



**Analysis of the economic and environmental
consequences of a phase out or considerable
reduction leakage of mobile air conditioners**

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EXECUTIVE SUMMARY

Refrigerant emissions from R-134a and CO₂ AC systems

In a first section emissions are analyzed based on documents, papers, and surveys permitting to fix the repartition of the different emission types. Several surveys performed in Europe as well as in the U.S. lead to similar figures for emission estimates, even if small differences can be noticed.

Table 1 summarizes four possible scenarios. The first three (optimistic, realistic, and pessimistic) are based on actual available technologies. The main differences are based on better servicing practices, recovery at end of life (for the optimistic and realistic scenarios), and the development of improved leak-tight components.

The enhanced R-134a AC system reduces significantly the refrigerant charge from 750 to 590g, and much lower emission rates from components.

Table 1 – Summary of emission estimates

	Optimistic case (g of R-134a)	Realistic case (g of R-134a)	Pessimistic case (g of R-134a)
Capacity heels	7,5	15,0	45,0
Filling of the system	5,0	7,5	10,0
Fugitive emissions (incl. accidental rupture)	900,0	1287,0	1287,0
Emissions during servicing	198,0	409,0	621,0
Emissions at End Of Life	67,5	41,1	428,3
TOTAL (g of R-134a)	1178,0	1759,6	2391,3
TOTAL (kg eq. CO₂)	1531,4	2287,5	3108,6

The emissions range from **545 to 2391g of R-134a** for a 12-year lifetime corresponding to **708 to 3108kg eq. CO₂**. Those substantial differences are based on different servicing practices, recovery at end of life, lower charge, and improved leak tightness.

For the CO₂ AC system, the assumptions for emissions during lifetime are as follows:

- annual emissions of 1/3 of 500g of CO₂ refrigerant charge,
- no recovery,
- total emissions during servicing, and at end of life.

Based on these assumptions, the total losses are of 12.2kg of CO₂.

Table 2 - Comparison of refrigerant emissions from MAC systems (kg eq. CO₂)

Refrigerant emission during lifetime	Current R-134a Realistic scenario	Enhanced R-134a	CO ₂ (pessimistic scenario)
kg eq. CO ₂	2 287.5	708.6	12.2

Table 2 summarizes the impact of low GWP of CO₂ compared to R-134a GWP, which is an indisputable advantage.

Energy consumption of CO₂ and R-134a AC systems

The level of information on R-134a AC system and CO₂ AC system, are significantly different in terms of consistency and reliability. CO₂ AC system are only prototypes, and information is often incomplete and sometimes biased. The main bias found in different

papers correspond to unfair comparison between a given R-134a system, which could be inefficient, and a properly tuned CO₂ prototype. A review of the essential papers permits to verify that at moderate outdoor temperature (between 20 and 25°C) the CO₂ AC system shows equal or better energy efficiency compared to actual R-134a AC systems. All papers indicate a progressive energy penalty for the CO₂ AC system for temperatures above 25°C.

Energy and fuel consumption of CO₂ and R-134a AC systems have been calculated:

- using the test results of R-134a and CO₂ MAC systems performed on the same test bench as detailed in SAE Alternate Refrigerant Cooperative Project (2002) [ACR02] (see section 3),
- for gasoline and diesel engines,
- including typical mileage of diesel and gasoline cars,
- using climatic data of Frankfurt, Seville, Tokyo and Phoenix.

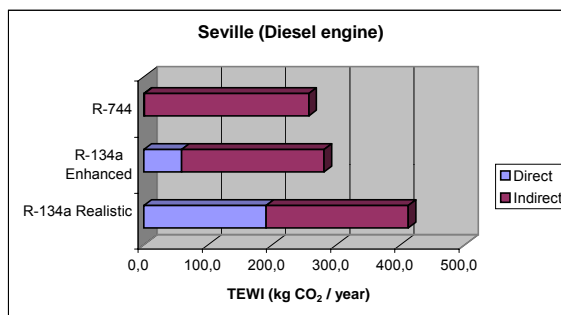
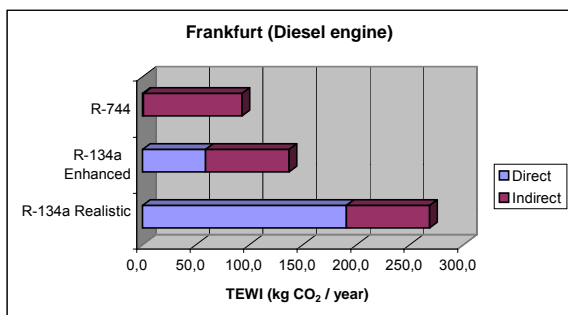
The main results are:

- **the additional energy consumption of CO₂ AC system compared to R-134a AC system ranges from +15% to +21.8%**,
- depending on climatic conditions, the additional fuel consumption is significantly different, **23 l/yr in Frankfurt**, representing +2.5% of annual fuel consumption to **165.2 l/yr in Phoenix** representing 12.7% annual fuel consumption.

The tests as performed in the SAE project [ACR02] may lower real differences between AC systems as installed in cars. **To draw more accurate conclusions, complementary analyses are necessary, based on tests on cars using R-134a and CO₂ AC systems under realistic climatic conditions.** Moreover tests shall be performed under regulatory driving cycles in order to measure effective fuel additional consumptions.

Integrated direct and indirect CO₂ emissions for R-134a and CO₂ AC systems

Based on the test results of [ACR02], and calculations as presented in Section 3.2, using also the results of Table 2 (see above), the actual R-134a AC system emissions are much higher compared to the CO₂ AC system. Moreover, the lower the cooling needs (Frankfurt), the higher the advantage for the CO₂ AC system, in the range of **81kg of CO₂/yr** compared to **270 kg of CO₂/yr** for the R-134a "realistic" AC system. The enhanced R-134a AC system with improved leak tightness permits to limit the emissions at **135kg of CO₂/yr**, which is a significant reduction but is still higher compared to the CO₂ AC system.



Figures 1 and 2 – Annual direct and indirect CO₂ emissions in Frankfurt and Seville respectively

When taking the Seville climatic conditions, the comparison between the R-134a enhanced AC system and the CO₂ AC system shows that the difference is significantly reduced due to the energy penalty of the CO₂ AC system, leading to:

- **257 kg de CO₂/yr** for the CO₂ AC system, and
- **280 kg of CO₂/yr** for the R-134a AC system.

Cost comparison between R-134a and CO₂ AC systems

Based on two different estimates detailed in section 4 and summarized in Table 3, the additional cost of the CO₂ AC system is estimated at **38 Euros** by the first estimate and at **147 Euros** based on the second expert advice. The reference cost for MAC R-134a actual system is considered to be of **300 Euros**.

Table 3 –Cost difference by component for CO₂ and R-134a (Euros) AC systems

	Condenser	Evaporator + LV Hex	Compressor	Expansion device	Hoses & Connections	Total
1 st estimate	61.5	62	156	6	52.5	338
2 nd estimate	30	74	138	9	196	447

Even if a number of small differences can be noticed for all components, the main disagreement between the two experts relies upon the hoses and connections estimates. The lower cost is associated to a new technology using aluminum tubing instead of metallic hoses. Those estimates do not take into account the safety aspect in order to handle the asphyxia risk associated with the sudden release of CO₂ in the cabin, specially when accidents occurs. The **additional cost** associated with sensors and **safety device** varies **from 10 to 45 Euros**.

Moreover, the reliability issue of the new CO₂ technology shall be demonstrated, and technology offer for CO₂ components is limited to a low number of suppliers making car manufacturers cautious.

1. R-134a and CO₂ EMISSION FORECAST

A review of published data, interviews of knowledgeable experts, have been performed from 15 December 2002 to 30 January 2003 in order to analyze the actual emission level of R-134a Mobile Air-Conditioning (MAC) systems and to compare it to possible emissions of future MAC CO₂ systems .

In order to receive comparable answers, a table has been issued by The Center for Energy Studies (Cenerg) summarizing what is known of the low and high levels of emissions of MAC systems by the authors. The questionnaire has been sent to about 30 European experts and some U.S. experts. Based on direct answers and complementary documents [SCH01] different scenarios of emissions along the MAC life time are fixed. The lifetime is assumed to be 12 years.

Emissions are structured as in the IPCC Guideline [IPC96], taking into account the lifecycle of the AC system and covering :

- manufacturing, before the car use
- during the lifetime
- at the end of life.

Emissions during the manufacturing process

- A part of the refrigerant charge is lost along the distribution circuit between refrigerant production and equipment charge. It is difficult to establish precisely this kind of losses. Losses due to refrigerant handling is comprised between 1 and 5% of the nominal charge [CLO97₂]. Those emissions are usually not taken into account because they are out of the control of car manufacturers and after sales service market but, need to be taken into account on a global basis.
- The refrigerant quantity lost effectively at the manufacturing process corresponds to the refrigerant charge of the air conditioning loop. Depending on the equipment used to charge the system, some refrigerant may remain into the hoses and could be released at the atmosphere. For well-designed refrigerant charge system, the hose volume can be evaluated to 20cm³. Depending on the content of this volume, liquid or gas, the R-134a lost quantity is of 0.6g (gas phase) or 2.5g (liquid phase).

During the lifetime, three types of emissions are possible.

- Fugitive emissions, and rupture: they occur mainly at fittings, at the compressor shaft seal, and in case of ruptures or accidents. The average emission rate ranges between 5 and 10%.
- Emissions during servicing: losses depend on recovery efficiency, which ranges from 0 (no recovery) to 90%. The servicing is usually performed when the residual charge is between 30 and 50% of the nominal charge. So, for the high fugitive emission rate, the servicing occurs every 3 or 4 years. For the lower one, it occurs after 7 or 8 years.
- Emissions at refilling during servicing: they depend on the quality of the operation and on the equipment used.

At the end of life, refrigerant recovery is not usually performed. So, the recovery efficiency at decommissioning ranges from 0 to 90%.

All those numbers on emission rates shall be carefully monitored and require a number of field inquiries and updates depending on technology improvements, better care of refrigerant containment, better awareness of all stakeholders of environmental impacts of refrigerant emissions. The report takes into account the best available information in order to estimate all those emission factors.

1.1 Actual R-134a MAC system emissions

Emissions from MAC depend on :

- component leak tightness and can be called "controlled" emissions;
- unpredictable failures due to: random defaults of components, rupture of components due to chocks, accidents... which can be called "uncontrolled" emissions,
- low efficient recovery at repairs, inefficient leak tightness control at repairs, improper leak fixing, emissions when recharging, negligent operation of service valves which can be called "servicing" emissions .

Those 3 types of emissions are addressed separately in the next subsections. Moreover best available estimates for refrigerant emissions associated with refrigerant production, refrigerant capacities handling and scraping of vehicles are also analysed.

1.1.1 Emissions during refrigerant production and refrigerant capacity handling

Source	David J. Bateman, Dupont Fluoroproducts, "A responsible Zero Leak and Zero Waste/Emission Philosophy", Wilmington, DE USA. Earth Technologies Forum [BAT99]				
Date	1999				
Subject	Information about emissions at manufacturing. Explanation of the processes used by Dupont to tightly reduce leakage, especially about unloading process: FEED (Fluorochemical Emission Elimination Delivery) system.				
Contents	<ul style="list-style-type: none"> ▪ Using the example of the Dupont R-134a plant at Corpus Christi, Texas (the largest R-134a plant in the world), the corporate "zero emission" philosophy is explained. The author wants to give a more accurate and realistic estimate of the emissions than those found in literature. ▪ According to him, in literature, some have estimated that HFC emissions during production, packaging and shipping are in the range of 2% during each of these steps. Based on his experience, global leakage at Corpus Christi is about 1% for all three steps combined. This percentage seems not to include releases caused by neither equipment failure nor human error. ▪ Philosophy is really put in practice: plant design, construction and operation as well as product packaging are realised with the goal of zero emission. Three types of emissions remain: permitted vents, fugitives emissions (which are minor but can not be accurately measured) and accidents. ▪ FEED system is a method of unloading tank trailers at customers locations which permits to avoid R-134a emissions. The main cause of emission during this step was connecting and disconnecting the hoses. FEED system uses male and female connections which allow quasi-zero emission process if customer is also equipped. ▪ The most important leakage concerns cylinder loading, when R-134a is repackaged from large bulk tanks into smaller cylinders (ton and half ton). Besides, emissions are again reduced to less than 1% with the use of disposable and returnable cylinders. ▪ Based on production and emissions records for the two last years, Dupont Fluoroproducts estimates "emissions throughout the portion of production and distribution where they have control" such as in the following table: 				
	Manufacturing process	Bulk loading	Bulk unloading (FEED)	Cylinder loading	TOTAL
	0.05 to 0.1%	0.0003%	0.0004% if customer is equipped 0.005 to 0.01% else	< 1%	1%

Reviewer comments

This very detailed presentation of D.J. Bateman presents a very low emission plant designed for "zero emissions". The 1% corresponding to the refrigerant plant emissions and the refrigerant handling process shall be considered as a very minimum emission level and must be generalised if the same type of precautions are not taken.

Source	Report of the UNEP TEAP HFC and PFC Task Force, p78. [UNE99]		
Date	October 1999		
Subject	LCCP (Life-Cycle Climate Impact) of refrigerant manufacturing		
Contents	Two figures are given in this paragraph:		
	<ul style="list-style-type: none"> ▪ According to the three largest global producers of R-134a, production losses are approximately estimated to 0.2% of the production levels. Furthermore, 0.2 to 0.3% are impacted to loading and transport. No more details are given about transport. It is not said if cylinders loading are taken into account. 		
	Production	Loading and transport	TOTAL
	0.2%	0.2 to 0.3 %	0.4 to 0.5%
	- CO2 equivalent of production energy to manufacture R-134a is 6 to 9 kg of CO2 per kg of refrigerant.		

Reviewer comments

This summary in the UNEP TEAP HFC report is certainly based on the previous paper generalising a very high efficient handling to all chemical manufacturers and refrigerant distributors, which can be argued.

Source	Denis Clodic. Zero Leaks – p.144 & 145 [CLO97 ₂]		
Date	1998		
Subject	Refrigerant handling		
Contents	<ul style="list-style-type: none"> ▪ Based on data coming from the main refrigerant distributor in France (Dehon Service) more than 200 metric tons are recovered from the containers and capacities of brand new refrigerants coming back and representing about 5% of the total refrigerant contained in those capacities. 		
	Possible emissions due to refrigerant capacity handling		
	Between 2 and 5%		

Reviewer comments

Refrigerant distributors use to call "refrigerant heels" the refrigerant quantities remaining in the capacities returned from customers.

Taking the example of a 930-liter container filled in at 90% of liquid R-134a at 20°C, (the liquid density is of 1126kg/m³), the total mass of refrigerant is about 1026kg. If all the liquid is charged by the customer in its different refrigerating systems, it will remain in the container the gas phase under the saturated pressure at 20°C, (vapour density of R-134a is 32.5kg/m³). So the remaining quantity that cannot be recovered by the end user is 30,26kg, representing 3% of the initial container charge. Moreover, it will always remain a small quantity of liquid that cannot be extracted and that can represent from 1 to 4% of the initial charge.

In order to be recharged, the container needs to be evacuated. Two cases are possible.

First case

In a first phase, the refrigerant is released to the atmosphere down to the atmospheric pressure by the sole opening of the valve. Then a vacuum pump evacuated the container down to 10 Pa. This practice was usual before the enforcement of the Montreal Protocol and can still be practiced now leading to a complete release of the remaining refrigerant.

Second case

A recovery machine recovers the refrigerant down to approximately 70 kPa abs., and the remaining quantity is evacuated by a vacuum pump releasing the residual refrigerant quantity to the atmosphere, which is approximately 2.75kg. This is the usual actual practice leading to an emission of about 0.3%.

No conclusion can be drawn before a complete description of the practice by all refrigerant distributors. Moreover, depending on the country, a significant part of the refrigerant market is sold in capacities that belong to the end users and are never returned to the refrigerant distributor. Nobody knows how the refrigerant heels liquid or vapour are handled.

Source	A. McCulloch and A. A. Lindley, From Mine to Refrigeration: a Life Cycle Inventory Analysis of the Production of HFC-134a, submitted to IIR Bulletin [MCU02]
Date	2002
Subject	Indirect emissions at manufacturing.
Contents	<p>Authors give an emission rate of 5.31ton of equivalent CO₂ per ton of R-134a produced, which takes into account</p> <ul style="list-style-type: none"> ▪ energy required to obtain and convert the raw materials ▪ energy required to deliver the product ▪ effect from other greenhouse gases released during production. <p>This rate is equivalent to 0.41% of the R-134a produced quantity.</p>

Reviewer comments

This paper addresses only the manufacturing process of refrigerant not taking into account the emissions related to partition of refrigerant from bulk wagons of 40 tons to capacities of some kilograms.

Summary for estimates of refrigerant emissions at the refrigerant manufacturing process and handling of refrigerant capacities

Emissions during the manufacturing process of refrigerants seem to be well known and well handled by chemical manufacturers. They are estimated at a maximum of 0.2%.

For bulk unloading and cylinder loading, depending on the refrigerant distributor practice, and moreover the final ownership of the capacities, the refrigerant emissions vary widely from 0.3 to 1% (lower estimates) to more than 5% (high estimates).

1.1.2 Brand new component leak tightness

Figure 1.1 shows a view of typical European MAC system. The "controlled" emission level or more precisely defined: the **maximum emission level as specified** by car manufacturers shall be assessed component by component of the MAC system.

