of fuel consumption between 4% and 8% in 2020 [ECCP 2003]. A recent study carried out at INRETS valuated an increase of fuel consumption in 2025 below 1% [Hugruel 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.

2. Air conditioning

2.1. Overview of air conditioning effect

A major study about air conditioning (AC) impact has been carried out in the framework of Mobile 6 by the United States Environmental Protection Agency in 2001. This study was mainly based on specific experimental data collected during the Mobile 6 project. This study is split in two parts: "air conditioning activity effects" [Koupal 2001] and "air conditioning correction factor" [Koupal 2001]. The first part analyses the real use of AC in real conditions. The second part is focused on effect of air conditioning running at full load on regulated pollutant (HC, CO, NOx). In Mobile 6, the definition adopted of the excess emission of pollutants due to air conditioning is the difference of emission with air conditioning running in "warm" climatic condition and without in ambient climatic condition (75°F - 23.8°C and 50 grains / pounds of humidity = 7.14 kg / kg dry air).

Some studies about air conditioning have been done in Europe focussed on specific objectives: evaluation of global AC effect [ECCP 20002, Hugruel 2004], evaluation of individual passenger car emission due to AC [Barbusse 1998, Gense 2000, Pelkmans 2002, Weilenmann 2004], improvement of AC [Bernoulli, 2003].

2.2. Data of air conditioning emissions

We have collected some various experimental data from European laboratories. Test method used could be slightly different, especially for testing climatic condition. Driving cycle, number of vehicle tests, type of vehicle, experimental objectives vary with experimentation. In each case, the definition adopted of the excess emission of pollutants due to air conditioning is the difference of emission with and without air conditioning running in the same condition. In the following, "excess emission" refers to the difference of pollutant emission with and without air conditioning running, even if pollutant emission with air conditioning on is lower than pollutant emission with air conditioning off.

Air conditioning database is made up of experimental data from 3 laboratories, 27 vehicles and 146 tests. The laboratories are UTAC, CENERG and VITO (Table 1 describes the types of vehicle tested by each laboratory). The choice of vehicles covers the main types of vehicle (small and large vehicles), different propulsion systems (gasoline and diesel engines) and the emission standards (Euro 1, Euro 3 and Euro 4); Notice that Euro 1 vehicles are mainly represented in the database.

	gasoline		diesel		total
laboratory	Euro 1	Euro 4	Euro 1	Euro 3	
UTAC	10		10		20
CENERG			5		5
VITO		1		1	2
total	10	1	15	1	27

Table 1: Types of vehicles tested per laboratory

The climatic conditions are specific to each laboratory; these conditions have been chosen in order to represent severe climatic conditions. The small size of the database allows us to perform a simple statistical analysis to determine important parameters.

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 the short list, we can add as proposed by Benoualli [2003], the regulation type and the compressor technology type.

The two next sections are focused on the analysis of the excess emission (CO_2 and regulated pollutants) according to vehicle parameters, driving and climatic conditions.

2.3. Excess fuel consumption and CO_2 emission analysis

This section is focused on the effect of AC on CO_2 emission and fuel consumption.

2.3.1. Effect of mean speed and cycle

Before starting the analysis, we have 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 excess fuel consumption due to air conditioning have to be expressed in volume per time (l/h for instance). In fact, speed can influence the air conditioning system, for instance the cooling of condenser can be improved with speed and the heat exchange coefficient depends on air speed around the cabin of the car. The Figure 1 shows excess fuel consumption as a function of mean speed of the driving cycle. Notice that experimentations have been carried out on test bench in which it could be difficult to provided correct air speed.

Figure 1 shows that mean speed has little impact on excess fuel consumption; variance test indicates that the relation is statistically significant. But the relationship between excess fuel consumption and mean speed is mainly influenced by the data at 90 km/h and 120 km/h, which correspond to constant speed driving cycles (without these two constant speed driving cycles, there are no significant relation between excess fuel consumption and mean speed). It seems that the main reason is linked to the efficiency of the engine, which varies with load and engine speed. For EUDC cycle without air conditioning, the engine load is low as the engine efficiency; For the same driving cycle but with air conditioning running, the engine load is higher, and the engine efficiency is improved (Figure 2): The effect of AC on fuel consumption is partially hidden by the improvement of engine efficiency. In the case of constant high speed cycle, the engine load is high, and the variation of load due to air conditioning is low, then with or without air conditioning running, the engine efficiency remains almost quite constant.

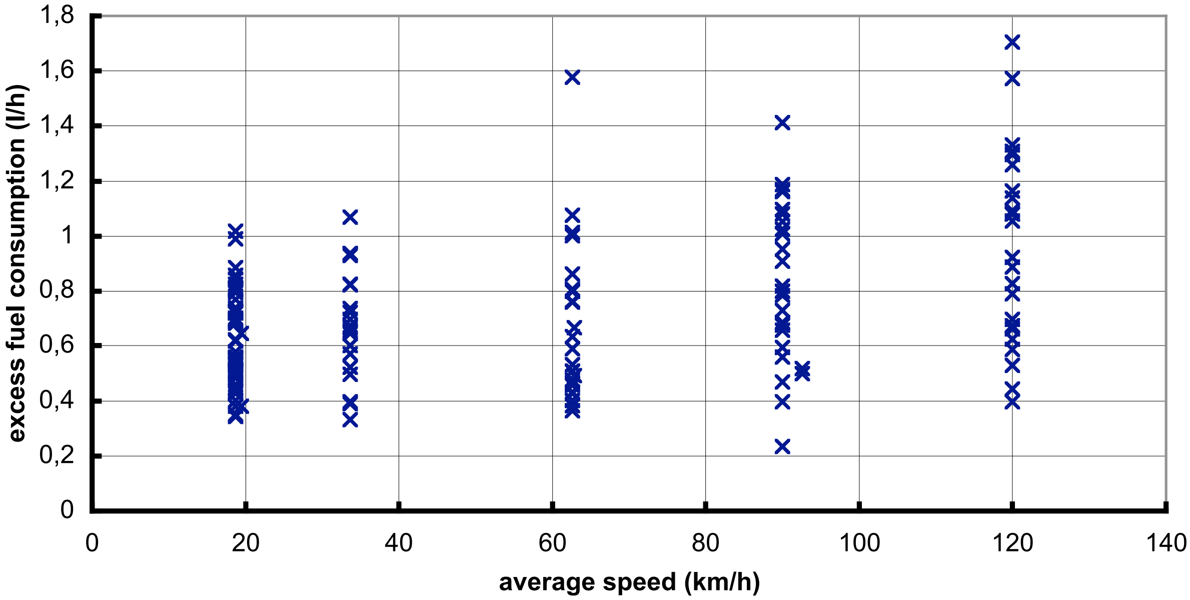


Figure 1: Excess fuel consumption due to air conditioning (l/h) versus mean speed (km/h)

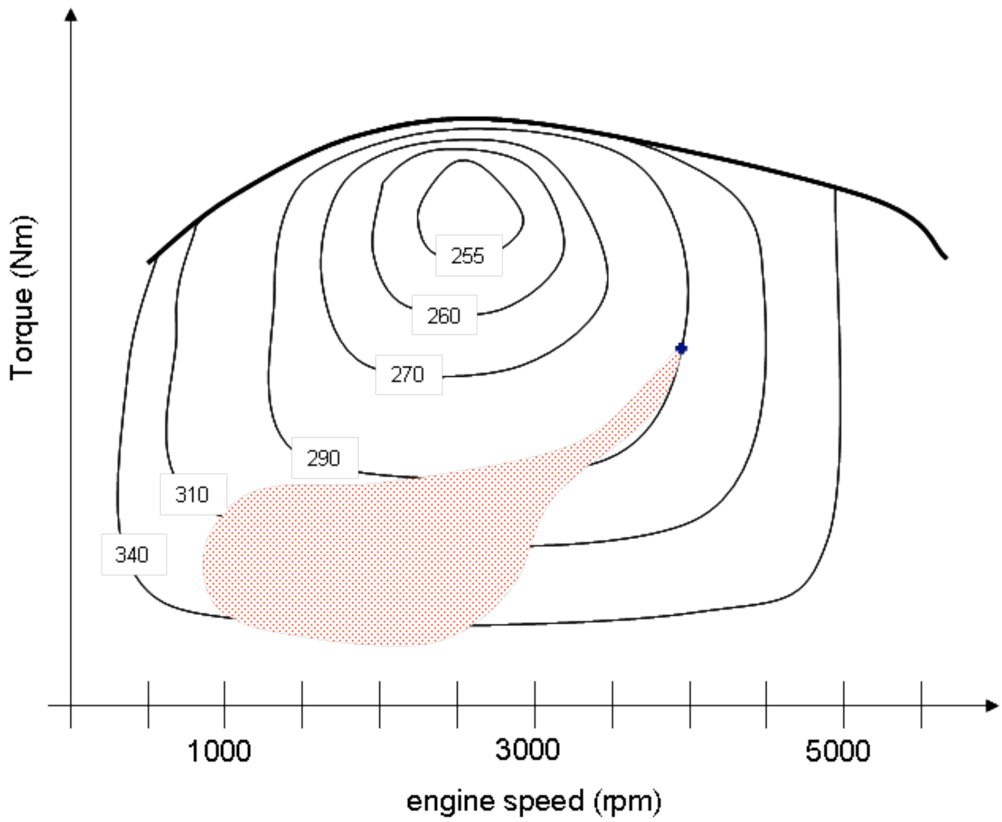


Figure 2: Diagram of fuel consumption map of conventional engine (g/kWh) with a scatter of running point of EUDC cycle (red) and the running point of constant speed at 120 km/h (black point)

A recent experimental study has been carried out at INRETS, in which two vehicles were studied in real driving conditions. A similar conclusion is given [Roumégoux, 2004].

To conclude, the effect of speed showed in Figure 1 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 constant and not vary with the speed or with the type of cycle.

2.3.2. Effect of technological parameters

Technological parameters analysed in this section are parameters connected to the vehicle engine, to the AC system and to the body shape of the vehicle. A statistical way is used to analyse the data set and to look for relationship between fuel consumption and technological parameters. Firstly, experimental results are ordered in agreement with technical specificities; Secondly, a statistical analysis is performed on fuel consumption due to AC. The main drawback of this method is that the accuracy of the results is directly linked to the number of experiments. For instance, if the number of classes is large, the number of experiments of each class will be low, and the statistical characteristics as mean or variance will be not accurate; Otherwise, the number of classes is low, technical specificities are not perfectly described but the statistical characteristics are accurate.

The number of vehicles and vehicle-tests in each class is displayed in Table 2; the vehicle classes are defined in accordance to the engine size, the fuel type and the vehicle size.

		Gasoline			Diesel		Total
		< 1.4 l	1.4 – 2 l	> 2 l	< 2 l	> 2 l	
Vehicle size	Small	5/28			2/10		7/38
	Medium 1		2/10		8/45		10/55
	Medium 2		1/10		2/8		3/18
	Large			2/10		3/15	5/25
	MPV - Multi Purpose Veh.		1/5			1/5	2/10
	Total	5/28	4/25	2/10	12/63	4/20	27/146

Table 2: Number of vehicles and vehicle-tests per class (number of vehicles/number of vehicle-tests) per vehicle size, fuel and cubic capacity

	displacement compressor type	
temperature regulation type	Variable	Fixed
Automatic	11/55	1/5
Manual	13/72	2/14

Table 3: Number of vehicles and vehicle-tests per AC technologies class (number of vehicles/number of vehicle-tests)

The two largest numbers of vehicles correspond to small gasoline vehicles (< 1.4 l) and to medium diesel vehicles (2 l).

Two others parameters linked to AC system have to be taking into account: the type of compressor and the type of regulation.

Most of the vehicles are equipped with variable displacement compressor; Fixed displacement compressor equipped only two small vehicles and one multi-purpose vehicle (MPV)

Every Medium 2, Large and SUV (sport utility veh.) vehicle is equipped with an automatic temperature regulation system. Nearly all the Small and Medium 1 vehicles are equipped with a manual temperature regulation system (only one vehicle is equipped with the automatic system).

According to the description of the database, we distinguished 4 types of vehicles:

- Small and Medium1 vehicles, gasoline engine (< 2 l) and manual AC regulation: SG
- Small and Medium1 vehicles, diesel engine (< 2 l) and manual AC regulation: SD
- Medium2, Large and SUV vehicles, gasoline engine (> 2 l) and automatic AC regulation: LG
- Medium2, Large and SUV vehicles, diesel engine (> 2 l) and automatic AC regulation: LD

		fuel consumption (l/h)	
vehicle type	Number of veh.-tests	average	standard dev.
SG	38	0.7	0.2
SD	55	0.68	0.22
LG	25	0.75	0.34
LD	28	0.85	0.35

Table 4: Average fuel consumption for the 4 vehicle types

Fuel consumptions are quite close and standard deviation is quite large; therefore we can do the assumption that the fuel consumption of AC does not depend on technical parameters.

2.3.3. Effect of climatic conditions

The climatic conditions and set temperature have certainly a huge influence on AC running, and then on pollutants emissions. The Figure 3 shows the climatic conditions (in terms of temperature and humidity) chosen for the experiments; notice that the outside temperatures are higher than 28°C. No experimentation is performed according to the solar radiation. According to Barbusse [1998], solar load represents 45% of the total load of the air conditioning. That is the reason why in UTAC experiments, two temperatures are chosen (30 and 40°C).

The Figure 4 shows the excess fuel consumption versus outside temperature; A linear regression is added. The variation of excess fuel consumption with the outside temperature is lower than expected: the neutral temperature (the outside temperature at which there is no cooling or heating and obtained by linear extrapolation) is below 0. 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.

