

## Life Cycle Climate Performance (LCCP) of Mobile Air-Conditioning Systems with HFC-134a, HFC-152a and R-744

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### ABSTRACT

Life Cycle Climate Performance (LCCP) of mobile air-conditioning (MAC) systems have been calculated based on published performance data of enhanced HFC-134a systems achieved during the *SAE AR CRP<sup>1</sup>* (2002), and measured performance data of an improved R-744 MAC system (Pilot 2002), results which are now also included in the *SAE AR CRP*. All experimental investigations were performed at equal conditions in the same test facility at the *University of Illinois (ACRC)*. The NEDC driving cycle (93/116) was applied for the European countries, while the US FTP75 combined city & highway driving cycle was applied in combination with the measured performance data to calculate the energy consumption of the Air Conditioning system of mid size vehicles.

Direct comparison of the two systems show that the COP of the R-744 system is equal or better than the efficiency of the enhanced HFC-134a system at the dominant operating conditions, *i.e.* moderate temperatures and high revolution speed of the compressor. At high ambient temperatures, where capacity is the most important parameter, the R-744 system can achieve a faster temperature pull-down, due to higher maximum capacity.

The results of the LCCP investigations show 18 to 49 % reduction in LCCP based on a compact 2002 R-744 system (evaporator volume reduced to 76% of HFC-134a evaporator volume), indicating significant environmental improvements by a change to R-744 systems.

Integrated seasonal data show that about 14 % reduction in energy (fuel) consumption can be obtained with R-744 in areas with moderate to hot climate. Even in a very hot climate (Phoenix), the 2002 R-744 system has equal energy consumption, when considering equal cooling capacities. The fuel consumption would be even lower with a 'full-size' R-744 evaporator, *i.e.* same size as for HFC-134a. The HFC-134a system has slightly better COP only at extreme operating conditions that seldom occur, and these conditions have no impact on annual energy (fuel) use.

Preliminary data from the *SAE ARCPR Phase II* project has been applied in a separate analysis to calculate the LCCP for *Best Technology (BT)* HFC-134a and *BT* HFC-152a systems (*SAE ARCRP, 2004*). Although the test data can only compare R-744 systems with *Phase I Baseline* and *Enhanced* HFC-134a systems, and *Phase II* compares *BT* HFC-134a with *BT* HFC-152a systems, the results indicate that *BT* HFC-152a and 2002 R744 (*from tests spring 2003*) systems have approximately similar energy efficiency and LCCP profiles. The test data have reconfirmed that the COP is no argument against R-744. Fuel use of R-744 systems is significantly lower than with HFC-134a, even in the warm climates considered in the present comparison. Also taking into consideration the good properties R-744 offers for using the system as a heat pump in reversed mode and the potential for compact design, R-744 systems represent a very good alternative for the future.

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<sup>1</sup> Cooperative Research Project

## INTRODUCTION

HFC-134a from mobile air conditioning systems is the largest source of direct greenhouse gas emissions within the refrigeration sector. Due to the growth in number of systems installed in the world fleet of cars, the emissions are likely to increase also in the future. The high global warming potential (GWP) of HFC-134a (GWP = 1300) has led to the development of alternative technology in order to decrease the global warming impact from such systems.

The flammable alternate refrigerant HFC-152a has about 10 % of the global warming potential of HFC-134a. Due to its lower GWP it has been suggested as a possible alternative to the commonly used HFC-134a.

Carbon dioxide, R-744, is a non-flammable and non-toxic refrigerant occurring naturally in the biosphere, with very favourable characteristics for compact and efficient systems. Carbon dioxide also offers good heat pump characteristics in reversed mode operation.

Simple theoretical analysis indicates low energy efficiency for R-744 systems compared to HFC-134a. However, experimental investigations have shown that R-744 systems can be made with equal or better energy efficiency than HFC systems if the design takes into account the special characteristics of the refrigerant.

## PERFORMANCE OF 2002 R-744 MAC SYSTEM

During spring 2003, *HRNJAK (2003)* conducted measurements on an improved R-744 system based on components manufactured using 2002 technology. The components of the R-744 2002 system were redesigned to be more compact and efficient than earlier prototypes. Measured performance was improved compared to the previous systems and the main reasons were:

- More efficient evaporator
- Reduced gascooler temperature approach (more efficient gascooler)
- Improved compressor efficiency (also during part load operation)

Heat exchanger sizes were reduced:

- Evaporator core volume is 76% of the enhanced HFC-134a evaporator (single-row evaporator)
- Gascooler core volume 90% of enhanced HFC-134a evaporator
- Gascooler face area 69% of enhanced HFC-134a evaporator

Tests were also performed with a 2-row evaporator, twice as large as the single-row evaporator, but still within the limits of the maximum tolerated evaporator depth in the AR CRP Project. In the following text, these heat exchangers are denoted as: “*Small-*” and “*2-row evaporator*”.

Figure 1 and 2 shows the main COP results as function of air inlet temperature, at idling (compressor: 900 rpm) and driving (compressor: 2500 rpm) conditions. Measured data are compared to reported results for the enhanced HFC-134a system (*SAE AR CRP, 2002*).

