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Mobile Air Conditioning

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EXECUTIVE SUMMARY

Mobile air-conditioning (MAC) systems have been mass-produced in the USA since the early 1960s and in Japan since the 1970s. However, the numbers of air-conditioned cars in both Europe and developing countries only started to significantly increase much later, in about 1995.

The rapid switch from CFC-12 to HFC-134a was a global decision taken by all car manufacturers in developed countries. The first HFC-134a system was installed in 1990 and by 1994 almost all vehicles including cars, light commercial vehicles, and truck cabins, sold in developed countries used this refrigerant. In developing countries the transition from CFC-12 to HFC-134a will be completed in 2008. Since 1990, significant progress has been made in limiting refrigerant emissions and the implementation of the Montreal Protocol has contributed to this. For example, recovery equipment has been developed, some countries have encouraged the intensive training of service technicians to improve servicing practices, component manufacturers have designed low-emission components (fittings, hoses, etc.) and car manufacturers have usually lowered the original refrigerant charge. These efforts led to a significant decrease in emission levels from about 400 g yr⁻¹ in the late 1980s to about 200 g yr⁻¹ in the mid-1990s (UNEP, 1998) and efforts are still underway to further reduce these emission levels to 100 g yr⁻¹ or less (Schwarz and Harnisch, 2003).

If all types of refrigerants are considered, emissions from MAC systems range from approximately 105,000 tonnes of CFC-12 in 1990 to 137,000 tonnes of CFC-12 and HFC-134a in 2003, with CFC-12 still representing 46% of those emissions. A business-as-usual scenario forecasts emissions in the range of 180,000 tonnes in 2015 (see Figure 6a), most of which will be HFC-134a. The CO₂-eq emissions fell from about 850 MtCO₂-eq in 1990 to 609 Mtonnes CO₂-eq in 2003 (see Figure 6b) and a business-as-usual scenario forecasts CO₂-eq emissions in the range of 270 Mtonnes CO₂-eq in 2015. The progressive phase out of CFC-12 in the fleet and its replacement by HFC-134a has

led to a significant decrease in CO₂-eq. emissions, despite the continued growth of the MAC system fleet.

CFC-12 was not widely used within the EU due to the very low number of air-conditioned cars before 1995. However, there have been increasing concerns about the significant increase of HFC-134a use in Europe. In its Fluorinated Gas regulation project, the European Commission has proposed the phase-out of HFC-134a, thereby creating a totally new context for refrigerant choices.

Evaluating the additional fuel consumption of MAC system operation is a complex task. Nevertheless, initial evaluations indicate that in 2003, CO₂ emission due to global MAC operation was in the order of 100 Mtonnes.

Options for greenhouse gas emission mitigation

There are three main options for reducing greenhouse gas (GHG) emissions: Improving the current HFC-134a system or switching to other low global warming potential (GWP) refrigerants such as HFC-152a or CO₂. Other options such as hydrocarbons (HCs) have been investigated but car manufacturers did not support these as a possible alternative technology. Other refrigeration techniques such as sorption systems and air cycle have been tested, but are not energy efficient enough to replace the vapour compression technology.

Current regulatory policies ignore the additional fuel consumption of air-conditioning (AC) system operation. It might be technically possible to reduce the fuel consumption of the AC system by up to 30–40%, depending on the option chosen and the climate. This could lead to a global reduction in CO₂ emissions of 40 Mtonnes yr⁻¹.

Improved HFC-134a systems have a low leakage rate and a higher energy efficiency. Moreover, further emission reductions might be obtained with a full professional service that includes recovery, recycling and systematic end-of-life (EOL) recovery. This would require refrigerant management policies governed by national regulations and incentives.

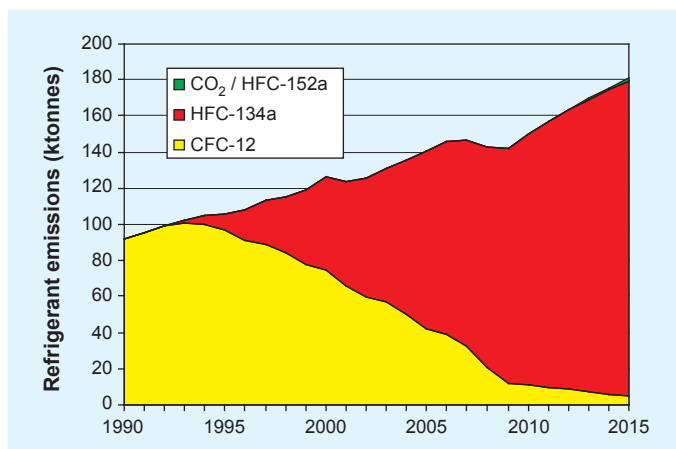


Figure 6a. MAC refrigerant emissions from 1990 to 2015 (Clodic *et al.*, 2004).

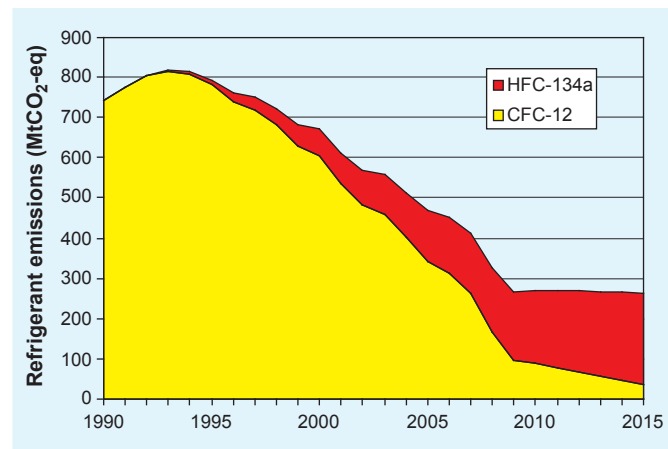


Figure 6b. MAC refrigerant emissions in CO₂-eq from 1990 to 2015 (Clodic *et al.*, 2004).

Alternate low GWP refrigerant systems

AC systems that use CO₂ have an entirely new design unique to this refrigerant as well as a safety system. A new infrastructure for servicing will also need to be implemented. The cooling performances of CO₂ systems have been demonstrated in passenger vehicles from most major car manufacturers as well as some commercial buses and an electrical hermetic system in prototype fuel cell vehicles. Direct emissions have a very low impact due to CO₂ GWP. For indirect emissions, CO₂ systems have shown energy efficiency comparable to an improved HFC-134a system. There are several barriers to the commercialization of this technology. These are the risk of suffocation, outstanding technical and cost issues and the need for an entirely new servicing infrastructure.

Systems using HFC-152a contain the same components as the HFC-134a system but have an added safety system. Cooling performances of HFC-152a systems have been demonstrated in passenger vehicles. Direct emissions (CO₂-eq) are very low (more than 90% reduction compared to HFC-134a base line) and HFC-152a systems have an energy efficiency comparable to the improved HFC-134a system. Barriers to the commercialization of this technology are the risk of flammability and guaranteeing a commercial supply of HFC-152a.

System comparison and design considerations

Safety concerns can be mitigated by using identified, existing technologies. Risk assessments for the CO₂ and HFC-152a systems are currently being undertaken.

The reference cost of a typical European HFC-134a system with an internally-controlled compressor is estimated to be about 215 US\$. Assuming mass production, the additional cost of a CO₂ system (including the safety system) is estimated to be between 48 and 180 US\$. The additional cost of an HFC-152a system is estimated to be about 48 US\$ for the safety devices used for a direct system, or for a secondary loop for the indirect system.

If development, validation and production lead times are considered, the improved HFC-134a system is likely to be ready first, followed by the HFC-152a system and then the CO₂ system.

The servicing infrastructure will need to be prepared for the transition to a new refrigerant. This is a significant issue for each alternative refrigerant system and the burden this will place on the service industry needs to be considered, especially in developing countries.

6.1 Introduction

Mobile air-conditioning (MAC) systems have been mass-produced in the USA since the early 1960s and in Japan since the 1970s. However, the numbers of air conditioned cars in Europe and in developing countries only started to significantly increase much later in about 1995.

The rapid switch from CFC-12 to HFC-134a was a global decision taken by all car manufacturers in developed countries. The first HFC-134a system was installed in 1990 and by 1994 almost all vehicles sold in developed countries used this refrigerant. In developing countries the transition from CFC-12 to HFC-134a will be completed in 2008.

This chapter addresses an evaluation of the additional fuel consumption due to MAC operation. In 2003, this was estimated to be in the order of 100 Mt CO₂-eq emissions. For the same year, CO₂ equivalent emissions from HFC-134a were about 96 Mtonnes and those for the remaining CFC-12 in cars were 514 Mtonnes.