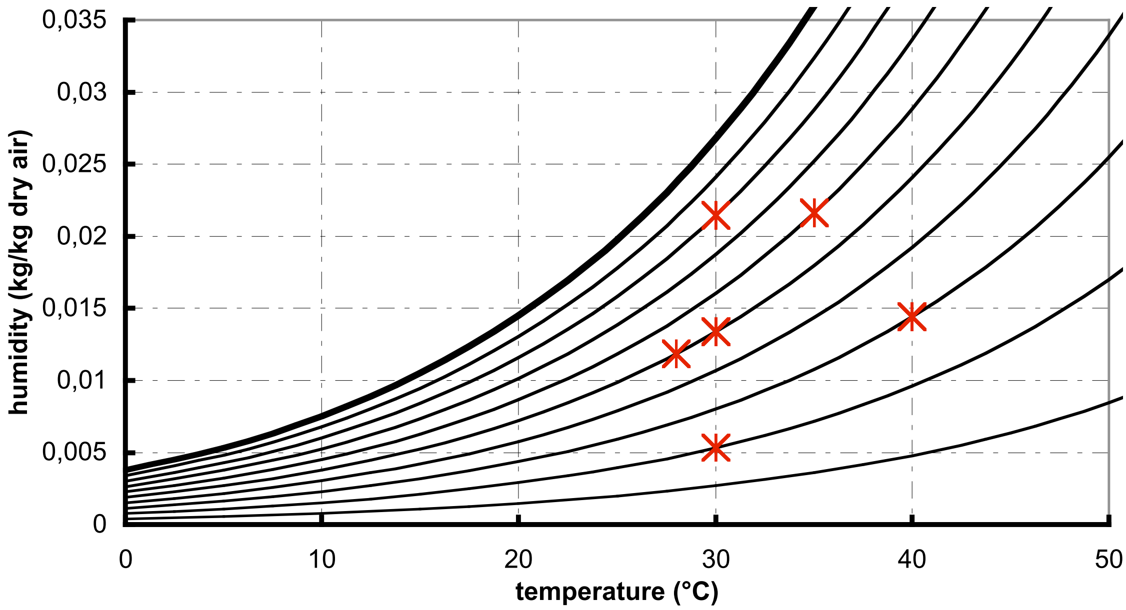


Figure 3: Outside temperature and humidity of AC testing points

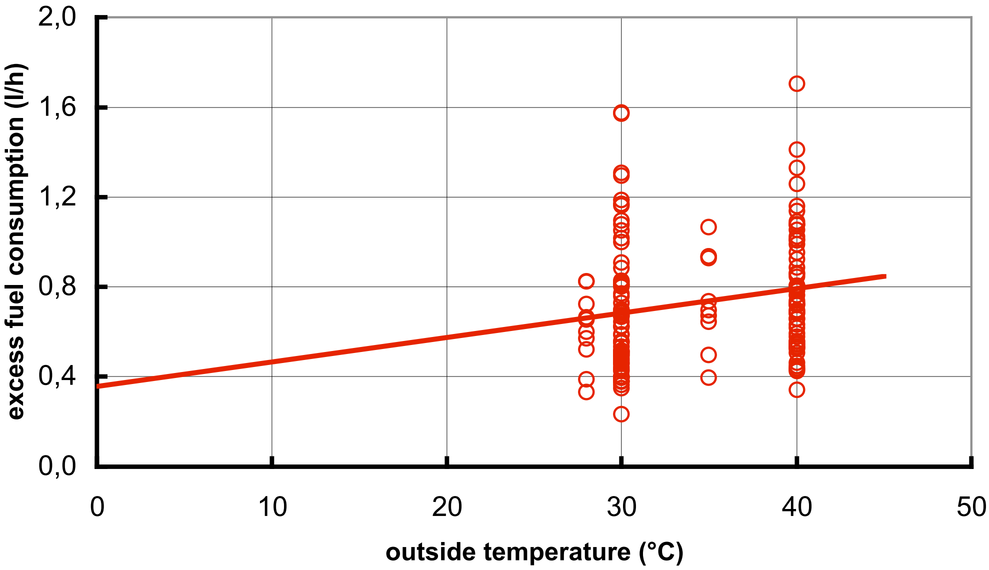


Figure 4: Excess fuel consumption (l/h) due to AC versus outside temperature (°C), with linear regression

2.3.4. Air conditioning physical modelling

Physical modelling approach needs to take into account each component involved in the system: cabin, air conditioner and engine. Physical phenomena taken into account are heat exchanges of the cabin with outdoor, heat exchange on evaporator of air conditioner, which allows reducing air, flow temperature and causes its dehumidification, air conditioner and engine running.

Passenger compartment modelling

The passenger compartment modelling is based on a description of heat exchange as it is usually done in mono-zone thermal building modelling [Bolher 1999]. Air temperature and humidity in the cabin is assumed to be uniform. This strong assumption is acceptable because the objective of modelling is the power consumption [Bolher 1999]. Heat exchanges governing temperature of cabin are due to:

- Global heat exchange coefficient, UA ($W.m^{-2}.K^{-1}$)
- Untreated air flow rate due to permeability, mp (kg.s-1)
- Internal heat gains due to occupants and electrical equipments, A_{int} (W)
- Solar gains, A_{sol} (W)
- Treated air flow, m_t ($kg.s^{-1}$).

Solar gains depend on direct and diffuse solar radiation, position of the sun in sky and geometric and physical properties of the vehicle window. The solar model is based on [Fraisse 2001].

Temperature and flow rate of treated air flow are regulated in order to maintained cabin air temperature to set temperature.

The thermal mass of the vehicle's interior is neglected in the proposed model. Thermal mass has an effect in dynamic behaviour, increasing cooling demands during cool down for instance, but has no effect during steady state cooling. Weilenmann [2004] has studied initial cool down. This test combines the effect of initial cool down of the overheated passenger compartment and the effect of cold start. During this test, 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 in case 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 of excess emission for a cold start in the same temperature conditions.

Conservative equation of energy is:

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

T_{int} is the internal temperature, T_t is the temperature of treated air, T_{ext} is the outside temperature.

Internal temperature is chosen according to 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. According to ASHRAE standard 55[1992] and to Charles [2003], an acceptable temperature in summer conditions is in the range of 23 - 26°C; In winter conditions, the range of acceptable temperature is 20 - 23°C. The differences are due to the assumption that the clothing insulation is higher in winter than in summer. 23°C is chosen as default value.

Sensible heat exchange at evaporator can be deduced:

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

P_{sens} is the sensible cooling needs to maintain internal temperature at the comfort temperature. This equation provides sensible cooling needed to maintain set temperature in the cabin. If air treated rate is known, air treated temperature can be calculated.

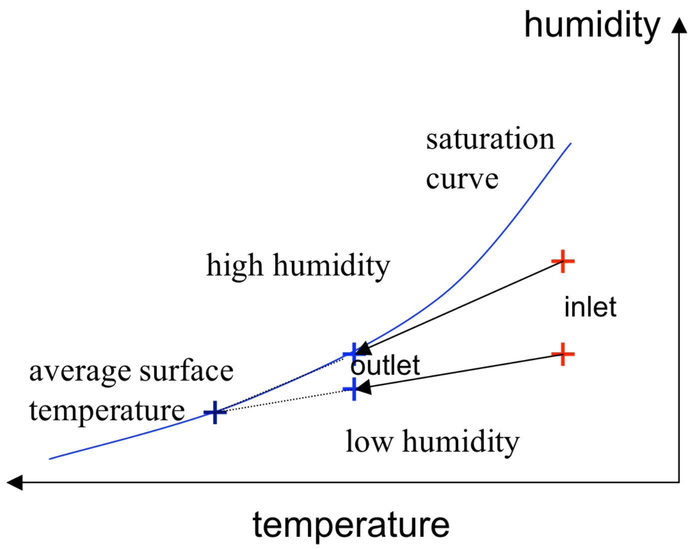


Figure 5: Sample of evolution of air treated on psychometric diagram

<u>Evaporator modelling</u>

Heat exchange at the evaporator can cause dehumidification of air treated (Figure 5).

The Figure 5 shows the evolution of temperature and humidity of air treated across the evaporator of air conditioning. According to Threlkeld's method [Threlkeld 1970, Morisot 2002], the evolution on psychometric diagram can be modelled by a straight line between inlet condition and average surface temperature. The average surface temperature is on the saturation curve. It depends on heat transfer coefficients of evaporator and temperature of coolant. The average surface temperature known, the air side heat exchange efficiency allows us to calculate average surface temperature and humidity of outlet air. The value of this efficiency is between 60% and 80% for usual air side heat exchanger [Morisot 2002]. For this range of value, the effect of the value of air side efficiency is low: If inlet humidity is high, straight line which represents the evolution of air temperature and humidity will be close to saturation curve, if inlet humidity is low, the dehumidification will be low, and a variation of efficiency doesn't change a lot the total cooling power. In the model, the value of air side efficiency is 0.8.

A sensibility study is carried out on the value of air side efficiency in order to valuate its effect on the total heat exchange at evaporator. Four temperatures (20, 25, 30, 35°C), five humidity figures (0.01, 0.015, 0.02, 0.025, 0.03 kg/kg dry air), and three set temperatures (20, 23, 26°C) have been chosen. Air side efficiency varies from 0.6 to 0.8. Notice that couple of temperature and humidity situated above the saturation curve is rejected.

The total heat exchange at the evaporator is the sum of sensible heat exchange and dehumidification.

$$P_{tot} = m_t \cdot (h_{ext} - h_t)$$

P_{tot} is the total heat exchange at the evaporator, h_{ext} is the enthalpy of outside air, at the inlet of the evaporator, h_t is the enthalpy of air at the outlet of the evaporator (kJ/kg)

Regulation modelling

As it is shown, air treated temperature can be calculated if the flow rate is known. So we suppose that the user or air conditioning regulation tries to keep a minimum air flow rate (in order to reduce thermal load). On the other hand, the air treated temperature has not to be too low because of comfort consideration and risk of freezing condensed water in the evaporator. So we consider a minimum air flow rate of 300 m^3/h and a minimum average surface temperature of 0°C.

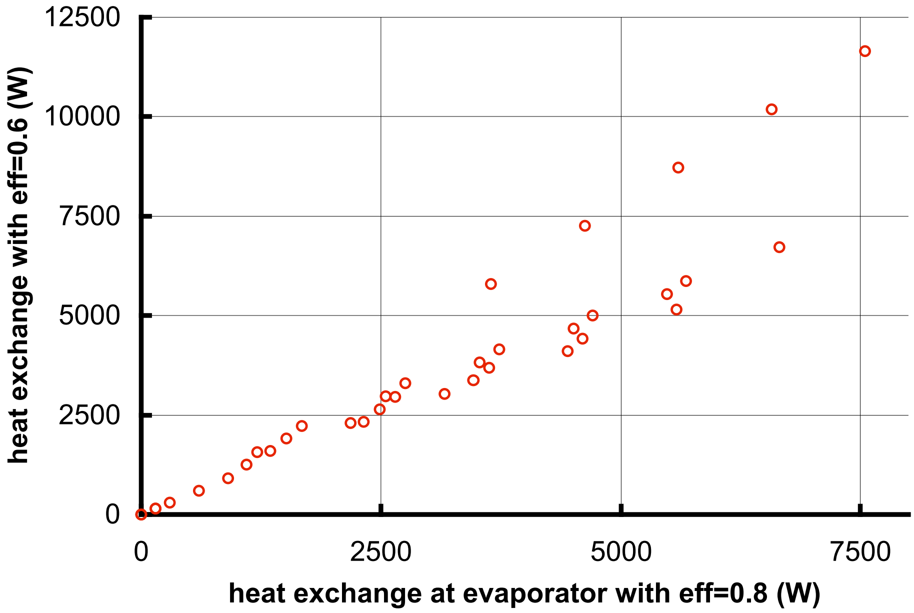


Figure 6: Comparison of total heat exchange at evaporator in function of air side heat exchange efficiency

Efficiency energy ratio of AC and energy efficiency of engine

We have assumed that the efficiencies of these systems are constant: this is a strong assumption and it is clear that energy efficiency depends on various parameters, but in the aim of the proposed model, these assumptions are justified. For energy efficiency of the engine, experimental data analyses on § 0 shows us that running conditions of the engine have a small effect on CO_2 emissions due to air conditioning. According to Park [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.

Validity of the model

The model is applied to all experimental conditions either presented in § 0, or EMPA ones [Weilenmann 2004]. These conditions are described in Table 5. Notice that temperature range chosen by EMPA is significantly larger than in other experimentations (13 - 37°C).

The results of this model are compared to the experimental results (presented in § 0 plus data from EMPA): see Figure 7.

Outside temperature (°C)	Outside humidity ratio (%)	Set temperature (°C)	Laboratory	Number of vehicles	Number of veh.-cycle
13	60	23	EMPA	5	15
23	60	23	EMPA	5	15
28	50	20	CENERG	5	10
30	50	20	UTAC + VITO[1]	12 + 1	60 + 3
30	60	23	EMPA	5	15
35	60	23	CENERG	5	10
37	60	23	EMPA	5	15
40	30	20	UTAC	12	60

[1] VITO experiments were carried out with two different humidity ratios (20% and 80%),; No effect of humidity was detected, so these experiments are merged with data at 50% HR

Table 5: Climatic conditions and number of vehicles tested

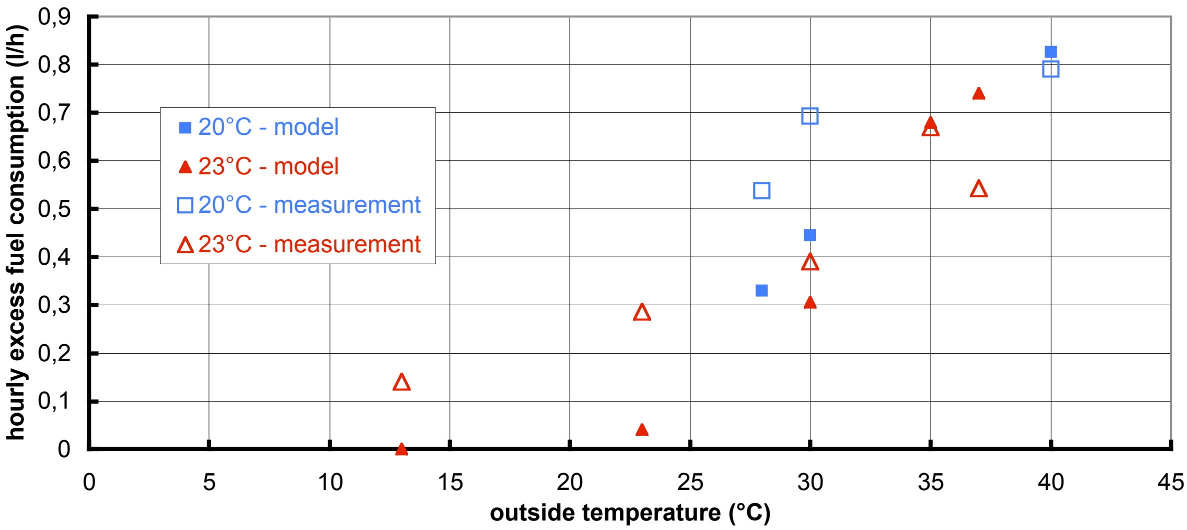


Figure 7: Comparison of the results from model and from experiments as a function of outside temperature for two internal temperatures (20 and 23°C)

Each experimental point corresponds to an average of experimental results obtained in the same climatic conditions (internal and outside temperatures, outside humidity) for different vehicles.

