Support for the preparation of a procedure to certify CO2 savings from the use of efficient Mobile Air Conditioning (MAC) systems (Article 11 of Regulation (EU) 2019/631 setting CO2 emission performance standards for new cars and vans)

Final report

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Abstract

The objective of this study was to suggest a proper testing methodology for measuring CO_2 emissions savings from innovative Mobile Air Conditioning (MAC) technologies, in the context of the EU eco-innovations scheme under Regulation (EU) 2019/631. Additionally, the study aimed to provide support to the European Commission in preparing a possible adjustment of the 7 g CO_2/km cap on eco-innovation credits and examining the level of eco-innovation savings that may be attained by MAC systems.

In order to propose an exhaustive methodology, this study assessed what is a baseline MAC system. Thanks to an extensive market survey and literature review, a baseline MAC system was identified and defined in a technologically neutral way. Therefore, any MAC technology would potentially be eligible for credits, as long as it proved to be sufficiently more efficient than the defined baseline.

To minimise the testing burden, a combination of simulations and vehicle testing is suggested. One test is suggested for the vehicle equipped with the innovative technology, which is based on type 1 testing, as described in UN Regulation 154. The differences with the type 1 test are the different ambient conditions of testing and the requirement for the MAC system to be on.

Taking into account the technological advancements of MAC systems and the methodology proposed, the possible revision of the eco-innovation cap has been considered and the maximum CO_2 credits that could be obtained from MAC systems has been estimated. For the latter, various scenarios with increased MAC system efficiency in comparison to the baseline were examined.

Executive summary

Mobile Air Conditioning (MAC) systems that are efficient and innovative will be eligible technologies under the EU eco-innovation (EI) scheme from 2025, as per Regulation (EU) 2019/631. This study aims to support the development of a procedure for determining the CO_2 emissions savings from the use of these MAC systems in passenger cars and light commercial vehicles within the eco-innovation scheme. The study also aims to support the Commission in preparing a possible adjustment of the 7 g CO_2/km cap on eco-innovation credits and provide a view of the level of eco-innovation savings that may be attained by efficient and innovative MAC systems.

The first step involved a market survey to identify current and potential technological developments for improving the energy efficiency of MAC systems. However, the collected feedback was limited and incomplete, so it was necessary to supplement it with data collected from a Joint Research Centre (JRC) survey conducted in April 2021, and an extensive literature review. The JRC survey collected information from 165 Internal Combustion Energy Vehicles (ICEVs), 5 Hybrid Electric Vehicles (HEVs) and 9 Plug-in Hybrid Electric Vehicles (PHEVs).

Additionally, the team performed an assessment of MAC related regulatory practices in major markets around the world. This included the relevant regulations and practices for the attribution of off-cycle CO_2 emission credits for MAC systems of cars and vans. The reviewed markets included the US, California, China, Mexico, Japan, India and Australia.

The AC17 testing methodology, developed in the US, is considered to be one of the most detailed, and is also relevant in the EU context. The calculation of credits is based on the difference between CO_2 emissions from the use of the MAC system in the baseline and the vehicle equipped with the EI. The EU proposed methodology followed the same approach, with the addition of the usage factor (UF), which determines the usage of the MAC for cooling over the total distance driven, estimated to be 17% for cars and vans.

The CO_2 savings formula in the eco-innovation scheme is defined in the Technical Guidelines for eco-innovations[1] as

$$CO2\ savings = UF_{MC} * (B_{MC} - E_{MC}) - UF_{TA} * (B_{TA} - E_{TA})$$

where B and E refer to the baseline and eco-innovative vehicle CO_2 emissions, respectively, and TA and MC to Type Approval conditions and Modified Conditions respectively.

The MAC CO_2 emissions are derived from the difference in the vehicle CO_2 emissions, considering the MAC system on and off. As MAC systems remain inactive during the Type Approval procedure, these CO_2 emissions are identical to the vehicle's emissions with the MAC turned off. Additionally, since the baseline vehicle is identical to the vehicle equipped with the EI, except for the MAC system, the difference between B_{TA} and E_{TA} is equal to zero. To estimate the CO_2 emissions from the MAC system the Modified Conditions take into account the activation of MAC systems and different testing ambient conditions from the TA procedure.

It has been identified that technologies concerning the heating mode of the MAC have a lower potential for CO_2 savings. This is because internal combustion engine heat waste supplies the heating, and other means of heating are only used when it is insufficient, such as in severe winter weather conditions or during the first seconds of a trip. However, when MAC is operating for cooling, the vehicle's total energy consumption always increases, independently of the powertrain. As a result, it was decided in

[1] European Commission, 2018, Technical Guidelines for the preparation of applications for the approval of innovative technologies pursuant to Regulation (EC) No 443/2009 and Regulation (EU) No 510/2011 – Revision: July 2018. [Online]. Available: http://europa.eu/!ch88vv (Accessed: May-2023)

collaboration with the study's stakeholders to focus on designing a methodology for measuring CO_2 savings from innovative MAC technologies related to cooling. Therefore, the proposed methodology only covers the cooling mode of the MAC system.

A simulation-based approach was used to estimate the CO_2 emissions from the baseline MAC system operation. Simulation models with the GT Suite software were created for ICEV and PHEV Including the vehicle cabin and MAC system to understand the vehicle's energy performance with MAC on or off. The simulation models were validated using measurement data from the JRC.

For PHEVs, CO_2 savings are achieved by reduced emissions during the charge-sustaining (CS) mode and an increased all-electric range (AER) during charge-depleting (CD) mode, due to the reduced energy consumption from the use of the innovative MAC system. Hence, to obtain the CO_2 emissions of the baseline MAC system for PHEVs, emissions during the CS and CD modes should be calculated.

The requirements for testing and soaking areas, the test vehicle, the dynamometer settings, and fuel specifications are the same as the TA type 1 test, as set out in UN Regulation 154. The only difference is the altered ambient conditions, which are estimated based on the moderate summer conditions across the EU. To simulate solar flux, it is suggested that an additional heat source be introduced on the front passenger seat during testing, rather than using solar lamps. The ambient conditions for testing, including the additional heat source value, are noted in Table 1.

Table 1. Ambient conditions for testing

Ambient conditions	Value
Ambient temperature (ºC)	26
Relative humidity (%)	50
Solar radiation (W/m^2)	0
Additional heat source (W)	585

The amount of CO_2 savings from innovative MAC systems depends on the system's efficiency. Several scenarios were examined where the system's efficiency increases from 10% to 50% from the baseline. The maximum obtainable MAC CO_2 savings are approximately 1 g CO_2/km.

Regulation (EU) 2023/851[2], which was adopted by the European Parliament and the Council in April 2023, amends the CO_2 emission performance standards for new passenger cars and light commercial vehicles and notably revises the eco-innovation cap downwards. Under the amended Regulation, the maximum credits that can be obtained will be reduced to 4 g CO_2/km per year between 2030 and 2034. This means that the EI cap aligns quite well with the CO_2 emission targets and therefore a further decrease of the cap is not recommended.

[2] EUR-Lex - 32023R0851 - EN - EUR-Lex (europa.eu)

1 Introduction

This is the Final Report for the project "Support for the preparation of a procedure to certify CO_2 savings from the use of efficient Mobile Air Conditioning (MAC) systems (Article 11 of Regulation (EU) 2019/631 setting CO_2 emission performance standards for new passenger cars and for new light commercial vehicles)"[3] (No. 090203/2021/857749/SER/CLIMA.C.4).

1.1 Aims and objectives

The objective of the project is to support the European Commission (DG CLIMA) in designing the suitable procedures related to the determination of CO_2 savings from the use of efficient MAC systems fitted in passenger cars and vans that will become eligible as eco-innovations in the context of Regulation (EU) 2019/631. Both cooling and heating functions of MAC systems fall within the scope of this study initially. In the course of the study, the decision to focus on cooling was taken after communication with the interested stakeholders and close examination on what technologies can lead to CO_2 savings.

Specifically, the scope of the assignment comprised the following major components:

- Critically review and assess the state-of-the-art technologies and improvements of MAC systems in cars/vans today and which are technologically feasible to appear in the market in the next 10 to 15 years approximately.
- Investigate and learn from relevant developments and testing practises around the world, regarding CO_2 emissions associated with MAC systems, especially in light of their relevance to EU needs.
- Define a baseline technology, which allows assessing, in the context of eco-innovations (Regulation (EU) 2019/631), the various MAC technologies, their characteristics and level of performance/innovation.
- Develop and propose testing approaches and methods, for accurately determining CO_2 savings due to the use of efficient MAC systems, building on past relevant studies.
- The initial task of re-evaluating the eco-innovations cap under Regulation (EU) 2019/631 was limited as the cap has been amended already under Regulation (EU) 2023/851[4]. An additional goal of this task was to estimate what part of the new Eco-innovation (EI) CO_2 credits cap could come from the use of innovative MAC technologies.

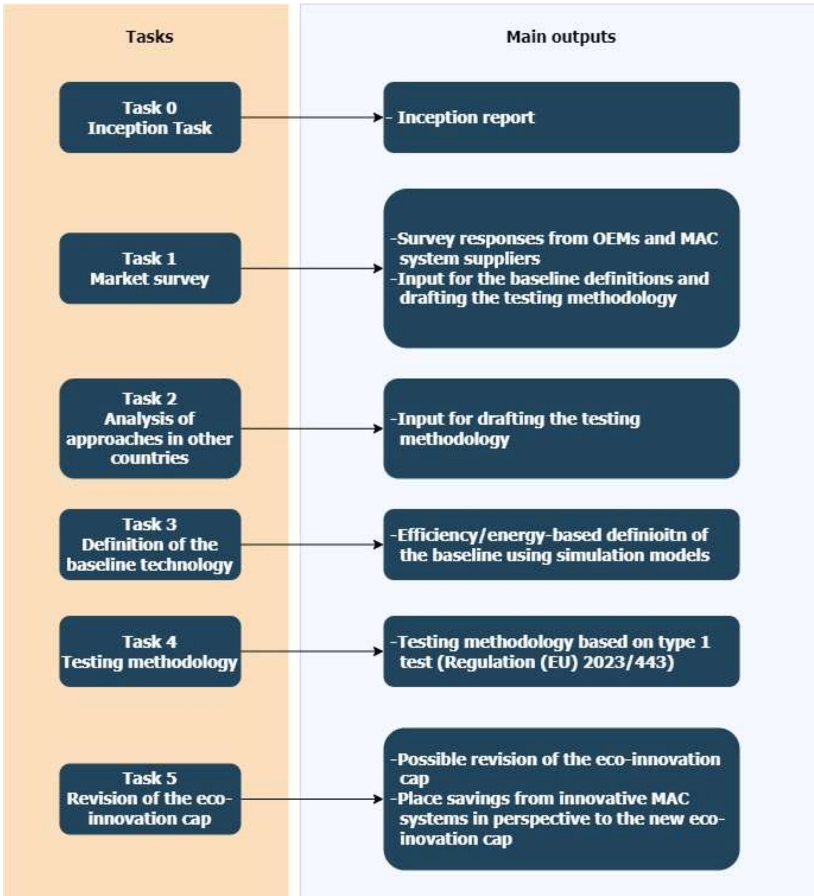
[3] See REGULATION (EU) 2019/ 631 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL - of 17 April 2019 - setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles, and repealing Regulations (EC) No 443 / 2009 and (EU) No 510 / 2011 (europa.eu)

[4] EUR-Lex - 32023R0851 - EN - EUR-Lex (europa.eu)

1.2 Method of approach

As illustrated in Figure 1 below, the project consisted of five tasks.

Figure 1. Overview of the project tasks and outputs.



1.3 Structure of this report

This Final Report is structured as follows:

- Section 2 summarises the Task 1 work and key results;
- Section 3 provides an analysis of approaches and experience in other countries (Task 2);
- Section 4 describes in detail the methodology and results for the definition of the baseline (Task 3);
- Section 5 includes details related to the testing methodology proposed for quantifying the CO_2 savings of innovative MAC technologies (Task 4);
- Section 6 estimates the amount of CO_2 credits that could potentially be rewarded from the use of innovative MAC technologies in the context of the reduced eco-innovation cap in the future (Task 5);
- Section 7 provides the study conclusions;
- Section 8 contains all references used during the study; and,
- Section 9 gives a table of abbreviations.

The Annexes provide the three different questionnaires used, as follows:

- Annex 1 - EMISIA questionnaire aimed at manufacturers;
- Annex 2 - EMISIA questionnaire aimed at system suppliers; and,

- Annex 3 - JRC questionnaire from 2021.

The suggested baseline definition (section 4), the testing methodology (section 5) and the estimation of the amount of CO_2 credits that could be rewarded due to innovative MAC technologies (section 6) are related only to the cooling part of the MAC system as the potential for CO_2 savings from technologies related to heating is low as described in section 2.11.

2 Task 1 – Market Survey

2.1 Task aims and objectives

MAC systems will be eligible technologies from 2025 on, within the framework of the EU eco-innovation scheme under Regulation (EU) 2019/631, the primary focus of this task was to identify in detail the available technologies, components and operational functions regarding current MAC systems and technological developments in improving their energy efficiency. To that end, the consultation of industrial stakeholders and technical entities was necessary to gain non-public, in-depth insights and expert opinions.

In order to perform this task, the project team decided to collect and critically assess feedback from stakeholders directly involved in the manufacturing, development and testing of MAC systems, to create a comprehensive list of the current and emerging MAC technologies, their characteristics, advantages and disadvantages. Additionally, data collected from a JRC survey from April 2021, were analysed and utilised in the context of this task along with various literature and online sources.

2.2 Fit of Task 1 with the overall study

The outcomes of this task will be used as input mainly in Tasks 3, 4 and 5. More specifically, the market survey is necessary to define the baseline technology in Task 3. Also, the information collected related to the testing methodologies used by manufacturers and suppliers, as well as their feedback on the regulations already in force in other parts of the world (US, China), provide useful insight and can assist in designing the testing methodology in Task 4. Finally, the expected advancements in the forthcoming years could be taken into consideration in the study with respect to the revision of the eco-innovation cap in Task 5.

2.3 Vehicle powertrains

In the study there is a categorization of vehicles according to their powertrain. The internal combustion engine vehicles are noted as ICEV and only an internal combustion engine (ICE) is used for propulsion. Partially-electrified powertrains are categorized based on whether the battery used for propulsion can be charged via an external source or not. The partially-electrified vehicles which cannot be charged with an external power source are hybrid electric vehicles (HEV) a.k.a Not-Off-Vehicle Charging Hybrid Electric Vehicles (NOVC-HEVs), and the partially-electrified vehicles where the battery can be also charged via an external power source are plug-in hybrid electric vehicles (PHEV), a.k.a. Off-Vehicle Charging Hybrid Electric Vehicles (OVC-HEVs). Full electrified vehicles (EVs) can use a battery, hence Battery Electric Vehicles (BEVs), or a hydrogen fuel cell, hence Hydrogen Fuel Cell-powered Vehicles (HFCVs). The eco-innovation scheme characterises the CO_2 emissions from EI, so accordingly all type of EVs are excluded from it.

2.4 Main findings from Task 1

The main outcomes of the market survey are summarised as follows (and are described in detail in the subsequent paragraphs):

Current and future innovative technologies

- No specific current and innovative technologies or criteria to evaluate the innovativeness of a technology were directly identified through the EMISIA questionnaire.
- An analysis of the data from the JRC questionnaire replies along with a literature review were utilised to develop the baseline technology definition. This definition is common for M1 and N1 vehicles, as respondents mentioned that MAC system components are common between the two vehicle categories.
- The analysis for defining the baseline technology was performed separately for C-segment vehicles and for all vehicle segments. This was done as C-segment includes medium size vehicles and could represent all vehicle segments. A comparison of the results (C-segment and all vehicle segments) supports this statement, as they are really close. On the other hand, the majority of vehicles in the JRC questionnaire replies were C-segment vehicles and consequently this statement should be further examined if it is going to be implemented in the EU regulatory scheme.

Testing methodology

- In general, the AC17 testing methodology is well perceived and supported by vehicle manufacturers, although it is considered to be a costly procedure because of the special lab equipment required.
- Component testing is strongly supported as an alternative to AC17 by manufacturers and MAC system suppliers, but it should be accompanied with a validation procedure (e.g. simulations), as the integration of an innovative technology in the whole MAC system plays an important role in the final CO_2 benefit. The Life Cycle Climate Performance (LCCP) Model, presented in section 2.6.2, was proposed as a component testing example since it is used by EPA.
- SAE standards are often used internally by manufacturers and suppliers for measuring the components' and the system's efficiency and could also be a good basis for the future testing methodology. See Table 6 in section 2.6.2.

2.5 Organization of the market survey

The vehicle manufacturers and MAC system suppliers are the stakeholders that will be most directly affected by any changes in the relevant regulatory scheme. Additionally, they should have the most relevant technical information related to MAC systems and the corresponding testing methodologies that are necessary in the course of this study.

Four different sources of information were used in this task: a) the replies to the EMISIA questionnaires; b) targeted interviews; c) data collected by the JRC from a related questionnaire in 2021; d) literature review.

Table 2 and Table 3 summarize the main aspects of the EMISIA and JRC questionnaires, respectively. The complete versions of the questionnaires are available in Annex 1 (EMISIA questionnaire aimed at manufacturers), Annex 2 (EMISIA questionnaire aimed at system suppliers) and Annex 3 (JRC questionnaire).

Table 2. Summary of EMISIA questionnaire.

	Questionnaire
Target audience	Vehicle Manufacturers (OEMs) MAC system and components suppliers
Structure	Section 1: Current and under development MAC systems (4 questions) Section 2: Testing methodologies (5 questions)

Table 3. Summary of JRC questionnaire.

	Questionnaire
Target audience	Vehicle Manufacturers (OEMs) MAC system suppliers
Structure	Section 1: MAC systems in vehicles sold in recent years (8 questions) Section 2: Methodology for CO2-savings calculation (3 questions)

The EMISIA questionnaire was disseminated to vehicle manufacturers and MAC system suppliers, both to associations (e.g., ACEA, CLEPA) and individual stakeholders. In total, four replies (4 positive replies and one negative) were received, and the quantitative analysis of the responses is presented in Table 4.

Table 4. Respondents to EMISIA questionnaire.

Type of organisation	Number of responses
Automotive component manufacturer/supplier	2
Vehicle manufacturer / OEM	1
Industry/business association	2
Total	5

2.6 Summary of interviews with stakeholders

Five interviews took place, where the project team had the opportunity to openly discuss with automotive/system suppliers associations, individual MAC system suppliers, vehicle manufacturers and regulators. The feedback provided was mainly related to the various testing methodologies (testing and simulations) used by MAC system suppliers and vehicle manufacturers.

More specifically, the analysis of the Life Cycle Climate performance method, which is presented in section 2.7.2, was proposed by a system supplier. After carefully examining the proposed method, EMISIA decided that it is out of the scope of the current study and it is not considered as a possible method for estimating the CO_2 benefit of innovative technologies.

One vehicle manufacturer provided useful information related to the definition of the baseline MAC system in terms of cooling and heating. Also, it was mentioned that there are no trends related to climactic or geographical data. This means that even though there are small variations between the MAC system of vehicles sold in northern and southern EU regions, the system’s efficiency is not expected to vary. The major difference is in the case of heating, where in colder climates there is the need to install additional PTC heaters in ICEVs, as waste heat may not be sufficient for providing heat in extreme cases. In the case of hybrid vehicles, high voltage electric heaters are utilised. This also provides insight in what is the baseline system in the case of heating, which was also identified through the literature review in section 2.10.1.2.

Finally, it was mentioned that no actual testing is performed by vehicle manufacturers, as the design is based on simulations and the suppliers' component testing.

During an interview with one of the automotive associations, the method for defining the baseline technology was discussed. Some members mentioned that for internal applications, the baseline technology is defined as the one previously in production, which is similar to the definition in the US regulation (section 3.2.1).

2.7 Analysis of the responses

The analysis of the outcome of the market survey is divided in two parts, one for each section of the EMISIA questionnaire.

2.7.1 Section 1: Current and under development MAC systems

The objective in the first section of the questionnaire was to collect information related to current and possible future innovative technologies. Technologies may refer to specific products or control systems, while the innovation in the context of this study refers to the ability of providing a CO_2 benefit. In order to characterize a technology as innovative, the current baseline technology needs to be identified. Consequently, three categories of products were defined. To make this categorization clear to the respondents of the questionnaire, the list of MAC technologies eligible for CO_2 credits created by the United Stated (US) Environmental Protection Agency (EPA) was utilised, as the US testing methodology is already well known and established.

2.7.1.1 Categorisation of MAC systems based on the US EPA list

The US EPA list consists of air conditioning technologies that can lead to CO_2 savings in the US regulatory context (40 CFR § 86.1868-12, list of technologies for 2017 and later models). The suggested categorisation of MAC technologies into three groups (A, B, C) was based on that list. The categorisation depends on the potential of the technologies listed in the US Off-cycle Credits programme to be considered eco-innovations under the EU framework.

Category A

This category includes all MAC technologies that are widely sold (thus cannot be considered eco-innovations under the EU framework) and are therefore not included in the US EPA Off-cycle credits programme list and thus cannot lead to CO_2 savings in the US context,

Category B

This category includes all MAC technologies included in the EPA list (3.2.1.1).

Category C

This category includes all MAC technologies that are new or under development and could potentially lead to CO_2 savings. However, as they are innovative technologies, they are not included in the US EPA list.

Table 5. Proposed categorisation of MAC systems.

Category	Technology is in the EPA list?	Technology can lead to CO_2 credits*?
A	No	No
B	✔	✔
C	No	✔

******Technology that can lead to CO_2 credits in the US regulatory context.*

2.7.1.2 Analysis of the feedback gathered and conclusions from section 1

All products mentioned by the respondents are category C technologies that are already approved by the EPA as innovative and for which the CO_2 benefit is recognized and quantified (noted in the parentheses). These technologies are:

- **Electric Scroll Type B (ESB) Compressor Technology** (1.9 g CO_2/mile ~ 1.2 g CO_2/km)

  This technology improves the efficiency of the electric scroll compressor using a pressure adjusting valve to optimize back pressure on the fixed scroll and reduce mechanical losses. (Toyota Motor North America, Inc., 2020)

- **Dual Layer HVAC Technology** (0.6 g CO_2/mile or ~ 0.4 g CO_2/km)

  Dual Layer HVAC uses two separate layers and a two-stage fan that can recirculate air through the lower outlets while flowing fresh, low humidity air through the upper ducts (includes the windshield defroster). The module has a door that selects full fresh, full recirculate, or dual layer mode based on logic parameters.
  Low humidity air is needed to better defog the windshield and recirculated air improves warm up performance. With the use of recirculated air less engine heat is needed to warm the cabin and both the cabin and the engine warms up faster. Faster engine warmup improves vehicle efficiency as engine Qout is reduced. (Toyota Motor North America, Inc., 2019)

- **Energy Saving Air Flow Control System (S-FLOW) HVAC Technology** (2 – 3.3 g CO_2/mile ~ 1.2 – 2 g CO_2/km)

  A technology that reduces the thermal load on the air conditioning system through targeted cooling of only occupied cabin areas. The variation in the credits depends on the system variation. The minimum credits are given for the driver concentration only S-FLOW, 2.5 g CO_2/mile for the front concentration variation and 3.3 g CO_2/mile for full (driver and front concentration) S-FLOW. (Toyota Motor North America, Inc., 2019)

- **Pulse Width Modulated HVAC Brushless Motor Power Controller Technology** (0.4 g CO_2/mile ~ 0.25 g CO_2/km)

  The brushed motor (BMM) uses mechanical switching while the Brushless Motor (BLM) uses circuit switching. A BMM uses brushes to deliver current to the motor windings on the rotor. BLM technology uses a magnet on a rotor with an electromagnetic static coil (stator) surrounding the magnet. A driver (commutator) changes the current direction in the magnetic coil which changes the magnetic field direction causing the rotor to turn (repel and/or attract against permanent magnets). The benefit of the BLM is there is removal of frictional loss, by eliminating the consumable brush and physical touch between stator and commutator, which reduces the amount of power lost to heat. The BLM also has 10 times the lifespan of the brushed motor. (Toyota Motor North America, Inc., 2019)

- **Denso SAS/SES Air Conditioning Compressor with CS Valve Technology** (1.1 g CO_2/mile ~ 0.68 g CO_2/km)

  This type of compressor offers improvements in energy consumption reduction. The SES & SAS A/C compressor is equipped with a variable CS valve which adjusts the flow rate to achieve optimum handling of different flow rates and as a result improving overall system efficiency. (Toyota Motor North America, Inc., 2017)

None of the respondents to the EMISIA questionnaire provided information regarding products under categories A and B. One of the main goals of the survey was to gather information related to products that can be considered as the baseline and information for currently innovative products. The expectations were to receive technical details related to specific commercial products under these categories. As this turned out not to be not the case, the information gathered from the JRC questionnaire replies, as well as the literature review, was expected to cover this information gap.