At idling conditions, the R-744 2002 Small system showed better performance compared to the enhanced HFC-134a system up to 23°C air inlet temperature. The 2-row evaporator system showed improved performance up to 32°C.

At driving conditions, the R-744 2002 Small system showed significantly better performance than the enhanced HFC-134a system at 15°C and 25°C air inlet temperatures, and comparable at 35°C. The 2-row evaporator-system outperformed the enhanced HFC-134a for all air inlet temperatures by 11% to 39%. Equal evaporator depth as the enhanced HFC-134a would give a curve in-between the two curves shown.

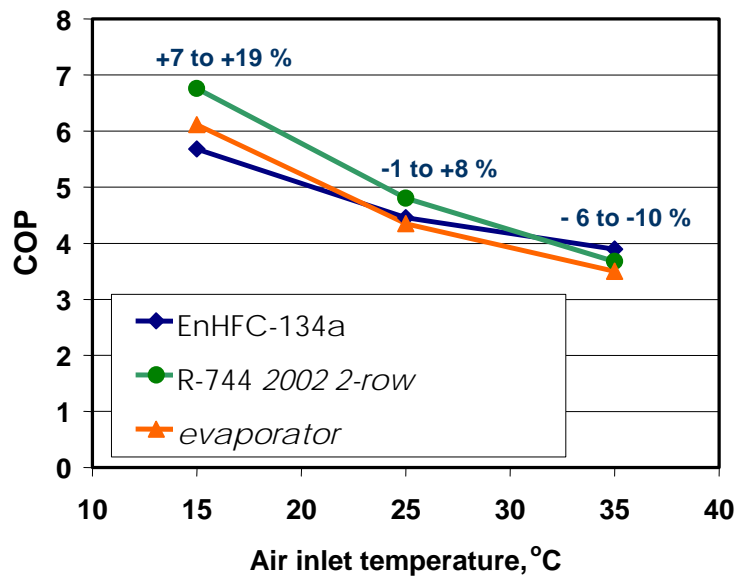


Figure 1: COP data at idling conditions, 5°C air from evaporator or equal capacity. HFC data from SAE AR CRP (2002), R-744 data from HRNJAK (2003)

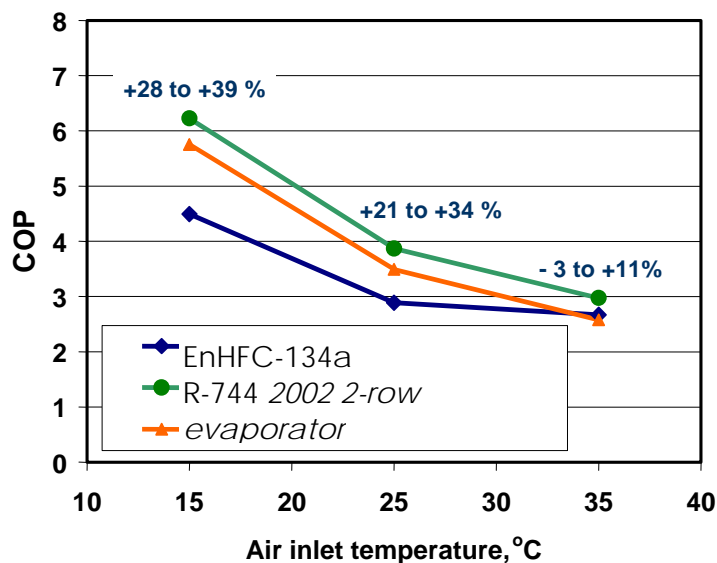
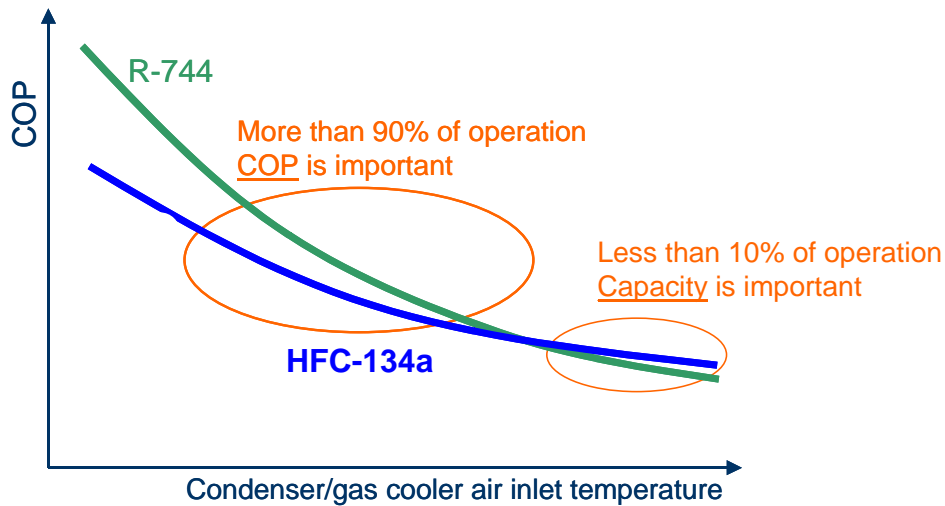