Results of Figure 7 provided by model and experiments are quite close for temperature higher than 30°C. From 20°C to 30°C, hourly fuel consumptions from model are lower than results of experiments, and below 20°C, hourly fuel consumption from model are null. Their authors explain the positive excess fuel consumption of the experimental results for temperatures below 20°C by running of AC to avoid windscreen fogging. Excess fuel consumption for temperatures below 20°C can be linked to the electrical consumption of ventilation.

A second comparison is done with the Mobile 6 model of demand factor based on experimental measurements. Demand factor is defined by Mobile 6 authors as the fraction of running time of AC; It can be also defined as the ratio of part load power consumption to the full load power consumption. The hourly excess fuel consumption at full load is estimated at 0.85 l/h.

The Mobile 6 model and the proposed model are applied with weather data of Seville in Spain.

The climate of Seville is the closest climate of a European city to the climate of Denver where vehicle were followed in order to determine demand factor of AC system in Mobile 6. Mobile 6 model distinguishes two cases of AC running conditions: daytime and night in order to take into account the solar loads. In our model, the solar loads are calculated for each climatic condition described in the weather data. Weather data are in an hourly format.

As shown on Figure 8, demand factors obtained by Mobile 6 model 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.

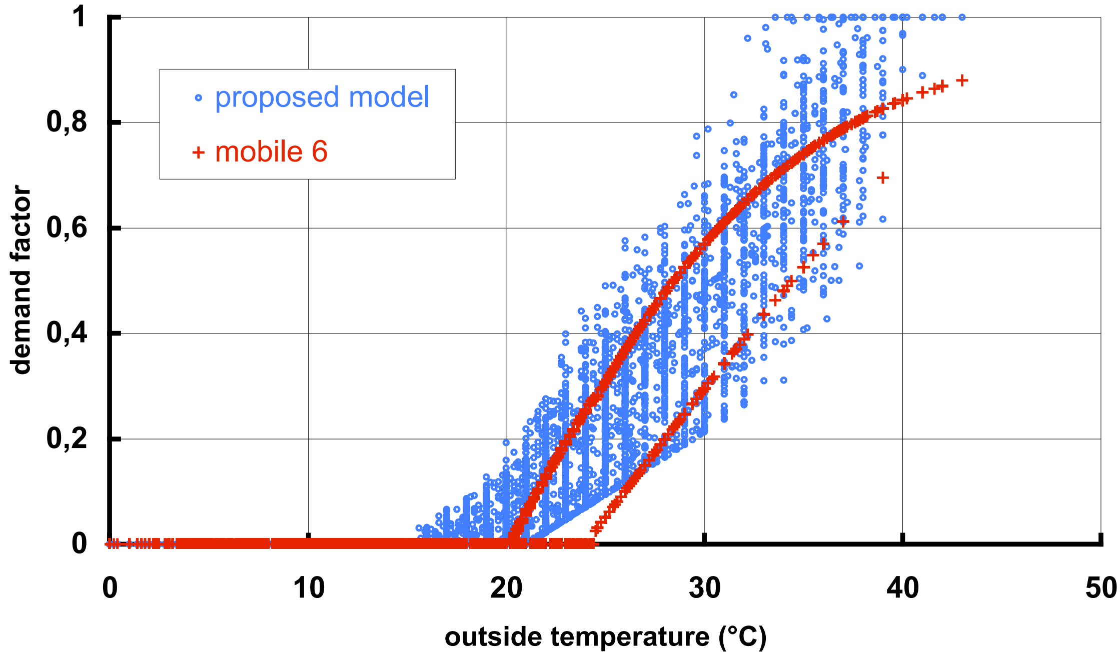


Figure 8: Comparison of the Mobile 6 model (upper curve for daytime and lower curve for night) with the proposed model (set temperature at 23°C)

To conclude, 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 at temperature below 20°C are not well understand and required additional experiments at these particular conditions.

2.3.5. 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. We proposed to simplify and to adapt the physical model according to the available data. The way chosen is to compute physical model with several weather data, and to look for a relationship between hourly fuel consumption and explicative variables.

2.3.5.1. Weather data

The physical model needs the internal temperature, external temperature and humidity, and solar radiation. The weather data are provided by the weather database of the thermal building software called Energyplus [DOE 2004]. The map presented in Figure 9 shows the 90 European cities for which weather data are available from meteorological stations (Annex 1).

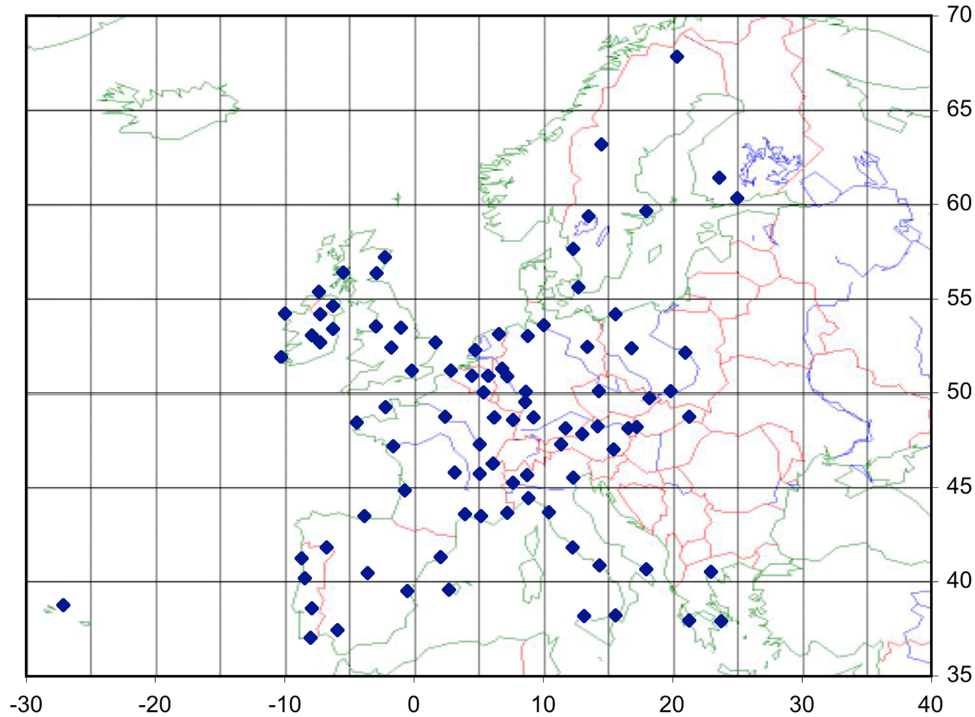


Figure 9: Location of the 90 European cities with weather data available

2.3.5.2. Simplified model

A simplified model of the excess fuel consumption due to AC has to take into account climatic conditions. Climatic conditions depend on temperature, humidity, solar radiation (direct and diffuse) and position of sun in the sky. Solar radiations can be quite difficult to obtain, so we preferred the use of the hour in the day than the use of solar radiation. Statistical regressions have been done on numerical results obtained with the physical model along 90 locations in order to determine the most appropriate form of the model and the value of the parameters. The general form of the simplified model is:

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

with:

hfc: hourly excess fuel consumption (l/h),

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

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

h: the hour (between 1 and 24),

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

The coefficients a_1 to a_5 are given in Annex 2. Two other sets of coefficient values a are provided in Annex 2: The first set is given according to the modified Köppen climate classification [DOE 2004] and the second set corresponds to an average. In the modified Köppen climate classification, the categories are based on the annual and monthly averages of temperature and precipitation. The system distinguishes 6 major climatic types, designated by a capital letter (see Table 6).

Köppen climate type	Description
A	Tropical moist climates (average temperature of each month is above 18°C)
B	Dry climates
C	Moist mid-latitude climates with mild winters
D	Moist mid-latitude climates with cold winters
E	Polar climates
H	Highland area

Table 6: Major climatic types of Köppen climate classification

Each major climatic type is sub-divided into sub-categories based on temperature and precipitation. For the considered locations presented in Figure 9, there are 6 Köppen climate classes:

Cfa : "C" indicates the "mild mid-latitude" type, the second letter, "f" comes from the German word "feucht" which means moist and the last letter "a" indicates that the average temperature of the warmest month is above 22°C.

Cfb: this climate is similar to Cfa with a cooler warmest month.

Csa: the group of letter "Cs" indicates a Mediterranean climate, "a" indicates that the average temperature of the warmest month is above 22°C

Csb: this climate is similar to Csa with a cooler warmest month.

Dfb: "D" indicates a moist continental mid-latitude climates, "f" indicates that the climate is wet at all seasons and "b" that the average temperature of warmest month is below 22°C and average temperature of the 4 warmest months is above 10°C.

Dfc: This climate is close to Dfb, "c" means that average temperature of 1 to 3 warmest months is above 10°C.

The Köppen classes of European locations are given in Annex 1.

2.3.6. Excess fuel consumption and CO_2 emission for a fleet

The general equation to calculate the excess fuel consumption fc_f for a fleet f due to the use of air conditioning is:

$$fc_f = \sum_{loc} \sum_{T} \sum_{TS} \sum_{i} n_{AC,i,TS,T,loc} \cdot hfc(h, T_{ext}, T_{\text{int}})$$

Excess CO_2 emission is:

$$eCO_{2f} = \sum_{loc} \sum_{T} \sum_{TS} \sum_{i} n_{AC,i,TS,T,loc} \cdot c_{CO_2,i} \cdot hfc(h, T_{ext}, T_{\text{int}})$$

with:

$n_{ac,i,TS,T,loc}$: number of vehicles with AC running for segment i, at the traffic situation TS (i.e. urban, road, highway), at the time T, at the location loc, expressed in number of vehicle per hour.

$$n_{AC,i,TS,T,loc} = n_{i,TS,T,loc} \cdot f_{clim,i}$$

hfc: hourly fuel consumption depending on the hour of the day, external temperature and internal temperature (l/h).

$c_{CO_2,i}$: transformation factor from fuel to CO_2 depending on vehicle segment i. The transformation factor is deduced from carbon balance equation [Joumard 2004] and density of fuel. To calculate this factor, we neglected the mass of non-CO_2 pollutants in comparison with the mass of CO_2.

$$c_{CO_2,i} = \frac{m_{CO_2}}{v_{fuel}} = \frac{44.011}{12.011 + 1.008 \cdot r_{H/C,i}} \cdot \rho_{fuel,i}$$

with:

$r_{H/C,i}$: Hydrogen Carbon ratio depending of the type of fuel: 1.8 for gasoline and 2 for diesel.

$\rho_{fuel,i}$: density of fuel (kg/l): 0.766 kg/l for gasoline and 0.8414 kg/l for gasoline.

$f_{clim,i}$: fraction of vehicles equipped with air conditioning in segment i. The fraction of vehicles equipped with AC is calculated with the penetration rate ($pr_{AC,i}$). Value of $pr_{AC,I}$ are given for the France in Annex 3 [Hugruel 2004].

$n_{i,TS,T,loc}$: number of vehicles belonging to segment i, at the situation of traffic TS, at time T, and at location loc:

$$n_{i,TS,T,loc} = \frac{n_{i,loc} \cdot k_{i,loc,TS}}{v_{TS}} \cdot d_{i,TS,T,loc}$$

with:

$n_{i,loc}$: total number of vehicles belonging to the segment i, at the location loc

$k_{i, TS, loc}$: annual mileage of a vehicle belonging to the segment i, in the traffic situation TS, at the location loc (km)

v_{TS}: mean velocity in traffic situation TS (km/h)

$d_{i,TS,T,loc}$: traffic distribution coefficient (Annex 4) [ARE 2000], [Urquiza, 2003]

2.4. Excess pollutants emissions analysis

Data available for pollutant emissions due to AC are rare in comparison with data available for CO_2 emission analyses, mainly because the number of test cycles was reduced. Tests at constant speed don't provide pollutant emissions and CENERG doesn't measure pollutant emissions of their 5 vehicles.

Measured pollutants are Hydrocarbon (HC), Carbon monoxide (CO), Nitrogenous oxides (NOx) and particulates for diesel vehicles. The number of vehicles is 13 for gasoline and diesel vehicles together: it reduced drastically the possibility of analysing data according to the emission standard for instance.

As it was shown in § 0, AC system is running quite close to the full load at the test conditions (outside temperature higher than 28°C). Pollutants emissions are assumed to be pollutants emissions at full load. For the modelling of pollutants emissions, we assume that pollutants emissions at part load are a fraction of pollutant emissions at full load; this fraction is equal to the demand factor. The demand factor is the ratio of hourly fuel consumption to the hourly fuel consumption at full load.

In Mobile 6, the authors have chosen to express excess emission as a function of pollutant hot emission with AC off (and in some cases, according to the mean speed) by distinguishing the type of emitters (normal or high) and the traffic situation. We have chosen a similar method, starting by plotting excess emission versus emission AC off, and then trying to distinguish classes of vehicle. On the following figures, Euro1 diesel, Euro3 diesel, Euro1 gasoline and Euro4 gasoline are distinguished.

2.4.1. Excess pollutants emissions at full load

2.4.1.1. CO emission

Figure 10 shows CO excess emission due to AC versus CO emission of vehicle with AC off. Some observations can be done on this figure. Firstly, the behaviour of diesel and gasoline vehicles is opposite: AC on increases CO emissions of gasoline vehicles but decreases the emissions of diesel vehicles according to the emission standard, CO emissions AC off of Euro 1 vehicles are higher than CO emissions of Euro 3 and 4 vehicles in spite of the fact that driving cycles of these latter are “real world driving cycles”, which are more severe.