2.7.2 Section 2: Testing methodologies

The objective through this section of the questionnaire was to collect information related to the applied testing methodologies for measuring the CO_2 emissions/savings associated with MAC systems. The examined methods were divided into two main categories, one referring to whole vehicle testing and one to component testing. In general, the replies received in this section of the EMISIA questionnaire were more complete and more detailed than for section 1.

At first, respondents were requested to evaluate the AC17 testing methodology (see section 3.2.1) on its practicality, robustness, effectiveness, efficiency, cost impact and resource/time impact. However, most of the respondents did not use these criteria. From the received feedback, it is concluded that the AC17 testing methodology is considered:

- both practical and technically feasible to apply, which is proved by the fact that numerous vehicle manufacturers already use this method as they sell vehicles in the US;
- effective in identifying the benefit of various innovative technologies, both related to hardware and to the software controlling the MAC system;
- less cost efficient than real-world testing, as special laboratory facilities are needed; and,
- exclusively used for measuring the benefits of cooling technologies, not covering heating.

The main suggested alternatives to the AC17 methodology include the Chinese testing methodology GB/T40711 (see section 3.2.2) and an approach similar to VECTO, where standard components or vehicle models are used as state-of-the-art reference. As such tool does not exist and would need to be developed, it is not further considered in this study as it would not match with the proposed timeline for implementation.

The testing methodologies used by vehicle manufacturers and MAC system suppliers, for measuring the system or component's efficiency could be useful in the context of the study. The mentioned methodologies are based on SAE standards (except for AC17 which refers to whole vehicle testing). Table 6 provides a full list of the testing methodologies, with a short description of each.

Table 6. Testing methodologies for whole vehicle and component testing.

Component	Testing methodology	Description
Whole system	SAE J2765	Procedures for measuring coefficient of performance (CP) of a MAC system on a test bench
	SAE J2766	Life Cycle Analysis to Estimate the CO_2-Equivalent Emissions from MAC Operation

Component	Testing methodology	Description
Pulse Width Modulation (PWM)*	J3109	PWM Blower Controller and Brushless DC (BLDC) Motor Controller Efficiency Assessment
Oil separator	J3112	A/C Compressor Oil Separator Effectiveness Test Standard
IHX	J3094	Test Procedure for Internal Heat Exchangers of Mobile Air-Conditioning Systems with R-134a or R-1234yf Refrigerant
Whole vehicle	AC17	US testing methodology

*For more information related to PWM blower controllers, please see section 2.9.5.

Alternatively, the use of a Life Cycle Climate Performance (LCCP) approach was proposed by one of the respondents, which includes both direct and indirect emissions.

This approach is different from the approach in this study, where only the CO_2 benefits from the use of efficient MAC technology is considered. As a result, although LCCP is a more holistic approach, it is out of the scope of this study (Rhoads et al., 2019).

2.8 JRC questionnaire

In April 2021, the Joint Research Centre (JRC) disseminated a questionnaire related to MAC components, regarding both the systems available in the market and newly emerging systems, along with questions related to the testing methodologies for measuring CO_2 savings.

The questionnaire consisted of two parts. The first one (main questionnaire) consisted of a Word document with general questions related to MAC technologies and their characteristics, as well as questions related to the methodology for calculating the CO_2 savings of an innovative technology. The second part (detailed questionnaire) was an Excel file, where the respondents were requested to fill in information related to the technical elements of the implemented MAC technologies. Both vehicle manufacturers and MAC system suppliers were contacted, but the latter did not respond. In total 11 vehicle manufacturers filled in the questionnaire providing information for a total number of 184 vehicle models (M1 and N1).

The collected data were taken into consideration and were used as a basis for the possible definition of the baseline technologies.

2.9 Analysis of the JRC questionnaire replies

The replies to the questionnaire disseminated by the JRC included data related to MAC systems installed on specific vehicle models. This information is organized in an excel file creating a small database of MAC system characteristics. The database was analysed to obtain more insight on the most used components installed in MAC systems. The results of this analysis along with the literature review will be the basis for the definitions of the MAC baseline technology.

The analysis was performed separately per powertrain type (ICEV, HEV and PHEV) and by including all vehicle segments, as well as for the C-segment vehicles separately. In total information was provided concerning 179 M1 and 5 N1 vehicles. For M1 vehicles, the segment and the year of the vehicles are shown in Figure 2 and Figure 3 respectively. Vehicles from all years were used in the analysis in order to increase the sample size and draw more concrete conclusions. Also, it is mentioned that the components used for MAC systems in M1 and N1 vehicles are common, so it is considered valid to assume that the definition of the baseline technology is common for M1 and N1 vehicles. The analysis includes only M1 vehicles.

Below there is a description of the most common characteristics of the basic MAC components, which are the condenser, expansion device, dryer, evaporator, compressor and blower. For each one, the most common type and average dimensions (if available) are identified and a description for each technology is added. By combining this information, a possible baseline MAC system is defined, which will be used as input in Task 3.

Figure 2. Vehicle segments of the vehicles in the JRC dataset.

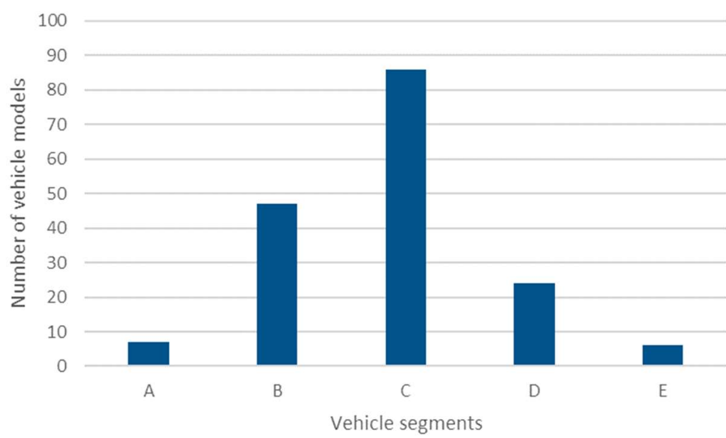
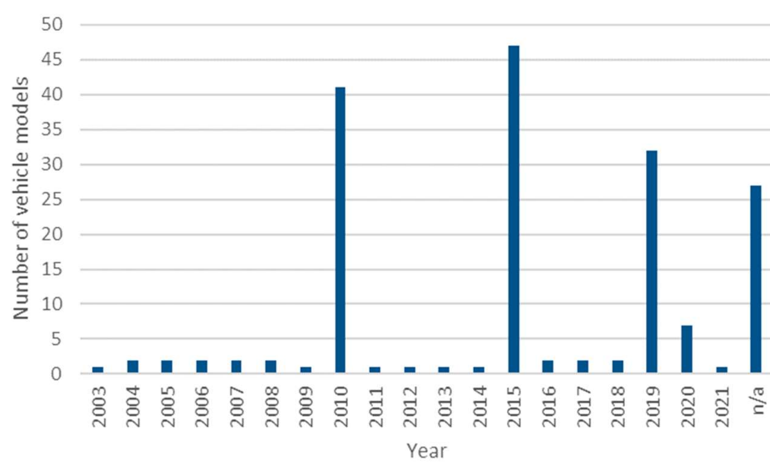


Figure 3. Vehicle model year of the vehicles in the JRC dataset.



2.9.1 Condenser characteristics

The condenser is at its core a heat exchanger and various types are used in MAC systems, such as flat tube, sub-cool, parallel flow and tube fin condensers. In Table 7 below the types of condensers used in the vehicles of the JRC dataset are presented.

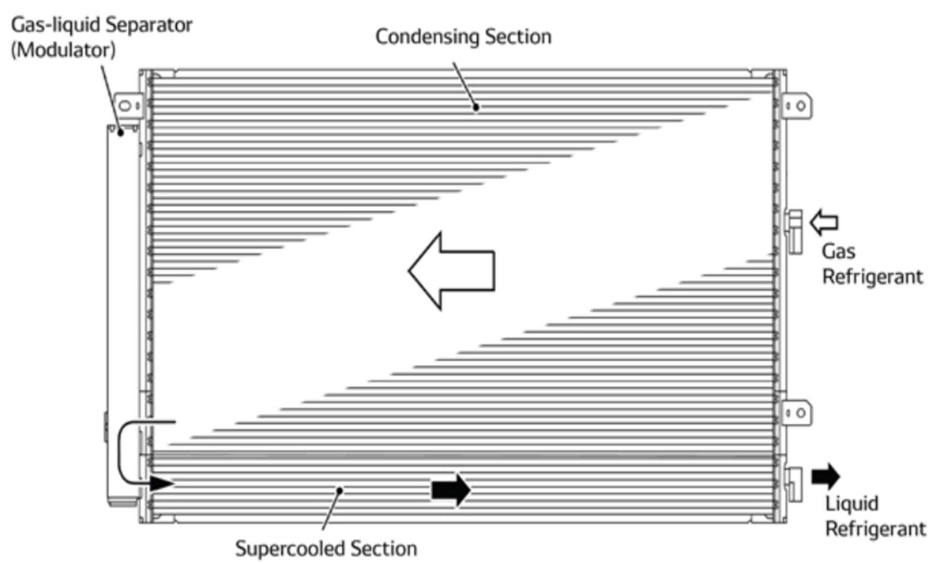
Table 7. Condenser type per powertrain for all vehicle segments.

	Flat tube	Sub-cool	Parallel flow	Tube-fin	No sub-cool	No information
ICEV	3	133	18	2	5	4
HEV	-	9	-	-		-
PHEV	-	-	5	-		-

For ICEV most vehicles are equipped with sub cool condensers. The same is true for HEVs even though there is less available information. In the case of PHEVs there is data only for 5 vehicles which are equipped with parallel flow condensers.

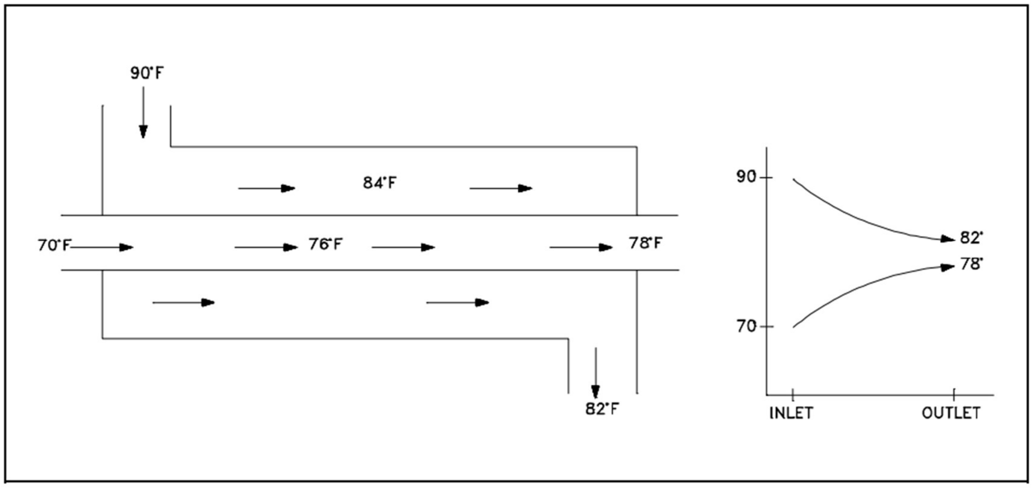
In sub-cool condensers (see Figure 4 below), the upper and middle part consist of a gas liquefaction area, while the lower part is the super cool area where there is an additional heat exchanger to further reduce the refrigerant's temperature. As a result, the refrigerant is cooled down to a lower temperature than a traditional heat exchanger, which results in better cooling performance with lower fuel consumption.

Figure 4. Sub-cool condenser (DENSO).



In the case of parallel flow condensers, the two fluids (in this case the air and refrigerant) are flowing in parallel as the name suggests. A simple design of this type of condenser is presented in Figure 5 below.

Figure 5. Parallel flow condenser (U.S. Department of Energy, 1993).



The same type of results is obtained in the case of the analysis of only C-segment vehicles, as shown in Table 8 below.

Table 8. Condenser type per powertrain for C-segment vehicles.

	Flat tube	Sub-cool	Parallel flow	Tube-fin	No information
ICEV	-	73	5	-	-
HEV	-	7	-	-	-
PHEV	-	-	1	-	-

There is not enough data to draw conclusions for additional details of the condenser design e.g., if a microchannel condenser or a traditional finned tube design is more common nowadays. Additionally, in Table 9 there is information related to the dimensions of the most commonly used Sub-cool condenser types. The sample size is noted in the parentheses in the first column. This may be used as input in simulation models in subsequent tasks. There is no data for the parallel flow condensers which are the most common type for PHEVs.

Table 9. Average Sub-cool condenser dimensions for all vehicle segments.

	Average length (mm)	Average width (mm)	Average height (mm)	Average fin spacing (FP) (mm)
ICEV (133)	473.7	487.3	13.8	1.87
HEV (9)	450.6	555.9	12.5	1.85

In Table 10 below the data for the C-segment vehicles is presented, which shows similar dimensions to the analysis covering all vehicle segments.

Table 10. Average Sub-cool condenser dimensions for C-segment vehicles.

	Average length (mm)	Average width (mm)	Average height (mm)	Average fin spacing (FP) (mm)
ICEV (73)	497.4	484.4	14.2	1.5
HEV (7)	461.7	564.3	12.6	2

2.9.2 Expansion device and dryer characteristics

The expansion device is used to control the amount of refrigerant flowing in the system which depends on the cooling needs of the vehicle. There are two types, an orifice tube which acts as a simple obstacle in the refrigerant's flow and an expansion valve which can actively regulate the flow. Based on the type of expansion device installed, the type of dryer is selected. If an orifice tube is installed, an accumulator is used as a dryer. If an expansion valve is installed, a receiver dryer is used (Nissens). In Table 11, the expansion device and dryer type installed on the vehicles within the JRC database are presented for all vehicle segments. The most commonly used expansion device is an expansion valve and as expected the accumulator is also the most common dryer in those vehicles. As expected, the amount of vehicles equipped with an expansion valve or an orifice tube is the same as the number of vehicles equipped with a receiver or a dryer respectively. Only 3% (5 vehicles) are equipped with an orifice tube and an accumulator. In the case of C-segment vehicles, all vehicles are equipped with an expansion valve and a receiver dryer.

Table 11. Expansion device type for all vehicle segments.

	Expansion valve and Receiver dryer	Orifice tube and Accumulator
ICEV	160	5
HEV	9	-
PHEV	5	-

2.9.3 Evaporator characteristics

The evaporator is a heat exchanger and has a lot in common with the condenser. The most common type of evaporator is the drawn cup evaporator which is shown in Figure 6 below. The conclusion of the analysis performed for ICEVs and HEVs is shown in Table 12 and Table 13, for all vehicle segments and C-segment vehicles accordingly, and summarized in the following section.

In the case of a drawn cup evaporator, the integral flow tubes and header pipes are created by brazing aligned pairs of appropriately formed stamping plates. The material for core plates is clad on both sides with braze liner because internal (turbulators generated by opposing ribs) and external (header pipes) brazing requirements must be met. The evaporator core plates are often made from long-lasting (very corrosion-resistant) aluminium brazing alloys. The manifolds are made of extruded tubes, which are linked, for instance, by induction/plasma brazing. (European Aluminium Association, 2011)

Figure 6. Drawn cup evaporator (DENSO)

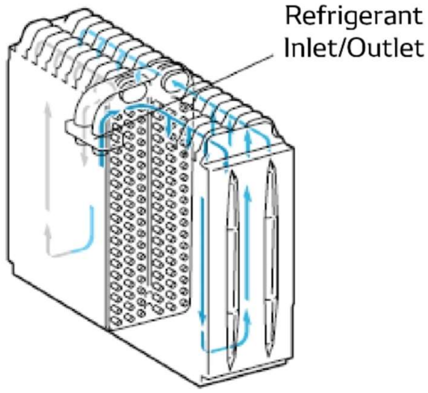


Table 12. Evaporator type for all vehicle segments.

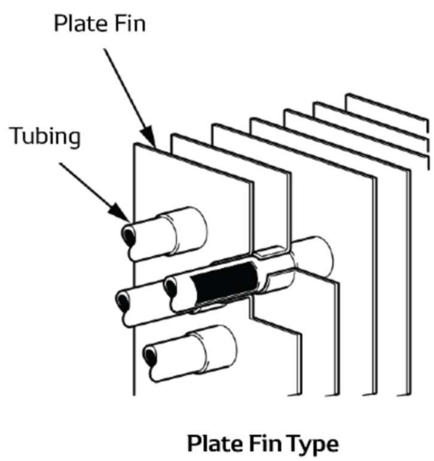
	Drawn cup	Flat tube	Plate-fin	Tube-fin	No information
ICEV	71	2	35	16	41
HEV	4	-	-	-	5
PHEV	-	-	5	-	-

Table 13. Evaporator type for C-segment vehicles.

	Drawn cup	Flat tube	Plate-fin	Tube-fin	No information
ICEV	31	-	15	8	24
HEV	2	-	-	-	5
PHEV	-	-	1	-	-

Plate fin evaporators are equipped with plates bonded together and stacked with layers of fins. Plate fin evaporators are the only type used in the PHEVs contained in the database. This creates a large surface area for cooling in a limited space. A simple design of this type of evaporator is presented in Figure 7 below.

Figure 7. Plate fin evaporator (DENSO)



The average dimensions of the evaporator are presented in Table 14 and Table 15 for all vehicle segments and C-segment vehicles accordingly.

Table 14. Average evaporator dimensions of the most used type for all vehicle segments.

	Average core height (mm)	Average core width (mm)	Average evaporator thickness (mm)
ICEV (Drawn cup)	224	233.4	42.3
HEV (Drawn cup)	191	212.7	38
PHEV	No data		

Table 15. Average evaporator dimensions of the most used type for C-segment vehicles.

	Average core height (mm)	Average core width (mm)	Average evaporator thickness (mm)
ICEV (Drawn cup)	222.6	257.4	46.9
HEV (Drawn cup)	253.4	249.4	42.4
PHEV	No data		

2.9.4 Compressor characteristics

The compressor is the component powering the whole MAC system and has the largest energy consumption. The findings of the analysis of the JRC dataset are in line with the findings from the literature review, presented in section 2.10. In Table 16 and Table 17, the power source (mechanical or electric) is displayed for each powertrain, for all vehicles and C-segment vehicles respectively. As expected, as the electrification of the powertrain grows, the electric-powered compressors are more dominant. Also, another possible trend is that rotary compressors are most commonly used in more electrified powertrains like PHEVs. However, the information in the dataset is rather limited to strongly support such a statement.

Table 16. Compressor power for all vehicle segments.

	Mechanical	Electric	No information
ICEV	117	-	48
HEV	4	5	-
PHEV	-	5	-

Table 17. Compressor power for C-segment vehicles.

	Mechanical	Electric	No information
ICEV	58	-	20
HEV	3	4	-
PHEV	-	1	-

The compressor design (piston or rotary) is presented in Table 18 and Table 19 for all vehicles and C-segment vehicles respectively.

Table 18. Compressor design for all vehicle segments.

	Piston	Rotary	No information
ICEV	96	18	51
HEV	2	1	6
PHEV	-	5	-

Table 19. Compressor design for C-segment vehicles.

	Piston	Rotary	No information
ICEV	42	9	27
HEV	1	1	5
PHEV	-	1	-

The data related to the design details of the compressor is also limited. A swash plate is used more often in the case of piston compressors. For ICEVs and HEVs equipped with rotary compressors, the vane type is most commonly used, while for PHEVs only scroll type rotary compressors exist in the database. This is also shown in Table 20 and Table 21, for all vehicle segments, for piston and rotary compressors respectively.

Table 20. Design details for piston compressors for all vehicle segments.

	Swash plate	Wobble plate	No information
ICEV	8	4	84
HEV	-	-	2
PHEV	-	-	-

Table 21. Design details for rotary compressors for all vehicle segments.

	Scroll	Vane	No information

ICEV	5	10	3
HEV	-	1	-
PHEV	5	-	-

Another important parameter is whether the compressor has fixed or variable displacement, where the latter has higher efficiency. The data suggests that both fixed and variable compressors are used, but variable compressors seem to be more common at least for ICEVs where data are available. The displacement can vary based on the compressor type, but there is not enough data to perform this analysis per compressor type. For this reason, the displacement of all compressor types is used to calculate the average values for each powertrain, as shown in Table 22 and Table 23 for all vehicles and C-segment vehicles respectively.

Table 22. Average compressor displacement for all vehicle segments.

	Average compressor displacement (cc)
ICEV	124.4
HEV	52.6
PHEV	No information

Table 23. Average compressor displacement for C-segment vehicles.

	Average compressor displacement (cc)
ICEV	135.6
HEV	54.1
PHEV	No information

In general, variable compressors tend to be more efficient in comparison to fixed compressors. In Table 24 below it is shown that at least for ICEVs, the variable displacement compressors are a more frequently used than fixed displacement ones. In the case of HEVs are only 4 vehicles with this data and are all equipped with fixed displacement compressors. There is no data related to PHEVs. The same is true for C-segment vehicles as shown in Table 25.

Table 24. Fixed or variable compressor displacement for all vehicle segments.

	Fixed	Variable	No information
ICEV	68	94	3
HEV	4	-	5
PHEV	-	-	5

Table 25. Fixed or variable compressor displacement for C-segment vehicles.

	Fixed	Variable	No information
ICEV	66	94	3

HEV	4	-	5
PHEV	-	-	5

2.9.5 Blower characteristics

Blowers are used to disseminate hot or cold air in the vehicle's cabin. There are also vents in the cabin where the hot or cold air exits. These are usually some in the front and some on the back of the cabin. In Table 26 the most common type of blower, as well as the number of vents, is presented for all vehicles, whereas the same type of results are presented only for C-segment vehicles in Table 27. In the parentheses the average number of vents is noted, whilst a dash translates into no data available. Brush motor blowers are by far the most common type in ICEVs and the same trend seems to be true for HEVs and PHEVs, even though there is not enough data to fully support this. Brush motors are the most common type of motors used in many engineering applications. They have a very simple design and the speed is controlled by the applied voltage. The other types of motors, e.g., brushless or Pulse Width Modulation (PWM) controlled motors, tend to be more efficient. PWM blower controllers utilize metal–oxide–semiconductor field-effect transistors (MOSFETS) for adjusting the fan speed and limit the power losses in the system (Bolloju, 2007).

Table 26. Blower type for all vehicles.

	Brush motor	Brushless	PWM	Radial
ICEV	127 (4)	10 (5)	23 (-)	3 (-)
HEV	7 (4)	2 (4)	-	-
PHEV	3 (4)	2 (4)	-	-

Table 27. Blower type for C-segment vehicles.

	Brush motor	Brushless	PWM	Radial
ICEV	60 (4)	-	18 (-)	-
HEV	5 (-)	2 (4)	-	-
PHEV	1 (4)	-	-	-

2.9.6 Heating

There are not enough characteristics related to the heating part of the MAC systems available in the replies to the JRC questionnaire. There is a field related to the existence of PTC heaters, but only limited registrations exist. This was not further studied, as the potential for CO_2 savings from heating is limited as described in section 2.11 below.

2.9.7 Additional information

In the database, there is information related to some additional MAC system characteristics such as the existence of an internal heat exchanger (IHX) and oil separator details. But for these additional characteristics, there is only limited data and, as a result, these are left out of the analysis, as it is not considered statistically correct to draw conclusions (e.g., under 10 registrations).

2.10 Literature review

Along with the market survey, a literature review was performed in order to collect information related to current and future MAC technologies. In general, it is observed that the main developments in the latest years are towards satisfying the needs for cooling, heating and dehumidifying in electric powertrains (HEVs, PHEVs and BEVs).

On the other hand, only minor developments are observed in the case of ICEVs and are analysed in section 2.10.1.

The MAC systems can be classified based on the power source (other than fossil fuels) and on the cooling techniques as demonstrated in Figure 8 and Figure 9 respectively. Out of these, only fossil fuel and electric energy are the two alternatives that are widely used. In order to use other types of energy, there are a lot of developments that need to be done to end up with a commercial product.

