Final Report

Establishment of Leakage Rates of Mobile Air Conditioners in Heavy Duty Vehicles

Part 2

Buses and Coaches

(ENV.C.1/SER/2005/0091r)

Prepared for the European Commission (DG Environment)

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Summary

On behalf of the European Commission, this study establishes empirically the annual leakage rate of mobile air conditioners (MACs) in buses and coaches for the use-phase of the vehicles. In buses, refills are carried out in relatively short service intervals to compensate for leakages whatever their nature. Such refills are recorded over a sufficiently long time and in appropriate detail in Sweden where annual inspection is mandatory for every installation with a refrigerant charge of HFCs more than 3 kg. The refill-based approach of this study consists in the analysis of approximately 2,000 report forms on inspections of mobile air conditioners (MACs) of buses and coaches in a specialised garage in South-East Sweden over the 1996-2005 period.

Equating refills with emissions, the following conclusions on the annual leakage rate can be drawn.

Over ten years, a total of 1,267 annual inspections were carried out on 309 different MACs in buses. For the ten-year period taken as a whole, the leakage rate per annually checked bus MAC averages 2.34 kg ± 0.26 kg. This leakage rate as a percentage of the full refrigerant charge amounts to 23%. These values still disregard any differences in type or design of the buses, and particularly in time of MAC installation.

Further analysis reveals significantly higher leakage rates for articulated compared to single buses, and for gas compared to diesel driven buses. There were differences in leakage rate between particular bus and MAC makes, however, they depend on differences in leak tightness by bus design and fuel type.

The analysis of age dependency splits the bus sample into three categories. MACs installed between1995-1999 show 2.1 kg/a within their first five inspection years and 2.9 kg/a in the next five years. New MACs, installed ex 2000 exhibit a leakage rate of only 0.9 kg/a over the 2001-2005 inspection period. These three figures indicate a double age-dependency. The leakage rates grow as the MAC systems age, and modern MACs are less leaky than older ones. This evidence might lend some support to the argument of MAC makers that there have been substantial improvements in leak tightness due to replacement of flexible hoses and to better connections..

As regards coaches, the average 1996-2005 leakage rate of the 308 annual inspections on 115 vehicles is 1.5 kg/a. This low value can be explained by the fact that all coaches are diesel-driven solo vehicles. The corresponding figure of MACs in solo diesel buses is of the same magnitude (1.25 kg/a).

A closer look at the data reveals differences between MAC types. The integrated split MACs show almost three times higher leakage rates than rooftop MACs. Higher leakage rates by makes of coaches were also found; those with higher leakage rates had higher shares of integrated split MACs.

In bus MACs like coach MACs there is an increase in the annual leakage rate as the MAC systems age. In contrast, the leak rate in new coach MACs (av. leakage rate

1.2 kg/a) in their first five years of operation is similar to the leak rate of older coach systems.

It can be concluded from a statistical analysis of the recorded refill data that the average leakage rate of new MACs in diesel driven coaches is of the order of 1 kg/a (1.20 ± 0.74 kg/a) and is of the same magnitude as leak rates from MACs of new buses with diesel drive, with 0.92 ± 0.40 kg. The percentage leakage rates are 13.3% and 13.7%, respectively.

One of the most important results of this study is that it is possible to reduce the annual leakage rates of modern bus and coach MACs to approximately 1 kg, equivalent to 13% of the full refrigerant charge. These values enable the European Commission to make projections of bus specific emission levels of HFC-134a beyond 2010 if no additional policies and measures are undertaken.

This report is structured as follows: Chapter I explains the "refill-based" approach of this study, and Chapter II presents the selection criteria for an EU representative survey that the sample should fulfil, pursuant to the specifications set by the EC. Chapter III describes the Swedish bus sample and discusses how close it comes to those selection criteria. Chapters IV and V present and broadly discuss the statistical results of the analysis of the recorded data for both buses and coaches. Annex I of this report tries to estimate to what extent the refill-based approach fails to cover the total of regular leakage. In Annex II issues relating to the accuracy of the recorded refill-data are discussed, and in Annex III the contribution of individual MAC components to the annual leakage rates is analysed.

Contents

I. Refill-Based Survey on Use-Phase Leakage Rate

In the framework of EU climate protection goals, the European Parliament and the Council of the EU passed Directive 2006/40/EC relating to emissions from air-conditioning systems in motor vehicles. This Directive of 17 May 2006 provides for a gradual phase-out of the high global warming refrigerant HFC-134a from mobile air conditioners (MACs) in passenger cars and in light commercial vehicles.

In this context, the European Commission (EC) is reviewing the use of HFC-134a in MACs of buses and trucks which requires as a first step obtaining knowledge about the leakage rates of MACs in such vehicles. The purpose of Part II of this study is to fill this knowledge gap as regards MACs in buses and coaches so that the EC has reasonably accurate data on current emission levels from such systems and so enable it to make empirically based projections of emission levels beyond 2010 if no additional policies and measures are undertaken.

I.1 Approach of this study: Analysis of recorded MAC refills

Generally, the leakage rate is defined as grams of HFC-134a that have leaked in one year from a vehicle with an air conditioner. The annual regular leakage rate is derived by relating the refrigerant loss measured (the difference between recovered quantity and standard ex-works charge), to the time elapsed since the vehicle's first registration[1].

While the leakage rates of passenger cars were measured in 2003[2] and those of trucks in 2006[3] to date no such information exists for buses. Overall, the losses of HFC-134a occur during (i) the manufacturing of the gas at the chemical plant, (ii) the charging of the MAC in the vehicle factory, (iii) the normal use of the vehicle and its air conditioner, (iv) the service of the air conditioner, (v) accidents and (vi) at the end-of-life of the vehicles when the MAC is dismantled. The EC specified that the first step was to establish the leakage rate of HFC-134a from MACs in buses during the operation phase, i.e. when the air conditioners are used (use-phase leakage rate).

The 2003 EC passenger car MAC study and the 2006 truck MAC survey are based on measurements of that part of use-phase emissions which is called "regular leakage".

This study on bus MAC leakage rates uses a different approach.

Regular leakage or emission takes place gradually from undamaged, functioning air conditioners. It is a steady refrigerant loss through seals, hoses, connections, valves, etc from every MAC over the entire use-phase. This is different to "irregular leakage", attributable to system failures caused by internal or external factors.

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[1] The calculation is done by dividing the difference in grams by number of years since first registration.
[2] Final Report on Establishing the Leakage Rates of Mobile Air Conditioners, prepared for the European Commission, DG Environment, by Winfried Schwarz and Jochen Harnisch, April 2003. http://ec.europa.eu/environment/climat/pdf/leakage_rates_final_report.pdf
[3] Final Report on Establishment of Leakage Rates of Mobile Air Conditioners in Heavy Duty Vehicles, Part 1 Trucks, for the European Commission (DG Environment), by Winfried Schwarz, January 2007.

The determination of regular leakage in MACs in buses using the Measurement Protocol proven for passenger cars and trucks is not methodologically meaningful for buses. The assessment of gradual refrigerant loss postulates intact MAC systems that have been neither repaired nor refilled, before. However, non-refilled buses MACs practically do not exist after a couple of years in operation.

As regards buses, it was assumed prior to this study and it was confirmed by this study itself, that not only 2-4% of a given vehicle fleet are refilled on inspection per year (like passenger cars or trucks), but up to a tenfold percentage, that is to say one third of the annually inspected vehicles[4].

There are at least two reasons for the high frequency of servicing and of refilling.

Firstly, bus MACs are notably susceptible to leakage. This is caused, inter alia, by specific MAC designs and by specific kinds of MAC assembly. Typically in buses there are long distances between individual MAC components so that refrigerant lines go through the whole vehicle body, high shares of flexible hoses and a large number of connections. Further-on, there is a huge variety of bus models even of the same type, with a multitude of customised versions and sizes of these models. Thus, in the factory the number of fully identical MAC systems is quite small so that standardisation on assembly is not prevalent; MAC systems must be fitted manually.

Secondly, bus operators set great value on viability and appropriate operation of MACs. Compared to passenger cars where the driver switches the air-conditioner on and off at his leisure, running of bus MACs is not a private matter for the operator but a comfort demanded by passengers on the basis of their tickets. The risk of a MAC breakdown must be minimized for the benefit of the customer and ultimately of the operator's turn-over.

The specifics of bus air conditioners, i.e. high leakage and short maintenance intervals in the use-phase do not only require regular service but also make it possible to use refrigerant refills, carried out on servicing, as indicators of use-phase emissions. The essential precondition of making use of refill data for the determination of leakage rate is that meaningful records of bus MAC servicing are available. Available records are meaningful if, approximately, every MAC service, whether on schedule or extraordinary, is recorded not only in appropriate detail and without gaps but also over a sufficiently large number of years.

The approach of this study consists in the analysis of such existing recorded data on refrigerant refills.

It is possible by equating refills with emissions to establish for individual buses and for several categories of buses absolute MAC leakage rates in kilograms per year, as well as relative leakage rates as percentages of the normal refrigerant charges. The approach applied in this study is called "refill-based".

[4] For example, in the bus sample of this study the service year 2002 includes 187 inspected bus MACs of which 62 were refilled.

I.2 Incomplete inclusion of regular leakage

Ideally, the leakage rate obtained from recorded refills reflects overall use-phase emissions, comprising both irregular and regular leakage. This is because refills are carried out to compensate for any leakage whatever its nature.

In reality, there is always a certain lime-lag between emission and refill. This is particularly true of regular leakage which does not lead to a sudden MAC breakdown which is perceived promptly. Gradual refrigerant emission can last for some time, even several years, before it is compensated on inspection.

Regular leakage that is not followed by a recorded refill goes unnoticed in documentation. This is the case when records stop before the next possible refill or, in the case of newer vehicles, before the first-ever refill.[5] Therefore, recorded refills cover every irregular leakage, but do not cover every regular leakage.

In conclusion it can be said that a refill-based approach systematically underestimates , to some extent actual leakage rates. The (small) inaccuracy resulting from this fact is discussed and tentatively quantified in Annex I to this report. As a consequence, the use-phase leakage rates assessed in this study should be taken as minimum values.

I.3 Quality and selection of service records

In the mid-1990s, Sweden and soon after in the Netherlands, introduced mandatory annual inspection and service recording for every stationary and mobile installation with a total charge over 3 kg of halogenated refrigerants (incl. HFCs). Since then, qualified service personnel (accredited at SWEDAC in Sweden, at STEK in the Netherlands) have to complete specified record forms on every regular and extraordinary service on bus MACs.[6]

The following data, as a minimum, have to be recorded: (1) identity of vehicle and MAC system, (2) date of service, (3) quantity and type of refrigerant drained from the system, (4) quantity and type of refrigerant charged into the system, (5) nature of inspection, maintenance, repair and installation activities on the system, (6) faults and alarms related to the system.

In both countries, the data records are kept in the workshop that does the MAC service, and a copy of every MAC check is kept by the bus operator.

After reviewing mandatory service records from selected MAC workshops in Sweden and in the Netherlands, the decision was made to analyse refill data from a Swedish garage. Its documents were deemed best qualified for the purpose of this study.

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[5] If buses change the garage, only the operator continues to know subsequent refills.

[6] Apart from mandatory service records, in a few more EU countries, there are sporadic voluntary records that possibly serve the same purpose as mandatory records do. For example, following on their records of recovery and charging quantities of CFC-12, some garages in Germany continue keeping "Record Sheets" for HFC-134a refrigerant. As far as such voluntary records could be checked for this study, their reliability was considered insufficient, particularly for lack of completeness.

Geographically, both the Netherlands and Sweden are located in the northern part of the EU. Therefore, it was clear from the very beginning of the study that the bus sample would not reflect the totality of climatic conditions that are typical in the whole of the EU and that, possibly, also have an influence on the leakage rate of MACs in buses. There is, however, no southern EU Member State that requires mandatory service records for bus MACs, and equivalent voluntary records also could not be found.. For lack of alternatives, with respect to climate a kind of bias (systematic error) must be taken into account. The bias can be assumed to go in one direction only, so that the leakage rates based on Swedish data must be taken as minimum values.

I.4 Other approaches to establishing leakage rates of vehicle MACs

Empirical studies on MACs of real road-going vehicles had not been undertaken before 2002. After 2002, a few empirical surveys were conducted on passenger cars[7]. Specific studies on emissions from bus air conditioners were not available by 2006.

The specific approach of this study, which is based on existing data records, has an inherent drawback because the analysed original data were not produced intentionally for the purpose of emission estimates. Retroactive evaluation must rely on the accuracy of recorded data. In the case of the Swedish records impreciseness of measured primary data is estimated at up to ±10% (see Annex II to this report).

In the context of EU legislation on fluorinated greenhouse gas emissions, another empirical approach was used, which provides a higher degree of data precision. Clodic (2005) reported results of a survey on a fleet of 30 cars whose MACs had been filled with exactly defined refrigerant quantities before their use in normal road traffic. Twelve months after the same MACs were tested to determine the remaining refrigerant level. In this approach the achievable data precision is high. The latter is necessary because the special purpose of the approach is implementation of leakage tests for type approval under Directive 2006/40/EC.

In preparation of this bus MAC study and particularly in the discussion of the interim report on the expert meeting in June 2006[8] some industry experts proposed that this study should also use an approach based on two, "before and after" measurements. The sample should be increased to some hundred units in order to achieve a high degree of representativity, comparable to this (refill-based) study.[9]

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[7] See overview in the parallel EU study "Establishment of Leakage Rates of Mobile Air Conditioners in Heavy Duty Vehicles", Part 1 Trucks", op. cit., p. 7-8.

[8] Interim Report "Establishment of Leakage Rates of Mobile Air Conditioners in Heavy Duty Vehicles, Part Two: Buses and Coaches", Minutes of the Expert Meeting with representatives from bus makers (EVOBUS, NEOMAN, IRIZAR) and MAC makers (Carrier-Sütrak, Konvekta, Webasto, Thermo King, Hispacold), Brussels, 14 June 2006.

[9] If the proposed study was limited to 30 vehicles only, the accuracy of the results would be poor because the sample would not reflect enough real-world situations. Systematic error (bias) would be too high then. According to clear statistical definitions, accuracy means the agreement between the true value and the measured observations. This is independent on precision which means exactness of measurements. Only the latter would be higher in the proposed twice-measurement approach, if applied to some thirty vehicles only.

At first sight this approach was impressive although it would not be free of artificiality (e.g. limitation of MAC runtime to one year.) Furthermore, it was recognised that such a project would require considerable human resources for obtaining the necessary vehicles, to accompany the heterogeneous fleet for a year and to conduct two long-lasting, "before and after" measurements on each individual MAC. Bus makers said that this approach is too expensive and not feasible without cost sharing with the EU Commission. Given these financial constraints this approach was not adopted.

This report is structured as follows: Chapter II presents the selection criteria for an EU representative survey that the sample should fulfil, pursuant to specifications set by the European Commission. Chapter III describes the Swedish sample and discusses how close it comes to those selection criteria. The main chapters IV and V present and broadly discuss the statistical results of the analysis of the recorded data, separately for buses and coaches. Annex I to this report tries to estimate to what extent the refill-based approach fails covering the total of regular leakage. In Annex II issues of the precision of the recorded refill-data are discussed, and finally in Annex III the contribution of individual MAC components to the annual leakage rates is analysed.

II. Selection Criteria for a Representative Bus Survey

According to international classification, buses and coaches comprise vehicles with more than nine seats below 5 t GVW (M2) and over 5 t GVW (M3). According to ACEA, in 2005 approx. 34,600 vehicles of this kind were newly-registered in EU-15 and additionally some 3,000 in new Member States (own estimation). Like trucks, neither the usual boundary between M2 and M3 class (5 t), nor the ACEA categories (> 3.5 t, > 16 t) provide an adequate definition of buses. As a matter of principle, the latter are vehicles with rear or mid-mounted engine with GVW from about 8 t upwards. In 2005, about 26,000 buses and coaches of this type were newly-registered in the EU-25, representing about 80% of all M2/M3 vehicles. The overall sector of buses and coaches can be split into city buses, intercity buses, and coaches with estimated shares of 40:20:40 (NEOMAN 2005, EVOBUS 2005).

II.1 Exclusion of front-driven buses from the survey

Light buses below 8 t GVW, which represent 20% of the total market, are called minis. They all have in common front engines, and their MACs are of LCV design. In fact, mini buses are essentially LCVs (N1, class 2/3, and N2, lower range) adapted to the purpose of passenger transportation (M2). Leading models are Mercedes Sprinter, Ford Transit, Renault Master, etc. In the upper mini range, M3 vehicles like Iveco Daily/Renault Mascott and Mercedes Vario should be mentioned. MACs of mini buses are LCV-MACs, and these are comparable to those in passenger cars (PC). Leakage rates of PC-MACs established in the EU study can be applied to mini-buses[10].

II.2 Main features of MACs of buses over 8 t GVW

The survey on bus MACs focuses on leakage rates of vehicles with bus-specific MAC design. MACs of buses > 8 t differ from other motor vehicle MACs firstly in that their compressor is not front fitted but mid or rear-mounted.

Secondly, the purpose of a bus MAC is air conditioning of the whole passenger compartment including the driver's place in the front. Its size and design is influenced by the length and volume of the bus body. In contrast, truck MACs are designed for the driver's cabin only, and variation in volume and length of the bodywork does not affect their size and function.[11]

[10] The majority of mini buses have a second evaporator, which requires additional piping and additional refrigerant. Therefore, the leakage rate of minis must be considered higher than that of passenger cars.

[11] According to NEOMAN (2005) and EVOBUS (2005), since 2000 in the city-bus sub-segment (only there) more than 10% of new vehicles have not been equipped with MACs for the whole bus but only with much smaller systems for the driver alone. The semi-hermetic compressors of these MACs are electrically driven, i.e. not by the rear-mounted engine; thus, refrigerant piping is short and presumably less emissive. Although MACs of this kind should be kept in mind they are of minor importance for a study on leakage rates of literal buses.

Thirdly, suppliers of MACs for buses (see Table 1, col. 3) are not the same as MAC suppliers for PCs, LCVs and trucks. In the EU, none of the specialist suppliers of bus MACs are active in the PC or truck MAC sectors. However, some of these suppliers deliver aggregates for refrigerated vehicles where, similar to buses, large volume bodywork has to be cooled down.

In bus bodies, distances between the main components of the refrigeration circuit are long and so are their connecting lines. At the minimum, piping must be laid from the rear (compressor) onto the roof (condenser and evaporator) and back, so that 8 to 10 metres is the minimum length. Clearly, 18 metres long articulated buses need at least twice the piping and the refrigerant charge of 10-metre solo buses, under otherwise unchanging conditions.