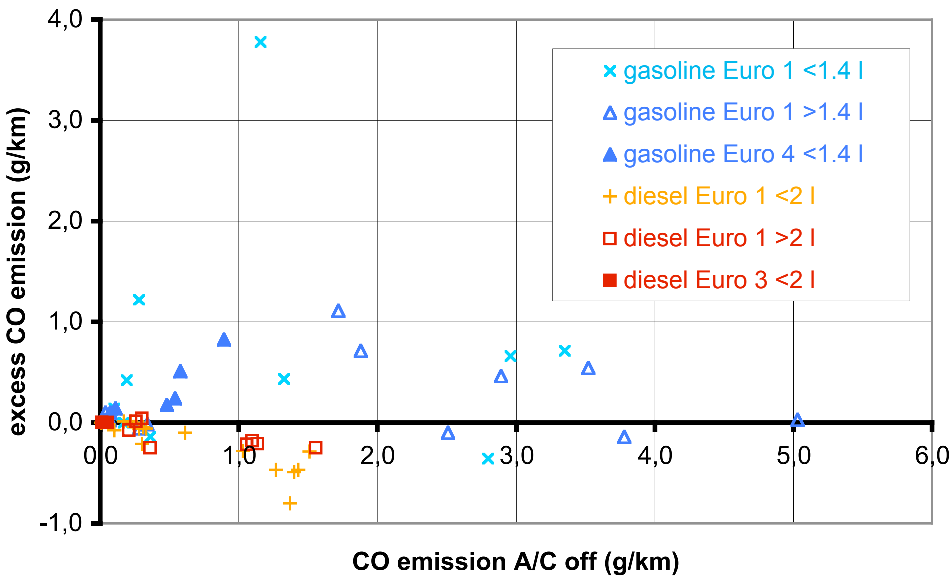


Figure 10: Excess CO emission versus CO emission AC off according to the vehicle technology

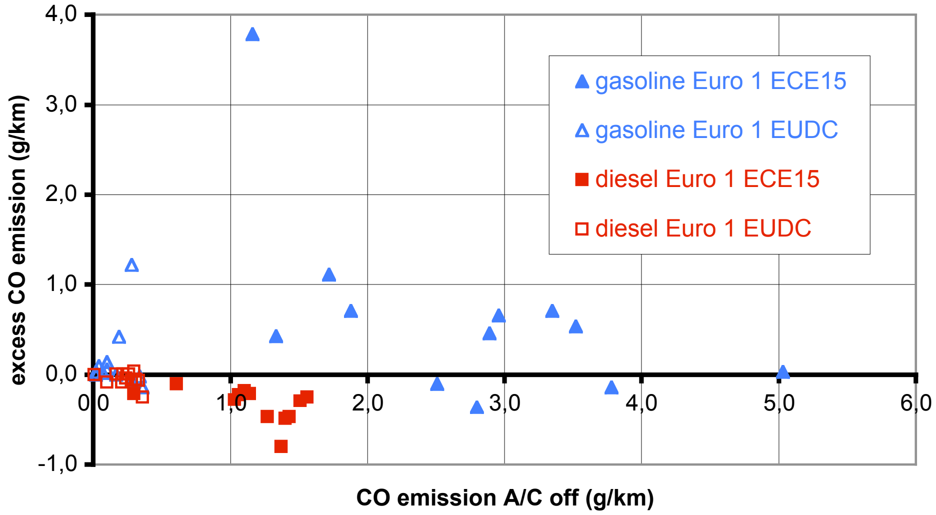


Figure 11: Excess CO emission versus CO emission AC off according to the fuel and driving cycle for Euro 1 vehicles

Figure 11 distinguishes the type of driving cycle for Euro 1 vehicles. Hot emissions during ECE15 cycle are higher than during EUDC cycle.

The proposed model (Figure 12) for CO emission due to AC considers the type of vehicle fuel (gasoline or diesel) and valuates the excess emission as a function of the hot emission with AC off. In addition, excess emission must be 0 when hot emission with AC off is 0. The coefficients of the model are in Annex 5.

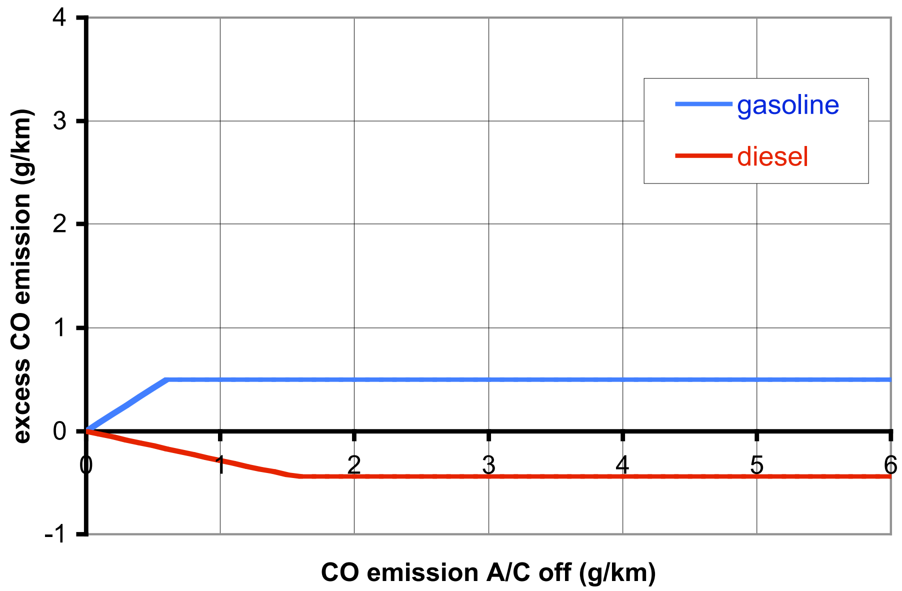


Figure 12: Excess CO emission modelling at full load

2.4.1.2. HC emission

Figure 13 shows clearly the difference of excess emission between gasoline and diesel vehicles: the effect of AC on Euro 1 diesel vehicles is a decrease of the HC emission; It is quite different for the gasoline vehicles: If HC emission without AC is low, the effect of AC is an increase of the HC emission; On opposite, if HC emission without AC is high, the tendency is to decrease HC emission. Classification along engine size shows no effect of this parameter. Emission standard has a large effect on HC emission without AC and with AC: for Euro 3 and 4 vehicles, HC emission and excess emissions are quite close to 0.

Figure 14 plots HC emission according to the driving cycle and the type of fuel. HC emissions during EUDC are lower than during ECE15.

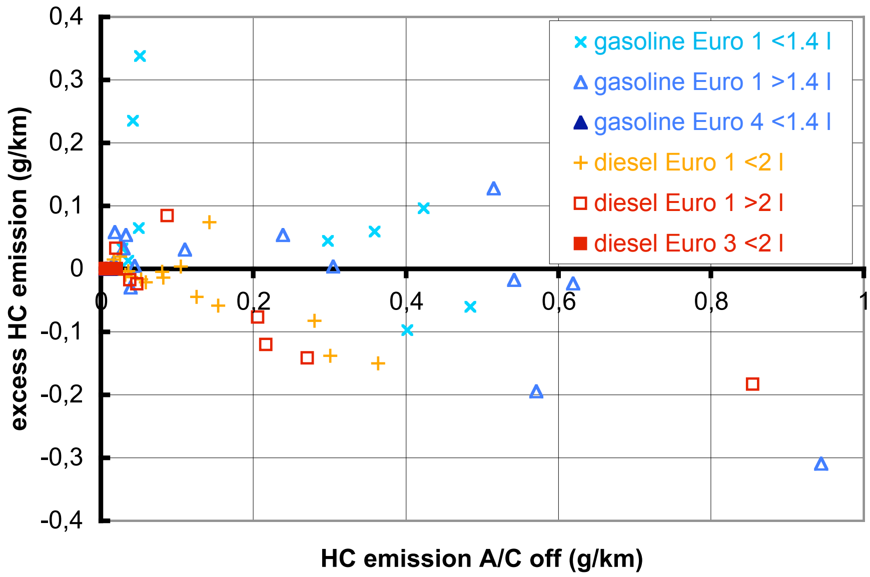


Figure 13: Excess HC emission versus HC emission AC off according to the vehicle technology

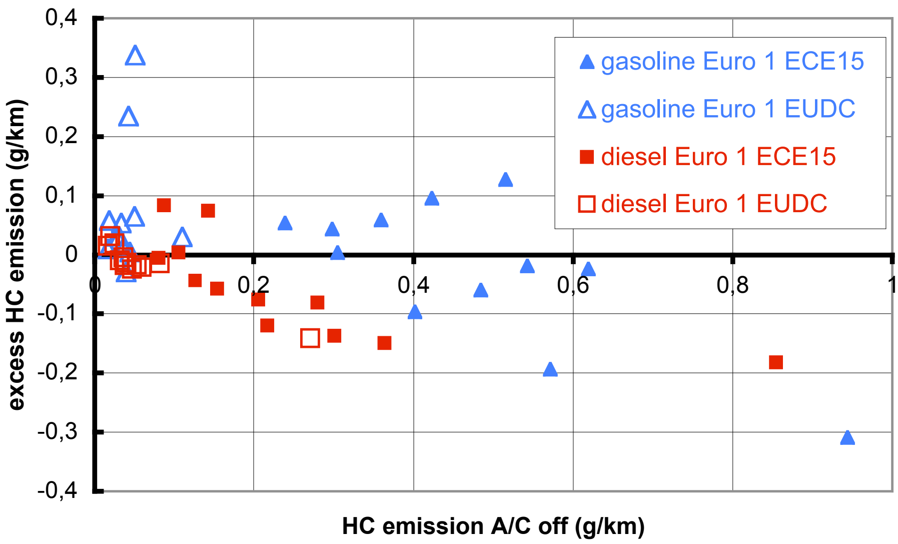


Figure 14: Excess HC emission versus HC emission AC off according to the fuel and driving cycle for Euro 1 vehicles

As for excess CO emission modelling, we proposed to distinguish the type of fuel and to calculate excess emission as a function of the hot emission without AC running (Figure 15). The coefficients of the model are in annex 6.

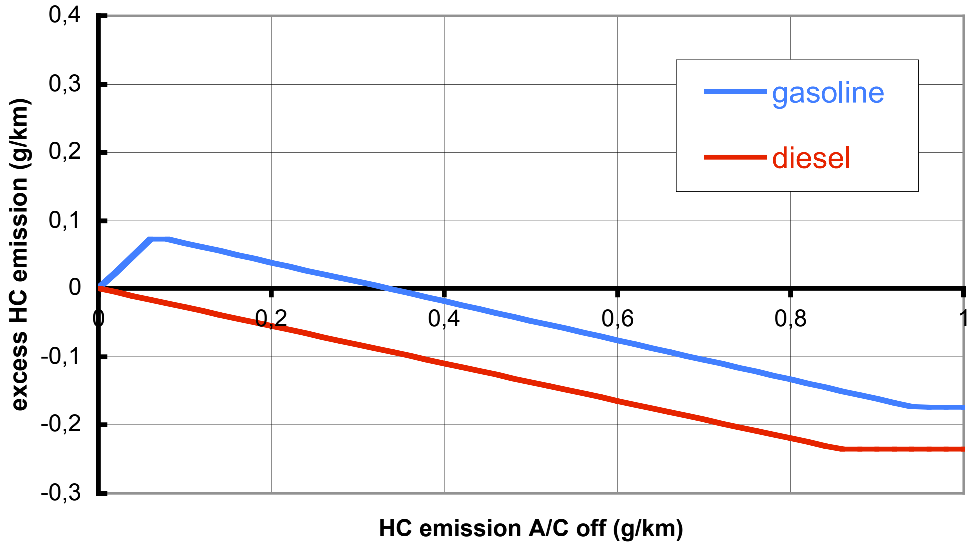


Figure 15: Excess HC emission modelling at full load

2.4.1.3. NOx emission

As shown in Figure 16, NOx emissions without AC of diesel are quite larger than these of gasoline vehicles; the effect of AC is in the same order of magnitude for both fuels. Except for the type of fuel, no additional distinction according to the technology can be done.

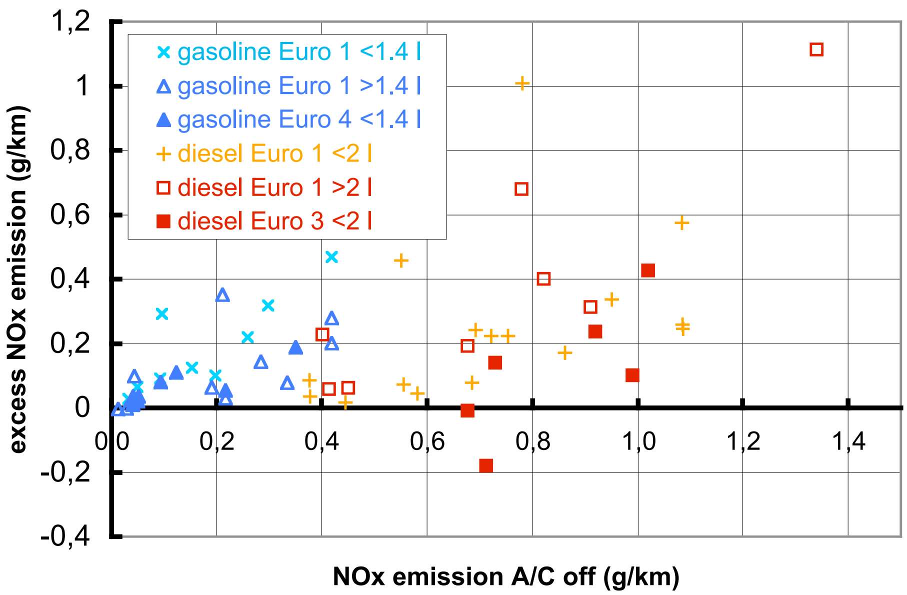


Figure 16: NOx excess emission versus NOx emission AC off according to the vehicle technology

As shown in Figure 17, emission and effect of AC during ECE are slightly larger than during EUDC.