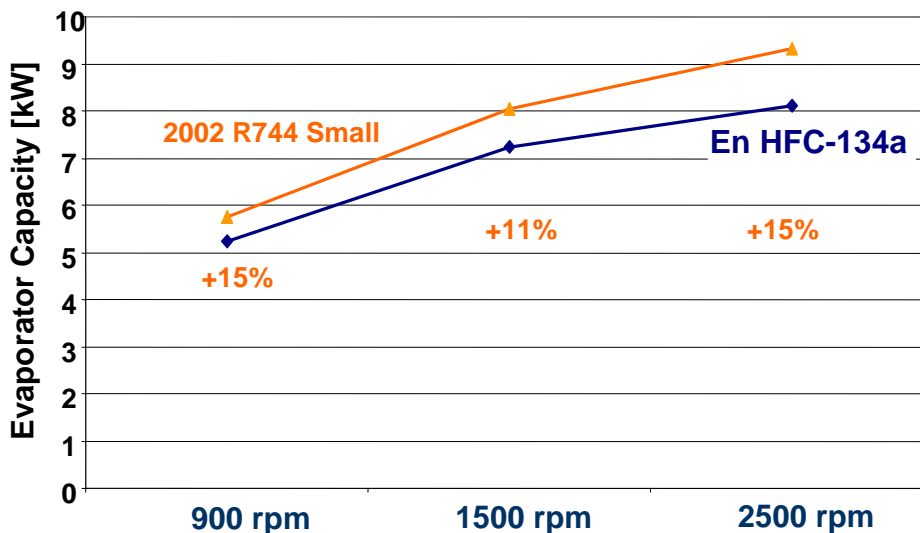
Figure 2: COP data driving conditions, 5°C air from evaporator or equal capacity. HFC data from SAE AR CRP (2002), R-744 data from HRNJAK (2003)

Figure 3 shows a principal presentation of the achieved COP results. Around 90% of car operational time will be at temperatures where the R-744 system has better performance. COP is important in this temperature range. Only 10% of the car usage time will be at high ambient temperatures where the efficiency of the HFC-134a is slightly better. In this temperature range, capacity is important, for which R-744 performs very well.



**Figure 3: Typical efficiency at varying condenser/gas cooler air inlet temperature**

Performance investigations for R-744 systems have so far been conducted based on the test data for HFC-134a systems, demanding equal cooling capacity. However, the maximum cooling capacity of the R-744 system is significantly larger. Figure 4 shows measured maximum cooling capacities for the CO<sub>2</sub> system at 35°C ambient temperature. Both at idling and driving conditions the 2002 R-744 *Small* system has 15% higher capacity. This will give a faster pull down at high ambient temperatures. If equal cooling capacity is required, the R-744 system will operate at part-load, where the efficiency of the compressor is slightly lower, compared to a system with smaller compressor (reduced displacement).



**Figure 4: Maximum evaporator capacity for 35°C ambient condition**

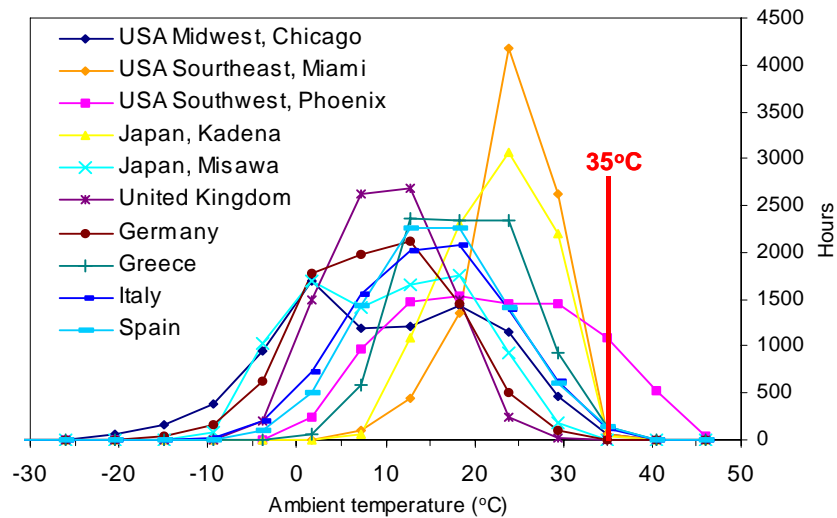
All experimental results show that the 2002 R-744 system has significant improvements in COP and offers better capacity compared to the enhanced HFC-134a system at the dominant conditions, *i.e.* moderate temperatures and higher compressor rpm.

## BASES FOR LIFE CYCLE CLIMATE PERFORMANCE (LCCP) CALCULATIONS

Simplified LCCP calculations have been carried out based on the following assumptions:

- Compressor power from
  - SAE AR CRP data for enhanced HFC-134a (*SAE ARCRP, 2002*)
  - 2002 R-744 Pilot Project data from *HRNJAK (2003)* – Small system (Single-row evaporator)
  - SAE ARCPR Phase II data for HFC-134a and HFC-152a (*SAE ARCRP, 2004*)
- 25% of the idle operation time at elevated air inlet temperatures (+15K) to the condenser/gascooler.
- NEDC driving cycle (93/116) applied for the European countries, and US FTP75 combined city & highway driving cycle, applied for the North American locations.
- AC on distribution based on *DUTHIE et al. (2002)*.
- Yearly driving distance: Germany & Greece (13.321 km), Spain (10.738) from *HOVLAND et al. (2003)*. US locations 22.000 km
- R-744 system 1.6 kg heavier than the enhanced HFC-134a systems, even though current prototypes show less weight difference than this. The assumed total weight of the HFC-152a system was in the same range as for the HFC-134a system.
  - Fuel use due to transportation of AC system was taken from (*AFEAS, 1991*). Conversion of fuel use to CO<sub>2</sub> emissions: 2.32 kg CO<sub>2</sub>/liter of gasoline (*AFEAS, 1994*).
- Direct HFC emission data per vehicle based on:
  - Controlled losses (*SCHWARTZ & HARNISCH, 2003*) of 53 g/yr, plus estimate for uncontrolled losses from *Öko-Recherche* of 16 g/yr, plus estimate for service losses 10 g/yr: **total 80 g/yr** (not applied in this analysis)
  - Achievable total controlled losses of 35 g/yr suggested by *FERNQVIST (2003)*, plus uncontrolled and service losses: **total 60 g/yr** (used in this analysis)
  - End-of-life recovery 80%
- CO<sub>2</sub> emission associated with energy input (kg CO<sub>2</sub>/kWh) is 0.243 (*AFEAS, 1994*)
- Engine efficiency: 27%. (*SAND et al., 1997*)
- Production of HFC-134a gives/causes an emission of 77 kg CO<sub>2</sub>-equivalents per kg HFC (*CAMPBELL & MCCULLOCH, 1998*), equal emissions were assumed for the production of HFC-152a. Vehicle life was assumed to 13 years, while 2 lifetime services are carried out during this time.

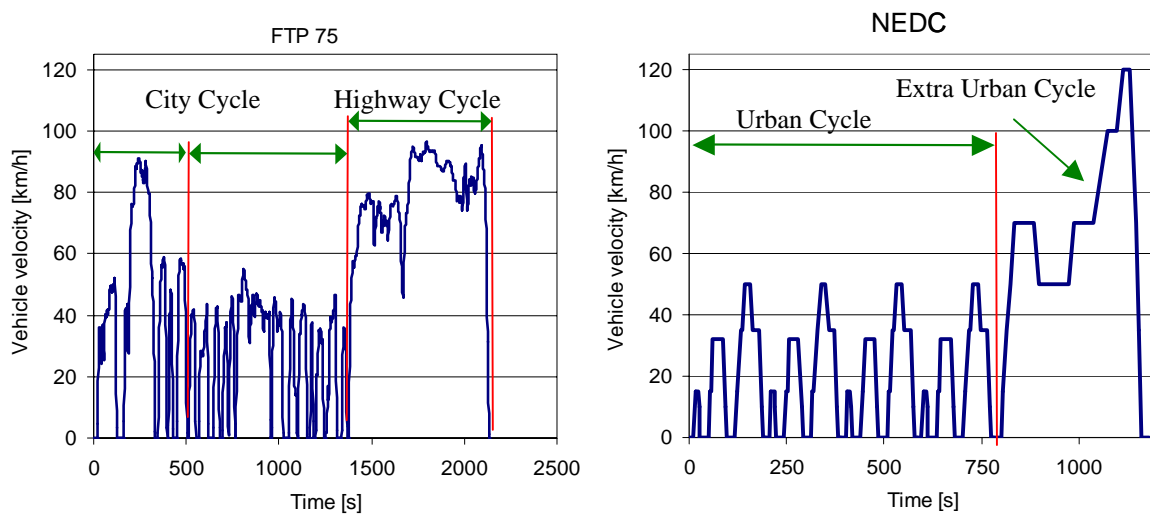
Figure 5 shows the temperature bin data for selected cities in USA, Japan and selected countries in Europe. Two extreme climates shown are Miami and Phoenix. Miami has a warm climate most of the year, but temperatures are hardly ever above 35°C. Phoenix has a very warm climate in the summer, and is the only city with significant number of hours with temperatures above 35°C. Chicago represents the climate of the Midwest. Taking all the presented locations into account, the figure clearly reveals that temperatures above 35°C hardly ever occur.



**Figure 5: Temperature bin data (SAND et al. 1997)**

Germany has the highest number of registered cars in Europe (HOVLAND et al. (2003)), while Spain and Greece are representatives for the warmest climates in Europe.

The LCCP calculations are conducted for six selected locations, three cities in the USA, and three locations in Europe, Germany, Greece and Spain, respectively. The US FTP75 combined city & highway driving cycle was applied for North America, while the NEDC driving cycle (93/116) was applied for the European countries, as shown in Figure 6.



**Figure 6: US FTP75 combined city & highway driving cycle & NEDC driving cycle (93/116) (WERTENBACH 2004)**

AC usage profiles are used as basis in the LCCP calculations. In the calculations, Europe and the USA have different AC-usage percentile profiles as suggested by *DUTHIE et al. (2003)* and also applied by *WERTENBACH (2004)*. The driving cycle data (rpm of the compressor) in combination with the measured performance data, as referenced earlier, are applied to calculate the energy consumption of the AC systems for a typical mid size vehicle. Cooling demand as a function of the ambient temperature, as suggested by *WERTENBACH (2004)*.