II.3 Five main technologies of bus MACs

Apart from bus length varying from 8 to 15 metres (solo) and even 18 and more metres (articulated), the main leakage risk factors like piping length, refrigerant charge and number of connections, joints, valves, depend on the specific MAC technology applied. Currently, there are five technologies in use (Bus MAC Survey 2006). Table 1, col. 4, contains an estimate of their particular market shares.

1.Mostly used for city buses, intercity buses, and coaches are systems with condensers and evaporators fitted to the rooftop, with partly flexible refrigerant lines connecting rooftop units to rear or mid-mounted compressors. From the rooftop unit, evaporator-cooled air is blown through the right and left air duct to the passengers. Piping length is 10, 20 metres, and often a similar line length once again for air-conditioning of the driver's place in the bus front (liquid line from rooftop condenser to driver place evaporator, suction line back to the compressor).

2. Articulated city buses are usually fitted with two rooftop units. Unlike the condenser-evaporator-unit on the roof of the rear section, the roof unit on the front section often includes only an evaporator (no condenser). A big challenge to engineers is bridging the articulated joint between rear and forward section. Here, flexible hoses must be applied, which significantly raise the leakage risk.

3. In some coaches, split systems are in use with the MAC unit being invisible from outside (integrated split). The condenser is mostly placed in the luggage compartment. From there, two lines (in case of double-deckers these lines are doubled) run forward and back through the air channels in order to provide an array of integrated evaporators with refrigerant. Compared to rooftop units where cool air is blown forward through the air duct, split-evaporators require additional piping and more connections, increasing refrigerant charge (up to 20 kg) and raising leakage risk.

4. Compact rear fitted MACs which are fitted to selected coaches (single and double-deckers) do not need (much) space on the roof. Condenser and evaporator are installed above the engine compartment, and cool air is blown forward through air channels. This system only requires relatively short lines and small refrigerant charges. Long refrigerant lines to the driver's place are still necessary (Bus MAC Survey 2006).

5. From 2001, some bus makers have used water chillers for MACs of luxury coaches. Instead of refrigerant, cold water circulates through lines between a compact compressor-condenser-evaporator unit in the engine compartment and a number of heat exchangers on top of the passenger compartment, substituting split evaporator systems as described sub 3. The cold water also cools down the driver's place, so that the whole system only requires some five metres piping (50% of which is non-metallic) and 4.5 to 6.5 kg refrigerant. (DCAG 2005, NEOMAN 2005)

II.4 High leakage risk due to long piping and numerous connections

Although there are bus MACs of different design, they all have in common:

- Long refrigerant lines (from 10 to 50 metres; only 5 metres by way of exception)
- High share of flexible hoses in piping (sometimes more than 30%)
- Large number of connections and joints
- High charges of refrigerant (from 5 to 20 kg).

Such systems are inherently susceptible to refrigerant leaks, predominantly from permeation through refrigerant hoses, brazed/mechanical joints, valves, and compressor shaft seals. The leakage rates are far in excess of those of passenger cars and of truck systems. The risk of refrigerant loss grows with increasing length of pipes and increasing number of joints. This survey must consider, amongst others, variations in MAC design as they indicate differences in length and structure of piping and hoses and in number of connections and joints.

II.5 Criteria for sample composition

A fundamental requirement for the empirical survey is to consider adequately the variety of MAC designs as described above (sub II.3) and in Table 1 (market shares). Should the study bring differences in leakage rate to light, the possibilities must be given to check the expert hypothesis of a connection between leakage risk and MAC design. Admittedly, inclusion of technology No. 5 (water chillers) is difficult because its use is still in its infancy. A sample without it is acceptable.

Concentration on design-related effects does not mean ignoring the existence of different bus makers[12] as well as different MAC suppliers on the EU market. It is, however, the position held prior to this study and confirmed by it that differences in leakage rates by bus makers and MAC suppliers are of minor importance compared to differences in design. All the EU bus makers use MACs from the five European suppliers (Table 1, col. 3) who in turn are capable of providing in principle every technical solution. It might be satisfactory for the sample to consider the most important makers of buses and of MACs (see Table 1). As a consequence, the

[12] In the first line, bus makers in Table 1, col. 1, are manufacturers of chassis, who sell them partly to independent bodybuilders for completion under different make. Statistically, all finished buses are attributed to chassis-manufacturers whoever the bodybuilder is. It should, however, be borne in mind that a relevant fraction of EU-made buses is fitted with bodyworks from manufacturers not listed in Table 1. (A few independent body makers are included in Table 1). The consequences for MACs that are installed by external bodybuilders are not deepened here but are discussed in Chapter IV.

representation of more than two relevant bus makers and MAC suppliers suffices to cover the majority of MAC-equipped buses (see Table 1, col. 1, and 3).

In contrast, the consideration of all different bus segments: city buses, intercity buses, and coaches is necessary. Different bus types do not express different application conditions of otherwise identical vehicles. The three bus classes vary in technical properties, such as bodywork (height of passenger deck above ground level, etc.) or interior equipment (constructed with areas for standing passengers or not, etc.)

Of more importance is that different bus types represent quite different usage patterns and strain. City buses, on the one hand, mostly run in unsteady stop-and-go conditions with doors open and close traffic, while coaches, on the other side often run steadily over long distances on straight roads without any stop. (Intercity buses have common features with both bus categories). The most decisive differences between city buses and coaches exist with respect to vehicle types and MAC design. Only city buses are divided into solo and articulated vehicles, and can sometimes be split additionally into diesel and gas drive. In contrast, coaches are exclusively solo diesel vehicles, which vary by different design and technology of their MACs. This is not the case with city buses, which are generally equipped with roof top systems.

In the light of these considerations, connections between bus type and MAC leakage rate cannot be excluded a priori, and must be duly examined.

Finally, a representative sample must reflect the real age structure of the EU bus fleet. Only if real age differences are considered, can relevant timely developments be analysed. It is important to know whether or not technical improvements have lead to significant reductions in leakage rates. In addition, analysis of leakage rate development in the course of time is precondition for any forecast of future HFC emissions from bus air conditioners.

Ideally, the sample mix should come as close as possible to the parameter mix presented in Table 1.

Table 1: New Buses and Coaches > 8 t GVW in the EU 25 (25,000 Units). Estimates of 2005 Markets Shares by Öko-Recherche

1. Bus maker (Market share)	2. Bus Segment (Market Share)	3. MAC Supplier (Market share)	4. MAC-System (Market Share)
EVOBUS (28%) - Mercedes (19%) - Setra (9%)	City-Bus* (40%): Solo 28%	Carrier Sütrak (25%)	**Rooftop** (>80%)
IRISBUS (18%)	City-Bus* (40%): Artic. (12%)	Webasto (20%)	**Integrated Split** (Coach) 8%
NEOMAN (14%) - MAN (10%) - Neoplan (4%)	Intercity-Bus (20%)	Konvekta (20 %)	**Compact Rear-Fitted** (Coach) (4%)
VOLVO (13%	Coach (40%) mostly single-decker, few double-decker	Thermo King (15%)	**Compact Water Chiller** (Coach) 4%
SCANIA (9%) - Omni City/Interc. (4%) - Irizar Coaches (5%)		Hispacold (15%)	
Dennis (6%)		Others (5 %)	
VDL Bova (4%)			
van Hool (3%)			
Solaris + Others (5%)			

* Please note this is the number of new registered buses, not of MAC equipped buses. The MAC quota of city buses is still substantially lower than of intercity buses and coaches where it is near to 100%.

In each column, sub-sections exclusively show parameter-specific market shares of this column alone. Equal level in different columns does not indicate interconnection of different sub-sections with each other.

III. Composition of the analysed Swedish sample

In Sweden, it is mandatory to have stationary and mobile refrigeration and air-conditioning systems inspected every 12 months if they contain halogenated refrigerants in excess of 3 kg. These inspections must be carried out by a company accredited by the national board SWEDAC (Swedish Board of Accreditation and Conformity Assessment). The technical check of mobile Air-Conditioners (MACs) and refrigerated vehicles follows the Swedish Refrigeration Code (Svensk Kylnorm) that had been developed by the refrigeration industry in a general form in 1992,and which focused on "mobile refrigeration equipment and units with CFC/HCFC/HFC refrigerants" in its 1995 amendment. The result of every inspection with or without refrigerant refill is entered in an official form (Kontrollrapport M) by the refrigeration company who hand the filled form over to the operator of the vehicle. The operator submits this form to the Technical Vehicle Inspection Agency in order to achieve the operating licence for his bus or coach for the following year. This is why MAC inspections are carried out in Sweden regularly.

The refrigeration company keeps a copy of every completed form for their records and also because these forms are checked by SWEDAC. The report form that has been used for mobile systems since 1996 requests the following data[13]:

Swedish Report Form for Mobile Refrigerant Systems
Address of the performing accredited refrigeration company.
Type of inspection: new installation, routine check, or check after repair.
Identity of the vehicle: no. of chassis (VIN), registration no., and, if available, inventory no. of the operator.
Identity of the MAC: make and model, refrigerant type, full refrigerant charge.
Operator: name, address, telephone.
Inspection according to refrigeration code: Yes or No. This question aims, amongst others, at the proper check-up equipment and at log-book keeping.
Service-Report in case of opening the refrigerant system:

- Recovery of oil, and if yes, how much.
- Sealing a refrigerant leak: Yes or No.
- Recovery of refrigerant, if yes, how much.
- Recharging of refrigerant, if yes, how much.

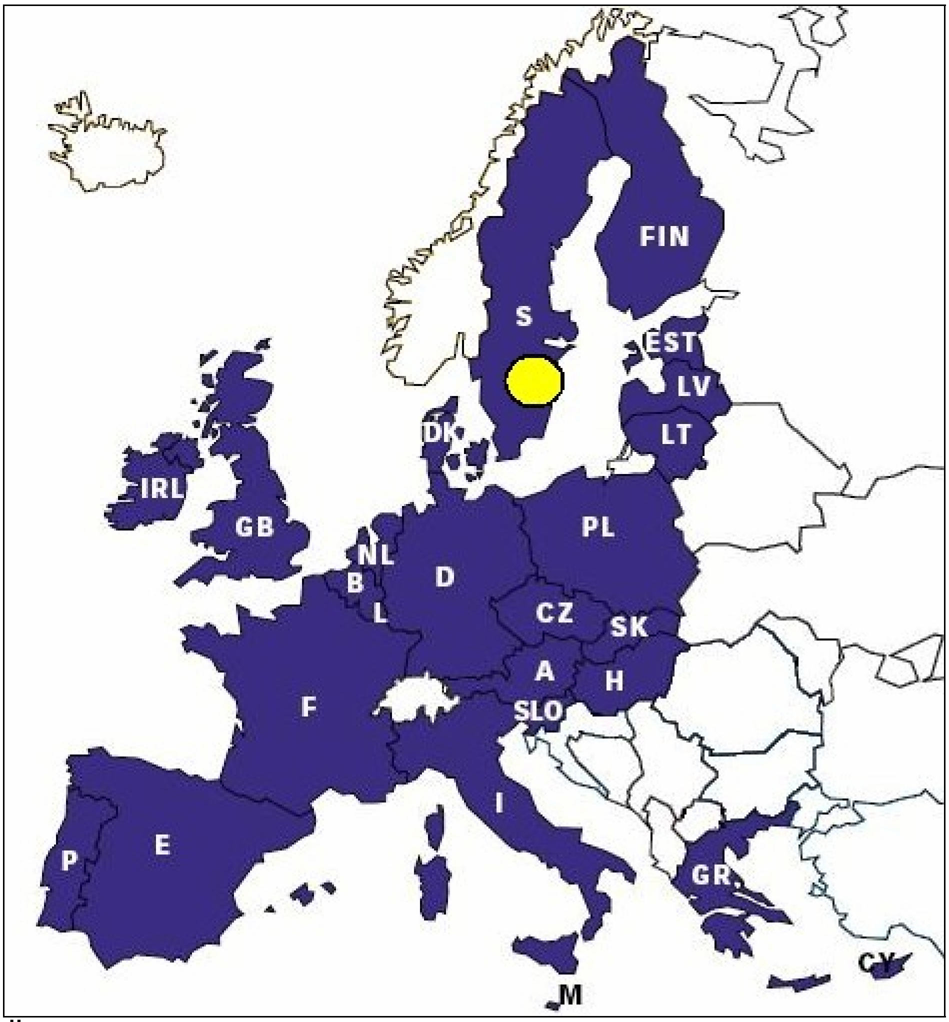
If the refrigeration circuit was opened, the reason must be briefly described; for instance 'exchange of the compressor shaft seal', 'leakage in the suction line', etc.
Date of inspection and signature of the mechanic.

III.1 Inspections of bus and coach MACs in the company Kylindustri

The accredited refrigeration company Kylindustri AB is located in the province of Östergötland in South-Eastern Sweden (410,000 population), near to Linköping, which is the fifth-largest Swedish town. The service area is the country between Lake Vättern and Baltic Sea, which extends about 100 km x 100 km. It stretches from Katrineholm in the North to Atvidaberg in the South, from Motala and Vadstena in the

[13] The forms have two insufficiencies: The mileage of the vehicle at inspection time is not required, nor is the vehicle's date of first registration asked for. The latter must be obtained from alternative sources.

West to Norrköping, Söderköping, and Nyköping in the East. The climate in Östergötland is relatively mild, with average temperatures from -2°C in January to 16 °C in July. The buses and coaches being inspected by Kylindustri are operated in this region, where Kylindustri is by far the most-frequented and largest specialised refrigeration workshop.



Östergötland, South-East Sweden, the area where the buses and coaches of the sample are operated. The circle indicates geographic location in the northern part of the EU-25, at the same latitude as Scotland or the Baltic States.

80% of the <u>buses</u> belong to Connex, the operator of the public transportation in Linköping and – to a lesser extent – in Motala. The remaining 20% come from four smaller short-range transit companies in the area. Before 2003, the predecessor of the nationwide operating Connex AB was the local company Linjebuss AB, the vehicles of which were largely taken over. Beforehand Linjebuss AB, in its turn, had acquired the bus pool from Näckros-Buss AB, in 1998. As a consequence, in spite of two changes in ownership, a high degree of vehicle continuity was ensured over the last ten years, even though in this period a number of buses were sent to other operating places and consequently no longer visited Kylindustri for inspection.

The <u>coaches</u> likewise come from the Östergötland area. They belong to thirty different, mostly smaller operators who operate from one to nine vehicles. There are only two larger coach operators with 22 and 15 coaches, respectively. These two companies also run buses (intercity buses).

III.2 February 2006: Making use of Kylindustri archives

Kylindustri kept records of all bus MAC inspections in the whole 1996-2005 period. In one year there are about 200 entries from inspections of bus and coach MACs – with a clear preponderance of buses over coaches (inspections of refrigerated vehicles are not considered). Some ten percent of the entries are multiple entries, which mean that some vehicles came twice or even more often in the same calendar year – mostly because a MAC fault had occurred after the routine check.

From 20 to 24 February 2006, two staff members of Öko-Recherche copied all the report forms on bus and coach MACs from 1996 to 2005 into their computers.

Left out: Driving place MACs
The forms from 1996 to 1998 also contain a series of inspections of just the driving cabin MACs in some buses, with refrigerant charges below 3 kg. In 1996, 28 of these small bus MACs underwent inspection; 14 of them already running with 134a after conversion, 14 of them still running with R-12. Further investigation brought to light that none of these buses was equipped with MACs for the passenger compartment, neither with an R-12 system before 1995 nor with an R-134a system after 1995. It was decided, to eliminate these cases from the sample.

Distinction of the vehicles into coaches and buses and their sub categories
Since the forms do not distinguish between coaches and buses, the director of Kylindustri, Stefan Danielsson, made the distinction, based on his personal knowledge.

Mr Danielsson also helped together with Mr Mutafoff (Sales Manager Nordic and Balticum for Carrier-Sütrak) break down the buses into either articulated or single and into either diesel or gas driven vehicles. For, it was sometimes impossible to establish the design or the fuel type of a bus from the installed air conditioning system. Gas and diesel buses do not use different MACs, and articulated buses are not always equipped with two condensers, i.e. one on the front and another on the rear part.

III.3 Further data correction and confinement

Removal of coincidental MAC check-ups
For several reasons, not all the buses or coaches that came to the Kylindustri workshop for their annual inspection in 1996-2005 did so regularly. On average, one third of the possible annual check-ups were carried out not in Kylindustri but elsewhere. There are even buses which came for a check-up only once in ten years. As this study aims at leakage rates of regularly checked vehicle MACs such buses/coaches are excluded from the sample. The minimum condition for inclusion in the sample is that the recorded MAC test can be evaluated at least once again, i.e. twice in the ten years period. This corresponds to 20% of possible annual visits. Buses with first registration after 2000 need only one visit according to this 20% rule. On the basis this principle, 43 buses and 39 coaches were removed from the original sample.

Removal of R-12 MACs
Given the objective of this study, only vehicles with R-134a MACs can be taken account; this excludes vehicles with R-12 MAC systems. This rule is irrelevant for city- and intercity buses that passed the Kylindustri check-ups; none of them had an R-12 MAC for the passenger compartment since the equipment of city and intercity buses with MACs was not common before 1994 in Sweden like elsewhere in Europe.

A significant proportion of coaches, however, have been air-conditioned since the end of the 1980s. In the year 1996, the uncorrected coach sample still contains 28 coach MACs running with R-12. Six of them were converted to R-134a in 1997, five in 1998, four in 1999, and one even in 2000. What happened to the remaining 12 coaches with R-12 MACs from 1996 is unknown because they did not visit the garage for a check after 1997. It is likely that they were never converted to 134a because they were too old, and the 15,000 Euro investment in conversion could not be expected to bring a return in their remaining operating years.

As long as coaches ran with R-12, they are not considered in the sample. After conversion to R-134a (exchange of all the refrigerant hoses, etc) an old MAC is in fact equivalent to a new one and can be treated like that or at least like an aftermarket system. There are four cases recorded when a coach with a converted MAC came at least twice in the time after conversion. According to the above-mentioned "20%-rule" these vehicles were included in the sample.

In the correction of the bus and coach data, 43 buses and 39 coaches were removed as coincidental one-time visitors. In addition, coaches with R-12 MACs were not considered: 28 in 1996, 22 in 1997, 15 in 1998, and 5 in 1999. Four of them were included again after conversion to R-134a systems.

Following these corrections to the data sample, 309 buses and 115 coaches that were serviced in the 1996-2005 period were left in the sample for analysis.

III.4 Representativity of the Swedish bus sample

After preparation of the recorded bus MAC data, the sample shows the composition preset out in Table 2.