Figure 8. MAC system classification based on the power source (Bentrcia et al., 2018)

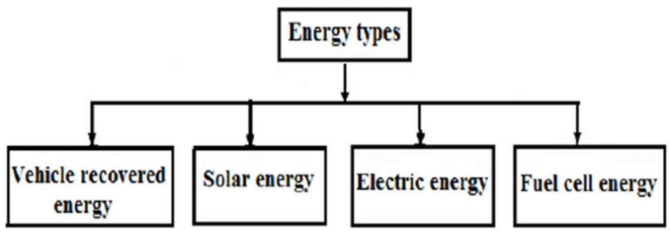
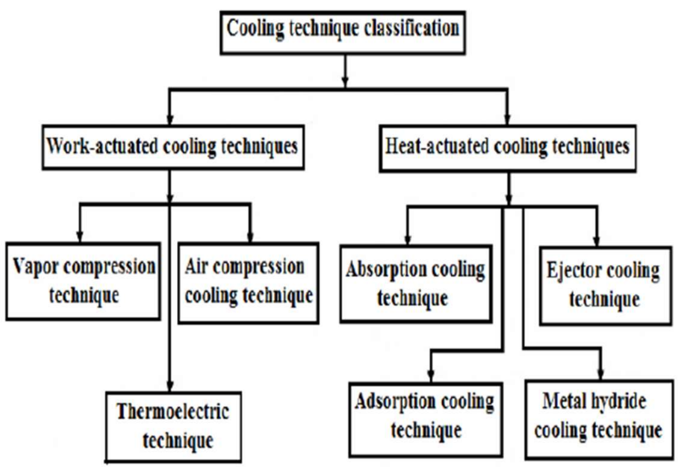


Figure 9. MAC system classification based on the cooling techniques employed (Bentrcia et al., 2018)



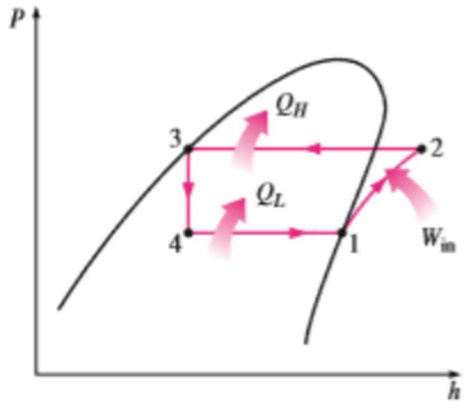
The work-actuated techniques are driven by energy in the form of work which usually comes from a compressor. They are the more mature and commonly used in vehicles and more specifically the Vapour Compression Refrigeration (VCR). In general, this VCR technique is well established and only minimal development has been achieved in the later years.

The heat-actuated techniques are driven by thermal energy and do not include moving parts, in contrast to the work-actuated ones. These techniques are usually not employed in commercially sold vehicles present on the market as they are rather complex and not compact enough to be fitted to e.g., passenger cars. Still, the efficiency is not satisfactory (low coefficient of performance, CP).

The CP is a ratio of the useful heating or cooling provided to work required. A VCR thermodynamic cycle is presented in Figure 10 below. The work required in the case of a VCR system is the work (W_{in}) provided by the compressor. The useful cooling provided is the Q_L and is the heat transferred from the cabin to the environment. The CP is calculated using the following formula (Jatadhara et al., 2019):

$$CP = \frac{Q_L}{W_{in}}$$

Figure 10. VCR thermodynamic cycle (Jatadhara et al., 2019).

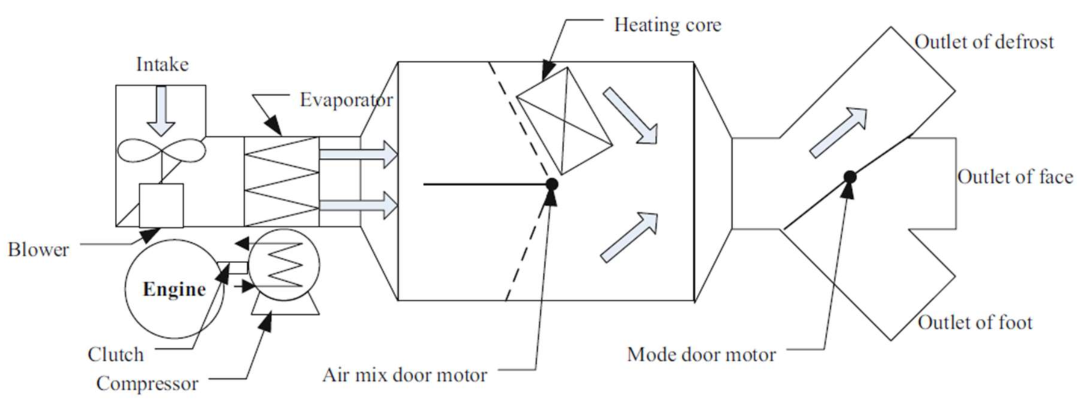


The findings of the literature review are presented in two sections: one regarding conventional powertrains (ICEVs) and one related to partly electric powertrains (HEVs and PHEVs).

2.10.1 Internal Combustion Engine Vehicles (ICEVs)

An outline of the cooling and heating system used in ICEVs is presented in Figure 11. This includes the VCR system, the heating core and additional compartments such as the outlets inside the vehicle cabin. This combination of a VCR system and a heater core is the most commonly used setup in ICEVs (Zhang et al., 2018). Some variations exist and are analysed in the next sections.

Figure 11. Overview of a typical MAC system. (Yang et al., 2017)



2.10.1.1 Techniques for cooling

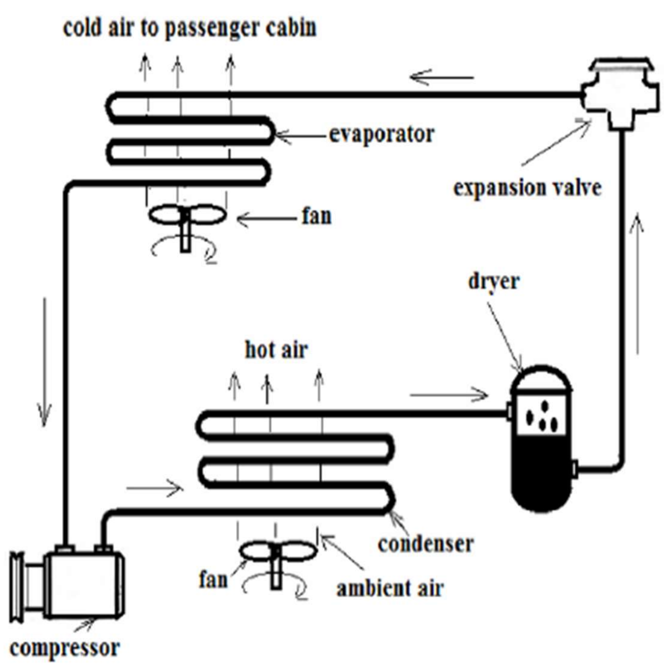
The VCR system is a well-established and mature technology and is the most commonly used method for cooling. Minor technological improvements have been achieved in the late years. One big part of the research around innovative MAC technologies, including VCR, is the use of specific strategies for operating the system. This comprises the use of sensors and algorithms to predict the heat load and the optimal use of energy, such as the low-energy consumption air-conditioning control system for a smart vehicle, which is presented in an article in the Journal of healthcare engineering (Chien-Lun Weng et al., 2019).

The main parts of a VCR system (see schematic in Figure 12) are:

- **Compressor**
  Compresses the system's refrigerant in order to raise its temperature and allow for heat transfer out of the condenser.
- **Condenser**
  A heat exchanger responsible for transferring heat from the refrigerant to the surrounding environment.
- **Evaporator**
  A heat exchanger responsible for cooling the vehicle's cabin by transferring heat from the air passing through its fins to the refrigerant.
- **Refrigerant controller**
  An orifice tube or an expansion valve that controls the amount of refrigerant flowing through the evaporator.

Additional parts of the system include fans, dryer and sensors.

Figure 12. Layout of a VCR system (Bentrcia et al., 2017).

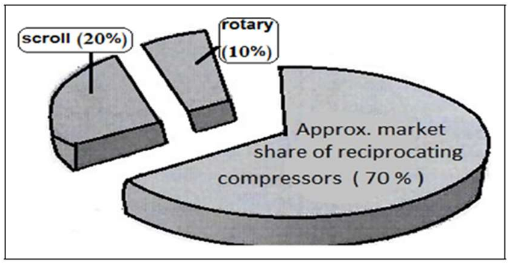


The biggest energy consumption of a VCR system comes from the compressor which can be driven by mechanical energy from the internal combustion engine (ICE) or by electric energy coming from a battery. The second case is more common in electric vehicles. Electric compressors are electric variable speed compressors instead of belt-driven ones (usually used in ICEV), which operate optimally under various conditions and thus lead to reduced energy consumption (Zhang et al., 2018).

Developments of VCR systems

The most widespread type of compressors is the swash plate design which consists of a reciprocating axial piston and they can have fixed or variable capacity. Variable compressors tend to be more efficient. The rotating vane design is an alternative design which is compact and has minimal friction losses while producing the greatest cooling capacity per unit mass of the compressor. Lastly, the rotating scroll design is characterized for its light weight, quietness and reaching 100% volumetric efficiency. The market share for each compressor type is presented in Figure 13.

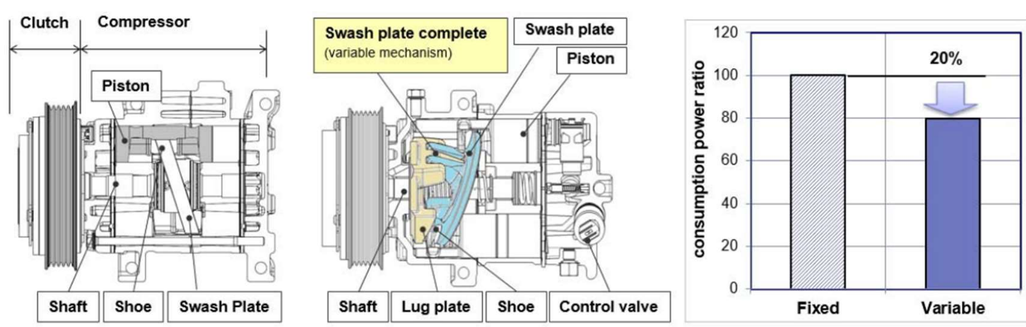
Figure 13. Market share per compressor type (Bentrcia et al., 2017).



Initially (before 1985), the control of the compressor in VCR systems was performed by switching it on and off using an electro-mechanical clutch. The use of axially-oriented pistons within the compressor which are driven by a variable angle swash plate are employed to improve the compressor's control. As the angle is changed, the compressor's capacity changes to meet the cooling demands. In a later design (around 20 years ago), various sensors to determine the thermal load have been added and control the compressor's capacity.

One example of the difference between a fixed and a variable (swash plate) displacement compressor is shown in Figure 14, where the energy consumption is 20% lower in the case of the variable displacement compressor.

Figure 14. Fixed and variable (swash plate) compressors and the difference in energy consumption (Taejin et al., 2018).



Refrigerant mixed with oil circulates in the compressor. An important parameter that defines the operation of the MAC system is the oil circulation ratio (OCR), as the oil contained in the refrigerant is influencing its properties. This means that OCR needs to be known in order to properly design heat exchangers in the system. OCR is defined by the formula shown below:

$$OCR = \frac{m_{oil}}{m_{refrigerant} + m_{oil}}$$

Where m_{oil} is the oil mass in the working fluid and $m_{refrigerant}$ is the refrigerant's mass (Wujek et al., 2008).

An oil separator is used to remove oil from the hot gas in the discharge line and return it to the oil reservoir in the crankcase of the compressor., to control the OCR. The oil separator is located between the compressor and condenser inlet or integrated into the compressor. No major technological advancements in oil separators used in vehicles in the latest years are identified through the literature review. There is research around this field e.g., an optimized oil separator used with a swash plate compressor, where the system's cooling performance is increased by 1.7%-6.5%, but there is no information on actual applications of these systems in massed produced vehicles (Taejin et al., 2018).

The condenser needs to provide high efficiency while staying compact enough to be fitted in even small vehicles. In the latest designs, the condenser's tubes are made of aluminum instead of copper (used in previous designs), which allows to increase the number of fins per meter, improving the cooling (heat removal) while reducing the condenser's size. The latest type of design is the sub-cool type. The evaporator has gone through similar design changes as the condenser as they both are heat exchangers.

Finally, regarding the refrigerant controller, both orifice tubes and expansion valves are widely used in today's vehicles. This device allows the expansion of the refrigerant as it enters the evaporator. Its pressure and consequently its temperature are lowered, allowing heat transfer from the cabin to the refrigerant. Orifice tubes can be fixed or variable which means that they can act as a simple obstacle in the refrigerant's flow in the first case or vary the flow depending on the cooling needs in the second case. (Bentrcia et al., 2017)

Internal heat exchanger (IHX)

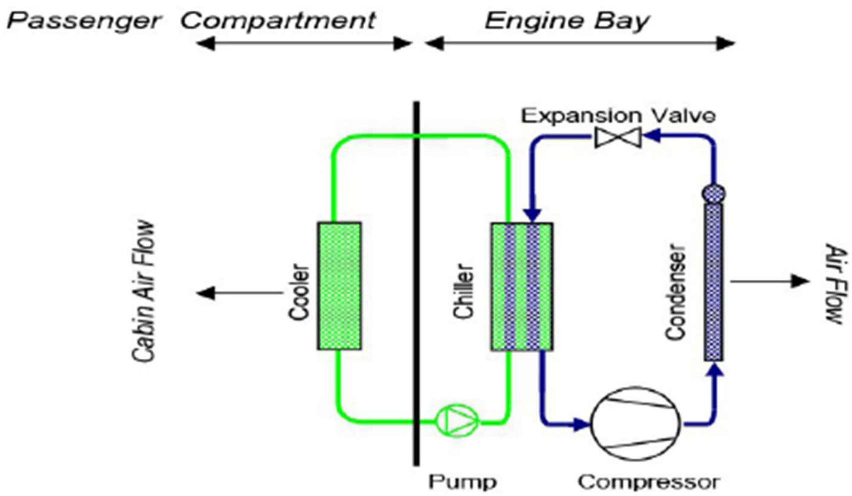
An internal heat exchanger is a device that transfers heat from the high-pressure, liquid-phase refrigerant entering the evaporator to the low-pressure, gas-phase refrigerant exiting the evaporator. In this way, the total CP of the MAC system is increased by further sub-cooling the refrigerant being supplied to the evaporator. It has a simple structure as it is simply a heat exchanger (Musser et al., 2016). It is used more frequently in the MAC systems in later years but there is not enough data related to the market share to determine whether it is part of the baseline system or not.

Secondary Loop MAC systems

One type of VCR systems is the direct expansion (DX) system. In DX systems, the refrigerant enters the vehicle's cabin to achieve cooling. For safety reasons, flammable refrigerants are not used in DX systems even if better efficiency could be achieved. On the other hand, this is not a problem for second loop (SL) MAC systems, where the refrigerant never enters the cabin and as a result, mildly flammable refrigerants can be used (e.g., HFC-152a instead of HFO-1234yf which is most commonly used in DX systems) (Andersen et al., 2018).

A typical SL system is presented in Figure 15 below, where it is clear that the refrigerant is isolated from the cabin and stays in the engine bay. It consists of a chiller (refrigerant to-coolant heat exchanger) and a cooler (coolant-to-air heat exchanger) to provide cooling. SL systems have 5% - 12% lower CP (in comparison to HFC-134a DX system), as the refrigerant must be at a lower temperature to achieve the same cooling effect as a DX system (Andersen et al., 2017). This is because there are losses in the chiller part which are absent in the DX systems.

Figure 15. Secondary Loop (SL) system (Andersen et al., 2018)



Additionally, the coolant in the cabin's circuit can be circulated in the passengers' area even when the compressor is off, achieving cooling for a short time. This can be utilised in cases where cooling is needed but the vehicle's engine is off, e.g., if the vehicle is equipped with start/stop technology. Also, an SL system requires a smaller amount of refrigerant to work properly, and it is circulated in shorter tubes, which leads to fewer emissions due to leakage and end-of-life emissions.

Second Loop MAC systems are not yet installed in mass-produced vehicles but could be an alternative to VCR systems in the future. From the information gathered up to this point, it is not clear if these systems will lead to CO_2 benefits, except for the environmental and safety benefits mentioned above.

2.10.1.2 Techniques for heating

In ICEVs approximately 30% of the energy coming from the fuel is converted into mechanical energy, while the rest is waste heat which must be removed in various ways to ensure good working temperature for the engine. Part of this waste heat is used to heat the cabin in most conventional vehicles. Coolant circulates the engine block and is heated before being sent to a heat exchanger called the heating core (presented in Figure 11 above). Then the air is heated through the heating core before it is distributed in the vehicle's cabin.

This simple technique is usually enough to meet the heating needs in cold climates, while assisting in cooling the engine down. If heating is not needed (e.g., during summer) the coolant goes through the radiator and the waste heat is transferred to the environment.

Even though this heating technique is efficient and results in minimal energy consumption (energy for the pumps circulating the coolant), it becomes less effective as the ICEs become more efficient. A better performing engine means less waste heat and this can lead to insufficient energy available for heating the cabin. For this reason, some vehicles are equipped with auxiliary electric heaters such as positive temperature coefficient (PTC) heaters. PTC heaters convert electric energy to heat and transfer it to the coolant to meet the heating needs (Zhang et al., 2018). Typically, the total energy consumption of PTC heaters is 900W to 2000W depending on the size of the vehicle's cabin and the heating demand (Musat et al., 2010).

2.10.2 Partially electric powertrains vehicles

In vehicles with partially-electrified powertrains, the ICE is not always running, which means that changes were made to adjust the MAC systems of ICEVs to HEVs and

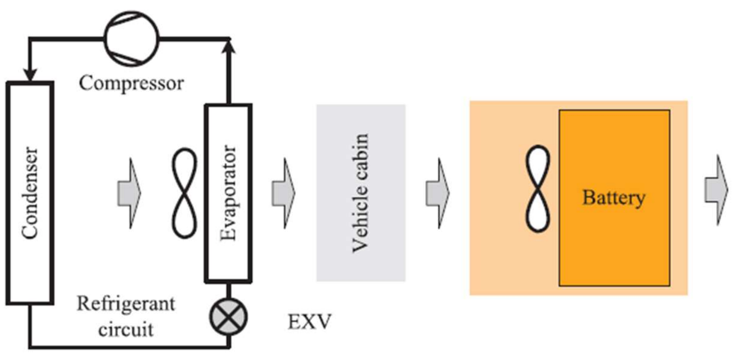
PHEVs. Still, the main components and the architecture of the MAC systems are common between ICEVs and hybrid powertrains. The main differences are presented in the next two sections separately for cooling and heating.

2.10.2.1 Techniques for cooling

As mentioned in section 2.10.1.1, the VCR system is the most commonly used technique for cooling, and this is also true for partially electric powertrains. The main difference to ICEVs systems is that the compressor is electrically driven, as these vehicles operate in electric mode as well. In those cases, the ICE is switched off and thus unable to provide energy to the compressor. As a result, the compressor's speed can be adjusted independently to the engine speed, which is more efficient than the belt-driven compressor and satisfies better the cooling needs (Li et al., 2020).

Additionally, hybrid electric vehicles are equipped with a battery thermal management system as the battery needs to be in a certain range of temperatures to operate properly and prolong its life. Usually, the cabin and battery cooling systems work in parallel. In some cases, an integrated thermal management (ITM) system is used when the thermal needs for the cabin and battery combined. An example is shown in Figure 16, where cool air from the cabin is used for battery cooling.

Figure 16. Example of Integrated Thermal Management system (ITM). (Li et al., 2020)

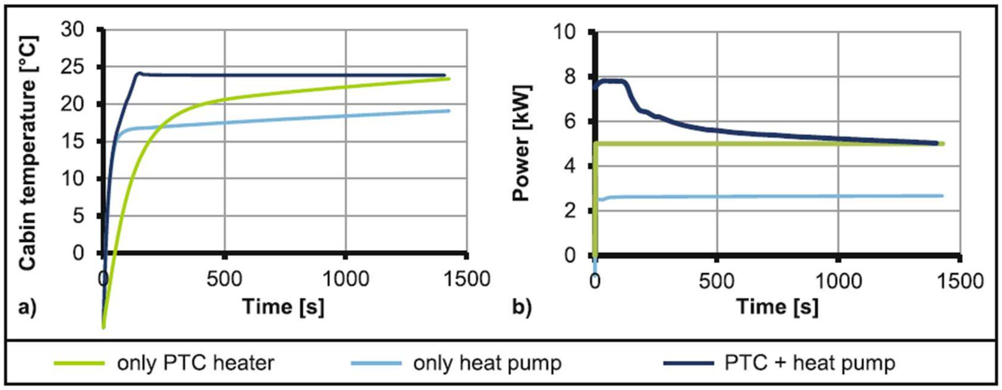


2.10.2.2 Techniques for heating

One of the main issues in heating in HEVs and PHEVs is the reduced amount of waste heat from the ICE. As mentioned in 2.10.1.2, waste heat is the main source of energy used for heating in ICEVs. For this reason, multiple solutions have been developed to heat the cabin with extra components, as PTC heaters. The common element between them is the reduction in the vehicle's electric range (mainly for PHEVs) because of the additional energy consumption.

PTC heaters are the most common electric heaters installed in electric vehicles and are usually installed under the hood (i.e., not in the cabin), the same way as in ICEVs. Its CP is close to 1. The main drawbacks are the large energy consumption and that, in some cases, they are not sufficient to achieve the heating that is required. As shown in Figure 17, for an ambient temperature of -10° C a 5 kW PTC heater is almost not capable of heating the cabin at the target temperature of 24° C in less than 25 minutes. On the other hand, if a PTC heater is combined with a heat pump, the target temperature is reached within 4 minutes (Moller et al., 2019).

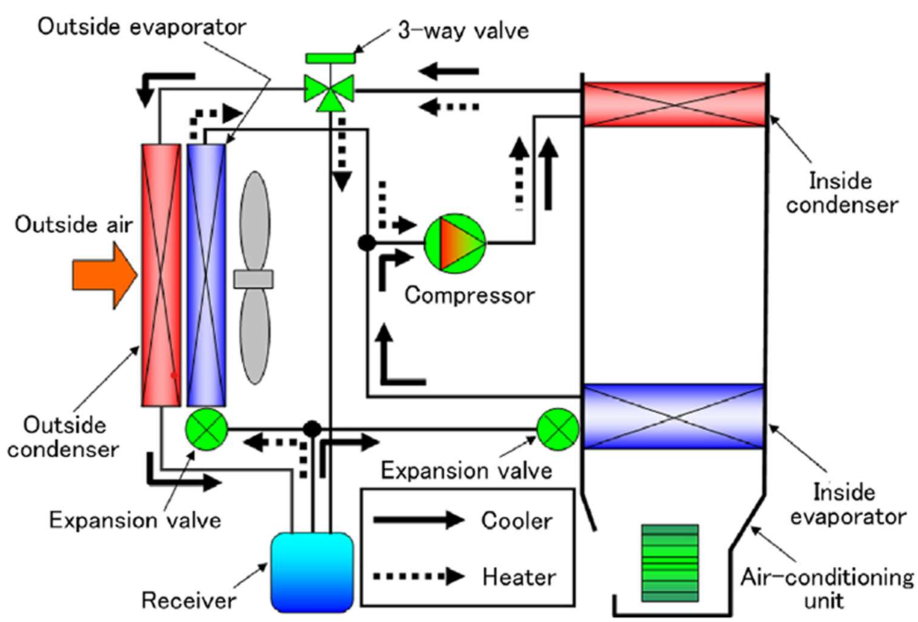
Figure 17. Heating using PTC heater and heat pump (Moller et al., 2019)



Heat pumps are another solution used for heating in electric vehicles (see Figure 18). It is similar to the VCR systems, but it works for both heating and cooling, instead of only cooling as in the VCR systems. The main components of heat pumps are one condenser, one evaporator, one throttling device, one compressor and one multi-way (3- or 4-way) valve. The multi-way valve is used to reverse the direction of the flow of the refrigerant, as heat pumps are used both for cooling and heating. The CP of heat pumps is larger than 1 and thus is more efficient than PTC heaters.

Heat pumps use share common refrigerants with VCR systems e.g., R134a, and in their working principles are identical in cooling mode. In heating mode, the 4-way valve is utilised and the refrigerant’s flow is reversed. Heat is then absorbed from the ambient temperature and is used to heat the vehicle’s cabin (Zhang et al. 2018).

Figure 18. Heat pump (Zhang et al. 2018)



As mentioned, the heat pumps are usually installed with PTC heaters in order to cover the heating needs under various conditions.

2.10.3 Improvements in MAC systems' energy consumption

In general, there are two strategies for reducing the GHG emissions of MAC systems: direct and indirect. The first strategy lowers the emissions by reducing the refrigerant leakage. The second one focuses on reducing the energy consumed during MAC operation. The first category is out of the scope of this study and information is not included to avoid confusion.

