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Emission of Refrigerant R-134a from Mobile Air-Conditioning Systems

Annual Rate of Emission from Passenger-Car Air-Conditioning Systems up to Seven Years Old

by

Dr. Winfried Schwarz

Öko-Recherche
Büro für Umweltforschung und -beratung GmbH
Environmental Research and Consultancy Office
Frankfurt am Main

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Rate of Emission from Car Air-Conditioning Systems up to Seven Years Old. Introduction and Summary.

The Kyoto Protocol on Climate Protection extends not only to the greenhouse-gases CO_2, methane and nitrous oxide, but also to the fluorinated gases (f-gases) HFC, PFC and SF_6. By far the most important of the fluorinated greenhouse gases is HFC, used mainly as a substitute for CFCs, while the most significant of the HFCs themselves is HFC 134a, accounting for about three-quarters of world production. Since HFC 134a is mainly used as a refrigerant, it is also called R-134a, 'R' standing for 'refrigerant'.

Purpose of Empirically Based Study

The greater part of R-134a use in Germany is associated with mobile air-conditioning systems. Rather than going by laboratory measurements and the estimations of experts, the present study has employed empirical and statistical methods in its attempt to determine the annual rate of R-134a emission from mobile air-conditioning systems. The study should also help in assessing the extent to which preventive maintenance and inspection might contribute to a reduction in emissions.

Our analysis concentrates mainly on passenger-car air-conditioning systems ('Öko-Recherche - *Ecological Survey* - 1999, 17) because they account for about 95% of refrigerant emission and consumption in the "mobile air-conditioning systems" sector. The survey is based on the records kept by garages on the quantities of refrigerant recovered and recharged when opening the refrigerant circuit of an air-conditioning system.

High Refrigerant Loss attributable to System Design

Unlike a stationary air-conditioning system, the refrigerant circuit of a car's air-conditioning system is unstable in state because its compressor is driven by the crankshaft. The compressor is necessarily open in design, and, being attached to the engine block, the need arises to avoid vibration as cooling capacity is transferred to the remaining parts of the refrigerant circuit connected to the chassis. As a result, only a limited proportion of metallic piping may be used in place of flexible hosing. Hoses, O-rings at component joints, and the rotary shaft seal of the compressor are weak points in the sealing system (Air-Conditioning Systems Conference - 2001), constituting the principal points of normal refrigerant leakage from systems which have not suffered "irregular" damage.

It is generally recognised that the emission of R-134a from car air-conditioning systems is not as high as that of CFC R-12 (still being newly installed up to as late as 1994 in some cases), where losses had amounted to nearly three charges per life cycle. Greater care is now taken in the handling of refrigerant, and although the HFC-134a molecule is smaller than the CFC-12's, the additional lining of hose interiors with polyamide film prevents any greater permeation.

At present, however, we have nothing more to go by than a series of estimates of the annual loss of refrigerant from car air-conditioning systems, with figures ranging from less than 5% to over 20% based on expert assessment or, rather more rarely, on laboratory measurement (see Clodic 2000; AFCE 1998; Baker 1999; Preisegger 1999, Öko-Recherche 1999; UNEP 1998; Fischer 1997, Pettersen/Hafner 1996, among others). To date, no estimate has yet been put forward on the basis of empirical measurements made on actual road-going vehicles.

Summary of Chapters A to G

Chapter A presents the study database, comprising approximately a thousand recorded recovery and recharging operations carried out by nine authorised dealers of three German car manufacturers during the period 1999 to May 2001.

Chapter B discusses recovery/recycling/recharging stations, duly examining the accuracy with which volumes recovered and charged are measured, reducing margins of error, and introducing corrective factors.

Chapter C analyses the reasons for the detected loss of refrigerant on opening an air-conditioning system. It emerges that the causes of 'total' loss (occurring in approximately 40% of cases and mainly attributable to outside influence) are different from the reasons for the equally high number of cases producing losses of less than 40%. A deficit of 40% refrigerant in relation to the normal charge is regarded here as the limit below which an air-conditioning system is still marginally intact (still no gaseous refrigerant or "flash gas", and still entirely liquid upstream of the expansion valve) and generally provides the same cooling action as a fully charged system. Provided they do not already occur during the initial phase of a system's use, refrigerant losses of less than 40% are generally the result of normal leakage rather than an 'irregular' event (accident, stone impact, etc.) which almost always produces greater loss. The study therefore sets out to examine two fundamentally different kinds of emission - normal and irregular. Refrigerant loss under 40% is the result of gradual, normal leakage, especially through seals, while the causes of any higher losses than that are 'irregular'. While it is true to say that continuous normal leakage of refrigerant can sometimes reach levels of over 40%, vehicles aged less than six or seven years (representing the majority of our chosen population) should not generally have arrived at that stage so early in their life. For the present, detected refrigerant loss less than 40% is deemed to be normal leakage.

Chapter D examines air-conditioning systems opened for various reasons other than lack of refrigerant and found to have lost less than 40%, interpreting them as (unintentional) "random sample" of normal emission, and relates the losses to the age of the vehicle in months since first registration. Initially, there is no relationship to be seen between the level of refrigerant loss and the age of the vehicle, due in the main to numerous unexpectedly high instances of refrigerant loss during the first eighteen months of operation. Since such instances can be assumed to have 'irregular' rather than normal causes, they were eliminated from the remaining study of normal emission. Having "removed" these instances of emission from the series of refrigerant losses less than 40%, the remaining 216 air-conditioning systems in the survey indicated a mean annual coolant loss of 6.3% (52 grams) as annual rate of normal emission over the first seven years in use. This rate varies by about ten percentage points up or down according to make of car, ranging from 5.8 to 7.0%. The mean 52-gram normal leakage figure comes within the scope of the car manufacturers' permitted tolerance of 34 to 83 gram per air-conditioning system.

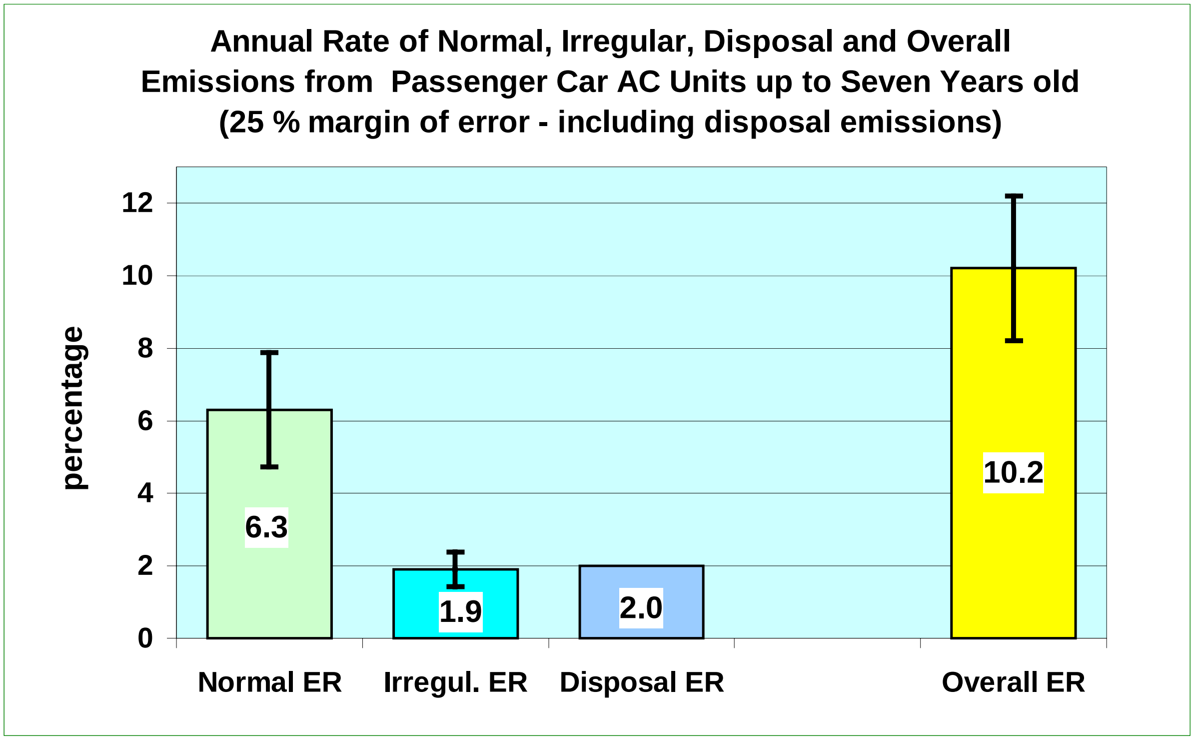
Chapter E: The study determined 'normal' emission indirectly from garage records, relating the emission behaviour of the few air-conditioning systems opened in the garage to the entirety of passenger-car air-conditioning systems in use for less than seven years. However, 'irregular' emission was determined directly from those records, relating the sum of irregular refrigerant loss in kilograms which a garage detected in one year to the number of air-conditioned cars inspected by the same garage in the same year. Passing through several intermediate stages, the examination disclosed an annual loss of about 1.9% of the refrigerant carried in vehicles regularly serviced by the nine authorised dealers within the period 1999 to May 2001. The percentage varies from 1.5 to 2.2 % according to make of car.

Chapter F adds the two rates of emission to arrive at an annual rate of 8.2% total emission, which varies from 7.7 to 9.2% according to make of car. To allow for this fluctuation between car brands and to cater for the inherent inaccuracy of recovery/recharging stations, the margin of error is extended by 25%

above and below the 8.2% figure to produce an annual total rate of emission varying between 6.2 and 10.3%. This defines the magnitude rather than the exact level of the rate of emission. It should be remembered that these figures relate only to air-conditioning systems less than seven years old, and as yet make no allowance for emission at time of disposal. Regular total emission of R-134a from car air-conditioning systems in the year 2000 has been estimated as between 685 and 1,140 tonnes. The variation depends on whether an emission rate of 6.2% (the minimum) or 10.3% (the maximum) is assumed for the 11,500 tonnes of refrigerant circulating in passenger cars in Germany. In turn, this 11,500 tonnes is an assumed figure based on 13 million air-conditioned cars (30% of the total car population being thus equipped) having an average R-134a charge of 850 grams.

Annual Rate of Emission increased to 10% on account of Loss at Time of Disposal

To guard against any misunderstanding, it should be said that an annual rate of emission over the first seven years in service will generally be lower than an annual rate of emission calculated over the entire life of a system. This is not simply due to the acceleration in normal system leakage (not quantified in this paper) which some experts expect to observe as a vehicle ages, it is mainly attributable to emission at time of scrapping an old car. Even with the improvements expected in the recovery of refrigerant by German old-car recyclers over the coming years, recovery related to a given originally German year of registration will still be limited on account of the 50% quota of used cars exported in that year to non-EU countries (Arge Altauto 2000 - Arge old cars, 2000). *Disposal loss per annum is estimated here at about 25% until further information becomes available. This 25% distributed over a life of twelve to thirteen years increases the annual total rate of emission by a further 2%, so in the medium term the rate fluctuates around about 10%.*



Chapter G finally examines the likelihood of reducing emission of refrigerant into the environment by regularly maintaining the air-conditioning system. In principle, preventive inspection does increase the reliability of a system's operation and can also contribute to a saving in energy, but it does not reduce the emission of refrigerant associated with either disposal, 'irregular' leakage, or normal leakage. Accordingly, it is not deemed appropriate to introduce compulsory maintenance alone with a view to reducing the emission of R-134a.

A. Database - Nine Motor-Vehicle Garages

The actual level of refrigerant in an R-134a air-conditioning system can only be ascertained by opening the refrigerant circuit in a suction-based recovery operation. While the checking of pressures in combination with temperature measurements may indicate whether or not the system still contains sufficient refrigerant for it to operate, this process cannot in fact determine the actual level of refrigerant. Unlike R-12 systems, the collector employed does not have an inspection glass for fast diagnosis. Accordingly, to establish the level of refrigerant and with that the difference in charge, the refrigerant must be recovered entirely from the system by means of a recovery/recharging station.

I. Refrigerant Record Sheets and Supplementary Information from the selected Garages

1. Refrigerant Records voluntarily completed by garages

Following on their records of consumption of CFC-refrigerant R-12, some garages in Germany continue to keep "Record Sheets on Quantities of CFC-containing Refrigerant consumed in the Maintenance of Air-Conditioning Systems" for the R-134a refrigerant introduced between 1991 and 1993. From the author's experience, this is done by about every one in ten manufacturer-tied ('authorised') workshops or dealership outlets. Half of these garages systematically enter the recovery and charge quantities read off the recovery/recharging station for every single air-conditioning system duly opened, and file the list both as record of their own work on the vehicle (for product-liability purposes) and as statistical instrument for internal management of resources.

The law does not require any such detailed recording of refrigerant consumption. The German Federal Law on Environmental Statistics (*Umweltstatistikgesetz*) simply rules that, on request, garages should report their total consumption of refrigerant (R-134a) in the previous year to their designated Federal State Statistics Office. However, garages were in fact recommended to report vehicle-specific consumption of refrigerant in the standard "Fundamentals of Technical Expertise in Vehicle Air-Conditioning Systems" leaflet issued by the VDA, ZDIK and ZDK (*German automobile industry associations*) in the winter of 1996.

2. Time-span and quality of garage Record Sheets on R-134a

Between April and July 2001, usable "Record Sheets on Consumption of Refrigerant" were collected from nine manufacturer-tied garages (authorised dealer garages/outlets) associated with three different German car brands, and were duly entered in our computer. The records were deemed 'usable' where they documented at least one full year (calendar-year 2000, or the period May 2000 to May 2001) and generally contained the following data:

1. Date of workshop visit,
2. Registration number of vehicle (or a Job Number),
3. Quantity of refrigerant recovered,
4. Quantity of refrigerant charged,
5. Charge difference,
6. Notes (brief) on reason for operation, and
7. Type of recovery/recharging station employed.

The line indicating reason for recovery and recharging was left uncompleted or was insufficiently informative ("leaking") in half of the cases examined, but was adequately specific in the other half ("accident, condenser replaced").

Five of the nine garages had records on year 1999 as well, three of these also having details on the period May 1998 to end of 1998, and one had even kept information on the whole period March 1997 to May 2001. We also examined any full 'year 1999s'. Incomplete 'year 1999s' and the parts of years 1998 and 1997 were entered in the computer for control purposes.