There are three main options for reducing GHG emissions: Improving the current HFC-134a system or switching to other low GWP refrigerants such as HFC-152a or CO₂.

6.2 Current refrigerant banks and emission forecast

Emissions from mobile air-conditioning systems of cars, light commercial vehicles (LCVs) and truck cabins are detailed by Palandre *et al.*, (2002), Clodic *et al.*, (2004) and Palandre *et al.*, (2004) (see also UNEP, 2003). Even though the car industry switched from CFC-12 to HFC-134a with effect from 1992, the number of vehicles and CFC-12 bank in this fleet is still significant (see Table 6.1).

Table 6.1. Evolution of the CFC-12 and HFC-134a fleet (Clodic *et al.*, 2004).

Year	AC vehicle fleet (million)	
	CFC-12	HFC-134a
1990	212	-
1991	220	-
1992	229	0.7
1993	229	10
1994	222	27
1995	215	49
1996	206	74
1997	197	100
1998	186	128
1999	175	161
2000	163	198
2001	149	238
2002	134	285
2003	119	338

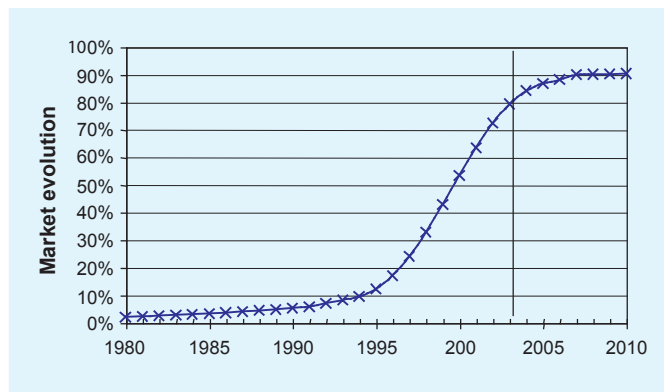


Figure 6.1. AC rate typical evolution: Western Europe example (Palandre *et al.*, 2000).

The average lifetime of cars depends on the country. It is typically 12 years in Europe and Japan and 16 years in North America.

For a number of countries, the last 10 years have seen a rapid penetration of air-conditioning systems in cars, as shown in Figure 6.1 for Europe. This S curve is typical for the introduction of a major technology and a corresponding change of consumer habits.

In 2000, the worldwide automotive fleet numbered some 720 million of vehicles. Nearly half of the fleet is equipped with AC (361 million).

6.2.1 AC system characteristics

The average refrigerant charge depends on the type of car and the type of refrigerant. Usually HFC-134a systems have about a 15% lower charge than CFC-12 charge due to the difference in liquid densities of those two refrigerants. Current HFC-134a charges vary from 500–900 g. The lifetime of the MAC system (9–12 years) is usually considered to be shorter than the car lifetime (12–16 years) due to the relatively high cost of repairing AC in older vehicles.

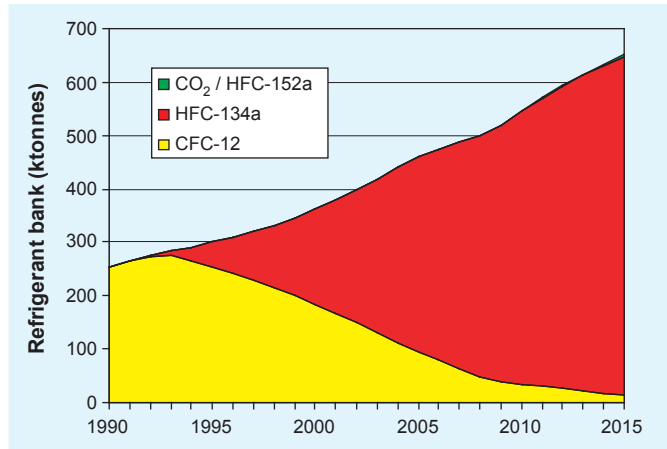
A number of studies (Palandre *et al.*, 2002; UNEP, 2003; Schwarz and Harnisch, 2003) have shown that annual emission rates, including accidents and servicing losses, are between 10 and 15% of the original charge. Servicing is assumed to take place for recharging when the residual charge is between 50 and 75%. Dependent on servicing habits and regulations, the recovery during servicing varies from 0–40% of recoverable refrigerant.

6.2.2 CFC-12, HFC-134a emissions from 1990 to 2003 and emission forecasts for the period 2004 to 2015

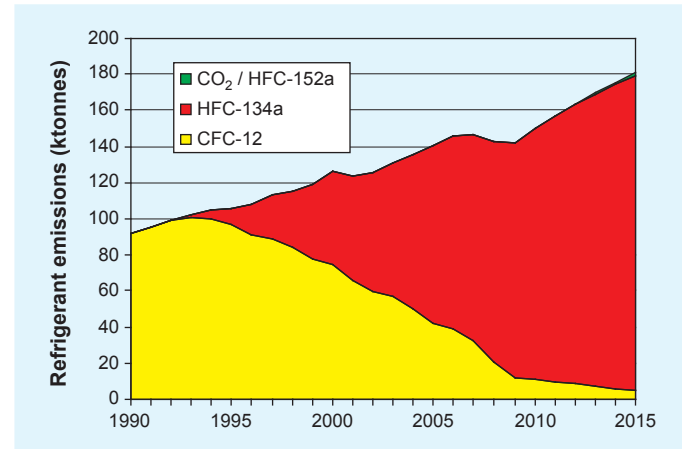
The emission inventory method described in Ashford *et al.* (2004) is based on IPCC inventory guidelines (IPCC, 1997). Using the results of Clodic *et al.* (2004), Figure 6.2 and Table 6.2 show the evolution of the refrigerant banks of HFC-134a

Table 6.2 MAC refrigerant bank (Clodic *et al.*, 2004).

Year	CFC-12 (tonne)	HFC-134a (tonne)	CO ₂ / HFC-152a (tonne)
1990	254,273	-	-
2003	131,365	287,185	-
2015	12,863	633,893	3177

**Figure 6.2.** MAC refrigerant bank evolution from 1990 to 2015 (Clodic *et al.*, 2004).**Table 6.3** MAC refrigerant emissions (Clodic *et al.*, 2004).

Year	CFC-12 (tonne)	HFC-134a (tonne)	CO ₂ / HFC-152a (tonne)
1990	104,707	-	-
2003	63,431	73,956	-
2015	5192	175,174	934

**Figure 6.3.** MAC refrigerant emissions from 1990 to 2015 (Clodic *et al.*, 2004).

and CFC-12 in the MAC fleet in the past (from 1990 to 2003) and for the future (up to 2015) according to a business-as-usual scenario¹.

Figure 6.3 and Table 6.3 present refrigerant emissions for the two refrigerant banks. Figure 6.4 and Table 6.4 transform CFC-12 and HFC-134a emissions into CO₂-eq emissions based on their GWP (values from IPCC Second Assessment Report (IPCC, 1996)).

Due to the huge difference of the GWP of these two refrigerants, Figure 6.4 underlines the significant decrease from approximately 900 MtCO₂-eq in 1993 to 610 MtCO₂-eq in 2003. The switch from CFC-12 to HFC-134a had a clear and positive effect on lowering global warming due to refrigerant emissions from MACs.

6.3 Fuel consumption due to MAC operation

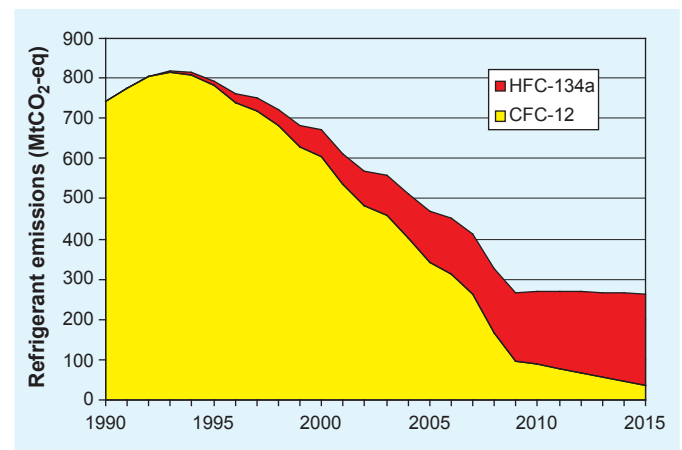
Nowadays the primary energy source for operating MACs is supplied by the car engine via two mechanisms: Firstly by the direct transfer of mechanical power to the compressor through a belt connected to the engine and secondly as the electrical power used by the fans and the control system.