1. The most important characteristic of the sample is its subdivision into two special samples, one of city buses (309) another of coaches (115). Separate analysis of city buses and coaches accounts for the fundamental difference between the two main types of buses. In both samples the number of cases (vehicles) is large enough for meaningful statistical evaluation. Herewith, sample representativity is given as to different bus types.

As a consequence of the fundamental division into two parts, there is no special sample of intercity buses. Vehicles of this type were allocated partly to city buses, partly to coaches, following the expertise of the Kylindustri manager. This procedure seems to be justified by the intermediate status of intercity buses between city buses and coaches. Intercity buses have common features with both main bus types, a clear and generally binding definition of this category does not exist; every bus maker uses his own classification.

Table 2: Composition of the Swedish bus and coach sample

	Buses (number)	**Coaches (number)**
Total	309	115
Year of assembly		
1985-1992*	51	19
1992-1999	190	56
2000-2004	68	40
Vehicle design/fuel type		
Solo Diesel	161	113
Articulated Diesel	86	0
Solo Gas	34	0
Articulated Gas	28	0
Double Decker	0	2
MAC type		
Rooftop	309	84
Integrated Split	0	20
Rear Compact	0	7
Chiller (two-loop)	0	1
MAC Make		
Sütrak	238	64
Thermo King	43	5
Konvekta	4	13
Webasto	3	12
Hispacold	1	12
Carrier (until 1997)	17	0
Other	3	9
Bus maker		
VOLVO	164	37
SCANIA	82	23
NEOMAN	38	31
EVOBUS	25	19
BOVA	0	3
Other	0	6

* Buses assembled prior to 1992 were retrofitted with R-134a-MACs in 1995/1996. Coaches assembled prior to 1992 were retrofitted 1995/1996 or had R-12-MACs already before 1995.

2. Adequate sample representativity is given with respect to age distribution, vehicle type, fuel type, and MAC design; this is true of both samples and it indicates agreement between sample composition and the real EU fleet with respect to the most important features. In addition, the coach sample fulfils the criteria of representativity as regards the real mix by MAC makes.

3. In some other aspects the sample mix deviates from the real mix. In the samples, four of five leading bus makers are represented in numbers large enough for meaningful statistical analysis. However, the second-largest EU bus maker IRISBUS is not included. In addition, the make composition of the city bus sample deviates from the real EU situation, showing clear preponderance of the Swedish bus makers VOLVO and SCANIA. Furthermore, with respect to MAC makes, the share of the Scandinavian market leader Sütrak in the city bus sample clearly outbalances his

share in the real EU mix. This preponderance goes along with too low shares of the three MAC suppliers Konvekta, Webasto, and Hispacold.

In conclusion, the city bus sample mirrors the real Swedish brand mix better than the EU brand mix. This is not surprising because the buses are in the sample not for the purpose of an EU study but because Swedish law requires an annual MAC inspection.

Limited sample representativity is peculiar to the refill-based approach. This was already discussed in the first chapter (I.3) related to the inevitably insufficient inclusion of all climatic conditions of relevance to the EU-27, in particular of those in southern Member States.

With certain reservations, the high representativity of the coach sample and acceptable representativity of the city bus sample in most parameters, allow for the use of both of them to establish leakage rates of air-conditioners in buses and coaches with a sufficiently high degree of representativity of the real situation in the EU.

IV. The Annual Leakage Rate of Bus Air-Conditioners

As discussed in Chapter I, leakage rates of buses and coaches are not assessed via direct measurements of refrigerant loss per vehicle but the indirect way. In accordance with the practice of emission estimation in stationary equipment, namely to use refrigerant refills as indicators of emissions or leakage, a refill-based approach is applied to MACs in buses and coaches. In the following sections, the annual refill per bus is assumed identical to the annual leakage rate per bus.

IV.1 Overall leakage rate of the 1996-2005 checked buses: 2.34 kg/a

In the ten-year time-span 1996-2005, 309 different city buses and intercity buses (in the following: buses) were brought to the Kylindustri garage for annual routine check or, additionally, because of a problem with their MAC systems. If a bus visited the garage more than once in one calendar year, these visits were combined and treated as one; the same summing-up was done with multiple top-ups in one year. First evaluation of the 1,457 (1,267) bus MAC report forms gives the following picture for the 309 different buses as per Table 3.

Table 3: Total of 1996-2005 bus MAC checks by year, number, and annual refills

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	**Total**
Refill in kg	101.9	208.7	263.2	391.2	211.5	355.9	489.3	443.9	219.1	278.9	**2964**
Check-ups	57	111	126	166	109	137	187	133	112	129	**1267**
kg/annual check	1.79	1.88	2.09	2.36	1.94	2.60	2.62	3.34	1.96	2.16	**2.34**
Refilled buses	14	22	31	44	29	43	62	51	29	37	**362**
Age at check	1.1	1.9	2.7	2.9	4.2	4.4	5.3	5.9	6.9	5.5	**4.3**

Source: record forms of the garage Kylindustri in Mantorp, South-East Sweden.

Over ten years, a total of 1,267 annual inspections were carried out (actually 1,457, before combination). On average, each bus of the sample had a check on its MAC approx. four times within the 1996-2005 periods (1,267/309). The refrigerant quantity refilled within the ten years amounts to 2,964 kg HFC-134a. For the ten-year period taken as a whole, the leakage (refill) per annually checked bus averages 2.34 kg.

Diagram 1 shows that the leakages widely scatter by kg/a. (Please note that the 905 "zero-leaks" are not reproduced true to scale in the following graph but end at 100.)

The MAC leakage rate of 2.34 ± 0.26 kg/a, which is calculated from 1,257 annual city-bus checks (on 309 different vehicles) over the whole 1996-2005 period, is achieved as an average of 905 annual "zero-leaks" and 362 actual annual leaks (refills) > 0 kg. The mean of 2.34 kg is estimated at a confidence level of 95 percent. As one Standard Error (1 SE) is 0.13, the 95 % confidence interval is 2.34 kg ± 0.26 kg (± 2 SE). An annual leakage rate of between 2.08 kg and 2.60 kg is the range within which the true mean of the population (MAC-equipped bus fleet in the EU) lies with a likelihood of 95%[14].

The average refill value of the 362 annual leakages is 8.2 kg (2,962/362). Together with 905 no-leak cases (0 kg), the 362 actual leaks form the average of 2.34 kg/a.

[14] The mean of the sample is the mean of reality so far the analysed sample includes and reflects all real-world situations that influence the bus MAC leakage rate.

The average full (norm) charge of the 309 checked bus MACs is 9.3 kg. Thus, the percentage leakage rate is 23.1 ± 2.4%. (Average age at check time is 4.3 years).

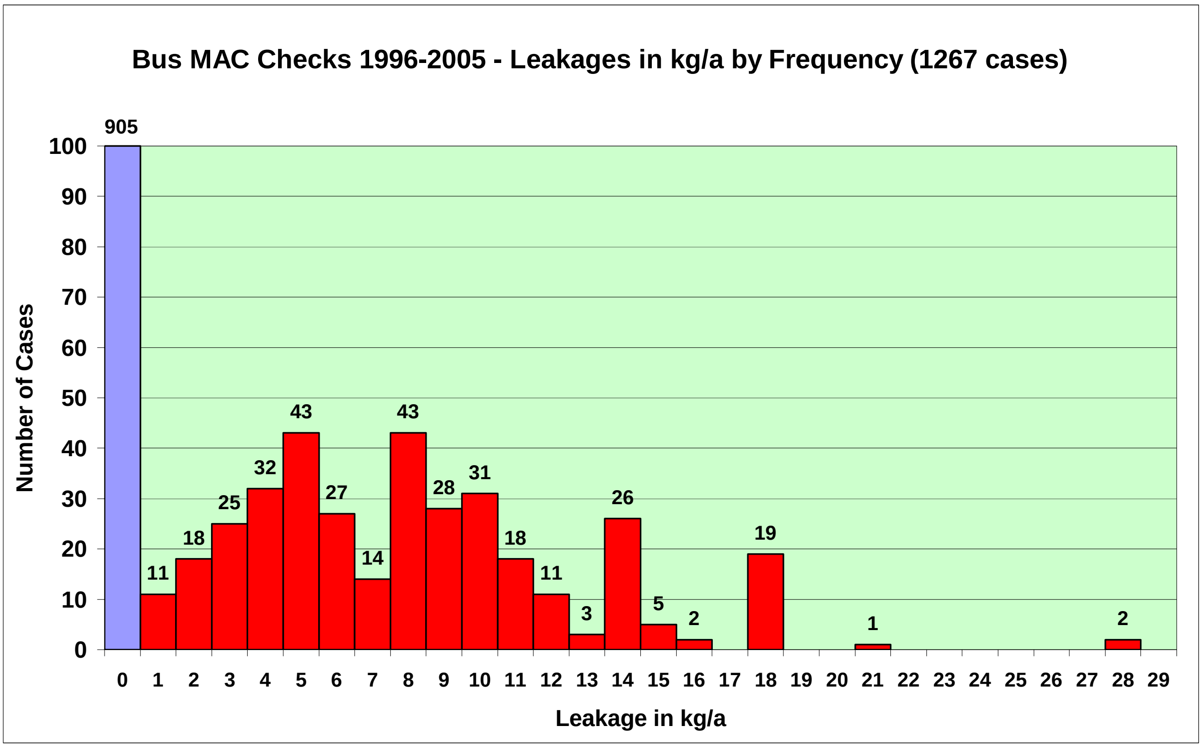


Diagram 1: The MAC leakage rate 2.34 kg/a of the bus sample is a computed figure which consists in reality of a large number of "zero-leaks" (blue bar) and a smaller number of highly diverse actual leaks (refills) varying from 1 to more than 18 kg/a (red bars).

The refills are unevenly distributed over the totality of buses. Averaging the 1996-2005 periods, in every year 71% of the buses passed annual check-ups with the MAC not being topped up.[15] This means that 29% (362/1267) of the checked MACs were refilled annually, with a peak of 38% in 2003. From 1996 to 2005, this quota was almost constant.

In the written service records refilling of completely empty systems prevails over partial top-ups. Of 395 refills (before combination to 362), 321 (82%) were refills of empty refrigeration circuits[16]. By mass, the relation of complete to partial refills is from 2,750 kg (93%) to 213 kg (7%).

As already noted, on average in every year 71% of the buses were not refilled. However, within the ten service years there were only 126 of the 309 buses, which did not need any top-up. Amongst these were 35 buses that were only one year old, having been first-registered in 2004.

It must be pointed out that Table 3, row 3 (kg/annual check) shows undifferentiated annual leakage rates of those buses which were inspected in a particular year during the 1996 to 2005 period. These annual leakage rates may be denoted "sample

[15] Often major repairs were carried out on MAC systems without lack of refrigerant being stated. The exchange of the filter dryer, which takes place on every regular check, does not cause considerable refrigerant release thanks to shut-off valves. Associated emissions are estimated at ~30 g.

[16] One refrigeration circuit is not always the same as one MAC system. Articulated buses often run with two circuits or better, two sub systems, of which one can be intact while the other leaks.

leakage rates". They still disregard any type and age differences between particular buses or MACs. A fortiori, this applies to the ten-year average of 2.34 kg/a.

Although the course of the annual sample leakage rates exhibits a high degree of constancy with comparably small oscillation around the 2.34 kg/a value, it should be repeated that they must not be mistaken as a time series that proves real invariance of the 1996-2005 leakage rates. This conclusion would be allowed only if the inner structure of the sample by bus type, age of MAC since installation, etc was identical in every year, which is not the case.

A closer look into these "unspecific" leakage rates is worthwhile as important qualitative and quantitative conclusions can be drawn on dependency or independency of leakage rates from structural features such as bus design, fuel type, bus or MAC make, etc.

This is done in the next sections of this chapter, before the final section of this chapter discusses the influence of age and ageing of MACs on the leakage rate.

IV.2 Leakage rates by bus design and fuel type

The 309 different buses, which were visiting the Kylindustri garage over the 1996-2005 periods, can be broken down into types as follows.

Solo Diesel 161, thereof retrofitted in 1995/96: 17,
Articulated Diesel 86, thereof retrofitted in 1995/96: 30,
Solo Gas 34, thereof retrofitted in 1995: 4[17],
Articulated Gas 28, all of them with ex-works MAC at commissioning 1997/98[18].

According to Table 4, the leakage rates of bus MACs vary significantly by bus design and fuel type. Over the whole 1996-2005 period solo diesel buses exhibit the lowest MAC leakage rate averaging 1.25 kg/a (± 0.22). This value is statistically significant vs. all the other bus types.

Table 4: 1996-2005 bus MAC checks and leakage rates of buses by design and fuel

Bus Type	Buses	Checks (n)	Refill in kg	Leakage rate kg/a
Solo Diesel	161	673	842	**1.25**
Articulated Diesel	86	324	1063	**3.28**
Solo Gas	34	161	562	**3.49**
Articulated Gas	28	109	496	**4.55**
Total	309	1,267	2,964	**2.34**

Statistical analysis shows that differences in the mean values between the vehicle types (leakage rates in kg/a) are partly significant, assuming a 95% confidence interval (with a margin of 2 x Standard-Error SE up and down). See Table 5. On the other hand, the high MAC leakage rate of articulated gas buses (4.55 kg/a ± 1.49)

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[17] The 51 old buses from 1985-1990, which had no R-12 MAC before and to which an 134a-aftermarket system was re-fitted in 1995/1996, were partly operated until 2004. In 2004 eight of these buses were still in use, in 2005 all of them were out of service.
[18] Articulated gas buses with MAC were acquired only in 1997 and 1998, single gas buses with MAC only from 1987 to 1999, no longer as of 2000. The newer gas buses are not air-conditioned.

falls short of statistical significance vs. MACs of articulated diesel buses and of solo gas buses, with average leakage rates of 3.28 kg/a and 3.49 kg/a, respectively.

Table 5: Statistical interpretation of design and fuel specific leakage rates

Bus Type	Average (mean)	Standard Deviation	Square Root (n)	1 SE	2 SE	2 SE up	2 SE down
Solo Diesel	1.25	2.89	25.9	0.1	± 0.22	1.47	1.03
Articulated Diesel	3.28	5.80	18.0	0.3	± 0.64	3.93	2.64
Solo Gas	3.49	4.23	12.7	0.3	± 0.67	4.16	2.82
Articulated Gas	4.55	7.76	10.4	0.7	± 1.49	6.04	3.06
Total	2.34	4.68	35.6	0.13	± 0.26	2.60	2.08
All without Articulated Gas	*2.13*	*4.22*	*34.0*	*0.12*	*± 0.25*	*2.38*	*1.88*

Comparing the leakage rate of articulated gas buses to those of all the other types together (Table 5, bottom row), the difference in leakage rate is statistically significant, with 4.55 ± 1.49 vs. 2.13 ± 0.25 kg/a. This can also be seen in Diagram 2 where the four mean values are shown together with their error bars.

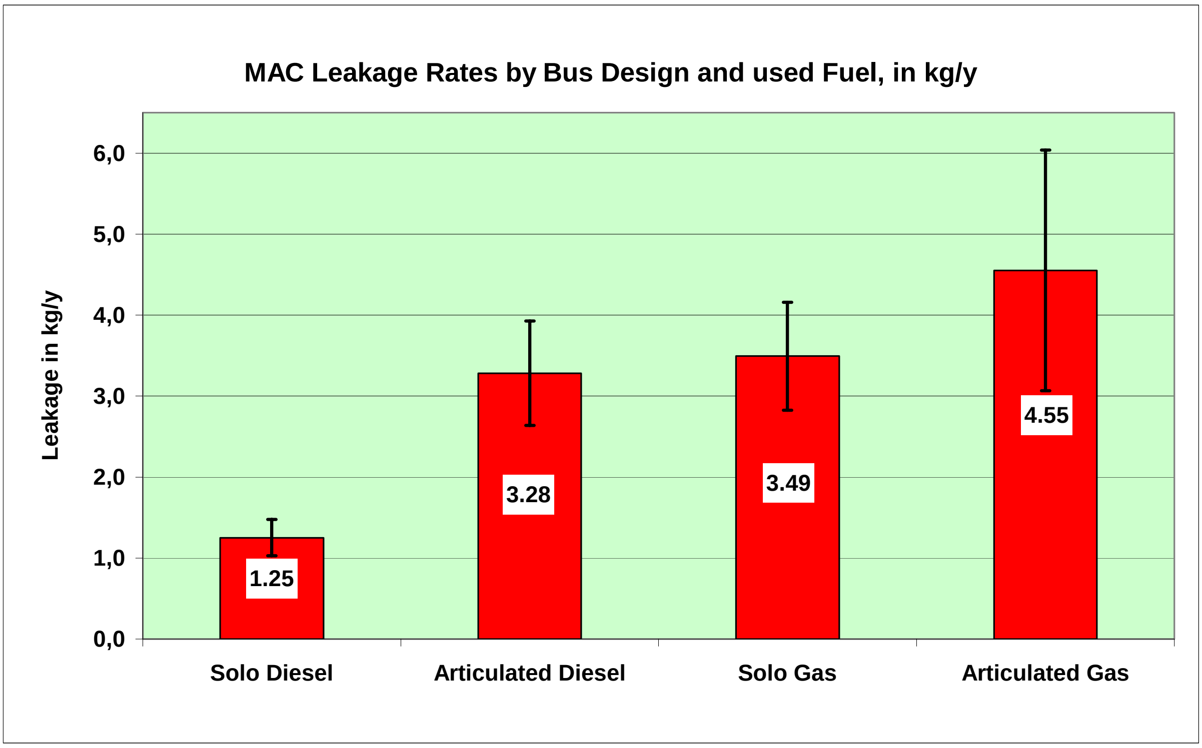


Diagram 2: Bus MAC leakage rates widely vary by vehicle design (solo or articulated) and by fuel type (diesel or gas). Solo diesel buses show the lowest values with 1.25 kg/a. This is a statistically significant difference from the other vehicles (no overlapping error bars).

In conclusion, solo diesel buses show significantly lower MAC leakage rates compared to the other bus types. Articulated gas buses show significantly higher leakage rates compared to the other bus types.

IV.2.1 Gas buses vs. diesel buses

Evidently, gas power puts strain on MACs. A comparison of gas buses (single plus articulated) with diesel buses (single plus articulated) shows the results in Table 6.

The MAC leakage rate of gas buses is significantly higher than that of diesel buses, 3.92 kg/a compared to 1.91 kg/a.

Table 6: MAC leakage rates of gas vs. diesel buses

Bus Type	Buses	Checks (n)	Refill kg	kg/a	margin up	margin down
Diesel (all)	247	997	1,905	1.91	2.18	1.65
Gas (all)	62	270	1,058	3.92	4.64	3.20

The explanation of the Kylindustri manager was that heat in the gas engine compartment is much higher than in the case of diesel engines. The MAC systems, especially compressor shaft seal and driving belt, were not yet sufficiently adapted to the strong strains arising from the operation of gas engine.