Refrigerant R-134 records going back any further than 1997 were inaccessible to the author (except for one very patchily documented 'year 1996').

Where an air-conditioning system undergoes recovery and recharging, garages generally write the type of refrigerant on the customer's invoice and (during the warranty period) on the invoice sent to the manufacturer. However, the record on the invoice notes a full system charge rather than the quantity recovered, which is reasonable enough in view of the refrigerant-cleansing carried out in the course of opening an air-conditioning system. It is for this reason that customer invoices have not been used as database for the present study.

3. Concentration of vehicles: Rhine-Maine Region

Seven of the reporting garages were in the Rhine-Maine Region, and two were in the Nuremberg area. This means that about 80% of the documented vehicles with duly maintained air-conditioning systems were reported in the Rhine-Main Region (concentrated mainly on Frankfurt am Main), 15% in Nuremberg and its environs, and about 5% had registration plates from outside those two regions.

4. Three German brands of passenger car

In the year 2000, the three German car brands serviced by our nine garages together enjoyed a market share of about 40% of German new passenger-car registrations (KBA 2001 - *German Federal Office of Motor Transport*). Their share in the registration of new vehicles fitted ex-works with an air-conditioning system was somewhat higher, being just under 50% by my own estimation. The reason for this is the traditionally higher rate of air-conditioning system installation in German cars as compared with imported brands, which make up a third of new registrations.

5. Recovery/recharging stations employed

All of the recovery/recharging stations employed for recovery and charging purposes had been manufactured during the period 1991 to 1996, so none of them were of the very latest design. The four different types used were

the SECUmat 134 by Behr: five units in five garages;
the FAST 2000 by Fischer: four units in two garages;
the RHS 850 by Waeco-A Gramkow: one unit in one garage, and
the Robinair Vacumaster by Robinair: one unit in one garage.

One garage has been using a Beissbarth MAC 26 instead of the SECUmat 134a since May 2001, but this unit had not yet been entered on the Record Sheets.

6. First stage of quantity correction - the 1,004 documented cases

Total number of entries from 1999 to 2001: 1,004

The number of entries in the Record Sheets for full years 1999, 2000 and 2000/2001 amounted to 1,004 in total. There were a further 209 entries from the previous period, which served as control indicating whether a vehicle may already have had its air-conditioning system opened, and if so, under what conditions.[1]

The 1,004 generally analysable entries on the opening of air-conditioning systems in the years 1999 to 2001 were distributed more or less uniformly over the three different car brands - Brand 1: 253, Brand 2: 317, Brand 3: 434.

Different air-conditioning systems having deducted duplicated entries: 932

Of the 1,004 entries, registration numbers duly identified vehicle air-conditioning systems that had been opened several times in the course of one or two years.[2] There were 72 duplicated entries in total, so the number of different air-conditioning systems effectively opened in 1999 to 2001 reduces to 932.

Ex-works R-134a systems - excluding R-12 conversions: 875

As a rule, mechanics expressly entered as such any conversions they made from R-12 to R-134a. (The list of old vehicles, which is to say vehicles not having an original ex-works R-134a air-conditioning system, was completed at a later stage with reference to the date of first registration and the type of vehicle). Reduced by the total of 57 system-openings effected for conversion or sometimes for retrofitting purposes during the period early 1999 to mid 2001, the number of different vehicles having ex-works R-134a air-conditioning systems and documented in the Record Sheets for 1999 to 2001 amounts to 875 (Brand 1: 216, Brand 2: 284, Brand 3: 375).

Ex-works R-134a systems excluding commercial vehicles: 841

One garage also opened and recorded the air-conditioning systems of commercial vehicles. The 34 cases in question having been duly identified and left out of the equation, the total number of genuinely passenger-car air-conditioning systems comes to 841.

Average charge quantities and losses - 841 passenger-car air-conditioning systems

The average charge quantity for all (841) air-conditioning systems was 856 grams. Differences of up to 30% were to be found between the individual brands - Brand 1: 734 g, Brand 2: 857 g, and Brand 3: 932 g.

The average loss of refrigerant determined per air-conditioning system opened was 546 grams, or 64% of the charge quantity. Here again, there were differences between the brands - Brand 1: 54%, Brand 2: 70%, Brand 3: 64%.

The total volume of refrigerant lost from the 841 systems amounted to 459.2 kilograms.

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[1] Only very limited use could be made of another 337 entries documenting all of year 2000 at one further garage (a tenth) associated with a fourth German manufacturer, because a figure of "1000 g" refrigerant (recovery/recharge) had been entered without exception for every vehicle serviced.

[2] Such cases often involved accidents, where the refrigerant was just recovered before bodywork repairs, and then just charged again after the repair work (several days later). The two entries related here to one and the same instance of damage. Occasionally, when first coming into the workshop, a system was charged with addition of contrast medium but the leak was not eliminated. Then on a second visit, the leak was finally rectified thanks to the contrast medium. Here again, the two entries relate to one and the same case.

7. Second stage of quantity correction - the 841 analysable cases

The age of a vehicle on its visit to the workshop is of decisive importance to certain aspects of the present study's investigations, especially the determination of so-called 'normal' emission, but this age is not entered in the Record Sheets.

In a second stage of our work, the nine garages were asked, through their service managers or through their environmental protection officers, to examine their duly retained workshop records and provide the following three extra items of data on each vehicle identifiable by workshop date and car registration number:

1. type of vehicle,
2. date of first registration, and
3. kilometre reading at time of workshop visit.

At this point I would like to thank all nine garages for completing this time-consuming task, some extending it to one year, but some again covering three. In addition to which I must say that the air-conditioning mechanic and/or electrical foreman in each garage showed great patience in answering my queries and providing me with technical information.

"Fully identified" vehicles out of the 841: 678

Of the 841 disparate passenger-cars having ex-works R-134a air-conditioning systems, 102 could not be identified mainly because they had been deleted from the garage records. Deletions are generally effected in connection with transfers of ownership, in other words after a vehicle has been sold by the customer and has had its registration plate changed accordingly. The quota of deletions associated with dismantling is not very significant to date.

I decided not to seek further identification of another 61 vehicles (all from record-year 1999 and all recording 'total' loss of refrigerant) by the garage concerned, because the additional knowledge thereby obtained for the purposes of the present study would have been disproportionate to the major work of research otherwise imposed.

In the final outcome, the study disposed of 678 fully identifiable vehicles whose air-conditioning system had been opened between 1999 and 2001: 188 from Brand 1, 252 from Brand 2 and 238 from Brand 3 (along with another 50 vehicles from the year 1998).

At 62.5%, the rate of emission for the 678 "fully identified" passenger-cars was slightly lower than the 64% for the 841 vehicles listed above. The charge quantities in their 678 systems were also somewhat lower, being on average 848 grams instead of 856 grams.

Average age of vehicle on first opening of air-conditioning system: 34 months

The average age of a vehicle on first visiting a workshop to have its air-conditioning system opened was 34 months, where the relevant information was available. This figure varies, being 32 months for Brand 1, 31 months for Brand 2, and 38 months for Brand 3. The greater age for Brand 3 is quite conspicuous. That brand was distinctly higher than the others in kilometre reading too.

Average kilometre reading on first opening of air-conditioning system: 74,400 km

The average kilometre reading at time of first visit to workshop to have the air-conditioning system opened was 74,400 km. Brand 1 clocked in at just under 71,000 km, Brand 2 coming clearly below that with 60,200 km. Brand 3, on the other hand, was well above, with a reading of 92,300 km.

8. Other information from the garages and the car manufacturers

The garages provided further data for some of our investigations (those into the "irregular", damage-induced proportion of the refrigerant emission rate), for instance their annual number of vehicle throughputs and inspections. Apart from lists of the standard charge quantities for air-conditioning systems in specific vehicles, the German car manufacturers also sent me the rate of installation of air-conditioning systems in specific types of passenger-cars sold annually on the German market since 1992. This extra data is expressly referred to in Chapter E of the present study - where it is duly applied - so there is no call to examine it any further at this point.

9. Workshop visits for opening of air-conditioning system distributed over individual months

One important aspect affecting accuracy in measuring the rate of refrigerant emission that ought to be introduced in this initial chapter (especially since it already arises out of the garage Record Sheets before they were 'corrected' - where they extend to cover a full twelve-month period, that is) is the likely distribution of air-conditioning-system openings over time (by the month) within a calendar year, as identified by the date entered for workshop visit.

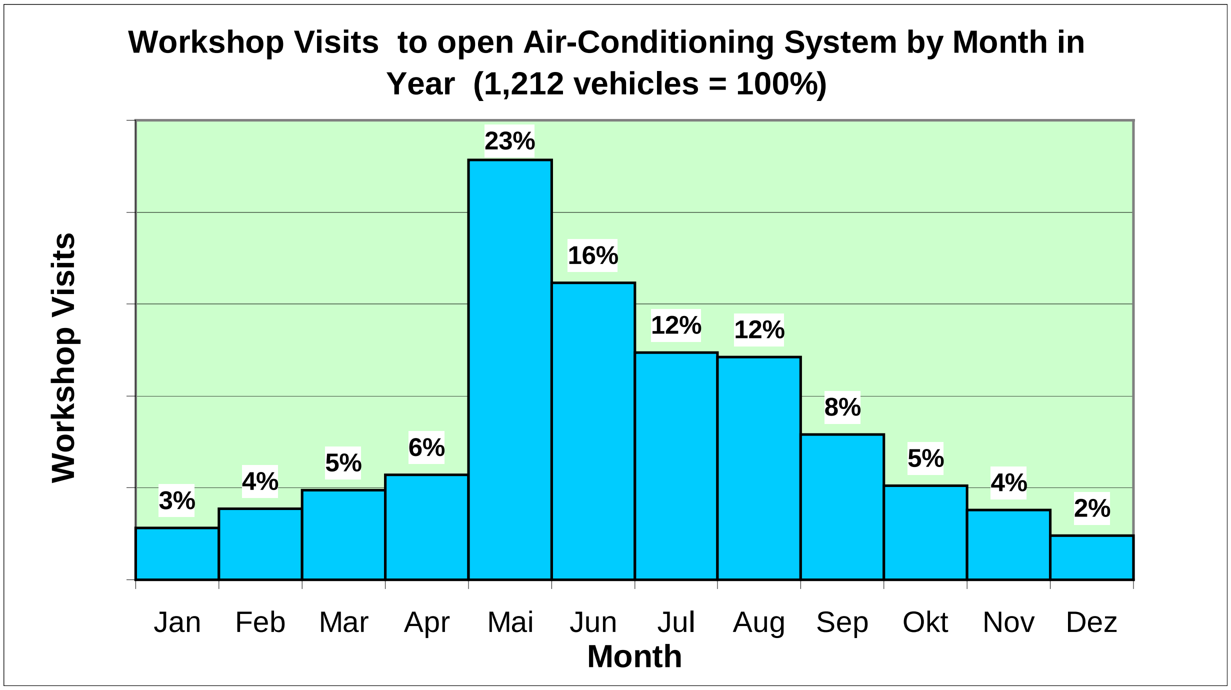

Diagram 1: Workshop visits to open air-conditioning system, distributed by month over calendar year. Based on 1,212 entries from ten garages. The diagram shows a significant accumulation in the warmer months of the year (May to August) and a distinct under-representation during the colder months from October to April. (We were also able to use the data from the tenth garage - fourth brand of car - for this graph).

Diagram 1 shows a significant concentration over the hot months of the year (May to August), and a clear under-representation in the colder months from October to April. Almost 25% of all air-conditioning-system openings are effected in May, this after only 6% in April.

Rather than reflecting any correspondingly more frequent occurrence of defects in air-conditioning systems in May, this lack of uniformity in distribution is far more likely to represent the more frequent perception of defects during the warmer time of year. Even where a defect might in fact be noticed in the colder months of the year, it apparently fails to constitute a disturbance until cooling is called for in the hotter months.

In the context of determining the rate of emission, this finding demonstrates that the time at which emission occurs does not coincide with the time at which it is examined and eliminated in the workshop, in fact several months may pass by between an actual loss of refrigerant and its entry in a Record Sheet. Since, in the following, a vehicle's age is defined as the period elapsing from its first registration to its recorded visit to a workshop (the date entered in the Record Sheet), our figures are systematically overstated; not just because of the time it takes to arrange a workshop visit, which would be a normal factor to take account of, but because the time between occurrence of a refrigerant loss and its detection in the workshop is probably a great deal longer still. Clearly, I have been unable to correct this overstatement of age in any single instance.

Accordingly, it should be duly borne in mind in examining this study that the recorded age of vehicles has been systematically overstated - by about two or three months in my own estimation.

B. Reliability of Records and Accuracy of Recovery/Recharging Stations

The quantities of refrigerant which mechanics enter in their Record Sheets as duly recovered and recharged by the recovery/recharging station are of decisive importance to this study. It is even more important to know how accurate these records are, which is to say how close a mechanic's entry may, or can, come to the actual quantities in question. In this connection, it is often impossible to distinguish between objective factors such as the technical characteristics of the recovery/recharging station, and subjective factors like the mechanic's accuracy in operating and reading off the unit. Consequently, our study sets out below to

- explain the recovery and charging process of a typical recovery/recharging station (taking the SECUmat 134 by Behr as example) by describing its four main phases with reference to a drawing;
- discuss errors in determination of quantity, their significance, and their possible correction, and finally
- estimate refrigerant losses in so far as caused by the servicing operation itself.

I. Recovery and Charging by Recovery/Recharging Station (see drawing)

The reader is recommended to refer to the drawing overleaf to assist with understanding the individual stages of the recovery and charging process.

1. Recovery (2 to 5 minutes)

The service connections of an air-conditioning system (see detail at bottom right) in a vehicle are arranged upstream of the compressor (grey 1) on the low-pressure side and upstream of the expansion valve - often on the dryer - on the high-pressure side (grey 2). The low-pressure hose (1) and the high-pressure hose (2) of the recovery station are joined to these service connections. The valves are opened by manually turning the cock on the quick-fitting pipe union duly attached. The air-conditioning system's low pressure (suction pressure) and high pressure (liquefying pressure) readings are displayed on the pressure gauges (5) provided. Both operating points (or just the high-pressure point where a controlled-output compressor is installed - because low pressure remains unaltered in that case at 2 bar) provide the first indication of a system's condition.