### **LCCP ANALYSIS: ENHANCED HFC-134a VERSUS 2002 R-744**

Figure 7 and 8 shows the LCCP comparison for enhanced HFC-134a and 2002 R-744 Small system at 60g leakage of HFC-134a per year. The HFC-134a and R-744 systems have three contributions to the total LCCP number indicated as: “Indirect” from AC usage, “Mass” from increased vehicle mass and “Direct” from the production of HFC-134a, emission from vehicle AC circuit, and from reclaiming of HFC at vehicle end of life. The “Direct -emission” of R-744 system is about 1 and cannot be observed in the figures.

As can be seen from Figure 7, the total LCCP numbers for the different US locations are between 18 and 39 % lower for the R-744 system. This may represent a significant contribution to reduced Green House Gas (GHG) emissions in North America.

The fuel consumption is reduced for the R-744 system in Miami (-3%) and in Chicago (-5%). Equal fuel consumption is estimated in the hot climate conditions of Phoenix.

Figure 8 shows the total LCCP numbers for the different European countries. For Germany a up to 49% reduction in LCCP can be obtained with a R-744 system. In Spain the reduction will be 39%, while a 31% lower LCCP can be achieved in Greece, by applying a R-744 system. . This represents a significant contribution to reduced GHG emissions in Europe.

The fuel consumption of the AC-system can be reduced by 13 % in Germany and Spain, while a 14 % reduction can be achieved in Greece.

All calculations for R-744 systems above are based on measurements performed with the small evaporator, which has 76% of the HFC-134a evaporator core volume. Measurements with the R-744 2-row evaporator (153 % of HFC-134a evaporator core volume), showed significantly improved performance. This indicates that energy use for R-744 systems would be even lower with equally sized evaporators.

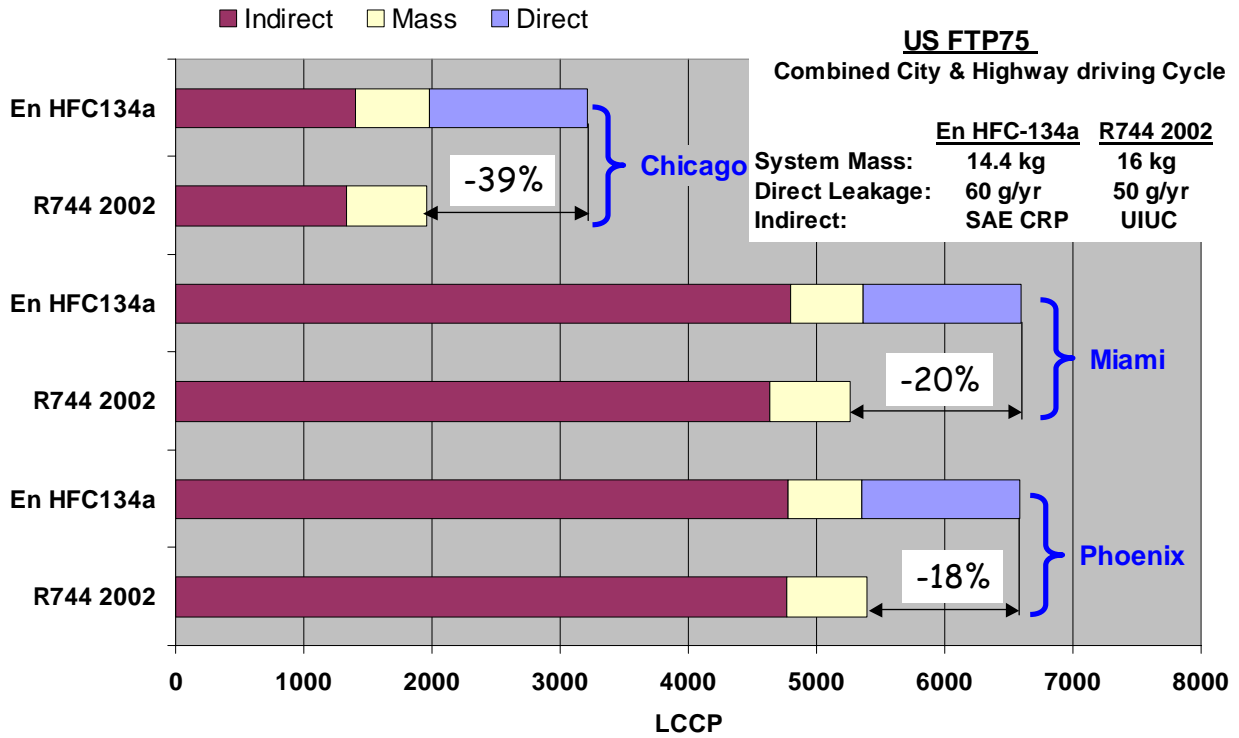


Figure 7: LCCP comparison of Enhanced HFC-134a system and R-744 (2002) system, based on US FTP75 driving cycle. HFC-134a leakage of 60 g/year.