The reduction of energy consumption can come from the heat load reduction and from improving the efficiency of the MAC system. According to Table 28, the potential reduction of GHG emissions can be 18%-31% and 3%-10% for load reduction and improved efficiency respectively. The heat load reduction techniques include solar reflective coatings, using window glass with lower solar light transmittance, and controlling the air circulation (direct air to passengers instead of circulating the air) (Yang et al., 2022). The improvement of the efficiency of the MAC system is thoroughly discussed in the previous section. From the aforementioned methods for reducing energy consumption, those related to the cooling strategy and the improvements of the efficiency are the methods that are useful in this analysis. These include improved control for blowers (such as PWM blowers) and motors and internal heat exchangers. These technologies are described in the sections above.

Table 28. Means of reducing indirect emissions of MAC systems in passenger cars (Yang et al., 2022).

Indirect emission reduction scheme	Main technological means	Potential for reducing indirect GHG emissions from MAC systems
Load reduction	Reduce heat absorption and heat insulation, and directional delivery of cooled air	18%–31%
Improving the efficiency of MAC system	Improve compressor shaft seal, improve controls for blowers and fan motors, improve the performance of the air-to-refrigerant heat exchangers	3%–10%

2.11 Potential for CO_2 savings from technologies used for cooling and heating

Based on the literature review and the feedback received from stakeholders, the main source for heating for ICEVs and HEVs is the waste heat from the internal combustion engine. Additional energy consumption for heating is required only when the waste heat is not sufficient for heating the cabin (e.g., on the start of a trip or in severe winter conditions). Hence, technologies related to heating have a limited potential for leading to CO_2 savings, especially in comparison to technologies used for cooling. After consulting stakeholders, the testing methodology for measuring CO_2 savings only includes technologies used for cabin's cooling and ventilation.

2.12 MAC components' average characteristics

After combining all available sources of information (JRC database and literature) the average characteristics of MAC systems are presented in Table 29 below. In some cases, the available information in the JRC database was minimal or non-existent for PHEVs. In such cases, if there was insufficient information from the literature review, the characteristics of PHEVs were considered to be the same as HEVs. This is noted in Table 29 by a parenthesis.

The information for the condenser, the evaporator and the blower come from the JRC dataset as no specific data was found in the literature. On the other hand, the use of an expansion valve along with a receiver dryer comes from the JRC data and is also supported by the literature. The same is valid for the main characteristics related to the compressor, as information comes from the JRC data and is also supported by the literature review. Finally, no conclusions could be drawn related to the heating part of the system from the JRC dataset. This information is used as input for Task 3 where the baseline system is defined.

Table 29. MAC average characteristics.

Condenser		ICEV	HEV	PHEV
		Sub-cool	**Sub-cool**	**Parallel flow**
Expansion device		Expansion valve		
Dryer		Receiver dryer		
Evaporator		Drawn cup	Drawn cup	Tube fin
Compressor	Power source	Mechanical	Electric	Electric
	Design	Piston	Rotary	Rotary
	Displacement	Variable - 124.4 cc	Variable – 52.5 cc	Variable – 52.5 cc
Blower		Brush motor (4 vents)		
Heating		Engine heat and PTC heaters (1.5 kW)		

2.13 Summary of innovative/emerging technologies

In the previous sections, both in the market surveys (JRC and EMISIA) and in the literature review, various innovative MAC technologies were mentioned. Some of these technologies are already part of the US EPA list of innovative technologies that can lead to CO_2 credits, while others are emerging technologies that may be used in the future. The following is a list of all the cited technologies:

- Reduced reheat, with externally controlled, variable-displacement compressor
- Default to recirculated air with closed-loop control of the air supply (sensor feedback to control interior air quality) whenever the ambient temperature is 75 °F or higher
- Blower motor controls which limit wasted electrical energy
- Internal heat exchanger (IHX)
- Oil separator
- Electric Scroll Type B (ESB) Compressor Technology
- Dual Layer HVAC Technology
- Energy Saving Air Flow Control System (S-FLOW) HVAC Technology
- Pulse Width Modulated HVAC Brushless Motor Power Controller Technology
- Denso SAS/SES Air Conditioning Compressor with CS Valve Technology
- Darkening windscreen
- Heat pump (ICEV, HEV, PHEV)
- Sun sensor
- Humidity sensor and misting prevention strategy
- Location of thermal comfort
- Reflective paint
- Heat pump
- Secondary loop MAC systems

For these technologies there is insufficient data related to their market penetration.

3 Task 2 – Analysis of approaches and experience in other countries

3.1 Task aims and objectives

Relevant practices in other parts of the world are reviewed to set a basis for an EU regulatory framework. In Task 2, the most relevant regulations and practices regarding the attribution of off-cycle CO_2 emission credits for MAC systems of cars and vans in major markets around the world, such as the US (and California specifically), China, Mexico, Japan, India and Australia, were collected and reviewed. The analysis is divided in two main sections. In the first one, the findings of this review are presented per region and in the second one, the best practices are discussed in the EU context.

The findings of Task 2, along with the results of Tasks 1 and 3, formed the basis of Tasks 4 and 5.

3.2 Regulations and approaches in other regions

Currently, in most parts of the world, the regulatory frameworks related to attributing CO_2 credits to innovative or off-cycle technologies, do not cover MAC systems. The most complete framework to date are those applied in the US and California, where certain innovative MAC system technologies can lead to CO_2 credits and there is a testing methodology introduced to verify them.

3.2.1 US and California

In the US, the type-approval of vehicles is conducted by manufacturers, while the US Environmental Protection Agency (EPA) carries out only confirmatory checks, mostly on randomly-selected vehicles to validate the reported results. According to EPA's Light-duty Vehicle Greenhouse Gas (GHG) Program, there are three pathways to accrue off-cycle credits for CO_2-reducing technologies, including innovative MAC system technologies.

3.2.1.1 Predefined list of technologies

The first way is a list of predetermined technologies that are considered innovative. By utilizing this pathway, the maximum allowable decrease in the manufacturer's combined passenger automobile and light truck fleet average CO_2 emissions is 9.3 g/km for model years 2023 through 2026 and 6.2 g/km in all other model years, rounded to the nearest 0.06 g/km.

The provisions for MAC systems are described in 40 CFR § 86.1868-12. For vehicles of 2017 and later model years, the predefined list of technologies is presented in Table 30, along with the corresponding maximum credits. Air conditioning efficiency credits are determined on an air conditioning system basis meaning that the credits are acquired by any vehicle equipped with this system. If multiple technologies are implemented in a system, the credits accumulate to a maximum of 3.1 g CO_2/mile (1.9 g CO_2/km) for passenger cars and 4.3 g CO_2/mile (2.7 g CO_2/km) for light trucks. Manufacturers must validate air conditioning credits by using the AC17 Test Procedure as described in 40 CFR 1066.845.

Table 30. Redefined list of MAC technologies that can lead to CO_2 credits in the US.

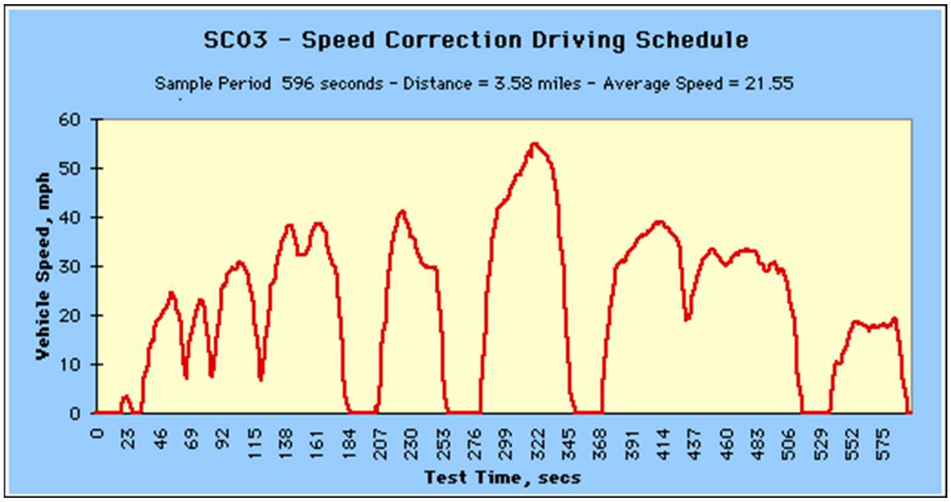
Air conditioning technology	Passenger cars (g/km)	Vans (g/km)
Reduced reheat, with externally-controlled, variable-displacement compressor (e.g. a compressor that controls displacement based on temperature setpoint and/or cooling demand of the air conditioning system control settings inside the passenger compartment).	0.9	1.4

Air conditioning technology	Passenger cars (g/km)	Vans (g/km)
Reduced reheat, with externally-controlled, fixed-displacement or pneumatic variable displacement compressor (e.g. a compressor that controls displacement based on conditions within, or internal to, the air conditioning system, such as head pressure, suction pressure, or evaporator outlet temperature).	0.6	0.9
Default to recirculated air with closed-loop control of the air supply (sensor feedback to control interior air quality) whenever the ambient temperature is 75 °F or higher: Air conditioning systems that operated with closed-loop control of the air supply at different temperatures may receive credits by submitting an engineering analysis to the Administrator for approval.	0.9	1.4
Default to recirculated air with open-loop control air supply (no sensor feedback) whenever the ambient temperature is 75 °F or higher. Air conditioning systems that operate with open-loop control of the air supply at different temperatures may receive credits by submitting an engineering analysis to the Administrator for approval.	0.6	0.9
Blower motor controls which limit wasted electrical energy (e.g. pulse width modulated power controller).	0.5	0.7
Internal heat exchanger (e.g. a device that transfers heat from the high-pressure, liquid-phase refrigerant entering the evaporator to the low-pressure, gas-phase refrigerant exiting the evaporator).	0.6	0.9
Improved condensers and/or evaporators with system analysis on the component(s) indicating a coefficient of performance improvement for the system of greater than 10% when compared to previous industry standard designs).	0.6	0.9
Oil separator. The manufacturer must submit an engineering analysis demonstrating the increased improvement of the system relative to the baseline design, where the baseline component for comparison is the version which a manufacturer most recently had in production on the same vehicle design or in a similar or related vehicle model. The characteristics of the baseline component shall be compared to the new component to demonstrate the improvement.	0.3	0.4
Advanced technology air conditioning compressor with improved efficiency relative to fixed-displacement compressors achieved through the addition of a variable crankcase suction valve.	0.7	0.7

The AC17 Test procedure was developed in 2013 to determine the efficiency test for MAC systems in the US. It is a test procedure used to quantify the additional vehicle CO_2 emissions caused by the use of MAC in the US, as it is designed to simulate an urban trip on a hot summer day (40 CFR § 1066.835 – Exhaust emission test procedure for SC03 emissions). It consists of two runs of the SC03 driving cycle (see

Figure 19). One run of the SC03, with the MAC system running at a target temperature of 22°C and one run of the SC03 with the MAC system turned off. The CO_2 emissions from the use of the MAC system come from the difference between the two runs.

Figure 19. SC03 driving cycle. (EPA, Dynamometer drive schedules)



The validation of the credits for each MAC system requires performing the AC17 test procedure two times. Using a vehicle with and without the innovative technology installed. Thus, the validation requires four separate runs, as shown in Table 31.

Table 31. Required test runs for validation of CO_2 credits.

	Required tests for validation
Vehicle without the innovative technology	SC03 with AC off SC03 with AC on
Vehicle with the innovative technology	SC03 with AC off SC03 with AC on

The results of the second test (vehicle with the innovative technology) are subtracted from the results of the first test (vehicle without the innovative technology). The credits to be generated are based on the result of this subtraction and there are three cases:

$$subtraction\ result \leq 0$$

the innovative technology is not eligible for CO_2 credits

$0 < subtraction\ result < 3.1\ g\ CO2/km$ for passenger cars

$0 < subtraction\ result < 4.3\ g\ CO2/km$ for vans

the generated CO_2 credits are equal to the subtraction result

$subtraction\ result \geq 3.1\ g/km$ for passenger cars

$subtraction\ result \geq 4.3\ g/km$ for vans

the maximum value (3.1 g/km or 4.3 g/km) of credits is generated

3.2.1.2 5-cycle testing

If an off-cycle technology is not on the list mentioned above but may still generate emission benefits, manufacturers can use a broader array of emission tests, known as "5-cycle" testing, to demonstrate and justify off-cycle CO_2 credits. The five different driving cycles are:

FTP - composed of the UDDS followed by the first 505 seconds of the UDDS

HFET - represents highway driving conditions under 60 mph

US06 - high acceleration aggressive driving schedule

SC03 - Air Conditioning "Supplemental FTP" driving schedule

cold FTP

The manufacturer is allowed to choose which cycles it will run to demonstrate the amount of CO_2 credits for the innovative technology. Out of these driving cycles, only SC03 considers the use of a MAC system.

3.2.1.3 Alternative method

In the case where the innovative technology is not part of the predefined list of technologies eligible for credits and the CO_2 savings cannot be demonstrated through the 5-cycle testing, the manufacturer can suggest an alternative methodology, such as a combination of testing and simulation runs

In this case, there are four steps to be followed . At first, the manufacturer must conduct testing and/or prepare engineering analyses that demonstrate the in-use durability of the technology for the full useful life of the vehicle. Then the manufacturer must demonstrate the GHG benefits of the off-cycle technology and carry out any necessary testing and analysis required. Next, an application for off-cycle credits has to be submitted according to 40 CFR 86.1869 12(e)(2). EPA reviews the application and decides whether it is accepted or not.

This scheme is already used by all vehicle manufacturers and system suppliers that have their products sold in the US. It assesses the whole MAC system and, in most cases, whole vehicle testing is required. The flexibility in the methodology helps evaluating new technologies in terms of both hardware (e.g., innovative compressor) and control systems (e.g., optimal climate control of the vehicle cabin).

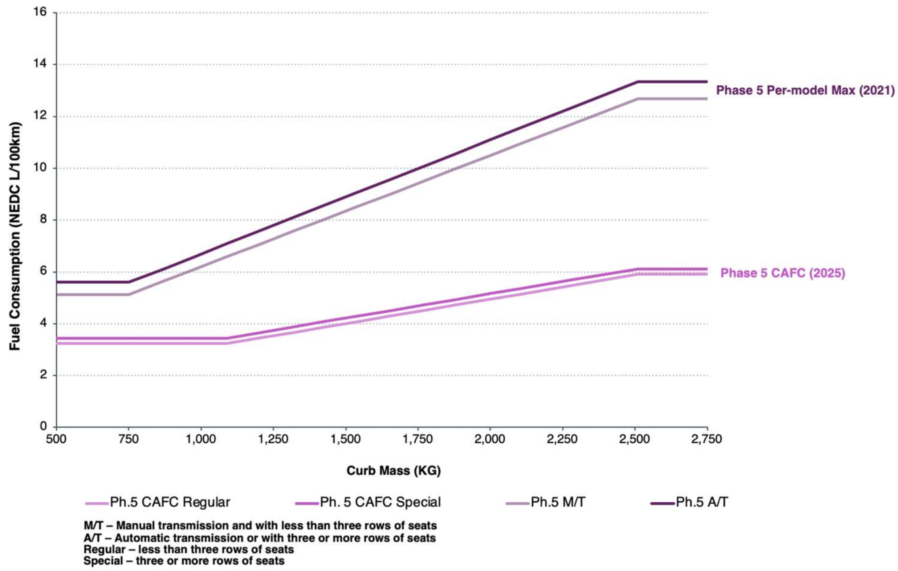
3.2.1.4 Baseline definition

One important element of the US eco-innovation scheme is the definition of the baseline technology. According to 40 CFR § 86.1868-12, for condensers, evaporators and oil separators, the baseline technology is considered the one employed in the most recent vehicle model that was in production by the manufacturer or a similar model. This means that the definition of the baseline technology is relative. So this is a strong motivation for vehicle manufacturers to use already known technologies equipped in more high-end models, to low-end ones. This can lead to great CO_2 benefits as low-end models usually have higher sales.

3.2.2 China

In October 2021, the Ministry of Industry and Information Technology (MIIT) issued a testing procedure for awarding credits for innovative MAC systems for passenger cars. Said procedure is based on the corporate average fuel consumption (CAFC) standards. This is the first fuel consumption standard, related to the average fuel consumption of the vehicle fleet of manufacturers and importers, that was issued in China in 2014. Phase V of the standard is in effect since January 2021 and sets the maximum CAFC equal to 4 l/100km for all passenger cars by 2025. The maximum value depends on the vehicle's curb mass, as shown Figure 20.

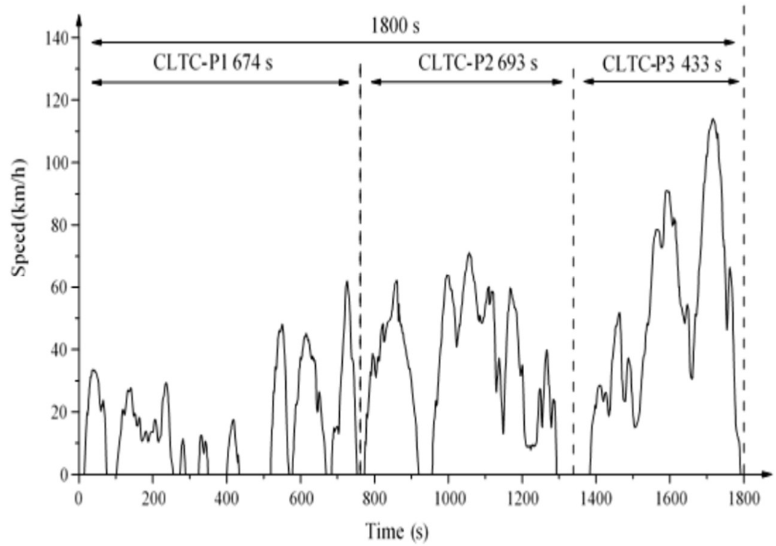
Figure 20. FC target as a function of vehicle curb mass. (Transport policy net)



For vehicles equipped with innovative MAC systems, the calculated CAFC value can be reduced by up to 0.2 l/100km (approximately 5 g CO_2/km), as described in GB/T 40711.3 – 2021. The reduction is based on the target CAFC value for the examined vehicle. The testing procedure is based on the China light-duty vehicle test cycle-passenger (CLTC-P, Figure 21) and is performed on the chassis dynamometer. The steps followed are:

- Soaking (open all windows, turn AC off) vehicle is driven at 90 km/h for 20 min
- Turn off the vehicle, close windows, turn on solar radiation and soak for 30 min
- Run CLTC-P and record cabin temperature
- Calculate the total FC in l/100 km (FC_{ON})
- Repeat the process without AC and solar radiation
- Calculate the total FC in l/100 km (FC_{OFF})

Figure 21. CLTC-P driving cycle. (Yu et al. 2020)



Then the FC because of the MAC system operation (FC_{AC}) is calculated according to the formula below.

$$FC_{AC} = FC_{ON} - FC_{OFF}$$

The FC_{AC} is compared to the CAFC target value (T_{AC}) which is calculated using the following formula:

$$T_{AC} = 0.00772 * CM + 0.726$$

Where T_{AC} is the target fuel consumption in l/100km and CM is the curb mass of the vehicle in kg. According to the result of the comparison, there are two possibilities:

If $FC_{AC} > T_{AC}$: The vehicle's FC during the CAFC calculation is not reduced.

If $FC_{AC} < T_{AC}$:

Calculate $FC_j = (T_{AC} - FC_{AC}) * K$

Where FC_j is the possible FC reduction in l/100 km and K=0.3 (constant).

$FC_{reduction}$ = min {FCj, 0.2}

3.2.3 Other regions

In other parts of the world, the CO_2 credits regulations for MAC are under development or lack important elements related to the calculation of the credits or the validation method.

For example, in Mexico there are two ways to grant credits to vehicles equipped with innovative MAC systems:

Reduction of CO_2 equivalent emissions related to refrigerant leaks (not relevant in the case of the current study); or,

Improvement of the efficiency of the MAC system based on the US list.

Any of these two requirements should be demonstrated to at least 80% of the vehicles sold, otherwise, the vehicle manufacturer does not have access to CO_2 credits. This approach was based on the US methodology, but it lacks some important elements. The most noticeable one is that the credits for any innovative technology on the US list are equal to the maximum credits given by the US regulation and without any requirement for verification testing. Table 32 shows the difference in the credits allowed by US and Mexico (Blumberg et. al, 2019).

Table 32. Difference in CO_2 credits between US and Mexico regulation. (Blumberg et al., 2019)

	U.S. credit allowances (maximum)		Mexico credits (any technology)
	PV	LT	PV and LT
	g/km		g/km
Off-cycle (includes thermal technologies)	6.2		6.25
AC efficiency	3.1	4.5	6.82
Belt-driven R134a (electric R134a)	3.9 (5.9)	4.8 (7.3)	4.12
Leakage and refrigerant change	8.6	10.7	9.04

Source: Reproduced from Blumberg et al., 2019

In both Japan and India, the regulatory schemes for rewarding CO_2 credits for innovative MAC systems are currently under development. However, no details are yet available.

Lastly, the Australian regulation closely follows the US and EU schemes. More specifically, any off-cycle credit technology that is accepted in either the US or EU will be accepted, and the same credit level will apply. Regarding air conditioning, it is mentioned that credits will be rewarded for systems utilising a low GWP refrigerant. If the GWP is below 10, the credits awarded are 10 g CO_2/km for passenger cars and 15 g CO_2/km for off-road vehicles (FCAI, 2020).

3.3 Best practices that could be applied in the EU context

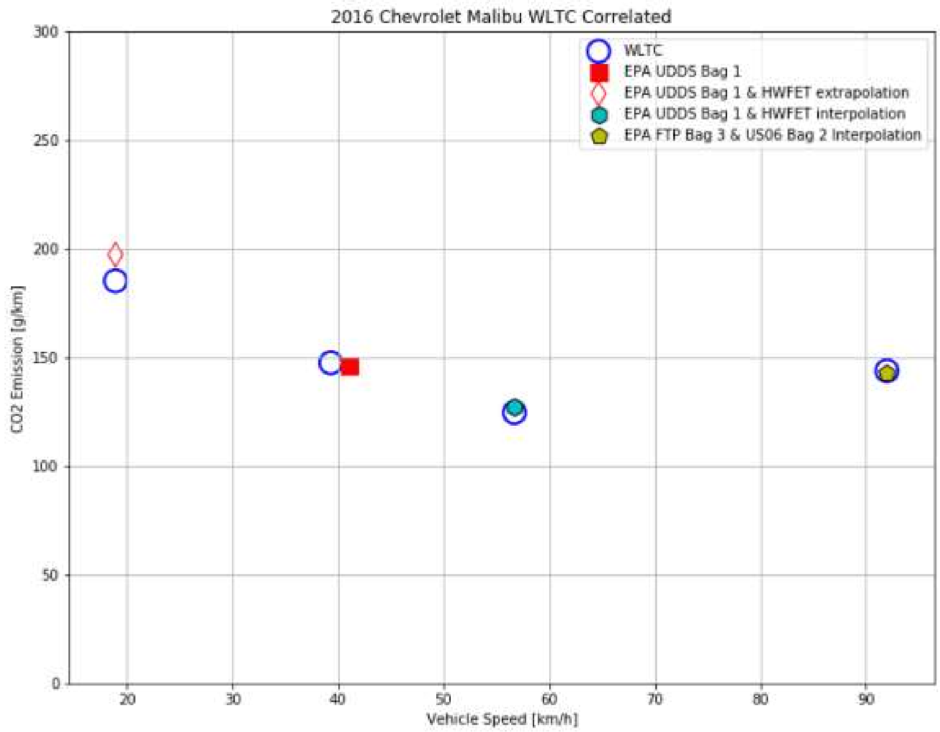
It is clear from the review presented above that the US regulatory scheme is the most detailed for attributing CO_2 credits to manufacturers for innovative MAC systems in the case of cooling. Some elements of the US regulations could be adjusted and used in the EU regulatory framework related to innovative technologies used for cooling.

As the 5-cycle testing used in the US is not included in any EU regulation, instead a driving cycle variant based on the WLTC but with the use of the MAC system could be used.

As demonstrated in a comparison presented at RDE 5th Session in Geneva, May 2019[5], the SC03 driving cycle and WLTC produce similar CO_2 emissions, as shown in Figure 22 below.

[5] For publicly available documents from the Session see: https://wiki.unece.org/display/trans/RDE+5th+Session+Geneva

Figure 22. SC03 and WLTC CO_2 emissions comparison. (RDE 5th Session Geneva, 2019, Comparison of US Cycles to WLTC v2)



4 Task 3 – Definition of the baseline technology

4.1 Task aims and objectives

The definition of the baseline technology is one of the most important steps in the design of a CO_2 benefit scheme for innovative MAC systems, as the credits to be awarded are directly linked to it. Regulations (EU) No 725/2011 (cars) and No 427/2014 (vans) stipulate a 'baseline' vehicle as one that shall not be fitted with the innovative technology, but that is in all other aspects identical to the vehicle equipped with an eco-innovation.

Building on the results of Task 1, Task 3 aimed to analyse all the information gathered through a literature review as well as from the replies to the JRC questionnaire and establish the MAC technologies used in the majority of vehicles today.