The two hoses are joined together by valve taps (3 and 4), so the refrigerant passes over a single main line leading inside the recovery/recharging station (the set of pressure gauges and the main line are usually inside the station, just the service hoses being connected on the outside). The refrigerant is drawn in by the compressor (K) and flows over the separator (6) which holds back any entrained refrigerant oil. All of the refrigerant is rendered gaseous by absorption of heat by this stage at the latest, to prevent the compressor from being damaged by liquid. The concentrated gaseous refrigerant is cooled in the condenser (7) and then liquefied again, after which it flows through the filter dryer (8) into the collecting tank (9).

In the region of 10 to 20 grams of refrigerant may still be left to evaporate inside the air-conditioning system after the first recovery (taking about 2 minutes), for instance refrigerant dissolved in oil or other liquid refrigerant which could come from the dryer, for example. This subsequent evaporation increases pressure in the system to over 0.6 bar, which causes renewed recovery from the compressor when operating automatically. Operating manually, the mechanic should wait briefly and must then himself switch on to recover the subsequently evaporated material.

The air-conditioning system is opened for repair work. As alternative, the internal refrigerant-cleaning program can be run beforehand, in a cycle driven by the compressor through collecting tank (9), separator (6), condenser (7), filter dryer (8) and back to the collecting tank (9) again.

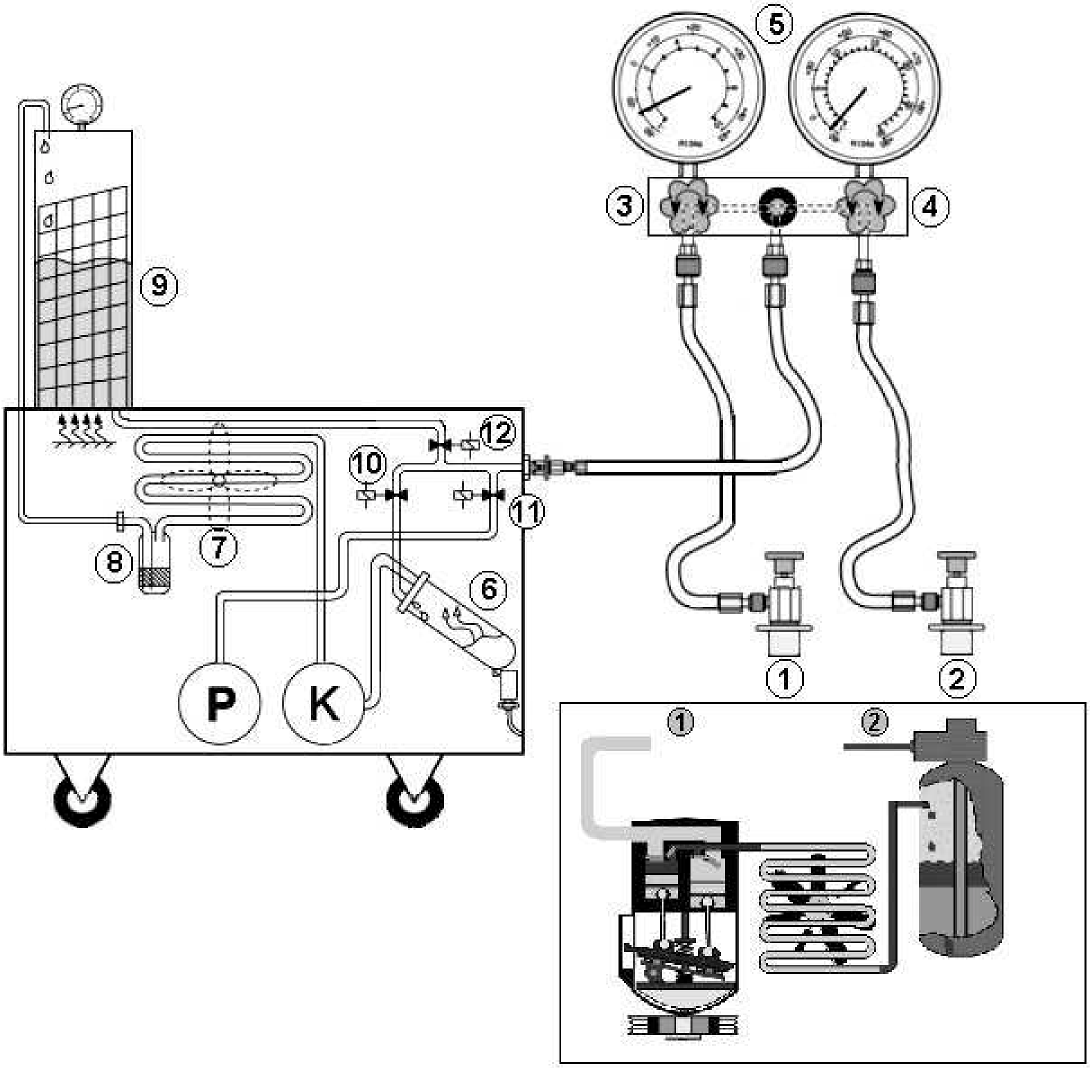

Fig. 1: Typical recovery/recharging station for evacuating and filling passenger-car air-conditioning systems - (1) low-pressure hose connection; (2) high-pressure hose connection; (3) and (4) valve cocks; (5) pressure gauge dials; (6) oil separator or trap; (7) condenser; (8) filter dryer; (9) reservoir tank; (10) (11) (12) solenoid valves; (P) vacuum pump; (K) compressor. Bottom right: compressor, condenser and filter-dryer of car air-conditioning system. Grey (1) and (2): low-pressure and high-pressure air-conditioning-system service connections. (Source: DaimlerChrysler 2001 - modified).

2. Evacuation (20 to 30 minutes)

The hoses of the recovery/recharging station are connected to the air-conditioning system. The line to the vacuum pump (P) is cleared by closing solenoid-valve (10) and opening solenoid valve (11) inside the recovery/recharging station. The pump sucks in the air and other non-condensable gases from the system, and the vacuum gradually produced in the process boils and draws out any moisture which may be present. Waste air is blown into the atmosphere, while low pressure develops in the system at the same as required condition for charging.

The leak test by vacuum ('vacuum check') is passed where the pressure-gauge dials (5) fail to display any readable rise in system pressure for at least five minutes after the vacuum pump has been turned off.

3. Recharging (1 to 3 minutes)

The low-pressure side (1) and high-pressure side (2) of the air-conditioning system are connected to the recharging station. The valve cock (3) on the low-pressure side is closed before charging, because liquid refrigerant must not be allowed to flow in upstream of the compressor. The valve cock (4) on the high-pressure side remains open. To make sure the refrigerant circuit is sufficiently well charged, the refrigerant in the reservoir tank of the recharging station is warmed by a heater to between 25 and 30°C, which increases the pressure in the tank to about 7 bar.

Liquid refrigerant flows into the system on the high-pressure side while the charging valve (12) remains open. The fill level on the transparent reservoir tank (9) falls as the tank contents flow out, so the amount of refrigerant discharged can be visually checked while recharging proceeds by reading off the measuring lines encompassing the tank at 50-gram intervals (show volume converted to weight and allow for temperature-induced expansion).

Instead of employing the pressure method, some stations use an additional electrical charging pump for charging purposes (this is actually essential when charging large quantities). Some old and all more recent stations permit charge quantities to be read off precisely to within one gram, being equipped with an electronic scale for the reservoir cylinder rather than a visual control system.

4. Emptying the recharging hose

Pressure in the air-conditioning system rises as the charging operation proceeds, which stops the hose and pressure-gauge fittings from being entirely emptied of refrigerant. The hose's quick-fitting pipe union closes when the service connection is taken off, to prevent loss of refrigerant from the incompletely emptied hose and to stop air or damp from getting in to it (an estimated quantity of just 1 to 3 grams of refrigerant evaporates with a hiss between service valve and the interior of the hose's quick-fitting pipe union.)

The hose is emptied by suction by turning on the compressor again. Up to 50 grams of refrigerant may still remain in the hose depending on its length and on the internal temperature of the air-conditioning system. This residue is emptied for labour safety reasons among others, because even the safest of closure systems would be unable to rule out the possibility of a minor flash of refrigerant (engendering the risk of localised frostbite) when manually attaching a full hose during the next recovery operation.

II. Errors in determining Quantity; their Significance and Correction

1. Rounding off when measuring by sight, also where weighing electronically

All modern and some older stations (made between 1990 and 1995) have an electronic scale for the reservoir tank which determines quantities duly recovered and recharged. The scale displays changes in the tank's weight digitally and therefore precisely to within a gram. Three of our nine garages had stations of this kind, two of them using the FAST 2000 (manufactured between 1990 and 1994) and one having the Robinair Vacumaster (made in 1996). With the FAST 2000, the mechanic has to calculate the recovery volume himself by reckoning the difference in reservoir-tank (cylinder) weight before and after the operation (about 5,329 related to 4,803 grams). The Robinair station displays the recovery volume as an absolute figure related to zero. When charging - regarded as the more important operation - the mechanic can enter the desired dosage to within exactly one gram in all three stations, usually about 1,000 grams, this dosage then being let precisely out of the reservoir tank (cylinder) along with the addition of a compensatory excess quantity.

The reservoir tank simultaneously serves as (transparent) measuring cylinder in the other most widely used types of station (SECUmat 134 or Waeco RHS 850). When recovering and recharging, the mechanic watches the measuring lines encompassing the cylinder at 50-gram intervals. The charge quantity cannot be read off from zero, but, like the recovery volume, as difference in level before and after the operation, so not only does the mechanic have to do mental arithmetic, he must also have a good eye. In practice, he usually marks the starting level on the outside of the measuring cylinder (using a felt pen) and thus reduces the risk of read-out errors.

The Record Sheets furnish no proof that stations with scales and electronic display might be in any way superior to those simply provided with visual control means, all hand-written entries (also those entered manually into a computer, as done at one garage) being made in 50-gram increments.

This is not particularly surprising in respect of charging. Almost all air-conditioning systems in German cars work with standard quantities stated within 50 or 100 gram limits, with 25 or indeed 10 gram limits rarely to be found. This is also the case with foreign makes (see Autodata 2000; Waeco 4/2000). So if the mechanic knows the standard charge quantity, why should he do otherwise than simply enter it along with the extra allowance for the hose?[3]

However, the 50-gram increment which both types of station use for entries seems astonishing at first glance in respect of the recovery quantity, because (but for a few exceptions) the recorded quantities must necessarily be based on figures duly rounded up or down - although it is easy to see why this method is used for measurement cylinders having 50-gram increments. With even the very best of visual inspection, a deviation of up to 25 grams from the effective quantity would be normal. As opposed to this, the electronic scale provides data precise to within one gram. Where not measured in relation to zero, the displayed weight of the reservoir tank should be noted down beforehand (on paper or pocket calculator) - if the weight is 4,803 grams before recovery, and then 5,329 afterwards, producing a difference of 526 grams, the mechanic will enter either 500 grams or 550 grams. However, he would also enter 500 grams for a figure of just 478. The inaccuracy of

measurement amounts to about 50 grams (25 grams up or 25 grams down). Where 200 grams of refrigerant is lost, this deviation makes up more than ten percent. Greater precision would take the mechanic more time and is not required of him. The same procedure is followed even in the garage

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[3] A station's accuracy of measurement when charging is not all that important to the present study in any case, the factory standard figure duly being taken as basis for a full air-conditioning system.

operating a Robinair station (recovery displayed to a precision of one gram), where the Record Sheets also document none other than 50-gram increments.

In all 841 cases covered by this study, the loss of refrigerant is determined as difference between the ex-works standard charge and the recovery quantity entered by the mechanic. From practical experience, there is no significant difference in the accuracy of entering recovered quantities measured by eye or by electronic display, both measurements, as we have said, being duly rounded off to 50 grams.[4] Given the mechanic's routine, there is little reason to think of the entries based on electronic measurement as being any more reliable than those made with the naked eye.

The foregoing has the consequence for the present study that the entries it records may generally incorporate a deviation of about 25 grams up or down from the effective quantity recovered. The only exception would be the 323 entries of 'total' loss of refrigerant (representing a recovery of zero grams), where rounding-off is less likely. Taken together, however, 'total' losses do make up almost forty percent of all 841 entries.

2. The residue in the hose as source of error in determining the charge quantity

As mentioned at the end of the description of the charging operation, the charging hose never empties entirely into the air-conditioning system. Were the mechanic simply to read off the exact standard charge from the charging cylinder, he would be systematically under-charging the systems he works on. As a result, some car manufacturers specify an 'over-dosage' of from 25 to 50 grams by way of compensation. This recommended extra quantity is also advised by the suppliers of recovery/recharging stations, into some of which the extra quantity can be permanently programmed as a function of the length of the recovery and recharging hoses. The advantage here is that the mechanic can still stay with the exact standard system charge.

2.1 Quantity recovered occasionally exaggerated because hose not emptied.

After charging, the mechanic must always make sure to have any residue sucked back out of the hose. If he forgets to do so, then when he connects up the unemptied hose to perform the next recovery, he risks frost-bitten hands from a flash of refrigerant gas even if only a little emerges from the closure. The important aspect in the present context is that the quantity of refrigerant recovered with an unemptied hose of this kind would then be greater than the actual content of the air-conditioning system - resulting in an "upward" error in measuring the quantity recovered. This measurement error was mentioned in the course of interviews with air-conditioning mechanics during the present study, its "occasional" occurrence being justified on the grounds of pressure of work associated with payment of an incentive wage.

2.2 Charge quantities entered in Record Sheets often deviate from standard charge

Whether or not the excess quantity is 'sucked back', the calculated extra quantity charged is actually more important to the exercise of determining quantities than occasional exaggerations attributable to recovery using an unemptied high-pressure hose. Where a car manufacturer indicates "plus 50 grams"

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[4] The latest stations with data interface to the workshop computer and/or integrated printers (for instance, the Beissbarth MAC 26 or Waeco RHS 800 in use with one garage since May 2001) save or directly provide recovered and charged quantities of refrigerant in 5-gram increments. As these types become more widespread, the accuracy of the data obtained should improve.

along with his type-specific charge quantity, mechanics tend always to let this greater quantity out of the reservoir tank and to enter it as 'charge quantity' in their Refrigerant Record Sheet. Understandably, the quantity 'sucked back' after charging is not measured, so it is not subtracted again from the quantity delivered. For this reason, the charge entered is in very many cases not the same as the standard charge of the air-conditioning system, it is in fact greater than same.