IV.2.2 Solo buses vs. articulated buses

A comparison of articulated buses of both fuel types with single buses of both fuel types shows that the MAC leakage rate of articulated buses is significantly higher than that of single buses (3.60 kg/a vs. 1.68 kg/a).

Table 7: MAC leakage rates of solo vs. articulated buses

Bus Design	Buses	Checks (n)	Refill kg	kg/a	margin up	margin down
Solo (Diesel + Gas)	195	834	1,404	1.68	1.91	1.45
Articulated (Diesel + Gas)	114	433	1,559	3.60	4.21	2.99

The explanation given by the garage is difficult bridging of the joint with relatively long stretches of flexible hoses. These hoses are subject to a particular strain when the bus is in operation.

MACs in articulated buses have higher refrigerant charges than MACs in solo buses because they have two instead of one refrigeration circuit (two evaporators, one or two condensers) and sometimes even two compressors instead of one. Thanks to higher charges of MACs in articulated buses, the difference in the relative leakage rates is smaller than in absolute amounts. In the Kylindustri sample the average full charges are as follows.

Single buses 8.0 kg,
Articulated buses 11.8 kg.

Even after the elimination of the influence of different charges, the difference in leakage rates between single and articulated buses remains statistically significant, 20.5% vs. 27.9% respectively.

Single buses 20.5% ± 2.7%,
Articulated buses 27.9% ± 4.4%,
All buses 23.1% ± 2.4%.

IV.3 Leakage rates by bus manufacturers

The good quality of bus MAC systems cannot be attributed to either the vehicle manufacturer or the MAC maker. Both of them are involved in producing quality MAC systems and efficient operation.

As a rule, MAC makers supply the pre-fabricated roof unit with evaporator and condenser and, generally, the compressor. Bus manufacturers not only fit these components to the vehicle body but also install and connect pipes and hoses. It can be said, that MAC makers are in charge of the MAC components, bus makers are in charge of the MAC assembly.

The bus manufacturers in the sample are, first of all, manufacturers of chassis. The final assembly of buses, including the assembly of MACs generally takes place outside chassis plants, in body shops. The latter do not need to belong to the chassis maker but can be run by a different company that makes the final assembly of buses elsewhere and independent from the chassis builder. This implies that the body builders are and not the chassis makers are responsible for the quality of the MAC assembly.

Actually, there are two main vehicle concepts. The first is the complete integral bus, built and supported wholly by one manufacturer. This concept is widely used in major markets such as France, Italy and Germany. The second is the combination of a chassis built by one manufacturer with a body made by an independent builder. These vehicles are dominant in the British Isles and the Iberian and Nordic countries. (Jack Doug, European bus builders facing change. Eurotransport, 2005, nr 2, 38-42).

Two of the four bus companies in our sample are Swedish, another two are German. The buses from Germany were completed in German body plants which run under the ownership of the two bus makers EVOBUS and NEOMAN. Although the two Swedish bus makers VOLVO and SCANIA sell most of their chassis to independent body builders[19] they supply the Swedish market with buses that have been completed in Scandinavian body plants under their control or even ownership[20].

From this it follows that for the buses in our sample the bus manufacturers are fully responsible for the good quality of the MAC assembly.

All 309 buses are equipped with rooftop MAC systems. Because of the arithmetic preponderance of bus maker no. 1 in the sample, the vehicle engine and thus the compressor is mostly installed in the middle of the bus. All the other buses have rear-fitted compressors in the rear engine compartment.

The 309 different buses are broken down into makers of the chassis - see Table 8.

Table 8: Bus number and MAC leakage rates by bus (chassis) makers

	Number of buses	Av. MAC age at checks	Number of checks	Av. Leakage rate in kg/a
Bus Make 1	164	4.6	673	2.7
Bus Make 2	82	4.0	351	1.3
Bus Make 3	38	3.6	136	4.0
Bus Make 4	25	4.1	107	1.25

[19] Scania complete less than 800 of overall 6,000 annual bus and coach chassis in own bus body plants, in Sweden (before 2002), afterwards in Poland and Estonia. In the coach sector, Scania does not run own body shops but is closely cooperating with Europe's largest coachbuilder, Irizar in Spain.
[20] The majority of Volvo buses come from the Swedish body plant Säffle, and a considerable number from the Finnish body builder Carrus. These two companies were acquired by Volvo in 1981 (Säffle) and 1998 (Carrus), respectively. Only one Volvo bus was completed in Belgium (Van Hool). The majority of Scania Buses were completed by Carrus in Finland before the Volvo take-over, afterwards by Vest Buss in Norway.

At first sight, the annual leakage rates clearly differ by bus (chassis) makers. It should be added that the differences in age at check-up are small and not of relevance. A closer look into the report forms reveals that 80% (28 units) of the buses from maker 3, who exhibits the highest annual MAC leakage rate (4.0 kg/a), are articulated buses with gas power, while only 20% (7 units) are single diesel buses. As shown in Table 4, articulated gas buses have by far the highest leakage rate, with 4.55 kg/a.

If we weight the particular MAC leakage rates of articulated gas buses (4.55 kg/a as per Table 4) and of solo diesel buses (1.25 kg/a as per Table 4) with the shares of this bus maker in both bus types, almost exactly his specific leakage rate of 4.0 kg/a (Table 8) arises, namely 3.85 kg/a.

The same applies to the other three bus makers. Their leakage rates likewise agree with those leakage rates that can be calculated from their specific vehicle composition by fuel and design types.

From this it follows that the data analysis does not provide reliable indication that MAC leakage rates depend on the bus make. The differences in leakage rates can be ascribed to differences in bus design and fuel type.

IV.4 Leakage rates by MAC makes

The sample is scarcely suited to identify differences in leakage rates of MACs from different makers. From all 309 vehicles, 238 (77%) come from only one MAC maker (no. A) who is the market leader in Scandinavia. In the sample, he dominates solo diesel buses 90%, articulated gas buses even 100%.

Table 9: Number of bus MACs by different makers

MAC make	Number of MACs	thereof ex-works MACs	thereof retro MACs
Make A	238	220	18
Make B	43	28	15
Make C	17	-	17
Make D*	11	10	1

* No. D is not an individual MAC maker but a collective category for 5 makers with only small representation in the sample.

The number of cases of makes other than make A is too small for sensible statistical analysis on significant differences. At the best, concerning 30 ex-works MACs in solo gas buses a comparison between Make A and Make B could be meaningful, and concerning 30 retrofit MACs in old articulated diesel buses the MAC leakage rates of A, B, and C could be compared with each other.

In the context of this study, these two cases are of minor interest and importance. Apart from that, the differences in leakage rates are not significant, neither in absolute amounts nor in percentages. As a consequence, these comparisons are not presented here in detail[21].

[21] Of some interest might be the technical explanation of the Kylindustri manager for the (nominally) high leakage rate of MACs in solo gas buses from Maker B. In order to save place, the systems are not driven by a compressor of usual size but by two smaller ones (dual compressor system). The latter are connected to the vehicle engine by only one belt instead of two. This MAC design is said to be more leak-prone than one-compressor systems with one-belt drive, in connection with intense heat.

IV.5 Age dependency of annual bus MAC leakage rates

So far bus MACs were analysed under several aspects; in doing so the time-span 1996-2005 was taken as a whole. It was secondary when buses were commissioned or retired. These conditions are dropped now.

This section explicitly deals with the question whether there is a dependency of leakage rates on the date of putting MACs into operation, and if yes, how strong this dependency is.

IV.5.1 Annual leakage rates of older and newer systems in kg/a

A dependency on the time of installation as well as on the length of operation can clearly be seen from a comparison of buses whose MACs were installed before 2000 (old MACs) with buses with a MAC from 2000 onwards (new MACs). The year 2000 is chosen as boundary because MAC makers claim that two vital technical improvements had been carried out by the end of the nineties. The first is a drastic, namely more than 80%, replacement of permeable flexible hoses by metallic pipeline. The second is leak-tighter connections between individual components and between different line-sections (e.g. press instead of reusable fittings, flange connections instead of simple flares, use of threads with o-rings, and suchlike). See box overleaf.

Table 10 presents three age categories of bus MACs.

I. MACs installed 1995-1999 and checked 1996-2000 (224 buses).
II. MACs installed 1995-1999 and checked 2001-2005 (additional 16 buses[22]).
III. MACs installed 2000-2004 and checked 2001-2005 (68 buses).

Category I) and II) include the older MACs. I) contains those which were inspected in the time-span of maximum five years after installation, II) includes the older MACs of the same installation period, however being checked (again) later, namely in the period of six to ten years after installation. Under III, there are the newer systems from 2000 onwards, which were checked within their first operation years, i.e. until 2005.

Table 10: Leakage rate of old and new bus MACs in kg/a

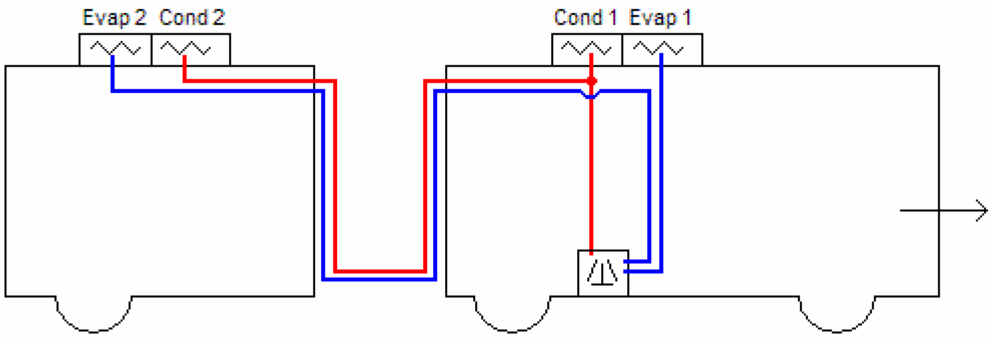
Time of MAC installation and check-ups	Number of checks	Av Leakage kg/a	Margin	Up to	Down to	Av. age at checks
I. Installed 1995-1999, checked 1996-2000	569	2.07	± 0.37	2.44	1.70	2.7
II. Installed 1995-1999, checked 2001-2005	568	2.94	± 0.44	3.37	2.50	6.3
III. Installed 2000-2004, checked 2001-2005	130	0.92	± 0.40	1.32	0.52	2.2
All MACs	1,267	2.34	± 0.26	2.60	2.08	4.3

[22] Additional 16 units mean that this number of older MACs was first checked in 2001-2005. 179 units of the first inspection period (1996-2000) were checked again in the 2001-2005 period. Thus, the old MACs of category I are not always identical to those in category II.

Reduction of flexible hoses from 39 to 12 metres

Before 2000: Volvo B10MA; 2 x Suetrak AC 132

Overall length of lines (all are hoses) ~39 m; refrigerant charge 14 kg.

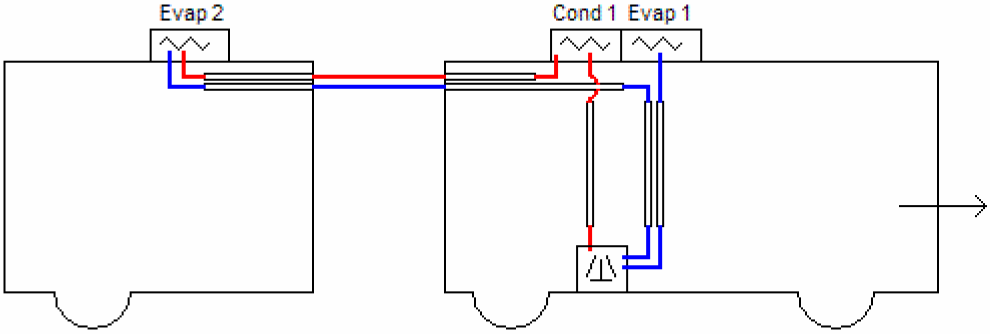


1. Hot gas from compressor up to condenser 1 on front roof (red - 3 m)
2. Suction gas from evaporator 1 on front roof back to compressor (blue - 3 m)
3. Hot gas from front roof (flowing off before condenser 1) across bottom of joint to condenser 2 on rear roof (red - 5 x 3 m)
4. Suction gas from evaporator 2 through joint bottom to front roof and down to compressor (blue - 6 x 3 m)

After 2000: Volvo B12MA; 1 x Suetrak AC 363

- No rear condenser; direct liquid supply from front condenser
- Route from front to rear roof across top of joint saves 12m
- Copper pipes where flexibility not necessary

Length of pipes 15 m, length of hoses 12 m; refrigerant charge 9 kg.



1. Hot gas from compressor up to condenser (red – pipe 1.8m/hose 1.2m)
2. Suction gas from evaporator 1 back to compressor (blue - pipe 1.8m/hose 1.2m)
3. Liquid from condenser across joint topside to evaporator 2 on rear roof (red – pipe 4.8m/hose 4.2m)
4. Suction gas from evaporator 2 across joint top to front roof and down to compressor (blue – pipe 6.6m/hose 5.4m)

Although new design requires 12 pipe-hose-connections, leak-tightness is improved: Replacement of flares by flanges, of re-usable by press fittings, use of or-rings for all threads (8 flanges for hot and suction gas, 4 threads for liquid).

Like Table 10, Diagram 3 shows that the differences in leakage rates between the three categories are statistically significant.

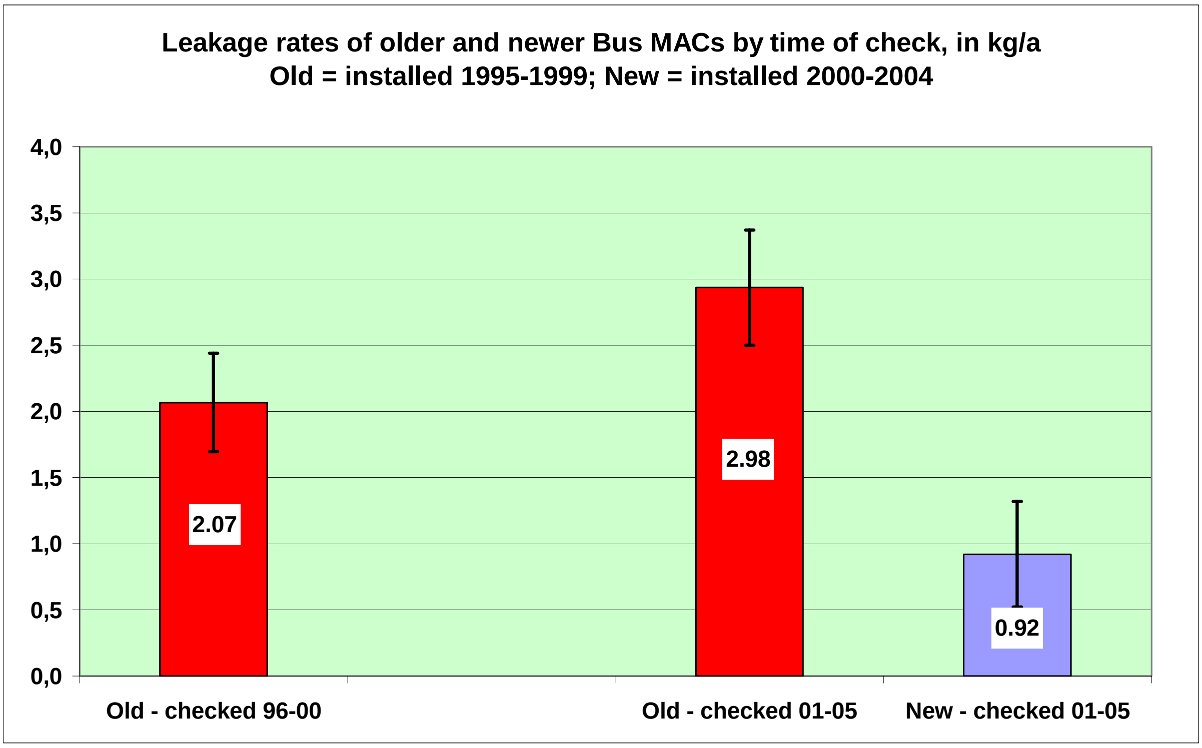


Diagram 3: Visible spaces between the error bars of the annual leakage rates of the three bus age-classes indicate that the differences between old buses, checked 1996-2000, and old buses, checked 2001-2005, are statistically significant; this also applies to the low leakage rate of new buses from 2000 onwards (checked 2001-2005) with just 0.92 kg/a.

Table 10 presents two important results.

Firstly, the average leakage rate of new MACs sub category III (installed 2000-2004) figures only 0.92 kg with a margin of ± 0.40 kg/a. This is far and significantly below the corresponding values of the older MACs. MACs of category I (installation 1995-1999; checks 1996-2000), which were installed and checked five years earlier than MACs of category III, exhibit a markedly higher leakage rate of 2.07 kg/a ± 0.37.

Category III and category I include MACs of different installation periods, but both were checked in the first five years of their operation. The statistically significant difference in the absolute leakage rates between MACs from before 2000 and MACs from after 2000 verifies the thesis of MAC makers about substantial improvements in leak-tightness of newer bus MAC systems.

Secondly, there is also a large difference in absolute leakage rates between same-aged MACs (installed 1995-1999) when checked the first five years and when checked the second five years of operation. The statistically significant difference between MACs of category I with 2.07 kg/a and category II with 2.98 kg/a clearly indicates that the leakage rates increase with growing age of the systems.

Incidentally, Table 10 demonstrates clearly that a simple top-down approach fails to understand inner differences of the average values shown in Table 3. The there *presented 2.34 kg/a average leakage rate, or the 2005 top-down value of 2.16 kg/a, consists of three very different averages by MAC sub categories I, II, and III.*

In conclusion, bus MAC leakage rates depend not only on technical parameters, i.e. improvements to former state of the art (comparison of III to I), but there is also an acceleration in leakage as the system ages (comparison of II to I).

Thus, age dependency means both lower leakage rates of newer systems compared to older ones, and increasing leakage rates of older systems through ageing.

If not only old MACs are subject to "ageing" (acceleration in leakage with growing age) but also new systems, the assumption could be drawn that the leakage rate of modern MACs, which averages 0.92 kg/a now, will increase over 1 kg/a in the next years. Such a rise in leakage rates is a hypothesis that cannot be proved currently.

In relative terms (Table 11) the leakage rate of 13.7 ± 5.7% of new MACs (category III) is significantly lower only vs. MACs of category II with 26.8 ± 3.6%, i.e. vs. older systems checked in the same period of time 2001-2005. Compared to old MACs checked in their first five years (1996-2000), a nominal difference in average values exists with 13.7% vs. 21.5%; this is, however, below statistical significance on a 95% confidence level. Thus, only the ageing effect can be validated but not the improved leak tightness of new systems compared to old ones.