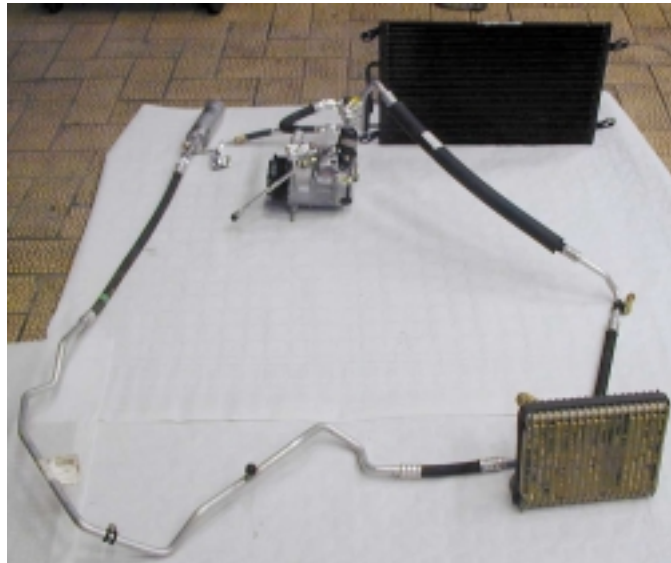


Photo 1.1 - The MAC system

H-EX

The 2 heat-exchangers, evaporator (Photo 1.2) and condenser (Photo 1.3) are fully brazed and leak tightness is thoroughly checked by efficient leak tightness control. The level of emission can be considered under 0.1g/yr and so is negligible.



Photo 1.2 – Evaporator with thermo expansion valve

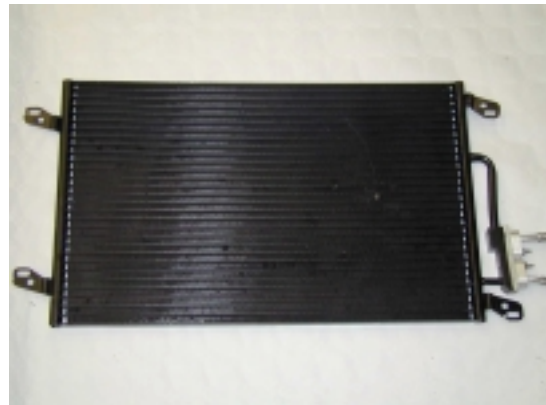


Photo 1.3 - Condenser

Fittings

Those 2 heat-exchangers fittings of different design permit to fit the thermo-expansion valve for the evaporator (Photo 1.4) and metallic hoses for the condenser (Photo 1.5).



Photo 1.4 – Details of inlet and outlet fittings of the evaporator to be fitted in the expansion valve



Photo 1.5 – Details of the inlet and the outlet fittings of the condenser

The leak flow rates are pressure dependent and may vary widely for fittings as shown in Figure 1.1 [CLO97₁].

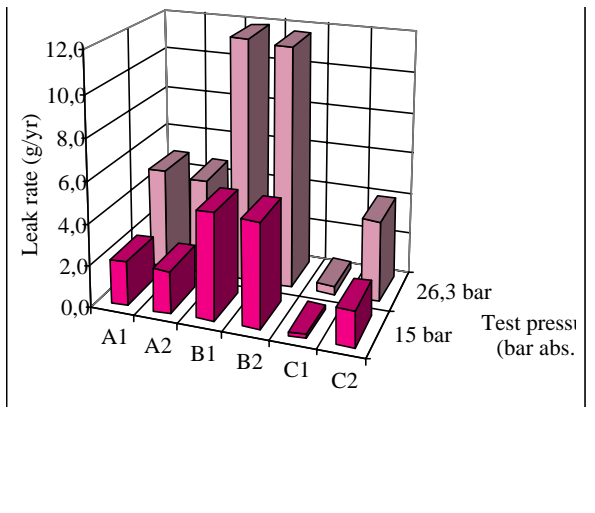


Figure 1.1 – Emissions from fittings depending on pressure and torque

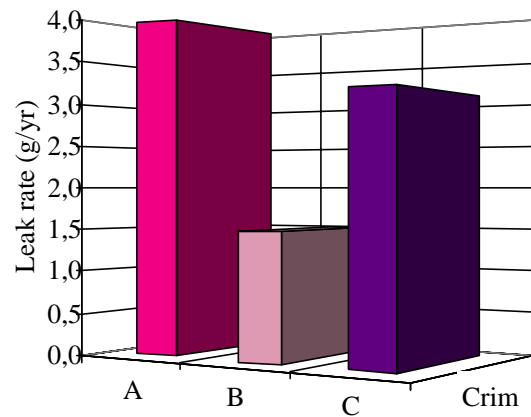


Figure 1.2 – Emissions from crimps

A typical MAC system includes 8 to 10 fittings for the compressor, the two heat exchangers, the expansion valve, and possibly two more for the high-pressure receiver or the low-pressure accumulator.

Hoses permeation

Photos 1.6 and 1.7 show a typical hose and a detailed view of the crimp permitting to connect the rubber part to the metallic part of the hose. The emission rate depends on operating conditions and ambient temperature.



Photo 1.6 – Hose and fitting



Photo 1.7 – Hose crimp (detailed view)

Figure 1.3 shows the leak flow rates of two hose technologies. A is an "old" rubber hose type technology and B is a rubber hose with inside plastic liner.

The levels of emissions are significantly different (more than a factor 9). The best technology should be chosen both for operating conditions at high pressure and when the system is stopped, according to the next calculations.

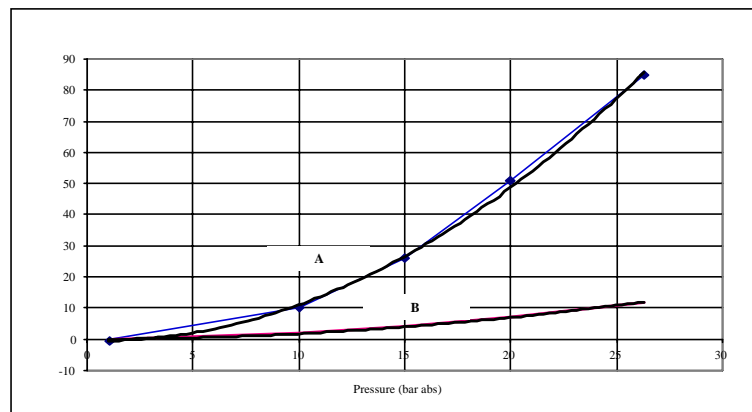


Figure 1.3 – Emission rates of two types of rubber hoses [CLO97₁]

Table 1.1 – Assumptions for calculations

Operation time of AC	Operation time of vehicle with AC off	Idle time
200 hr/yr at pressure and temperature of a reference cycle	400 hr/yr at 38°C average temperature	8 160 hr/yr at 15°C average temperature

Taking into account simplified climatic and operating conditions (see Table 1.1), reference [CLO97₁] presents two emissions estimates (see Table 1.2) choosing in one case the best available technology, and in the other case the usual one.

Table 1.2 – Emission rates of components depending on the technology

Technology	m(g/yr)			Total g/yr
	Hoses	Fittings	Crimps	
Usual technology	12.8	4.25	1.3	18.35
Best available technology	1.15	0.9	0.3	2.35

The differences are significant if for each and every component, the best available technology is chosen, which requires specific methods of test for hoses alone, fittings, and crimps.

Compressor shaft seal

A typical shaft seal on the rotating axis, and the fixed seal are presented respectively on Photo 1.8 and 1.9. The compressor shaft seal constitutes the most emissive component of the MAC system [CLO01]. Moreover, the leak tightness depends on appropriate lubrication of the rotating O-ring. The long winter standstill period may be critical leading to dry contact and consequently to deformation of the O-ring and/or the fixed seal.



Photo 1.8 – Rotating shaft with its O-ring



Photo 1.9 – Fixed seal

The method of tests is a concern and usual compressor manufacturer's methods are neither well known nor reliable when known.

Reference [CLO01] presents a test method and results on emission levels for different compressors. Tests are performed either when the compressor is running or stopped. Results show:

- a higher emission rate when the compressor is running, and the higher the running speed, the higher the emission rate;
- aged compressors show a higher emission rate compared to brand new ones. The emission rate seems to be steady after about 150 hours;
- taking into account various climatic conditions and operating conditions, the annual leak rate of the analyzed compressors varies between 3 and 20g/yr, depending on the technology.

Service valves

Photo 1.10 shows a typical service valve (without its cap). It is a Schrader valve. When connecting the hose, the closing system is pushed in permitting to charge or to discharge the refrigerant to or from the circuit.

The initial leak tightness is good, if the cap is properly screwed on.

Usual AC systems are equipped with 2 service valves one for the low-side pressure and the other one for the high-side pressure.

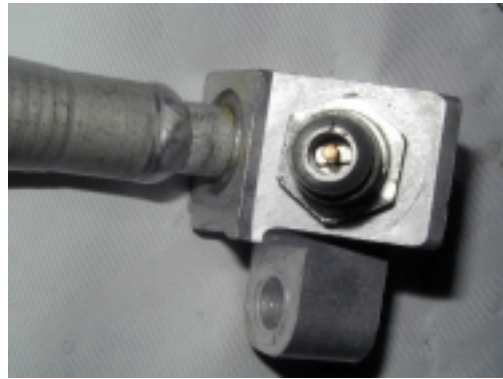


Photo 1.10 – Service valve

Low and high estimates for "controlled" annual emissions of AC systems

Maximum emission levels for fittings, hoses, compressor shaft seal, and service valves are specified by car manufacturers to their suppliers. As shown in previous Tables, a wide range of emissions are measured depending on technology components. Table 1.3 summarizes the high and the low estimates for a typical AC system comprising:

- 3 hoses (liquid, suction, and discharge lines),
- 8 fittings,
- 2 service valves, and
- the compressor shaft seal.

Table 1.3 – High and low estimated for controlled annual emissions (g/yr)

Estimates (g/yr)	Hoses and fittings	Compressor shaft seal	Service valves	Total
High estimate	18.3	20	2	40.3
Low estimate	2.3	3	0.5	5.8

1.1.3 Surveys of emissions during lifetime

Surveys have been performed in Germany, by Öko Recherche, in The Netherlands [NOK02] and in Sweden, Germany and Portugal by Öko Recherche and Ecofys for the DG Environment.

Emissions when charging the MAC system at the car manufacture

Source	W. Schwarz Position of Öko-Recherche and Ecofys, replying to our survey. [SCH03]
Date	January 03
Subject	Emissions at filling
Contents	According to his contact at Dupont, W.Schwarz precise that, at each single charging a MAC 2 grams are lost in the normal process, not in case of mischarging or of defective and leaking MACs.

Emissions during MAC life operation

Source	W. Schwarz. Position of Oeko-Recherche and Ecofys, replying to our survey. [SCH03]		
Date	January 03		
Subject	Regular and irregular MAC leakage		
Contents	Two figures are given in this summary. Results are based on German vehicles of three makes that are at the maximum 8 years old.		
	<ul style="list-style-type: none"> ▪ After statistical evaluation and integration of 140 Novem measurements, regular leakage is ranging around 7.7% of the nominal charge per year. ▪ Irregular losses are caused by accidents, stone impacts or corrosion or defective components and defined as loss more than 40% of the nominal charge. This rate is difficult to estimate: at the moment, it could be said that it can not be less than 3.3%. 		
	“Regular losses”	“Irregular losses”	Global fugitive emissions
	7.7%	≥ 3.3%	≥10%

Source	National Survey of Refrigerant flows (NOKS), RAI Vereniging (Natherlands Association of Bicycle abd Automotive Industries), Motor Vehicles Section [NOK02]		
Date	2002		
Subject	Fugitive emissions in The Netherlands		
Contents	<ul style="list-style-type: none"> ▪ This survey obtains an average annual average emission rate for fugitive emissions of 9 % for the private cars in 2000 in the Netherlands (leak rate of 60g/yr). ▪ Based on interviews of garage mechanics the possible causes of leak emissions are indicated in the Table below. 		
	Possible cause	Weighted total occurrences of cause per year	As a percentage
	Faulty compressor	16	19%
	Compressor shaft seal	6	7%
	Faulty evaporator	10	12%
	Faulty condenser	15.5	18%
	Faulty (expansion) valves	5	6%
	Metal conduction	6.75	8%
	Plastics conduction	5.75	7%
	Faulty connections	6	7%
	Faulty valves/seals	1	1%
	Miscellaneous, unknown	13	15%
	of which damage	9	11%
	Total	85	100%

Source	SWECO Theorells AB for the Swedish National Environmental Protection Agency, Survey of the number of cars in Sweden fitted with AC units in 1999 and their emissions of refrigerants [SWE02]
Date	2002
Subject	Refrigerant consumption at servicing in Sweden
Contents	<p>Survey asking information on the consumption of refrigerant by workshop and refrigeration contractors is analysed.</p> <p>106 replies (on 841) give the following results:</p> <ul style="list-style-type: none"> - At least 17.4 ton of R-134a was used for servicing MAC units in 1999 and “probably less than 61.4 ton” - As a percentage of the 700 000 vehicles charge, emission rate at servicing is estimated in the range of 3% to 11% of the original charge. <p>It is important to underline that the average year of MAC units was only about 3.3years in 1999. Furthermore, this result only takes into account serviced vehicles so the validity of the equivalent leak rate could be questioned.</p>

Reviewer comments

*From those surveys it appears that the average emission rate not taking into account accidents, and ruptures represents about **57.5g/yr per vehicle**, which is significantly above the higher "controlled level" of emissions as defined above, which was **40.3g/yr**. Certainly some components are more leak prone. Additional comprehensive analysis is necessary to understand those differences.*

1.1.4 Estimates of emissions at servicing and repair

Source	A. Cheballah, ValeoClimService, replying to our survey. [CHE02]
Date	January 03
Subject	Fugitive emissions and emissions at servicing
Contents	<ul style="list-style-type: none"> ▪ Fugitive emissions are in the range of 25 to 75g by year (3 to 10%) ▪ Improvements at servicing: losses do not exceed 50g during recovery and 20g during refilling.

Source	J. Ingvarlsen, CHRISTONIK, replying to our survey. [INV03]		
Date	15.01.03		
Subject	Information about emissions at servicing		
Contents	Losses at servicing are detailed in the case of garages following good practices (according to J.I, it is the case of the quasi-whole garages):		
	Grams R-134a	At each servicing	If repair after recovery
	Left in hoses	92	92
	Connecting recovery unit	5-10	5-10
	Lost during recycling	2-5	2-5
	Left in the A/C system after recovery		100
	Total	99-107	199-207
	<p>J.I underlines that additional 100g can be evaporate from oil if maintenance (repair) is necessary after recovery. That is not the case if the MAC is recharged immediately after recovery.</p> <p>If "best practice" would be followed, HFC-134a"left in hoses" and "left in the A/C system after recovery" can be reduced considerably. But from what amount?</p>		

Reviewer comments

*Those two estimates, one coming from a specialised network (Valeo Clim Service) and the other one coming from the description of usual practices in garages show very different figures between the low level of about **70g/serviced car** to a level of about **103g/serviced car**, reaching up to **203g/serviced car** if a repair is realised in addition to servicing.*

1.1.5 Estimates of emissions at end of life

Source	Arend Koppenol, Novem. "Contents MAC system at end of life. Conclusions Auto Recycling Nederland (ARN) Investigation 2002-2003". [KOP03]		
Date	January 29, 2003.		
Subject	Refrigerant quantities in the scrapped cars at the Netherlands		
Contents	Investigation was made in the Netherlands with a sample in which only 0.3% of scrapped cars had a MAC. The average age of the total sample is 6.3 years and the average nominal charge of refrigerant is 775g. Among them:		
	<ul style="list-style-type: none"> ▪ 85% of the cars had R-134a loops ▪ 46% of them were empty. The others contained 63% of their nominal charge. 		
	Cars with MAC	Total	Normal end of life cars
	Number of scrapped cars	176	22%
	Number R134a systems	146	7%
	Empty R134a systems	67	4%
	Original R134a contents (kg)	113.2	7%
	Actual R134a contents (kg)	38.7	8%
			Damaged cars (accidents)
			78%
			93%
			96%
			93%
			92%
	The representativeness of the sample is questioned by the author.		

Source	2000/53/EC. End-of-Vehicle Directive. European Commission [EUR00]		
Date	2000		
Subject	Recovery at the end of life		
Contents	European Commission states that refrigerant used in MAC shall be recovered. 85% of the total weight of the car need to be recovered.		

Reviewer comments

The average lifetime of European vehicles is about 12 years. It is mainly the 1990 fleet that is going at scrape now. Most of them were using CFC-12, and MAC was anyway in its infancy at this time in Europe. So the lesson learnt from what is remaining in those vehicles need to be updated in the next years when the samples of cars at scrape is more meaningful.

*The actual figures coming from the Novem study indicate about **46% of empty MAC systems, and the remaining 54% contained still about 63% of their nominal charge.***

1.1.6 Low and High estimates for R-134a emissions from cradle to grave

This section includes:

- results coming from the field and additional calculations (UNEP TOC Draft Report 02),
- rough evaluations coming from car manufacturers [ADI03],
- measurements performed by gas chromatography in a hood around vehicles, permitting to forecast annual emissions [SIE01],
- estimates performed by the Center for Energy Studies, based on the surveys, particularly on the work performed by Öko Recherche.