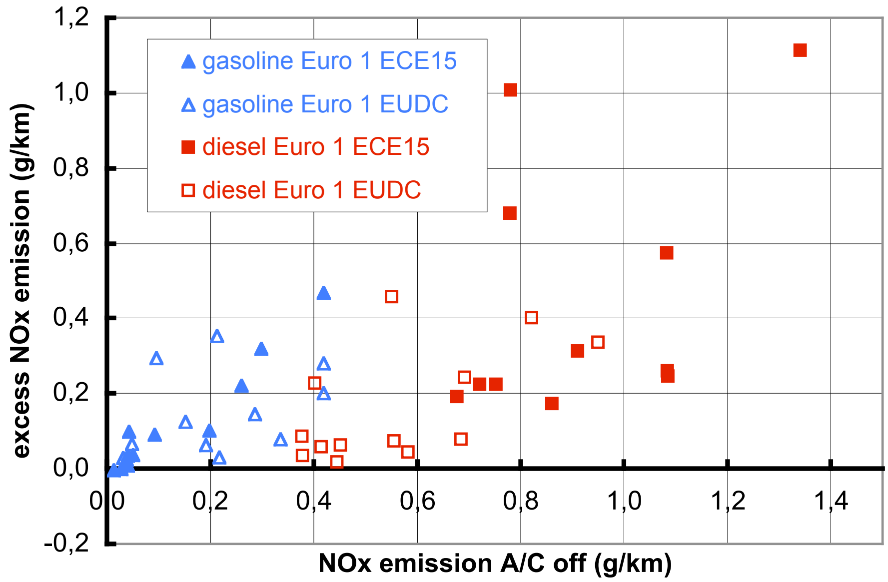


Figure 17: NOx excess emission versus NOx emission AC off according to the fuel and driving cycle for Euro 1 vehicles

As for excess CO emission modelling, we proposed to distinguish the type of fuel and to calculate excess emission as a function of emission without AC running (Figure 18). The coefficients of the model are in annex 7.

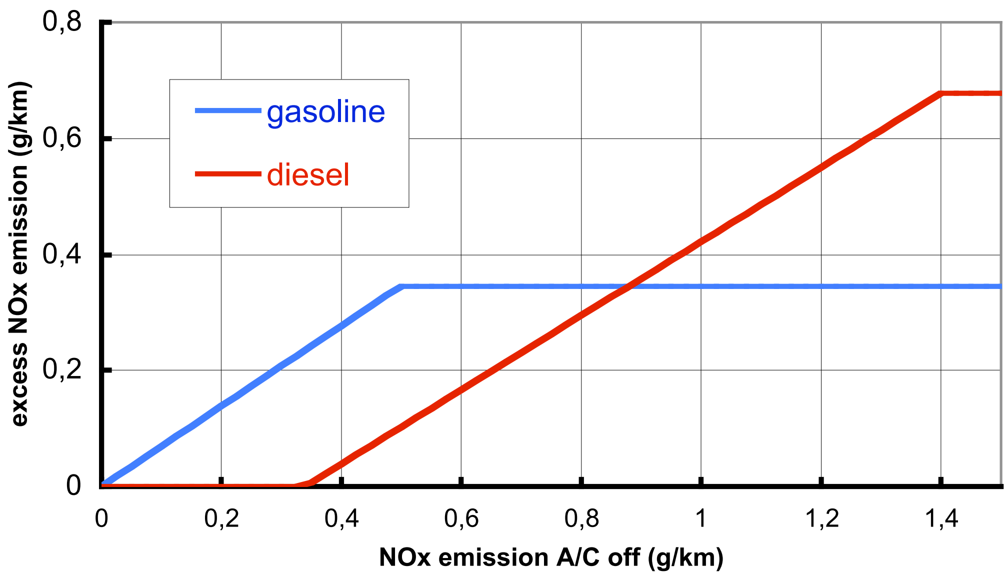


Figure 18: Excess NOx emission modelling at full load

2.4.1.4. Particulates emission

Figure 19 and Figure 20 show that there are no clear relationships between excess emission and technological parameters or type of driving cycle.

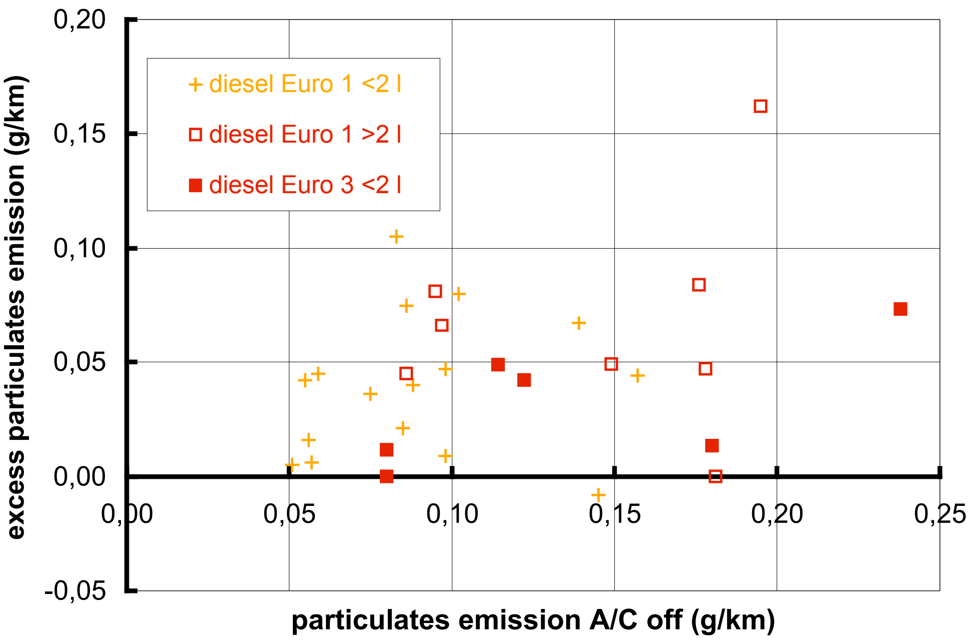


Figure 19: Particulates excess emission versus Particulates emission AC off according to the vehicle technology

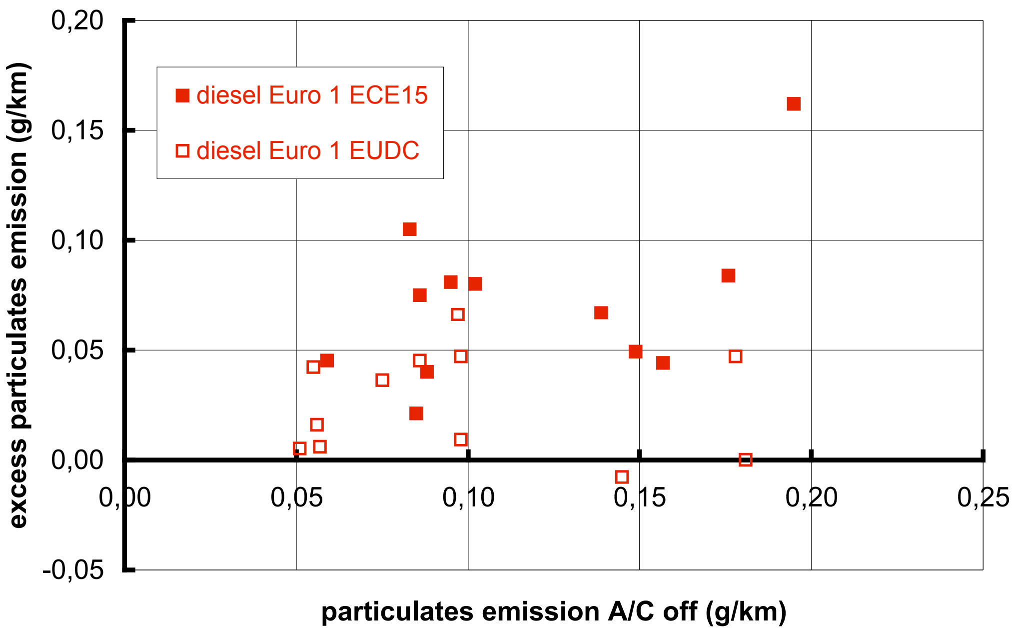


Figure 20: Particulates excess emission versus Particulates emission AC off according the driving cycle for Euro 1 vehicles

Excess emission is calculated as a function of emission without AC running (Figure 21). The coefficients of the model are in Annex 8.

2.4.1.5. Conclusion of the excess pollutant emissions modelling at full load

Because of the lack of data, only one distinction between the types of vehicle is proposed (gasoline or diesel). A relationship for each pollutant is proposed between excess emission and hot emission without AC. Results of gasoline vehicles are in accordance with the theoretical explanation proposed by Soltic [2002]: if the increase of torque does not cause a stoichiometry enrichment, an increase in the exhaust temperature, slight reductions of HC and CO emissions, and an increase of NOx emission are expected. If an increased torque level causes an increase of enrichment, CO and HC emissions will increase also.

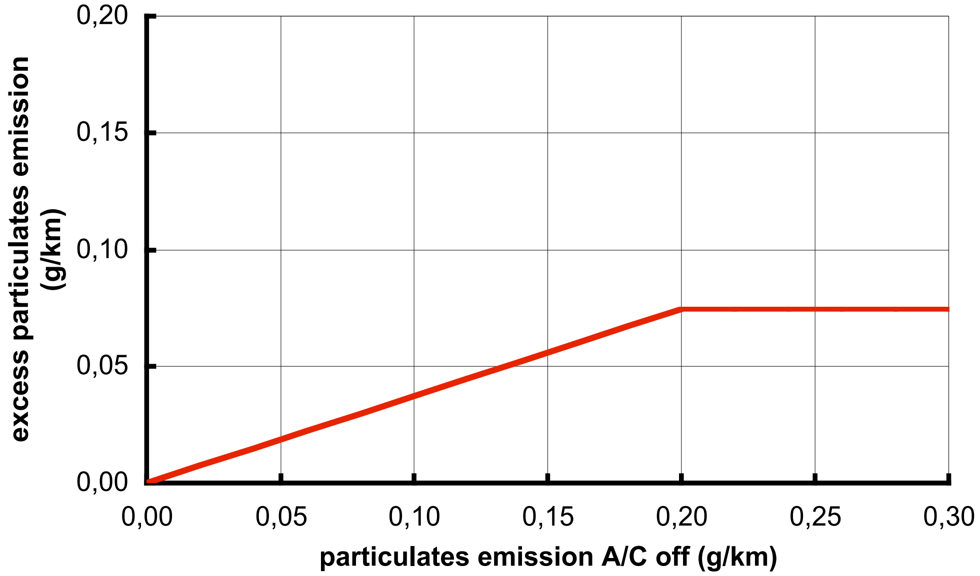


Figure 21: Excess Particulates emission modelling at full load

2.4.2. Excess pollutants emission at part load

Excess pollutant emission at part load of one vehicle is expressed as a function of excess pollutant emission at full load and demand factor.

$$ef_{pollutant,AC} = ef_{pollutant\ ACfull} \cdot \tau_{AC}$$

$ef_{pollutant,\ AC}$: excess pollutant emission due to AC at given conditions (g/km)

$ef_{pollutant,\ ACfull}$: excess pollutant emission due to AC at full load (g/km) provided by models presented in section 2.4

τ_{ac}: demand factor; ratio of hourly fuel consumption at given condition to hourly fuel consumption at full load

$$\tau_{AC} = \frac{hfc}{hfc_{full\_load}}$$

hfc_{full_load}: hourly fuel consumption at full load = 0.85 l/h

2.4.3. Excess pollutants emissions for a fleet

In the same way of excess CO_2 emissions, excess pollutant emission is given by:

$$E_{pollutant} = \sum_{loc} \sum_{T} \sum_{TS} \sum_{i} n_{AC,i,TS,T,loc} \cdot v_{TS} \cdot ef_{pollutant,AC}$$

with:

$E_{pollutant}$: excess pollutant emission of a fleet (g)

v_{TS}: average speed of the traffic situation

2.5. Future evolution of the emissions due to AC

We proposed a model of pollutant emission for existing vehicles. The proposed model does not explicitly distinguish the age of vehicle. The study concluded that age of vehicle does not have any influence on excess CO_2 emission, and the effect of emission standard on pollutant emission is taken into account by the fact that excess pollutant emission is a function of 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 thermal load of vehicle [Turler 2003, Farrington 1999, Farrington 1998]: The way investigated to reduce thermal load are 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 [Benoualli 2002, Barbusse 2003]. The first improvement of efficiency of AC system will be due to the improvement of AC component as external control of compressor, electrical compressor, 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 CO_2 emission due to the use of AC. For instance, the window area is continuously increasing, and the number of electrical equipments (as GPS and video screen) in passenger compartment is also increasing. The constraint against refrigerant leakage drives to use alternative refrigerant with a lower Global Warming Potential as HFC 152a and CO_2. 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 CO_2 allows using AC system as a heat pump in order to warm passenger compartment. Currently, the warming of passenger compartment is done by thermal losses of the engine, but the development of high efficiency engine could reduce the possibility to use the heat from the engine to warm passenger compartment and justify the development of reversible system.

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

3. Other auxiliaries

The following analysis is mainly based on the work done by EMPA [Soltic, 2002] on the effect of auxiliaries on emissions. The group of auxiliaries excludes some other important electrical power consumers as components linked to the engine or linked to security. The Table 7 lists auxiliaries and gives electrical power consumption [Soltic, 2002]:

Auxiliary	Electrical consumption (W)	Use of auxiliary (time proportion)
Dipped headlight	160	during night
Full headlight	170	
Turn indicator / stop light	40	1 %
Fresh air ventilator	60	50 %
Wipers	60	
Radio	15	85 %
Rear window defroster	150	50 % if outside temperature < 0°C
Seat heating	150	1%

Table 7: Power consumption of auxiliaries and estimation of the use of auxiliaries

3.1. Excess fuel consumption and CO_2 emission

Excess fuel consumption due to auxiliaries can be express in l/h as for AC. According to Soltic [2002], we have 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.

3.2. Excess pollutants emission

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.

4. Synthesis of the Artemis modelling

4.1. Influence of air conditionning (AC)

- Excess fuel consumption
  - For a vehicle:

    The excess fuel consumption due to AC is hfc, defined in § 2.3.5.2:

    hfc = f(outside temperature, set cabin temperature, hour, location)
  - For a traffic:

    The excess fuel consumption due to AC for a traffic is the summation of hfc defined before on the vehicles equipped with AC: see § 2.3.6.
- Excess CO_2 emission

  The excess CO_2 emission is deduced from the excess fuel consumption by carbon balance, assuming that the whole carbon of the fuel is transformed into CO_2: see § 2.3.6.
- Excess pollutant (non-CO_2) emission
  - For a vehicle:

    The excess pollutant emission due to AC is $ef_{pollutant, AC}$ defined in § 2.4.2, in g/km.