The Record Sheets clearly indicate that workshops with stations compelling the mechanic to enter the additional quantity himself on every occasion (this being the case with six out of the nine) enter higher charge quantities - and therefore greater charge differences - than workshops where the extra quantity is permanently pre-set. The latter workshops can work directly with the lower charge quantity. In our own study's case, in fact, the air-conditioning systems of vehicle makes whose charge quantities are specified precisely to within a gram for every model, therefore without compensatory addition, are recovered and charged exclusively with stations in which excess quantity of refrigerant is permanently pre-programmed.

The consequence for the present study is that the differences between recovery and recharging that are duly entered in the Record Sheets cannot always be taken as actual refrigerant loss from the vehicles in question. Corrections may sometimes be necessary. Refrigerant loss in the present case generally comprises the difference between entered recovery and the manufacturer's specified standard charge, whether or not the latter is actually entered as charge in the Record Sheet.

The varying data specific to particular vehicles and also to years of manufacture is gleaned from lists provided by the three car manufacturers and from the literature on the subject (Autodata 2000; Waeco 4/2000), an approach which I think should reduce the incidence of measurement errors. At any rate, the present study is concerned with refrigerant loss determined on the occasion of an air-conditioning system's first visit to the workshop since first registration. For this reason too, the 'ex-works charge' is a better measure to go by than the 'workshop charge' - after all, it can readily be assumed that no car manufacturer is likely to fill his systems with any more refrigerant than absolutely necessary.

3. Temperature differences between recovery/recharging station and air-conditioning system when recovering

Another possible source of error relating not to the charge quantity, but to the recovery quantity - one that may arise in connection with all designs of recovery/recharging station - is discussed in the following for the sake of completeness.

The only propelling force transporting the refrigerant throughout the recovery and charging operation is the compressor in the recovery/recharging station. Not only does the compressor suck the refrigerant out of the air-conditioning system and force it into the condenser, it is also the only agent causing the refrigerant already disposed in the liquids pipeline downstream of the condenser to flow on into the reservoir tank, in that liquid continues flowing out of the condenser thanks to the workings of the compressor. As soon as this flow peters out (once the system is sucked empty), the refrigerant remains stationary in the final stretch between

condenser (7) and collecting vessel (9). Measurement errors do not generally arise in this connection, since when recovering the next air-conditioning system, this residue originating from the preceding system, downstream of the condenser in the recovery/recharging station, is in fact the first material carried into the reservoir tank. Not until that operation is completed does refrigerant begin to flow in from the system currently under recovery, once again minus the residue downstream of the condenser, and so on and so forth.

In principle, the incomplete throughput of the one recovery is continuously compensated in this manner by the likewise incomplete throughput of the next recovery. Distortions only occur in connection with temperature differences and therefore differences in expansion between in-flowing new refrigerant and old refrigerant - which distortions, not having been examined in the present study, have not been taken into account.

4. Recovery of after-evaporation forgotten

We explained when describing the basic operation of recovery that, after the first recovery taking about two minutes, approximately 10 to 20 grams of refrigerant (which may have been dissolved in oil, or was not immediately withdrawn from the lower parts of the refrigerant circuit) may still evaporate within a system which is not yet completely empty. In automatic operation, which is a facility of all of the recovery/recharging stations in the present population, the recovery process is set up to extend for at least an extra three minutes, so that, after the station is turned off for the first time, it will start again on any renewed rise in pressure in the air-conditioning system and then continue with the recovery of residues.

In manual operation, the mechanic must wait for any possible rise in pressure after the first recovery (observing the pressure gauges), and then turn on the station again where necessary.

Clearly, this after-evaporation may well be neglected from time to time under general pressure of work. Any subsequently evaporating refrigerant of this kind is noticeable as emerging cloud by no later than the stage of opening the air-conditioning system. In such cases, the recovery quantity read off the recovery/recharging station understates the content of the system by from 10 to 20 grams.

This study has not attempted to quantify the differences in measurement attributable to this neglect of after-evaporation (and thus the emission of refrigerant due to improper servicing). I also felt unable to give any estimates, in fact all I would say is that six of the nine stations did provide the option of manually terminating the recovery period.

5. Omitted entries

In concluding our discussion of sources of error in determining refrigerant quantities when servicing an air-conditioning system, we should mention the mistake that actually occurs most frequently: unintentional neglect to enter the recovery and charging operation in the Record Sheet.

Although the Refrigerant Record Sheet is usually kept in the workshop, in a folder directly attached to the recovery/recycling station, it is inevitable that hand-written records of this or that operation can sometimes be forgotten in the general hustle and bustle of everyday garage routine. Then looking at the Record Sheets themselves, there is no need to be a handwriting expert to see quite clearly the sometimes unusually careful and identical writing of one and the same mechanic, using one and the same ball point, as he attempts to catch up

on the entries that should have been made for a number of vehicles over the past three or four days. Then again, it should be said, this 'catching up' is not always done.

Air-conditioning mechanics interviewed in the course of our study gave estimates of forgotten entries ranging from "none at all" in smaller garages, to "at least ten percent" in the larger firms. Although I think myself that the mean of 5% is too low, it has been taken as the maximum in this study. Which means that refrigerant losses in the region of 477.2 kilograms should be regarded as 5% or 24 kilograms higher than that in reality, amounting, in other words, to about 500 kilograms (501 kg). The loss per vehicle does not alter as a result, because this allowance also increases the number of air-conditioning systems by 5%, from 841 to 883.

This correcting factor produces a slight increase in determination of the so-called 'irregular' rate of emission (see Chapters E and F), while the 'regular' rate of emission (see Chapter D) remains unaffected.

III. Refrigerant Loss caused by the Servicing Operation itself

Apart from neglected after-evaporation, two other sources of refrigerant emission associated with servicing would be loss while locating leaks, and loss when detaching the charging hose.

1. Loss when charging

The maximum loss on detaching the charging hose from the service connection (see description of basic process) is estimated at between one and three grams. The hose end closes of itself as it is withdrawn from the service valve (the coupling cannot be removed unless the cut-off valve is closed by hand), this being a major technical improvement over the period before 1991, when refrigerant R-12 was generally released entirely into the atmosphere on opening an air-conditioning system. According to the suppliers of recovery/recharging stations, the reliability of this closure system has to a large extent been technically perfected by now, so the mean loss estimated at two grams would be regarded as unavoidable at the present time (Recovery/Recycling/Recharging Stations Conference - 2001).

Since, when we subtract 31 renewed charges not effected (including vehicles sent for dismantling) and then add the 72 multiple charges in the same or the succeeding year (in so far as recorded in both situations), the 841 different air-conditioning systems in our survey population would in fact have been charged 882 times in total, 882 times two grams or in total just under two kilograms of refrigerant being released into the ambient air in the process.

To put it another way, loss during charging adds two grams or 0.4% to the mean loss of 546 grams (64% in relation to the mean charge quantity of 856 grams) recorded for all opened air-conditioning systems in the study population, so we end up with a total of 548 grams.

2. Refrigerant loss when locating leaks with contrast medium

The 'total' losses we referred to above extend not only to air-conditioning systems 'irregularly' harmed by outside influences (the main category being 'accident damage') and usually producing 100% emission, but also include vehicles having losses of over 100%. These are cars which, due to the one leak, have lost refrigerant in the course of more than one charging

operation, because instead of being repaired during the first visit to the workshop, the leaking system was simply filled up. 29 of the 323 recorded 'total' losses come under this heading.

Where the mechanic fails to find a fault in an empty system on visual inspection or on performing the vacuum check after recovery, he continues by filling the system with liquid nitrogen or with refrigerant to localise the leak, observing the pressure-producing gas that duly emerges. To find the leak, he uses an electronic leak indicator unit which reacts to refrigerant escaping from the system either in pure form or (where flushing with liquid nitrogen) as entrained residue. Although not yet generally approved by compressor manufacturers as a method of locating leaks[5], it is normal practice in many garages to add a contrast medium or 'tracer' when charging the refrigerant. The tracer comprises a few drops of refrigerator oil mixed and dyed with a fluorescent substance and incorporated with the in-flowing charge of refrigerant. This method is used in eight of the nine garages in our population.[6]

Having allowed the air-conditioning system to run for a few minutes, an ultraviolet lamp will usually locate the tracer as luminous coloured stain around the leak (since a case of this kind involves renewed emergence of refrigerant, loss from the vehicle in question rises to more than 100%). The stain is generally cleaned off after the leak has been repaired, to prevent any misunderstanding the next time the car is maintained (any residue left behind might otherwise be interpreted as a new leak).

If, even where using a tracer, the mechanic still fails to find a suspected leak on the same day, the leak may be regarded as active but minute, only allowing the associated volume of refrigerant to escape over a prolonged period under real driving conditions, so its location by staining may take days or weeks of further operation. The fault will not then be found and rectified until the next time the car visits the workshop. This method of leak detection is associated with emission rates of 200% - apart from the few vehicles (only two in the present population) that had different leaks in the one year.

Refrigerant loss occurring over and above 'total' loss where a leak is first found on emergence of tracer-containing refrigerant (whether this happens on the first visit or during a subsequent visit to the workshop) is regarded in this study as 'service-induced' emission associated with leak location. The 29 affected vehicles in the study population suffered an extra loss of 20.5 kilograms in addition to their (first) 'total' loss of 27.5 kilograms. These 20.5 extra kilograms are 'service' emissions in the narrower sense of the word.

Accordingly, of the total recorded refrigerant loss of 459.2 kilograms from the 841 vehicles in the study, 20.5 kilograms (or 4.5%) is attributable to loss during leak detection.

Other, rather more 'unusual' losses of refrigerant in the workshop should also be mentioned at this point. For example, one 1997 Record Sheet from one garage documents total leakage

from the tank of the recovery/recharging station ("charge 25 kg, recovery/recharging station leaking"). The refrigerant released over night in this case more or less equalled the above 29 cases of 'service' emission in the course of leak detection (20.5 kg in eight garages).

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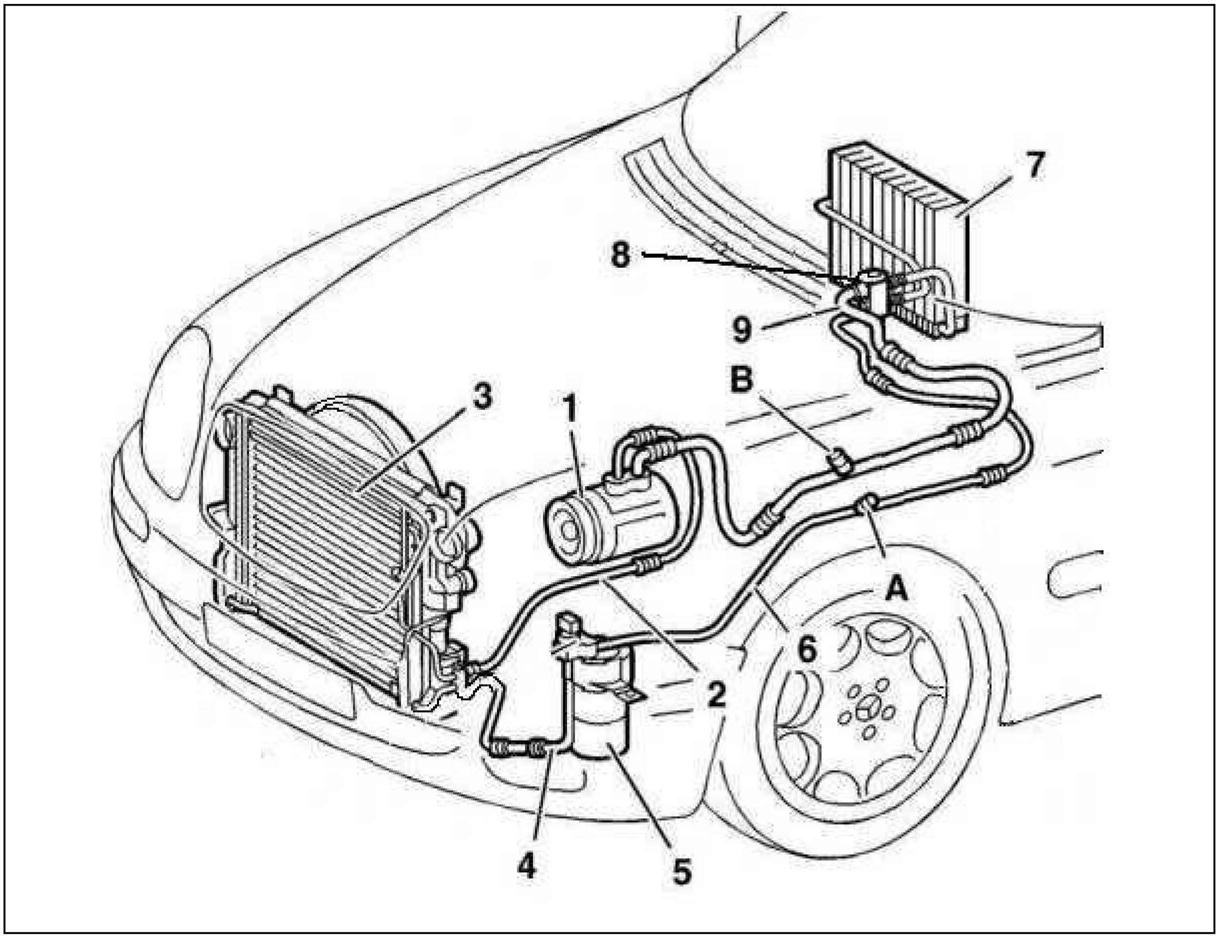
[5] The principal reason for their reluctance is concern that the tracer might damage the compressor. One thing that can definitely be said, however, is that the tracer dissolves in oil, not in refrigerant. The refrigerant sucked in by the recovery/recharging station's compressor is colourless when it reaches the reservoir tank.