Source	James. A. Baker, Vehicle Air Conditioning Chapter, UNEP Refrigeration Technical Options Committee Report. [BAK03] Ward Atkinson, "Servicing Mobile Air Conditioning Systems" [ATK03]						
Date	2003 January						
Subject	Results of MACS Vehicle Survey Calculations in two emissions Scenarios: current R-134a and future R-134z						
Contents	A real service shop experience on 313 vehicles, obtained by MACS-W (Mobile Air Conditioning Society-Worldwide) in 2000, shows that, 68.4% of serviced vehicles had 88% of their nominal charge. Including those with empty systems at servicing, the average for all vehicles serviced is 66% of the original charge. They find an average charge of about 910g for R-134a systems. J. Baker bases his calculations on the fact that serviced systems contain 66% of the nominal charge and assumes that 6% are lost at servicing. Also, he takes into account an additional charge used to bring the system to full charge before to find the system problem. The recoverable charge at scrap is estimated about 40% of the original charge. Next, emissions calculations depend on assumptions concerning the number of recharges needed in a lifetime and if recycling and recovery occur. The results are presented below:						
		Original Charge (g)	Number of recharges	Recycling at servicing	Recovery at scrap	Emissions (g of R-134a)	Emissions on the lifetime (g of R-134a)
	Current scenario	910	2	No	No	267	3 190
		910	2	Yes	Yes	106	1 270
	Future scenario	800	1	No	No	167	2 000
800		1	Yes	Yes	67	800	

Source	"Leakage of HFCs during the manufacturing, operation, maintenance and end-of-life of MACs." ACEA official statement passed by B. Adiprasito [ADI03]
Date	2003, January
Subject	Survey about emissions by step
Contents	<ul style="list-style-type: none"> ▪ According to three different car manufacturers, the average fugitive emissions during the lifetime of a car are in the range of 15 to 25g by year. Losses are not linear with time: until the fourth year of operation, leakage is nearly constant and tiny. ▪ Leaks are because of the compressor in half of the cases and 25% are due to hoses permeation. Hans Fernquist is quoted to underline a problem concerning maintenance for an engine or transmission repair. " It is very often claimed that when a car with AC problem comes to the repair shop, the AC system is always empty... I know of numerous cases where a mechanic have been trying to find/solve the problem by the "trail and error" method. This has meant that he has been replacing part by part and for each replacement he has emptied and recharged the system. Then, if you do not use a recovery station and collect all, or at least >= 90% of the charge, but just vent it to the air, the emissions would be a full charge every time and thereby very large. Same thing is applicable if you have to do multiple engine/transmission repairs where you have to open the AC-system." ▪ No figure is given concerning leaks at servicing. Volvo estimates that losses due to accidents is less than 0.5% of the fleet.

Source	W. O. Siegl and T. J. Wallington, Ford Motor Company. R-134a Emissions from Vehicles. Environment, Science and Technology [SIE01]							
Date	2001, October							
Subject	Quantify R-134a evaporative emissions from MAC of parked vehicles. Extension of this leak rate to a global emission rate based on results of the literature.							
Contents	Experimental study occurs on 28 light duty vehicles. Tests realised on stationary vehicles with motor and air-conditioning system turned off.							
	<ul style="list-style-type: none"> ▪ Diurnal emissions vary in the range of 0.01g to 0.36g by 24 hours with an average rate about 0.07g by day. ▪ It is observed that “higher mileage vehicle tend to leak more than low mileage vehicles”. ▪ To take into account leakage during vehicle operation, it is assumed that leak rate increases linearly with pressure and the system operates 1 hour by day. Average fugitive emissions rate becomes 0.08g by day. ▪ Losses at servicing are counted in the same way as Baker (“Mobile Air Conditioning and Global Warming”, Phoenix Alternative Refrigerant Proceedings, 1998). A mean value about 0.33g/day is used to take into account leakage at servicing and at disposal. 							
	Experimental emissions from parked vehicles (g of R-134a)		Global fugitive emissions (g of R-134a)		Average emissions rate at servicing and disposal (g of R-134a)		Total average leakage (g of R-134a)	
	By day	By year	By day	By year	By day	By year	By day	By year
0.07	25.5	0.08	29.2	0.33	120.5	0.41	149.7	

Calculations by the Center for Energy Studies

Each scenario considers original refrigerant charge of 750 g, a lifetime of 12 years, and the refrigerant is recovered when the residual charge is of 60%, leading to 2 or 3 servicing operations along the lifetime. Each assumption is justified by a reference presented in the previous sections. Interestingly enough the scenario presented by Baker and Atkinson in the TOC Report is intermediate between our optimistic and realistic scenarios.

Optimistic scenario

Table 1.4 – R-134a emissions along the car lifetime (optimistic scenario)

Assumptions : OPTIMISTIC SCENARIO														
Vehicle : M2 segment, 750 g original refrigerant charge, lifetime 12 years														
1. Emissions at manufacturing														
1.1. Capacity heels : 1% of the nominal charge is lost along the distribution circuit, between refrigerant production and the equipment charge [BAT99]														
1.2. Filling of the system : at least 5g are lost at the connection [INV03]														
2. Emissions During lifetime														
2.1. Fugitive emissions : emissions at fittings, compressor shaft seal, ruptures and accidents. Regular and irregular losses are evaluated, based on the best scenario given by [SCH03]														
2.2. Emissions during servicing take into account recovery and refilling steps. The servicing is performed when the residual charge is 60% of the nominal charge [SCH03]. Refrigerant losses are given by [INV03]														
3. Emissions at the end of life														
3.1. Emissions at decommissioning. The recovery efficiency at decommissioning is considered equal to the European recommendation of 85% recovery [EUR00]														
		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	total (g R-134a)
Emissions at manufacture	Capacity heels	7,5												7,5
	Filling of the system	5,0												5,0
Emissions during life time	Fugitive emissions (incl. accidental rupture)	75,0	75,0	75,0	75,0	75,0	75,0	75,0	75,0	75,0	75,0	75,0	75,0	900,0
	Emissions during servicing				99,0				99,0					198,0
End of life	Emissions at End Of Life												67,5	67,5
		87,5	75,0	75,0	174,0	75,0	75,0	75,0	174,0	75,0	75,0	75,0	142,5	1178,0
	Nominal charge (g)	750												98,17 g/yr

Realistic scenario

Table 1.5 – R-134a emissions along the car lifetime (realistic scenario)

Assumptions : REALISTIC SCENARIO														
Vehicle : M2 segment, 750 g original refrigerant charge, lifetime 12 years														
1. Emissions at manufacturing														
1.1. Capacity heels : 2% of the nominal charge is lost along the distribution circuit, between refrigerant production and the equipment charge ([BAT99] with 1% more due to transport from one ton containers to garage containers).														
1.2. Filling of the system : 7.5g are lost at the connection (average figure according to [INV03])														
2. Emissions During lifetime														
2.1. Fugitive emissions : emissions at fittings, compressor shaft seal, ruptures and accidents. Regular and irregular losses are evaluated, based on [SCH03] with double irregular losses														
2.2. Emissions from recovery during servicing. The servicing is performed when the residual charge is 60% of the nominal charge [3]. Refrigerant losses are given by average value of [INV03]. Emissions at refill during servicing depend on the quality of the operation and the equipment used. The case with repair (plus 100g) given by [INV03] is considered once during the lifetime. Other servicings are considered without disconnecting/reconnecting (minimal losses).														
3. Emissions at the end of life														
3.1. Emissions at decommissioning: recovery rate of 85% applied to the 64% of the scrapped cars which are not empty [KOP03]														
		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	total (g R-134a)
Emissions at manufacture	Capacity heels	15,0												15,0
	Filling of the system	7,5												7,5
Emissions during life time	Fugitive emissions (incl. accidental rupture)	107,3	107,3	107,3	107,3	107,3	107,3	107,3	107,3	107,3	107,3	107,3	107,3	1287,0
	Emissions during servicing			103,0			203,0			103,0				409,0
End of life	Emissions at End Of Life												41,1	41,1
		129,8	107,3	210,3	107,3	107,3	310,3	107,3	107,3	210,3	107,3	107,3	148,4	1759,6
Nominal charge (g)		750												146,6 g/yr

Pessimistic scenario

Table 1.6 – R-134a emissions along the car lifetime (pessimistic scenario)

Assumptions : PESSIMISTIC SCENARIO														
Vehicle : M2 segment, 750 g original refrigerant charge, lifetime 12 years														
1. Emissions at manufacturing														
1.1. Capacity heels : 6% of the nominal charge is lost along the distribution circuit, between refrigerant production and the equipment charge [BAT99]														
1.2. Filling of the system : 10g are lost at the connection [INV03]														
2. Emissions During lifetime														
2.1. Fugitive emissions : emissions at fittings, compressor shaft seal, ruptures and accidents. Regular and irregular losses are evaluated, based on [SCH03] with double irregular losses. They imply three recharges during the lifetime.														
2.2. Emissions during servicing. The servicing is performed when the residual charge is 60% of the nominal charge [SCH03]. Refrigerant losses are given by high value of the range of [INV03]. Emissions at refill during servicing depend on the quality of the operation and the equipment used. The case with repair (plus 100g) and maximal losses of the range given by [INV03] is considered. This case only concerns a part of the fleet of vehicles which has several breakdowns.														
3. Emissions at the end of life														
3.1. Emissions at decommissioning: no recovery.														
		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	total (g R-134a)
Emissions at manufacture	Capacity heels	45,0												45,0
	Filling of the system	10,0												10,0
Emissions during life time	Fugitive emissions (incl. accidental rupture)	107,3	107,3	107,3	107,3	107,3	107,3	107,3	107,3	107,3	107,3	107,3	107,3	1287,0
	Emissions during servicing			207,0			207,0			207,0				621,0
End of life	Emissions at End Of Life												428,3	428,3
		162,3	107,3	314,3	107,3	107,3	314,3	107,3	107,3	314,3	107,3	107,3	535,5	2391,3
Nominal charge (g)		750												199,3 g/yr

Summary of the three scenarios

Table 1.7 – Summary of emission scenarios

	Optimistic case (g of R-134a)	Realistic case (g of R-134a)	Pessimistic case (g of R-134a)
Capacity heels	7,5	15,0	45,0
Filling of the system	5,0	7,5	10,0
Fugitive emissions (incl. accidental rupture)	900,0	1287,0	1287,0
Emissions during servicing	198,0	409,0	621,0
Emissions at End Of Life	67,5	41,1	428,3
TOTAL (g of R-134a)	1178,0	1759,6	2391,3
TOTAL (kg eq. CO2)	1531,4	2287,5	3108,6

The main differences between the realistic and the pessimistic scenarios are based on the assumption that the recovery at end of life is effectively realised. The actual situation for many European countries corresponds to the pessimistic scenario. Moreover much better servicing practices are performed in the realistic scenario compared to the pessimistic one.

The optimistic scenario implies the use of best available technologies but without changing significantly the MAC system. Efforts are made to lower the emission level for servicing.

In the next section, enhanced R-134a system takes advantage of a much lower refrigerant charge, and changes significantly the "controlled emissions".

1.2 Future low emissions of R-134a MAC systems

Source	Stephen O. Andersen, Ward Atkinson, James A. Baker, Simon Oulouhojian and Jill E. Phillips. "Technical Options For Motor Vehicle Air Conditioning Systems". For SAE, US EPA and MACS [AND00]	
Date	March 2000	
Subject	General state of the MAC systems and of the possibilities for reducing greenhouse emissions	
Contents	<ul style="list-style-type: none"> ▪ This paper underlines that greenhouse gas emissions occur in every step of lifecycle from manufacturing to disposal. In this way, using LCCP (Life-Cycle Climate Performance) is the most complete calculation. As TEWI, it includes direct emissions of refrigerant and indirect emissions from energy combustion. It also includes energy used to produce the components and refrigerant gas and the energy necessary for parts replacement and service. ▪ General trend to reduce direct and indirect emissions is given: 	
	Direct emissions can be reduced by: <ul style="list-style-type: none"> ▪ Recovery and recycling at servicing and disposal ▪ Using components and hoses with low leak rate ▪ Minimising refrigerant charge ▪ Changing refrigerant type 	Indirect emissions resulting from fuel consumption can be reduced by: <ul style="list-style-type: none"> ▪ lowering the amount of heating and cooling needed ▪ controlling the compressor ▪ improving the energy efficiency of components ▪ reducing weights ▪ changing refrigerant or system type
	Authors list six technology options for reducing MAC emissions. Three of them concern improvements of R-134a systems <ul style="list-style-type: none"> ▪ The first one already exists in the United States, in Sweden and is going to be implemented in Japan. It is recovery and recycling during servicing and disposal. It is considered that recycling rates of 90% could be quickly implemented. ▪ The second consists in improving R-134a systems with reduced nominal charge, high quality components and high energy efficiency. ▪ The third would be the use of an hermetically sealed R-134a system as an adaptation of the hermetic refrigerant system used in the stationary market. But at the time of this paper, it is considered that long developments are still needed. ▪ The fourth is the use of hydrocarbon refrigerants, which requires additional tests, especially on flammability. ▪ The fifth is a particular case of last category with R-152a system. ▪ Finally, transcritical CO₂ systems According to them, improved R-134a systems could be introduced faster and at lower cost than the other ones.	
	R-134a systems in 2000	Diminution for enhanced R-134a systems
Average vehicle charge		- 80g to 90g
Average annual vehicle leakage	70 g/year	- 30 g/year
	According to the authors, recovery and recycling of R-134a is undertaken in about 60% of vehicles during service and disposal. But this percentage is not detailed for service and for disposal. Further, it is said nothing about the sample of vehicles or the countries concerned.	

Visteon paper

In [LUN02], Visteon propose an enhanced R-134a system with a refrigerant charge reduced to 590g. Comparison with CO₂ system is not established and as a conclusion, it is mentioned that other studies shall be carried out especially to reduce leakage. It is quoted that downsizing of system components and a better system sealing are necessary "to be environmentally competitive with CO₂ systems".

Taking into account this low charge level, and considering that the emissions at the servicing and, of course the emissions at end of life will be reduced according to the original charge, the new emission scenario leads to a much lower level of emissions (see Table 1.8).

Table 1.8 - Emissions of an enhanced R-134a system (g)

Assumptions : ENHANCED R-134a SYSTEM														
Vehicle : M2 segment, 590 g original refrigerant charge, lifetime 12 years [LUN02]. <u>Potential improvements at each step of the lifetime are taken into account.</u>														
1. Emissions at manufacturing														
1.1. Capacity heels : 0.5% of the nominal charge is lost along the distribution circuit, between refrigerant production and the equipment charge. Best value of the literature given by [UNE99]														
1.2. Filling of the system : according to [SCH03], losses at filling can not be lower than 2g														
2. Emissions During lifetime														
2.1. Fugitive emissions : emissions at fittings, compressor shaft seal, ruptures and accidents. According to [AND00], leakage rate would be reduced to 40g/year.														
2.2. Emissions from recovery and refilling during servicing. The servicing is performed when the residual charge is 60% of the nominal charge [SCH03]. Refrigerant losses are reduced to 7g by servicing ([INV03] in the case no hoses losses, no repair)														
3. Emissions at the end of life														
3.1. Emissions at decommissioning: recovery rate of 90% without counting damages														
		Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	total (g R-134a)
Emissions at manufacture	Capacity heels	3,0												3,0
	Filling of the system	3,0												3,0
Emissions during life time	Fugitive emissions (incl. accidental rupture)	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	40,0	480,0
	Emissions during servicing				7,0				7,0					14,0
End of life	Emissions at End Of Life												45,1	45,1
		46,0	40,0	40,0	47,0	40,0	40,0	40,0	47,0	40,0	40,0	40,0	85,1	545,1
Nominal charge (g)		590												45,4 g/yr

Those technical options lead to an emission level of **545g of R-134a for the MAC lifetime (12 years) leading 708,6 kg eq. CO₂**.

1.3 CO₂ AC system

Mainly qualitative information are available about emissions from CO₂ MAC system. According to [VISweb], “system provides a more tightly closed loop”, which suggests that CO₂ emissions level would be lower for CO₂ system than for R-134a one, without more details. Indeed, optimized new-developed components allow to reduce leakage during lifetime.

However, in “Experience of a CO₂ fleet test” [MAG02], CO₂ MAC system works with one refrigerant charge for 10 months (at this step of the investigation). According to the respondents to the survey, that means one third of the nominal charge –at least- has been lost in 10 months.

Presently, neither recovery nor recycling procedure is explained.

Taking into account available data, the forecast for CO₂ emission along the lifetime of a CO₂ AC system is performed using the following assumptions:

- a nominal CO₂ charge of 500g (given by [BHA97]),
- fugitive emissions about one third of the nominal charge by year,
- no recovery and total emission at servicing,
- total emission at the end of life,
- CO₂ emission during refrigerant charge and refill is 30 times more than current R-134a one, according to [PET00] and based on the existing equipment.

Table 1.9 - Emissions of a CO₂ system (g)

			Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	total	
Emissions at manufacture	Capacity heels	High value	5													5
		Low value	25													25
	Filling of the system	High value	30													30
		Low value	150													150
Emissions during life time	Fugitive emissions (incl.)	High value	150	150	150	150	150	150	150	150	150	150	150	150	150	1800
		Low value	250	250	250	250	250	250	250	250	250	250	250	250	250	3000
	Emissions from recovery	High value	100	100	100	100	100	100	100	100	100	100	100	100	100	1100
		Low value	500	500	500	500	500	500	500	500	500	500	500	500	500	5500
	Emissions from refilling	High value	150	150	150	150	150	150	150	150	150	150	150	150	150	1650
		Low value	300	300	300	300	300	300	300	300	300	300	300	300	300	3300
end of life	Emissions depending on recovery	High value													315	225
		Low value													350	250
															4 900	4 810
															12 325	12 225

With those conditions, **total losses along the lifetime of a CO₂ MAC system do not exceed 12.2kg of CO₂**. This confirms that the direct global warming impact of CO₂ MAC system is negligible compared to the one of R-134a [BHA97].

1.4 R-134a/CO₂ direct emission comparison for MAC systems

Frequently underlined, for direct emissions, the advantage of CO₂ compared to R-134a is its GWP value of 1 (R-134a GWP: 1300). This huge impact of difference in CO₂ equivalent level can be verified in Table 1.10.