¹ The Business as Usual Scenario integrates several assumptions detailed in Ashford *et al.*, (2004) and Clodic *et al.*, (2004): the Montreal Protocol schedule for CFC phase-out in developed and developing countries is taken into account, and economic growth rates are defined for 10 different regions as well as for the penetration of AC systems for the annual production of new cars.

Vehicle ACs consume more energy (including its weight) than any other auxiliaries currently present in vehicles. Yet

Table 6.4. MAC refrigerant emissions in CO₂-eq (Clodic *et al.*, 2004).

Year	CFC-12 (MtCO ₂ -eq)	HFC-134a (MtCO ₂ -eq)	CO ₂ / HFC-152a (MtCO ₂ -eq)
1990	848	-	-
2003	514	96	-
2015	42	228	0.11

**Figure 6.4.** MAC refrigerant emissions in CO₂-eq from 1990 to 2015 (Clodic *et al.*, 2004).

this additional energy consumption is not currently taken into account in fuel economy regulatory test cycles. The fuel consumption due to MAC operation can only be measured if the usage profile and system energy consumption characteristics are known. Up until now, such data has been sparse and incomplete.

6.3.1 Hours of operation by climate/region

In order to estimate the annual fuel consumption of MACs, both the climatic conditions (including temperature, humidity and solar load) and the usage profile (including average mileage, time of day when driving occurs and urban or extra-urban driving conditions) must be known. As indicated in Figure 6.5, there are significant differences in the cooling energy required due to climatic conditions. Temperate climates such as that in Frankfurt, differ from hot and humid climates, such as in Orlando or Miami, by nearly a factor 5 in terms of heat load and therefore in cooling energy.

The usage profile first of all includes the cool-down operation with a higher energy consumption and the stabilized operating conditions with a lower energy consumption. To assess the global energy consumption impact of MAC, the repartition of urban and extra-urban driving durations needs to be known

and these differ per country.

At present there are no widely accepted standards for these parameters per country or region, even though there is a clear need for these. However, initial estimates can be made on the basis of several published publications (Benouali *et al.*, 2003b; Rugh *et al.*, 2004).

6.3.2 Fuel consumption and equivalent CO₂ emissions

Several factors need to be known in order to calculate CO₂ emissions from MAC operation systems. Firstly the mechanical and electrical energies used by MACs must be measured. Secondly the type of engine and the management of the energy for the MACs required from the engine must be considered. Then from the additional fuel consumption the CO₂ emission of MAC can be calculated.

The additional fuel consumption due to MAC operation mainly depends on climatic conditions. Table 6.5 shows the calculated mechanical power required by the compressor. This varies from 0.4–3.4 kW depending on the ambient temperature and the engine speed (Barrault *et al.*, 2003; Benouali *et al.*, 2003b).

MAC systems operate for about 24% of the vehicle running time in northern Europe, 60% in southern Spain and up

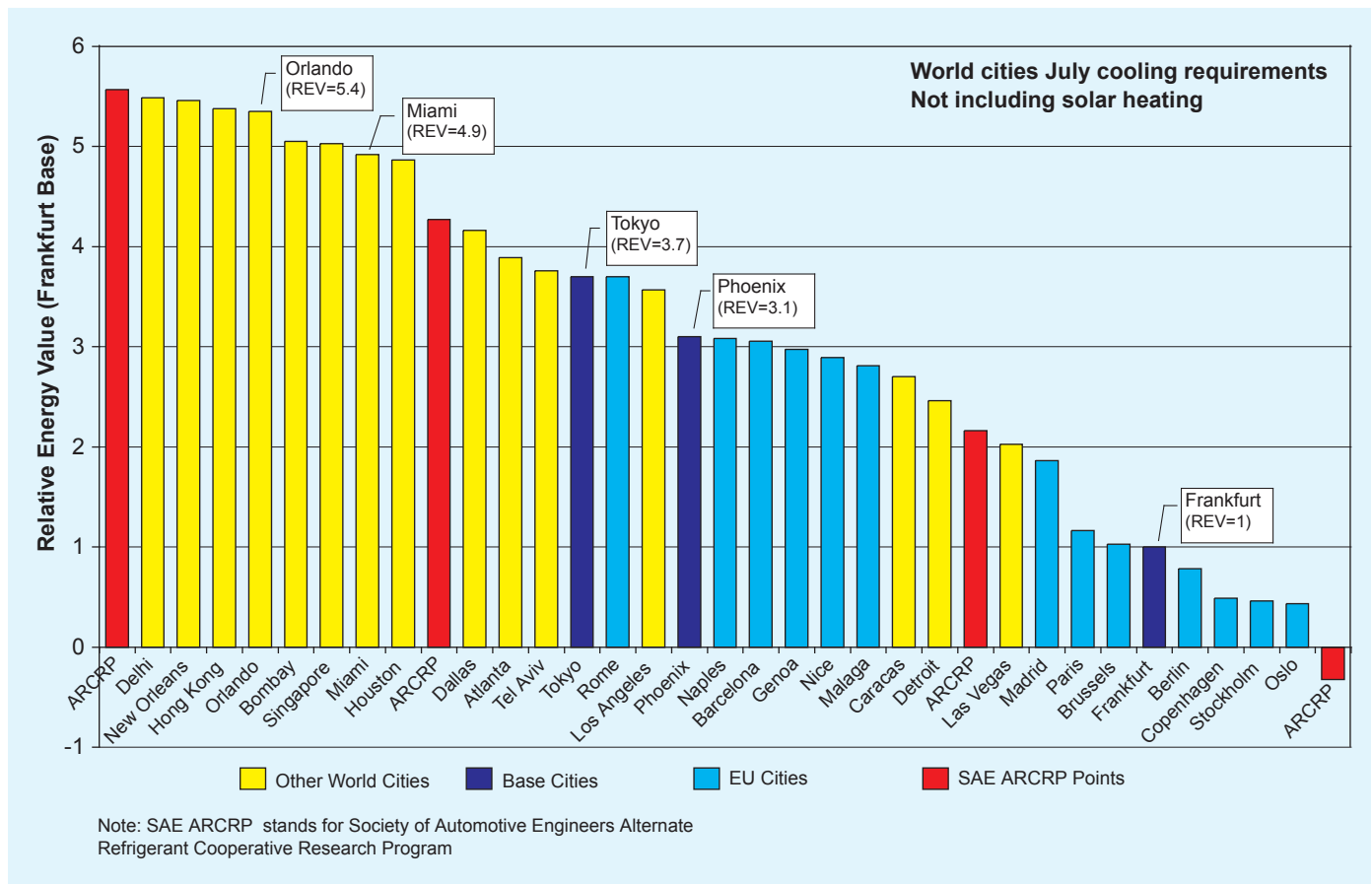


Figure 6.5. MAC cooling energy required depending on climatic conditions (based on Atkinson *et al.*, 2003).

Table 6.5. Mechanical power for HFC-134a system (kW) (Barrault *et al.*, 2003).

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

Table 6.6. Fuel consumption and CO₂ emissions in Seville and Frankfurt (Barrault *et al.*, 2003).

City	Engine type	Total (kWh)	Energy consumption (L yr ⁻¹)	System weight (L yr ⁻¹)	Total (L yr ⁻¹)	% of the annual fuel consumption	Emissions (kg CO ₂ yr ⁻¹)
Seville	Gasoline (HFC-134a)	473.00	55.54	7.61	63.15	6.8	148.0
	Diesel (HFC-134a)	769.25	75.79	7.92	83.71	6.4	221.5
Frankfurt	Gasoline (HFC-134a)	134.07	15.74	7.61	23.35	2.5	54.7
	Diesel (HFC-134a)	218.33	21.51	7.92	29.43	2.3	77.9

to 70% in Phoenix, Arizona. For European diesel engines the additional consumption ranges from 23 l yr⁻¹ (Paris) to about 80 l yr⁻¹ (Sevilla) (see Table 6.6).

If climatic conditions, engine type (diesel or gasoline) and user profile are taken into account, the annual additional fuel consumption is between 2.5 and 7.5%. This corresponds to an additional CO₂ emission due to MAC operation of between 54.7 and 221.5 kg CO₂ yr⁻¹ per vehicle.