    $ef_{pollutant, AC}$ = f(hot emission without AC) . hfc / 0.85

    f(hot emission without AC) is defined in § 2.4.1.1 to 2.4.1.4 according to the pollutant. hfc is defined in § 2.3.5.2.
  - For a traffic:

    The excess pollutant emission due to AC for a traffic is the summation of $ef_{pollutant, AC}$ defined before on the vehicles equipped with AC: see § 2.4.3.
- Future vehicles

  No evolution of the excess fuel consumption, neither of the formulae of the excess pollutant emissions are foreseen. Therefore the excess pollutant emissions of the future vehicle will decrease as the hot emissions.

4.2. Influence of other auxiliaries

- Excess fuel consumption

  The excess fuel consumption due to given auxiliaries hfc_{aux} is defined in § 3.1.

hfc_{aux} (l/h) = 0.075 (l/h). Power of the auxiliaries (W) / 160 (W) . % of use time

The power of the auxiliaries is given in Table 7.

- Excess emission

  The excess pollutant emission due to given auxiliaries $ef_{pollutant, aux}$ is defined in § 3.2.

  $ef_{pollutant, aux}$ = f(hot emission without AC) . hfc_{aux} / 0.85

  f(hot emission without AC) is defined in § 2.4.1.1 to 2.4.1.4 according to the pollutant. hfc_{aux} is defined in § 3.1.

5. Conclusion

Various analyses of excess fuel consumption are carried out. They show that 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 AC 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. Experiments on real world of AC vehicles could improve the knowledge of user's behaviour.

For calculating the excess pollutants emissions, it is possible to distinguish the type of fuel.

Annexes

Annex 1: Characteristics of the 90 European cities considered

Id	country	city	longitude	latitude	Köppen class	average temperature
1	AUT	GRAZ	15.43	47	Dfb	9.5
2	AUT	INNSBRUCK	11.35	47.27	Dfb	9.0
3	AUT	LINZ	14.2	48.23	Dfb	9.2
4	AUT	SALZBURG	13	47.8	Dfb	9.3
5	AUT	VIENNA_ SCHWECHAT	16.57	48.12	Dfb	10.0
6	BEL	BRUSSELS	4.53	50.9	Cfb	10.3
7	BEL	OOSTENDE	2.87	51.2	Cfb	10.3
8	BEL	SAINT HUBERT	5.4	50.03	Dfb	7.5
9	CHE	GENEVA	6.13	46.25	Cfb	10.4
10	CZE	OSTRAVA	18.18	49.72	Dfb	8.5
11	CZE	PRAGUE	14.28	50.1	Dfb	8.1
12	DEU	BERLIN	13.4	52.47	Cfb	9.8
13	DEU	BREMEN	8.8	53.05	Cfb	8.9
14	DEU	DUSSELDORF	6.78	51.28	Cfb	10.5
15	DEU	FRANKFURT AM MAIN	8.6	50.05	Cfb	10.1
16	DEU	HAMBURG	10	53.63	Cfb	9.0
17	DEU	KOLN	7.17	50.87	Cfb	9.9
18	DEU	MANNHEIM	8.55	49.52	Cfb	11.1
19	DEU	MUNICH	11.7	48.13	Dfb	8.0
20	DEU	STUTTGART	9.22	48.68	Dfb	9.1
21	DNK	COPENHAGEN	12.67	55.63	Cfb	8.3
22	ESP	BARCELONA	2.07	41.28	Cfa	15.7
23	ESP	MADRID	-3.55	40.45	Cfa	14.3
24	ESP	PALMA	2.73	39.55	Cfa	16.7
25	ESP	SANTANDER	-3.82	43.47	Cfb	14.8
26	ESP	SEVILLA	-5.9	37.42	Csa	18.4
27	ESP	VALENCIA	-0.47	39.5	Cfa	17.3
28	FIN	HELSINKI	24.97	60.32	Dfb	5.2
29	FIN	TAMPERE	23.58	61.42	Dfb	4.3
30	FRA	BORDEAUX	-0.7	44.83	Cfb	13.2
31	FRA	BREST	-4.42	48.45	Cfb	11.2
32	FRA	CLERMONT-FERRAND	3.17	45.78	Cfb	11.4
33	FRA	DIJON	5.08	47.27	Cfb	10.7
34	FRA	LYON	5.08	45.73	Cfb	11.9
35	FRA	MARSEILLE	5.23	43.45	Cfa	14.8
36	FRA	MONTPELLIER	3.97	43.58	Cfa	14.8
37	FRA	NANCY	6.22	48.68	Cfb	10.2
38	FRA	NANTES	-1.6	47.17	Cfb	12.2
39	FRA	NICE	7.2	43.65	Cfa	15.5
40	FRA	PARIS_ ORLY	2.4	48.73	Cfb	11.1
41	FRA	STRASBOURG	7.63	48.55	Cfb	10.3
42	GBR	ABERDEEN/DYCE	-2.22	57.2	Cfb	8.4
43	GBR	AUGHTON	-2.92	53.55	Cfb	9.5
44	GBR	BELFAST	-6.22	54.65	Cfb	9.1
45	GBR	BIRMINGHAM	-1.73	52.45	Cfb	9.7
46	GBR	FINNINGLEY	-1	53.48	Cfb	9.5
47	GBR	HEMSBY	1.68	52.68	Cfb	9.9

48	GBR	JERSEY/CHANNEL ISLANDS	-2.2	49.22	Cfb	11.2
49	GBR	LEUCHARS	-2.87	56.38	Cfb	8.7
50	GBR	LONDON/GATWICK	-0.18	51.15	Cfb	10.2
51	GBR	OBAN	-5.47	56.42	Cfb	9.3
52	GRC	ANDRAVIDA	21.28	37.92	Csa	16.7
53	GRC	ATHENS	23.73	37.9	Cfa	17.9
54	GRC	THESSALONIKI	22.97	40.52	Cfa	15.4
55	IRL	BELMULLET	-10	54.23	Cfb	10.3
56	IRL	BIRR	-7.88	53.08	Cfb	9.6
57	IRL	CLONES	-7.23	54.18	Cfb	9.1
58	IRL	DUBLIN	-6.25	53.43	Cfb	9.8
59	IRL	KILKENNY	-7.27	52.67	Cfb	9.7
60	IRL	MALIN	-7.33	55.37	Cfb	9.7
61	IRL	VALENTIA OBSERVATORY	-10.25	51.93	Cfb	11.0
62	ITA	BRINDISI	17.95	40.65	Cfa	17.1
63	ITA	GENOVA	8.85	44.42	Cfa	16.1
64	ITA	MESSINA	15.55	38.2	Cfa	18.9
65	ITA	MILAN	8.73	45.62	Cfa	11.8
66	ITA	NAPLES	14.3	40.85	Cfa	16.3
67	ITA	PALERMO	13.1	38.18	Cfa	18.8
68	ITA	PISA	10.38	43.68	Cfa	14.6
69	ITA	ROME	12.23	41.8	Cfa	15.8
70	ITA	TORINO	7.65	45.22	Cfa	12.2
71	ITA	VENICE	12.33	45.5	Cfa	13.2
72	NLD	AMSTERDAM	4.77	52.3	Cfb	10.0
73	NLD	BEEK	5.78	50.92	Cfb	10.1
74	NLD	GRONINGEN	6.58	53.13	Cfb	9.1
75	POL	KOLOBRZEG	15.58	54.18	Dfb	8.5
76	POL	KRAKOW	19.8	50.08	Dfb	8.2
77	POL	POZNAN	16.83	52.42	Dfb	8.6
78	POL	WARSAW	20.97	52.17	Dfb	8.4
79	PRT	BRAGANCA	-6.73	41.8	Cfb	12.4
80	PRT	COIMBRA	-8.42	40.2	Csb	15.3
81	PRT	EVORA	-7.9	38.57	Cfa	15.8
82	PRT	FARO	-7.97	37.02	Cfa	17.8
83	PRT	LAJES	-27.1	38.77	Cfa	17.5
84	PRT	PORTO	-8.68	41.23	Csb	14.3
85	SVK	BRATISLAVA	17.2	48.2	Dfb	10.4
86	SVK	KOSICE	21.27	48.7	Dfb	9.1
87	SWE	GOTEBORG_ LANDVETTER	12.3	57.67	Dfb	6.5
88	SWE	KARLSTAD	13.47	59.37	Dfb	5.9
89	SWE	KIRUNA	20.33	67.82	Dfc	-1.1
90	SWE	OSTERSUND/FROSON	14.5	63.18	Dfc	3.1
91	SWE	STOCKHOLM_ ARLANDA	17.95	59.65	Dfb	6.5

Table 8: Parameters of each location, in terms on longitude, latitude, temperature and Köppen class

Annex 2: Values of hourly fuel consumption simplified model

Id (see Annex 1)	a_1	a_2	a_3	a_4	a_5
1	-0.86	0.04	-0.04	0.0334	-0.0016
2	-0.72	0.03	-0.03	0.0355	-0.0016
3	-0.73	0.03	-0.03	0.0348	-0.0017
4	-0.83	0.04	-0.03	0.0383	-0.0018
5	-0.81	0.04	-0.03	0.0360	-0.0016
6	-0.89	0.04	-0.03	0.0391	-0.0017
7	-0.95	0.04	-0.03	0.0556	-0.0023
8	-0.82	0.03	-0.03	0.0536	-0.0022
9	-0.80	0.03	-0.03	0.0386	-0.0017
10	-0.83	0.04	-0.03	0.0377	-0.0018
11	-0.80	0.03	-0.03	0.0385	-0.0018
12	-0.73	0.03	-0.03	0.0344	-0.0016
13	-0.84	0.04	-0.04	0.0406	-0.0018
14	-0.76	0.03	-0.03	0.0356	-0.0015
15	-0.80	0.03	-0.03	0.0377	-0.0017
16	-0.83	0.04	-0.03	0.0399	-0.0017
17	-0.76	0.03	-0.03	0.0367	-0.0017
18	-0.79	0.03	-0.03	0.0359	-0.0016
19	-0.80	0.03	-0.03	0.0440	-0.0020
20	-0.76	0.03	-0.03	0.0396	-0.0018
21	-0.79	0.03	-0.03	0.0484	-0.0020
22	-1.11	0.05	-0.04	0.0481	-0.0019
23	-0.82	0.03	-0.03	0.0437	-0.0019
24	-1.18	0.05	-0.05	0.0471	-0.0019
25	-0.97	0.04	-0.03	0.0484	-0.0019
26	-0.92	0.04	-0.04	0.0407	-0.0018
27	-1.06	0.05	-0.04	0.0408	-0.0017
28	-0.79	0.03	-0.03	0.0517	-0.0021
29	-0.73	0.03	-0.03	0.0461	-0.0019
30	-0.88	0.04	-0.04	0.0458	-0.0019
31	-1.19	0.04	-0.03	0.0888	-0.0033
32	-0.80	0.03	-0.03	0.0408	-0.0018
33	-0.93	0.04	-0.04	0.0440	-0.0020
34	-0.90	0.04	-0.04	0.0442	-0.0019
35	-0.99	0.04	-0.04	0.0469	-0.0020
36	-0.92	0.04	-0.04	0.0413	-0.0017
37	-0.87	0.04	-0.03	0.0406	-0.0018
38	-0.86	0.03	-0.03	0.0477	-0.0020
39	-1.14	0.05	-0.04	0.0536	-0.0022
40	-0.86	0.04	-0.03	0.0416	-0.0018

Id (see Annex 1)	a_1	a_2	a_3	a_4	a_5
41	–0.92	0.04	–0.04	0.0389	–0.0018
42	–1.06	0.04	–0.03	0.0662	–0.0027
43	–0.79	0.03	–0.03	0.0491	–0.0020
44	–0.79	0.03	–0.03	0.0462	–0.0019
45	–0.80	0.03	–0.03	0.0523	–0.0022
46	–0.74	0.03	–0.03	0.0428	–0.0019
47	–0.90	0.04	–0.03	0.0539	–0.0023
48	–0.99	0.04	–0.03	0.0672	–0.0028
49	–0.81	0.03	–0.03	0.0458	–0.0019
50	–0.84	0.03	–0.03	0.0500	–0.0022
51	–0.73	0.03	–0.02	0.0494	–0.0020
52	–0.97	0.04	–0.04	0.0380	–0.0016
53	–0.95	0.04	–0.04	0.0483	–0.0020
54	–0.90	0.04	–0.04	0.0461	–0.0020
55	–0.79	0.03	–0.02	0.0502	–0.0020
56	–0.87	0.03	–0.03	0.0504	–0.0021
57	–1.03	0.04	–0.03	0.0681	–0.0027
58	–0.88	0.03	–0.03	0.0548	–0.0022
59	–0.91	0.03	–0.03	0.0575	–0.0024
60	–0.68	0.02	–0.02	0.0541	–0.0021
61	–0.91	0.03	–0.03	0.0594	–0.0023
62	–1.26	0.05	–0.05	0.0495	–0.0021
63	–1.20	0.05	–0.04	0.0523	–0.0021
64	–1.11	0.05	–0.04	0.0461	–0.0019
65	–0.95	0.04	–0.04	0.0409	–0.0018
66	–1.02	0.04	–0.04	0.0382	–0.0017
67	–1.17	0.05	–0.04	0.0527	–0.0021
68	–0.95	0.04	–0.04	0.0399	–0.0017
69	–1.11	0.05	–0.04	0.0420	–0.0017
70	–1.03	0.05	–0.04	0.0410	–0.0018
71	–1.06	0.05	–0.04	0.0367	–0.0016
72	–0.90	0.04	–0.03	0.0502	–0.0021
73	–0.85	0.04	–0.03	0.0394	–0.0017
74	–0.93	0.04	–0.04	0.0443	–0.0019
75	–0.77	0.03	–0.03	0.0515	–0.0022
76	–0.80	0.04	–0.03	0.0359	–0.0017
77	–0.75	0.03	–0.03	0.0319	–0.0015
78	–0.79	0.04	–0.03	0.0352	–0.0017
79	–0.72	0.03	–0.03	0.0412	–0.0018
80	–0.99	0.04	–0.04	0.0544	–0.0023