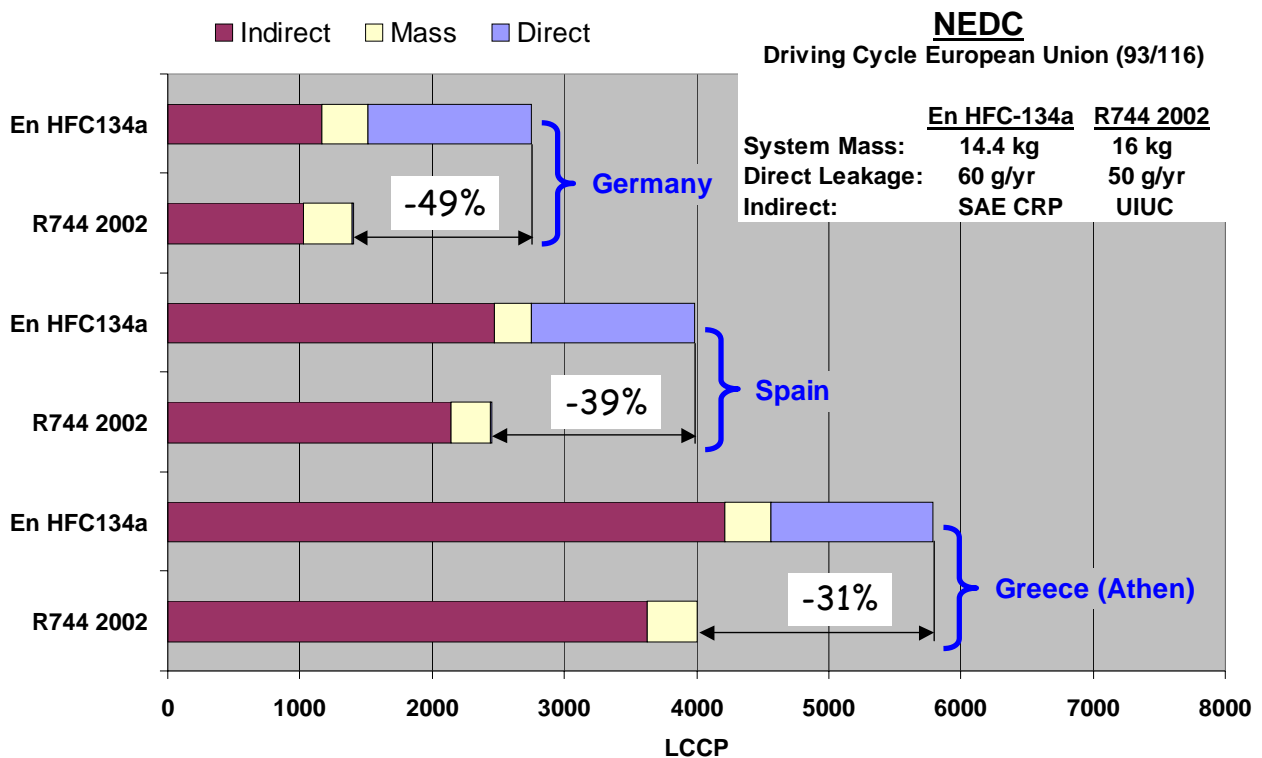


Figure 8: LCCP comparison of Enhanced HFC-134a system and R-744 (2002) system, based on NEDC driving cycle. HFC-134a leakage of 60 g/year.

### **LCCP ANALYSIS HFC-134a VERSUS HFC-152a:**

System COP data measured during the Phase II *SAE ARCRP* program are applied for the calculation of the required energy of the HFC AC systems. It must be emphasised that these data are only available in a preliminary report, so far. Thus, changes may be made before the final report is available.

Figure 9 and 10 shows the LCCP comparison for HFC-134a (2004) and HFC-152a system at 60g leakage of HFC per year. "Direct" contribution to the total LCCP from the production of HFC-134a, emission from vehicle AC circuit, and from reclaiming of HFC at vehicle end of life are around 1230 [eq. kg CO<sub>2</sub>]. The "Direct -emission" of a HFC-152a system is about 200 [eq. kg CO<sub>2</sub>].

As can be seen from Figure 9, the total LCCP numbers for the different US locations are between 18 and 31 % lower for the HFC-152a system. The largest reduction can be obtained in areas with more moderate climates (like in the Midwest), since the total LCCP is lower in these areas; the reduction of the direct contribution has a larger impact.

The fuel consumption is reduced for the HFC-152a system in Miami and in Chicago by about 3 %. The fuel consumption of AC systems, operating in hot climate conditions like in the Phoenix, are reduced by about 5 %, when applying a HFC-152a system.

Figure 10 shows the total LCCP numbers for the different European countries. For Germany a up to 40% reduction in LCCP can be obtained with a HFC-R152a system. In Spain the reduction will be 31%, while a 22% lower LCCP can be achieved in Greece when applying a HFC-152a system.

The fuel consumption of the AC-system can be reduced by 3 % in Greece and Spain, while a 4 % reduction can be achieved in Germany.

Direct comparison to the Phase I *SAE ARCRP* data is not possible.