6.3.3 Estimates of fleet-wide fuel consumption

For the USA, an NREL study has estimated that 26 billion litres of gasoline per year (62 Mtonnes CO₂) are currently used for cooling (not including defrost). This is equivalent to 5.5% of US light-duty vehicle gasoline consumption (Rugh *et al.*, 2004). The study assumed that compressor power varied with rotations per minute (rpm) up to 3.7 kW at 3500 rpm. The assumed AC load penalized the fuel economy by 18% (22 mpg² to 18 mpg) for US cars and 14% (18.8 mpg to 16.2 mpg) for US trucks. Using the same methodology NREL (Rugh *et al.*, 2004) estimates the EU MAC fuel consumption to be 6.9 billion litres (equivalent to 16 MtCO₂) and the Japanese to be 1.7 billion litres (equivalent to 4 MtCO₂). These figures represent 3.2 and 3.5% of vehicle fuel use respectively. Worldwide, the total emissions of air-conditioned cars is estimated to be about 100 Mtonnes of CO₂. Tables 6.7 and 6.8 show the growth of air conditioned vehicles in China and India respectively. In 2002 Hu (Hu *et al.*, 2004) estimates the air-conditioned fleet to be 6.4

million vehicles. Based on data by Kanwar (2004), the Indian AC fleet was estimated to be 4.2 million cars in 2003.

6.3.4 Future trends and possible improvements in energy efficiency

Most of the MACs currently used in the total fleet are still basic technology (especially in the USA) with a fixed displacement compressor and manual control. These systems were not designed with a view to fuel savings. They produce an excess cooling capacity and the desired comfortable temperature is obtained by mixing heated air from the heater core to compensate for the excess cooling capacity. An on/off control is used to manage the system with respect to driving conditions (outside temperature and engine rpm). The Improved Mobile Air-conditioning (I-MAC) partnership is a current global effort to reduce direct refrigerant emissions by 50% and indirect emissions by 30%.

Since the mid-1990s, variable capacity technology (internal control) has been introduced, mainly in Europe and Japan, to limit the energy consumption of MACs. Comparisons of the three types of compressor control: On/off, internal control and external control (introduced in 2000) show that significant energy savings can be achieved with the appropriate control (Karl *et al.*, 2003).

However, a reduction in the requested cooling capacity is another option for reducing fuel consumption. Insulation of doors and roof, limitation of window size and special glass for solar load limitation are all parameters which influence the final energy consumption of MACs. In practice these solutions have a limited usefulness due to the additional cost, extra weight, consumer demand for larger windows or safety issues related to driver visibility.

² 'mpg' stands for 'miles per gallon'. 1 mile per US gallon equals about 0.425 km per litre.

Table 6.7. Evolution of air-conditioned vehicle fleets in China (Hu, Li and Yi, 2004).

	1995	1996	1997	1998	1999	2000	2001	2002
Air-conditioning automobile ⁽¹⁾ population ⁽²⁾ (thousand units)	1650	2090	2650	3210	3900	4700	5530	6430
CFC-12 air-conditioning automobile population (thousand units)	1590	1930	2330	2590	2770	2910	2920	2760
HFC-134a automobile population (thousand units)	60	160	320	620	1130	1790	2610	3670

⁽¹⁾ automobiles = vehicles including buses, trucks and cars.

⁽²⁾ population means fleet

Table 6.8. Evolution of the annual sales of air-conditioned cars in India (Kanwar, 2004).

Year	1996	1997	1998	1999	2000	2001	2002	2003
Car ⁽¹⁾ AC sales (thousand units)	202.5	259	278.2	369.6	464.9	459.8	488.6	616.2

⁽¹⁾ car means cars only

Low consumption MAC systems can only be developed if there are accepted standards for measuring the energy consumption of the MAC system and the additional fuel consumption of the vehicle equipped with a given MAC system.

6.3.5 Future vehicles and MACs

Environmental concerns are also driving technology changes in powertrains, which in turn is affecting MAC design.

The first trend is improvements in the energy efficiency of internal combustion engines (diesel or gasoline). This trend affects both the heating and the cooling modes of the MAC system. In cooling mode, a higher engine energy efficiency results in a higher relative energy penalty due to MAC. This requires significant efforts to improve MAC energy efficiency. High-efficiency engines result in a heating cabin deficit which necessitates the installation of an additional heating function. This is why efficient heat pump systems are still being developed in competition with current existing solutions based on electrical heaters or burners.

A second trend is to introduce new functions such as stop-start (engine is stopped at idle and then restarted), stop & go (engine is stopped at idle, then restarted so that a short electrical driving period is possible) and electrical driving mode (as with a hybrid powertrain). In order to improve fuel consumption, especially in city traffic conditions, all of these solutions are based on a more or less deep electrification of the car. However, with current MACs, stopping the engine means stopping the AC and vehicle occupants do not accept such a loss of comfort. Usually the only strategy for sustaining comfortable conditions is to restart the engine whilst still in idle. To solve this problem, different solutions have been investigated with

respect to the availability of electrical energy: Cooling power storage, hybrid compressors and electrically-driven compressors. Some of these have been introduced onto the market. For example, the two-way driven compressor has been developed for mass-produced, mild-hybrid vehicles which do not generate enough electrical power (Sakai *et al.*, 2004). This compressor can be driven by the engine belt whilst the engine is running and by the electric motor during engine stop. An electrically-driven compressor has also been developed for mass-produced, strong-hybrid vehicles (Petitjean *et al.*, 2000; Takahashi *et al.*, 2004). Even if the engine stops, the air-conditioning can still be operated efficiently.

A third trend is to change the energy source of the powertrain by replacing the internal combustion engine with a fuel cell. MACs adapted to this type of powertrain will benefit from the high level of electrical power available and will be able to compensate long stop & go as well as heating or cooling deficits of the cabin. One example exists in Japan, where there is a fuel cell vehicle equipped with electrical hermetic CO₂ heat pump systems.

Adapted efficient MACs will be a key issue for the marketability of these new powertrains. Methods to qualify efficiency or fuel consumption will have to be adapted to take into account both the special energy management of this new type of powertrain and the adapted driving cycle, especially in city traffic.

6.4 Technical options for reducing direct and indirect emissions

Concerns about global warming associated with HFC-134a emissions mean that the impact of the MAC industry on anthropogenic greenhouse gas emissions needs to be assessed.

This involves assessing both industry emissions and proposed emission-reduction initiatives for their environmental impact and cost-effectiveness. Such initiatives include improving the current system as well as investigating possible alternative refrigerant systems with a lower climate impact.

6.4.1 Improved HFC-134a systems

HFC-134a systems can be improved in two ways. Firstly by improving the containment of the refrigerant and secondly by increasing the energy efficiency. Improvements to the HFC-134a system are concerned with optimizing current systems and not in developing a completely new design.

6.4.1.1 Improved leak tightness

The future European Union F-Gas regulation will limit maximum annual emissions. This will lead to significant new efforts for improving the leak tightness of MAC systems.

At present there is not an agreed leakage test method to guarantee the leakage rate of an MAC system installed in a car. Each supplier of compressors, condensers, evaporators, hoses, etcetera, has their own methodology, using trace gases such as helium, for checking the leak tightness of their components. SAE standards (SAE, 1989, 1993) define a test method for hose permeation but none of these permit certification of the emission level of AC systems installed in a car. Several projects are underway to define a certification method that can ensure the certified level of refrigerant emissions. Various publications (Clodic and Fayolle, 2001; Clodic and Ben Yahia, 1997) indicate a large range of leakage rates depending on the technology used for hoses, compressor shaft seals and service valves. A certification method will certainly need to be developed for each component: The refrigerant lines, the two heat exchangers and the compressor. Complementary calculations from test results are necessary to predict annual emission. Moreover, the leak rates depend on the refrigerant pressure and so in turn on the climatic conditions under which the car operates throughout the year.

6.4.1.2 Servicing issues and vehicle end of life

In developed countries car servicing is performed by at least three categories of garage: After-sales service from car manufacturers, private garages and specialized networks servicing only certain parts of vehicles (batteries, exhaust pipes, brakes, tyres). Europe now has specialized networks for MAC servicing. In the USA the MACS Association (Mobile Air-Conditioning Society) has developed a training programme which has generalized recovery systems in nearly all garages in line with the US regulation which has made the recovery of CFC-12 mandatory since 1992 and HFC-134a mandatory since 1996. In order to significantly reduce service-related emissions, technicians should be trained to use a recovery and recharge system with near zero emissions as a standard procedure. Leak detection with high sensitivity leak detectors (in the range of 1 g yr^{-1}) and sufficient knowledge to fix the leaks when found, are comple-

mentary steps towards realizing low refrigerant emissions during servicing. Nevertheless many of these steps forward can be compromised by end-users recharging MACs themselves if disposable cans of HFC-134a are available. The global emissions related to these practices are high, and disposable cans of HFC-134a will be forbidden by new EU regulation.