The data from the JRC questionnaire were used to define the most common type of technologies used in the case of each MAC component. For each one of those, the average characteristics were identified. The results of this analysis are presented in Table 29.

4.2 Methodology

The baseline MAC system should be a well performing, state-of-the-art MAC system. Also, in order to leave room for innovation, a technologically neutral approach for defining the baseline is considered appropriate. Any technological improvement on MAC components that can lead to CO_2 savings is eligible for CO_2 credits, both hardware (e.g., more efficient compressor) and software (more efficient control). More specifically, the type of technology is not relevant e.g., credits will not be awarded if a specific type of compressor is used, as for example in the case of the US EI scheme where credits are awarded when a variable compressor is used instead of a fixed one. Also, CO_2 credits can be a result of a combination of improvements on various MAC components. This approach is preferable in comparison to a technology specific baseline definition as it does not exclude any technologies from receiving credits as long as they fulfil the eco-innovation eligibility criteria.

The suggested definition is based on the MAC system's efficiency which is estimated. In order to define the baseline efficiency, simulation models were created for an ICEV and a PHEV. These models were then validated against lab measurements performed by the JRC. After validation, the simulation models can accurately predict the MAC system's energy performance under various ambient conditions. The WLTC driving cycle is utilised for all simulation runs and the detailed conditions are presented in section 5.3.

It should be noted that any technology that is part of the MAC system (as presented in section 2.9) can be part of the eco-innovation scheme, e.g., the compressor, the evaporator, the condenser or even how these components are connected. This means that technologies that could potentially impact the MAC's operation, but which are not part of it, are out of the scope of the current study. Some examples are reflective paints and solar control glazing. Finally, MAC system operation refers only to the cooling and ventilation, as the heating is not examined in the current study as mentioned in section 2.11.

4.3 Determination of eco-innovation CO_2 savings

In order to make clear how the baseline system is defined, it is described how the determination of CO_2 savings from innovative MAC systems is envisaged. The CO_2 savings (which may be credited by a manufacturer) are the reduction in the CO_2 emissions due to the use of the innovative technology as compared to the use of the baseline technology. For this, account is taken of the expected use of this technology during the vehicle's operation and this in the form of a Usage Factor (UF). More details on the calculation of the UF can be found in section 4.3.3.

The CO_2 savings formula in the eco-innovation scheme is defined in the Technical Guidelines for eco-innovations (European Commission, 2018).

$$CO2\ savings = UF_{MC} * (B_{MC} - E_{MC}) - UF_{TA} * (B_{TA} - E_{TA})$$

Where UF refers to the usage factor, B and E refer to the baseline and eco-innovative vehicle CO_2 emissions, respectively, and TA and MC to type-approval conditions and modified conditions respectively.

This study applies solely to MAC systems, which are not active during the Type Approval procedure. Hence, the difference between the terms B_{TA} and E_{TA} equal to zero. The Modified Conditions considers the activation of MAC systems and different testing ambient conditions to the TA procedure ones (as described in 5.3). Then, the MAC system CO_2 emissions is derived from the difference in vehicle's CO_2 emissions considering MAC on and off. For all this, the MAC system CO_2 savings formula is presented as follows.

$$MAC\ CO2\ Savings = UF * [(\mathrm{B}_{MAC_{ON}} - B_{MAC_{OFF}}) - (E_{MAC_{ON}} - E_{MAC_{OFF}})]$$

Where:

UF is the usage factor,

$B_{MAC_{ON}}$ are the CO_2 emissions from the vehicle equipped with the baseline MAC system with the MAC on, in g CO_2/km,

$B_{MAC_{OFF}}$ are the CO2 emissions from the vehicle equipped with the baseline MAC system with the MAC off, in g CO_2/km,

$E_{MAC_{ON}}$ are the CO_2 emissions from the vehicle equipped with the eco-innovative MAC system with the MAC on, in g CO_2/km,

$E_{MAC_{OFF}}$ are the CO_2 emissions from the vehicle equipped with the eco-innovative MAC system with MAC off, in g CO_2/km.

4.3.1 CO_2 emissions from a baseline MAC system

A baseline vehicle is not fitted with an innovative technology and is in all other aspects identical to the vehicle equipped with the EI. As a result, the baseline vehicle may not be in production and thus cannot be tested to measure the MAC system's CO_2 emissions.

For the calculation of $(B_{MAC_{ON}} - B_{MAC_{OFF}})$, which are the CO_2 emissions coming from the operation of the baseline MAC system (B_{MAC} g CO_2/km), a simulation-based approach is suggested. This approach reduces the testing burden and allows for running numerous virtual tests (simulations) faster, with lower cost and possible uncertainties. This also enables the study of various parameters, such as ambient conditions, cabin volume, MAC system characteristics, on the system's energy consumption and efficiency.

Following the technologically neutral approach, the definition of the baseline is based on the systems energy consumption and efficiency which is also a criterion of innovativeness as innovative systems tend to be more energy efficient. To convert energy to CO_2 emissions the Willans factors (VPe g CO_2/MJ) are utilised as shown in the formula below. The Willans factors are defined in UN Regulation No 154, Annex B6 – Appendix 2.

$$B_{MAC}\ for\ ICEVs\ and\ HEVs = B_{MAC_{ON}} - B_{MAC_{OFF}} = VPe * EC_{baseline}$$

Where $EC_{baseline}$ is the energy consumption of the baseline MAC system alone. The baseline system's efficiency is defined as the cooling Load Demand (LD) (described in 4.3.1.4) over the total MAC Energy Consumption ($EC_{baseline}$, described in 4.3.1.6).

$$Efficiency = \frac{LD}{EC_{baseline}}$$

The CO_2 savings can then be calculated as follows:

$$CO_2\ Savings\ for\ ICEVs\ and\ HEVs = UF * [VPe * \frac{LD * 3.6}{Efficiency * 23.2} - (\mathrm{E}_{MAC\ ON} - E_{MAC\ \mathrm{OFF}})]$$

The constant values in the formula represent the conversion from kWh to MJ (3.6) and the total distance driven during WLTC (23.2 km). This approach is proposed for ICEVs and HEVs. For the calculation of LD and Efficiency, validated simulation models are used. An overview of the software used and the simulation models is presented in section 4.3.1.1.

The efficiency of the system can vary based on the vehicle and MAC system characteristics and the ambient conditions. The cooling load demand depends on the vehicle characteristics, on ambient conditions, and the occupancy rate. The parameters affecting LD and Efficiency, are presented in more detail in sections 4.3.1.4 and 4.3.1.6.

The CO_2 savings for PHEVs are the result of the reduced CO_2 emissions during CS mode and the increased all-electric range (AER) due to the reduced energy consumption that comes from the use of the EI. For calculating the CO_2 emissions of the baseline MAC system for PHEVs, the emissions during CS and CD should be calculated.

The baseline MAC CO_2 emissions are the result of $B_{MAC_{ON}} - B_{MA\ OFF}$. These values were estimated for various ratios of battery capacities over the total EC during a WLTC and the results are presented in section 4.4.

For the calculation of CO_2 emissions during CS mode ($CS_{CO\ \_savings}$ in g/km), the CO2 mass emission correction coefficient (K_{CO} in (g/km) (Wh/km)) as defined in 2.3.2. of Appendix 2 of UN Regulation 154 is used.

$$CS_{CO} = \Delta E * Utility\ Factor * K_{CO}$$

Where ΔE is the difference in vehicle energy consumption during a WLTC from the use of the MAC in Wh and K_{CO} is the CO_2 mass emission correction coefficient.

In the case of the CD mode, the AER is expected to reduce in the case of MAC operation. This is directly linked to a lower utility factor and thus higher weighted CO_2 emissions. By utilizing experimental data, the reduced AER and the difference in the utility factor are estimated. By calculating the utility factor weighted CO_2 emissions with the two utility factor values (with MAC off and on), the CO_2 emissions from the MAC operation during CD mode are estimated.

The total baseline MAC CO_2 emission for PHEVs during CS and CD modes are calculated according to the formula below.

$$B_{MAC}\ for\ PHEVs = (1 - Utility\ factor) * CS_{CO} + CD_{CO}$$

Then CO_2 savings can then be calculated as follows:

$$CO_2\ Savings\ for\ PHEVs = UF * [(1 - Utility\ factor) * CS_{CO} + CD_{CO} - (\mathrm{E}_{\mathrm{MAC\ ON}} - \mathrm{E}_{\mathrm{MAC\ OFF}})]$$

4.3.1.1 Simulation models

The MAC system technologies used for each powertrain mainly depend on the level of electrification, mainly due to the main difference in the power source of the compressor: for ICEVs and usually for HEVs, the compressor is mechanical (belt driven) while in the case of PHEVs it is electric driven.

The MAC operation of HEVs and ICEVs are considered identical as they are both belt-driven compressors. Additionally, there is no difference in the calculation of the CO_2 emissions between ICEV and HEV and consequently it is not considered necessary to introduce a separate category of baseline technology exclusively for HEVs.

For these reasons, two different simulation models were created, one for ICEVs (covering also HEVs) and one for PHEVs. The main characteristics of the modelled vehicle and the MAC system are presented in Table 33 and Table 34 respectively.

Table 33. Vehicle characteristics of the modelled ICEV.

Powertrain	ICEV	PHEV
Vehicle segment	C-segment	C-segment
Engine displacement (cc)	1598	1395
Euro standard	Euro 6	Euro 6
Fuel	Diesel	Petrol

Table 34. MAC system characteristics of the modelled ICEV.

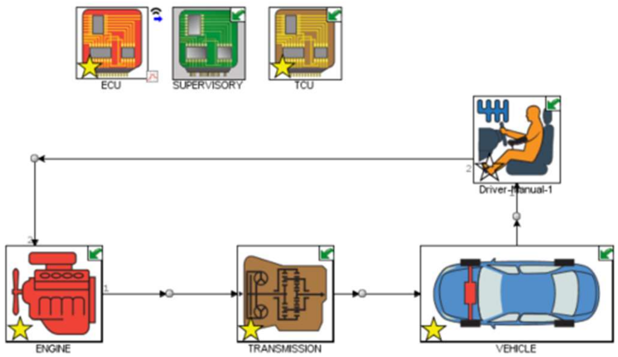
Powertrain	ICEV	PHEV
Compressor type	Variable	Variable
Compressor displacement (cc)	170	115
Refrigerant	R134a	R134a

4.3.1.2 Simulation software

The basic approach of simulations is based on the GT-SUITE software, which is an industry-leading simulation tool with capabilities and libraries aimed at a wide range of applications and industries. In the current assignment, GT-SUITE is used for the simulation of the energy performance of the MAC system for vehicles with different powertrains (i.e., ICEVs and PHEVs). More specifically, two different system models are created:

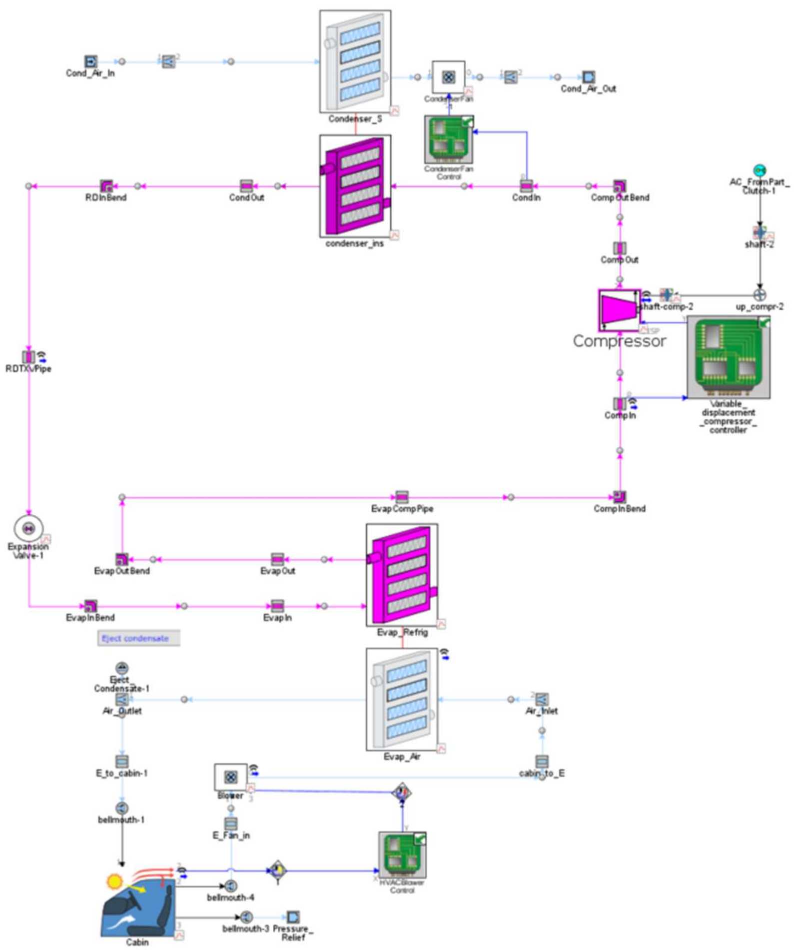
(i) The vehicle system model, which includes the drivetrain architecture as well as several controls (e.g., Transmission Control Unit (TCU) system, Electronic Control Unit (ECU) system)

Figure 23. The ICE vehicle system topology in GT-SUITE software.



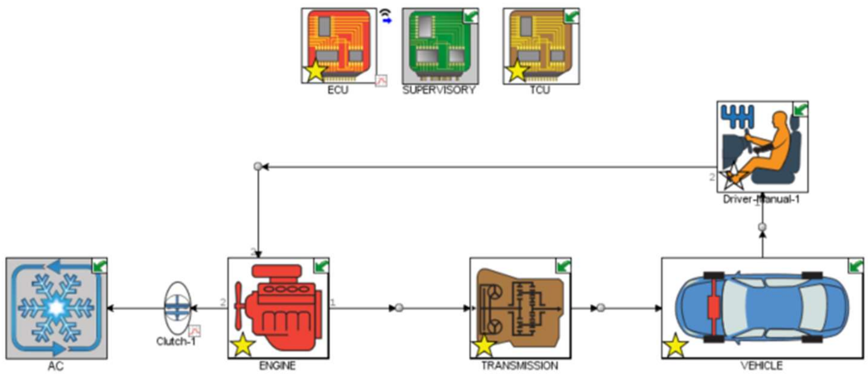
(ii) The MAC system, which contains the components described in Table 34 (see Figure 24 below).

Figure 24. The MAC system topology for the ICEV in GT-SUITE.



The final model for the baseline scenario is an integration of the previously described models. For the baseline scenario, the MAC compressor is mechanically driven, engaged with the engine through a clutch (see Figure 25).

Figure 25. The complete system model for the ICEV.



4.3.1.3 Simulation models validation

The simulation models used in this study consist of three main elements: the vehicle's cabin, the MAC system and the vehicle's powertrain. The validation of the simulation models for ICEV and PHEV was achieved by using data from measurements performed by the JRC.

The thermal behaviour of the cabin is calibrated against measured data, so that the model estimates accurately the temperature inside the vehicle. The ICE and the MAC are considered off during this calibration.

Using the calibrated cabin model, the MAC system is then calibrated against the compressor torque and the MAC's energy consumption. In the final step, the model is calibrated by considering all three elements: vehicle cabin, MAC system and powertrain. The vehicle's energy consumption is validated with the MAC off, to ensure that the model accurately simulates the ICE operation. Then, the MAC is integrated into the simulations and both the total vehicle and the MAC energy consumption are calculated. The model is considered validated when the simulated and measured data for these two energy consumption parameters match.

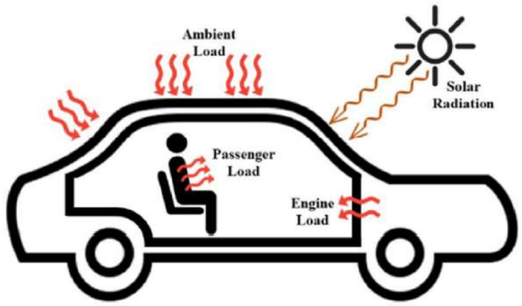
Several controllers were implemented to simulate the climate control behaviour of the MAC system. More specifically, these controllers are described below:

- The cabin temperature was controlled by a Proportional Integral (PI) controller so as to achieve a cabin target temperature of 22°C, as it was observed from the measurements.
- The condenser fan controller, which was using the compressor outlet pressure to adjust the condenser fan speed.
- The controller of variable displacement compressor, which was a PI controller using the compressor inlet pressure to adjust the amount of displacement.

4.3.1.4 Cooling load demand

The cooling load demand is the energy transferred from the vehicle cabin to the MAC's refrigerant through the evaporator, in order to achieve thermal comfort. Essentially, this is how the cabin's target temperature and humidity are reached. The LD depends mainly on four parameters: solar irradiation, enthalpy to cool and dehumidify the cabin, driver's and passengers' body heat, heat transferred through the vehicle's body (Subiantoro et al., 2014) – see Figure 26.

Figure 26. Factors affecting cooling load demand. (Vashist et al.,2021)



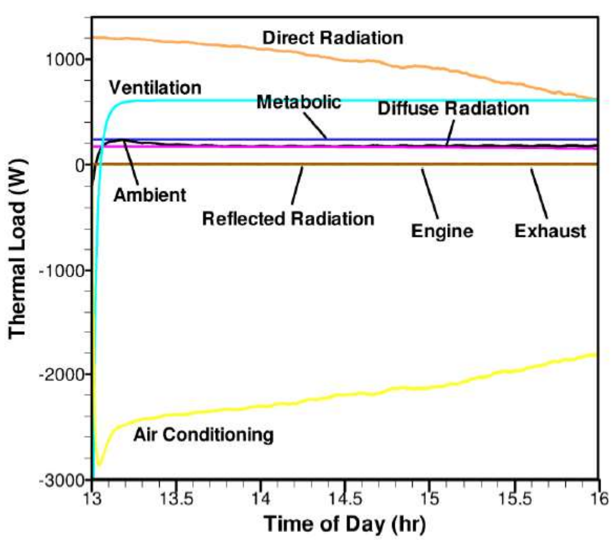
The instant LD during the MAC system's operation is equal to the heat exchanged through the evaporator, which is calculated as follows:

$$Q_{evap} = \dot{m}(h_{out} - h_{in})$$

Where Q_{evap} is the cooling load in kW, $\dot{m}$ is the mass flow rate of the refrigerant (kg/s) and h_{in}, h_{out} are the refrigerant's specific enthalpy in the inlet and outlet of the evaporator respectively (kJ/kg). (Vaghelaa et al., 2016)

As observed in Figure 27, direct solar radiation and ventilation are mainly contributing to the cabin's LD, followed by the heat coming from the passengers (metabolic load) and the diffused radiation. Heat from exhaust, engine and the reflected radiation loads are almost zero. This also indicates the parameters affecting LD, which is the intensity and angle of the solar radiation, the occupancy rate (or the number of passengers) and the ambient conditions such as ambient temperature which affect the load coming from the ventilation. These results refer to a summer day in Houston, Texas where the ambient temperature was 34.4 °C and the initial cabin temperature was 80 °C.

Figure 27. Load demand inside the vehicle cabin. (Fayazbakhsh et al., 2013)



By using the validated simulation models, the effect of ambient temperature and solar radiation on LD is studied. For this reason, multiple sensitivity analyses were performed and the results are presented below. More specifically, the effect of the number of passengers (2-5 for a passenger car) is studied. Additionally, the LD values were calculated for a range of moderate to more severe ambient temperatures (24-36 °C) along with various solar intensities.

Figure 28 (below) shows that the LD increases by approximately 26% for each additional passenger inside the vehicle cabin. The linear increase is explained through the linear increase of the metabolic load inside the cabin. Each passenger's metabolic load is considered to be around 200 W (Hudie, L., A., 2016).

Figure 29 (below) shows the effect of the ambient conditions (ambient temperature and solar load) on the load demand: a higher temperature or solar radiation lead to an increase in the heat that needs to be removed from the cabin.

Figure 28. Load demand as a function of the number of passengers (Ambient temperature 26 °C, RH 50%, no solar load).

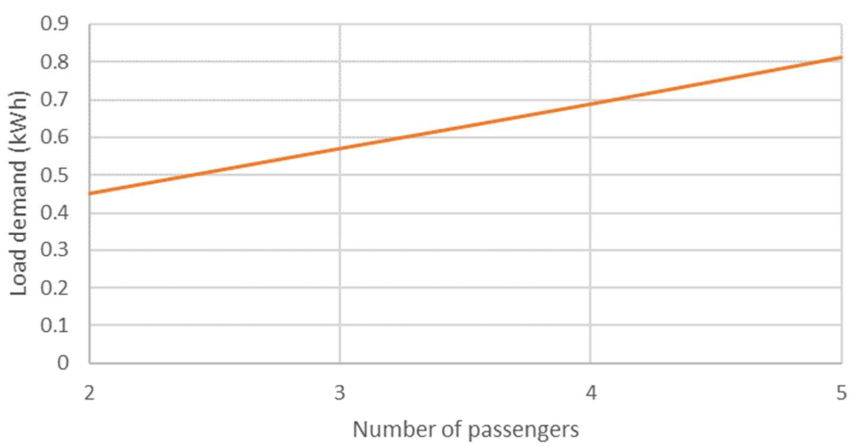
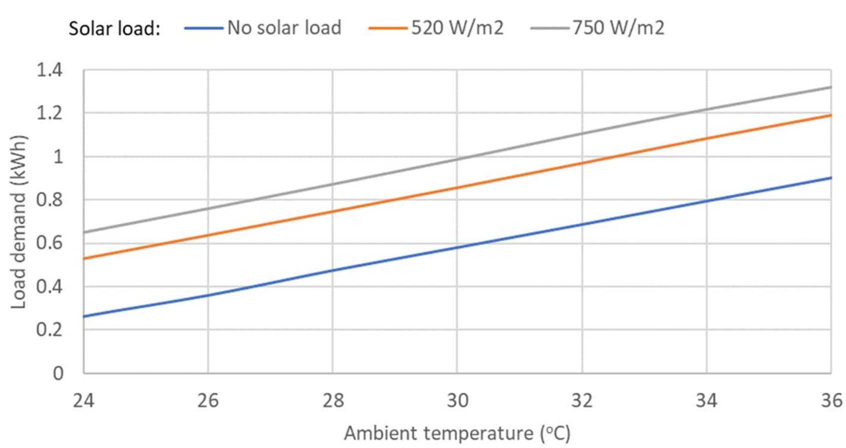


Figure 29. Load demand as a function of solar radiation and ambient temperature.



4.3.1.5 Coefficient of Performance (CP)

The CP is used to measure a system's energy efficiency and is defined as the ratio of the heat added to or removed from the system over the compressor's work. As the heat transferred to or from the vehicle cabin is equal to the heat exchanged in the MAC system's evaporator, the CP of the MAC system may be calculated as:

$$CP = \frac{Q_{evap}}{W_{Comp}}$$

Where Q_{evap} is the heat exchanged in the evaporator (in kWh) and W_{comp} is the compressor's work (in kWh).

Higher CP values translate into higher efficiency, as less work is needed to remove the same amount of heat (Moo-Yeon, L., 2017).

Typical CP values for VCR systems are between 2.5 and 3.5 and can vary based on system characteristics and ambient conditions, refrigerant type and load, compressor type and speed, and the cabin's cooling load demand (i.e., evaporator's work). In the simulation models the R134a is the refrigerant used and the expected CP is over 3. In a study by Vashist et al., the CP values for various refrigerants and air conditioning technologies are summarised. The values for VCR systems are presented in Figure 30.

Figure 30. COP values for various refrigerant types for VCR systems. (Vashist et al., 2021)

The COP of different automobile air conditioning technologies.