[6] Obviously, pressure-based leak testing with nitrogen is a more environmentally friendly method of locating leaks than charging with refrigerant and contrast medium. One of the nine garages does not use tracer to locate leaks, with successful results according to the Record Sheets, in that none of them include any entry of multiple visits because of one and the same leak.

C. Reasons for Opening an Air-Conditioning System and Causes of Detected Refrigerant Loss



Picture: DaimlerChrysler 2001 (modified)

Fig. 2: Potentially defective components of a passenger-car air-conditioning system*

1. Compressor,
2. High-pressure line (gaseous) to condenser,
3. Condenser,
4. High-pressure line (liquid) to dryer,
5. Dryer/collector (with high-pressure and low-pressure switches),
6. High-pressure line (liquid) to expansion valve,
7. Evaporator,
8. Expansion valve for evaporator,
9. Intake line (gaseous) to compressor,

A. Service connection on high-pressure side,
B. Service connection on low-pressure side.

* Evaporator injection through expansion valve, not choke. If using choke, the collector would be downstream rather than upstream of the evaporator.

The Record Sheets document the refrigerant which a mechanic recovers from each vehicle (having opened its air-conditioning system) and measures with varying degrees of accuracy. Any shortage of refrigerant discovered on opening is therefore recorded at the same time, as difference between the quantity recovered and the standard level of charge. The rates of loss determined in this manner cover the whole spectrum from 0% to 100% (and sometimes above). While the explanation provided by the air-conditioning mechanic is not always that informative, the proportion of precisely recorded cases is sufficient in size to provide a picture of the principal reasons for opening an air-conditioning system.

In Table 1, all recorded rates of refrigerant loss are separated into small, medium and large volumes. The percentages of these losses out of all opened air-conditioning systems is shown in Column 2, their percentage of total refrigerant loss in Column 3.

Table 1: Percentage of small, medium and large refrigerant loss within total loss of 459.2 kg (841 systems)

Refrigerant loss	Percentage of all opened systems	Percentage of total refrigerant loss
small - less than 40%	39%	9%
medium - 40% to < 100%	23%	24%
large - 100% and over*	38%	67%

* Losses > 100% are attributable to multiple losses from the one system in the same year

Small losses (less than 40%) were found in about 40% of air-conditioning systems opened. This group's percentage of total refrigerant loss is just 9%. 'Total' losses of 100% and above represent the other extreme, also found in nearly 40% of opened air-conditioning systems but making up two thirds of total recorded refrigerant loss (see bottom line of Table 1).

I. Elimination of Leaks, the Main Reason for Opening on Total Loss of Refrigerant

Total loss of refrigerant results in failure of the air-conditioning system. Even before 'total' loss actually occurs, however, the system will already have come to a standstill when there is only about 100 to 200 grams left in its circuit. This is because extreme lack of refrigerant drops the system's high-pressure below about 2 bar (the setpoint value), on which the compressor is automatically switched off either by a special low-pressure switch, or by an internal control system. If there is too little pressure, the refrigerant will even begin to evaporate below zero degrees centigrade, causing the system to ice up. The compressor itself needs to be protected against running hot or clogging up, because lubricant also ceases to circulate once the refrigerant runs out. The driver himself will usually notice and report his air-conditioning system's lack of performance, nor can any such lack escape routine workshop-inspection using an electronic fault readout unit, which will register the fact that the compressor is switched off. For the mechanic, lack of refrigerant is the obvious diagnosis inducing him to start recovery with the recovery/recharging station so as to find and repair a leak in the system.

Air-conditioning systems suffering total loss of refrigerant are generally opened for one single reason, namely to remedy the cause of this particular kind of loss. That is the main reason. Which seems an obvious and trivial thing to say, but it isn't in fact, because the same does not apply to air-conditioning systems experiencing losses of less than 40%.

The cause of a total loss is mainly external, but can also be internal.

The cause is <u>external</u> where mechanical action from outside produces leaks in components of the refrigerant circuit. Such action would be an accident damaging the front panelling, or the impact of thrown stones. The condenser is by far the most likely component to be found leaking where loss is total, being placed well forward on the vehicle, right in front of the radiator.

The cause of a total loss is internal where a component, without being exposed to forceful outside influence, suffers an 'irregular' defect which creates an effective point of emergence for the refrigerant. This would not include normal wear and tear, to which every component is physically prone, but some unusual instance such as a burst or corroded compressor, a burst dryer, perforations in the pipeline, cracks in the evaporator, etc. What accidents or stone impact on the one hand and irregular component defects on the other share in common is an emissive pattern of damage.

The three recorded causes of total refrigerant loss were

1. accidents involving body damage (40%),
2. minor collisions, stone impact or internal emissive component defects (40 to 50%), and
3. unknown causes where the vehicle was simply recharged (10 to 15%).

1. Empty air-conditioning system after accident involving body damage

Accidents involving severe panel damage in the front region of the vehicle account for around 40% of recorded total losses. In the process, frontally positioned components of the air-conditioning system are pushed in and caused to leak - generally abruptly. The condenser is damaged in 90% of cases, sometimes the high-pressure lines connected to it too, and the adjacently fitted dryer.

Where an accident damages the body rather than the bumper, the vehicle is given to the body shop which, in addition to repairing the damaged panels, also replaces the defective components of the air-conditioning system. In such cases, the air-conditioning mechanic checks the system beforehand to make sure it is empty, then afterwards he checks it for leaks and recharges it with refrigerant.

The mechanic, completing his Record Sheet, may enter the whole operation in two stages: "Recovery: 0 g, recharge: 0 g" and then some days later - "Recovery: 0 g, recharge: 1000 g", adding the note "accident" each time. Or, alternatively, he may combine the whole operation into one entry: "Recovery: 0 g, recharge: 1000 g; Note: accident". Normally, he does not name the defective part, because he is not the person replacing it[7]*.*

2. Total loss due to stone impact or irregular component defect

Another 40 or 50% of total losses are attributable to leaks caused by a minor collision, an unnoticed knock from a stone, or an unusual component defect. The repair work is not given to the body shop in such instances, but is done by the air-conditioning mechanic himself, who then also makes a record of the replacement of components. Here again, the condenser

is a typical source of leakage, albeit that its leaks are mainly caused by stones. A thrown stone destroys the surface of one of the flat refrigerant-conducting tubes, which then corrodes (by pitting) at the point of impact. It takes at most a week for an emissive leak to develop, the process in fact being accelerated by damp or salty air passing through the condenser.

The Record Sheets would indicate that, at a rate of 40 to 50%, the condenser is the most frequent single cause of total refrigerant loss in the absence of panel damage, so it is also the component most frequently replaced by the air-conditioning mechanic himself; but by no means the only one, of course.

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[7] The absence of a second entry after the "Recovery: 0 g, recharge: 0 g, Note: accident" entry in the Record Sheet indicates total failure and dismantling of the vehicle - apart from occasions where the second entry may simply be forgotten.

Table 2 reproduces the order of frequency with which components are replaced, in so far as expressly documented in the Record Sheets (70 instances).

Table 2: Defective components causing total refrigerant loss and replaced by the air-conditioning mechanic himself (70 recorded instances - excluding accidents damaging body)

Component	Percentile share of components replaced by air-conditioning mechanic
Condenser	42%
Pipelines	17%
Evaporator	17%
Expansion valve	9%
Compressor	8%
Dryer	3%
Seals	4%

A replaced component is only listed here where it has been the prime cause of total loss. It is important to mention this, since some components may be replaced because of secondary defects. For instance, the dryer, which generally becomes inoperative once the air-conditioning system has been running empty for a while. The expansion valve, too, must often be replaced in consequence of some other component defect, in this case a defective compressor, whose chips can clog the valve. Piping often needs to be replaced as well, when the component (say the condenser, evaporator, or expansion valve) to which it is connected suffers damage.

While stone impact and accidents involving a minor collision bear the main responsibility for leaks in condensers (42%), and similarly affect the high-pressure refrigerant lines connected to the condenser (17%), leaks in the few other exposed components (41%) are far more rarely caused by outside influences. Where a defective compressor, expansion valve, dryer, connection or pipeline abruptly lets so much refrigerant through that total loss occurs, the reason is often 'irregular' internal damage, due, for example, to corrosion (including the electrochemical type), overload (excess pressure), or defective workmanship on the part of the manufacturer. It can also happen that components will be so severely damaged by a preceding lack of refrigerant (insufficient lubrication of the compressor, etc.) that they begin to leak of themselves, letting the very last of the refrigerant finally escape.

3. Total loss followed simply by recharging without repair work

Components of the refrigerant circuit are not always actually replaced when they leak, even where the work would be technically feasible or had even been begun (by adding tracer, for instance). In fact, about 10 to 15% of systems with total loss are simply recharged, the main reasons being

- customer failure to have the necessary work done, or to bring their vehicle in on the due date for inspection, hoping they will get by with just a recharge especially where a leak is thought just to allow a very slow escape of refrigerant;

- risk of renewed total loss after a simple recharge being taken, by customers who have to pay for the repair work themselves where out of warranty or not covered by goodwill, given that a recharge costs up to ten times less than a repair;

- customer reluctance to undergo time-consuming repairs, for instance because they are travelling on business and just want their air-conditioning system "quickly patched up" and running again;

- cases in which the mechanic simply cannot find a leak and therefore has no option but to recharge the system.

The characteristic shared in common by all "simple recharge" cases is that it proves impossible to identify a mechanical leak and associate it with a particular component, as a result of which the Record Sheet shows no record of a component being replaced.

II. Opening a System where Refrigerant Loss is less than 40%

Every car air-conditioning system (even when switched off) is subject to a certain degree of slow leakage of its permanently pressurised refrigerant through hose unions, compressor seals and connection seals, especially where such parts - like the functional components of the refrigerant circuit themselves - are subject to the irregular movements of engine and vehicle. This "normal" loss has no deleterious effect on operation of the air-conditioning system over time, especially in view of the relatively generous margin that exists for continued operation of the system despite some reduction in the original charge of refrigerant.

"Normal" refrigerant leakage has no real long-term influence on cooling capacity, at least for as long as exclusively <u>liquid</u> refrigerant continues to leave the collector where, normally, gaseous refrigerant from the condenser is finally separated out, and injected by the expansion valve into the evaporator. As is known, the cooling performance of the evaporator relies on the change in phase between liquid and gas. As soon as the refrigerant in the system falls below a certain level, the collector obtains too little liquid from the condenser and then loses its ability to separate saturated gas from the condenser to produce liquid refrigerant.[8] From this point on, gaseous refrigerant ("flash gas") extends up to the expansion valve, as evidenced by the formation of small gas bubbles in the liquid line between collector and expansion valve.[9] The expansion valve is not designed to conduct gaseous refrigerant and ceases to provide the evaporator with a steady supply. The evaporator, for want of liquid refrigerant, can no longer produce its cooling effect. The process proceeds fairly swiftly once begun, continuing until the system virtually stops delivering cooled air (Haussmann, 2001).

The level of refrigerant loss below which an air-conditioning system will cease to work is not a fixed quantity. After all, 'cooling' is in the first place a matter of subjective feeling, and in the second place, a system's capacity to continue operating on a given volume of refrigerant will depend objectively on its technical design, viz. the capacity of the collector, the length of the liquid pipeline between condenser and expansion valve, etc. Nonetheless, a rough order of magnitude of "around 40%" can be presumed, which means that in the individual situation, one system might work just as well with a 45% loss as another one would at 35%.

The "40% mark" standing for <u>low loss of refrigerant</u> is based on the experience of mechanics[10] interviewed in the course of our study, who reported that a level of 60% is the bottom limit above which a passenger-car air-conditioning system will still be marginally able to operate sufficiently well unless it contains some other defect (see Chapter D).

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[8] The process of undercooling the refrigerant to prevent undesirable evaporation also fails in this context, because it can only occur in the liquid phase. Temperature then begins to rise.

[9] In systems having a choke (orifice tube), where the collector is arranged upstream of the condenser (and after the evaporator), flash gas forms in similar fashion on shortage of refrigerant.

[10] The mechanics generally considered that an air-conditioning system will no longer work normally once it reaches "half its level of refrigerant", but that its performance already begins to fall off so much beforehand that the driver readily notices it is failing.

As we saw above, air-conditioning systems suffering total loss of refrigerant are opened to find and rectify an 'irregular' cause of emission (a leak, so to speak). In contrast, refrigerant losses of less than 40% do not generally give occasion to open the system. It is not the goal of vehicle inspection to arrange for "a system to be as full as possible". Routine measurements are omitted[11], especially since the whole volume of refrigerant has to be recovered and recharged for the purpose (there are as yet no other methods of conducting this measurement). As a result, refrigerant loss less than 40% goes unnoticed in the majority of the vehicles passing through a workshop (unlike the case of 'total' loss).

Despite this, the Refrigerant Record Sheets reported 40% of vehicles with opened air-conditioning system as having a rate of loss of less than 40% (see Table 1). The reasons for opening these particular systems are substantially different from those associated with 'total loss', however, being four in number:

1. replacement of components not causing refrigerant loss (32%),
2. air-conditioning system hindering repairs to engine and cooling system (22%),
3. location of damage and preparatory work in advance of body repairs (24%), and
4. leak tests on customer's or workshop's initiative (30%).

It should be clearly emphasised that these were simply reasons for opening the air-conditioning system, and not causes of refrigerant loss already perceived - as would in fact be the case on 'total loss'. Although refrigerant loss is always made up when recharging, seeking the cause is not the primary concern when the loss is only slight.

1. Component defects not themselves responsible for release of refrigerant

Component defects adversely affecting operation, unusual behaviour of the air-conditioning system accounted for 32% of recorded recoveries from systems which still contained sufficient refrigerant to operate properly (loss being less than 40%). Total failure of the system was exceptional. Fault diagnosis was based here, for instance, on unusual noises (rattling compressor, whistling expansion valve), unpleasant odours (condensed water encouraging development of bacteria on the evaporator), erratic operation due to constant restarting of the compressor (because of insufficient supply of refrigerant and oil through a clogged refrigerant circuit) or the fan (continuously re-activated by the high-pressure switch due to reduced heat-exchanging capacity of a dirty or clogged condenser), etc. Unlike the 'total loss' defects, component faults of this kind are only indirectly associated with the tightness of the refrigerant circuit, if at all. Such "non-emissive" defects in components replaced by an air-conditioning mechanic are manifestly different from the "emissive" component defects causing total loss.[12]

Table 3: Percentages of components replaced because defective in systems where refrigerant loss is < 40% - 48 mentions (compared with 'total loss' percentages*)

Replaced component	Refrigerant loss < 40%	Total loss of refrigerant*
Compressor	63%	8%
Expansion valve	16%	9%
Evaporator	5%	17%
Condenser	5%	42%
Seals	5%	4%
Dryer	3%	3%
Pipelines	2%	17%

* excluding 'total losses' with body damage, where the condenser is replaced in 90% of cases.