In many European countries, recovery during servicing is not yet mandatory and this might result in high emissions. However, good practices have been adopted in many after-sales service garages and specialized networks, which systematically use standard recovery equipment when the circuit needs to be opened.

The increased use of air-conditioned cars in developing countries requires the training of servicing personnel and the availability of recovery/recycling equipment. The current phase out of CFC-12 has permitted the implementation of good practices in some developing countries, but a number of efforts are still needed to avoid large emission rates due to poor servicing practices.

Looking to the future, the aim is to produce very low-emission HFC-134a systems by decreasing the level of AC system leak tightness to the extent that no recharge is required during the system's lifetime.

The recovery of refrigerant at vehicle end of life could be integrated into the global management of the recycling process of cars. Such a global recovery and recycling process would significantly reduce the additional cost associated with refrigerant recovery. At the EU level, refrigerant recovery will be integrated in the End-of-Life Vehicle Directive (OJEC, 2000).

6.4.1.3 High efficiency systems

As indicated in section 6.3.4, a number of programmes are underway to achieve better control of compressor power. Despite this, see (Benouali *et al.*, 2003c; Benouali *et al.*, 2003a), the coefficient of performance (COP) measured under realistic conditions (typical driving conditions) is low, 1.3–1.4 for an outdoor temperature of 35°C. The use of an external control compressor yields significant gains in the range of 25–35% on the COP, even if the mechanical efficiencies of external control compressors are in the same range as internal control compressors. Up until now systems have been designed for low cost, reliability and cooling capacity but not for energy efficiency. A number of improvements can still be realized in the development of high efficiency compressors. Improvements in the evaporator and condenser design as well as the control system will result in better airflow management and therefore energy efficiency.

With respect to energy efficiency improvements, progress could be made in standardizing the measurement of energy consumption due to MAC operation in order to facilitate the comparison of technical proposals (see section 6.3.4).

6.4.1.4 LCCP/TEWI

To calculate Life Cycle Climate Performance (LCCP), all types of emissions over the entire cycle should be taken into account, including energy consumption related to refrigerant production,

Table 6.9. Example of TEWI calculations for a MAC system operating in the Frankfurt area (Barrault *et al.*, 2003).

	Current system		Improved system	
	Diesel	Gasoline	Diesel	Gasoline
Indirect emissions (kg CO ₂ yr ⁻¹)	77.9	54.7	54.5	38.3
Direct emissions (kg CO ₂ -eq yr ⁻¹)	138–345	138–345	30.4	30.4
TEWI (kg CO ₂ yr ⁻¹)	215.9–422.9	192.7–399.7	84.9	68.7

direct emissions throughout the lifetime and indirect emissions due to energy consumption by the AC system. For HFC-134a AC systems, a number of publications (UNEP, 2003; Barrault *et al.*, 2003; Schwarz and Harnisch, 2003) indicate that the most significant parameter is the direct emission level. Depending on the recovery policy, the annual refrigerant emissions for current systems are estimated to be 0.106–0.266 kg yr⁻¹ leading to 138–345 kg CO₂-eq yr⁻¹.

If the previous results of CO₂ emissions related to MAC operation and those different emission levels are taken into account (see section 6.2.2), the total equivalent warming impact (TEWI) of a given MAC system can be calculated. Table 6.9 presents an example of TEWI calculations for gasoline and diesel engines for a MAC system operating in the Frankfurt area.

Table 6.9 summarizes possible gains on indirect emissions due to energy consumption and direct emissions of refrigerant. Considering the extreme values, it can be seen that refrigerant emission reductions can be a highly effective method for reducing emission impacts. However, at this stage it has yet to be demonstrated that MAC systems can be designed with servicing limited to ruptures and accidents.

Based on current knowledge of possible energy efficiency improvements as well as reduction of emissions, Table 6.10 compares the old CFC-12 and the current HFC-134a systems to the improved HFC-134a, CO₂ and HFC-152a systems.

6.4.2 CO₂ systems

6.4.2.1 Description of system

Carbon dioxide has zero Ozone Depletion Potential (ODP). Its GWP of 1 is negligible compared to the GWP of HFC-134a. Moreover, there is no need to specifically produce carbon dioxide, since it can be recovered from industrial waste gas. Carbon dioxide (when used as refrigerant it is called R-744) is cheap, readily available in sufficient quantities throughout the world and its properties are well known and documented. If used as refrigerant there is no need for recovery, which would necessitate servicing, and the recycling cost would be totally eliminated. The refrigerating equipment safety standard (ASHRAE 34, EN-378) classifies CO₂ as an A1 refrigerant, a non-toxic and non-flammable refrigerant. But if accidentally lost in large quantities, CO₂ has a certain asphyxiation risk that needs to be mitigated by engineering systems. A refrigeration cycle with carbon dioxide as refrigerant operates at comparatively high pressures (5–10 times higher than HFC-134a systems).

However the safety risk of these high pressures is comparable to current HFC-134a systems due to the small volume used and the low refrigerant mass of the system.

As the critical temperature is approached or even exceeded, the ideal cycle efficiency decreases with increasing high-side pressure. On an ideal basis, the efficiency of a transcritical CO₂ cycle is unfavourable compared with that of a HFC-134a cycle. However, for real cycles this is compensated by the favourable transport properties of CO₂ (high heat transfer and low pressure loss), the inclusion of an internal heat exchanger and the improved compressor efficiency due to low pressure ratios. Under normal operating conditions for vehicle air-conditioning systems the carbon dioxide cycle often operates in the ‘transcritical’ mode due to the low critical temperature (31°C). For example, Pettersen (1994) showed that the high-side pressure influences the COP of the system and there is an optimum pressure for this. He suggested that during normal operation a high-side pressure close to the optimum pressure should be selected in order to maintain a satisfactory COP. This means the pressure should be kept at a certain level dependent on the heat rejection temperature (ambient air temperature).

A special flow circuit enabling efficient operation and high-side pressure control has been designed and patented by Lorentzen *et al.* (1993) (see also Lorentzen and Pettersen, 1993). This particular refrigeration cycle is shown in Figure 6.6 and serves as the worldwide basis for the majority of car AC systems which use carbon dioxide as a refrigerant. The p-h diagram in Figure 6.6 depicts two different high-side pressures for different control conditions for which the compression process has been calculated with the same isentropic efficiency.

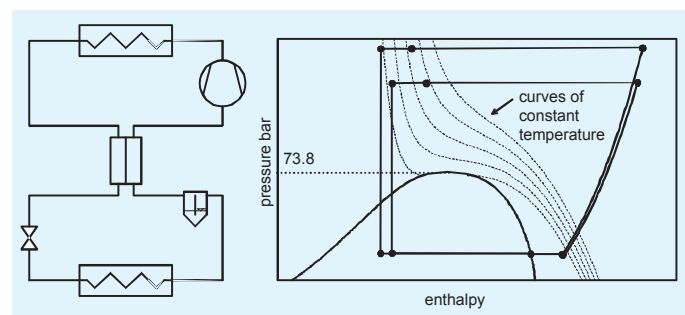


Figure 6.6. Refrigeration cycle and pressure-enthalpy diagram of the transcritical cycle commonly used for car applications (Lorentzen and Pettersen, 1993).

Table 6.10. Comparison of MAC options.

	HFC-134a (reference)	Improved HFC-134a	CFC-12 (old type development)	CO ₂ (under development)	HFC-152a (direct system, under development)
Substance characteristics					
Radiative efficiency (W m ⁻² ppb ⁻¹)	0.16	0.16	0.32	See ch. 2	0.09
Atmospheric lifetime (yr)	14	14	100	See ch. 2	1.4
Direct GWP (100-yr time horizon)	1410	1410	10,720	1	122
Technical data					
Stage of development	Commercial	Near commercial	Commercial	Demonstration	Demonstration
System lifetime	12–16	12–16	12–16	12–16	12–16
Cooling capacity (kW)	6	5	6	6	6
Charge (kg/system)					
- range	0.7–0.9	0.6–0.75	1–1.2	0.5–0.7	0.45–0.55
- relative figures (%)	100	80	125	70	70
# Charges over lifetime	2–3	1–2	4	2–4	1–2
Coefficient of Performance (COP)	0.9–1.6	1.2–2.5	0.9–1.2	0.9–2.0	1.2–2.0
Seasonal Performance Factor (SPF)	NA	NA	NA	NA	NA
Energy consumption (relative figures)	100	80	130	70	70
Emissions per functional unit					
Direct emissions					
- in % of charge yr ⁻¹	15	7	20	15	7
- in kg CO ₂ -eq yr ⁻¹	166	64	1782	0.09	4.9
- relative figures (%)	100	40	1043	0.05	2.9
Indirect CO ₂ -emissions (kg CO ₂ yr ⁻¹)					
- Sevilla	184	147	239	129	129
- Tokyo	126	101	163	88	88
- Phoenix	369	295	480	258	258
End-of-life emissions recovery efficiency ⁽²⁾	0	50	0	0	50
TEWI (kg CO ₂ -eq 14 years) ⁽¹⁾					
- Sevilla	4900	2954	28,294	1807	1875
- Tokyo	4088	2310	27,230	1233	1301
- Phoenix	7490	5026	31,668	3613	3681
(without recovery)					
Costs per functional unit					
Investment costs (US\$)	(215 US\$)	+24–36 US\$	NA	+48–180 US\$	+48 US\$

⁽¹⁾ The GWP values used for the calculations are taken from the Second Assessment Report (IPCC, 1996).