Table 1.10 - Comparison of refrigerant emissions from MAC systems (kg eq. CO₂)

Refrigerant emission during lifetime	Current R-134a Realistic scenario	Enhanced R-134a	CO ₂ (pessimistic scenario)
kg eq. CO ₂	2 287.5	708.6	12.2

However, it is important to underline that CO₂ system components are optimized and newly developed.

Concerning leakage during the use of the air conditioner along the car lifetime, it can be supposed that most of the improvements of the CO₂ system could be applied on a R-134a enhanced system. For instance, it is quoted in [PET00] that for a same type of sealing, R-134a leakage rate is 30 times less than the one of CO₂. So, annual emission rate of 5g/yr could be accessible for enhanced R-134a system.

Servicing system and end of life treatment really penalize the R-134a option. Emissions are linked to the quality of servicing, to the ecological awareness of the users... The fact that handling of refrigerant could be neutral for the environment is considered as a decisive advantage for CO₂ system in [GEN98]. So, it is important that further investigations about enhanced R-134a systems consider possible improvements about servicing methods and end of file treatment.

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2. AIR-CONDITIONING SYSTEM ENERGY CONSUMPTION – Literature review

A review of the best available papers has been realized in order to compare the energy performances of AC systems using R-134a or CO₂ as refrigerant. These papers have been found in conferences, websites, and specially from the 1998 and 2000 SAE Automotive Alternate Refrigerant Systems Symposiums. In this section the main issues are analyzed, and a detailed analysis of the papers is presented in Annex 1.

The paper presenting the HFC-152a creates by itself a subsection dedicated to this refrigerant (see section 2.5). Additional information on the flammability of R-152a is given due to possible biased data, which have been presented in some papers.

2.1 R-134a and CO₂ (R-744) performances comparison: theoretical approach and calculations

The 2 following papers are based on calculations and show the energy penalty associated with the transcritical cycle compared to a subcritical cycle.

The first reference paper is written by J. S. Brown, S. F. Yana-Motta, P. Domanski [BRO02] (see Annex A1.3).

The title is "*Comparative analysis of an automotive air-conditioning systems operating with CO₂ and R-134a* ". This paper evaluates performance advantages of CO₂ and R-134a automotive air-conditioning systems using semi-theoretical cycle models.

In the introduction, the authors present the actual context where the air-conditioning industry is in the process of evaluating and introducing new refrigerant (especially the CO₂) as replacements of CFCs and HCFCs, and the HFC-134a in automotive air-conditioning system, which can be seen as a refrigerant "non sustainable in the long term" due to its GWP of 1300 kg eq. CO₂.

The authors make a literature review analyzing various studies (see Annex A1.3), that CO₂ systems present equal or lower energy performances than R-134a and R-22 systems, both for heating and cooling, especially when using cross-flow air-refrigerant heat exchangers. **The only case where CO₂ systems show a better performance compared to HFC refrigerant is for water-heaters.** When heating water from about 15°C up to 60°C, then the large glide of temperature of CO₂ in the supercritical state makes a real advantage when the heat process is realized in a counter current heat exchanger.

Other studies showing that CO₂ MAC systems have equal or better energy performances than R-134a systems are based on tests of CO₂ and R-134a systems which were not comparable either in term of Heat exchanger technology or in term of compressor efficiency.

After the literature review, the authors present the semi theoretical simulation model they have developed permitting to model each component of the A/C refrigerating loop.

The compressor is modeled using empirical correlations for isentropic and volumetric efficiencies. These correlations were obtained by curve fitting of various experimental data. These efficiencies are pressure ratio dependent.

Heat exchangers are modeled using the UA approach and in both cycle models, the expansion is isenthalpic.

The R-134a system is modeled with a TXV (superheat and sub-cooling are kept constant) and the CO₂ system uses an expansion device associated with the high-side pressure control.

The analysis shows CO₂ having an inferior COP to R-134a. The COP differences depend on compressor speed and ambient air temperature; the higher the speed and ambient air temperature, the greater the COP difference.

For 100 RPM, the COP for CO₂ ranged from being lower by 21% at 32.2°C, to 34% at 48.9°C.

At the same speed and lower ambient temperatures, the difference between CO₂ and R-134a will decrease. On the contrary, at high speed and high ambient temperature, the energy penalty for CO₂ will increase. Hence CO₂ has better transport properties and shows a better compressor efficiency. Those advantages do not compensate its thermodynamic disadvantages compared to R-134a, when equivalent heat exchangers are used for both refrigerants, even if an internal heat exchanger is used in the CO₂ cycle to reduce throttling irreversibilities.

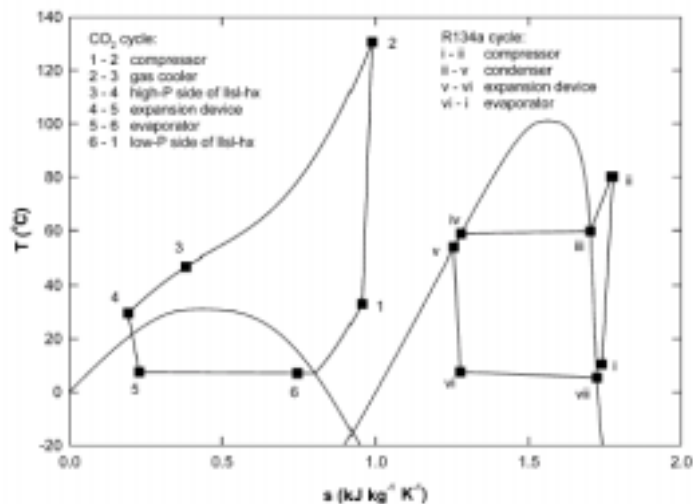


Fig. 1. CO₂ transcritical cycle and the R134a subcritical cycle at an ambient temperature of 43.3°C and 1000 compressor RPM.

The entropy generation calculation indicated that CO₂ has a somewhat better performance than R-134a at the evaporator, but has significantly poorer performances in the gas cooler than the R-134a condenser. **The large CO₂ temperature glide in the gas cooler (as indicated in figure 1) and the larger amount of heat to be rejected are responsible for the higher entropy generation.** This large entropy generation in the gas cooler is the primary cause for the lower CO₂ performance and is unavoidable in air-to-refrigerant cross flow heat exchangers.

Reviewer comments

To have fair comparisons between systems using different refrigerants, it is important to use the same technology. It is obvious in some studies (J.S. Brown et al highlight this point in their paper) that CO₂ systems use most advance heat exchangers and compressors and use moreover an internal heat exchanger

The second reference paper “A critical look at CO₂ and R-134a mobile air conditioning systems” is written by M. S. Bhatti of Delphi Harrison thermal systems and named ([BHA97] see Annex A1.4). The author analyzes the performances of both systems in terms of fuel consumption and global warming impact.

The first part of this paper is dedicated to the theoretical analysis of the sub-critical cycle of the R-134a AC system and the trans-critical cycle of the CO₂ AC system. The author

compares the COP of both cycles depending on the ambient air temperature and the cooling capacity.

Table 2.1 shows that the R-134a cycle out-performs the trans-critical CO₂ cycle since the theoretical COP of the R-134a AC system is twice to three times higher than the COP of the CO₂ cycle.

Table 2.1 - Theoretical cycle COP for R-134a and CO₂ AC systems depending on ambient air temperature

T ambient (°C)	Cooling capacity (kW)	COP CO ₂	COP R-134a	COP ratio
15.6	0.7	16.9	48.4	0.35
21.1	1.4	6.4	24	0.39
26.7	2.2	6.3	15.5	0.4
32.2	2.9	4.6	11.3	0.4
37.8	3.6	4.0	8.7	0.46
43.3	4.4	2.9	7	0.42

◆ TEWI analysis

The second part of the paper is dedicated to the realistic comparison of both AC systems. The author insists on the fact that the compressors used for CO₂ AC systems are more efficient than the ones used for R-134a AC systems. This fact shall be noticed because a good comparison between two AC systems shall be performed with the same technologies. According to Bhatti, with a good optimization of the R-134a compressors used for MAC system, it is even possible to have for R-134a AC systems, higher COP than idealistic COP of CO₂ AC systems.

In the last part of the paper, the author calculates the global warming impact for the two AC systems based on a 88.3 l/yr fuel additional consumption for the R-134a AC system. It appears that the CO₂ TEWI is higher than the R-134a TEWI, even if a refrigerant leak rate of 55 g/yr is chosen as a basis.

Equivalent warming	R-134a system	R-744 system	Ratio
Direct	71.5	0.0	0.0
Indirect	209.7	355.6	1.7
Total	281.2	355.6	1.3

Table 2.2 – Annual total equivalent CO₂ emissions

Table 2.3 – TEWI depending on AC system COP

R-134a COP _{sys}	TEWI, kg/yr		
	R-134a system	R-744 system	TEWI ratio
1.0	395	356	1.11
1.5	296	356	0.83
2.0	247	356	0.69
2.5	217	356	0.61
3.0	197	356	0.55

Table 2.4 – TEWI depending on leak rate

m ₁₃₄ gm/yr	TEWI, kg/yr		
	R-134a system	R-744 system	TEWI ratio
0	211	356	0.59
55	283	356	0.79
110	354	356	0.99
165	426	356	1.20

In Tables 2.3 and 2.4 it can be seen that the COP improvement and leak rate reduction can both lead to a lower TEWI for the R-134a AC system. These two series of improvements are technically feasible. In fact today most investments are made to develop CO₂ programs but nothing new is proposed for actual R-134a systems (except the external control compressor, but this technology is also used for CO₂ compressors).

Reviewer comments

The calculation of Bhatti is not completely fair with R-744 because Bhatti did not take into account the key role of internal heat exchanger that can be considered as a necessary component for R-744 cooling system, event if it constitutes an additional cost.

Even if the author analyzes the problem of R-134a leaks, he does not take into account the issue of vehicle end of life. So the remaining charge of R-134a shall be integrated in the TEWI calculation, if no refrigerant is recovered.

2.2 Experimental comparison of R-134a and CO₂ (R-744) AC systems

Along this section, three papers are reviewed, compared and analyzed:

- “Experimental comparison of mobile A/C systems when operated with transcritical CO₂ versus conventional R-134a”, McEnaney & al (1998) [McE98],
- “Comparison of automotive air-conditioning systems operating with CO₂ and R-134a”, Preissner & al (2000) [PRE00],
- “SAE alternate refrigerant Cooperative Research Project” ACRC (2002) [ACR02].

All these papers present a comparison between R-134a and CO₂ AC systems and are detailed respectively in Annex 1.

♦ Experimental comparison of mobile A/C systems when operated with transcritical CO₂ versus conventional R-134a, McEnaney & al (1998) [McE98]

McEnaney & al [McE98] presented experimental results of a CO₂ AC system prototype and a commercially available R-134a AC system (Ford Escort). The CO₂ AC system is equipped with an internal heat exchanger and a manual metering valve. The CO₂ evaporator and gas cooler were new generation micro-channel heat exchangers, while the R-134a system heat exchangers were of conventional technology. The external volume of the evaporators were identical, with the CO₂ evaporator having a **20% larger air-side surface**. The CO₂ gas cooler had 23% lower external volume and had **28% lower external surface**.

The comparison carried out by the ACRC team shows that the CO₂ mobile AC system has a higher cooling capacity for most conditions.

The CO₂ MAC system has been designed to have the same cooling capacity as the R-134a AC system at an ambient temperature of 54°C and rotation speed equal to 950 RPM (worst case working conditions). For these conditions, the COP of the CO₂ AC system is about 10% lower than the one measured for the R-134a AC system.

For ambient temperatures lower than 40°C (which represents the majority of the climatic conditions that can be encountered), the CO₂ MAC system presents better energy performances in terms of cooling capacity.

Reviewer comments

The comparison has not been performed under similar conditions. In fact, heat exchangers and compressors were not of the same technology, which can lead to very important differences.

♦ Comparison of automotive air-conditioning systems operating with CO₂ and R-134a, Preissner & al (2000) [PRE00]

Preissner & al [PRE00] presented experimental results for CO₂ and R-134a automotive air conditioners. The major difference with this study and previous ones is that the R-134a evaporator and condenser were prototype heat exchanger based on the latest technology similar to CO₂ ones. Moreover, an internal heat exchanger was used with the R-134a system (not just in the CO₂ system as in previous studies).

The major results were that the capacity of the CO₂ MAC system ranged from 13% lower to 20% higher, depending of the testing conditions, compared to R-134a system. The COP of the CO₂ AC system ranged from 11 to 23% lower compared to R-134a MAC system.

In this study, for the first time, the two analyzed systems (R-134a and CO₂ have used the same heat exchangers and an internal heat exchanger). The results show that the energy performance of the CO₂ MAC system is lower compared to the performances of the R-134a MAC system; this difference can reach 25%.

◆ **SAE Alternate Refrigerant Cooperative Research Project ACRC (2002) [ACR02]**

At the end of 2002, ACRC [ACR02] presented a report named "SAE alternate refrigerant Cooperative Research Project". The main goal of this report is to provide a directly comparative engineering evaluation of the existing R-134a AC systems and other refrigerant technologies. This work was commissioned by car manufacturers and suppliers from Europe, Asia and USA; they also obtained the support of U.S army and US EPA, and Environment of Canada.

In the study, the ACRC team tested 3 different MAC systems:

- Baseline R-134a system,
- Enhanced R-134a system,
- CO₂ prototype system.

These systems were tested under the same conditions; three rotations speed are investigated : 900, 1500 and 2500 RPM (steady state conditions), and four ambient air temperatures were used for the tests.

According to the results presented, it appears that the higher the rotation speed, the lower the COP. The same behavior is observed when the temperature increases and thus for the three systems tested.

Comparison of the AC systems

A first series of tests showed that the three systems have the same cooling capacity. On all the tests carried out, the COP of the enhanced R-134a AC system was equal or higher than the CO₂ AC system COP (the difference can reach 25%). The CO₂ AC system COP is always lower than the baseline R-134a AC system when the ambient air temperature is higher than 30°C at 900 RPM. Nevertheless, it can be noticed that the higher the rotation speed, the lower the difference between the R-134a enhanced AC system and the CO₂ AC system.

A second series of tests carried out with an air temperature at the condenser / gas cooler inlet equal to ambient temperature + 15°C (representing idle conditions or urban city traffic) showed that the energy performances of the CO₂ AC system are significantly much lower than the two R-134a AC system, and especially the enhanced R-134a. Under these conditions, the difference in terms of COP is significant, between 25 and 45%.

A third series of tests has been carried out to measure the performances of the three AC systems for medium ambient conditions and low blower operation.

The results show that at 15°C, the enhanced R-134a and CO₂ AC systems have the same COP. But at 25°C, the CO₂ AC system performances fall dramatically and are even lower than the baseline R-134a AC system ones. The difference between the CO₂ AC system and the enhanced R-134a AC system ranged from 20 to 40%.

The results presented in this report show that if under “normal” working conditions, the CO₂ AC system can match the energy performances of the enhanced R-134a AC system, at high temperatures, its performances fall even under the baseline R-134a ones.

When the air temperature of the condenser / gas cooler inlet corresponds to idle conditions, **the COPs of the CO₂ AC systems are lower of 25 to 45%** compared to the enhanced R-134a AC system. For low ambient conditions, which represent the higher fraction of time during the year where the MAC is used, **the energy performances of the CO₂ AC system are lower of 20 to 40%** compared to the enhanced R-134a AC system.

Reviewer comments

In all the papers presented, the tests are carried out in steady state conditions. To have a adequate comparison between the systems, it is important to perform realistic tests using driving cycles with typical high transient conditions.

Moreover, the chosen rotation speeds in the tests are low (1000 and 1800 RPM for Preissner and 900, 1500 and 2500 RPM for ACRC). When installed on the car, the pulley ratio between the motor and the compressor is between 1.1 and 1.5 (depending on the cars), so the compressor rotation speed is higher than the engine rotation speed. In Europe, gasoline engine cars are running at high speed up to 4000 to 5000 RPM; so tests at higher rotation speed shall be carried out according to a regulatory driving cycle.

Impact of test conditions

During all the reported tests, the condenser / gas cooler is installed in the test rig without any obstacle in front. In the vehicle, this heat exchanger is always behind the car front layout. Various studies Hager et al [HAG01], and Benouali [BEN02] showed that the obstacle modifies and reduces the air flow that crosses the heat exchanger. This can lead to important fuel additional consumption up to 300% compared to a system tested without any obstacle.

At 900 or 1000 RPM (idle conditions), during all the tests presented in the papers, the air flow blown on the condenser was around 425 l/s (i.e 1530 m³/h). When the system is installed in the car under-hood, the air flow depends on the car speed, and if the pressure reaches a certain value, then the fan starts. When using a regulatory cycle, it appears that the air flow ranges from 0 to 3500 m³/h depending on the car speed.

Reviewer comments

The presented tests do not take into account the condenser / gas cooler fan control. The electrical and so mechanical energy consumed by this fan is high, up to 700 W (taking into account an alternator efficiency of 50%). Since high pressure controls are different for R-134a and CO₂ AC systems, those controls shall be taken into account for tests.

It shall be mentioned that the level of the technology level of components are different. CO₂ AC systems benefit from the latest developments. Specially for the compressor, the impact on energy efficiency can be very high when comparing high efficiency CO₂ compressor to current R-134a compressors.

2.3 The RACE project

From 1994 to 1997, 5 European car manufacturers and 4 European suppliers participated in the RACE project (Refrigerant and Automotive Climate systems under Environmental aspects), to investigate the feasibility of CO₂ as a refrigerant in MAC systems.