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[11] Except for diagnosis of electronic faults, the air-conditioning system test on inspection is mostly limited to a brief manual examination of the flow of cold air from the evaporator during a test drive with air-conditioning system switched on. Some mechanics briefly press down the valve of the high-pressure service connection to check the outlet pressure of the refrigerant.

[12] See Waeco 3/2000b for summary of most frequent air-conditioning-system defects, their causes and their possible remedies.

The centre and right-hand column of Table 3 below show how significantly the list of components replaced where loss of refrigerant is slight differs in order of priority from the series of component defects producing total loss without damage to the bodywork.

The compressor is by far the most frequently replaced of components (64%) where refrigerant loss is low, unlike the 'total loss' situation where the same unit makes up only 8% of replacements. The opposite can be said of the condenser, which only accounts for 5% of component defects associated with less than 40% loss, while it constitutes 42% of defective parts where loss is total (in cases not involving panel damage). Evidently, damage to the compressor (defective magnetic coupling, faulty control valve, seizing piston, penetrating humidity) is less likely to result in emissive leaks - and tends more to be contained within the component itself - than faults in the condenser, which almost always result in abrupt emergence of refrigerant.[13] This bears out the assumption that component defects falling within the low-loss category are different by nature from defects that lead to high or even total loss.

2. Air-conditioning system as obstacle to engine or radiator repairs

About 22% of all recoveries from an air-conditioning system that had not yet lost 40% of its refrigerant were performed not because of the system itself, but because it left other components inaccessible. In 17% of these cases, the air-conditioning system was in the way when dismantling and re-installing the engine, while on 5% of occasions, it created a problem

when dismantling and fitting the radiator. Condensers and high-pressure lines were the main items requiring temporary removal. In such instances, an air-conditioning system is not actually opened because it is losing refrigerant, even if such loss may well be found in the process and duly rectified.

3. Establishment of accident damage and preparation for bodywork repairs

About 24% of recoveries in which less than 40% refrigerant was found to have been lost were performed on vehicles that had been in an accident.

Just as there are 'emissive' and 'non-emissive' component defects, accidents can also be 'emissive' or 'non-emissive.[14] Accidents affecting the front of a vehicle can damage the air-conditioning system severely, this being the main cause of 'total' loss of refrigerant. However, even an accident involving serious damage to panelling can also leave the air-conditioning system undamaged, or simply buckle its more exposed components.

Accordingly, there are two reasons for recovery from an accident vehicle. Firstly, the process serves to locate possible damage (loss of refrigerant) to the air-conditioning system, and secondly, the refrigerant must in any case be removed from the system before the vehicle is handed over to the body shop. An air-conditioning system cannot be welded or soldered when full, nor can welding or soldering work be done on the vehicle - or oven-drying after repairs to paintwork - because of the risk that portions of the system might heat up, the heat then producing excess pressure that could destroy its components. Furthermore, the refrigerant might produce decomposition products which are not only toxic, but can

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[13] The condenser may suffer a 'non-emissive' defect when it is merely bent or dented in the course of a minor collision, without actually developing a leak. This component may also have to be replaced where heat exchange is inhibited by severe soiling, if the mechanic is concerned that steam-jet cleaning might damage its fine blades.

[14] Fischer (1997) had already distinguished between accidents destroying the air-conditioning system, and those leaving it undamaged.

also corrode piping and other parts of the system. The principal culprit here would be hydrogen fluoride (HF).

4. Leak tests at customer's or workshop's initiative

The level of refrigerant in a system had only been measured as a 'side-effect' in all of the recoveries mentioned so far, whereas recovery in about 30% of cases was directly aimed at (preventive) measurement of the refrigerant level.

Two thirds of these 'direct measurements' were carried out at the request or on the complaint of the customer, the principal motive being dissatisfaction with the cooling effect ("not cooling properly").[15] The interesting point is that these measurements revealed only about 10 to 15% loss of refrigerant on average, with just a few exceptional figures of up to 30%. In other words, it is unlikely that cooling capacity would have noticeably improved after recharging. I suspect, myself, that customers complain so often about deficient working of intact air-conditioning systems because they expect far more of these systems than they can actually provide.

One third of these measurements were made at the initiative of the mechanic, often because of the (unconfirmed) suspicion that a system fault whose cause was not otherwise to be found could in fact be due to lack of refrigerant.

III. Consequences for Method of Estimating the Rate of Emission

Even leaving out the 'middle' group of refrigerant losses between 40 and 99% (where specific reasons for opening the air-conditioning system overlap and are more difficult to distinguish), our analysis of system openings in connection with total loss and losses of less than 40% provide an important foundation for the principal goal of this study, namely the estimate of the annual rate of emission from passenger-car air-conditioning systems based on empirical findings.

The two results of our ideally typical[16] comparison of air-conditioning-system openings are

firstly: high ('total' in this instance) loss of refrigerant is attributable to 'irregular' defects in the refrigerant circuit. The resultant leak causes the air-conditioning system to fail. The system has to be opened, this being arranged and done right away in the direct aim of remedying the source of loss; and

secondly: limited loss (assumed as up to 40% of the standard charge) does not in itself cause failure of the air-conditioning system. Loss of this kind is merely detected indirectly, when opening a system for reasons other than remedying the source of loss - for instance the replacement of internally defective components, provision of access to the engine, emptying the system for work on the body, and preventive checking of the charge level.

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[15] One exception would be the vehicle owner wanting to know if his air-conditioning system was still refrigerant-tight after rubber components had been nibbled by martens (incidentally, the system had not lost a single gram of refrigerant). Another was the driver wishing to be reassured of a full system before holidaying in a southern climate - an unusual case.

[16] It should be clearly borne in mind that this comparison is 'ideally typical' because in reality, there is no sharp, distinguishing line to separate 'high' loss from 'low'. 'Total' loss may also be due to a 'regular' and not very emissive defect persisting over a sufficiently long period of time. Likewise, refrigerant loss less than 40% may be attributable to 'irregular', emissive damage which simply did not have sufficient time to permit any higher emergence of refrigerant.

In connection with the first of these two results we found that in principle, workshop records - provided they have been kept continuously for one year - document all instances of repairs to irregular leaks. Accordingly, they cover the sum of 'irregular' emissions produced by all of the air-conditioned vehicles serviced by the workshop in question. An annual rate of irregular emission can therefore be determined from these records (see Chapter E).

The second result shows us that refrigerant loss of less than 40% is not generally attributable to 'irregular' damage, but, in principle, to regular leakage consequent on the design and mode of operation of mobile air-conditioning systems. Since these losses do not interfere with the system's operation, they are not usually measured directly. Some, however, are measured indirectly in the process of recovery, representing an unintentional but thoroughly usable random sample of 'normal' emission. An annual rate of regular emission can be determined from these measurements (see Chapter D).

Together, the annual rates of 'irregular' and 'regular' emission go to form the total annual rate of emission.

D. The Annual Rate of Normal Emission

I. Regular Loss of Refrigerant from Intact Air-Conditioning Systems

'Regular' refrigerant loss does not mean that emission will take an identical course in every single air-conditioning system. For instance, the period of time for which individual systems remain switched on scatters widely about a mean of 150 hours per annum (Taxis-Reischl 2000). Then the life of a vehicle's engine (as it undergoes vibration and the development of heat), actually a more important aspect in the context of normal leakage, also varies widely about an average of 450 hours (in the same year, 1997) - and this is not allowing for mileage or for traffic conditions. Another factor would be the driver's personal style at the wheel, which will have a varyingly stressful effect. Again, the way the air-conditioning system is handled and used has a part to play[17], and the ambient temperature co-determining a system's pressure is not the same for every system (car garaged or parked in the open). Moreover, the quality of workmanship in one air-conditioning system is very rarely quite the same as in the next.

As starting point for the statistical analysis provided below, it has been taken that, while 'regularly' emitting car air-conditioning systems - originally charged ex-works with refrigerant R-134a (from 1993 on) - may have lost varying quantities of refrigerant up to the measurement period 'mid 1999 to mid 2001', as a general rule they still contain enough to permit normal operation - provided they are free of any 'irregular' defect.

In a first approximation, air-conditioning systems found to have lost less than 40% refrigerant were duly selected from the study population and deemed to be 'normally' or 'regularly' emitting systems, because to go by the experience of interviewed air-conditioning mechanics, 60% of the original refrigerant charge is the mean limit at which a system is still marginally intact - see Chapter C, Section II.

Bearing in mind its technical imprecision, the '40% Mark' should be applied with a margin of error extending above and below, as necessary statistical aid for want of more suitable criteria governing the quantity of refrigerant deemed "sufficient" or "no longer sufficient" for a system's continued operation. Another factor to be taken into account is the general imprecision, discussed in Chapter B, in the measurement of recovery volumes (deviation by up to 50 grams is usual) and therefore inherent in all empirically determined rates of loss. The present study deals only with general orders of magnitude, not with absolutely exact quantities.

The average refrigerant charge in air-conditioning systems having losses of less than 40% is 825 grams, consequently being somewhat lower than in all 678 fully identified vehicles (where the average is 848 grams). See Chapter A. 7. The charge for Brand 1 is 738 grams, for Brand 2 it is 831 grams, and for Brand 3, 898 grams.

II. All 282 Emission Rates of < 40% as a Function of Vehicle Age

Plotting the rate of loss recorded (as difference between recovered quantity and standard ex-works charge) at the time of opening all air-conditioning systems whose age could be determined and which had lost < 40% refrigerant (282 units) against the period elapsing since the vehicle's first registration, the scatter diagram (Diagram 2) shows hardly any relation between the two quantities.

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[17] Only a minority of drivers occasionally run their air-conditioning system for brief periods during the cold part of the year. This is an important way of caring for hoses and seals, allowing oil and refrigerant to pass through them and protect them from drying out, becoming brittle, and therefore ageing more rapidly.

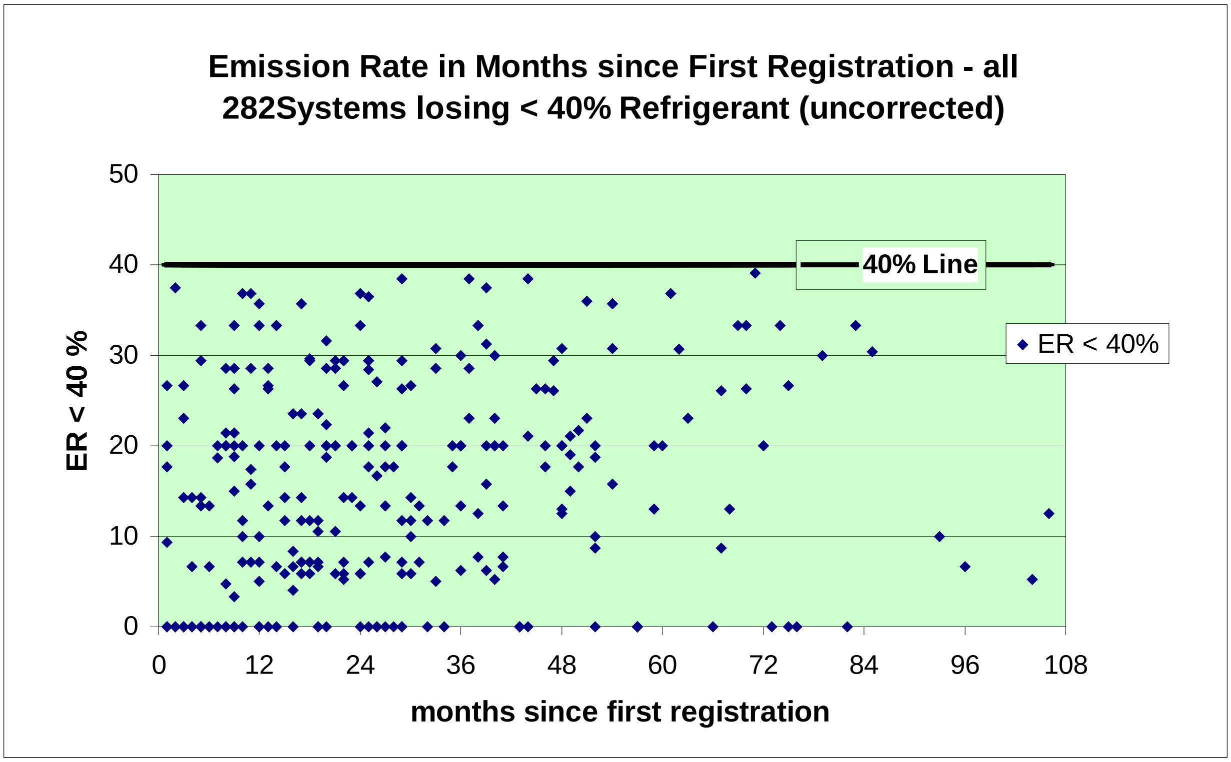

Diagram 2: Emission rates (rates of loss) of all 282 systems losing < 40% refrigerant (uncorrected) in months since first registration. The data points of the 282 individual emission rates are broadly scattered below the 40% Line without taking any clear direction. The only significant factor is their anticipated accumulation on the left of the x-axis, workshop visits being concentrated on the first 48 months duly covered by warranty or goodwill provisions. ER = emission rate.

Diagram 2 reveals a diffusely scattered point cloud below the 40% Line. The only significant factor is the expected accumulation to the left of the x-axis, 82% of workshop visits being concentrated within the first 48 months, which are still covered by warranty or goodwill arrangements.

There is still no clear trend to be discerned on calculating the average figure per year (mean value for months 0 to 12, 13 to 24, etc.) of the widely scattered individual loss rates

The annual averages do generally continue to rise up as far as the seventh year, from 13% to 24%, but then they fall back again to the initial figure in the following two years - see Diagram 3.