Table 11: Percentage MAC leakage rates of the three age categories of buses

Time of MAC installation and service	Number of checks	Full charge	Av. Percentage Leakage	Margin	Up to	Down to
I. Installed 1995-1999, checked 1996-2000	569	9.4	21.5%	±3.6%	25.1%	17.9%
II. Installed 1995-1999, checked 2001-2005	568	9.9	26.8%	±3.6%	30.3%	23.2%
III. Installed 2000-2004, checked 2001-2005	130	6.6	13.7%	±5.7%	19.4%	7.9%
All MACs	1,267	9.3	23.1%	±2.4%	25.4%	20.7%

Altered refrigerant charges are the reason why the differences between percentage leakage rates are smaller than between absolute leakage rates. From Table 11 it can be seen that average full charges have decreased from 9.4/9.9 kg to 6.6 kg.

Thus, reduction in absolute leakage rate (kg/a) as per Table 10, results only partially from enhanced leak tightness of the systems. To a considerable part it is caused by smaller refrigerant charges.

This statement implies no debasing of the achievements of MAC engineers. Both improved tightness and lower charges, given unchanged refrigeration capacity, are measures that effectively contribute to reduction in greenhouse gas emissions.

IV.5.2 Annual MAC leakage rates of older and new diesel buses

The new MACs of our sample are exclusively fitted to diesel buses. This is because the local chief operator has acquired new gas buses only without air condition since 1999. Gas buses, as was shown, exhibit significantly higher MAC leakage rates than diesel buses of both design types. In order to adapt the comparison of older to newer MACs to these circumstances, in this sub-section gas buses (single and articulated) are removed from the sample.

As expected, this removal leads to a reduction in leakage rates of older buses. This can be read off from Table 12.

Table 12: MAC leakage rates of different-aged diesel buses (excl. gas buses)

Time of MAC installation and service	Number of checks	Average Leak rate kg/a	Margin	Up to	Down to
I. Installed 1995-1999, checked 1996-2000	461	1.66	± 0.34	2.00	1.32
II. Installed 1995-1999, checked 2001-2005	406	2.51	± 0.50	3.01	2.01
III. Installed 2000-2004, checked 2001-2005	130	0.92	± 0.40	1.32	0.52

The comparison of different aged diesel buses with each other shows that the difference in leakage rate between new MACs (III.) and older MACs of both checking periods (I. and II.) is not as large as in Table 10 (all types of buses). Nonetheless, these differences are statistically significant. The error margins do not overlap.

As a consequence, the double age dependency can be attested also to diesel buses alone: both lower leakage rates of new systems vs. older systems and increasing leakage rates of older systems through ageing.

Table 13: Percentage leakage rates of the three age categories of diesel buses

Time of MAC installation and service	Number of checks	Full charge	Av. percentage Leakage	Margin	Up to	Down to
I. Installed 1995-1999, checked 1996-2000	461	8.9	18.7%	3.7%	22.4%	15.1%
II. Installed 1995-1999, checked 2001-2005	406	9.3	23.2%	4.0%	27.3%	19.2%
III. Installed 2000-2004, checked 2001-2005	130	6.6	13.7%	5.7%	19.4%	7.9%

As shown afore for all buses including gas buses, in diesel buses the differences in relative leakage rates are likewise smaller than in absolute leakage rates. This convergence-effect is a result of the marked drop in full refrigerant charges by almost 30%. Although there are still nominal differences between the three averages, none of them is statistically significant. Even leakage rates of new systems installed 2000-2004 slightly fail statistical significance vs. either of the old MAC categories.

IV.5.3 Annual MAC leakage rates of older and new solo diesel buses

Finally, leakage rates of the 161 solo diesel buses, which are the majority not only of diesel buses but of all buses in the sample, are presented. See Table 14.

The amount of nominal leakage rates is very low, averaging 1.25 kg/a for all 161 solo vehicles. Although the differences between the three age-categories fail statistical significance even in absolute terms (kg/a), the quantitative relationship between the three mean values shows the same structure as in the two preceding comparisons:

category II exhibits the highest value (1.37 kg/a), and the average of category III (new systems) is the lowest, figuring even below 1 kg/a (0.80 ± 0.38 kg/a).

Table 14: MAC leakage rates of different-aged solo diesel buses (excl. articulated)

Time of MAC installation and service	Number of checks	Average Leak rate kg/a	Margin	Up to	Down to
I. Installed 1995-1999, checked 1996-2000	306	1.30	± 0.35	1.65	0.96
II. Installed 1995-1999, checked 2001-2005	263	1.37	± 0.37	1.74	1.00
III. Installed 2000-2004, checked 2001-2005	104	0.80	± 0.38	1.18	0.42
All Solo Diesel Buses	673	1.25	± 0.22	1.47	1.03

It is certainly one of the most important results of statistical analysis of leakage rates that a reduction below 1 kg/a is possible for new MAC systems in buses.

V. The Annual Leakage Rate of Coach Air-Conditioners

This chapter considers first the overall annual fleet leakage rate (sample leakage rate) over the 1996-2005 periods, which is taken as a whole. Going further under these conditions, differences in MAC technologies are analysed, especially between standard rooftop systems and integrated split systems. Afterwards, it is examined if different coach makes and different MAC makes exhibit differences in leakage rate. In the final section, we look into the age dependency of leakage rates.

V.1 Overall leakage rate of the 1996-2005 checked coaches: 1.50 kg/a

As mentioned in Chapter III, in the ten-year time-span 1996-2005, 115 different coaches were brought to the Kylindustri MAC garage for annual routine check or, additionally, because of a problem with their MAC systems. If a coach visited the garage more than once in one calendar year, multiple visits per year were combined in one; the same summing-up was done with multiple refrigerant top-ups in one year.

The evaluation of the 347 (308) coach MAC report forms shows the picture as per Table 15.

Table 15: Total of 1996-2005 coach MAC checks by year, number, and annual refills

	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	**Total**
Refill in kg	4	3	1	20	46.3	36	57.5	65.3	148.2	81.5	**463**
Check-ups	6	19	20	26	22	30	37	47	57	44	**308**
kg/ann. check	0.67	0.16	0.05	0.77	2.10	1.20	1.55	1.39	2.60	1,85	**1.50**
Age at check	1.8	2.1	2.7	3.3	3.5	3.9	4.5	5.3	5.6	5.6	**4.4**

Source: record forms of the garage Kylindustri in Mantorp, South-East Sweden.

Over ten years, a totality of 308 annual inspections were carried out (actually 347, before combination), if 17 checks of R-12 systems are not considered. On average, each bus of the sample had a check on its MAC about three times within the 1996-2005 periods (308/115). The refrigerant quantity refilled within the ten years amounts to 463 kg R-134a.

Looking at the whole ten-year period, the average leakage per checked MAC coach figures 1.50 kg/a (error margin ± 0.42). This is markedly lower than the average leakage rate of buses with 2.34 kg/a. This is, certainly, the most important difference between MACs of coaches and buses when looking at the whole samples.

The MAC leakage rate of 1.50 ± 0.42 kg/a, which results from 308 annual coach checks (at 115 different vehicles) over the whole 1996-2005 period, is achieved as an average of 239 annual "zero-leaks" and 69 actual annual leaks > 0 kg.

The average value of these 69 annual leakages is 6.6 kg. Together with the 239 no-leak cases (0 kg), the 69 actual leaks form the above average of 1.50 kg/a.

Diagram 4 shows that the leakages widely scatter by kg/a. (Please note that the 239 no-leaks are not reproduced true to scale in the following graph but end at 100.)

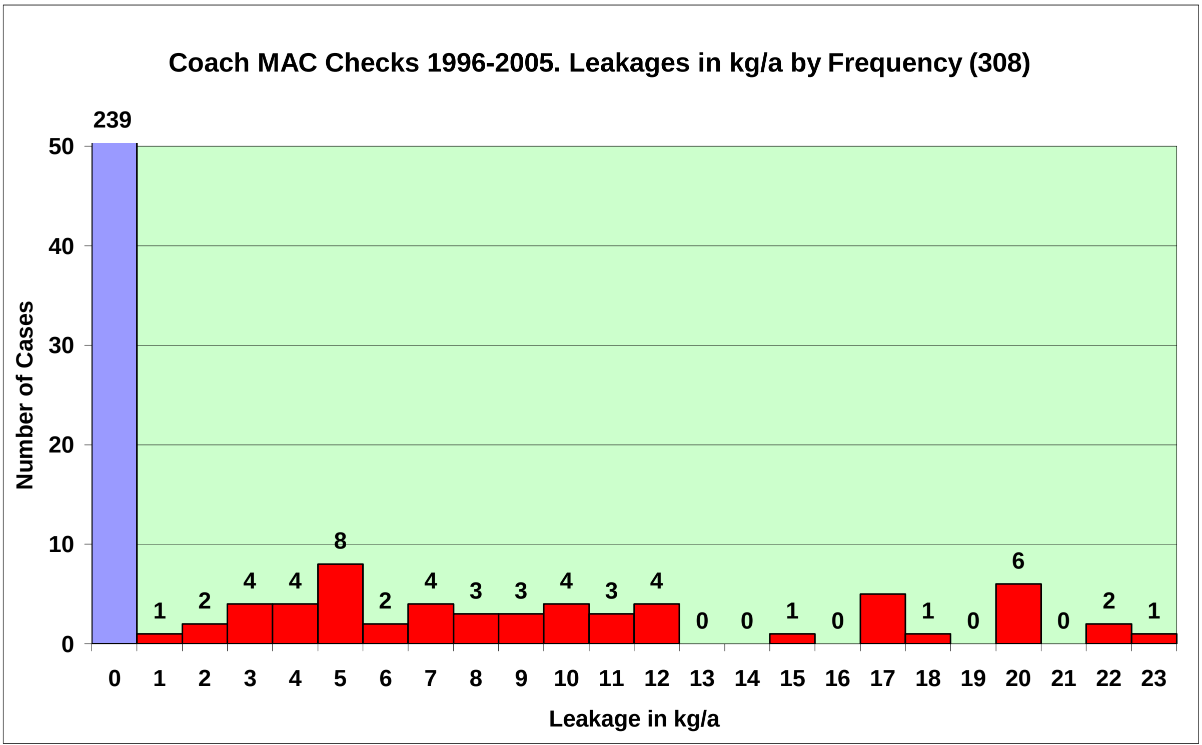


Diagram 4: The average annual MAC leakage rate of the coach sample of 1.50 kg/a is an arithmetic figure which consists in reality of a large number of "zero-leaks" and a smaller number of highly diverse actual leaks varying from <1 to more than 20 kg/a.

The average full charge of the checked coaches is 9.6 kg (buses: 9.3 kg). The percentage leakage rate of coach MACs is only 15.2 ± 4.1% compared to 23.1% of bus MACs. (Similar to buses, age at check time of coaches averages 4.4 years).

The distribution of the refills over the totality of coaches is even more uneven than in the case of buses. Averaging the 1996-2005 periods, 78% of the annual check-ups were carried out with no refill (for comparison, this quota was only 70% in buses). This means that only 22% of the coaches (buses: 30%) visiting the garage for annual inspection were refilled in the same year. From 1996 to 2005, this quota constantly grew from 9% in the 1996-1999 periods to 27% in 2000-2005. This is also noticeably different to buses, which exhibit a constant quota over the entire 1996-2005 period.

In real terms, the top-up quantity per faulty MAC was not 1.5 kg, but 6.6 kg, which is two thirds of one total fill (9.6 kg) per detected leak. In the written service records, partly top-ups numerically prevail over refills of empty systems by 41 to 31; by mass, the relation of partly to complete refills is inverse with 138 kg/325 kg (30%/70%).

As already noted, on an average every year 78% of the coaches visiting the garage for their MAC were not refilled. Within the ten service years there were even 70 of the 115 vehicles, i.e. 61%, which did not need any top-up. This figure is much higher than that of buses of which only 39% did not need to be refilled over the same time-span. The leakage rate of coach MACs is a result of only 45 refilled MACs.

It must be pointed out that Table 15 (kg/annual check) shows the annual leakage rate of the coach sample as a whole, disregarding any differences in design, and - what is even more important - time of installation. Nonetheless, 1.5 kg/a express the actual leakage rate of the whole coach MAC sample for the 1996-2005 period.

V.2 Reasons for lower MAC leakage rate of coaches compared to buses

While buses could be analysed by vehicle design and fuel type, and showed significant differences, this categorisation is not meaningful for coaches[23] because all coaches are single diesel vehicles.

In the light of this fact, it is not surprising that the MAC leakage rate of the coach fleet does not differ significantly from the corresponding value of the bus fleet if only single diesel vehicles are compared with each other. The average MAC leakage rate of single dieses buses was 1.25 ± 0.22 kg/a (as per Tables 4 and 5); this figure is close to the coach leakage rate of 1.50 ± 0.42 kg/a.

Apart from the 'single-diesel' property, a further reason for the comparably low leakage rate of coach MACs might be the steady and saving driving style over long distances. This is quite different to buses, especially to city-buses, which are involved in straining stop-and-go and doors-open-and-close traffic.

V.3 Difference between roof-top and other MAC design

As regards MAC design, coaches exhibit a wide variety of technical solutions. While all the buses in the sample are equipped with rooftop systems, the coach sample includes also some rear-fitted compact systems, and a number of integrated split systems in one-deck coaches, and even in two double-deck coaches. There is also a two-loop MAC in the sample where a cold-water circuit is chilled by a primary refrigerant circuit.

MACs of the integrated split type show by far the highest particular leakage rates.

Compared to rooftop systems, split systems need, due to the long distance between AC unit (compressor + condenser) and the evaporators that are distributed across the whole coach-body, more and longer refrigerant lines, more heat exchangers, and more joints – what increases the refrigerant charge and the leakage risk.

Table 16: MAC leakage rate of rooftop, compact, and integrated split systems

MAC technology	Number of coaches*	Number of checks*	Av. Leak rate kg/a	Margin	Up to	Down to	Age at check
Standard rooftop system	84	215	1.05	± 0.42	1.47	0.64	4.0
Integrated split in single and double-deckers	20	61	3.24	± 1.28	4.52	1.96	6.5
Rear-fitted compact systems	7	25	[0.94]	± 1.44	2.38	- 0.50	3.4
All systems	111	301	1.49	± 0.42	1.91	1.06	4.4

* Three MACs in the sample were not named in the report form and could not be identified later on. The two-loop system is not included in Table 16.

The average sample leakage rate (1.50 kg/a) would be considerably lower without MACs of split design, see Table 16.

[23] Although the coach length varies considerably from < 9 to almost 15 metres this variety also exists with buses and is not assumed to affect the leakage rate substantially.

From a statistical point of view, the leakage rate of integrated split systems is significantly higher than that of rooftop systems, with 3.24 ± 1.28 kg/a vs. 1.05 ± 0.42 kg/a. Compact systems, which show a numerically low leakage rate, are too small in number for meaningful statistical analysis.

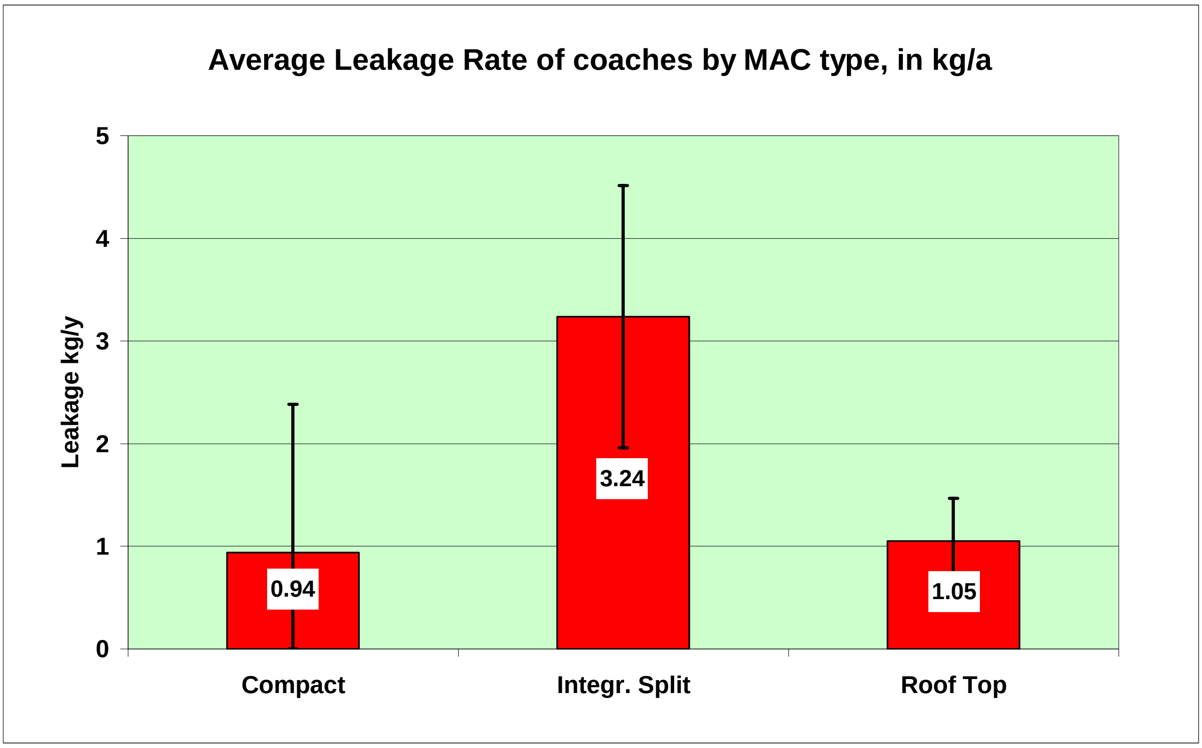


Diagram 5. Leakage rates of coaches widely vary by MAC design. Integrated split systems show a significantly higher average value with 3.24 kg/a compared to only 1.05 kg/a of roof top systems (no overlapping error bars). Compact systems, which show a numerically low leakage rate of 0.94 kg/a only, are too small in number for meaningful statistical analysis.

It is true that in the sample the coaches with split MAC systems are two-and-a-half years older (age at checks) than the other vehicles, with 6.5 years on an average compared to 4.0 and 3.4, respectively (see Table 16, last column). Fourteen of the 21 systems originate from 1987 to 1995, so that refrigerant lines are almost completely flexible hoses; nine of these 14 old coaches are even converted R-12 systems.

Nevertheless, the age difference is not so high that the higher leakage rate of split systems had to be put into question.