Id (see Annex 1)	a_1	a_2	a_3	a_4	a_5
81	–0.78	0.03	–0.03	0.0472	–0.0020
82	–0.97	0.04	–0.04	0.0552	–0.0022
83	–1.13	0.05	–0.04	0.0442	–0.0017
84	–0.96	0.04	–0.03	0.0596	–0.0024
85	–0.87	0.04	–0.04	0.0373	–0.0017
86	–0.82	0.04	–0.03	0.0375	–0.0018
87	–0.78	0.03	–0.03	0.0582	–0.0023
88	–0.86	0.03	–0.03	0.0564	–0.0024
89	–0.62	0.02	–0.02	0.0441	–0.0018
90	–0.67	0.03	–0.03	0.0421	–0.0018
91	–0.73	0.03	–0.03	0.0421	–0.0019

Table 9: Values of hourly fuel consumption simplified model for hourly weather format for each location, as described in Annex 1

Id	a_1	a_2	a_3	a_4	a_5
1	–0.4030	0.0138	–0.0067	0.0493	–0.0019
2	–0.2190	0.0090	–0.0043	0.0259	–0.0010
3	–0.3450	0.0132	–0.0058	0.0381	–0.0014
4	–0.3010	0.0106	–0.0047	0.0381	–0.0014
5	–0.3710	0.0148	–0.0060	0.0392	–0.0015
6	–0.2580	0.0114	–0.0041	0.0252	–0.0009
7	–0.2930	0.0126	–0.0049	0.0267	–0.0010
8	–0.1490	0.0058	–0.0034	0.0182	–0.0007
9	–0.4250	0.0160	–0.0063	0.0443	–0.0016
10	–0.3220	0.0129	–0.0051	0.0375	–0.0014
11	–0.2890	0.0107	–0.0050	0.0352	–0.0013
12	–0.2790	0.0118	–0.0051	0.0286	–0.0011
13	–0.2540	0.0107	–0.0045	0.0284	–0.0011
14	–0.2350	0.0101	–0.0044	0.0248	–0.0009
15	–0.3070	0.0123	–0.0051	0.0331	–0.0012
16	–0.2160	0.0092	–0.0044	0.0243	–0.0009
17	–0.2470	0.0100	–0.0048	0.0275	–0.0010
18	–0.3860	0.0150	–0.0060	0.0409	–0.0015
19	–0.3360	0.0120	–0.0054	0.0416	–0.0016
20	–0.3640	0.0132	–0.0055	0.0407	–0.0015
21	–0.2460	0.0106	–0.0044	0.0246	–0.0010
22	–0.7050	0.0260	–0.0110	0.0655	–0.0024
23	–0.6290	0.0201	–0.0084	0.0648	–0.0022
24	–0.7960	0.0304	–0.0120	0.0764	–0.0029
25	–0.3940	0.0171	–0.0061	0.0322	–0.0012
26	–0.8330	0.0273	–0.0113	0.0779	–0.0027
27	–0.8030	0.0290	–0.0115	0.0718	–0.0026
28	–0.2200	0.0088	–0.0043	0.0253	–0.0009
29	–0.2130	0.0084	–0.0042	0.0243	–0.0009
30	–0.4950	0.0177	–0.0070	0.0520	–0.0019

Id	a_1	a_2	a_3	a_4	a_5
31	−0.3680	0.0134	−0.0050	0.0355	−0.0013
32	−0.3830	0.0138	−0.0057	0.0445	−0.0016
33	−0.4850	0.0176	−0.0070	0.0523	−0.0019
34	−0.4440	0.0168	−0.0067	0.0472	−0.0017
35	−0.6410	0.0232	−0.0094	0.0656	−0.0025
36	−0.6230	0.0227	−0.0089	0.0639	−0.0024
37	−0.3720	0.0154	−0.0057	0.0384	−0.0014
38	−0.4140	0.0157	−0.0063	0.0420	−0.0015
39	−0.7020	0.0271	−0.0105	0.0641	−0.0024
40	−0.4250	0.0160	−0.0062	0.0417	−0.0015
41	−0.5030	0.0189	−0.0067	0.0515	−0.0019
42	−0.2780	0.0069	−0.0029	0.0363	−0.0014
43	−0.1230	0.0061	−0.0024	0.0110	−0.0004
44	−0.1220	0.0055	−0.0026	0.0115	−0.0004
45	−0.3290	0.0119	−0.0045	0.0346	−0.0013
46	−0.2720	0.0110	−0.0040	0.0280	−0.0011
47	−0.2330	0.0118	−0.0043	0.0196	−0.0008
48	−0.3010	0.0131	−0.0052	0.0282	−0.0011
49	−0.2830	0.0084	−0.0031	0.0321	−0.0012
50	−0.5080	0.0149	−0.0054	0.0548	−0.0019
51	−0.1330	0.0049	−0.0020	0.0129	−0.0005
52	−0.7220	0.0266	−0.0101	0.0683	−0.0025
53	−0.7550	0.0269	−0.0116	0.0707	−0.0026
54	−0.6760	0.0230	−0.0104	0.0705	−0.0026
55	−0.2120	0.0053	−0.0027	0.0256	−0.0010
56	−0.1930	0.0085	−0.0033	0.0177	−0.0007
57	−0.3040	0.0084	−0.0034	0.0337	−0.0012
58	−0.1700	0.0079	−0.0034	0.0152	−0.0006
59	−0.2400	0.0124	−0.0042	0.0191	−0.0007
60	−0.1800	0.0052	−0.0022	0.0202	−0.0008
61	−0.1540	0.0079	−0.0036	0.0125	−0.0005
62	−0.8520	0.0344	−0.0127	0.0702	−0.0027
63	−0.5850	0.0256	−0.0104	0.0469	−0.0018
64	−0.7290	0.0329	−0.0130	0.0497	−0.0020
65	−0.6660	0.0212	−0.0101	0.0755	−0.0028
66	−0.8200	0.0302	−0.0119	0.0760	−0.0029
67	−0.6910	0.0319	−0.0120	0.0461	−0.0018
68	−0.5890	0.0228	−0.0098	0.0579	−0.0021
69	−0.7120	0.0275	−0.0109	0.0674	−0.0025
70	−0.6320	0.0225	−0.0099	0.0646	−0.0023

Id	a_1	a_2	a_3	a_4	a_5
71	–0.6450	0.0253	–0.0109	0.0553	–0.0020
72	–0.2520	0.0106	–0.0044	0.0266	–0.0010
73	–0.2820	0.0117	–0.0049	0.0289	–0.0011
74	–0.2210	0.0097	–0.0041	0.0240	–0.0009
75	–0.1870	0.0082	–0.0044	0.0207	–0.0008
76	–0.2940	0.0120	–0.0052	0.0347	–0.0013
77	–0.2620	0.0111	–0.0050	0.0298	–0.0011
78	–0.3280	0.0132	–0.0054	0.0371	–0.0014
79	–0.5040	0.0178	–0.0065	0.0547	–0.0020
80	–0.5380	0.0211	–0.0073	0.0527	–0.0020
81	–0.6460	0.0232	–0.0080	0.0606	–0.0022
82	–0.7170	0.0275	–0.0109	0.0637	–0.0024
83	–0.5970	0.0275	–0.0087	0.0358	–0.0014
84	–0.5360	0.0226	–0.0067	0.0474	–0.0018
85	–0.5230	0.0176	–0.0073	0.0614	–0.0023
86	–0.4730	0.0178	–0.0069	0.0516	–0.0020
87	–0.2080	0.0045	–0.0034	0.0291	–0.0011
88	–0.2520	0.0090	–0.0050	0.0300	–0.0011
89	–0.1030	0.0028	–0.0018	0.0145	–0.0005
90	–0.1160	0.0055	–0.0023	0.0125	–0.0005
91	–0.1960	0.0069	–0.0040	0.0250	–0.0009

Table 10: Values of hourly fuel consumption simplified model for monthly weather format for each location

Köppen classes	a1	a2	a3	a4	a5
Cfa	–1.0368	0.0436	–0.0404	0.0455	–0.0019
Cfb	–0.8575	0.0343	–0.0315	0.0480	–0.0020
Csa/Csb	–0.9618	0.0393	–0.0380	0.0482	–0.0020
Dfb	–0.7937	0.0333	–0.0319	0.0417	–0.0019
Dfc	–0.6450	0.0242	–0.0250	0.0431	–0.0018

Table 11: Values of hourly fuel consumption simplified model for hourly weather format for Köppen classes

Köppen classes	a1	a2	a3	a4	a5
Cfa	–0.6914	0.0264	–0.0106	0.0629	–0.0023
Cfb	–0.3029	0.0117	–0.0046	0.0313	–0.0012
Csa/Csb	–0.6573	0.0244	–0.0088	0.0616	–0.0023
Dfb	–0.2979	0.0111	–0.0051	0.0349	–0.0013
Dfc	–0.1095	0.0041	–0.0020	0.0135	–0.0005

Table 12: Values of hourly fuel consumption simplified model for monthly weather format for Köppen classes

a1	a2	a3	a4	a5
–0.886	0.0363	–0.0339	0.0458	–0.0019

Table 13:Average values of hourly fuel consumption simplified model for hourly weather format

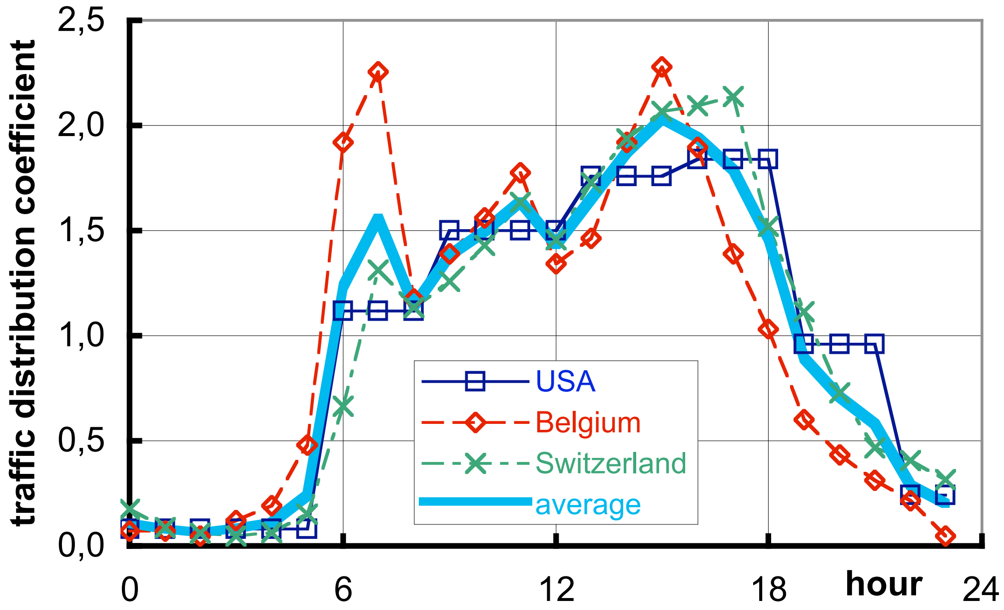
a1	a2	a3	a4	a5
−0.407	0.0155	−0.00631	0.04068	−0.00151

Table 14: Average values of hourly fuel consumption simplified model for monthly weather format

Annex 3: Values of penetration rate of AC (Hugrel 2004)

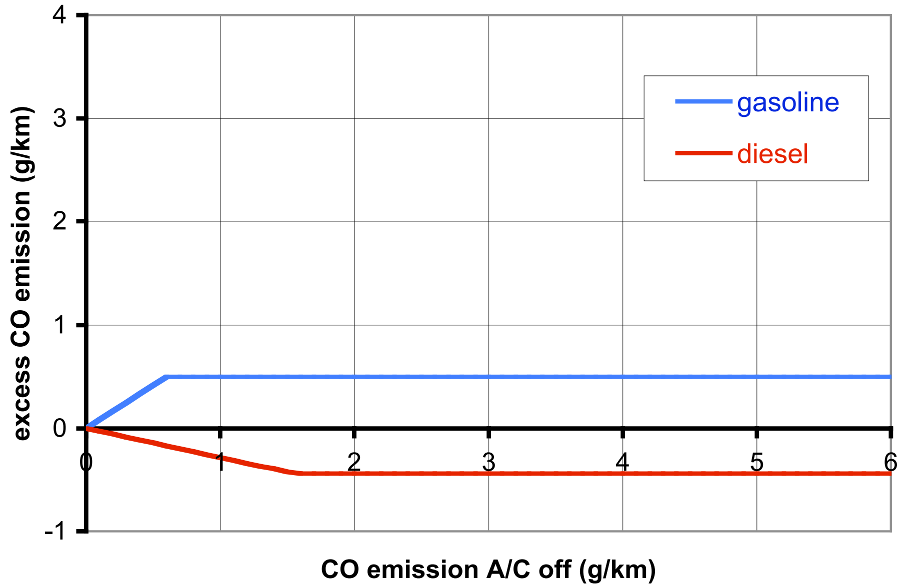
year	gasoline			diesel	
	< 1.4 l	1.4 – 2 l	≥ 2 l	< 2 l	≥ 2l
1989	0	0	0	0	0
1990	0	0	0	0	0
1991	0	0	0.01	0	0.01
1992	0	0.01	0.02	0.01	0.02
1993	0	0.02	0.05	0.02	0.05
1994	0.01	0.05	0.1	0.05	0.1
1995	0.02	0.15	0.2	0.15	0.2
1996	0.05	0.3	0.4	0.3	0.4
1997	0.15	0.5	0.65	0.5	0.65
1998	0.3	0.65	0.8	0.65	0.8
1999	0.5	0.75	0.9	0.75	0.9
2000	0.65	0.8	1	0.8	1
2001	0.75	0.83	1	0.8	1
2002	0.8	0.85	1	0.8	1
2003	0.8	0.86	1	0.8	1
2004	0.8	0.86	1	0.8	1
2005	0.8	0.86	1	0.8	1
2006	0.8	0.86	1	0.8	1
2007	0.8	0.86	1	0.8	1
2008	0.8	0.86	1	0.8	1
2009	0.8	0.86	1	0.8	1
2010	0.8	0.86	1	0.8	1
2011	0.8	0.86	1	0.8	1

Annex 4: Sample of traffic distribution coefficients (% of the hourly average)