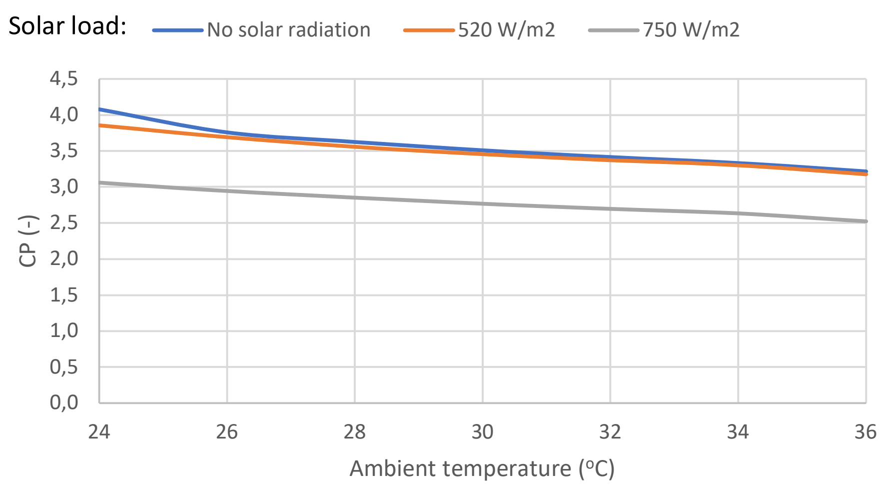
Author	Type of AAC	Category	Details	COP
Park and Jung (2007)	VCR	R502/(R22/R115)	48.8:52.2	0.633
		R1270/R290	10:90	0.806
		R1270/R290	20:80	0.793
		R290/R152a	90:10	0.785
Park et al. (2007)		R22		3.78
		R1270/R290	20:80	3.9
		R1270/R290	50:50	3.91
		R1270/R290	80:20	3.92
		R290/R152a	60:40	3.84
		R290/R152a	71:29	3.91
		R290/R152a	75:25	3.91
		R1270/R290/RE170	45:40:15	3.99
Subiantoro et al. (2014)		R134a	–	3.19
		R1234f	–	3.02
Santoso and Tjahjana (2017)		HC-134	–	5.37
		HC-134a	–	3.93
Vaghela (2017)		R290	–	2.499
		R600a	–	2.64
		R407C	–	2.36
		R410A	–	2.256
		R404A	–	2.185
		R134a	–	2.562
		R152a	–	2.668
		R1234yf	–	2.4
Subiantoro et al. (2014)		Temperature control	Indoor temp 20 °C	2.836
			Indoor temp 24 °C	3.19
Alahmer (2016)		Desiccant with regeneration	–	3.5–4.5
Pang et al. (2019)		PV system	–	2.9

CP is influenced by multiple parameters that can be categorized in two groups. The first one includes parameters related to the vehicle and MAC system's characteristics and the second one to ambient conditions.

As mentioned in section 4.1, the vehicle characteristics like reflective paints are out of the scope of this study. Considering this, the vehicle cabin volume is the only link between the vehicle characteristics and LD as it directly influences the cooling load by increasing the mass of air to be cooled. Regarding the MAC system characteristics, any parameter that affects the compressor's work or the load demand (i.e., evaporator's work) can affect CP.

In Figure 31 the CP is presented as a function of solar radiation and ambient temperature. These values were estimated using the validated simulation models. The results are the same as expected from the literature review, where the CP of the system reduces as the conditions of operation are getting harsher (higher ambient temperature and more intense solar radiation). The results below refer to simulations run with 50% RH, under WLTC, for an ICEV with a MAC compressor of 170cc.

Figure 31. CP as a function of solar radiation and ambient temperature.



CP is a good measure of the system's efficiency. However, it does not include the energy consumption of all MAC components such as the blower, but only the compressor's work. An EI could lead to both decrease in the compressor's work and the total MAC energy consumption. For example, if a more efficient blower fan is used, the compressor's work could be reduced in addition to the lower blower energy consumption. If CP was utilised, the reduction of the blower energy consumption would not be taken into consideration. This is why the efficiency is used as described below, while the CP remains a good metric to evaluate a MAC system alone, ignoring the system's integration to the vehicle.

4.3.1.6 MAC system efficiency

According to the formula for the CO_2 credits calculation in section 4.3, the MAC efficiency is used instead of CP. In order to include technologies related to components other than the compressor that can lead to CO_2 savings, their energy consumption should be included in the calculation of the CO_2 emissions for the baseline system. In the next section the energy consumption of the main MAC system components is presented. For this reason, a literature review was performed along with simulation runs.

4.3.1.7 MAC energy consumption

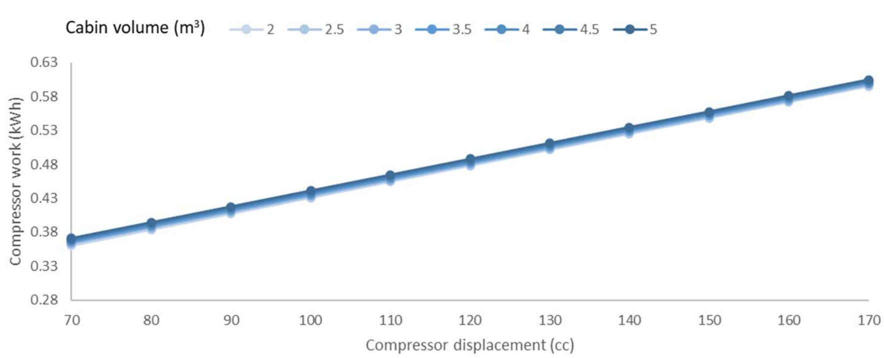
The MAC system's EC consists of mechanical power and electrical power. The mechanical power is needed for the compressor's operation if it is belt driven (otherwise the entire MAC EC is electrical) and electrical energy for the operation components such as the blower, the compressor clutch and the control system.

The compressor's energy consumption for various ambient temperatures and compressor speeds is presented in Table 35. These values offer a sense of the order of magnitude, as to what is to be expected for the compressor's work. By multiplying these values with 0.5 an approximation of the energy consumption during a WLTC is obtained. This value (0.5) is to convert the power units (kW) to energy units (kWh), since the duration of a WLTC is approximately 30' (0.5 hours). In Figure 32 the corresponding simulation results are presented for various vehicle cabin volumes. These refer to 26 °C, 50% relative humidity and no solar radiation.

Table 35. Expected values for compressor work under various conditions (IPCC/TEAP 2005).

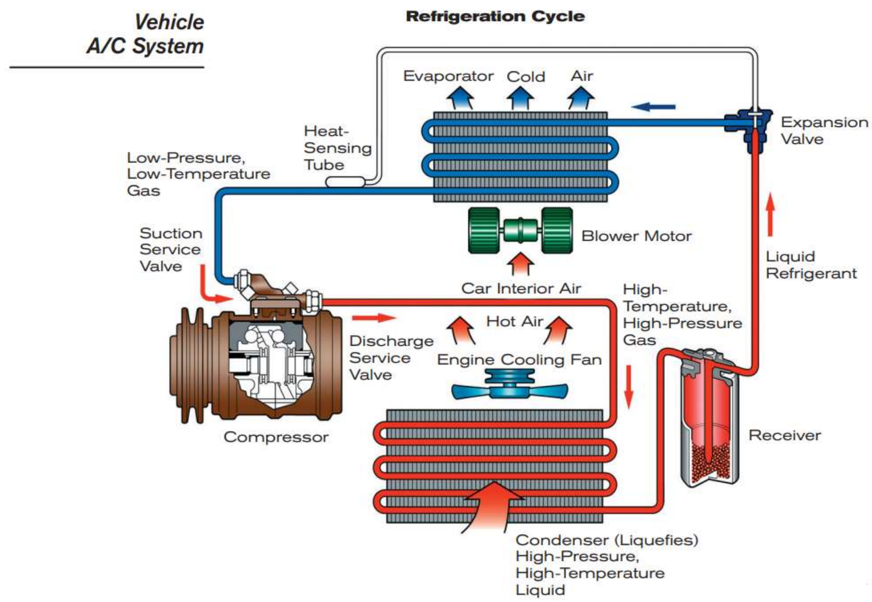
Rotation speed (RPM)	**Mechanical power (kW)**						
	Ambient air temperature (°C)						
	15°C	**20°C**	**25°C**	**30°C**	**35°C**	**40°C**	**45°C**
900	0.4	0.7	0.9	1.1	1.25	1.32	1.39
1500	0.5	1.2	1.8	1.8	1.9	2.3	2.7
2500	0.7	1.4	2.1	2.4	2.7	2.9	3.1
3500	0.7	1.5	2.2	2.6	3.0	3.2	3.4

Figure 32. Compressor work as a function of cabin volume and compressor displacement.



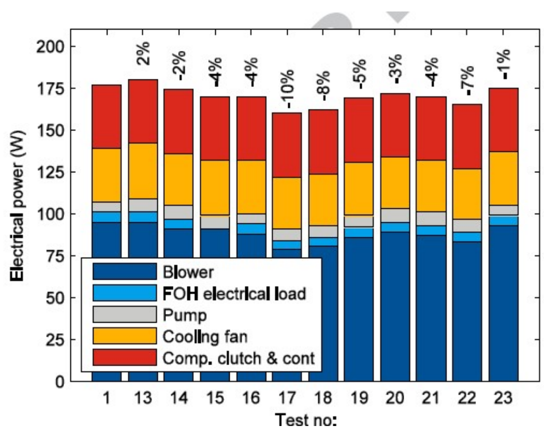
In Figure 33 below the main components of a MAC system are presented. The compressor powers the condenser, the receiver, the expansion valve and the evaporator through the refrigerant's circulation. As a result, when referring to the compressor's work, this includes the energy consumed by all these components.

Figure 33. Main components of a VCR A/C system. (Toyota, Air conditioning and climate control course 752)



From all these components the blower fan has the higher energy consumption. The energy consumption of the condenser fan is not independent of the vehicle's operation, as it is used for the cooling of the engine as well. The expected energy consumption of the condenser fan and other MAC components are presented in Figure 34, for various scenarios. In the current analysis only the effect of the blower energy is taken into account, as the other component's energy consumption is minimal in comparison to the compressor's work.

Figure 34. Electrical power of various MAC components. (Nielsen et al., 2016)



4.3.2 CO_2 emissions from the eco-innovative MAC system

As the vehicle fitted with the EI may be available for testing the most accurate way of estimating $(E_{MAC\ ON} - E_{MAC\ OFF})$ is by measuring it through testing. Besides, the contribution of MAC to CO_2 emissions during TA is zero, hence only $EI_{MAC_{ON}}$ needs to be estimated and $EI_{MAC_{OFF}}$ is the same as the TA CO_2 emissions value. The values for TA CO_2 emissions are not corrected for vehicles equipped with periodically regenerating by the Ki factor or for ambient temperature correction test (ATCT) correction. For these reasons, a testing methodology is developed and presented in chapter 0.

4.3.3 Usage factor (UF)

The MAC system is not always operating, and the UF expresses the percentage of the total distance driven during which the MAC system is activated. The UF is affected by ambient conditions, driver-influenced parameters and vehicle cabin characteristics.

The ambient conditions affect thermal comfort in a well-studied manner and more specifically ambient temperature is one of the most influencing parameters. Additionally, no sufficient data were collected (through literature review or a survey) related to driver-influenced parameters such as the perceived comfort and fuel prices. Also, these parameters are subjective and can rapidly change over time. Consequently, for the purpose of this study, it was decided that the calculation of the UF would be solely based on ambient temperature and thermal comfort.

4.3.3.1 Methodology for UF calculation

The required data to determine UF is the threshold temperature over which cooling inside the vehicle cabin is needed in combination with information related to the distance driven (in km) by passenger cars and light commercial vehicles under these conditions (ambient temperature over the threshold). This will result in the percentage of the distance driven where MAC is needed for cooling.

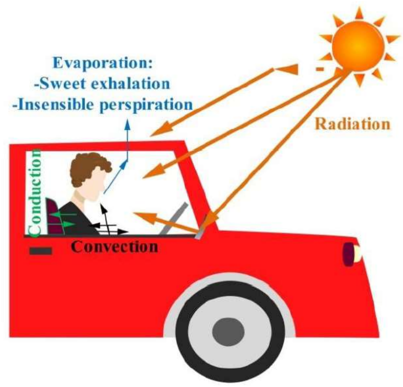
The determination of the temperature threshold is solely based on thermal comfort. A literature review was performed to determine over which temperature passengers might experience discomfort. For the distribution of the kilometres driven over various ambient temperatures, a previous work performed by EMISIA in the context of a Euro 7 Impact Assessment Study is utilised as presented in 4.3.3.3.

4.3.3.2 Thermal comfort

Assessing thermal comfort in a vehicle's cabin is a rather complex issue as it involves various parameters and non-uniform conditions. The definition of thermal comfort according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 55 standard is *"a subjective concept characterized by a sum of sensations, which produce a person's physical and mental wellbeing, condition for which a person would not prefer a different environment*" (ASHRAE 55 standard). There are various parameters for evaluating thermal comfort such as the Equivalent Temperature (ET) defined as "*the uniform temperature of the imaginary enclosure with air velocity equal to zero in which a person will exchange the same dry heat by radiation and convection as in the actual non-uniform environment"* (SAE Journal, 2012).

The factors affecting thermal comfort can be divided in two categories: measurable and personal factors. The measurable ones refer to ambient conditions such as ambient temperature and relative humidity, while the personal factors include clothing and activity level. There are additional aspects that affect thermal comfort such as age, health and season. In Figure 35 the elements contributing to thermal comfort inside the vehicle are presented. It is evident that thermal comfort inside a vehicle is a complex situation as the conditions change rapidly. Heat is exchanged through conduction, convection, radiation and bodily functions such as breathing and perspiration. When the driver's body is exposed to sunlight, it is heated by solar radiation that passes through the glass and by long wave thermal radiation from the surrounding surfaces.

Figure 35. Elements contributing to thermal comfort inside the vehicle. (Simiona et al., 2015)



In Table 36 the recommended inside temperature and relative humidity for thermal comfort are presented in correlation with the outside temperature. By utilizing this data, a function of the outside and the inside temperature for thermal comfort is obtained (Simiona et al., 2015). In general, cooling is needed when the inside temperature for thermal comfort is lower than the outside temperature. Based on this rule and the function of inside and outside temperature, the threshold temperature for MAC on is set to 22.5 °C. This means that when the ambient temperature reaches this threshold (or above), cooling is needed to maintain the vehicle occupants' thermal comfort.

Table 36. Recommended thermal comfort values for cabin temperature and relative humidity corelated with the outside temperature. (Simiona et al., 2015)

Season	Outside temperature (°C)	Inside temperature (°C)	Minimum relative humidity (%)	Maximum relative humidity (%)
Winter	≤±20	22	35	70
Summer	+20	22	Not available	70
	+25	23	Not available	65
	+30	25	Not available	60
	+32	26	Not available	55

4.3.3.3 Usage factor calculation

After defining the MAC on threshold, the UF calculation is performed. For this purpose, the distribution of the annual vehicle-kilometres (vkm) driven by the European passenger cars and light commercial vehicles to temperature ranges, as previously estimated by EMISIA in the context of Euro 7 Impact Assessment Study (Ntziachristos et al., 2022) is utilised. In the case when cooling is needed, the UF is the sum of all the temperature bin ranges over the MAC on threshold (22.5 °C). The distribution is presented in Table 37 for the year 2020.

Table 37. Distribution of vehicle-kilometres driven by European passenger cars and light commercial vehicles to temperature ranges. (Ntziachristos et al., 2022)

Temperature Classes	Passenger cars	Light commercial vehicles	Total
< -20 °C	0.00%	0.00%	0.00%
-20 … -10 °C	0.03%	0.00%	0.03%
-10 … 0 °C	2.91%	0.41%	3.33%
0 … 2 °C	3.38%	0.41%	3.80%
2 … 4 °C	4.16%	0.54%	4.70%
4 … 6 °C	6.74%	1.15%	7.89%
6 … 8 °C	7.30%	1.23%	8.53%
8 … 10 °C	7.27%	1.25%	8.52%
10 … 20 °C	39.46%	7.02%	46.48%
20 … 22 °C	5.60%	1.06%	6.65%
22 … 24 °C	3.77%	0.75%	4.52%
24 … 26 °C	2.68%	0.51%	3.19%
26 … 28 °C	1.51%	0.29%	1.80%
28 … 30 °C	0.39%	0.09%	0.48%
30 … 40 °C	0.06%	0.02%	0.07%
> 40 °C	0.00%	0.00%	0.00%

Additionally, since cooling is also needed in some cases where the ambient temperature is below the threshold, e.g., in cases when a vehicle is exposed to solar radiation for long periods of time, the temperature bin of 20-22 °C is also taken into consideration. This sums to a UF equal to 17% (16.7%), meaning that MAC is on for cooling during 17% of the total mileage driven by passenger cars and light commercial vehicles.

4.4 Baseline MAC system definition

Considering all of the aforementioned elements, the definition of the baseline MAC system should include two main parameters. The values of these parameters are calculated for a variety of scenarios. These are the LD and the system's efficiency ($Efficiency_{baseline}$).

The LD and $Efficiency_{baseline}$ values should be determined to perform the CO_2 credits calculation, after the vehicle is tested according to the methodology described in chapter 0. In the following section, the values for all the mentioned parameters are presented for ICEVs. These values are used as input in the CO_2 credits calculation formula along with the measurement results. The simulations are performed under the equivalent ambient conditions described in 5.3.5.

In Figure 36 and Figure 37 the load demand is presented as a function of the cabin volume and the compressor's displacement for ICEVs – HEVs and PHEVs. It is not affected by the compressor's displacement, as the heat to be removed from the cabin is irrelevant of the compressor size. On the other hand, the load demand increases as the cabin volume increases, due to the higher mass of air that needs to be cooled. The difference between the values for various compressor displacements that is visible in the figures, comes from simulation errors.

Figure 36. Load demand as a function of compressor's displacement and cabin volume for ICEVs and HEVs.

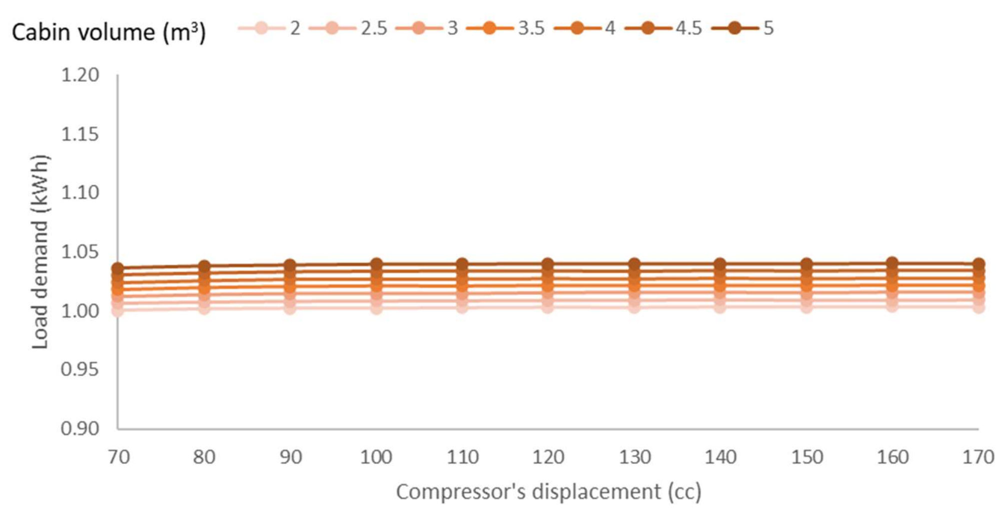
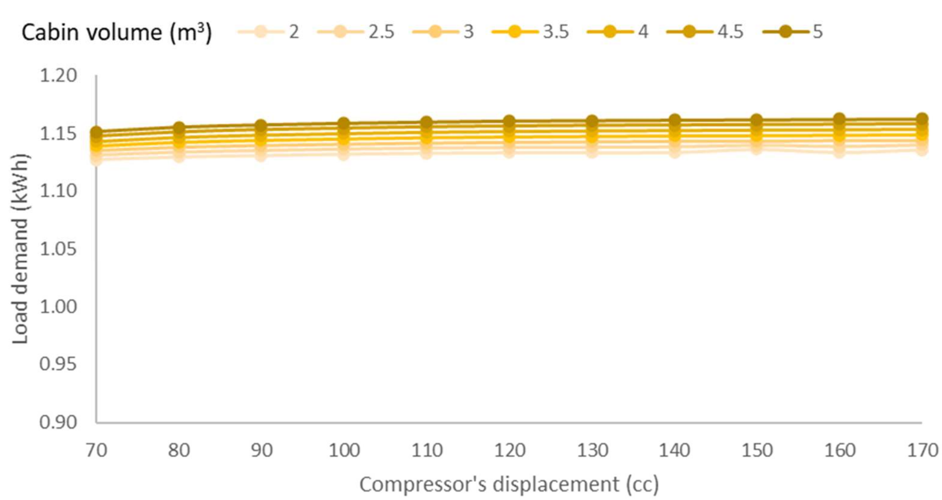


Figure 37. Load demand as a function of compressor's displacement and cabin volume for PHEVs.



In Table 38 below, the values for load demand to be used in the calculation of CO_2 credits are noted for all powertrains. The difference in LD between ICEVs – HEVs and PHEVs is due to different cabin characteristics of the vehicles modelled. The LD is different between ICEVs and PHEVs because of the differences in the cabin characteristics between the two modelled vehicles.

Table 38. Load demand (LD) values to be used for the CO_2 credits calculation for ICEVs and HEVs.

Cabin volume (m3)	**Load demand (kWh)**	
	ICEV and HEV	**PHEV**
2	1.00	0.92
2.5	1.01	1.14
3	1.02	1.14
3.5	1.02	1.15
4	1.03	1.15
4.5	1.03	1.16
5	1.04	1.16

The effect of the cabin volume on the efficiency is minimal, while the main parameter influencing it is the size of the compressor. The system's efficiency is mainly influenced by the compressor; and so, it is suggested that the efficiency value that defines the baseline is selected based on the vehicle's compressor displacement. The values of efficiency for the baseline are presented in Table 39 (see below) for all powertrains.

Figure 38. Efficiency as a function of compressor's displacement and cabin volume for ICEVs and HEVs.

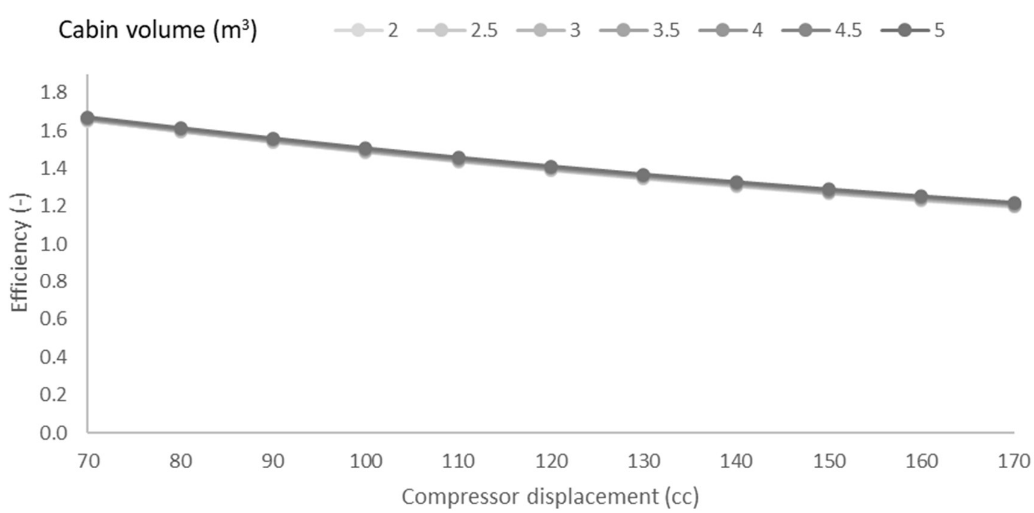


Figure 39. Efficiency as a function of compressor's displacement and cabin volume for PHEVs.

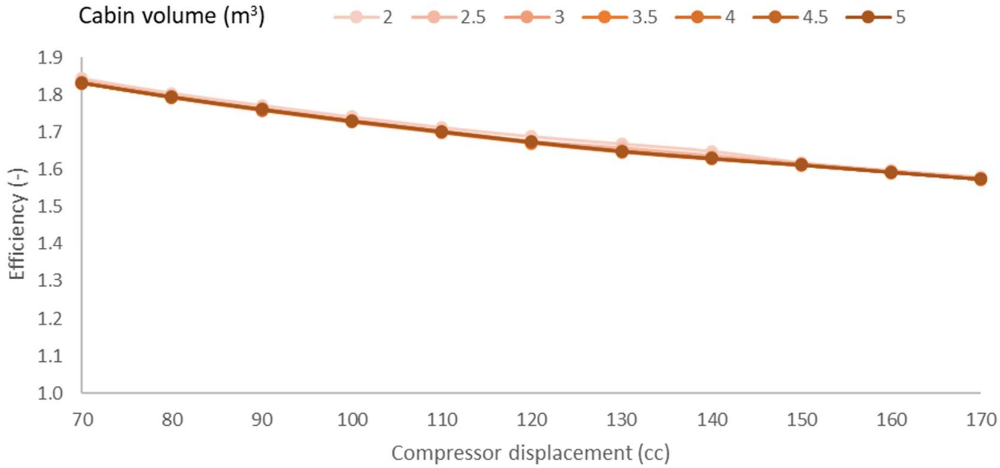


Table 39. Efficiency values to be used for the calculation of CO_2 credits for ICEVs and HEVs.