V.4 Differences in leakage rates by MAC makes and coach makers

V.4.1 Introduction

Introducing, the same comment as in the chapter on bus MACs has to be made, namely that both MAC maker and vehicle manufacturer are involved in the good quality of air-conditioners. While specialised MAC makers supply pre-fabricated components of the refrigeration circuit, specialised coach makers fit them to the body and link them to one another with pipes and hoses. Therefore, the same conclusion as in the bus chapter can be drawn: MAC makers are more in charge of the MAC components; bus makers are more in charge of adequate assembly of the system.

One more word should be said about vehicle manufacturers and body builders. Like bodies of buses, most bodies of coaches in the sample are built by body shops under ownership of the leading bus companies VOLVO, EVOBUS, and NEOMAN[24]. The exception is SCANIA. Overall, 21 of the 23 coaches with chassis from this manufacturer are assembled in Spain by IRIZAR, Europe's largest independent coachbuilder. As no other coach makes of the sample are assembled there, Scania and Irizar can be treated as one maker, in this section[25].

First, we give an overview of the make-structure of coaches and of MACs in the sample before moving on to their differences in MAC leakage rates.

From Table 17 it can be seen, how many different makes of coaches and of MACs are included in the sample as well as which and how many MACs are fitted to each of the coach makes.

Table 17: Coaches and MACs by makes

Makes	Sütrak	Konvekta	Hispacold	Webasto	Thermoking	Other*	Total
VOLVO	29			3	4	1	37
SCANIA**	8		12	1		2	23
NEOPLAN	24	3				2	29
MAN		2					2
SETRA		2		4		4	10
MB		6		2	1		9
BOVA	3						3
Jonckheere				1			1
Drögmöller				1			1
Total	64	13	12	12	5	9	115

* 'Other' include 4 x Thermal, 1 x ATR, 1 x Finnotso, and 3 x "no indication".
** Only chassis is Scania, body is from Irizar in Spain, were these MACs were installed.

As the first and last columns show, the 115 coaches come half from Sweden, namely 37 VOLVO and 23 SCANIA, and almost half from Germany, namely 31 from NEOMAN (Neoplan + MAN) and 19 from EVOBUS[26] (MB, SETRA). The remaining three are Dutch BOVA and Jonckheere and German Drögmöller (today VOLVO).

In Table 17, columns 2 - 6 reproduce the 115 coach MACs by their makes. Leader in the sample is Sütrak (Carrier-Sütrak as of 1997) which is installed in more than half the coaches (64), with focus on VOLVO and NEOPLAN. The second-largest MAC make in the sample, Konvekta, is fitted to 13 German coaches, followed by Webasto (12) with MACs in both Swedish and German coaches, and Hispacold (12) which is installed in Scania/Irizar exclusively. Finally, there are five MACs from Thermo King.

[24] Unlike buses, some coaches of German make are not assembled in Germany but in Turkey.
[25] For the remaining 5 coaches (3 x BOVA, 1 x Jonckheere, and 1 x Drögmöller) the chassis could not be identified although the chassis of the three BOVA (Futura) likely stem from DAF.
[26] At the time of their commissioning most of the NEOPLAN coaches did not yet belong to NEOMAN, nor did SETRA belong to DaimlerChrysler's EVOBUS. The classification is made here for simplicity.

V.4.2 Leakage rates by MAC makes

The calculation of average sample leakage rates for the four most-represented MAC-makes (Carrier-Sütrak, Konvekta, Webasto, and Hispacold) shows statistically significant differences from each other. (For confidentiality, the four makes are encoded, and numbers of units or check-ups are not given).

Table 18: Average leakage rates by MAC makes (incl. split systems)

MAC make	Average leakage kg/a	Margin	Up	Down	Age
Make A	1.98	± 0.62	2.60	1.36	3.61
Make B	1.12	± 1.13	2.25	- 0.02	4.05
Make C	0.38	± 0.38	0.76	- 0.01	4.03
Make D	0.50	± 0.64	1.14	- 0.14	3.06

Note: The makes Carrier-Sütrak, Konvekta, Webasto, and Hispacold are encoded.

The leakage rates of makes B, C, and D are not significantly different from each other. However, against make A (1.98 ± 0.62), make C (0.38 ± 0.38) and D (0.50 ± 0.64) show statistically significant differences. There is no overlapping of the margins with down to 1.36 and up to 0.76 and 1.14, respectively.

There are no relevant differences in age between the four makes. However the figures conceal differences in technical design of the MACs that the makers have supplied.

On second sight it becomes apparent (what cannot be proved here for confidentiality), that make A alone comprises 75% of the integrated split systems, for which Table 16 shows extraordinary high average leakage rates of 3.24 kg/a. After exclusion of split systems from make A, the average leakage rate of make A drops from 1.98 ± 0.62 down to 1.29 ± 0.57, and the new error band ranges from 0.72 to 1.86. Significant differences vs. make C and D do no longer exist.

In conclusion, different leakage rates by MAC makes are ascertained in coaches not because of the makes themselves but because of different technologies of the MACs.

V.4.3 Leakage rates by coach makers

The calculation of average sample leakage rates for the four leading coach-maker groups (VOLVO, SCANIA-IRIZAR, NEOMAN, EVOBUS) results in nominal values of average leakage rates that vary widely from 0.67 to 2.36 kg/a. But statistically significant differences do not exist. (For confidentiality, the four groups are presented anonymous, and numbers of coaches or check-ups are not given).

Table 19: Average leakage rates by coach maker-groups

Coach maker	Average leakage kg/a	Margin	Up	Down	Age
Maker 1	2.36	± 1.15	3.51	1.21	4.5
Maker 2	0.67	± 0.60	1.27	0.07	3.7
Maker 3	0.99	± 0.66	1.65	0.34	4.6
Maker 4	1.71	± 0.77	2.47	0.94	4.4

Although the error bands of all four leakage rates overlap, the difference between Maker 1 and Maker 2 fails statistical significance only by a narrow margin.

V.5 Age dependency of coach MAC leakage rates

So far, the time-span 1996-2005 was taken as a whole. It was secondary when coaches and their MACs were commissioned or retired. Like section IV.5 on buses, this final section explicitly deals with the timely, i.e. age dependency of coach MAC leakage rates on the year of taking MACs into operation.

V.5.1 Leakage rates of older and new coach MAC systems in kg/a

In Chapter IV on bus MACs a double age dependency was ascertained.

Bus MACs checked in the first five years of their operation differ from each other in leakage rate pursuant to their respective installation period. Systems installed before 2000 (1995-1999) exhibit higher leakages than systems installed after 2000 (2000-2004). This reduction in amount expresses advanced leak tightness of newer MACs compared to older ones thanks to technical improvement of which the substantial shift in length of flexible vs. metallic refrigerant lines needs to be highlighted. At the end of the 1990s, the reduction of permeable flexible hoses in overall piping had ended for the time being, so that the year 2000 was taken as a boundary.

There is still another kind of age dependency (called ageing effect), which was identified in Chapter IV. It became apparent that bus MAC systems installed in the period 1995-1999, showed a significantly higher leakage rate at later inspections (2001-2005) compared with early check-ups (1996-2000).

Table 20 presents three age categories of coach MACs.

I. MACs installed through 1999[27] and checked 1996-2000 (40 units).
II. MACs installed 1995-1999 and checked 2001-2005 (additional 33 units)[28].
III. MACs installed 2000-2004 and checked 2001-2005 (42 units).

As a consequence of the calculation of particular average values (with error margins), the same structure as in buses emerges in coach MACs only if category II is compared with category I. The ageing effect of systems installed 1992-1999 becomes apparent.

Table 20 shows that there is a statistically significant difference in absolute leakage rates between same-aged MACs (installed 1992-1999) when checked their first five years and when checked their second five years of operation. Average leakage rate of the former is only 0.78 ± 0.55 kg/a, the value of the latter is 2.16 ± 0.73 kg. There is no overlapping of the two error margins. The difference in absolute amounts clearly indicates that the leakage rate increases with growing age of the systems.

[27] From the 43 older coaches with check-ups before 2000, five have ex works 134a MACs from 1992-1994. Therefore, installation period is not exactly 1995-1999. This is meant by "through 1999".
[28] Additional 33 units mean that this number of older MACs was first checked up in 2001-2005. 20 units from the first inspection period (1996-2000) were checked again in the 2001-2005 period.

Table 20: Annual leakage rates of older and new coach MACs in kg/a

Time of MAC installation and check-ups	Number of checks	Av Leakage kg/a	Margin	Up to	Down to	Av. age at checks
I. Installed through 1999, checked 1996-2000	93	0.78	± 0.55	1.33	0.23	2.9
II. Installed 1995-1999, checked 2001-2005	137	2.16	± 0.73	2.90	1.43	6.6
III. Installed 2000-2004, checked 2001-2005	78	1.20	± 0.74	1.94	0.47	2.4
All systems	308	1.50	± 0.42	1.92	1.09	4.4

In conclusion, not only bus but also coach MAC leakage rates undergo acceleration in absolute leakage as the systems age (comparison of II. to I.)

If the ageing effect is assumed to be applicable also to new systems installed from 2000 onwards, leakage rates of more than 1 kg (current five-year average: 1.20 kg/a) must be expected over the next couple of years.

The second comparison, namely that of new MACs of category III (installed 2000-2004, checked the first five operating years), to the older MACs of category I, which were likewise checked the first five years of their operation time but were installed five years earlier (1995-1999) shows a surprising result. The older MACs do not only show no higher average leakage rate, but exhibit even a lower leakage rate with nominal 0.78 vs. nominal 1.20. (In buses, the corresponding values were 2.07 vs. 0.92). Although the difference of old vs. new coach MACs is statistically not significant, there is neither a clue that new coach MACs are more leak light than older MACs checked the first years of their operation.

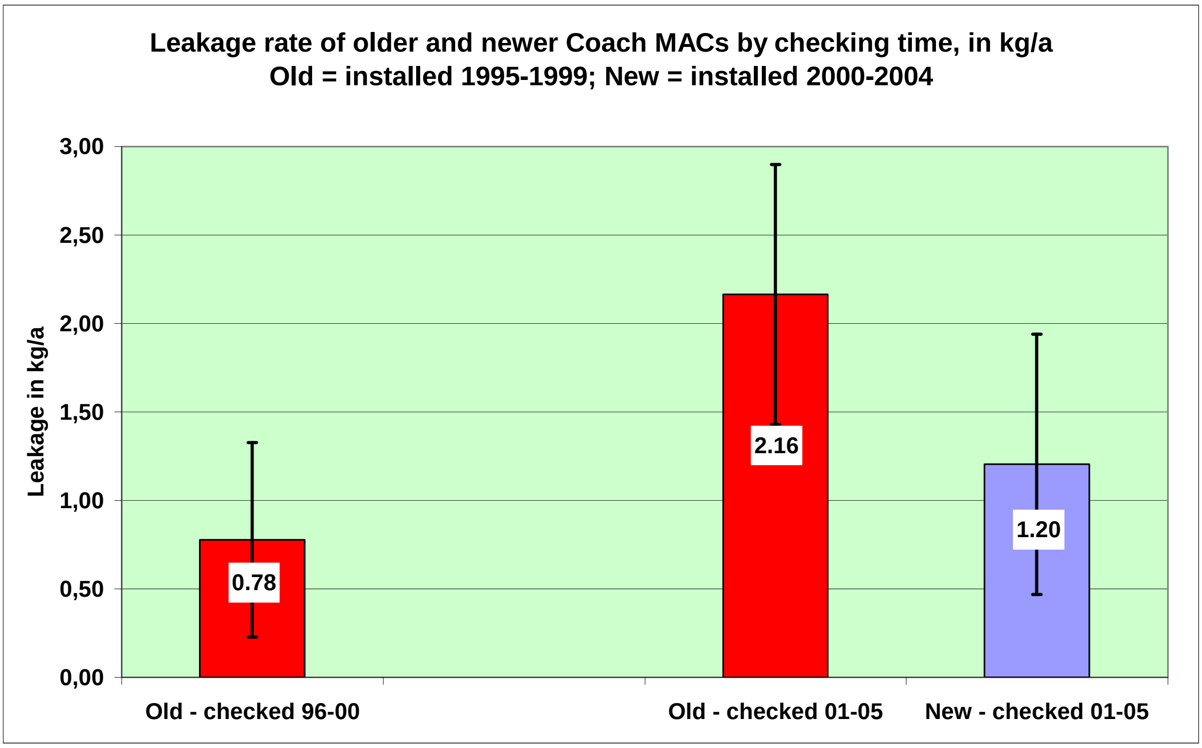


Diagram 6: Visible small spaces between the error bars of the leakage rates of the two old age-classes (red) prove that the differences between old coaches, checked 1996-2000, and old coaches, checked 2001-2005, are statistically significant, indicating the so-called ageing effect. The nominal leakage rate of 1.20 kg/a of new coaches checked 2001-2005 (blue) is not lower but higher than that of old systems, checked the first five years from installation.

Like Table 20, Diagram 6 shows that only the differences in leakage rate between the two categories of old MACs are statistically significant.

Compared to bus MACs, coach MACs installed before 2000 and after 2000 do not show a difference in leakage rates from each other that is qualified for proofing the thesis on substantial technical improvement in leak-tightness of new coach systems.

V.5.2 Annual leakage rates of older and new coach MACs in percent

In percentages, the result is in principle identical to that in absolute amounts (kg/a) because the average refrigerant charges are almost the same in each age category.

Table 21: Annual leakage rate of older and new coach MACs in percent

Time of MAC installation and check-ups	Number of checks	Av Leakage in percent	Margin	Up to	Down to	Average charge
I. Installed through 1999, checked 1996-2000	93	7.2	± 4.9	12.2	2.3	9.7
II. Installed 1995-1999, checked 2001-2005	137	21.7	± 7.3	29.0	14.4	9.9
III. Installed 2000-2004, checked 2001-2005	78	13.3	± 7.6	20.9	5.7	9.0
All systems	308	15.2	± 4.1	19.3	11.1	9.6

The difference in relative leakage rates between category I (old MACs checked 1996-2000) and category II (old MACs checked 2001-2005) is significant with 7.2% vs. 21.7% and no overlapping of the error bands. In contrast, the difference in leakage rate between new and old MACs, both checked over the first five operation years, is statistically not significant. The nominal leakage rate of old MACs is even lower than the corresponding value of new MACs.

Due to much the same level of full refrigerant charges in all three age-classes, the percentage leakage rates do not show different results compared to absolute leakage rates.

V.6 Similar leakage rate of new coach and bus MACs of approx. 1 kg/a

Based on the evaluation of approx. 2,000 Swedish report forms on MAC inspections and refills over the 1996-2005 periods, different statements on age dependency must be given as to MACs of buses and coaches in the EU.

In kind and structure, the age dependency of coach MACs is equal to the age dependency of bus MACs only as far as acceleration in annual leakage rates with growing age of the systems is concerned (ageing effect). In contrast, better leak tightness cannot be attested to MACs of new coaches compared to older coaches in their first five years of operation. This is quite opposite to bus MACs where new systems could be proved significantly less leaky than older systems (effect of technical improvement).

The statistical evaluation of the recorded refills leads to the insight, that the leakage rate of new MACs in - diesel driven - coaches is in the order of 1 kg/a (1.20 ± 0.74 kg/a) and herewith of the same magnitude as MACs of new buses with diesel drive, with 0.92 ± 0.40 kg. The percentage leakage rates are 13.3 and 13.7%, respectively.

It is certainly one of the most important results of this study that it is possible to reduce the annual leakage rates of modern bus and coach MACs to approximately 1 kg, or to approx. 13% compared with the full refrigerant charge. These values enable the European Commission to make projections of bus specific emission levels of HFC-134a beyond 2010 if no additional policies and measures are undertaken.

This is true even under consideration that use-phase leakages rates established on the basis of recorded refrigerant refills systematically underestimate real emissions because so-called regular leakage is included in refills only partially. Annex I of this report tries to quantify the possible increment in use-phase leakage rates if every regular leakage was accounted for. An inherent leakage understatement of more importance is associated with the fact that only refill records from a northern EU country were accessible to statistical analysis. As a consequence, leakage rates typical of southern parts of the EU and herewith of higher outside ambient temperature are not considered[29]. From both reservations it follows that the leakage rates established in this study must be considered being minimum values.

Several experts claim that the possibilities of improving leak tightness of bus and coach MACs are exhausted based on conventional refrigeration technology. Leakage rates below 1 kg/a, so they say, is the optimum with systems running on evaporation of halogenated refrigerants in a single closed circuit. Some of them see the future technology in two-circuit systems, some in the use of hermetically sealed systems with electric compressors, and others do not believe in a future of halogenated refrigerants at all. The latter speak for refrigerant substitution by natural fluids such as CO_2, which probably will be used in MACs of passenger cars within a short time.

[29] In the course of this study, experts from the MAC maker HISPACOLD communicated interesting "top-down" data from four Spanish fleet operators on annual refrigerant refills per bus (city and intercity buses and coaches) in 2005. The amounts are 4.8, 4.45, 5.14 and 5.25 kg/a, with average age of the fleets from 4 to 6 years. The corresponding 2005 value in our bus sample is 2.16 kg/a, age 4.3 years (Table 3). With all due reserve, the communicated data indicate leakage rates in the southern EU country Spain being considerably higher than in Sweden. Clearly, this data is not robust enough for conclusions on leakage rates typical of the entire EU-27. Nonetheless, they suggest taking the Swedish values as minimum values.

Annex I

Estimation of excluded regular leakage

So far, exclusively refills have served as indicators of use-phase emissions from MACs in buses and coaches. As known from Chapters IV and V, Diagrams 1 and 4, the leakage rate is calculated from a certain number of refills and a much bigger number of "zero-refills", i.e. inspections with no leak detected. Almost all recorded refills were carried out to compensate for refrigerant loss caused by a defect in the MAC system. In conclusion, emissions indicated by refills are essentially so-called irregular emissions. Unlike regular leakage, "irregular leakage" or emission is attributable to system failures induced by internal or external factors.

It is safe to assume that bus and coach MACs are subject to regular emissions, too. Regular leakage or emission takes place gradually from undamaged, functioning air conditioners. It is steady refrigerant loss through sealing, hoses, connections, valves, etc from every MAC over the entire use-phase.

1. Included regular emissions

A closer look into the Swedish records reveals that documented refills of bus and coach MACs do not only cover irregular emissions but also regular emissions to a certain extent. This may be illustrated by the following example.

A bus/coach with a 10-kg charged MAC, put into service in 1999, is inspected once a year from 2000 onwards. In 2000, 2001 and 2002 no refrigerant is refilled; in 2003, a total loss is detected, and 10 kg are refilled due to irregular leakage. The following table (Records I) shows the years of inspection in the first row, and below the recorded refills in kg. Three times "zero-refills" and once a refill of 10 kg are entered.