The 'annual averages' curve making its way through the point cloud of 282 "monthly emission rate" combinations fails to reveal any dependence of emission rate on vehicle age.

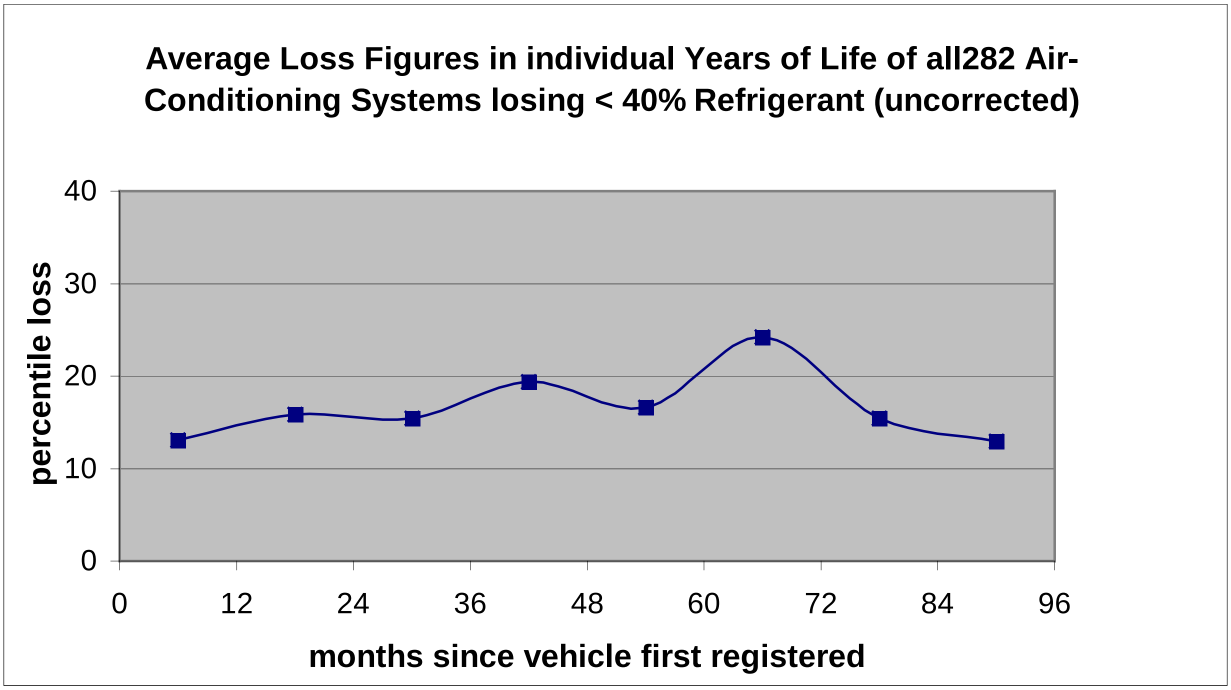

Diagram 3: Trend by month of emission rates under 40% (uncorrected). The path of the curve leading through the point cloud of Diagram 2 (*q.v.*) reveals nothing specific to indicate a dependence of emission rate on vehicle age. The rise observed up to the seventh year (between months 54 and 66) stops, and then the curve drops back down again.

Diagrams 2 and 3 demonstrate that while concentration on air-conditioning systems losing less than 40% refrigerant may be a **necessary or unavoidable means** of identifying exclusively 'regular' or 'normal' emission**, it is not in itself sufficient**. The sources of emission in our 282 air-conditioning systems losing less than 40% refrigerant are clearly not all of a 'regular' nature, so the next stage in the study was to make a correction, attempting to eliminate systems with 'irregular' refrigerant losses from the total figure.

III. Statistical Correction of Normal Emission Rates

Of the 282 air-conditioning systems losing less than 40% refrigerant, 216 (77%) still remained after statistical correction aimed at restricting the number of cases to genuinely 'regular' emissions. For me, this selection represents our unintentionally made random sampling of car air-conditioning systems (a) sufficiently charged with refrigerant and (b) solely producing 'normal' emission. Seven of the 66 eliminations were based on the explanation given in the Record Sheet, and then there were 59 anomalies either above or below the line.

1. Recognisable as 'irregular' from the Record Sheets: seven cases

In three of these cases, the mechanics' notes in the Record Sheets made it possible to categorise refrigerant loss < 40% as 'irregular'. Twice the notes expressly indicated leaks in the compressor, and once they recorded an accident as cause of 20% emission (a year and half after first registration). In a further four cases, the Record Sheets indicate previous losses in preceding years, which, when added to the loss in the current year (2000, 2001), produce more than 40% leakage of refrigerant and can therefore be taken out of the equation.

2. Eliminating anomalies above and below the line: 59 cases

Most of the 'irregular' cases of emission were identified as anomalous peaks or troughs when we applied a plausible criterion.

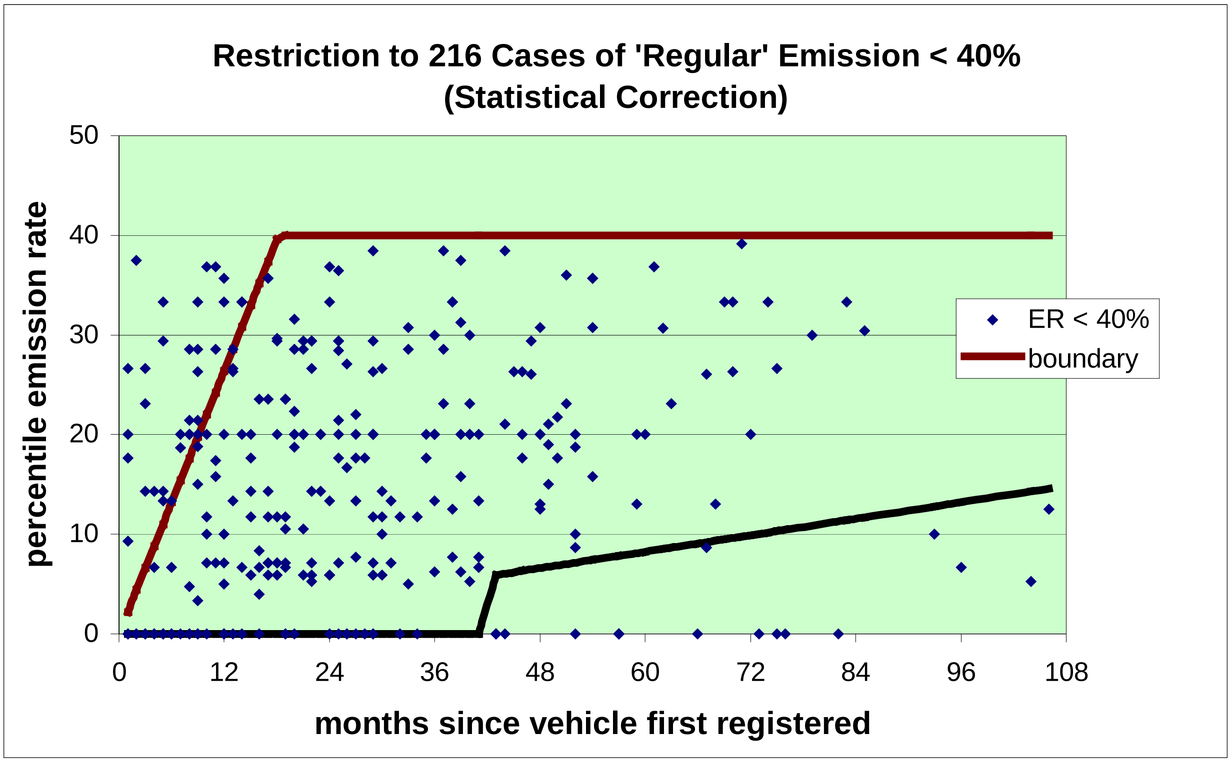

Diagram 4: Restriction to 216 cases of 'regular' emission < 40%. The diagram shows the same 282 cases of emission as in Diagram 2, but, following statistical correction, 66 of them are now outside the boundary (outside left and bottom right) and 216 are left inside. Basically, cases of emission are conditionally eliminated as 'irregular' where they are either four times higher or four times lower (measurements of that order first occurring after 42 months) than the average.

Losses amounting to four times the average (before correction) are classified here as abnormal peaks. This factor is not based on any general statistical rule - indeed, in the final analysis, it is somewhat arbitrary. Importantly for me, though, I feel it is high enough to prevent any emissions that might in fact be 'normal' from being ruled out as being 'irregular'. To my mind, emissions of over four times the average would seem to be so excessive that they are highly likely to have their source in an 'irregular' defect.[18]

The average loss per month is 0.55% - which is 5.5% after ten months. Constellations like "10 months / 22% loss" can therefore be eliminated (22% being 4 x 5.5%). 38 cases met this criterion for anomalous peaks. 33 indicated losses of over four times the average in the first year, six more reaching this level

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[18] Reducing the factor 4 to 3 for anomalies above the line and, correspondingly, from ¼ to 1/3 for those below would only just about exclude no more than six further cases (three up and three down), so I did not think there was any particular benefit to be gained from this kind of preliminary restriction of the range of emissions.

after at most 17 months. By definition, anomalous peaks are to be found only during the first 18 months of vehicle age, the 40% emission limit being exceeded after 19 months and air-conditioning systems above that limit no longer being taken into consideration.

Emissions amounting to no more than a quarter of the average rate of loss (before correction) were deemed to be anomalous troughs. Such low emissions as these are regarded as unrealistic, since it would have to be assumed that air-conditioning systems falling under that heading would have suffered some previous loss. However, this criterion only applies to emissions from vehicles older than 3.5 years or 42 months. All lower losses up to that time are regarded as 'regular', including the numerous 'zero' emissions.

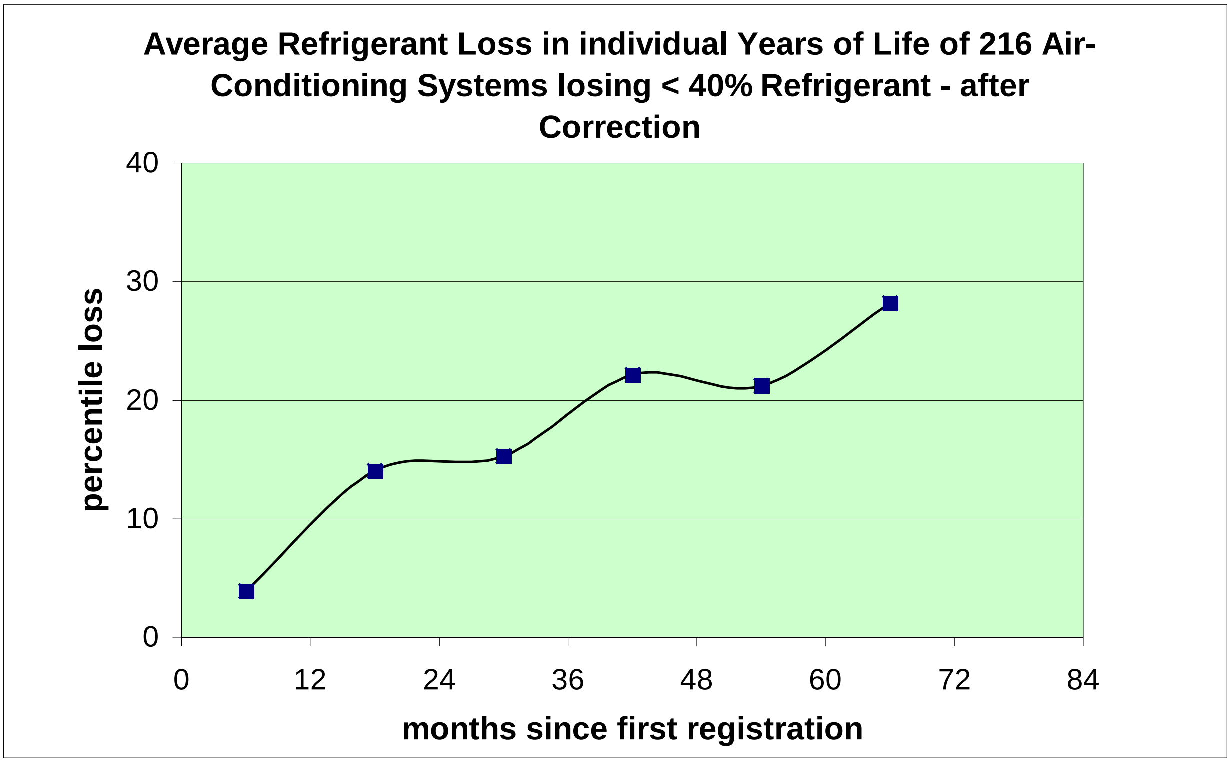

Diagram 5: Average refrigerant loss in individual years of life of 216 air-conditioning systems losing < 40% refrigerant, after correction. The curve now shows a clearly rising trend, passing from about 4% (the mean for the first 12 months) to just under 29% (the mean for months 60 to 72), even if the rise is briefly interrupted between the 48th and 60th month. Our correction leaves us with no meaningful average for the period after seven years, because there is only one instance of loss left in that period. Compared with Diagram 3 (uncorrected trend), the scattered annual averages for the 'corrected' cases now follow a distinct principal direction going from bottom left to top right. The curve is neither moved up by overly high emission rates to the left, nor forced down by understated rates to the right.

After 42 months, zero losses are in the first place unlikely, and in the second place, 42 months was the maximum period for which I had an unbroken record of the opening of air-conditioning systems. The eliminating criterion 'less than a quarter the average loss of 0.55% per month' first began to take effect in the 43rd month, duly identifying 20 anomalous troughs (14 zero losses and 5 losses of less than 10%). Only one of these cases exceeded 10% (actually 12%), being found after 106 months. That case was eliminated like the others because, although nothing can be proven in the absence of relevant data, it is highly likely to be associated with a previous loss.

The corrected cases of emission are to be found inside the boundary in Diagram 4. The location of the anomalies above and below the line is graphically obvious, the excessive emissions of the first year and a half being left outside to the left, and the understated emissions after the first three and a half years appearing at bottom right. Diagram 5 shows at first glance that, where combined to produce annual averages, the emission rates left after eliminating the 59 anomalies (and the other seven 'irregular' cases) follow a definite upward trend in pace with the life of the vehicle - unlike the situation in Diagram 3. It is my opinion that the corrected cases furnish suitable foundation material for the attempt made in Section IV to arrive at a quantitative determination of the annual rate of normal emission.