Genther, in his paper "Passenger car air conditioning using carbon dioxide as refrigerant" (1998) [GEN98], presents some results of this experimentally-based project. The system installed on a BMW 5 series is composed of:

- a variable displacement swash plate compressor,
- an internal heat exchanger (*),
- micro-channel evaporator and gas cooler,
- a solenoid expansion valve,(+)
- a spherical receiver,(*)
- an oil separator,(*)
- sensors for ambient temperature, high-side and suction pressure for capacity and high-side pressure regulation (*).

The components with an (*) are not installed in standard R-134a AC system and permit, specially for the internal heat exchanger and for the solenoid expansion valve to reach higher performances both for CO₂ and R-134a. Only the CO₂ AC system benefits of those components.

The vehicle fitted with CO₂ and R-134a MAC systems were tested in a climatic wind tunnel. The tests carried out during this work were performed under steady state conditions:

- 32 km/h (3rd gear),
- 64 km/h (4th gear),
- idle.

The author presents some of the results. The CO₂ AC system matches the R-134a AC system in terms of cooling capacity since temperatures achieved inside the car follow the same dynamic and are within $\pm 1K$ for the two driving conditions (32 and 64km/h). Under idle conditions, the CO₂ AC system suffers a lack of cooling capacity compared to the R-134a AC system.

In the paper the author claims that the CO₂ AC system presents:

- Sufficient cooling capacity to reach a high level of comfort
- A comparable fuel consumption to R-134a MAC systems,
- A lower TEWI,
- An extra weight of 3 kg.

It is indicated at the end of the paper that the compressor used for the R-134a AC system is a fixed displacement compressor and the author agrees that the use of variable displacement compressor will increase the system COP by at least 20% !

Many aspects for CO₂ systems need more attention:

- the seals and hose lines,
- the price due to necessary supplementary components.

2.4 Works presented at 2002 SAE Automotive Alternate Refrigerant System Symposium (Phoenix)

During this meeting many car manufacturers and suppliers presented their latest development to limit MAC system TEWI.

In this section, three presentations are analyzed and commented:

- R. Mager from BMW Group “Experience of a CO₂ fleet test” [MAG02],
- S.O. Andersen (US EPA), J.A. Baker and M. Ghodbane (Delphi) and W.R. Hill (GM) [AND02],
- E. Lundberg (Visteon) “An enhanced R-134a climate system” [LUN02]

◆ R. Mager from BMW Group “Experience of a CO₂ fleet test” [MAG02]

During his presentation, R. Mager compares the performances of R-134a and CO₂ AC systems mounted on a BMW 3 series. Tests seem to have been carried out in a climatic wind tunnel.

The author does not give any detail on the tested AC system, so it is hard to know if the R-134a AC system is a state-of-the art system.

Tests have been performed according to the cool down mode, which is a succession of 3 steady state points. The CO₂ AC system presents a faster answer in terms of cooling than the R-134a AC system. To evaluate the comfort inside the car, only the head zone temperature is used (it would have been better to use a thermal mannequin). The temperature in the head zone is not a sufficient criterion to state the level of comfort (Reviewer note). In the head zone, the air temperature reaches 15°C with the CO₂ AC system. This level of temperature is not achieved by the R-134a AC system.

Fuel consumption

At 35°C (ambient air temperature), the CO₂ AC system consumes more fuel than the R-134a AC system, but the difference is small (+4 to +5%). At 24°C, the CO₂ AC system consumes around 60% less fuel than the R-134a AC system, which is very significant. But strangely enough, at 13°C (ambient temperature) the CO₂ AC system consumes more energy than at 24°C, which is quite surprising since the difference between source and sink is lower.

The author calculates also the annual additional fuel consumption for 3 cities and it appears that the CO₂ AC system consumes less energy than the R-134a AC system:

- Frankfurt (-23%)
- Phoenix (-10%),
- Dubai (-13%).

Reviewer comments

In the paper the so-called “additional fuel consumption of the AC-system”, which is used for the comparison between R-134a and R-744 AC systems is unclear because for R-134a the emissions are converted in equivalent fuel consumption of +0.23 l/100km. This leads to confusion between real additional consumption and integrated CO₂ emissions that need to be addressed separately.

At the end of the presentation, the author presents heat up test results to show the effectiveness of the CO₂ heat pump compared to current supplementary heaters used in the automotive industry. The results show that the CO₂ heat pump presents very good performances. Anyway, no fuel consumption is given and no comparison with a R-134a heat pump is presented.

Reviewer comments

This presentation on slides is not comprehensive enough and specially the conditions for the calculation of fuel additional consumption is unclear and seems not consistent due to the fact that the R-744 system consumes more energy at 24°C than at 13°C which is quite surprising.

Moreover, tests have been carried out for cool down cycles (NEFZ-cycle) and not for regulatory driving cycles (like MVEG); the extrapolation for annual fuel consumption for various cities is not based on realistic operating conditions. When tested during the cool down process, the MAC system works at its highest capacity where CO₂ systems are known to show the best energy efficiency.

◆ **E. Lundberg (Visteon) "An enhanced R-134a climate system" [LUN02]**

The presentation made by E. Lundberg shows the benefits of an enhanced R-134a AC system with a reduced charge of 590g, indicating a higher energy efficiency of 20% by the use of available technologies (oil separator, high efficiency condenser, small diameter liquid line, and external control compressor) but, the tests have been performed under steady state and so, the effective gains due to the control system cannot be taken into account as demonstrated in [BEN02]. Using driving cycles, the gains with external control compressor are much higher, if the control logic is efficient.

Conclusions and advice

All the reviewed papers analyze the energy performance of R-134a and CO₂ AC systems.

Steady state vs. dynamic tests

All the comparisons are made in steady state conditions, which is not sufficient to conclude on energy consumption of systems. As shown in section 3, tests should be performed according to driving cycles permitting to measure the fuel or the energy consumption related to the dynamic behavior of the AC system.

AC system integration in the car

The front layout of the car has a major influence on the air flow on the condenser. Depending on the design, the energy penalty due to the front lay-out can be significant. When the energy performances are measured on test bench without any obstacle, the results are overestimated, and this overestimation is strongly dependent on the refrigerant. It implies usually a higher energy penalty for CO₂ compared to R-134a. Energy performance tests should be completed by tests in climatic wind tunnel on the AC car.

"Apples and oranges"

It appears that many comparisons between R-134a and CO₂ systems are not fair. Mostly R-134a systems are current technology. This may lead to a huge difference in terms of additional fuel consumption.

The CO₂ compressors are always prototypes and they seem to be well optimized. If the same effort were realized with R-134a compressors, the mechanical power consumed by R-134a system will decrease drastically.

Even if R-134a compressors have been improved in the last years, for standard production components the cost is the main driver due to a strong competition among AC system suppliers. Moreover the energy efficiency of MAC systems is not, up to now, a constraint, and so the price for car manufacturers is still the criterion of choice. This price competition does not concern R-744 prototypes.

2.5 The R-152a technical option

- ◆ S.O. Andersen (US EPA), J.A. Baker and M. Ghodbane (Delphi) and W.R. Hill (GM) [AND02]

This paper has also been presented at the 2002 SAE Automotive Alternate Refrigerant System Symposium (Phoenix).

In "R-152a Mobile AC system", Andersen & al show that the R-152a may be an alternative to the R-134a since it has a lower GWP (140 vs. 1300). Tests have been performed in steady state conditions and in climatic wind tunnel. The results show that the energy performances of the system running with R-152a are better than the R-134a ones (the same components were used for both systems). The gains, in terms of COP, ranged between +2.6 and 17.3%. R-152a showed 1.8 to 17% mechanical COP improvement over R-134a baseline.

The authors study also the potential efficiency improvement with enhanced systems (R-152a or R-134a) with capacity control compressor, oil separator and controlled re-circulation. All these technologies are readily available.

The author presents an LCCP (Life Cycle Climate performance of refrigerant) for:

- R-134a system,
- Enhanced R-134a system,
- R-152a system,
- CO₂ system.

For 3 cities around the world:

- Frankfurt,
- Tokyo,
- Phoenix.

The LCCP takes into account the energy and refrigerant emissions from all phases of manufacturing, use, servicing recycling and scrap throughout the lifetime of the AC system. It compares the baseline R-134a system to an enhanced R-134a system and to R-152a and CO₂ at various ambient temperatures and driving cycle conditions.

Whatever the city, the R-152a system has always the lower LCCP. Except in Frankfurt, the enhanced R-134a system presents a lower LCCP than the CO₂ system. In phoenix, the CO₂ system has the highest LCCP compared to all other systems as it can be seen Figure 2.1.

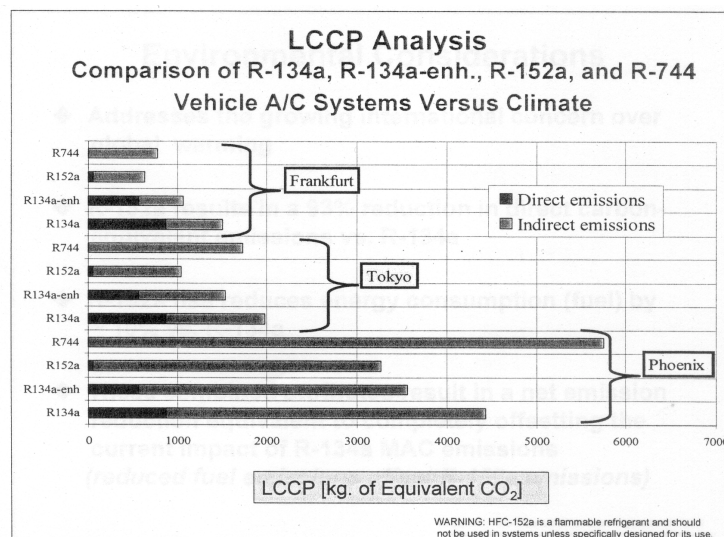


Figure 2.1

The use of R-152a results in 93% reduction in direct CO₂ equivalent emissions vs. R-134a.

R-152 use reduces energy consumption by nearly 10% vs. R-134a. So the use of R-152a offers both reduction in CO₂ equivalent emissions as well as a significant fuel saving potential with the same components developed for R-134a. Moreover this system can be enhanced without any problem.

The major issue for R-152a is its flammability so it may be hazardous to use it in AC cars. The authors show that this refrigerant has a moderate flammability (A2 classification in ASHRAE Standard 34). To use it safely, the authors state that the charge shall be reduced to a less than one pound (454g).

Additional safety components could be installed such as solenoid valves that create multiple containment volumes to protect passenger and engine compartments.

Flammability of R-152a

Table 2.1, from ARTI Database, is recognized as a reference document for basic physical properties, safety classification according to the US Standard ASHRAE 34, and giving complementary data on toxicity and flammability.

Table 2.1 – Summary physical, safety, and environmental data for refrigerants (sorted by ASHRAE 34 designation) [CAL01]

Refrigerant Data Summary

TABLE 1. Summary physical, safety, and environmental data for refrigerants (sorted by ASHRAE 34 designation)

refrigerant number	refrigerant chemical formula or blend composition - common name	physical data						safety data				environmental data					
		molec-ular mass	boil-ing (°C)	cond (°C)	subl (°C)	triple (°C)	critical (°C)	TUP-TWA (PPM)	LFL (%)	HOC (kJ/kg)	Std 34 safety group	global-warm-potential (GWP)	ozone-depleting potential (ODP)	ASHRAE 34			
11	CCl3F	137.37	25.1	74.7	198.8	588.4	4.41	640	0	0	0	0	0	0	0	0	0
12	CCl2F2	120.91	-40.8	-21.4	112.8	233.6	4.24	600	0	0	0	0	0	0	0	0	0
13	CClF3	148.91	-51.7	-73.9	57.2	152.8	3.95	574	0	0	0	0	0	0	0	0	0
14	CF4	104.46	-81.5	-114.3	38.9	84.0	3.89	563	0	0	0	0	0	0	0	0	0
15	CF3Br	196.91	-21.8	-7.2	173.3	263.8	3.95	573	0	0	0	0	0	0	0	0	0
16	CF3I	238.03	-120.1	-108.6	-45.6	-53.1	3.75	544	0	0	0	0	0	0	0	0	0
17	CF2Br2	182.90	5.9	46.0	119.3	202.9	5.28	751	10	0	0	0	0	0	0	0	0
18	CF2I2	254.03	-40.8	-41.4	96.2	206.2	4.99	728	0	0	0	0	0	0	0	0	0
19	CF2Cl2	120.91	-82.1	-115.8	35.9	74.6	4.44	702	0	0	0	0	0	0	0	0	0
20	CF2BrCl	184.93	-40.2	-104.4	237.8	458.5	4.00	682	0	0	0	0	0	0	0	0	0
21	CF2ClBr	167.46	-9.1	15.6	117.0	217.8	4.17	691	0	0	0	0	0	0	0	0	0
22	CF2ClF	120.91	-81.1	-111.1	38.0	112.8	5.80	841	0	0	0	0	0	0	0	0	0
23	CF2BrF	184.93	-24.2	-11.6	143.1	289.6	4.67	767	0	0	0	0	0	0	0	0	0
24	CF2IF	238.03	-70.1	-108.6	44.1	111.4	5.90	856	0	0	0	0	0	0	0	0	0
25	CF2I2	254.03	-181.5	-198.7	-92.6	-116.7	4.80	867	0	0	0	0	0	0	0	0	0
26	CF2ClF2	184.93	-41.4	-111.1	112.3	212.1	4.42	725	0	0	0	0	0	0	0	0	0
27	CF2ClCF2	170.90	3.6	36.5	145.7	254.3	3.25	473	0	0	0	0	0	0	0	0	0
28	CF2CF2	104.46	-82.9	-106.0	38.0	119.0	3.12	493	0	0	0	0	0	0	0	0	0
29	CF2CF3	138.01	-78.7	-108.8	19.9	67.8	3.85	641	0	0	0	0	0	0	0	0	0
30	CF2CF2F	152.93	27.8	82.0	203.8	362.8	3.66	531	0	0	0	0	0	0	0	0	0
31	CF2CF2F2	178.96	-32.0	-10.4	122.3	232.1	3.42	525	0	0	0	0	0	0	0	0	0
32	CF2CF2F3	192.92	-48.1	-54.6	66.2	151.2	3.83	528	0	0	0	0	0	0	0	0	0
33	CF2CF2F4	196.91	-47.0	-83.6	81.3	138.3	3.35	486	0	0	0	0	0	0	0	0	0
34	CF2CF2F5	182.93	-25.1	-15.0	101.1	214.8	4.05	589	0	0	0	0	0	0	0	0	0
35	CF2CF2F6	152.93	5.2	43.2	250.8	331.4	4.23	614	0	0	0	0	0	0	0	0	0
36	CF2CF2F7	178.96	32.0	89.6	204.7	309.4	4.28	618	0	0	0	0	0	0	0	0	0
37	CF2CF2F8	192.92	-9.0	15.8	137.2	279.0	4.12	598	0	0	0	0	0	0	0	0	0
38	CF2CF2F9	184.93	-47.2	-53.0	72.9	162.2	3.78	548	0	0	0	0	0	0	0	0	0
39	CF2CF2F10	169.94	-24.1	-11.4	104.9	219.8	3.83	525	0	0	0	0	0	0	0	0	0
40	CF2CF2F11	184.93	-34.2	-11.7	112.3	219.9	4.02	608	0	0	0	0	0	0	0	0	0
41	CF2CF2F12	198.91	-13.1	55.6	187.3	268.1	5.27	764	0	0	0	0	0	0	0	0	0
42	CF2CF2F13	184.93	-37.1	-34.0	132.2	218.0	4.79	602	0	0	0	0	0	0	0	0	0
43	CF2CF2F14	198.91	-88.9	-108.0	32.2	98.0	4.87	708	0	0	0	0	0	0	0	0	0
44	CF2CF2F15	184.93	-24.8	-12.6	119.8	218.8	5.32	712	0	0	0	0	0	0	0	0	0
45	CF2CF2F16	198.91	-36.4	-33.9	71.9	160.4	4.64	608	0	0	0	0	0	0	0	0	0
46	CF2CF2F17	178.96	-15.6	3.9	132.0	217.0	2.58	432	0	0	0	0	0	0	0	0	0
47	CF2CF2F18	152.94	-1.4	29.5	124.9	216.8	3.29	464	0	0	0	0	0	0	0	0	0
48	CF2CF2F19	134.95	16.1	99.2	194.1	300.4	4.43	643	0	0	0	0	0	0	0	0	0
49	CF2CF2F20	158.96	5.9	42.6	133.2	212.7	2.89	418	0	0	0	0	0	0	0	0	0
50	CF2CF2F21	172.97	-33.5	-28.3	125.2	212.7	3.58	618	0	0	0	0	0	0	0	0	0
51	CF2CF2F22	186.98	-44.0	-44.0	96.7	206.1	4.25	618	0	0	0	0	0	0	0	0	0
52	CF2CF2F23	200.99	-8.8	21.2	116.7	218.4	3.18	603	0	0	0	0	0	0	0	0	0
53	CF2CF2F24	200.99	29.4	84.9	160.6	323.4	2.55	370	0	0	0	0	0	0	0	0	0
54	CF2CF2F25	141.93	-29.8	-5.4	128.9	264.0	3.52	588	0	0	0	0	0	0	0	0	0
55	CF2CF2F26	136.94	-23.2	-9.8	125.4	257.7	3.59	579	0	0	0	0	0	0	0	0	0
56	CF2CF2F27	146.95	-34.4	-29.9	105.3	221.5	4.61	668	0	0	0	0	0	0	0	0	0
57	CF2CF2F28	156.96	-35.7	-32.3	105.5	216.3	4.68	679	0	0	0	0	0	0	0	0	0
58	CF2CF2F29	166.97	-38.5	-22.9	109.9	219.6	4.42	638	0	0	0	0	0	0	0	0	0
59	CF2CF2F30	176.98	-49.2	-56.6	76.0	198.8	4.23	614	0	0	0	0	0	0	0	0	0
60	CF2CF2F31	186.99	-47.2	-53.3	83.0	191.4	4.53	657	0	0	0	0	0	0	0	0	0
61	CF2CF2F32	196.99	-44.0	-47.2	91.2	196.2	4.68	680	0	0	0	0	0	0	0	0	0
62	CF2CF2F33	206.99	-43.8	-46.8	88.7	191.7	4.48	638	0	0	0	0	0	0	0	0	0
63	CF2CF2F34	216.99	-48.8	-51.9	72.1	181.8	3.74	602	0	0	0	0	0	0	0	0	0
64	CF2CF2F35	226.99	-32.9	-27.2	105.0	222.0	4.29	622	0	0	0	0	0	0	0	0	0
65	CF2CF2F36	236.99	-38.4	-38.3	91.5	196.9	4.48	650	0	0	0	0	0	0	0	0	0
66	CF2CF2F37	246.99	-42.8	-45.3	88.5	191.0	4.73	686	0	0	0	0	0	0	0	0	0
67	CF2CF2F38	256.99	-45.4	-49.9	83.3	181.9	4.62	661	0	0	0	0	0	0	0	0	0
68	CF2CF2F39	266.99	-35.4	-31.7	105.9	224.4	4.68	680	0	0	0	0	0	0	0	0	0
69	CF2CF2F40	276.99	-36.5	-33.7	104.4	219.9	4.71	683	0	0	0	0	0	0	0	0	0
70	CF2CF2F41	286.99	-53.8	-60.9	72.5	182.5	4.96	718	0	0	0	0	0	0	0	0	0
71	CF2CF2F42	296.99	-53.5	-60.7	71.0	180.6	4.78	693	0	0	0	0	0	0	0	0	0
72	CF2CF2F43	306.99	-39.7	-39.5	89.1	212.4	4.95	718	0	0	0	0	0	0	0	0	0
73	CF2CF2F44	316.99	-43.6	-42.9	96.0	204.8	4.99	718	0	0	0	0	0	0	0	0	0
74	CF2CF2F45	326.99	-43.8	-43.2	95.5	203.9	4.95	718	0	0	0	0	0	0	0	0	0
75	CF2CF2F46	336.99	-38.4	-33.5	107.5	225.5	4.88	708	0	0	0	0	0	0	0	0	0
76	CF2CF2F47	346.99	-29.3	-29.7	101.4	214.5	4.24	615	0	0	0	0	0	0	0	0	0
77	CF2CF2F48	356.99	-34.0	-29.2	110.7	231.3	4.75	682	0	0	0	0	0	0	0	0	0