⁽²⁾ Recovery has not been taken into account for the TEWI calculations, due to large uncertainties of the recovery effectiveness and so the average direct emission per year for 'improved HFC-134a systems' is 100 g yr⁻¹.

With this refrigeration cycle the high-side pressure can be controlled, for example, by an electronic expansion valve. Each high-side pressure corresponds to a particular refrigerant charge circulating in the cycle. The receiver located between the evaporator and the internal heat exchanger on the low-pressure side stores the refrigerant charge which is not needed for the particular operating condition. The presence of the internal heat exchanger provides protection for the compressor from liquid slugging and may yield to an increased cooling capacity at high

ambient air temperature conditions.

A CO₂ refrigeration cycle different from the Lorentzen/Petersen cycle approach was used by Sonnekalb (2002) (see also Sonnekalb and Köhler, 2000) for bus AC systems which use carbon dioxide as refrigerant. Based on the fact that the COP compared with high-side pressure curve is relatively flat, Sonnekalb designed a low-cost CO₂ system for bus air-conditioning. This system (which can be seen in Figure 6.7) has only four major components with a fixed refrigerant charge.

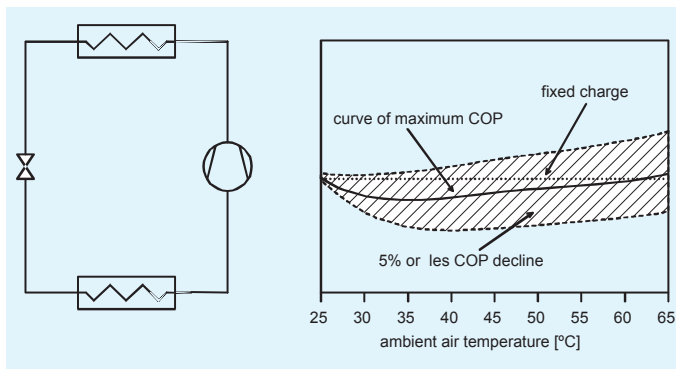


Figure 6.7. Refrigeration cycle and charge-ambient air temperature diagram of a low-cost transcritical cycle used for bus applications (Sonnekalb, 2002).

Sonnekalb showed that it is possible to operate this particular cycle over a wide range of ambient air temperatures close to the maximum COP without a high-side pressure control. Figure 6.7 presents on the right-hand side a charge-ambient air temperature diagram with the optimal COP curve. The range of a 5% or less decline of this optimal COP can also be seen as a shaded area. The dashed horizontal line in the diagram shows that it is possible to cover a wide range of ambient air temperature conditions with a fixed charge whilst incurring only minor COP losses (5% or less).

In the years 1996 and 1997 two CO₂ prototypes based on this cycle were installed in standard city buses in Bad Hersfeld, Germany. By the end of 2003 the AC systems of these two buses had together accumulated more than 4000 running hours on the road, indicating that this CO₂ system is technically and economically feasible for bus AC (for more details see also Köhler *et al.*, 1998 and Foersterling *et al.*, 2002).

Since 1997 prototype CO₂ systems have been demonstrated by many vehicle manufacturers and their suppliers in a wide range of vehicles (Wolf 2004). For example, BMW successfully ran a small test fleet of 7 vehicles with prototype AC systems between 2000 and 2002 (Mager 2002). Toyota have also run a first fleet test in Japan and the USA using approximately 15 fuel cell hybrid vehicles .

If used in a heat pump mode, CO₂ has a superior refrigerant performance (see for example Heyl and Fröhling, 2001 or Hesse *et al.*, 2002). Modern fuel-efficient direct injection gasoline or diesel engines may not have enough waste heat to sufficiently heat the passenger compartment. Additional heaters (for example positive temperature coefficient (PTC) heaters, fuel burners, or other technologies) increase fuel consumption and CO₂ emissions. The CO₂ heat pump might be an attractive future alternative with respect to performance, energy efficiency and total cost (AC plus heater). More research is needed to determine which is the most suitable for car application.

In summary, CO₂ systems need a new design for all components (compared to usual HFC-134a technology). This involves an ongoing learning process.

6.4.2.2 Energy efficiency

Carbon dioxide is a typical high-pressure refrigerant with a correspondingly high volumetric cooling capacity. Therefore, compared to low-pressure HFCs, higher cooling capacities can be achieved in a given volume. This results in excellent cool down curves (or heat up curves for the heat pumps) as demonstrated, for example, by Vetter and Memory (2003). However, comparing the energy efficiency and fuel consumption of a carbon dioxide and corresponding HFC system is far more difficult. From the results in a number of publications it can be surmised that compared to an improved HFC-134a system, carbon dioxide has a comparable or even better COP and a correspondingly lower fuel consumption, especially for lower ambient air temperatures. At high ambient air temperatures, improved HFC-134a systems have advantages at lower compressor speeds. Based on measurements made by Hrnjak (2003), Wertenbach (2004) calculated the AC energy demand for typical European and US driving cycles. His results show different energy demands for Europe and the USA are due to the selected running time in the drive cycles and the different climatic conditions. Nevertheless the energy efficiency benefits of the systems are about the same for Europe and the USA. Compared to a baseline HFC-134a system, an improved HFC-134a system showed 23% less energy demand whereas an efficiency-optimized CO₂ system showed about 30% less energy demand. Hafner *et al.* (2004) obtained comparable results in their energy analysis.

Compared to HFC-134a, CO₂ has a disadvantage of low efficiency at idling and high load conditions. Compact vehicles are generally at a disadvantage as far as the refrigeration cycle efficiency is concerned compared to medium or large vehicles. This is due to space constraints which limit the condenser and evaporator sizes. Actual vehicle tests have shown that in compact vehicles, the increase in compressor power consumption with CO₂ has an adverse effect on vehicle driving characteristics such as acceleration and fuel economy, even though equivalent or better cooling performance can be maintained (Kobayashi *et al.*, 1999). Further technical developments are required for CO₂ compact vehicles to counteract this. An ejector, which can recover the expansion energy and reduce the compressor power might be a potential solution (Takeuchi *et al.*, 2004).

6.4.2.3 Cost

The real cost of a CO₂ AC system (or the additional cost compared to current AC systems) is hard to estimate as the CO₂ system has not yet entered mass production. The additional costs compared to a current system are expected to be between 48 and 180 US\$ (Mager *et al.*, 2003; Barrault *et al.*, 2003; NESCCAF, 2004) for the first generation of mass-produced systems. No cost data are available regarding the conversion of the service system.

6.4.2.4 LCCP/TEWI

Aspects concerning the certainty of energy efficiency also apply to calculations of the Life Cycle Climate Performance (LCCP) or the Total Equivalent Warming Impact (TEWI). The results

from different publications are not always comparable, as the specific results depend strongly on the assumptions made. In an LCCP study, Hafner *et al.* (2004) compared an improved HFC-134a system with a corresponding CO₂ system (based on measured data published by Hrnjak, 2003). The authors assumed NEDC and US FTP 75 driving cycles. The total hours with AC on were based on regional climate data and usage profiles provided by Sand *et al.* (1997) and Duthie *et al.* (2002). The direct HFC-134a emissions were calculated assuming total system losses of 60 g yr⁻¹. The end-of-life recovery was assumed to be 80%. The authors also took into account the 77 kg CO₂-eq emissions caused by the production of 1 kg of HFC-134a (see Campbell and McCulloch, 1998). The authors analyzed the LCCP of the HFC-134a and the CO₂ systems for different climatic regions in the USA and Europe. Their results show a 17–49% reduction in LCCP for the CO₂ system compared to the improved HFC-134a system. Table 6.10 shows a reduction of nearly 40% in the LCCP for the CO₂ system.