Records I

Inspection year	1999	2000	2001	2002	2003	2004	2005	Total
Refill in kg	start	0	0	0	10			10

If it is realistically supposed that in the 2000-2002 period regular emissions occurred too, amounting to e.g. seven percent per year, three times 0.7 kg had already escaped before the complete loss broke out in 2003. In conclusion, the latter does not total 10 kg but only 10 kg minus 3 x 0.7 kg, i.e. 7.9 kg. Real amounts of emissions, both regular and irregular, are shown in the next table (Real emissions I). Regular emissions are three times 0.7 kg; irregular emissions are 7.9 kg.

Real emissions I

Inspection year	1999	2000	2001	2002	2003	2004	2005	Total
Refill in kg	start	0.7	0.7	0.7	7.9			10

From this it follows that in 2003 not the full charge emitted but the full charge reduced by regular emissions of the preceding years. At the same time it is evident that the total of regular and irregular real emissions is equal to the full charge as recorded. The records do not correctly reflect the time of occurrence of real emissions. Nevertheless, they cover correctly the sum of real emissions (regular plus irregular).

The 2003 refill of 10 kg does not only include one case of irregular leakage but also three cases of regular leakage. This is the reason why in this report the term "irregular leakage" has been avoided deliberately so far when talking about refills. Strictly speaking, the recorded refills never cover solely irregular leakage but always include regular leakage in a smaller or larger part.

2. Additional regular emissions

While recorded refills always include some regular emissions, there are further regular emissions that are not included in refills.

This shall be explained for the years 2004 and 2005 using again the example of the bus/coach commissioned in 1999. Neither in 2004 nor in 2005 refrigerant was refilled so that the records show "0" for these two years. This can be seen from the next table (Records II).

Records II

Inspection year	1999	2000	2001	2002	2003	2004	2005	Total
Refill in kg	start	0	0	0	10	0	0	10

Actual 2004 and 2005 emissions were those shown in the next table (again assuming 7% annual regular leakage rate).

Real emissions II

Inspection year	1999	2000	2001	2002	2003	2004	2005	Total
Refill in kg	start	0.7	0.7	0.7	7.9	0.7	0.7	11.4

The records do not cover regular emissions of two times 0.7 kg (2004 and 2005). This is why the total in the records is smaller by 1.4 kg than the total of real emissions. The records accounting for refills only, cannot include 2004 and 2005 regular leakage because they end in 2005, before subsequently possible refills.

The Swedish records go until 2005 only and therefore often stop before the next possible refill or, which is particularly true of newer vehicles, before the first-ever refill. Hereby, regular leakages go unnoticed by documentation. This is also the case when vehicles are either decommissioned or transferred to other places of operation, before subsequent (recorded) refills.

In conclusion, regular emissions occurring in the 1996-2005 period are partly included in recorded refills ("included regular leakage") and partly excluded. We call the latter "additional regular leakage". To supplement refill-based use-phase leakage rate with regular leakage rate, not the total of "zero refills" have to be estimated quantitatively but only that part which represents additional regular emissions.

3. Roughly corrected use-phase leakage rates

Quantitative estimation of regular emissions is faced with the difficulty that the actual rate of regular emissions is unknown. Above, 7% per year was assumed because this is the order of magnitude known from MAC measurements on passenger cars and trucks. As a raw notion of the additional regular leakage is satisfactory under given circumstances, we retain the 7% leakage rate, conscious that it is only a plausible hypothesis. The amount could be 5% or 9% with equal justification[30].

- The 1,267 annual cases of the bus sample consist of 362 refills, 379 included regular leakages and 526 additional regular leakages.

- The 308 annual cases of the coach sample consist of 69 refills, 36 cases of included regular leakage and 203 cases of additional regular leakage.

Rating for each bus the recorded additional regular emissions with 7% of its full MAC charge, additional 0.26 kg/a must be accounted for. As a consequence, the leakage rate of the whole 1996-2005 bus sample increases from 2.34 to 2.60 kg/a, or by 11%.

Rating for each coach the recorded additional regular emissions with 7% of its full MAC charge, additional 0.44 kg/a must be considered. The leakage rate of the whole 1996-2005 coach sample increases from 1.50 to 1.94 kg/a, or by 29%.

It should be noted that there is no general increment, identical for every vehicle category or age class. This is because the ratio between refills, included regular emissions and additional regular emissions is different in each particular case. The more cases of additional leakage must be accounted for, the higher is the increment to the refill-based leakage rate. In new vehicles the share of additional regular emissions is inevitably higher than in old vehicles because the share of refills in inspections is still small during the first years of operation. It should be borne in mind that this is only true under the assumption of unchanged regular leakage rates.

The most interesting leakage rate values are reproduced in Table 22.

Table 22: Selected use-phase leakage rate values for buses and coaches after inclusion of all regular leakage, in kg/a (final state)

	Refill based leakage rate	Additional regular leakage rate	Total use-phase leakage rate
All buses ex 1995	2.34	0.26	2.60
Diesel buses ex 2000	0.92	0.32	1.24
Solo diesel ex 2000	0.80	0.27	1.07
All coaches	1.50	0.44	1.94
Coaches ex 2000	1.20	0.45	1.66

Please note that statistical error margins are not given for additional regular leakages. They are not considered meaningful as they are based on estimation only.

When we use the above presented approach for a rough estimate of the order of magnitude of regular leakage so far not included in recorded refills, we arrive at additional amounts varying from 0.26 to 0.45 kg/a. As percentages, these amounts increase the refill-based leakage rates by 10 to 33%. Leakage rates in MACs of new vehicles, corrected in this way, remain in the range of 1 kg/a.

[30] More than 10% per year are not likely. Refrigerant loss over forty percent of the full charge leads to a breakdown of the MAC system and thus induces a refill. With 10% annual leakage rate, 40% loss would be found after four years already, and this contradicts the occurrence of a considerable number of cases of even six consecutive annual inspections without refills, in the sample. Of the 309 buses, six show a sequence of six annual check-ups without refill, and three buses a refill-free sequence of even 7 annual checks. Although none of the 115 coaches exhibits a sequence of six or seven refill-free years, there are three buses that have not been refilled in eight consecutive inspection years.

Annex II

Issues of measurement uncertainty in recorded refills

In Chapter IV and V data uncertainty was already dealt with. Statistical error margins indicated how far average leakage rate values of the sample deviate from the true means of the population that the sample represents. The value 2.34 ± 0.26 indicates that the true value can vary from 2.08 to 2.60 kg/a – at a confidence interval of 95%.

In this annex, in terms of data uncertainty no longer the agreement between sample and real population is discussed but the measurement precision of the sample data itself. The question is how exactly refilling quantities entered in the garage records correspond to real refrigerant emissions; what size are possible discrepancies? This topic has to be covered particularly because MAC experts criticised the interim report for lack of transparency with respect to data precision and uncertainty.

1. Quantification of uncertainties associated with refill processes

In the underlying Swedish charging records there are the following three types of refills each of which shows specific sources and sizes of error.

1. Complete refill (total loss)
2. Partial refill (simple top-up)
3. Refill after extraction.

1.1 Complete refill (total loss)

At the latest, total refrigerant loss[31] is detected on pressure check with manometers, in the garage. After leak detection and repair and subsequent exchange of filter dryers the MAC system is charged to the norm charge specified by the manufacturer and labelled on spot or indicated in manuals. If the total loss is the first-ever since the vehicle was put into service, total emissions before inspection are equal to the initial MAC fill from the factory – however exactly the garage refill meets that initial charge. Interviewed MAC experts from bus makers agreed that the initial charge in the assembly plant may deviate from the norm charge by up to ± 250 grams. As a consequence, in the case of total loss the impreciseness of emissions obtained from the records is estimated ± 250 grams (see Table 23).

In the case of repeated total refrigerant loss of the same MAC, again an error margin of ± 250 grams is supposed. This is because the preceding garage refill is likewise assumed to deviate from the norm charge by this amount (see italicised paragraph).

After elimination of the leak the mechanic decants refrigerant from a 60-kg container into a portable 10-kg cylinder. He weighs out the proper quantity when this bottle is

[31] Total loss means empty refrigeration circuit. If a bus has two circuits (e.g. articulated buses), one empty circuit is treated as a case of total loss, even if the other circuit is still full. If both of them are empty, likewise one case of total loss is counted.

on scales (resolution 0.001 kg) and then increases the inside pressure to 5 bars by heating up the bottle in hot water for enough pressure difference even at the end of the MAC refill. He takes the bottle with him up the vehicle roof by means of a scaffold alongside the vehicle. Once he has attached the filling hose of the bottle to the MAC service port, he quickly charges the system with refrigerant in liquid state. The quantity actually poured-in hereby and the quantity written in the service records might differ from each other by ± 250 grams at the maximum.

Kylindustri garage. Before refilling, refrigerant HFC-134a is decanted from a 60-kg container into a portable 10-kg cylinder which is weighed out on the scale.

1.2 Partial refill (simple top-up)

Following the Kylindustri manager, partial refrigerant loss can be noticed on pressure check as drop in gauged pressure (first at low pressure side) if the refrigerant deficiency exceeds ten percent of the norm charge. This does not mean that every partial leakage over ten percent is immediately refilled. MAC systems continue operating with virtually unchanged performance if the refrigerant loss exceeds even thirty percent, if only the minimum refrigerant mass flows from receiver to evaporator.

Partial refrigerant loss is often caused by a defective component that can be exchanged without opening the whole refrigeration circuit; it is enough to shut off the upstream and downstream valves. After repair, the mechanic must estimate by naked eye how much refrigerant is necessary to compensate for the quantity that has been released through the leak (and additionally due to the service). It is not very likely that his refill exactly meets the norm charge because he does not even intend to do so. He wants the MAC to run properly, and this proper full charge is not firmly established but a quite flexible quantity, beyond minimum charge.

For determination of the discrepancy between quantity written in the service records and real emission two different processes have to be considered. First, there is a difference of recorded quantity from actual refill, which is estimated ± 250 grams (see section above). Second, the refilled quantity itself can substantially deviate from the real emission (refrigerant level compared with norm charge); this deviation is estimated 0.5 to 1 kg[32]. As a consequence, combined uncertainty of partial refill is assumed to total ± 1 kg.

Kylindustri garage. Rolling scaffolds are used for repair and recharge both aggregates of refrigerated vehicles and MAC systems on the roof of buses.

1.3 Refill after extraction

Unlike MACs of passenger cars or trucks, bus or coach MACs are rarely evacuated completely. Sometimes a small leak can be eliminated only if the entire system is emptied afore by means of a recovery station – for example in order to carry out leak detection with nitrogen.

[32] In the samples, average quantity of partial refills is 2.3 kg (coaches) and 2.9 kg (buses).

Impreciseness associated with the use of recovery/charging stations (weighing by inside scales, reading off from measuring cylinder) is quantified as follows.
- Impreciseness of suction extraction ± 100 grams,
- Impreciseness of refilling ± 100 grams,
- Initial factory norm fill ± 250 grams.

In the case of refills after extraction, the combined impreciseness of the recorded data is estimated ± 450 grams.

Table 23 gives the uncertainties for all three types of recorded refills.

Table 23: Uncertainties of the three types of recorded refills, in grams

	Complete refill	Partial refill	Refill w extraction
Initial factory fill	± 250		± 250
Preparation of filling bottle	± *250**	± 250	
Determination of deficit		± 750	
Recovery station			± 200
Overall inaccuracy	± 250*	± 1,000	± 450

* Uncertainty in preparation of filling bottle is relevant only for the second or subsequent complete refill,s not additionally but alternatively to initial factory fill.

2. Refill uncertainties of selected leakage rates of buses/coaches

Now we are able to quantify the uncertainty in annual leakage rates, as far as caused by deviations of recorded refills from real use-phase emissions. Such a quantification is carried out for the most important particular leakage rates established in Chapter IV and V of this report.

The refill-related uncertainty is not a general increment, identical for every particular leakage rate. It is a question of the quantitative ratio between the three types of refills that constitute a particular leakage rate.

When determining the refill-based uncertainty of e.g. the 1996-2005 bus MAC leakage rate of 2.34 kg/a the following factors have to be considered.

Total number of annual inspections is 1,267, thereof 362 refills:

285 x complete refills (specific uncertainty ± 250 g),
71 x partial refills (specific uncertainty ± 1,000 g),
6 x refill after extraction (specific uncertainty ± 450 g).

The addition of the products of specific uncertainties and number of their cases results in the combined uncertainty of all the refills underlying the 1996-2005 bus MAC leakage rate. This is 145 kg. Dividing this sum by the total number of annual inspections, the specific uncertainty of the annual 1996-2005 bus MAC leakage rate arises: ± 0.11 kg/a.

Following the same procedure, refill uncertainties are computed for annual leakage rates of diesel buses ex 2000, solo diesel buses ex 2000, all coaches, and coaches ex 2000. Table 24 presents these particular refill uncertainties together with the corresponding figures for all buses ex 1995.

The third column contains the quantitative ratios between complete refills, partial refills and refills after extraction (in this sequence), and, additionally the total number of annual inspections.

Table 24: Selected leakage rates of buses/coaches with refill uncertainties, kg/a

	Refill based leakage rate, kg/year	Ratio of refill types*, total ann. checks	Refill uncertainty, kg/year
All buses ex 1995	2.34	285/71/6, 1267	± 0.11 = 5%
Diesel buses ex 2000	0.92	16/6/0, 130	± 0.08 = 8%
Solo diesel ex 2000	0.80	12/6/0, 104	± 0.09 = 11%
All coaches	1.50	32/37/0, 308	± 0.15 = 10%
Coaches ex 2000	1.20	7/8/0, 78	± 0.13 = 10%

* Ratio of refill types: Complete refills/Partial refills/Refills after extraction. After comma: total number of annual inspections.

Considering the most important particular annual leakage rates, the refill uncertainties assessed in the above presented way vary from 0.08 to 0.15 kg/a. Expressed as percentages of the leakage rates obtained from recorded refills these uncertainties amount up to 11%.

We consider these uncertainties low enough not to jeopardize the validity of the values analysed and presented in Chapter IV and V of this report.

Annex III

Contribution of individual components to the leakage rates

The annual leakage rate of MAC systems is a computed value. In the reality behind this value, there is an array of individual components leaking to a varying extent. The contribution of these components to the average annual leakage rate is not yet sufficiently well analysed so that a look into the Swedish records is worthwhile. This is be done in the following annex, separately for city-buses and coaches.

1. City-Buses

1.1 Ranking of leaky components in the total bus sample

Before looking at differences between old and new bus MACs, we list the components of the refrigeration circuit which were identified as faulty and which are behind the total number individual leakage rates that constitute the overall 1996-2005 average leakage rate. In order to reach a more detailed picture of the involved components, multiple checks in one year are not combined to one so that the total number of cases increases from 1,267 to 1,491. The number of leaks grows from 362 (after combination) to 395 (before combination); it increases additionally to 432 because in 37 cases more than one component was identified as leaky at one check. Please note that this study includes only such vehicles that came more often than just once to the annual MAC control.

Table 25 Leaky MAC Components in City-Buses, by Number and % of Cases

Component	Cases	% of all cases	% of leaky comp
Compressor	126	8%	29%
- *Shaft Seal*	*36*		
- *Magn Clutch*	*14*		
Condenser	16	1%	4%
Evaporator	7	0.5%	2%
Receiver	6	0.4%	1%
Filter Dryer	10	1%	2%
Connections	55	4%	13%
Valves	82	5%	19%
- *Rotalock*	*29*		
- *Schrader*	*25*		
- *Pressostat*	*12*		
- *EXV*	*4*		
Hoses	81	5%	19%
- *Hoses in Joints*	*17*		
Other	49	3%	11%
- *Simple Refills*	*9*		
- *No Comments*	*31*		
No Leak	1059	71%	
Total	1491	100%	432 = 100%

Table 25, in particular the last column, proves the compressor (29%) to be the leakiest single component of the refrigeration circuit amongst the 432 leakage cases.

In contrast, the "roof components" condenser, evaporator, receiver, and dryer, have a joint share of only 9% in the total of leakages. This is completely different from passenger cars where the condenser is by far the most-damaged component because of the exposed placing in the vehicle front (Schwarz 2001).

However, "peripheral" components like hoses (19%), connections (13%), and valves (19%) are responsible for the vast majority of leaks, with a joint share of over 50%.

It should be noted that Table 25 comprises both old and new buses.

The dominant position of compressor and periphery (hoses, valves, connections) amongst the leaky components of bus MACs is clearly shown in the graph.

For comparison, the 1,059 no-leak cases, which represent the vast majority of cases, are entered too. Please note that the bar "No Leak" is not true to scale but ends at "200", for transparency.

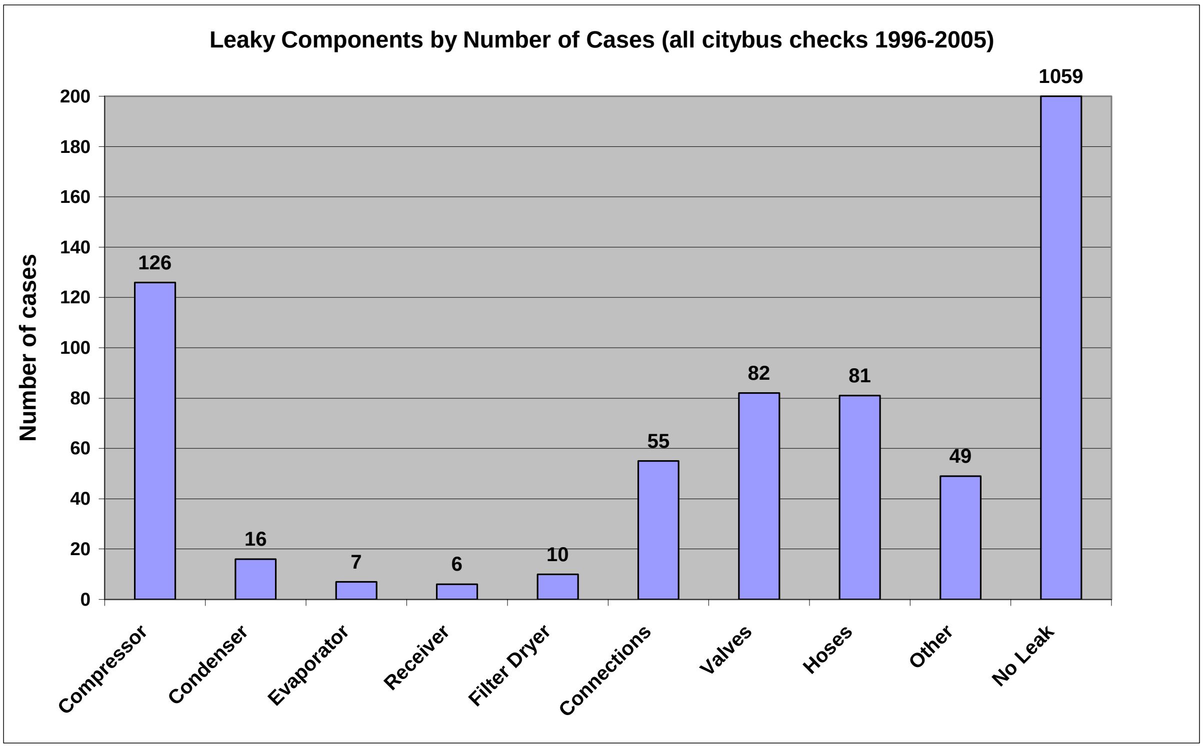


Diagram 7: In the greatest part, the 432 leaks consist of 126 defective compressors and 218 faulty peripherals: 82 times valves, 81 times hoses, and 55 times connections.