J. M. Calm and G. C. Hourahan, "Refrigerant Data Summary," *Engineered Systems*, 18(11):74-88, November 2001

As indicated by Table 2.1, the Heat Of Combustion (HOC) of R-152a is of 17.4 MJ/kg, and a Lower Flammability Limit of 3.1%. ASHRAE 34, as many other safety standards for refrigerants, including European EN-378, has determined 3 classes for the flammability:

1. non flammable
2. moderately flammable
3. highly flammable.

Class 1 exhibits no flame propagation at 23°C according to the standard ASTM E 681-01. Class 2 has been determined historically for ammonia with 2 criteria:

- a lower flammability limit inferior to 0.1 kg/m³, and
- a heat of combustion inferior to 19 MJ/kg.

So, R-152a is also in Class 2. This ASHRAE classification is under discussion in Standard Committees, specially in TC 86/SC8/WG5, in charge of the update of ISO 817.5, where additional criterion seems necessary to reach a more well based physical determination of flammability classification. Different proposals are under study, and a recent paper by Kondo [KON02] summarizes in Table 2.2 different flammability properties and a new index, called RF, permitting a continuous classification of the flammability of pure substances and blends. The RF number of R-152a in Table 2.2 is of 14.9 significantly higher than the one of ammonia (6.9) and the one of R-32 (4.6). On-going work based on burning velocity shows that the flammability of R-152a is intermediate between highly flammables like propane and much lower flammability substances as R-32.

Table 2.2 – Values of F-number, R-index, and Burning velocity for a number of Compounds [KON02]

Substance	Heat of combustion (kJ/g)	Stoichiometric (vol%)	Flammability limits (vol%)		F-number	R-index	RF-number (kJ/g)	Burning velocity (cm/s)
			LFL	UFL				
Acetylene	48.1	7.72	2.5	100	0.84	3.09	256.2	155
Ammonia (R-717)	18.6	21.8	15.0	28	0.27	1.45	6.8	8
Benzene	40.5	2.71	1.3	7.9	0.59	2.08	59.3	45
1,2-dimethyl-Benzene	41.1	1.95	1.1	6.4	0.59	1.77	58.1	34
n-Butane (R600)	45.8	3.12	1.8	8.4	0.54	1.73	52.9	35
1-Butene	45.2	3.37	1.6	10.0	0.60	2.11	67.8	46
n-butyl-Benzene	41.8	1.53	0.8	5.8	0.63	1.91	70.7	36
Carbon disulfide	14.5	6.52	1.3	50	0.84	5.02	75.5	54
Carbon monoxide	10.1	29.50	12.5	74	0.59	2.36	14.5	43
Cyclohexane	43.8	2.27	1.3	7.8	0.59	1.75	63.4	42
n-Decane	44.5	1.33	0.8	5.4	0.62	1.68	71.1	40
1,1-difluoroethane (R-152a)	16.55	7.8	4.8	17.3	0.47	1.61	14.9	21
Difluoromethane (R-32)	9.40	17.4	13.3	29.3	0.33	1.31	4.6	5.5
2,2-dimethyl-n-Butane	44.8	2.16	1.2	7.0	0.59	1.80	63.4	39
2,3-dimethyl-n-Butane	44.9	2.16	1.2	7.0	0.59	1.80	63.5	40
2,3-dimethyl-n-Pentane	44.7	1.87	1.1	6.7	0.59	1.70	65.7	40
Ethane	47.4	5.64	3.0	12.4	0.51	1.88	49.0	44
Ethene	47.1	6.52	2.7	9.8	0.73	2.41	124.8	75
Ethylene oxide	27.7	7.72	3.0	100	0.83	2.57	132.0	100
n-Heptane	44.9	1.87	1.2	6.7	0.58	1.56	61.1	42
n-Hexane	45.0	2.16	1.2	7.4	0.60	1.80	66.6	42
1-Hexene	44.7	2.27	1.2	6.9	0.63	1.89	77.1	46
Hydrogen	119.7	29.5	4.0	75	0.77	7.38	398.8	291
Methane	49.9	9.47	5.0	15.8	0.44	1.89	38.8	37
2-methyl-n-Butane	45.1	2.95	1.4	7.6	0.57	1.82	60.0	40
methyl-Cyclohexane	43.6	1.95	1.1	6.7	0.59	1.77	64.1	41
2-methyl-n-Pentane	44.9	2.16	1.2	7.0	0.59	1.80	63.6	40
2-methyl-Propene	45.5	3.12	1.8	8.4	0.54	1.73	52.8	38
2-methyl-Propene	44.9	3.37	1.8	8.8	0.55	1.87	54.4	41
n-Pentane	45.3	2.55	1.5	7.8	0.56	1.70	58.0	42
1-Pentene	44.9	2.71	1.5	8.7	0.58	1.81	63.2	46
cis-2-Pentene	44.8	2.71	1.3	8.3	0.63	2.08	75.0	48
Propene (R290)	46.3	4.02	2.1	9.5	0.53	1.91	52.1	37
Propene	45.7	4.44	2.0	11.0	0.57	2.22	61.5	48
Toluene	40.8	2.27	1.2	7.1	0.59	1.89	58.5	38
2,2,3-trimethyl-n-Butane	44.6	1.87	1.0	6.7	0.61	1.87	70.9	39
2,2,4-trimethyl-n-Pentane	44.6	1.65	1.1	6.0	0.57	1.50	59.5	38

* Numbers in yellow squares are from the minutes of ISO/TC86/SC8/WG5 held on April 22-23 2002.

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3. Integrated CO₂ emissions along the AC vehicle lifetime

In order to evaluate the life cycle CO₂ emissions due to the use of AC cars, a number of parameter shall be taken into account:

- Driving conditions (urban, extra urban and highway conditions),
- Climatic conditions,
- Real use of cars based on social habits.

Realistic conditions taking into account driving conditions are already set up by EU regulation in order to measure fuel consumption of cars. Those fuel consumptions are displayed in all advertisements. To make a realistic evaluation of CO₂ emissions due to the use of MAC systems, the MVEG regulatory cycle constitutes an appropriate reference.

Taking into account the different European conditions and typical use of cars, which are known by a number of studies [BEN02₁, BEN02₂, BEN02₃, FAR02], it is possible to define an average number of hours per year of MAC use related to the different European climatic zones.

Integrating low and high performance R-134a systems and best available data on CO₂ AC system performances, it is possible to compare annual CO₂ emissions depending on climatic conditions and the number of hours of use. Knowing annual CO₂ emissions resulting from the AC system use, and adding the equivalent CO₂ emissions of the refrigerant, it is then possible to compare integrated CO₂ emissions.

In this section, based on available technical papers, the following issues will be successively addressed:

- Measurement of fuel additional consumption according to regulatory driving cycles comparing fuel consumption with AC system on and off.
- Impact of AC system control when fuel consumption is measured on driving cycles,
- Annual integrated CO₂ emissions of low and high efficiency R-134a AC systems,
- Comparison of annual integrated CO₂ emissions of R-134 AC and CO₂ AC systems.

3.1 Review of tests for MAC additional consumption prevision based on driving cycles

Papers issued by ADEME [BAR98], the Centre for Energy Studies [BEN02.1, BEN02.2, BEN03], and CRF [MAR03] indicate the interest of using the European regulatory cycle to measure the additional consumption of AC cars. Moreover, the use of driving cycles simulating urban and extra urban driving conditions, permits to study the impact of the control system.

◆ MVEG cycle

MVEG cycle is composed of 2 parts : the first one simulating urban driving conditions called also ECE cycle, and an extra urban cycle, also called EUDC cycle. Figure 3.1 presents the car speed variation that needs to be simulated. This cycle is used to measure in third party laboratory the effective fuel consumption of all vehicles sold on the European market. It is considered by car manufacturers as sufficiently representative of driving conditions and has been verified by real fuel consumption. So for now it can **be considered as the reference for fuel consumption measurement.**

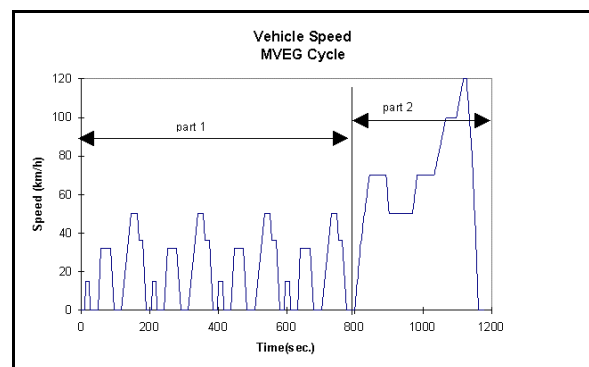


Figure 3.1 - MVEG Vehicle Speed Cycle

Using those driving conditions to measure either mechanical consumption of compressor and electrical consumption of the condenser fan, permits much more realistic testing of AC systems permitting to integrate the dynamic behavior of the compressor (see Figure 3.2), and also the significant variation of air flow on the condenser as indicated in Figure 3.3.

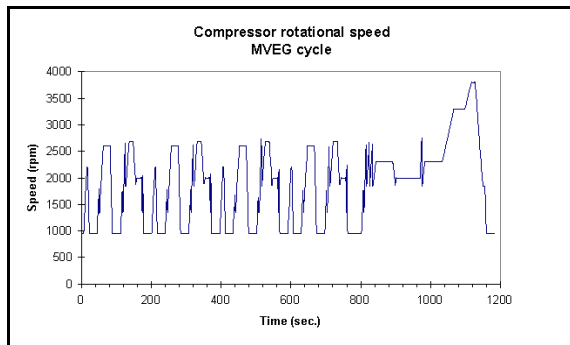


Figure 3.2 - MVEG Compressor Speed Cycle

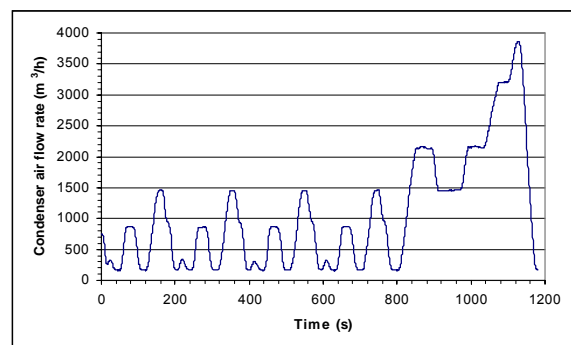


Figure 3.3 - Mass air flow rate at the condenser reproduced on the bench during the MVEG cycle

Moreover, the additional fuel consumption due to the operation of the car AC system can be measured on the vehicle test bench used to measure fuel consumption of cars. A complementary number of detailed operating conditions need to be addressed taking into account realistic soaking process, and realistic testing room temperature to measure the fuel additional consumption when AC is operating.

◆ Results of MAC additional consumption using MVEG conditions

Tests have been performed at UTAC on 20 vehicles in order to measure AC additional consumption at two level of air temperature (30 and 40°C), each vehicle is soaked during the night before test and in temperature equilibrium with the room. The tests have been successively realized with and without the AC system running [BAR98].

The results of three different cars respectively equipped with gasoline, diesel and turbo charged diesel engine are shown in Table 3.1.

Table 3.1 : Relative additional consumption for various cars

Cycle	Relative additional consumption (%) referred to the baseline consumption of the car					
	<i>Gasoline engine</i>		<i>Diesel engine</i>		<i>Turbo-Diesel engine</i>	
Air temperature	30°C	40°C	30°C	40°C	30°C	40°C
Urban	31 %	38 %	26 %	28 %	40 %	42 %
Extra-urban	16 %	20 %	12 %	15 %	28 %	33 %

The results show that the additional consumption is quite high, between 12% and 42%, depending on the engine type and the outside air temperature. The additional consumption is higher during the urban cycle. The values obtained are nearly two times higher than the ones measured during the extra urban cycle.

The type of engine has a significant influence on the level of the additional consumption. The highest levels in terms of relative additional consumption are obtained for Turbo Diesel engines, followed by gasoline and diesel engines.

◆ Results of MAC additional consumption using US cycle conditions [FAR02]

Tests carried out by NREL showed that for a conventional car using AC system, the fuel consumption increases by 35%. For a Honda insight, the fuel consumption increases by 46%. For a 3X Hybrid car, the fuel consumption increases by 128%.

◆ **Results of MAC additional consumption using MVEG cycle in climatic room [MAR03] and [BEN02₃]**

In 2002 a series of tests have been performed by CRF in test chamber where temperature and humidity are controlled and where airflow is also controlled around the car.

Five diesel engine cars all equipped with common rail injection technology have been chosen in order to analyze the impact of AC system on efficient engine. As indicated in Table 3.2:

- the vehicle sizes are different 3 of the B class and 2 of the D class, and
 - the compressor technologies are different.
- Comparison is also performed between external and internal control compressors. Two types of external control are compared.

Table 3.2 - Characteristics of cars and compressors

	Engine	Class	Compressor	A/C Control
Car 1	Diesel 1900	B	Fixed displacement	Manual
Car 2	Diesel 1900	D	Variable displacement, internal control	Automatic
Car 3	Diesel 1900	D	Variable displacement, external control	Automatic
Car 4	Diesel 2000	B	Variable displacement, internal control	Manual
Car 5	Diesel 1900	B	Variable displacement, external control	Automatic

Test conditions

Two series of temperatures and humidity have been chosen:

- 35°C and 60% relative humidity, and
- 28°C and 50% relative humidity.

The cars have been soaked respectively at these temperatures before tests.

MVEG cycle has been chosen for driving conditions, and fuel consumption has been measured on usual roll-bench test.

The comfort conditions have been analyzed with thermal manikin for all the studied cars, and the fuel additional consumptions have been measured (see Tables 3.3 and 3.4).

Table 3.3: Comfort and consumption tests results (35°C and 60% humidity)

	Mode	Asymmetry [°C]	Discomfort [°C]	Cabin Mean [°C]	Outlet Mean [°C]	Fuel consumption [litres per 100 km]		Over-consumption	
						A/C on	A/C off	[litres per 100 km]	%
Car 1	LO	3.98	6.02	28.87	22.97	7.67	4.90	2.77	57%
	LC	4.99	5.48	28.37	19.29	6.90		2.00	41%
Car 2	LO	4.51	6.86	29.26	23.07	8.04	5.25	2.79	53%
	LC	6.34	5.64	28.12	16.30	7.17		1.92	36%
Car 3	LO	4.07	5.82	28.54	20.93	8.85	5.66	3.18	56%
	LC	3.70	5.91	28.68	21.12	8.46		2.79	49%
Car 4	LO	6.08	8.04	29.07	21.18	7.52	5.34	2.19	41%
	LC	7.86	6.89	27.78	13.35	7.41		2.07	39%
Car 5	LO	3.40	2.12	23.37	13.22	6.38	4.90	1.48	30%
	LC	3.32	2.23	24.85	13.21	6.08		1.18	24%

Table 3.4: Comfort and consumption tests results (28°C and 50% humidity)

	Mode	Asymmetry [°C]	Discomfort [°C]	Cabin Mean [°C]	Outlet Mean [°C]	Fuel consumption [litres per 100 km]		Over-consumption	
						A/C on	A/C off	[litres per 100 km]	%
Car 1	LO	4.55	1.64	20.35	12.90	7.06	4.97	2.09	42%
	LC	5.69	0.73	21.62	12.01	6.31		1.34	27%
Car 2	LO	3.40	1.08	22.02	15.96	7.33	5.18	2.15	42%
	LC	4.29	1.17	22.08	12.64	6.73		1.55	30%
Car 3	LO	4.95	1.68	20.49	11.80	8.11	5.65	2.46	44%
	LC	3.39	3.03	23.81	18.18	7.60		1.95	35%
Car 4	LO	4.99	1.24	19.86	12.11	6.94	4.96	1.98	40%
	LC	5.21	2.03	18.92	5.99	6.75		1.79	36%
Car 5	LO	4.47	0.91	20.59	13.29	5.60	4.61	0.99	21%
	LC	4.70	1.79	21.73	11.96	5.77		1.16	25%

A number of lessons can be learnt from those tests performed under regulatory driving conditions. The dynamic operating conditions permit to analyze the impact of AC control system.