6.4.2.5 Leakage rate of complete system

Froehling *et al.*, (2003) assessed the upper acceptable limits of refrigerant leakage. He assumes that the operating time of CO₂ AC systems without recharging should be about 6 years. This leads to an annual emission rate of 25g or less, half of which is related to the shaft seal of the compressor. Additional research and development on low leakage hoses and fittings, compressor shaft seals, durability and accurate methods of leak rate measurements is currently being undertaken to realize this goal.

6.4.2.6 Reliability

Air-conditioning with CO₂ is a new system and virtually all of the components need to be redesigned. In terms of reliability the main tasks to be completed are:

- Development of economical, leak-tight CO₂ hoses and compressor shaft seals;
- Demonstration of reliability under real-world conditions;
- Development of service and maintenance best practices.

In order to ensure uniform quality and reliability, a workgroup of German OEMs has proposed a component specification Standard CO₂ AC System (Mager *et al.*, 2004). This specification defines the main and auxiliary components of the system and sets their operating conditions, performance and limits.

6.4.2.7 Safety

Due to the high pressure of the CO₂ systems risks of rupture which could lead to burst hazards must be mitigated. The basic design concept of car air-conditioners is described in SAE J639 (SAE, 1999). CO₂ car air-conditioners are currently being standardized and the revisions of the set values for safety devices such as the design pressure, proof pressure and pressure relief valve took into account the significant pressure levels that can arise in CO₂-refrigerant car air-conditioners (Kim *et al.*, 2003; Wertenbach, 2004).

Leakage of CO₂ into the passenger cabin creates risks of

impairment. The US EPA allows 6% v/v and 4% v/v as upper boundary limits for exposure of up to 2 minutes and 60 minutes respectively and specifies that the exposure should not exceed 6% under any circumstance. An active safety system, such as a refrigerant-based sensor safety concept (which is also currently under scrutiny for flammable refrigerants), might not be effective enough due to uncertainties about the sensor, its location and the actuators behind the sensor. The VDA ad hoc working group of car manufacturers has proposed a passive safety concept based on supplementing the standard specifications mentioned in Section 6.4.2.6. These additional specifications would cover all AC systems from manual to automatic control and would consider all vehicle operating conditions (Rebinger, 2004). This passive safety concept is based on the so-called ‘safe evaporator’, which means a negligible risk of leaking or bursting under any operating condition of the car.

As well as the aforementioned issues, the safety of the ‘service’ offered in the marketplace – how to handle CO₂ safely – is another important safety issue. Devices such as a refrigerant charging machine, which can read the amount of refrigerant from bar-coded information in the service manual and automatically charge CO₂, have already been developed (Lorenz, 2002).

6.4.3 HFC-152a systems

6.4.3.1 Description of a direct expansion system

HFC-152a systems are identical to the current HFC-134a system, but may have added safety features, such as solenoid valves or discharge devices.

A direct expansion HFC-152a system was demonstrated at the 2002 SAE Alternate Refrigerants Symposium (SAE, 2002a). This was a joint venture between the US government, a major car manufacturer and a major MAC system supplier (Andersen *et al.*, 2002). The large vehicle system contained just 0.45 kg of refrigerant and compared to the equivalent current HFC-134a system it showed a better cooling performance for high loads and a comparable cooling performance for low loads. In a direct refrigerant replacement with no component changes, HFC-152a showed a 3–17% lower energy usage than HFC-134a and was on average about 10% lower (Ghodbane *et al.*, 2003).

Leakage of HFC-152a into the passenger cabin creates risks of fire. The US EPA allows 3.7% v/v for up to 15 s as an upper boundary limit in any part of the free space of the passenger cabin.

The safety system (Figure 6.8) consists of an HFC-152a sensor, mounted in the evaporator case, capable of detecting the presence of HFC-152a. If detected above a threshold level, a signal is sent to a controller, which activates a directed relief mechanism. The relief mechanism consists of two squib-initiated discharge devices, one on the high-pressure side and one on the low-pressure side of the system. The discharged refrigerant is directed away from the vehicle by hoses attached to the discharge devices. Therefore, the system is designed to safely discharge the refrigerant away from the vehicle when leakage

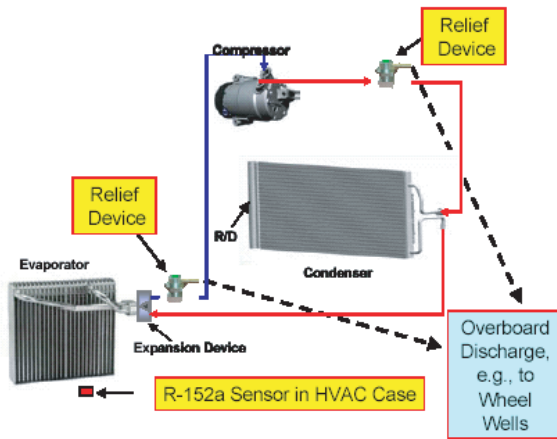


Figure 6.8. Direct HFC-152a System with Safety System.

is detected or a vehicle crash situation occurs. In the case of a crash, the discharge would be activated by the airbag crash-sensing system. Such a discharge quickly reduces the pressure in the system. This rapidly eliminates the driving force (pressure) for unwanted leakage elsewhere, thereby reducing any risk. The sensing system is capable of continuous monitoring when the vehicle is being driven and intermittent monitoring when the vehicle is parked.

In the event of a leak into the passenger cabin the safety system is reported to be able to discharge the refrigerant so fast that no significant amount of HFC-152a enters the passenger cabin.

6.4.3.2 Description of a HFC-152a indirect system

At the 2003 SAE Alternate Refrigerants Symposium (SAE, 2003), a direct expansion HFC-152a system and a secondary loop HFC-152a system were demonstrated (Ghodbane and Fernqvist, 2003).

The secondary loop system (Figure 6.9) was jointly demonstrated by a major European car manufacturer and a major MAC system supplier (Ghodbane and Fernqvist, 2003). The system was demonstrated on a Sport Utility Vehicle (SUV) with front and rear evaporators. A secondary loop system (Figure 6.9) would overcome the concern of leakage into the passenger cabin by allowing the refrigerant to be contained under the hood where it is completely separated from the passenger compartment. The refrigerant cools a chiller (liquid-liquid heat exchanger), which, in turn, chills a water-glycol mixture that is then pumped into the passenger cabin heat exchanger(s) for cooling. This system would use the same components as the current HFC-134a system, with the addition of a chiller and liquid pump. It would therefore require a limited capital investment. For the dual evaporator SUV, the HFC-134a charge was 1.3 kg compared to just 0.59 kg of HFC-152a for the secondary loop system – a significant reduction. This vehicle had one of the highest cooling performances of all of the vehicles demonstrated at the symposium.

From an energy perspective, a secondary loop requires about 10% more energy than a direct system. However, the greater energy efficiency of HFC-152a compared to HFC-134a (about 10%) would result in comparable cooling performance with comparable energy efficiency (Ghodbane and Fernqvist, 2003).

From a general safety perspective, the small amount of HFC-152a refrigerant needed, combined with its relatively low flammability and an effective safety system such as those described above, would result in a vehicle that would be both safe to drive and safe to park in a garage. Of course, safety during vehicle servicing and repair must also be considered.

6.4.3.3 Energy efficiency

The HFC-152a system described in 6.3.3.1 was an HFC-134a system that was first tested with HFC-134a and then simply charged with HFC-152a to provide a direct comparison with no component changes. HFC-152a provided better cooling (2–3°C) and used 7–20% less energy than HFC-134a, reinforcing the results of the 2002 study. This vehicle had one of the highest cooling performances of all of the vehicles demonstrated at the symposium.

6.4.3.4 System costs and availability of HFC-152a

At present, only relatively small amounts of HFC-152a are produced globally; the major manufacturer is in the USA. Three manufacturers producing small quantities exist in China and one in Japan. Production capacity would have to be developed for HFC-152a to be used in MAC systems and with the necessary capital investment this would take several years to achieve.