Compressor's displacement (cc)	**Efficiency**	
	ICEV and HEV	**PHEV**
70	1.58	1.98
80	1.51	1.98
90	1.44	1.98
100	1.37	1.96
110	1.32	1.93
120	1.26	1.91
130	1.21	1.88
140	1.17	1.85
150	1.13	1.83
160	1.09	1.81
170	1.05	1.78

In general, the effect of the cabin volume on the calculation of the CO_2 savings is minimal. More specifically, the relative difference in LD between the 2 m^3 and 5 m^3 cabin is around 2%. In the context of the EI scheme (detailed discussion in chapter 6) this translates in around 0.2 g CO_2/km. Additionally, since there is no regulated method for measuring the cabin's volume, stakeholders suggested that cabin volume should not be a parameter affect CO_2 credits. Taking everything into consideration, it is suggested that the highest value of load demand is used as input in the CO_2 savings calculation formula. After this, Figure 27 (covering Load demand) is replaced by Table 40.

Table 40. Load demand values for ICEVs, HEVs and PHEVs.

	ICEV and HEV	**PHEV**
Load demand (kWh)	1.04	1.16

After defining the LD and efficiency values for PHEVs, the CO_2 emissions from the baseline vehicle with MAC on and off are calculated by JRC and the results are presented in Table 41. These were estimated by combining experimental data and simulation results used as input. The simulation results included the MAC power consumption during WLTC under the equivalent ambient conditions both under CS and CD modes. The method described in 4.3.1 was utilised.

Table 41. Vehicle CO_2 emissions for PHEVs with MAC off and on

MAC	Off	On	On	On	On	On
AC compressor displacement (cc)	N/A	70	110	130	150	170
MAC power (kW)	0	-0.226	-0.243	-0.251	-0.256	-0.263
Ratio (battery capacity)/(cycle energy) (Ah/Wh)	Vehicle CO_2 emissions (gCO_2/km)					
1.52	51.22	53.694	53.903	53.954	54.019	54.075
3.04	29.99	31.123	31.242	31.301	31.342	31.400
6.18	6.848	7.640	7.676	7.696	7.711	7.725

After subtracting the MAC off from the MAC on CO_2 emissions, the CO_2 emissions of the baseline MAC system during WLTC under the equivalent ambient conditions are calculated and presented in Table 42. After estimating the CO_2 emissions from the MAC system with the EI, the CO_2 savings can be estimated.

Table 42. Baseline MAC CO_2 emissions for PHEVs

AC compressor displacement (cc)	70	110	130	150	170
Ratio (Ah/Wh)	Baseline MAC CO_2 Emissions (gCO_2/km)				
1.52	2.478	2.687	2.737	2.802	2.858
3.04	1.125	1.244	1.303	1.343	1.401
6.18	0.792	0.828	0.848	0.863	0.877

As a result, for determining the baseline MAC CO_2 emissions to be used in the calculation formula for CO_2 savings, the ratio of battery capacity to cycle energy is calculated. Interpolation between successive rows is allowed when the exact value is not contained in Table 42. Then, based on the compressor's displacement, the value for the baseline MAC CO_2 emissions is selected.

5 Task 4 – Testing methodology

5.1 Task aims and objectives

Manufacturers or suppliers applying for an innovative technology to be approved as an eco-innovation should propose a testing methodology that will determine the CO_2 savings. This methodology shall be robust and sufficiently detailed and shall allow to accurately determine the CO_2 credits to be awarded. Any related test results that already required to be run by the manufacturers or suppliers, are taken into consideration (e.g. testing during TA) to reduce the testing burden. For example, the CO_2 emissions determined during TA for the vehicle with the EI, are used as input in the formula for calculating CO_2 savings (4.3).

5.2 Methodology

According to the formula for the calculation of CO_2 credits for innovative MAC technologies as described in 4.3, the CO_2 emissions of the vehicle equipped with the innovative technology with the MAC system on must be determined. For this reason, a testing methodology is proposed, where the vehicle with the MAC on is tested under ambient conditions representative of the climate in EU27. The target conditions inside the vehicle cabin are based on thermal comfort. The testing methodology proposed refers only to the cooling part of the MAC system and is based on type 1 test described in Regulation (EU) 2023/443. Additionally, the technical specifications of the current testing facilities around EU play an important role. More specifically, solar lamps are not available in most testing facilities and a workaround to simulate the effect of solar radiation had to be determined.

5.3 Test cell conditions

The test cell ambient conditions need to be determined to perform simulations and estimate the parameters for the baseline definition,, as they will be used as simulation input. These conditions need to be representative of the weather conditions across EU27 when cooling is needed. For this reason, the ambient temperature is defined for typical weather conditions. Then, the relative humidity and solar radiation are selected accordingly as presented in the sections below.

5.3.1 Ambient temperature

For the determination of the representative ambient conditions inside the test cell, historical weather data of the EU were analysed. The dataset obtained contains 3-hour average ambient temperature for all EU27 regions for the whole year. Based on thermal comfort, as presented in 4.3.3.2, cooling is needed when the ambient temperature is over 22.5 ºC (MAC on threshold). Based on the region, usually the ambient temperature is over the MAC on threshold during 09:00-18:00. For the majority of EU27 regions, cooling is needed during summer months (June – August). In southern countries cooling might be needed in late spring (May) and early autumn (September) as well. The average ambient temperature for all regions, when the temperature is over the MAC on threshold is presented in Table 43, both for summer (June – August) and for the extended period (May – September).

Table 43. Average ambient temperature for values over the MAC on threshold (EU27).

Period	Average temperature for values over the MAC on threshold (ºC)
June to August	26
May to September	25.2

In order to select the ambient temperature for testing the summer period (June to August) plays a more important role, as MAC is expected to be used for cooling mostly during that period. Additionally, the average temperature from May to September is 25.2 °C. The average temperature from these two periods is 25.6 °C. This means that 26 °C is also representative for the extended period of May to September, where MAC might be used for cooling.

5.3.2 Relative humidity

No data related to humidity was available to the research team. As a result, a literature review is performed to determine the average relative humidity during summer in EU. According to Malvicino et al. (2006), the European average relative humidity for summer is 50.2%. This value is also set as the RH in the test cell in AC17 and is proposed in the case of the MAC EI testing methodology.

Figure 40. European average summer thermal conditions (Malvicino et al., 2006)

Temperature (°C)	R.H. (%)	Irradiation (W/sqm)
25.6	50.2	516

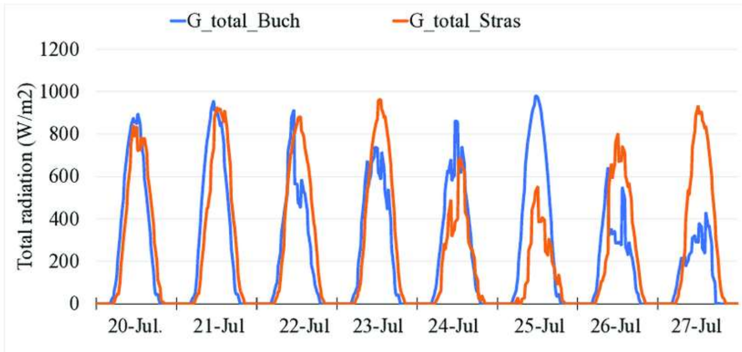
Table 1 – European average summer thermal conditions. These values have been obtained weighing the national data of with the number of car sold in each of the considered countries

5.3.3 Solar radiation

In the case of solar radiation intensity, similar data as in the case of the ambient temperature were collected but it was averaged over the whole year and not for the summer conditions. For this reason, an additional literature review was performed. In a study by Kilic et al. (2012), measurements of solar radiation at approximately 29 °C of ambient temperature resulted in approximately 860 W/m^2 (measurements in August, Bursa, Turkey) of solar radiation while in a study by Malvicino et al. (2006), the average solar radiation weighted by sales of new vehicles sold yearly is around Europe is 516 W/m^2. The corresponding value in the AC17 is set rather high at 805 W/m^2.

Additionally, in Figure 41, the solar radiation during a summer period in Bucharest and Strasburg are presented. The average solar radiation for the two regions is around 600–900 W/m^2. These cities can be considered representative of moderate ambient conditions in the EU as their climate is somewhere between the extreme summers of the southern regions and milder summer conditions experienced in northern countries.

Figure 41. Solar radiation for Bucharest and Strasburg for a summer period. (Barbu et al., 2019)



Taking everything into consideration, in the case of the current testing methodology, a value of 750 W/m^2 is suggested in the case of moderate summer conditions for solar radiation.

5.3.4 Moderate ambient conditions

The conditions defined in the previous sections are representative of moderate conditions in the EU27 and are summed up in Table 44. Depending on the regions these average conditions could be lower or higher.

Table 44. Moderate summer ambient conditions in EU27.

Conditions	Value
Ambient temperature (°C)	26
Relative humidity (%)(%)	50
Solar radiation (W/m^2)	750

5.3.5 Equivalent ambient conditions

For the solar radiation simulation, solar lamps would be required by the testing facilities, which in most cases are absent across the EU. Additionally, the introduction of such a requirement would result in high cost. As technologies related to glazing and reflective paints are out of the scope this EI scheme, only the increase in the LD due to solar flux inside the vehicle cabin needs to be considered in the testing methodology.

In this context, equivalent ambient conditions without solar lamps, that could lead to the same load demand as in the case where solar radiation is present should be estimated. The main parameters examined are the test cell ambient temperature and relative humidity and the option to add an additional heat source inside the vehicle cabin, in order to increase the load demand. The cabin's load demand (LD), i.e., the evaporator's work, and the compressor’s work are the two values used to determine the equivalent ambient conditions, as they need to result in similar MAC system energy consumption as in the case where solar radiation is present. Additionally, the CP values are examined, since it characterises the system’s energy efficiency. In order to get the same load demand without solar radiation, the ambient temperature and/or the relative humidity of the test cell should be increased. Since it is challenging and costly to control these parameters in the test cell, an alternative solution was examined by the study team.

The use of an additional heat source inside the vehicle cabin is examined. This is expected to lead to similar LD and consequently compressor work as in the case where solar radiation is present, without greatly affecting the system's CP. A sensitivity analysis to identify the value of the additional heat source took place and the results are presented in Table 45. The baseline scenario (scenario 0) includes 30 minutes of soaking with closed windows and the MAC off, while the solar radiation is 750 W/m^2. The same period of soaking is simulated in the cases of the additional heat source.

Table 45. Sensitivity analysis results for estimating equivalent ambient conditions.

	Scenario	Solar radiation (W/m^2)	Additional heat source (W)	Load demand (kWh)	W_{comp} (kWh)	CP (-)
Moderate ambient conditions (baseline)	0	750	0	0.981	0.270	3.634
Additional heat source inside the cabin	2	0	580	0.977	0.266	3.672
	3	0	585	0.982	0.268	3.669
	4	0	590	0.986	0.269	3.665

An additional point towards selecting an additional heat source inside the vehicle cabin to estimate the equivalent ambient conditions is that the increase in the LD due to solar flux inside the cabin is what has to be simulated and it would be more straightforward to add an additional heat source inside the vehicle cabin. More specifically, based on Table 45, the closest results to the baseline scenario are obtained for an additional heat source between 580W and 590W. To estimate the exact value, further sensitivity analysis was performed and resulted to 585W for the additional heat source. The load demand, compressor's work and CP are presented in Table 46.

Table 46. Load demand, compressor's work and CP for 585 W of additional heat source.

	Load demand (kWh)	W_{comp} (kWh)	CP (-)
Moderate ambient conditions (baseline)	0.981	0.270	3.634
Additional heat source of 585 W	0.982 (0.93 %)	0.268 (-0.02 %)	3.664 (0.82 %)

(in the parentheses the relative differences from the baseline scenario are noted).

Taking all the above into consideration the estimated equivalent ambient conditions are noted in Table 47. In the additional heat source, the metabolic load of the driver is not included (200W).

Table 47. Equivalent ambient conditions without solar radiation.

	Ambient and cabin soak temperature (°C)	Relative humidity (%)	Solar radiation (Vertical) (W/m^2)	Additional heat source (W)
Equivalent ambient conditions	26	50	0	585

The additional heat source is suggested to be placed on the front passenger seat. The placement is based on the fact that most temperature sensors are usually placed on the front part of the vehicle and it is also the part of the vehicle that would be mostly affected by the solar load. In general, the placement is not expected to greatly affect the results, as the purpose of the additional heat source is to simulate the additional load that would be present in the case of solar lamps.

5.4 Cabin target temperature

Thermal comfort is achieved by ensuring an ambient temperature between 20 °C and 22 °C depending on the activity level and clothing, by avoiding human touch with too hot or too cold surfaces and by avoiding air currents (high air velocity). (Helerea E., 2009)

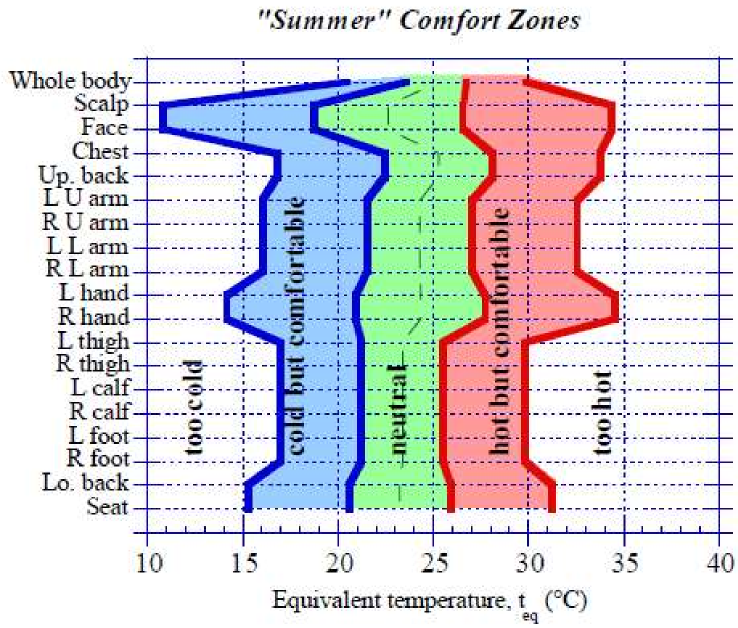
According to ASHRAE 55 a neutral temperature setting (generally perceived as not too hot or too cold), is 22 ° C. This is also the set temperature inside the vehicle cabin during AC 17 testing. Finally, according to ASHRAE 55 standard, RH between 30% and 70% does not have a great impact on thermal comfort. If RH is below 30%, a dry sensation is sensible and has a bad influence on mucous membranes. On the other hand, if RH is over 70%, it will prevent sweat evaporation causing overall discomfort to the passengers.

In a study by Nilsson H. (2004) the thermal comfort inside the vehicle's cabin was assessed by using a manikin model. The measurements on the manikin's surface were correlated with thermal comfort ratings. In Figure 42 three zones are distinguished, characterising thermal comfort within the vehicle's cabin under summer conditions as a function of the equivalent temperature which is defined by the formula below.

$$t_{eq} = t_s - R_T * \ddot{q_T}$$

Where t_{eq} is the equivalent temperature (°C), t_s is the manikin surface temperature (°C), R_T is the total insulation based on clothing (m^2 *°C/W), $\ddot{q_T}$ is the measured manikin heat loss during the actual conditions (W/m^2).

Figure 42. Thermal comfort zones inside the vehicle's cabin during summer conditions. (Nilsson H., 2004)



For light clothing (1.1 clo), R_T=0.167 m^2K/W and q_T=56 W/m^2, and manikin surface temperature ts~34 °C (308.15 K), the ambient temperature is around 22 °C (296.15 K) and this is also the suggested target temperature inside the cabin in the proposed testing methodology.

5.4.1 Manual MAC systems

- The driver controls the MAC system's operation through the vehicle's dashboard. Usually, the user selects the target temperature, and the fan speed, air distribution, air intake control are automatically set to maintain the selected interior temperature. This task is done through various sensors and strategies for cooling and heating and are part of the climate control system. In some vehicles, the climate control is absent, the MAC system is called manual and the selection of these parameters is performed by the driver. This includes:
- the selection of the temperature which is usually on a scale of hot to cold, meaning that it is not possible to set a specific target temperature;
- the blower fan speed; and,
- recirculation on/off (if it is present).

Manual MAC systems are not different than those equipped with climate control, except for the additional sensors and control system which are present in the latter (Toyota motors sales, U.S.A., Inc., Air conditioning and climate control course 752). Since the selection of a specific target temperature may not be available, a separate set of MAC system settings is proposed for manual MAC systems and is based on thermal comfort. At the start of a trip, in the case of a hot day, the temperature inside the vehicle is higher than the ambient mainly due to solar radiation. The MAC system usually operates at maximum capacity in order to quickly cool the cabin. This can be done in the first 3-4 minutes. After this initial intensive operation, the temperature inside the vehicle cabin is already lowered and closer to conditions that result to passengers' thermal comfort. The load demand and the blower fan speed are then reduced to maintain the target conditions.

A similar operation strategy is proposed in AC17 for manual systems. More specifically, the temperature control is set at the maximum option (full cold) and the airflow to recirculate (if the system is equipped with this option). Then, the fan speed is reduced at 50% after around 3-4 minutes (between 186 and 204 seconds of the driving cycle) of operation and the airflow is set to fresh air (if the system is equipped with this option) and select the proper temperature setting to achieve 13 °C of air from the dashboard outlet.

The suggested ambient conditions for the present testing methodology are similar to the ambient conditions of AC17 testing, as showed in Table 48. As thermal comfort principles are global, a similar control strategy for manual MAC systems is suggested for the EI MAC testing procedure. The two steps are described in Table 49.

Table 48. Ambient conditions comparison between MAC EI testing methodology and AC17.

	MAC EI testing methodology	AC17
Test cell temperature (°C)	26	25
Test cell relative humidity (%)	50	50
Solar radiation (W/m^2)	0	805
Additional heat load inside the cabin (W)	585 (equivalent to 750 W/m^2 of solar radiation)	-
Driving cycle	WLTC	SC03

Table 49. Control strategy during testing for manual MAC systems.

Time (s)	Temperature control setting	Fan speed	Recirculation (if present)
0 - 200	Max (full cold)	Max	On
200 – 1800	13°C at the outlet of the dashboard	50%	Off

5.5 Climate control sensors

The climate control system performs based on the reading from various sensors installed on the vehicle. If such sensors exist, the applicant for the eco-innovation should inform the TA authorities and measures should be taken by the applicant so that the climate control system works properly under the equivalent ambient testing conditions. Some examples of these sensors and the corresponding measures are:

- **Solar sensors**
- The reference value of solar radiation should reach the sensing element(s) of the sensor(s) during the test with MAC activated. The vehicle shall not receive any solar radiation during the proposed MAC testing.
- **Seat occupancy sensor**

- Average seat occupancy rate is under 1.5. Since it is larger than one, seat occupancy should be set at 2.
- **Humidity sensor**
- The reference value of humidity for ambient and cabin conditions separately should reach the sensing element(s) of the sensor(s) during the test with MAC activated.

5.6 Requirements for testing, soaking area and CO_2 emissions calculation

The basic requirements for the testing and soaking area, the test vehicle, the dynamometer settings and fuel specifications are the same as the type 1 test. More specifically, the measurement of ambient, dilution and sampling system temperatures are performed with an accuracy of ± 1.5 °C. And the relative humidity measurements with an accuracy of ± 5%. Specifications for atmospheric pressure and specific humidity measurement are also included. The vehicle shall be presented in good technical condition and driven between 3000 and 15000 km before testing and the test fuel specifications are described in detail. More specifically, the fuel used is reference fuel according to Annex B3 to UN Regulation No 154.

For all powertrains the testing methodology is described in Annex B6 of UN Regulation No 154. There is a major difference between testing ICEVs or HEVs and PHEVs, as in the latter there are 4 different options for testing as described in Annex B8 of UN Regulation No 154. These include charge depleting, charge sustaining modes and combinations of them.

The calculation of CO_2 emissions is performed according to Annex B7 for ICEVs, HEVs and for PHEV. Additional information for the calculation of CO_2 emissions of PHEVs is located in Annex B8.

For ICEVs and HEVs, the proposed testing methodology is no different than the one described in Regulation (EU) 2017/1151, except for the testing conditions which are substituted with the equivalent ambient conditions (Table 47) and the requirement for the MAC to be on. The exact regulatory references are laid out in Table 50 for what concerns the testing and soaking area, the preconditioning, the soaking and testing. Technical details of the type 1 test are set out in UN Regulation 154 and European legislation refers to it. Thus, Table 50 presents references in UN Regulation 154.

Table 50. Requirements for testing in UN Regulation No 154.

Requirement	UN Regulation No 154	Comments
Basic requirements for testing and soaking area	Annex B6, §2.2	Measurement of ambient, dilution and sampling system temperatures with an accuracy of ± 1.5 °C Specifications for atmospheric pressure and specific humidity measurement.
Test vehicle requirements	Annex B6, §2.3	The vehicle shall be presented in good technical condition and driven between 3000 and 15000 km before testing. Reference fuel specifications.
Preconditioning	Annex B6, §2.6	Drive vehicle under one WLTC cycle on the dynamometer. More WLTCs might be requested by the manufacturer or TA

		authority to bring the vehicle and its control systems to a stabilized condition.
Soaking	Annex B6, §2.8	Equivalent ambient conditions as described in Table 47.
Testing	Annex B6, §2.8	

It is also suggested to measure temperature inside the vehicle cabin to ensure the target temperature of 22 °C is reached. The temperature inside a vehicle cabin is usually inconsistent. The measured temperature is suggested to be in the place of the driver's head, as this plays an important role in thermal comfort. The measurement of the cabin temperature is suggested to follow the measurement tolerance of the temperature inside the test cell (± 1.5 °C). The cabin temperature should reach the target temperature after approximately 200s from the beginning of the test. This is the same time when the fan speed in manual systems is suggested to be lowered.

6 Task 5 – Revision of the eco-innovation cap

6.1 Task aims and objectives

According to Article 11 of Regulation (EU) 2019/631 (prior to the amendments introduced by Regulation (EU) 2023/851), the potential reduction of eco-innovations over a manufacturer's average specific CO_2 emissions could not exceed 7 g CO_2/km. Additionally, Article 11(1) foresaw a possible revision of this cap with effect from 2025 onwards to take into account technological developments while ensuring a balanced proportion of the level of that cap in relation to the average specific emissions of CO_2 of manufacturers. Based on this, the objective of this task was to assess the need to adjust the cap, in view of the level of EI savings that may be attained by MAC systems.

However, during the course of this study, Regulation (EU) 2019/631 was revised by the co-legislators, who agreed on stricter CO_2 emission performance standards for new passenger cars and light commercial vehicles, adopted on 19 April 2023 as Regulation (EU) 2023/851.

The amendments adopted notably revise downwards the eco-innovation cap down to 6 g CO_2/km per year between 2025 and 2029 and to 4 g CO_2/km per year between 2030 and 2034 (EU, 2023). In addition, the empowerment for the Commission to adjust the cap is now limited to a revision of the values downwards, taking into account technological developments while ensuring a balanced proportion of the level of that cap in relation to the average specific emissions of CO_2 of manufacturers.

6.2 Revision of the cap

Since a reduction of the cap has already been included in the legislation, the proposed possible revision can only be in the downwards direction. It is suggested by the study team that the EI cap may follow the same trend as the CO_2 emission targets. The CO_2 targets are 55% CO_2 emission reduction target for new cars and 50% for new vans by 2030 compared to 2021 level. As a result, a further decrease of the cap below 4 g CO_2/km is not suggested, as this reduction is already in line with the CO_2 targets.

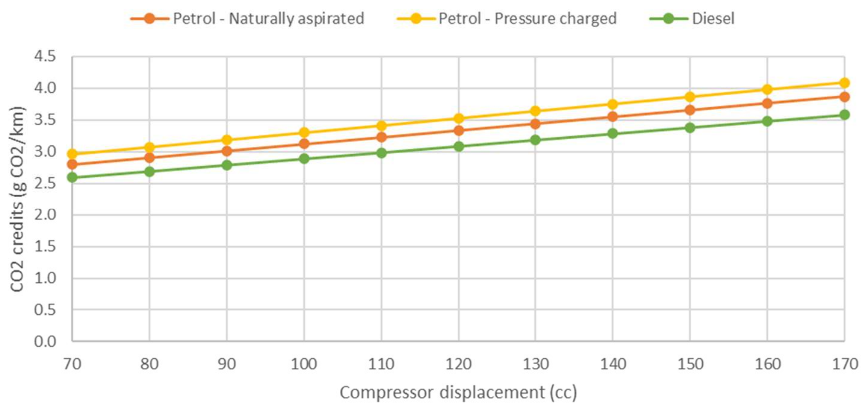
6.3 Possible EI savings attained by MAC systems

Except for the revision of the cap, the amount of CO_2 credits that could be gained by utilizing innovative MAC technologies in the EI scheme is estimated. For this reason, the maximum theoretical CO_2 savings that could be obtained from MAC EI is estimated. Then, scenarios of more efficient MAC systems are examined. These two approaches provide insight on what part of the total CO_2 credits could come from utilizing innovative MAC technologies.