When comparing the highest and the lowest additional consumptions (cars 1 and 5), there is a ratio of 2 on the urban cycle. Car 1 is equipped with a fixed displacement compressor and manual control, car 5 with variable displacement compressor and external control. This ratio is only 15% for extra urban cycle at 28 °C. But at 35°C, the relative additional consumption at 35°C is of 90% for urban cycle , and 70% for extra urban cycle.

Also comparing car 4 and car 5 of the same category, one with internal control and the other one with external control compressor, energy consumption gains varying from 50 to 100% are noticed showing the impact of control, and permitting significant energy savings while using the same type of compressors and heat exchangers.

◆ **Comparison of two control systems of R-134a AC system [BEN02₂, BEN03]**

Tests have been performed on a test bench describes in [BEN02₂], permitting to measure cooling capacity, and the compressor mechanical power. The AC system tested is installed on a class B European car. The components are:

- A parallel flow condenser with integrated receiver for sub-cooling,
- a multi-tank evaporator,
- an orifice tube associated with a low pressure accumulator, and
- successively on Internal Control swash-plate Compressor (ICC) and the same compressor type with External Control (ECC).

Note: the analysis of the compressor energy efficiency performed in [BEN02.2] shows that the two compressors have exactly the same energy efficiency when running at the same swept volume.

Test conditions

To compare the performances of ICC and ECC on MVEG cycle, 6 tests have been performed with 2 outside air temperatures (25 and 35°C) and 3 airflow rates at the evaporator (175; 300 and 420 m³/h) with adapted set point temperatures (air blown in the cabin) as indicated in Table 3.5.

Table 3.5 – Test conditions.

Ambient temperature (°C)	Mass Flow (m ³ /h)	Evaporator air outlet Temperature(°C)
25	175	4
	300	7
	420	9
35	175	5
	300	10
	420	12

Results [BEN03]

Refrigerating capacity and mechanical power are integrated along the MVEG cycle, and permit to calculate the average cycle COP for ICC and ECC AC systems for the 6 testing conditions mentioned previously. Results are presented in Tables 3.6 and 3.7 respectively for ambient temperature of 25°C and 35°C.

Table 3.6 – Results for an ambient air temperature of 25°C

Mass Flow (m ³ /h)	Control	Evaporator air outlet Temp(°C)	Mechanical power (kW)	Cooling Capacity (kW)	COP
175	ICC	3.6	1.2	1.85	1.54
	ECC	4.0	0.92	1.60	1.95
	Gain	-	-23.2%	-8%	+26.7%
300	ICC	6.7	1.50	2.40	1.6
	ECC	7	1.20	2.1	2.02
	Gain	-	-20%	-7%	+26.7%
420	ICC	8.7	1.72	2.75	1.6
	ECC	9	1.4	2.46	2.13
	Gain	-	-18.6%	-3.3%	+33%

Table 3.7 – Results for an ambient air temperature of 35°C.

Mass Flow (m ³ /h)	Control	Evaporator air outlet Temp (°C)	Mechanical power (kW)	Cooling Capacity (kW)	COP
175	ICC	4.6	1.83	2.44	1.33
	ECC	5.0	1.29	2.12	1.71
	Gain	-	-29.5%	-9.4%	+28.5%
300	ICC	10.5	2.32	2.95	1.27
	ECC	10	1.67	2.61	1.65
	Gain	-	-28.1%	-6.4%	+29.9%
420	ICC	11.4	2.66	3.69	1.39
	ECC	12	1.88	3.23	1.82
	Gain	-	-29.3%	-7%	+31.5

Analyzing the comparison of the integrated COP along the MVEG cycle, the gain in term **of energy efficiency is substantial, between 26 and 33%**, systematically in favor of the ECC AC system. Those tests indicate that with the same technology, the control system permits a significant energy gain, which shall be taken into account for enhanced AC systems.

Reviewer comments

Those four papers indicate how driving conditions are of importance to analyze additional consumption of car AC system.

The outdoor air temperature level also impacts directly on the additional consumption.

The progresses made in term of control cannot be evaluated using steady state tests, which are those that have been used for all the comparisons between CO₂ and R-134a as shown in the previous section.

3.2 Annual CO₂ emissions due to operation of R-134a and CO₂ AC systems

To compare the annual fuel consumption with R-134a and CO₂ MAC systems, the data presented in the “SAE alternate refrigerant Cooperative project” (2002) [ACR02] are used. Those data are summarized in section 2.2 and in Annex A1.2. Compared to the results of section 3.1 based on driving cycle, the data from the SAE Cooperative Project do not permit to take into account the improvements due to control of the AC system. **Those comparisons shall be considered as a first estimate due to the lack of more detailed data.**

3.2.1 Calculations of mechanical input power of R-134a and CO₂ AC systems

The available figures give the cooling capacity (kW) and the COP for different ambient air temperatures, and different rotation speeds. Based on those two sets of data, the mechanical input power required by the compressor is directly calculated. Testing temperatures are 15, 25, 35 and 45°C, and a linear regression has been used to determined mechanical power at 20, 30 and 40°C.

The systems have been tested at three rotation speeds : 900, 1500 and 2500 RPM, the mechanical input power has been extrapolated for 3500 RPM.

In [ACR02] the R-134a system is called “enhanced” system but it is not well defined. For example, no precision has been given on the compressor type and on its energy efficiency. The only precision is that the condenser has an integrated receiver. The reference to an enhanced system seems arguable.

The values presented in Tables 3.8 and 3.9 are for the same conditions for the air temperature at the evaporator outlet fixed at 5°C.

Note: this choice is easy for the repeatability of the tests but, does not permit to estimate the energy gain associated with a much higher evaporating temperature fixed according to the comfort conditions in the cabin.

Table 3.8 - Mechanical power for R-134a system (kW)

R-134a	Ambient air temperature (°C)						
	15	20	25	30	35	40	45
Rotation speed (RPM)							
900	0.42	0.67	0.91	1.08	1.25	1.32	1.39
1500	0.55	1.19	1.82	1.88	1.94	2.31	2.67
2500	0.67	1.39	2.10	2.39	2.67	2.90	3.13
3500	0.73	1.47	2.20	2.60	3.00	3.20	3.40

Table 3.9 - Mechanical power for CO₂ system (kW)

CO ₂	Ambient air temperature (°C)						
	15	20	25	30	35	40	45
Rotation speed (RPM)							
900	0.42	0.72	1.02	1.35	1.67	1.84	2.00
1500	0.61	1.22	1.82	2.00	2.17	2.63	3.09
2500	0.67	1.39	2.10	2.39	2.67	3.21	3.75
3500	0.73	1.47	2.20	2.60	3.00	3.60	4.20

Table 3.10 gives the mechanical input power for R-134a and CO₂ systems with the same outdoor air temperature at the condenser inlet (R-134a) or the gas cooler inlet (CO₂) when the engine is idling. Taking into account the recirculation of hot air in the underhood, a higher temperature is taken into account for those idling conditions, the air at the inlet is 15°C above the ambient air temperature.

Table 3.10 – Mechanical power of the two systems at idling conditions (kW)

Air inlet temperature Evaporator / Condenser (°C)	R-134a idling conditions	CO ₂ idling conditions
15/30	0.64	1.19
20/35	0.88	1.41
25/40	1.13	1.64
30/45	1.26	1.87
35/50	1.40	2.11
40/55	1.47	2.26
45/60	1.54	2.42

Air recirculation on the evaporator

It is a known control strategy in order to limit energy consumption to recirculate the cabin air on the evaporator in order to blend this previously cooled air and the hot outdoor air.

As indicated in Table 3.11, the recirculation strategy yields to a significant improvement for R-134a leading to minimizing the mechanical input power in between 15 to 41%.

Table 3.11 - Mechanical power for R-134a system outdoor air vs. recirculation (kW)

R-134a	900 tr/mn			
Outdoor air		Recirculation		Difference (%)
30 °C	1.08	15 / 30	0.64	-41%
35°C	1.25	20 / 35	0.88	-29%
40°C	1.32	25 / 40	1.13	-15%
45°C	1.39	30 / 45	1.13	-19%

Surprisingly, the results from [ACR02] indicates that air recirculation on the evaporator leads to an energy penalty for the CO₂ system.

Table 3.12 - Mechanical power for CO₂ system outdoor air vs. recirculation (kW)

CO ₂	900 tr/mn			
Outdoor air		Recirculation		Difference (%)
30°C	1.35	15 / 30	2.11	56%
35°C	1.67	20 / 35	2.11	26%
40°C	1.83	25 / 40	2.26	24%
45°C	2.00	30 / 45	2.42	21%

So, for idling conditions, recirculation will be taken into account for R-134a system but not for the CO₂ system, in order to avoid undue energy penalty for the CO₂ system.

3.2.2 Complementary assumptions to simulate driving conditions, and deriving fuel consumption

Since the [ACR02] tests have been performed under steady state conditions, it is necessary to make a number of complementary assumptions to define the repartition of engine RPM for the different cycles. The calculations have been performed using assumptions as presented in Table 3.13.

Table 3.13 – Driving cycle assumptions

	900 RPM	1500 RPM	2500 RPM	3500 RPM
Urban	50%	50%	0%	0%
Extra-urban	0%	35%	35%	30%
Highway	0%	0%	40%	60%

Values published by CITEPA indicate a different repartition of use depending on the engine type, and are summarized Table 3.14.

Table 3.14 - Repartition of travels

% of time	Urban	Extra_urban	Highway
Gasoline	35%	50%	15%
Diesel	26%	53%	21%

Moreover, typical uses of cars in France are defined in Table 3.15, and fix the fuel consumption base line without MAC operating, and the associated annual CO₂ emissions.

Table 3.15 – Annual fuel and CO₂ emissions

	Annual distance (km)	Fleet repartition (%)	Average annual fuel consumption (l/100km)	CO ₂ emissions (kg CO ₂ /l)	Annual CO ₂ emissions (kg CO ₂ /yr)
Diesel	19 696	35	6.6	2.64	3 432
Gasoline	11 359	65	8.2	2.34	2 180

To evaluate the fuel power needed to run the MAC system, it is necessary to know the engine efficiency. Engine efficiencies depend on driving conditions and typical values are fixed and presented in Table 3.16.

Table 3.16 - Engine efficiencies depending on driving cycles (gasoline and diesel)

Engine efficiency	Urban	Extra_urban	Highway
Gasoline	22%	26%	30%
Diesel	24%	28%	33%

To calculate the annual fuel consumption due to AC system operation, the weight of the AC system itself shall be taken into account (Tables 3.17 and 3.18).

Table 3.17 - Fuel consumption for 10 kg

Fuel cons for +10 kg	
Gasoline	0.05 l/100km
Diesel	0.03 l/100km

The weight of R-134a and CO₂ systems are different and are fixed based on [ACR02] report (see Table 3.18).

Note: the weights given in the ACRC report do not include the control, the fans, and the hoses, so additional weights have been added as presented in Table 3.18.

Table 3.18 : Systems weight

System mass	Base (kg)	Additional weight (kg)	Total (kg)
R-134a	10.9	2.5	13.4
CO ₂	14.8	4.5	19.3

AC use depending on the outdoor temperature

The assumptions made to calculate the annual fuel consumption due to the use of MAC systems are presented Table 3.19.

Table 3.19 - Calculation assumptions

Outside T° (°C)	12.5 < T° < 17.5	17.5 < T° < 22.5	22.5 < T° < 27.5	27.5 < T° < 32.5	32.5 < T° < 37.5	37.5 < T° < 42.5	T° > 42.5
A/C Use	30%	60%	90%	100%	100%	100%	100%
Recirculation mode use	0%	0%	0%	25%	50%	50%	50%
Evap air flow (kg/h)	150	150	150	350	550	550	550
	100% low charge	70% low charge 30% high charge	40% low charge 60% high charge	25% recirculation 75% high charge	50% recirculation (20 / 35) 50% high charge	50% recirculation (25/40) 50% high charge	50% recirculation (30/45) 50% high charge

Using these assumptions and all the values presented, it is possible to calculate for each temperature range, the additional engine energy required to run the MAC system.

3.2.3 Annual fuel consumption and emission calculations for R-134a and CO₂ AC systems

Tables 3.20 to 3.23 present the additional engine energy required by the operation of the AC system depending on the outdoor temperature range and the driving conditions for R-134a and CO₂.

Tables 3.20 and 3.21 correspond to R-134a AC systems, respectively for gasoline and diesel cars.

Table 3.20 : R-134a system on gasoline car

R-134a (gasoline)							
Outside T° (°C)	12.5 < T° < 17.5	17.5 < T° < 22.5	22.5 < T° < 27.5	27.5 < T° < 32.5	32.5 < T° < 37.5	37.5 < T° < 42.5	T° > 42.5
Urban	0.23	1.33	4.05	6.42	6.49	7.95	8.61
Extra urban	0.35	1.65	5.02	7.87	8.93	9.90	10.67
Highway	0.39	1.60	4.69	7.55	8.17	9.50	9.88
Additional engine energy (kW)	0.31	1.53	4.63	7.32	7.96	9.16	9.83

Table 3.21 - R-134a system on diesel car

R-134a (diesel)							
Outside T° (°C)	12.5 < T° < 17.5	17.5 < T° < 22.5	22.5 < T° < 27.5	27.5 < T° < 32.5	32.5 < T° < 37.5	37.5 < T° < 42.5	T° > 42.5
Urban	0.21	1.22	3.72	5.89	5.95	7.28	7.89
Extra urban	0.33	1.53	4.66	7.31	8.29	9.20	9.90
Highway	0.35	1.46	4.27	6.86	7.43	8.63	8.98
Additional engine energy (kW)	0.30	1.43	4.33	6.85	7.50	8.58	9.19

Tables 3.22 and 3.23 correspond to CO₂ AC systems, respectively for gasoline and diesel cars.

Table 3.22 – CO₂ system on gasoline car

CO2 (gasoline)							
Outside T° (°C)	12.5 < T° < 17.5	17.5 < T° < 22.5	22.5 < T° < 27.5	27.5 < T° < 32.5	32.5 < T° < 37.5	37.5 < T° < 42.5	T° > 42.5
Urban	0.23	1.59	5.32	8.80	9.73	11.11	12.52
Extra urban	0.35	1.76	5.20	8.91	9.63	12.02	14.05
Highway	0.39	1.64	4.75	8.39	9.56	11.48	13.40
Additional engine energy (kW)	0.31	1.68	5.17	8.79	9.65	11.62	13.42

Table 3.23 - CO₂ system on diesel car

CO2 (diesel)							
Outside T° (°C)	12.5 < T° < 17.5	17.5 < T° < 22.5	22.5 < T° < 27.5	27.5 < T° < 32.5	32.5 < T° < 37.5	37.5 < T° < 42.5	T° > 42.5
Urban	0.21	1.45	4.88	8.06	8.92	10.19	11.48
Extra urban	0.33	1.64	4.83	8.27	8.94	11.16	13.05
Highway	0.35	1.49	4.32	7.62	8.69	10.44	12.18
Additional engine energy (kW)	0.30	1.56	4.73	8.08	8.88	10.75	12.46

Those results indicate that the additional engine energy is the same for R-134a and CO₂ systems when the outdoor temperature is in between 12.5 and 17.5°C but, when the temperature is above 17.5°C, the CO₂ system requires always additional engine energy.

3.2.4 Fuel additional consumption forecast for 4 cities: Frankfurt, Seville, Tokyo, and Phoenix

To calculate the annual fuel consumption due to the AC system, it is necessary to choose reference cities because the climatic conditions are very different depending on the location.

As indicated in Table 3.24, for each city, and according to weather conditions, the annual percentage of each range of temperatures is determined.

Table 3.24 - Climatic data for the 4 selected cities

Outside T° (°C)	12.5 < T° < 17.5	17.5 < T° < 22.5	22.5 < T° < 27.5	27.5 < T° < 32.5	32.5 < T° < 37.5	37.5 < T° < 42.5	T° > 42.5
Frankfurt	20.7%	13.9%	5.6%	0.7%	0.0%	0.0%	0.0%
Seville	24.7%	22.4%	15.7%	8.9%	3.5%	0.2%	0.0%
Tokyo	17.3%	17.5%	19.9%	5.5%	1.0%	0.0%	0.0%
Phoenix	17.9%	16.7%	15.9%	16.3%	9.8%	5.7%	0.9%

Using the values presented above, the annual MAC fuel additional consumption and CO₂ emissions for each city are calculated depending on:

- The type of engine (gasoline or diesel),
- The type of MAC system (R-134a and CO₂).