1.2. Leaky components in old and in new bus MACs

In the next step, we compare old to new air-conditioned buses. Old are those MAC systems that were installed before the year 2000, i.e. through 1999. New are systems that were put in operation from 2000 onwards.

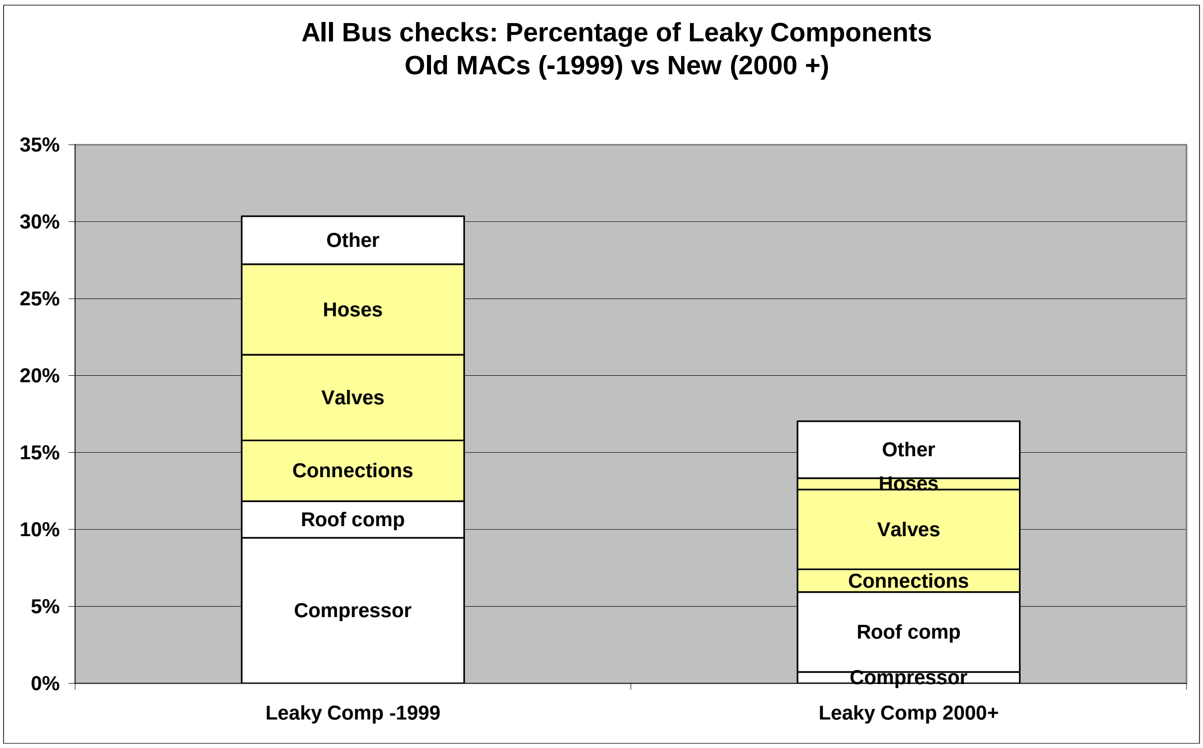
The average annual leakage rate of old bus MACs installed before 2000, checked over the whole 1996-2005 period, is 2.50 ± 0.29 kg/a. In contrast, the corresponding rate of systems in operation from 2000 onwards figures only 0.92 ± 0.39 kg/a.

Table 26 shows absolute and relative values for leaky components as well as for the cases without a leakage – on the left hand for systems installed through 1999, on the right hand for systems installed as of 2000.

Table 26 Number and shares of leaky components and of no-leaks in the total of inspections of old and new City-Bus MACs

	Bus MACs through 1999		Bus MACs from 2000	
Components	Number	%	Number	%
Compressor	125	9%	1	1%
Roof comp	32	2%	7	5%
Connections	53	4%	2	1%
Valves	75	6%	7	5%
Hoses	80	6%	1	1%
Other	44	3%	5	4%
No Leaks	947	70%	112	83%
Total	1,356	100%	135	100%

The percentage values in Table 26 are graphically reproduced in Diagram 8. This graph deliberately leaves out no-leak cases so that the particular shares of the leaky components become more evident.



Both Table 26 and Diagram 8 show marked differences between older and newer MAC systems. (It should be realised that the percentage shares of the components do not add up to 100% but to 100% minus the shares of "zero leaks").

Firstly, the 17% share of leaky cases in new MACs is almost only half as high as in older MAC systems with a share of 30%. This means that 83% of the annual check-ups of new systems did not find a leak, whereas this figure amounts to only 70% in checks of older systems. This improved leak tightness of new systems is behind the reduction in the average bus MAC leakage rate in kg/a.

Secondly, a shift between the single leaky components has taken place as far as their shares in the total of cases are concerned. Although it is advisable, facing the rather small number of cases, to be careful with statements on leaks of new MACs, nevertheless a certain trend seems to be emerging. In relation to the total of leaky cases, some categories gain in weight, while other loose in importance:

<u>Decrease</u>:
Compressor from 9% to 1%,
Hoses from 6% to 1%,
Connections from 4% to 1%.

<u>Constance</u>
Valves from 6% to 5%.
(*Leaky rotalock [shut-off] valves represent six of the seven leaky valves at new MACs.)*

<u>Increase</u>:
Roof components from 2% to 5%.
(Four of the seven leaky cases in new MACs are faulty condensers.)

1.3 Summary on leaky components of bus MACs

With all due reserve because of the small number of cases, from the comparison of the damage symptoms between newer and older systems the following trends seem to establish themselves:

1. Difficulties arising from leak-prone compressors have largely been corrected.

2. The efforts of MAC suppliers to achieve higher leak tightness of peripheral components such as hoses, connections, and valves had the expected effects in case of hoses and connections.

3. Room for improvement seems to exist as to valves, especially to shut-off valves.

4. Because of the drop in weight of peripheral components and of the compressor, the other main components of the refrigeration circuit increase in contribution to MAC leakage: Condenser, evaporator, and receiver/filter dryer. In absolute terms their liability to leakage has not grown.

2. Coaches

2.1 Ranking of leaky components in the total coach sample

Before looking at differences between old and new coach MACs, we show the components of the refrigeration circuit which were identified as faulty and which are behind the total number of the leakages detected in 1996-2005. In order to reach a more detailed picture of the affected components, multiple checks in one year are not combined to one so that the number of cases increases from 308 to 345. The number of leaks grows from 69 (after combination) to 75 (prior to combination); it increases further-on to 79 because of 4 cases in which more than one component were identified as leaky at one check. Please note that this study includes only such vehicles that came more often than once to the annual MAC control.

Table 27 Leaky MAC Components in Coaches, by Number and % of Cases

Component	Cases	% of all cases	% of leaky comp
Compressor	15	4%	19%
- Shaft Seal	*10*		
- Magn Clutch	-		
Condenser	4	1%	5%
Evaporator	1	0.3%	1%
Receiver	3	1%	4%
Filter Dryer	4	1%	5%
Connections	3	1%	4%
Valves	23	7%	29%
- Rotalock	*8*		
- Schrader	*4*		
- Pressostat	*4*		
- EXV	*3*		
Hoses	14	4%	18%
Other	12	3%	15%
- Simple Refills	*4*		
- No Comments	*8*		
No Leak	266	77%	
Total	345	100%	79 = 100%

Table 27, especially the last column, proves the compressor (19%) to be the leakiest single component of the refrigeration circuit amongst the 79 leakage cases.

The "roof components" condenser, evaporator, receiver, and dryer, have a joint share of 15% in the total of leakages.

Peripheral components such as hoses (18%), connections (4%), and in particular valves (29%) are responsible for the majority of leaks, with a joint share of 49%.

This share is nearly the same as in city-buses. There, however, leaky connections preponderate amongst leaky peripherals whereas valves cause significantly fewer leaks in city-bus MACs.

It should be noted that Table 27 comprises both old and new vehicles.

The dominant position of compressor and periphery (hoses, valves, connections) amongst the leaky components of coach MACs is clearly shown in the graph.

For comparison, the 266 no-leak cases, which make up the majority of cases, are also entered. Please note that the bar "No Leak" is not true to scale but ends at "50", for transparency.

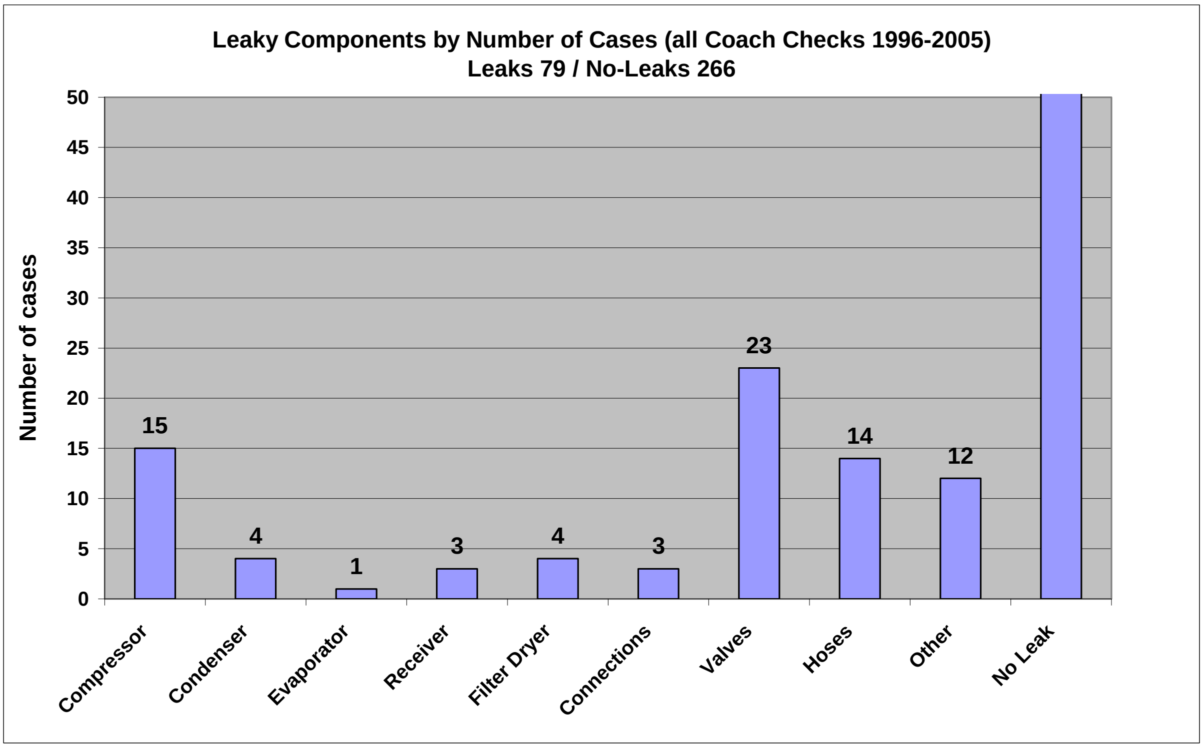


Diagram 9: In the greatest part, the 79 leak cases consist of 15 compressors and 40 faulty peripherals: 23 times valves, 14 times hoses, and (only!) 3 times connections.

2.2 Leaky components in old and in new coach MACs

In the next step, we compare old with new air-conditioned coaches. Old are those MAC systems that have been installed before the year 2000, i.e. through 1999. New are systems that have been put in operation from 2000 onwards.

The average annual leakage rate of old coach MACs installed before 2000, checked over the whole 1996-2005 period, is 1.60 ± 0.52 kg/a. In contrast, the corresponding rate of systems in operation from 2000 onwards figures only 1.20 ± 0.74 kg/a.

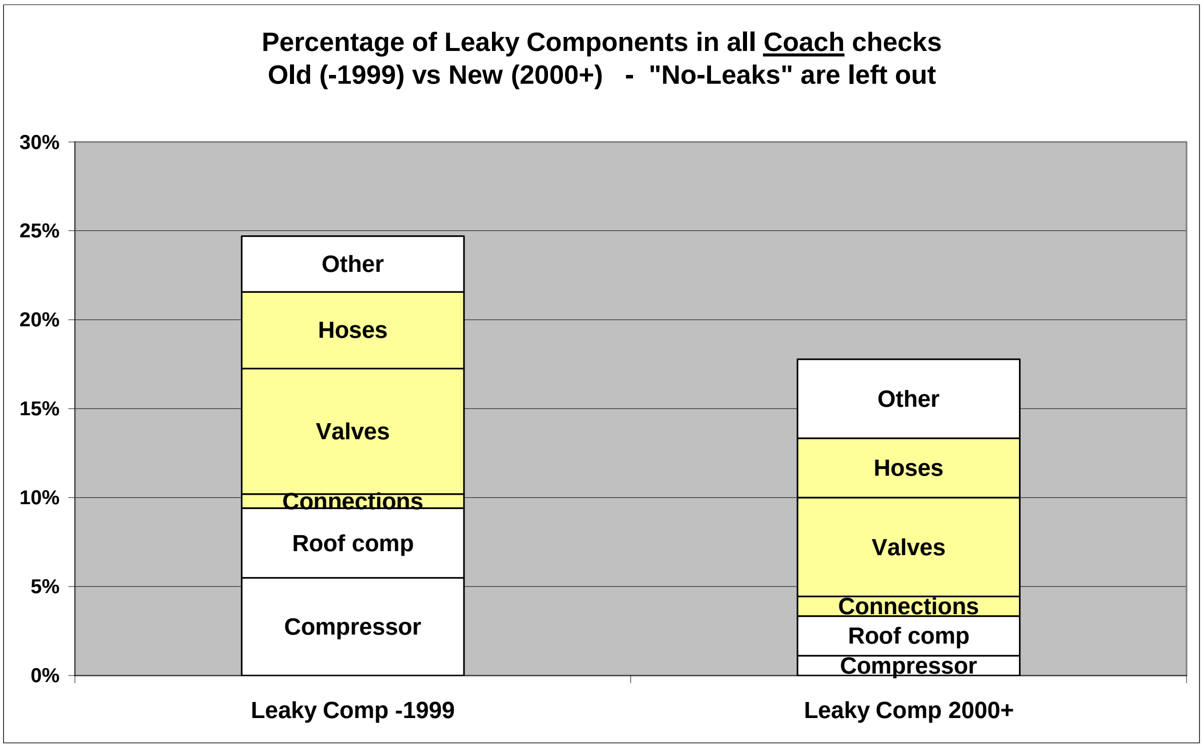
As contrasted with city-buses, the difference in leakage rate between old and new MACs is statistically not significant. The leakage rate of old coach MACs is low compared to the rate of old city-buses so that the room for further reduction in leakage of coach MACs is not very large. However, the leakage rate of new coaches is in the range of that of new city buses.

Table 28 gives the absolute and relative values for leaky components as well as for the cases without a leakage – on the left hand for systems installed through 1999, on the right hand for systems installed as of 2000.

Table 28 Number and percentage of leaky components and no-leaks in the total of checks of old and new Coach MACs

	Coach MACs through 1999		Coach MACs from 2000	
Leaky components	Number	%	Number	%
Compressor	14	5%	1	1%
Roof comp	10	4%	2	2%
Connections	2	1%	1	1%
Valves	18	7%	5	6%
Hoses	11	4%	3	3%
Other	8	3%	4	4%
No Leaks	192	75%	74	82%
Total	255	100%	90	100%

The percentage values of Table 28 are graphically reproduced in the following Diagram. The graph deliberately leaves out no-leak cases so that the particular shares of leaky components become more evident.



Both Table 28 and the Diagram show results of interest. (It should be realised that the percentage shares of the components do not add up to 100% but to 100% minus the shares of "zero leaks").

Firstly, the total of leak cases has decreased relatively, from 25% to 18%. The other way round, 82% of the annual check-ups of new systems did not find a leak, whereas this figure amounts to only 75% when checking older systems. This improved leak tightness of the systems is behind the reduction in average MAC leakage rate of coaches from 1.60 to 1.20 kg/a. This difference is not so much marked as the difference between old and new MAC of city buses. It is worth noting that the share in leakage cases is nearly the same in new coach MACs as in new city bus MACs, with 18% and 17% respectively.

Secondly, unlike city buses, coaches do not exhibit a substantial shift amongst individual leaky components as far as their shares in the total of cases are concerned. The comparison of new with old systems shows that each component or group of components is represented in the total of inspections with the same or with a just slightly reduced share. Only the compressor proves to be less leak-prone in new MACs compared with old MACs. Cases of leaky compressors have dropped from 5% to 1% of all MAC checks. For comparison with city buses: there the share of the leaky component compressor has likewise decreased down to 1%, from even a higher level of 9%. Peripheral components such as hoses, valves, and connections have scarcely changed in relative terms. This is an important difference to city buses.

2.3 Summary on components of coach MACs

With all due reserve because of the small number of cases, from the comparison of the damage symptoms between new and older systems the following trends seem to establish themselves:

1. As with city buses, the defects of compressors seem to be largely corrected.

2. In coaches, peripheral components such as hoses, connections, and valves do not exhibit that marked drop in importance for leakages as in city buses. The initial level had never been as high as in old city buses. However, this level has hardly decreased further since 1999. This is surprising because our assumption was that the suppliers of MAC systems have concentrated their efforts to tighten the systems through improvement of exactly these peripheral components. At least, from the Swedish data it follows that such an improvement has taken place or better had been necessary only in city buses, not in coaches.

3. Most room for improvement seems to exist as to valves, especially to shut-off valves and pressostats. This applies, as mentioned afore, also to MACs of city buses.

Generally, the room for further technical improvement, and herewith of further reduction in leakage rate, seems to be marginal. This applies both to MACs of city buses and to MACs of coaches.

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