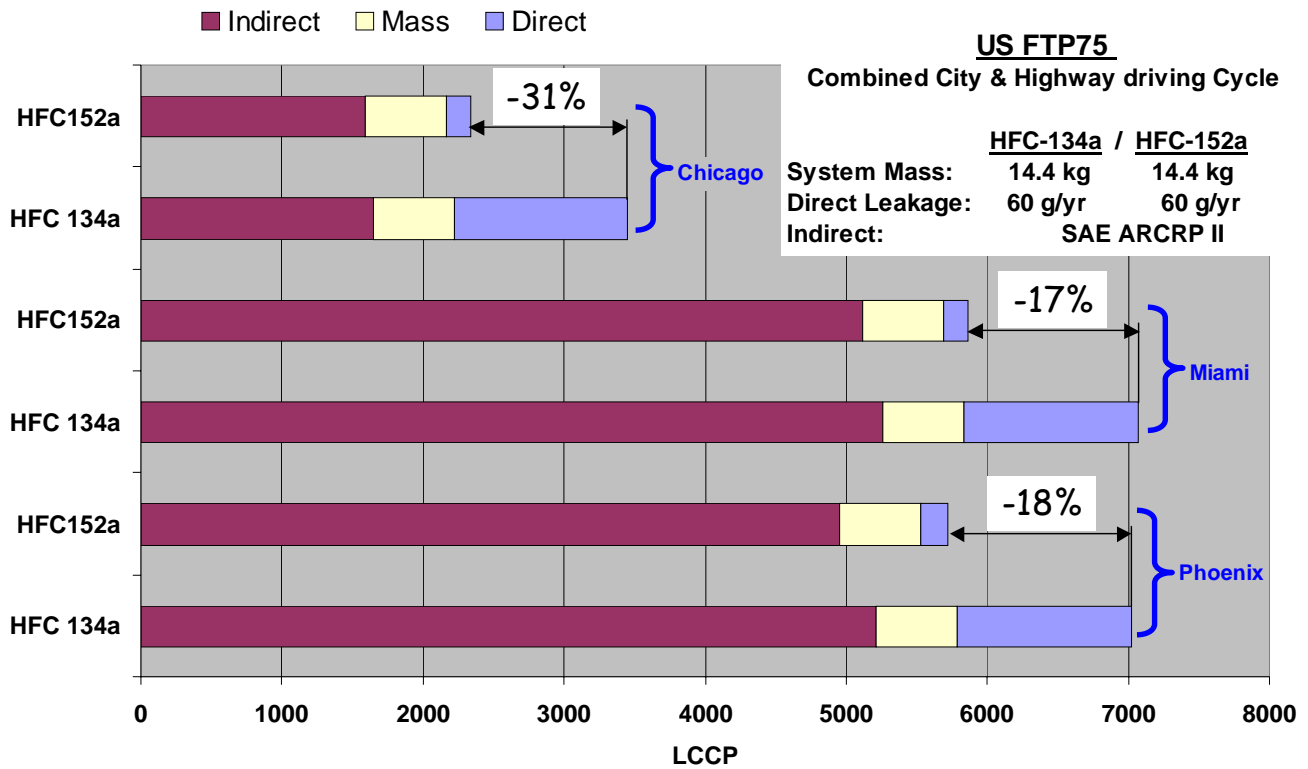


Figure 9: LCCP comparison of HFC-152a and HFC-134a systems, based on US FTP75 driving cycle. HFC leakage of 60 g/year. System COP data, from SAE ARCRP II (2004).