Table 3.25 - Fuel consumption and CO₂ emissions in Frankfurt

Frankfurt	Total (kWh)	Energy cons (liter/year)	System weight (liter/year)	Total (liter/year)	% of the annual fuel consumption	Emissions (kg CO ₂ / year)
Gasoline (R-134a)	134.07	15.74	7.61	23.35	2.5%	54.7
Gasoline (CO ₂)	148.21	17.40	10.96	28.36	3.0%	66.5
Difference (%)		10.5%		21.5%		
	Total (kWh)	Energy cons (liter/year)	System weight (liter/year)	Total (liter/year)	% of the annual fuel consumption	Emissions (kg CO ₂ / year)
Diesel (R-134a)	218.33	21.51	7.92	29.43	2.3%	77.9
Diesel (CO ₂)	237.57	23.41	11.40	34.81	2.7%	92.1
Difference (%)		9%		18%		

Table 3.26 - Fuel consumption and CO₂ emissions in Seville

Seville	Total (kWh)	Energy cons (liter/year)	System weight (liter/year)	Total (liter/year)	% of the annual fuel consumption	Emissions (kg CO ₂ / year)
Gasoline (R-134a)	473.00	55.54	7.61	63.15	6.8%	148.0
Gasoline (CO ₂)	543.81	63.85	10.96	74.81	8.0%	175.3
Difference (%)		15.0%		18.5%		
	Total (kWh)	Energy cons (liter/year)	System weight (liter/year)	Total (liter/year)	% of the annual fuel consumption	Emissions (kg CO ₂ / year)
Diesel (R-134a)	769.25	75.79	7.92	83.71	6.4%	221.5
Diesel (CO ₂)	868.27	85.54	11.40	96.95	7.5%	256.5
Difference (%)		12.9%		15.8%		

Table 3.27 - Fuel consumption and CO₂ emissions in Tokyo

Tokyo	Total (kWh)	Energy cons (liter/year)	System weight (liter/year)	Total (liter/year)	% of the annual fuel consumption	Emissions (kg CO ₂ / year)
Gasoline (R-134a)	391.87	46.01	7.61	53.62	5.8%	125.7
Gasoline (CO ₂)	444.55	52.20	10.96	63.16	6.8%	148.0
Difference (%)		13.4%		17.8%		
	Total (kWh)	Energy cons (liter/year)	System weight (liter/year)	Total (liter/year)	% of the annual fuel consumption	Emissions (kg CO ₂ / year)
Diesel (R-134a)	636.75	62.73	7.92	70.65	5.4%	186.9
Diesel (CO ₂)	708.85	69.84	11.40	81.24	6.2%	215.0
Difference (%)		11.3%		15.0%		

Table 3.28 - Fuel consumption and CO₂ emissions in Phoenix

Phoenix	Total (kWh)	Energy cons (liter/year)	System weight (liter/year)	Total (liter/year)	% of the annual fuel consumption	Emissions (kg CO ₂ / year)
Gasoline (R-134a)	821.21	96.42	7.61	104.03	11.2%	243.8
Gasoline (CO ₂)	977.23	114.74	10.96	125.70	13.5%	294.6
Difference (%)		19.0%		20.8%		
	Total (kWh)	Energy cons (liter/year)	System weight (liter/year)	Total (liter/year)	% of the annual fuel consumption	Emissions (kg CO ₂ / year)
Diesel (R-134a)	1335.62	131.59	7.92	139.51	10.7%	369.1
Diesel (CO ₂)	1560.92	153.79	11.40	165.19	12.7%	437.1
Difference (%)		16.9%		18.4%		

The analysis of Tables 3.25 to 3.28 indicates that the CO₂ system consumes more fuel whatever the climatic conditions. **The difference in energy consumption compared to the R-134a AC system ranges from +15% to +21.8 %, which is significant.** This difference between the two systems is lower for diesel engines.

When looking at the same Tables, the climatic conditions have a huge influence on the additional consumption level due to the use of MAC system: from 23 liters/year (+2.5%) in Frankfurt to 165.2 liters/year (+12.7%) in Phoenix.

The fan operation:

- of the evaporator blowing the air in the cabin, and
- of the condenser in order to limit the high pressure, constitutes a non negligible energy, and subsequently fuel additional consumption.

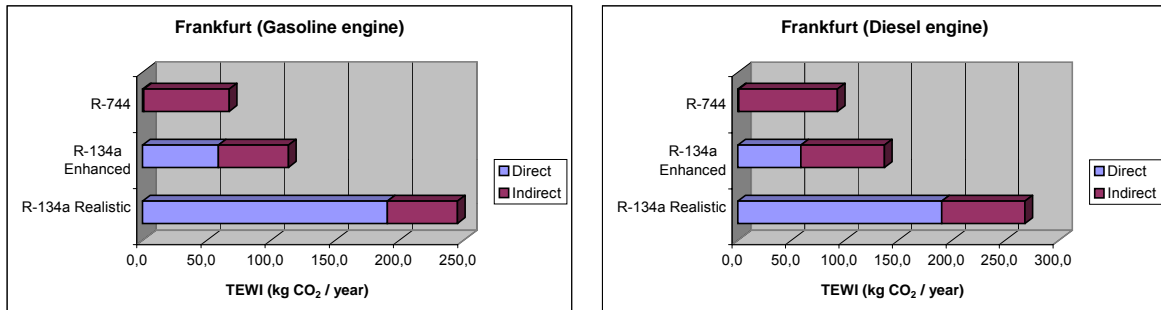
The consumed energy is dependent on the air mass flow rate, which itself depends on the outdoor temperature and on the cooling needs. The fan consumption is evaluated from 1.9 l/yr for gasoline engine in Frankfurt to 17.9 l/yr for a diesel engine in Phoenix, corresponding from 0.2% to 1.4% of the annual fuel consumption.

When comparing R-134a and CO₂ AC systems, this additional fuel consumption could be higher for the CO₂ AC system due to the significant impact of air temperature on the gas cooler. But, no data is available to forecast the possible energy consumption of fans for CO₂ AC systems. For this reason the comparison is limited to the energy and the fuel required for the sole AC compressor operation.

3.3 Comparison of annual direct and indirect CO₂ emissions of CO₂ (R-744) and R-134a MAC systems

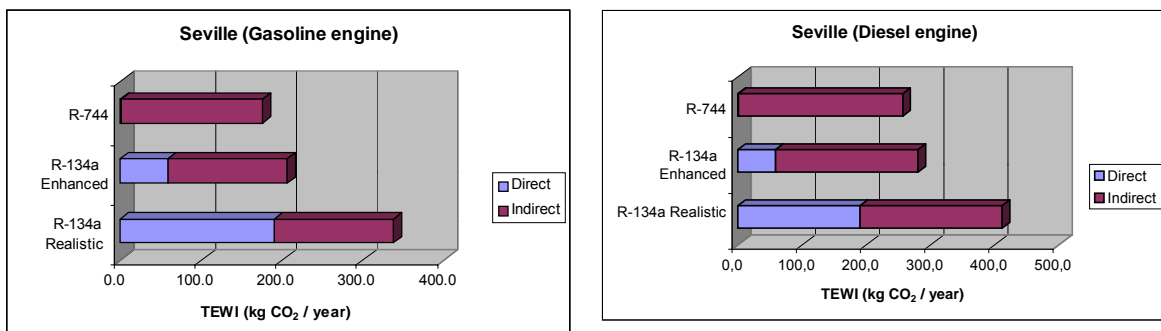
Notes:

1. The enhanced R-134a system corresponds to the low charge and leak tight R-134a system as defined in Section 1.2.
2. The direct emissions of the CO₂ system are considered of about 1kg/yr according to assumptions made in Section 1.4. Those emissions are taken into account in the different bar charts, even if it does not appear clearly on the Figures.



Figures 3.4 and 3.5 – Annual direct and indirect CO₂ emissions in Frankfurt

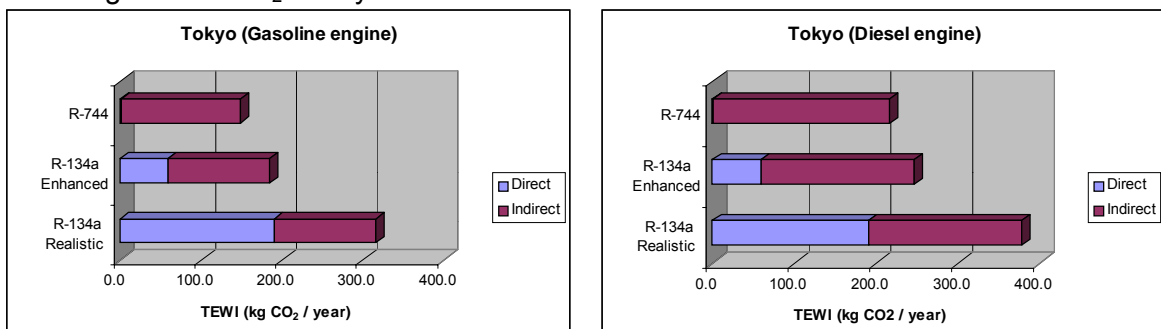
Figures 3.4 to 3.7 show the CO₂ emissions in Frankfurt and Seville from gasoline and diesel engines, the global impact (direct + indirect) of the actual R-134a AC system is much higher compared to the CO₂ AC system. The lower the cooling needs, the higher the advantage of the CO₂ AC system (in the range of 67 to 81kg of CO₂/yr compared to 245 to 270kg of CO₂/yr for the R-134a "realistic" AC system). The reduction of the refrigerant charge, and the improved leak tightness of the R-134a enhanced AC system permit to lower the global impact in the range of 115 to 135kg of CO₂/yr for this option, but is still significantly higher compared to the CO₂ AC system.



Figures 3.7 and 3.8 - Annual direct and indirect CO₂ emissions in Seville

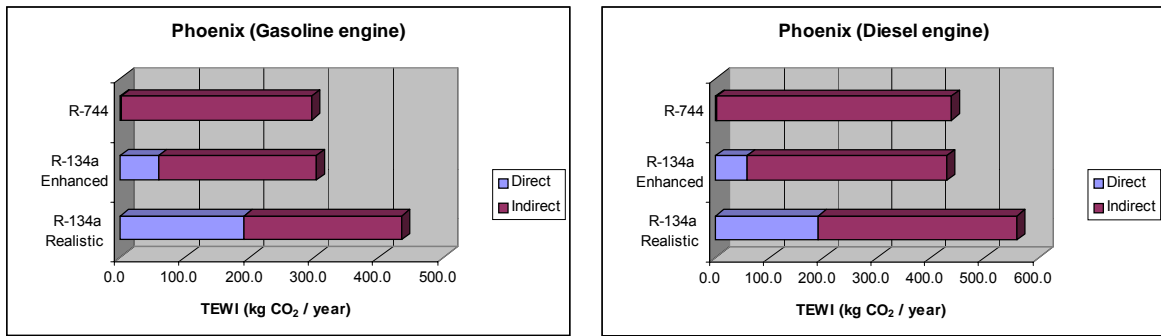
For Seville, the difference between the enhanced R-134a AC system and the CO₂ AC system is not so high, respectively about 207kg of CO₂/yr for the enhanced R-134a AC system compared to 176kg of CO₂/yr for the CO₂ AC system (gasoline engine).

The Tokyo conditions are in between the Frankfurt and Seville conditions, and so the advantage of the CO₂ AC system is about 10 to 15%.



Figures 3.8 and 3.9 - Annual direct and indirect CO₂ emissions in Tokyo

When comparing those two systems under the Phoenix conditions, the enhanced R-134a AC system and the CO₂ AC system are nearly equal.

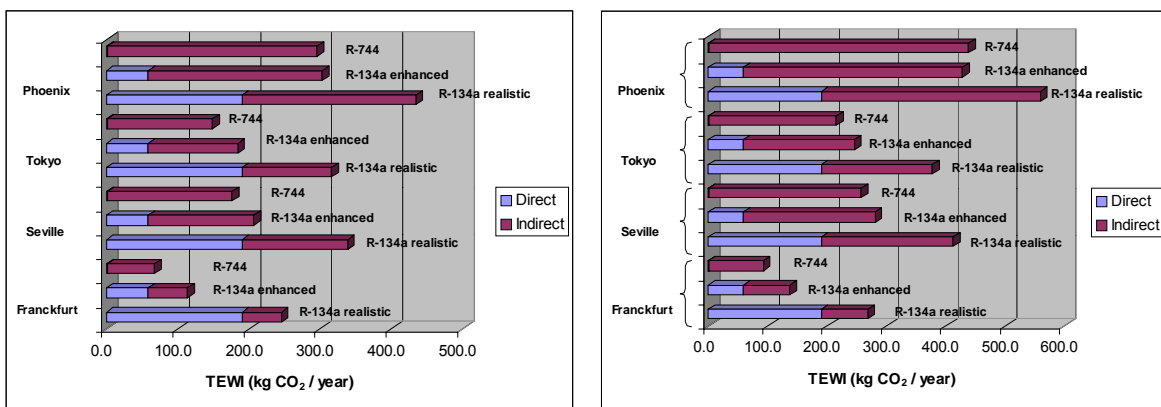


Figures 3.10 and 3.11 - Annual direct and indirect CO₂ emissions in Phoenix

These results are dependent on the data that are used, coming from SAE project [ACR02]. As indicated previously the tests have been realized only in steady state conditions not permitting to analyze the energy penalties that can occur differently for CO₂ and R-134a AC systems depending on the control system, but also on the thermodynamic behavior of R-134 and CO₂.

To draw more accurate conclusions, complementary analyses are necessary, based on tests on cars using R-134a and CO₂ AC systems under realistic climatic conditions. Moreover, tests shall be performed under regulatory driving cycles in order to measure effective fuel additional consumptions.

Nevertheless, the impact of R-134a direct emissions is significant. It represents nearly 50% of the equivalent CO₂ emissions under the Frankfurt climatic conditions, but only 28% under the Seville climatic conditions. This is directly related to the operating time. The fuel consumption is proportional to the number of hours of the AC system operation. The emissions are related to the leak tightness of components, which is very slightly related to the operation time.



Figures 3.12 and 3.13 – Summary of direct and indirect emissions of R-134a and CO₂ AC systems running either with gasoline and diesel engines respectively

Figures 3.12 and 3.13 summarize all the calculations for the 3 AC systems and for 2 types of engine under the climatic conditions of the 4 chosen towns. This summary shows that:

- CO₂ emissions due to the AC system operation are the dominant factor for hot climate;
- on the contrary, the direct emissions of R-134a are the dominant factor for temperate climate.

The emission level of the enhanced R-134a AC system still needs to be significantly decreased, in order to mitigate its direct emission effect.

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4. COSTS

In order to forecast what could be the total cost for a CO₂ mobile air-conditioning system, the first path is to know the relative and absolute costs of each component of the complete system. Table 4.1 presents two estimates for a typical actual R-134a MAC system. As it can be seen the two estimates are significantly different and specially for the evaluation of compressor, and hoses and connections costs. Even if the total cost is identical, the repartition is totally different.

Table 4.1 –Component costs of R-134a MACS (Euros)

	Condenser	Evaporator	Compressor	Expansion device	Hoses & Connections	Total
1 st estimate	48	27	138	6	81	300
2 nd estimate	24	57	81	9	129	300

This significantly different repartition of the component costs has a major importance in order to forecast what could be the future additional cost of a CO₂ AC system.

Table 4.2 – Cost difference by component for CO₂ and R-134a (Euros) AC systems

	Condenser	Evaporator + LV Hex	Compressor	Expansion device	Hoses & Connections	Total
1 st estimate	61.5	62	156	6	52.5	338
2 nd estimate	30	74	138	9	196	447

Depending on the first consulted expert (not taking into account safety devices), the additional cost of CO₂ AC system could be limited to about 13% due to a new technology for hoses and connections leading to lower cost of those components compared to actual R-134a technology.

The second expert forecasts exactly a contradictory advice on the cost of hoses and connections, leading to nearly a factor 4 between the two estimates of those components.

Notes

1. The costs have been calculated for a AC system produced at 400 000 units/yr.
2. For the CO₂ system, a suction line heat exchanger is necessary to reach good energy performances and also for control easiness. This heat exchanger is not installed in the actual R-134a AC system, even if it could be installed to reach higher performances. So the additional cost for the first estimate includes this suction line heat exchanger.

Comparing the two estimates, the first one forecasts only about 38 Euros of additional cost, whereas the other one forecasts 147 Euros of additional cost, which represents 50% of the reference costs. The main concern (whatever the other differences), is to know more about the low cost technology for hoses and connections.

Safety issues

Due to the risk of asphyxia if a rapid CO₂ leak occurs in the cabin, and specially in the case of accidents, safety additional costs are estimated from 10 (lower estimate) to 45 Euros of the total cost of the CO₂ AC system. This safety issue needs certainly a more thorough study because of the high importance of safe use of CO₂.

Control system

For the control system, depending on the technical solutions, significant differences may exist for this component implying up to an additional 5% on the total AC system cost.

Total additional cost of a CO₂ AC system

Merging those elements the additional cost of a CO₂ AC system is evaluated between 65 and 215 Euros, which makes a wide variation of the additional cost.

Technology availability and reliability

One of the major issues for car manufacturers is related to the component supply for CO₂ AC system. Some suppliers may have significant advantage compared to their competitors for a given technology, specially for efficient CO₂ compressor, and "zero emission hoses". Some companies have a clear leadership for certain components, leading to a kind of monopoly, which is not an acceptable situation for many car manufacturers.

Another issue is related to the learning process leading to a high level of reliability for CO₂ AC systems. Reliability requires at least 2 to 3 years to be reached, implying high additional cost in case of systematic failures, which require free repair during the guarantee period.

Those possible additional costs associated to the launching of the new technology make car manufacturers cautious.