Due to the simpler processing, HFC-152a ought to cost less than HFC-134a. However, the MAC system would cost an additional 25–48 US\$ to cover the cost of the safety system for a

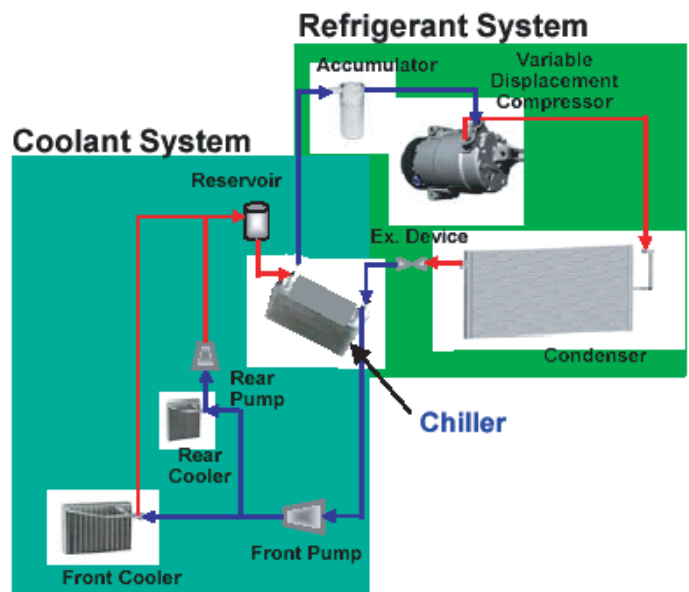


Figure 6.9. Secondary Loop HFC-152a System.

direct system or the additional cost of the secondary loop for an indirect system.

6.4.3.5 LCCP, TEWI

HFC-152a has been proposed as a replacement for HFC-134a because its global warming potential is about 10 times lower and it can be used with current HFC-134a components without any major modification (Baker *et al.*, 2003; Ghodbane, 2003; Scherer *et al.*, 2003).

HFC-152a has been assigned a GWP of 122 as opposed to 1410 for HFC-134a leading to a reduction in global warming impact of more than 90%. Moreover, the lower liquid density of HFC-152a compared to HFC-134a implies a refrigerant charge that is only 65% of the reference HFC-134a charge. For example, an HFC-134a system using 0.5 kg would be replaced by an HFC-152a system using 0.325 kg. This reduction in refrigerant charge will lead to lower emissions in the event of rupture and at vehicle end of life. The greater energy efficiency of the HFC-152a over HFC-134a would result in enough fuel savings to offset the GWP of HFC-152a. The net result of replacing HFC-134a with HFC-152a would be the elimination of the direct climate impact associated with current HFC-134a MAC systems. This has also been shown by Hafner *et al.* (2004). Table 6.10 shows a reduction of almost 40% in LCCP for the HFC-152a system compared to an energy-optimized HFC-134a system.

6.4.3.6 Safety aspects of future vehicle air-conditioning systems

HFC-152a is a moderately flammable gas and is listed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 34 (ASHRAE, 2001) as a Class A2 refrigerant, defined as being of lower flammability than Class A3 (hydrocarbons such as propane). As a reference, HFC-134a is Class A1, low toxicity and non-flammable. The flammability of HFC-152a will probably require added safety features such as those described below.

HFC-134a systems and the CFC-12 systems they replaced, are considered safe for the intended use. Replacement refrigerant systems must also provide a comparable level of safety for both vehicle occupants and service technicians. SAE J639 (SAE, 1999), SAE J1739 (SAE, 2002b) and refrigerant manufacturer's safety data information all serve as reference documents for designing safe systems. The latest draft of SAE J639 (SAE, 1999) provides an example of the conditions for safe design that must be met. For example, 'For refrigerants contained in components that are located within the passenger compartment, or in direct contact with passenger compartment airflow (e.g., evaporators and associated lines and fittings), system design shall be such that neither a harmful nor a flammable condition will result from a release of refrigerant into the passenger compartment.'

SAE J1739 (SAE, 2002b) requires a safety assessment of proposed systems (by Failure Mode and Effects Analysis using the Risk Priority Number) for the purpose of identifying all anticipated events that result in safety concerns and then taking

appropriate preventative, or mitigating action.

In addition, all regional, national and local regulations and codes for the safe handling of new refrigerants and new refrigerant systems must be satisfied (e.g., flammability and pressure vessel requirements). Managing costs and risks will be an important part of implementing alternatives.

6.4.4 HC-blend systems

In Australia and the USA, hydrocarbon blends, mostly HC-290/600a (propane/isobutane) blends, have been introduced as drop-in refrigerants to replace CFC-12 and to a lesser extent for HFC-134a. The real number of cars that have been retrofitted with such HC refrigerant blends is unknown. MacLaine-Cross (2004) has estimated that it is about 330,000 vehicles in Australia, although no data exist to confirm this. No accidents have been reported to date. These retrofits with HCs are legal in some Australian states and illegal in others and in the USA. US EPA has forbid the uses of HCs for retrofit but has considered the possible use of HCs for new systems, providing safety issues are mitigated.

HCs or HC-blends, when correctly chosen, present suitable thermodynamic properties for the vapour compression cycle and permit high energy efficiency to be achieved with well-designed systems. They have zero ODP and low GWPs, but their high flammability (lower flammability limit in the range of 1.8–2.1% v/v) means that they have not been considered by car manufacturers.

Some studies have been carried out using hydrocarbons in indirect systems, in which a water-glycol circuit provides cooling capacity in the cabin. This water-glycol coolant is in turn refrigerated by the refrigerating system using hydrocarbons (same system as the secondary loop system presented above for HFC-152a). Nevertheless, even with indirect systems, HCs are not seen by vehicle manufacturers as replacement fluids for mass-produced AC systems.

6.4.5 Alternative technologies to vapour compression

There are two types of alternative technologies: The Brayton-Joule air cycle and a number of heat-generated cooling systems.

6.4.5.1 Air cycle

The air cycle has been thoroughly investigated by Bhatti (1998). Even if air is used as a refrigerant, with a zero GWP, the energy efficiency of the system is very low. Calculations of air cycle efficiency compared to the current HFC-134a system show an energy penalty of about 35%. Nevertheless, from the TEWI analysis the author concludes that the amount of CO₂ emitted per year is in the same range (303 kg CO₂ for the air cycle compared with 282 kg CO₂ for current HFC-134a systems).

6.4.5.2 Metal hydrides

A review by Johnson (2002) evaluates the opportunities for dif-

ferent cooling cycles using the available heat from the exhaust gas. A first approach is the use of a metal hydride heat pump which makes use of the adsorption and desorption of hydrogen by metals. Desorption is an endothermic reaction and so absorbs heat, whereas adsorption is exothermic and releases heat. Metal hydride systems are interesting due to the small number of moving parts. No refrigerant is needed but the COP is significantly lower, in the range of 0.4–1.5. The possible heat recovery from the exhaust gas is also interesting. A first prototype has been developed in the USA, with a 5 kW AC system. The system weight was 22 kg and the COP was 0.33.

6.4.5.3 Absorption systems

Absorption systems that use either ammonia water or water-LiBr as working solution are well known. These systems use mainly heat but they need electrical energy for the fans and pump. The main drawback of absorption systems for cars is the heating-up time needed before cooling capacity can be produced to create the temperature level necessary in the boiler to produce refrigerant vapour. This system therefore needs a refrigerant storage as well as a minimum operating time of about half an hour before efficient cooling operation.

6.4.5.4 Adsorption zeolite systems

Zeolite systems are similar to metal hydride systems but use zeolite and water instead of metal hydride and hydrogen. The adsorption / desorption cycles usually need several separate reaction chambers for successive cycles in order to reach pseudo-continuous operation. Studies have been actively carried out for electrical vehicles using a burner to operate the AC system. The COP is considered to be relatively low (0.3–1.2). No prototype has been built in real cars in order to verify the performances.

6.4.5.5 Thermo-acoustics

Sound waves create small temperature oscillations. If those oscillations release or absorb heat within a regenerator, a significant temperature difference can be realized between the hot and the cold ends. A resonant cavity is used to enhance the efficiency of thermo-acoustics systems. A COP up to 2 has been achieved on a laboratory test bench. However, the integration of the system into cars could be difficult due to the possible size of system needed for a capacity of about 3 kW.

6.5 Heat-load reduction and new design of AC systems

Independent of the vapour compression system, research is underway to improve comfort conditions in car cabins. If energy consumption is not integrated as a constraint in those developments then it might be compromised by them. For example, panoramic roofs may increase heat loads in the cabin, but development of efficient reflecting glasses can mitigate the extra heat loads while improving the vision of car passengers. New designs such as ventilated seats associated with heating and cooling systems may lower the needed cooling or heating capacity, due to a far more effective diffusion of cooling or heat close to the body. Insulation of the car itself may have contradictory effects for summer and winter conditions and compromises will have to be found in order to improve the fast heat-up of the vehicle in the winter and fast cool-down in the summer. The AC system and car cabin must be jointly designed to achieve thermal comfort and low energy consumption.

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