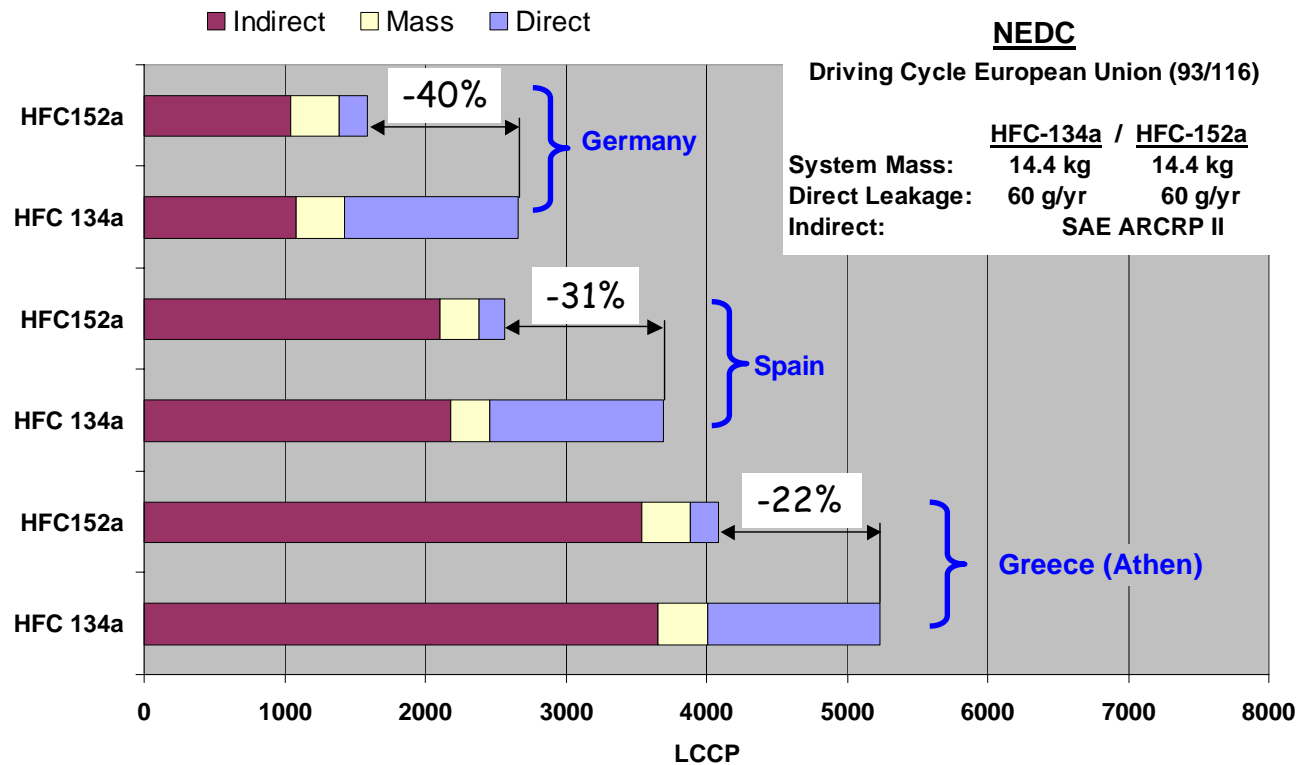


Figure 10: LCCP comparison of HFC-152a and HFC-134a systems, based on NEDC driving cycle. HFC leakage of 60 g/year. System COP data, from SAE ARCRP II (2004).

## DISCUSSION / COMMENTS

A few comments can be made to the test program and the choice of components in the two systems that are the basis for the first LCCP comparison (Enhanced HFC-134a and 2002 R-744):

- Very good baseline in SAE Enhanced HFC-134a system:
  - Extremely high COP
  - Large heat exchanger sizes
  - Condenser with high air flow rate and low refrigerant-side pressure drop
  - Large difference to common AC systems in production today, probably giving large challenges when introducing such an enhanced HFC-134a system into vehicles, due to packaging problems.
  
- Limited focus of test program:
  - Focus on very high ambient temperature conditions
  - Focus on COP data at high ambient, instead of seasonal comparison of energy use
  - No test points were measured at high compressor revolution speeds (above 2500 rpm)
  
- Unfortunate R-744 compressor sizing:
  - Large compressor displacement giving part-load losses

Only low leakage rates (60 g/year) have been applied in the LCCP analysis. These leakage rates are believed to be obtainable in vehicles of the future, if enough effort is given to this issue.

During idling, the air inlet temperature to the condenser/gascooler is sometimes elevated for some car models, due to recirculation of hot air from heat rejecting components. This effect is strongly dependent on the design of the engine compartment, at the same time; this effect occurs mainly if the wind comes from the backside of the car, i.e. tailwind situations. The temperature distribution of the recirculated airflow is in addition not homogeneous. The efficiency of different AC-systems reacts differently to inhomogeneous air inlet temperatures. Therefore, a conservative assumption of 25% occurrence of increased air inlet temperature (+ 15 K) during idling was applied in this analysis.

The second analysis showed the possible LCCP reduction potential of replacing the common HFC-134a by a so-called drop in solution, HFC-152a. The energy consumption of the HFC-152a system did not show an equal improvement at different operating conditions compared to the HFC-134a system. The LCCP analysis showed a energy saving potential of the AC system from 3 to 5 %.

Preliminary data from the *SAE ARCPR Phase II* project has been applied in the second analysis to calculate the LCCP for HFC-134a and HFC-152a systems (*SAE ARCPR, 2004*). These data are not directly comparable to the *SAE ARCPR Phase I* data, however, a comparable LCCP reduction on the *Phase I* HFC-134a data would still give LCCP values for R-744, which were lower or at the same level

Heat pump operation was not included in this LCCP analysis. As high-efficiency car engines with less waste heat are developed, extra heating of the passenger compartment is needed in the cold season. Reversible R-744 systems represent a high-efficiency auxiliary heating

device. Such reversible R-744 systems can give high air delivery temperature, which results in rapid heating of the passenger compartment and rapid defogging or defrosting of windows, as presented by *FRÖHLING et al. (2002)*, *MAGER et al. (2002)* & *MEMORY et al. (2003)*. An LCCP analysis of different auxiliary heating systems has to be conducted. Reversible R-744 systems have clear advantages.

## CONCLUSIONS

- The test data have reconfirmed that COP is no argument against R-744 systems.
- Fuel use of 2002 R-744 system is significantly lower than with *Enhanced* HFC-134a (up to 14 % in Europe), even in the warm climates (Phoenix) the total energy consumptions will be at the same level.
- LCCP of the 2002 R-744 system is improved by 18 – 49 % compared to *Enhanced* HFC-134a system.
- The *Best Technology (BT)* HFC-152a system uses 3 to 5 % less energy (fuel) than the *BT* HFC-134a system.
- The LCCP of the *BT* HFC-152a system is improved by up to 40 % compared to an *BT* HFC-134a system.

The test data have reconfirmed that the COP is no argument against R-744. Fuel use of R-744 systems is significantly lower than with HFC-134a, even in the warm climates considered in the present comparison. Also taking into consideration the good properties R-744 offers for using the system as a heat pump in reversed mode and the potential for compact design, R-744 systems represent a very good alternative for the future.

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