6.3.1 Theoretical maximum CO_2 savings

Based on the proposed approach, the maximum CO_2 credits would be rewarded to a MAC system that has virtually no energy consumption. This is a theoretical case, as such a system cannot be created, but it provides valuable information related to the limits of the maximum CO_2 credits that could potentially be awarded through this upcoming eco-innovation. In Figure 43 these theoretical maximum CO_2 credits are presented for different fuels and range approximately from 2.5 g CO_2/km to 4 g CO_2/km.

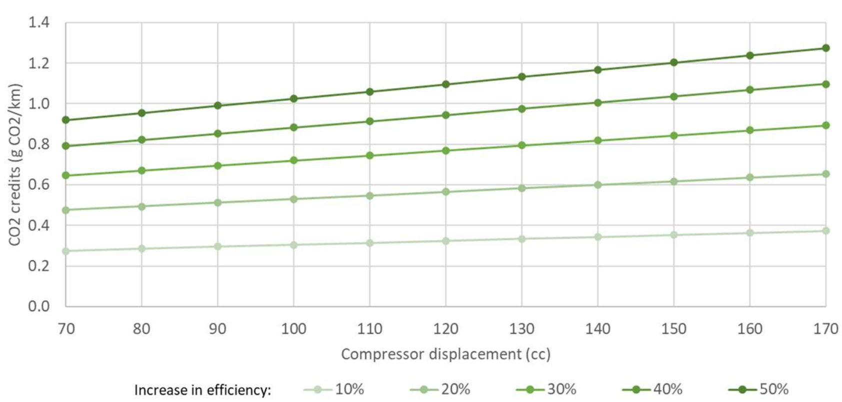
Figure 43. Theoretical maximum CO_2 credits for ICEVs.



6.3.2 MAC efficiency improvement and CO_2 credits

The amount of CO_2 credits depends on the MAC system's efficiency, as some innovations that could affect the load demand are out of the scope (e.g. reflective paints). In Figure 44, the CO_2 credits that could be rewarded in scenarios where the system's efficiency increases up to 50% are presented, for a naturally aspirated petrol ICEV. The maximum credits are approximately 1.3 g CO_2/km in the most optimistic scenario. Technologies that would help improve the system's efficiency and reach these savings are for instance better performing compressors, more efficient blower fans and changes to the control system.

Figure 44. CO_2 credits as a function of the increase in the system's efficiency



7 Conclusions

The objective of this study was to provide support for the development of a procedure for determining the CO_2 savings from the use of efficient MAC systems fitted in passenger cars and light commercial vehicles in the framework of the eco-innovation scheme under Regulation (EU) 2019/631. Furthermore, it aimed to provide support to the European Commission in preparing a possible adjustment of the 7 g CO_2/km cap on eco-innovation credits and provide a view of the level of eco-innovation savings that may be attained by efficient and innovative MAC systems.

The first step was to complete a market survey along with a literature review, where the characteristics of the current and possible future MAC technologies were identified. This was followed by an assessment of the regulations around the world where the CO_2 savings of innovative MAC systems are assessed. The most relevant regulatory elements were identified in the AC17 testing methodology and were used as a basis to define a European methodology to determine CO_2 emissions savings from efficient and innovation MAC systems.

The approach for calculating CO_2 savings from innovative MAC systems is based on estimating the difference of CO_2 emissions coming from the operation of the MAC system between the baseline vehicle and the vehicle equipped with the EI. The baseline vehicle was determined in accordance with the market survey and is defined in a technologically neutral way, relying on the MAC system’s energy efficiency. The estimated difference in CO_2 emissions is then multiplied by the UF (17%) which represents the use of the vehicle under ambient conditions where cooling might be needed.

The proposed testing methodology for measuring the CO_2 savings for a vehicle equipped with an innovative MAC system is based on the type 1 test as described in Regulation (EU) 2017/1151. The ambient conditions of the test are different than the ones described in the aforementioned Regulation and the MAC is required to be active during the test. The proposed ambient conditions were estimated based on historic weather data in the EU. Initially the testing conditions included solar flux simulation using solar lamps. After the feedback received from stakeholders and experts on the field, it was decided that an alternative to the use of solar lamps would be part of the proposed methodology. Hence, equivalent ambient conditions were calculated using an additional heat source placed on the front passenger seat to simulate the additional load demand that would be present if the solar radiation was considered.

The amount of CO_2 credits that could be obtained from innovative MAC systems depends on the system’s efficiency, as certain innovations that could affect the load demand are out of the scope (e.g. reflective paints). Several scenarios were examined where the system’s efficiency increases from 10% to 50% from the baseline. The maximum savings are estimated to be about 1 g CO_2/km for the most efficient systems assessed.

As regards the possibility to adjust the EI cap set in the Regulation, this task was revised taking into account the amendments introduced by Regulation (EU) 2023/851, which revise the EI cap downwards to 6 g CO_2/km between 2025 and 2029 and to 4 g CO_2/km between 2030 and 2034. This follows the goals for reduction of CO_2 emissions from cars and vans by 55% and 50% respectively by 2030, in comparison to 2021 levels, so no further adjustment of the cap is deemed necessary at this stage.

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9 Abbreviations

AER	All-Electric Range
BEV	Battery Electric Vehicle
BLM	Brushless Motor
CAFC	Corporate Average Fuel Consumption
CD	Charge-depleting
CP	Coefficient of Performance

CS	Charge-sustaining
EC	Energy Consumption
EI	Eco-innovation
EPA	Environmental Protection Agency (USA)
ESB	Electric Scroll Type B
EU	European Union
FC	Fuel Consumption
FTP	Federal Test Procedure
GHG	Greenhouse Gas
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
HVAC	Heating, Ventilation and Air Conditioning
ICEV	Internal Combustion Energy Vehicle
JRC	Joint Research Centre
LCCP	Life Cycle Climate Performance
LD	Load Demand
MAC	Mobile Air Conditioning
MC	Modified Conditions
MIIT	Ministry of Industry and Information Technology (China)
PEMS	Portable Emissions Measurement Systems
PHEV	Plug-in Hybrid Electric Vehicle
PI	Proportional Integral
RDE	Real Driving Emissions
TA	Type Approval
UF	Usage Factor
VCR	Vapour Compression Refrigeration
WLTP	Worldwide harmonised Light vehicle Test Procedure

ANNEXES

Annex 1 EMISIA questionnaire aimed at vehicle manufacturers

Questionnaire on "Support for the preparation of a procedure to certify CO_2 savings from the use of efficient Mobile Air Conditioning (MAC) systems"

Background

Article 11 of Regulation (EU) 2019/631 setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles (vans) provides a possibility for manufacturers to take into account CO2 savings from certain innovative technologies, referred to as "eco-innovations", in order to meet their specific CO2 emissions targets. Such technologies have to deliver CO2 savings, which cannot, or only partially, be determined during the type approval emission test (WLTP). The total contribution of CO2 savings from 'eco-innovations' to reducing the average specific emissions of CO2 of a manufacturer may be not more than 7 g CO2/km. Commission Implementing Regulations (EU) No 725/2011 and (EU) No 427/2014 establish the detailed procedures for the approval and certification of eco-innovations for passenger cars and light commercial vehicles, respectively.

According to Article 11(3) of Regulation (EU) 2019/631, from 1 January 2025 on, efficient Mobile Air Conditioning (MAC) systems will be eligible technologies in the framework of the eco-innovation scheme. In order to allow manufacturers or component suppliers to apply for such technologies to be approved as eco-innovations, procedures to do so need to be established, in particular the testing methodology for determining the CO2 savings achieved by implementing such systems.

Objective

The European Commission (DG CLIMA) has assigned ICF S.A. and EMISIA with the task to support the development of a procedure for determining the CO2 savings from the use of efficient MAC systems fitted in passenger cars and light commercial vehicles in the framework of the eco-innovation scheme under Regulation (EU) 2019/631.

The scope of assignment comprises the following major components:

Critically review and asses the state-of-the-art technologies and improvements of MAC systems in cars/vans today and technologically feasible to appear in market at mid-term

Investigate and learn from relevant developments and testing practises around the world, regarding CO2 from MAC systems, especially in light of their relevance to the EU needs

Define today's available technology as a benchmark, to better asses the various MAC technologies, their characteristics and level of performance/innovation

Develop and propose testing approaches and methods, for accurately determining CO2 savings of MAC, building on past relevant studies

Re-evaluate the current eco-innovations cap and asses the possibility of an adjustment, particularly in view of the level of eco-innovation savings that may be attained by state-of-the-art MAC systems

What we need from you – guidelines

We would like to invite you to contribute to this project and provide your feedback related to:

The state-of-the-art in MAC systems
Testing procedures of MAC systems

- For this reason, we prepared a short list of questions to make clear what kind of information would be useful in our study.
- We propose to **schedule a call** to have a better understanding of the study's objectives and provide your feedback.
- If you prefer providing your views in writing, please take your time to fill in the questionnaire and add any other suggestions or comments you consider necessary.
- You can substantiate your input (if possible) by documents, references to literature and practical examples, own measurements, or any other suitable information that can help.
- Feel free to forward the questionnaire to other relevant experts in your company/institution.

Please feel free to contact Giorgos Mellios (giorgos.m@emisia.com) or Nikos Kapetanios (nikos.k@emisia.com) for any additional information.

Overview of the questionnaire

The questions are grouped in two categories.

- The first refers to information about implemented and under development MAC system technologies. For this reason, a type of grouping of MAC systems or components is suggested, based on their potential as eco-innovation.
- The second group of questions is related to the testing of MAC systems or their components for measuring their energy/fuel efficiency.

Questions

Section 1: Current and under development MAC systems
United Stated (US) Environmental Protection Agency (EPA) developed a **list of air conditioning technologies that can lead to CO2 savings (**40 CFR § 86.1868-12, list of technologies for 2017 and later models**)**. Each technology is described and accompanied with the savings both for passenger cars and light trucks. We suggest the categorization of MAC technologies based on their eco-innovation potential to be based on this list, as it represents the state-of-the-art. We propose three categories: A, B, C, as described below.

Category A

This category includes all MAC technologies that are widely sold and cannot be categorized as eco-innovative. This means that they are not included in the mentioned list and they cannot lead to CO2 savings.

Category B

This category includes all MAC technologies that are well established and can lead to CO2 savings. This category contains all the technologies mentioned in the EPA list.

Category C

This final category includes all MAC technologies that are new or under development and could lead to CO2 savings. These are innovative technologies that do not belong in the mentioned list.

Table 1.1 *Description of the suggested categorization of MAC technologies*

Category	Technology is in the EPA list?	Technology can lead to CO2 credits?
A	no	no
B	✔	✔
C	no	✔

Having in mind these categories please answer the following questions.

Q1. Are there components installed in the MAC systems of sold vehicles that are covered by this list? (**Category B**)?

□ Yes □ No

Q2. Are there components installed in the MAC systems of sold or under development vehicles that could lead to CO2 credits but are not included in this list? (**Category C**)

□ Yes □ No

Q3. Are there vehicles with MAC systems that do not belong to any of the two previous categories? These systems do not have technologies that belong in the list and they could not lead to CO2 credits. (**Category A**)

□ Yes □ No

Q4. If you answered "Yes" in Q1, Q2 or Q3, please provide information for the components or systems that belong to each mentioned category.

For each one, please provide:

• Information related to the compressor, evaporator, condenser, blower, sensors, control system.

- Performance characteristics (e.g., efficiency, energy source and consumption)
- Type of product and supplier (to make a link between data provided from vehicle manufacturers and suppliers)
- Operation logic and energy saving strategies/mode.

• information regarding the **market penetration** (absolute or percentage of the total of this product category)**.**

• If available, information related to the market sales trends related to any **geographical or climactic data.**

• information regarding the **vehicle characteristics** (e.g., cabin volume, energy characteristics of glazing (heat transfer coefficient, radiation blocking etc.), air duct number type and architecture).

Please provide above information per powertrain type (ICE, HEV, PHEV), if applicable.

Section 2: Testing methodologies

There are three main options for determining the CO2 savings of efficient MAC:

1. **Whole vehicle testing**, i.e. a test run under controlled ambient conditions establishing a well-defined load on the MAC systems to be tested (chassis dynamometer approach)
2. **Separate component testing**, i.e. determining the CO2 savings of MAC through benchmarking of individual components/subsystems, instead of whole vehicle tests (component test bench approach)
3. A **combination** of both approaches

The application for an approval of an innovative technology as eco-innovation has to include a testing methodology that is suitable to determine and quantify the CO2 saving effect of the technology. The methodology should provide accurate and verifiable results. Some factors that can determine the suitability of a testing method are:

1. **Practicality** – Is the test practical and technically feasible to apply?
2. **Robustness** – Will it always identify the strategies it is expected to?
3. **Effectiveness** - Will the result be clear and identifiable?

4. **Efficiency** – Which procedures have the potential to identify the greatest range of strategies for least complexity?
5. **Cost impact** – How do they compare for likely cost for building infrastructure and performing the test?
6. **Resource/time impact** – What is the burden on the type-approval authorities and stakeholders in terms of time and resource requirement?

2.1 Whole vehicle testing

An example of whole vehicle testing is the **AC17** air conditioning efficiency test procedure (40 CFR § 1066.845). According to this procedure, the whole vehicle is tested with and without the use of the MAC system. In this way the extra energy/fuel consumption coming from the MAC system is calculated.

Q5. Please evaluate this methodology according to the provided criteria above (practicality, robustness, effectiveness, efficiency, cost impact, resources/time impact). If these criteria are not considered suitable for the evaluation, feel free to use your own.

Q6. Do you use a different method for measuring the system's efficiency? If yes, please describe it.

Q7. Are there any components or a complete system which can deliver CO2 benefits that cannot be captured by the existing testing methodologies? If yes, what testing methodology would you suggest?

2.2 Component testing

Component testing refers to testing the system's components separately and below are some examples of component testing methodologies of a compressor. The questions below refer to all MAC system components.

Compressor testing

The performance of an MAC system compressor can be normally tested on a test bench. To determine the CO2 reductions that can be attributed to the use of a tested compressor, it is necessary to establish testing procedure to be followed for determining the efficiency of compressor.

To that end, compressor performance test procedures have been developed internationally, the most notable are:

1. ISO 917: Testing of refrigerant compressors 2. DIN EN 13771-1: Compressors and condensing units for refrigeration - Performance testing and test methods - Part 1: Refrigerant compressors 3. ASHRAE23: Methods of Testing for Rating Positive Displacement Refrigerant Compressors and Condensing Units Please answer each question separately for the various MAC system components.
Q9. Do you perform testing of individual components for measuring their energy/fuel efficiency? If yes, please briefly mention a list of these methodologies.
Q10. Do you have any suggestions for alternative component testing methodologies for measuring their energy/fuel efficiency? If yes, please briefly mention a list of these methodologies.

Annex 2 EMISIA questionnaire aimed at MAC system suppliers

Background

Article 11 of Regulation (EU) 2019/631 setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles (vans) provides a possibility for manufacturers to take into account CO2 savings from certain innovative technologies, referred to as "eco-innovations", in order to meet their specific CO2 emissions targets. Such technologies have to deliver CO2 savings, which cannot, or only partially, be determined during the type approval emission test (WLTP). The total contribution of CO2 savings from 'eco-innovations' to reducing the average specific emissions of CO2 of a manufacturer may be not more than 7 g CO2/km. Commission Implementing Regulations (EU) No 725/2011 and (EU) No 427/2014 establish the detailed procedures for the approval and certification of eco-innovations for passenger cars and light commercial vehicles, respectively.

According to Article 11(3) of Regulation (EU) 2019/631, from 1 January 2025 on, efficient Mobile Air Conditioning (MAC) systems will be eligible technologies in the framework of the eco-innovation scheme. In order to allow manufacturers or component suppliers to apply for such technologies to be approved as eco-innovations, procedures to do so need to be established, in particular the testing methodology for determining the CO2 savings achieved by implementing such systems.

Objective

The European Commission (DG CLIMA) has assigned ICF S.A. and EMISIA with the task to support the development of a procedure for determining the CO2 savings from the use of efficient MAC systems fitted in passenger cars and light commercial vehicles in the framework of the eco-innovation scheme under Regulation (EU) 2019/631.

The scope of assignment comprises the following major components:

1. Critically review and asses the state-of-the-art technologies and improvements of MAC systems in cars/vans today and technologically feasible to appear in market at mid-term
2. Investigate and learn from relevant developments and testing practises around the world, regarding CO2 from MAC systems, especially in light of their relevance to the EU needs
3. Define today's available technology as a benchmark, to better asses the various MAC technologies, their characteristics and level of performance/innovation
4. Develop and propose testing approaches and methods, for accurately determining CO2 savings of MAC, building on past relevant studies
5. Re-evaluate the current eco-innovations cap and asses the possibility of an adjustment, particularly in view of the level of eco-innovation savings that may be attained by state-of-the-art MAC systems

What we need from you – guidelines

We would like to invite you to contribute to this project and provide your feedback related to:

1. The state of the art in MAC systems
2. Testing procedures of MAC systems

- For this reason, we prepared a short list of questions to make clear what kind of information would be useful in our study.
- We propose to **schedule a call** to have a better understanding of the study's objectives and provide your feedback.
- If you prefer providing your views in writing, please take your time to fill in the questionnaire and add any other suggestions or comments you consider necessary.
- You can substantiate your input (if possible) by documents, references to literature and practical examples, own measurements, or any other suitable information that can help.
- Feel free to forward the questionnaire to other relevant experts in your company/institution.
- Please feel free to contact Giorgos Mellios (giorgos.m@emisia.com) or Nikos Kapetanios (nikos.k@emisia.com) for any additional information.

We would appreciate receiving your feedback until 29 April 2022.

Overview of the questionnaire

The questions are grouped in two categories.

- The first refers to information about implemented and under development MAC system technologies. For this reason, a type of grouping of MAC systems or components is suggested, based on their potential as eco-innovation.
- The second group of questions is related to the testing of MAC systems or their components for measuring their energy/fuel efficiency.

Questions

Section 1: Current and under development MAC systems

United Stated (US) Environmental Protection Agency (EPA) developed a **list of air conditioning technologies that can lead to CO_2 savings (**40 CFR § 86.1868-12, list of technologies for 2017 and later models**)**. Each technology is described and accompanied with the savings both for passenger cars and light trucks. We suggest the categorization of MAC technologies based on their eco-innovation potential to be based on this list, as it represents the state-of-the-art. We propose three categories: A, B, C, as described below.

Category A

This category includes all MAC technologies that are widely sold and cannot be categorized as eco-innovative. This means that they are not included in the mentioned list and they cannot lead to CO2 savings.

Category B

This category includes all MAC technologies that are well established and can lead to CO2 savings. This category contains all the technologies mentioned in the EPA list.

Category C

This final category includes all MAC technologies that are new or under development and could lead to CO2 savings. These are innovative technologies that do not belong in the mentioned list.

Table 1.1 Description of the suggested categorization of MAC technologies

Category	Technology is in the EPA list?	Technology can lead to CO2 credits?
A	no	no
B	✔	✔
C	no	✔

Having in mind these categories please answer the following questions.

Q1. Are there products in your portfolio that are covered by the mentioned list? (**Category B**)?

□ Yes □ No

Q2. Are there are products in your portfolio or under development that could lead to CO2 credits but are not included in this list? (**Category C**)

□ Yes □ No

Q3. Are there products in your portfolio that do not belong to any of the two categories mentioned? For example, products that are widely sold but they are neither included in the mentioned list, nor can lead to CO2 credits. (**Category A**)

□ Yes □ No

Q4. If you answered “Yes” in Q1, Q2 or Q3, please provide information for the products that belong to each mentioned category.

For each product, please provide:

• **Specifications** (e.g., efficiency, energy consumption)

• **Number of sales** (absolute or percentage of the total of this product category)

Section 2: Testing methodologies

Vehicle manufacturers have the right to apply innovative technology to be approved as an eco-innovation, however, they are obligated to determine the CO2 savings using a proper methodology (testing and calculation). There are three main options for testing:

1. **Whole vehicle testing**, i.e. a test run under controlled ambient conditions establishing a well-defined load on the MAC systems to be tested (chassis dynamometer approach)

2. **Separate component testing**, i.e. determining the CO2 savings of MAC through benchmarking of individual components/subsystems, instead of whole vehicle tests (component test bench approach) 3. A **combination** of both approaches The application for an approval of an innovative technology as eco-innovation has to include a testing methodology that is suitable to determine and quantify the CO2 saving effect of the technology. The methodology should provide accurate and verifiable results. Some factors that can determine the suitability of a testing method are: 1. **Practicality** – Is the test practical and technically feasible to apply? 2. **Robustness** – Will it always identify the strategies it is expected to? 3. **Effectiveness** - Will the result be clear and identifiable? 4. **Efficiency** – Which procedures have the potential to identify the greatest range of strategies for least complexity? 5. **Cost impact** – How do they compare for likely cost for building infrastructure and performing the test? 6. **Resource/time impact** – What is the burden on the type-approval authorities and stakeholders in terms of time and resource requirement?
2.1 Whole vehicle testing An example of whole vehicle testing is the **AC17** air conditioning efficiency test procedure (40 CFR § 1066.845). According to this procedure, the whole vehicle is tested with and without the use of the MAC system. In this way the extra energy/fuel consumption coming from the MAC system is calculated.
Q5. Please evaluate this methodology according to the provided criteria above (practicality, robustness, effectiveness, efficiency, cost impact, resources/time impact). If these criteria are not considered suitable for the evaluation, feel free to use your own.
Q6. Do you use a different method for measuring the system's efficiency? If yes, please describe it.
Q7. Are there any components or a complete system which can deliver CO2 benefits that cannot be captured by the existing testing methodologies? If yes, what testing methodology would you suggest?

2.2 Component testing Component testing refers to testing the system's components separately and below are some examples of component testing methodologies of a compressor. The questions below refer to all MAC system components. Compressor testing The performance of an MAC system compressor can be normally tested on a test bench. To determine the CO2 reductions that can be attributed to the use of a tested compressor, it is necessary to establish testing procedure to be followed for determining the efficiency of compressor. To that end, compressor performance test procedures have been developed internationally, the most notable are: 1. ISO 917: Testing of refrigerant compressors 2. DIN EN 13771-1: Compressors and condensing units for refrigeration - Performance testing and test methods - Part 1: Refrigerant compressors 3. ASHRAE23: Methods of Testing for Rating Positive Displacement Refrigerant Compressors and Condensing Units Please answer each question separately for the various MAC system components.
Q8. Do you perform testing of individual components for measuring their energy/fuel efficiency? If yes, what testing method do you use?
Q9. Do you have any suggestions for alternative component testing methodologies for measuring their energy/fuel efficiency?

Annex 3 JRC Questionnaire

A3.1 Mobile Air-Conditioning Systems - Main Questionnaire

Please provide the following information based on market data covering new passenger cars and vans registered between 2010-2021

Detailed information can be provided in the accompanying Excel file (sheet "SURVEY")

Q.0	Manufacturer name
A.0	
Q.1.	A list of the MAC systems installed in light-duty vehicles in the market in the last 10-20 years, including their main evolution. (see Excel file)
A.1.	
Q.2.	A list with the influencing parameters of the MAC systems from Q.1. (see Excel file)
A.2.	
Q.3.	Which are the components used in the MAC systems from Q.1? Please provide a list of the characteristics of these components, including their efficiency. (see Excel file)
A.3.	
Q.4.	Which vehicle category do the vehicles with the MAC systems installed from Q.1 belong to? (M1, N1)
A.4.	
Q.5.	Which vehicle type do the vehicles with the MAC systems installed from Q.1 belong to? (ICE, HEV, PHEV)
A.5.	
Q.6.	Which vehicle's powertrain architecture/configuration does the vehicles with the MAC systems installed from Q.1 belong to?
A.6.	
Q.7.	What is the market penetration (% of new vehicles registered) for each year (or range of years) of the MAC systems from Q.1?
A.7.	
Q.8.	In which countries were the vehicles with the mentioned MAC systems sold?
A.8.	
	Methodology for CO_2-savings calculation
Q.9.	Would it be possible to implement the test procedure set out in the study https://op.europa.eu/en/publication-detail/-/publication/47cbda8a-66e0-4f9b-ab4f-0bc2b17c4b27 with regard to the MAC equipment installed on your vehicles? What would be the challenges or problems to do so (if any)?

A.9.	
Q.10.	Would it be possible to assess the MAC CO_2 savings by testing the separate components? What would be the limitations with regard to the implementation of such approach? Could this approach be applied to different vehicle architectures?
A.10.	
Q.11.	Please provide customer studies to support determining the “usage factors” for MAC systems? Which geographical or ambient factors could affect those usage factors?
A.11.	

Thank you for your replies.

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