Hour	USA	Belgium	Switzerland
0	0.08	0.07	0.17
1	0.08	0.07	0.09
2	0.08	0.05	0.06
3	0.08	0.12	0.05
4	0.08	0.19	0.06
5	0.08	0.48	0.15
6	1.12	1.92	0.66
7	1.12	2.26	1.31
8	1.12	1.18	1.14
9	1.50	1.39	1.26
10	1.50	1.56	1.43
11	1.50	1.78	1.64
12	1.50	1.34	1.46
13	1.76	1.46	1.73
14	1.76	1.92	1.94
15	1.76	2.28	2.07
16	1.84	1.90	2.09
17	1.84	1.39	2.14
18	1.84	1.03	1.52
19	0.96	0.60	1.11
20	0.96	0.43	0.73
21	0.96	0.31	0.47
22	0.24	0.22	0.41
23	0.24	0.05	0.31
average	1	1	1

Annex 5: Model of CO excess emission at full load



<u>gasoline:</u>

if $ef_{CO,ACoff}$ <0.6 $\quad cf_{AC,CO,diesel}\left(ef_{CO,ACoff}\right) = -0.83 \cdot ef_{CO,ACoff}$

else $\quad cf_{AC,CO,gasoline}\left(ef_{CO,ACoff}\right) = 0.5$

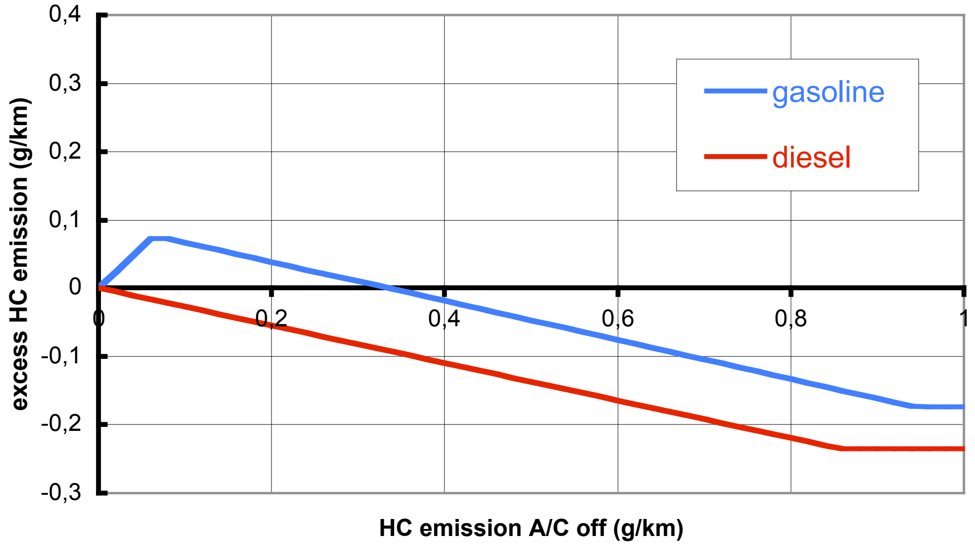
<u>diesel:</u>

if $ef_{CO,ACoff}$ <1.56 $\quad cf_{AC,CO,diesel}\left(ef_{CO,ACoff}\right) = -0.2825 \cdot ef_{CO,ACoff}$

else $\quad cf_{AC,CO,diesel}\left(ef_{CO,ACoff}\right) = -0.2825 \cdot 1.56 = -0.441$

	Excess emission	
Hot CO emission	gasoline	diesel
0.000	0	0
0.100	0.08333333	–0.02825
0.200	0.16666667	–0.0565
0.300	0.25	–0.08475
0.400	0.33333333	–0.113
0.500	0.41666667	–0.14125
0.600	0.5	–0.1695
0.700	0.5	–0.19775
0.800	0.5	–0.226
0.900	0.5	–0.25425
1.000	0.5	–0.2825
1.100	0.5	–0.31075
1.200	0.5	–0.339
1.300	0.5	–0.36725
1.400	0.5	–0.3955
1.500	0.5	–0.42375
1.600	0.5	–0.441
1.700	0.5	–0.441
1.800	0.5	–0.441
>1.800	0.5	–0.441

Annex 6: Model of HC excess emission at full load



<u>gasoline:</u>

if $ef_{HC,ACoff} < 0.06$g/km $\qquad cf_{AC,HC,gasoline}(ef_{HC,ACoff}) = 1.21646 \cdot ef_{HC,ACoff}$

if $ef_{HC,ACoff} > 0.06$g/km and < 0.08 $\qquad cf_{AC,HC,gasoline}(ef_{HC,ACoff}) = 0.072988$

if $ef_{HC,ACoff} > 0.08$ and < 0.944g/km $\qquad cf_{AC,HC,gasoline}(ef_{HC,ACoff}) = -0.2864 \cdot ef_{HC,ACoff} + 0.0959$

if $ef_{HC,ACoff} > 0.944$g/km $\qquad cf_{AC,HC,gasoline}(ef_{HC,ACoff}) = -0.2864 \cdot 0.944 + 0.0959 = -0.174$

<u>diesel:</u>

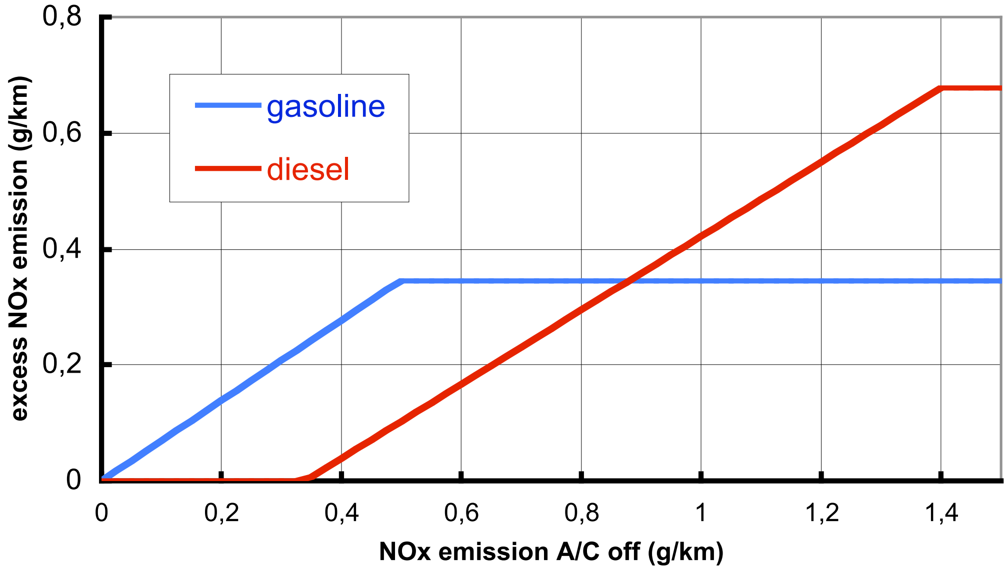
if $ef_{HC,ACoff} < 0.855$g/km $\qquad cf_{AC,HC,diesel}(ef_{HC,ACoff}) = -0.2743 \cdot ef_{HC,ACoff}$

else $\qquad cf_{AC,HC,diesel}(ef_{HC,ACoff}) = -0.2743 \cdot 0.855 = -0.235$

Hot HC emission	Excess emission	
	gasoline	diesel
0	0.000000	0
0.02	0.024329	-0.005486
0.04	0.048658	-0.010972
0.06	0.072988	-0.016458
0.08	0.072988	-0.021944
0.1	0.06726	-0.02743

Hot HC emission	Excess emission	
	gasoline	diesel
0.12	0.061532	-0.032916
0.14	0.055804	-0.038402
0.16	0.050076	-0.043888
0.18	0.044348	-0.049374
0.2	0.03862	-0.05486
0.22	0.032892	-0.060346
0.24	0.027164	-0.065832
0.26	0.021436	-0.071318
0.28	0.015708	-0.076804
0.3	0.00998	-0.08229
0.32	0.004252	-0.087776
0.34	-0.001476	-0.093262
0.36	-0.007204	-0.098748
0.38	-0.012932	-0.104234
0.4	-0.01866	-0.10972
0.42	-0.024388	-0.115206
0.44	-0.030116	-0.120692
0.46	-0.035844	-0.126178
0.48	-0.041572	-0.131664
0.5	-0.0473	-0.13715
0.52	-0.053028	-0.142636
0.54	-0.058756	-0.148122
0.56	-0.064484	-0.153608
0.58	-0.070212	-0.159094
0.6	-0.07594	-0.16458
0.62	-0.081668	-0.170066
0.64	-0.087396	-0.175552
0.66	-0.093124	-0.181038
0.68	-0.098852	-0.186524
0.7	-0.10458	-0.19201
0.72	-0.110308	-0.197496
0.74	-0.116036	-0.202982
0.76	-0.121764	-0.208468
0.78	-0.127492	-0.213954
0.8	-0.13322	-0.21944
0.82	-0.138948	-0.224926
0.84	-0.144676	-0.230412
0.86	-0.150404	-0.235
0.88	-0.156132	-0.235
0.9	-0.16186	-0.235
0.92	-0.167588	-0.235
0.94	-0.173316	-0.235
0.96	-0.174	-0.235
>0.96	-0.174	-0.235

Annex 7: Model of NOx excess emission at full load



gasoline:

if $ef_{NOx,\ ACoff} < 0.5$g/km $\quad cf_{AC,NOx,gasoline}(ef_{NOx,ACoff}) = 0.6918 \cdot ef_{NOx,ACoff}$

else $\quad cf_{AC,NOx,gasoline}(ef_{NOx,ACoff}) = 0.6918 \cdot 0.5 = 0.3459$

diesel:

if $ef_{NOx,ACoff} < 0.3397$ $\quad cf_{AC,NOx,diesel}(ef_{NOx,ACoff}) = 0$

else if $ef_{NOx,ACoff} > 0.3397$

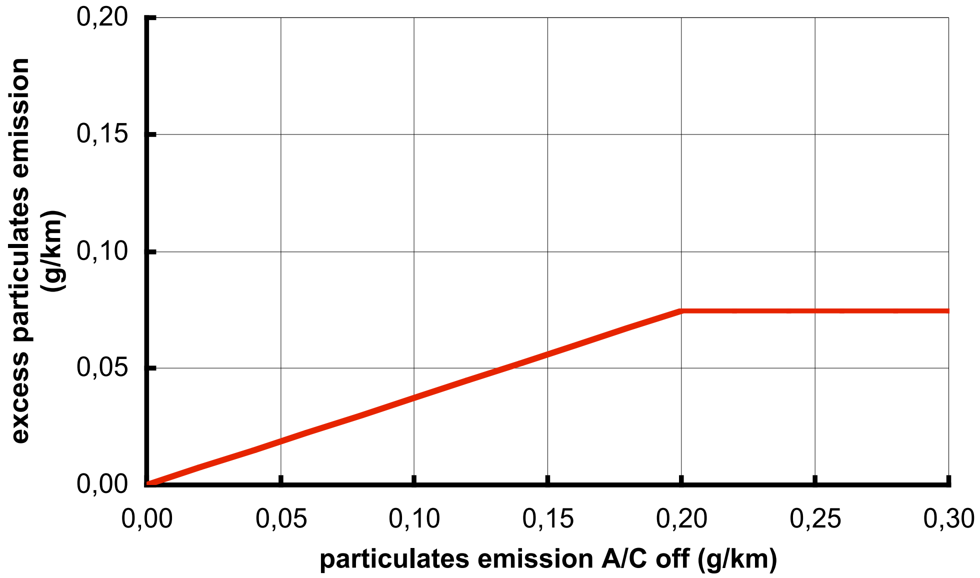
and $ef_{NOx,ACoff} < 1.4$ $\quad cf_{AC,NOx,diesel}(ef_{NOx,ACoff}) = 0.6395 \cdot ef_{NOx,ACoff} - 0.2172$

else $\quad cf_{AC,NOx,diesel}(ef_{NOx,ACoff}) = 0.6395 \cdot 1.4 - 0.2172 = 0.6781$

Hot NOx emissions	Excess emission	
	gasoline	diesel
0.000	0.000	0.000
0.025	0.017	0.000
0.050	0.035	0.000
0.075	0.052	0.000
0.100	0.069	0.000

	Excess emission	
Hot NOx emissions	gasoline	diesel
0.125	0.086	0.000
0.150	0.104	0.000
0.175	0.121	0.000
0.200	0.138	0.000
0.225	0.156	0.000
0.250	0.173	0.000
0.275	0.190	0.000
0.300	0.208	0.000
0.325	0.225	0.000
0.350	0.242	0.007
0.375	0.259	0.023
0.400	0.277	0.039
0.425	0.294	0.055
0.450	0.311	0.071
0.475	0.329	0.087
0.500	0.346	0.103
0.525	0.346	0.119
0.550	0.346	0.135
0.575	0.346	0.151
0.600	0.346	0.167
0.625	0.346	0.182
0.650	0.346	0.198
0.675	0.346	0.214
0.700	0.346	0.230
0.725	0.346	0.246
0.750	0.346	0.262
0.775	0.346	0.278
0.800	0.346	0.294
0.825	0.346	0.310
0.850	0.346	0.326
0.875	0.346	0.342
0.900	0.346	0.358
0.925	0.346	0.374
0.950	0.346	0.390
0.975	0.346	0.406
1.000	0.346	0.422
1.025	0.346	0.438
1.050	0.346	0.454
1.075	0.346	0.470
1.100	0.346	0.486
1.125	0.346	0.502
1.150	0.346	0.518
1.175	0.346	0.534
1.200	0.346	0.550
>1.200	0.346	0.550

Annex 8: Model of particulates excess emissions



gasoline:

$$cf_{AC,Pa,gasoline}\left(ef_{NOx,ACoff}\right)=0$$

diesel:

if $ef_{HC,ACoff} < 0.2$ g/km $\quad cf_{AC,Pa,diesel}\left(ef_{HC,ACoff}\right)=0.3722\cdot ef_{HC,ACoff}$

else $\quad cf_{AC,Pa,diesel}\left(ef_{HC,ACoff}\right)=-0.07444$

Hot particulates emissions	Excess emission for diesel
0	0
0.02	0.007444
0.04	0.014888
0.06	0.022332
0.08	0.029776
0.1	0.03722
0.12	0.044664
0.14	0.052108
0.16	0.059552
0.18	0.066996
0.2	0.07444
0.22	0.07444
>0.22	0.07444

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