IV. The corrected 6.3% Annual Rate of Normal Emission

The annual rate of normal emission is calculated from the 0.523% monthly average of all 216 corrected emission rates during the period 0 to 85 months, being twelve times the monthly average, viz. **6.3%**. Specifically, this rate of emission applies solely to air-conditioning systems in vehicles up to seven years old, and is subject to some degree of uncertainty on account of the rather arbitrary choice of correction factor. The rate comprises the emission of all three car brands taken together, distinctions between them being examined in Section V below.

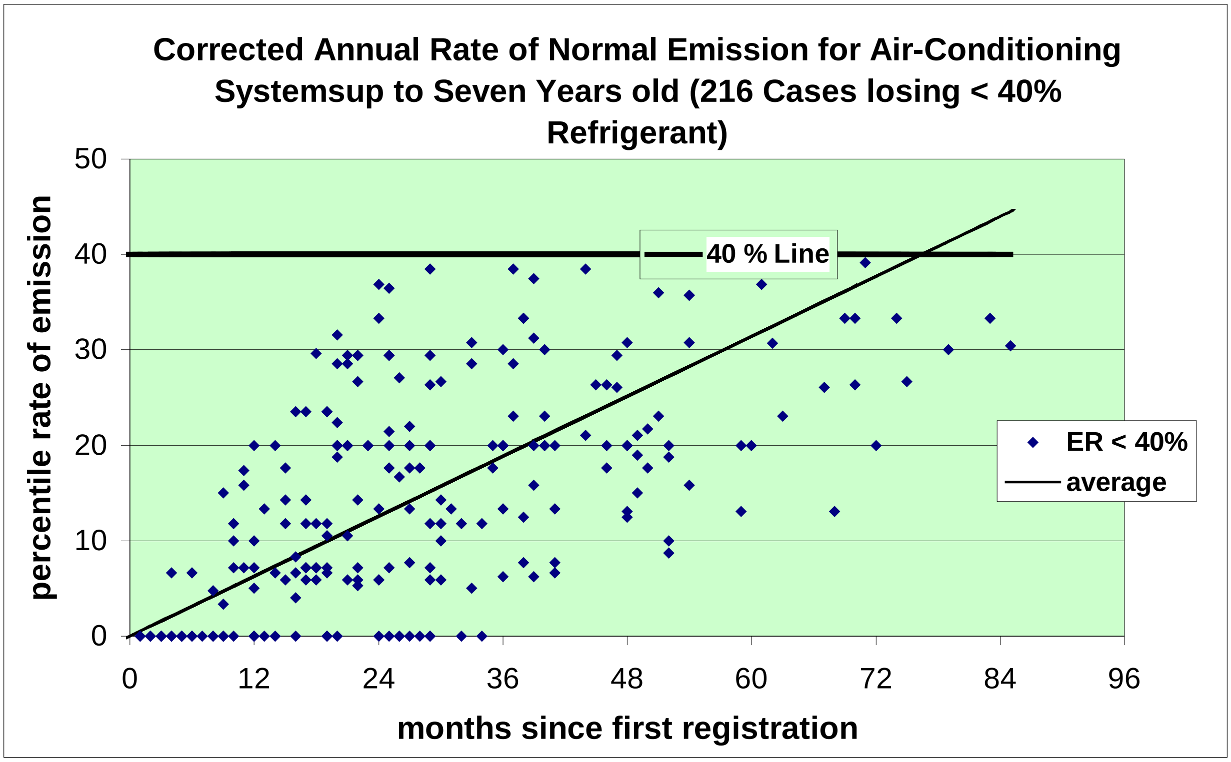

Diagram 6: The annual rate of normal emission from all 216 systems losing < 40% refrigerant (corrected). The amount by which these normal emissions increase each year is the 'annual average refrigerant loss' from all corrected cases, so it appears as a straight line in the graph. The rate is 6.3%. The straight-line average extends from intersection-point zero to intersect with the 40% Line after 76 months. Incidentally, because of this 40% barrier, data points after the 76th month are always below the straight-line average, never above it, which lowers the average mathematically.

Plotting the monthly 0.52% or annual 6.3% along the x-axis (months since first registration of vehicle), a straight line is produced which intersects the 40% Mark (still just enough refrigerant) after 76 months (76.4), i.e. after six years and five months.

Since the 6.3% figure is an average calculated from widely scattered individual cases, duly compensating for major variations upwards and downwards, it would not of course be true to say that in practice, all car air-conditioning systems will come to a standstill after 76 months. Drivers' experience would indicate to the contrary, one having visited the workshop as often as two times in seven years on account of his air-conditioning system, another never having been there at all. (A third driver had his air-conditioning system charged elsewhere, this case not being examined any further in our study). However, the figure does mean that - leaving aside any of the other empirical inaccuracies of the present study - on average 6.3% of the original refrigerant charge is lost by other than 'irregular' means when we take the first seven years as our base line.

V. Differences in Normal Emission between the Three Car Brands

The following three diagrams (7 to 9) show the normal annual emission rates for each of the study's three brands of car. It should be emphasised that the cases are not sufficient in number to let us draw any direct conclusions from them (or from their average) with regard to the situation in reality. However, the indicated differences are none the less important for all that, allowing us as they do to see how the annual rates of normal emission range upwards and downwards.

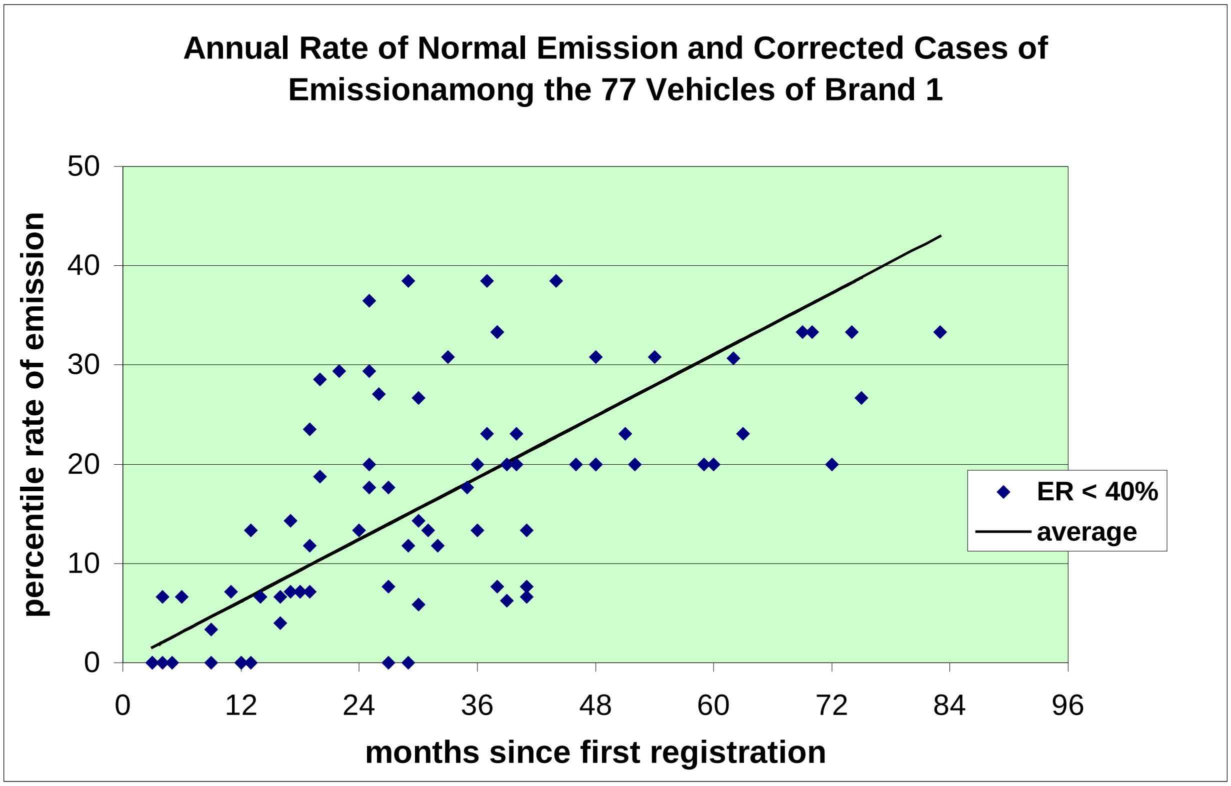

Diagram 7: Annual rate of normal emission and corrected cases of emission among the 77 vehicles of Brand 1. Conditions for Brand 1 are almost the same as in the overall selection - monthly rate: 0.52%; annual rate: 6.2%; 40% Line intersected after 77.3 months.

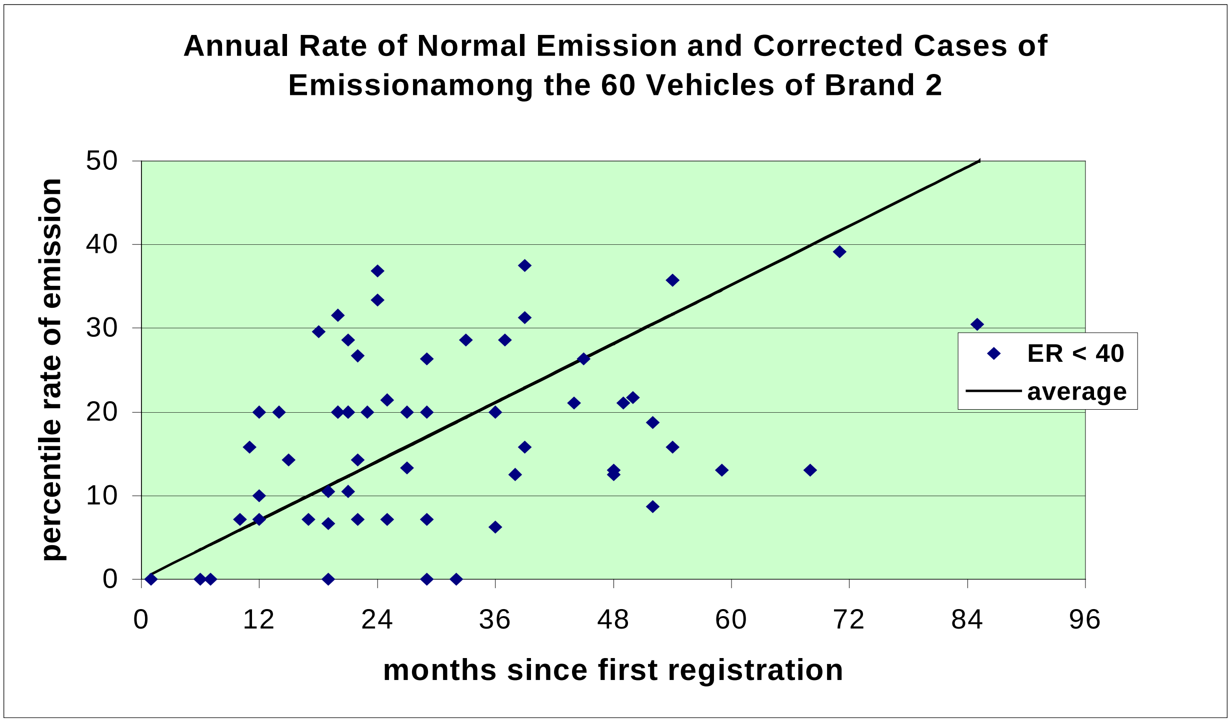

Diagram 8: Annual rate of normal emission and corrected cases of emission among the 60 vehicles of Brand 2. Brand 2 indicates the highest emission rates - 0.59% per month and 7.0% per year. The 40% Line is intersected by as early as 68.2 months.

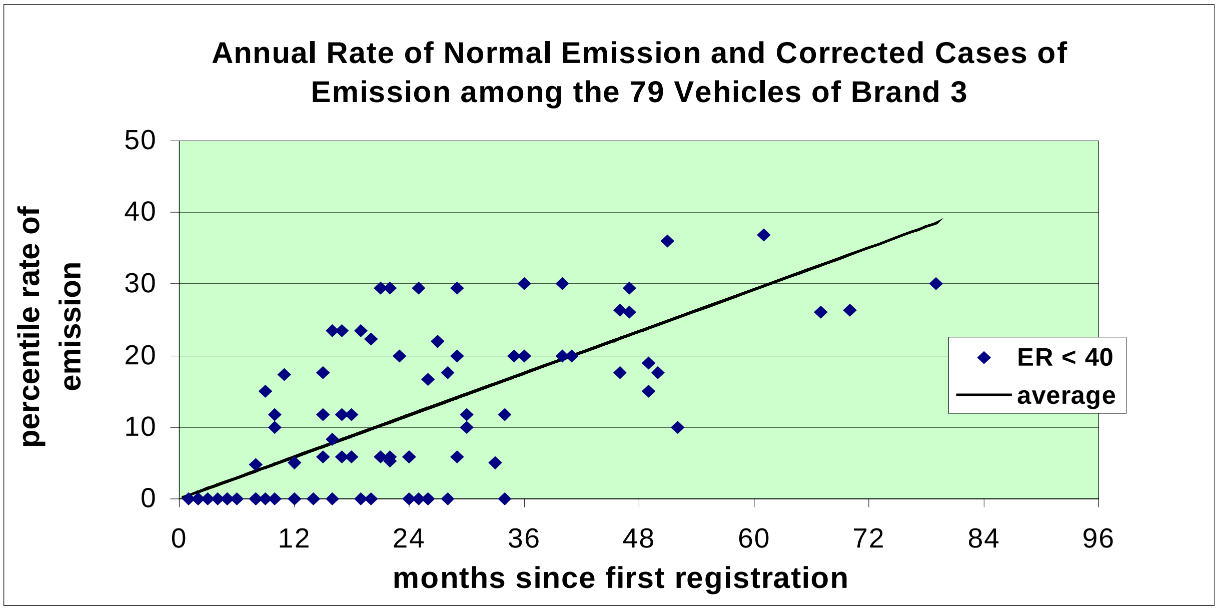

Diagram 9: Annual rate of normal emission and corrected cases of emission among the 79 vehicles of Brand 3. Brand 3 has the lowest emission rates of the whole population, being just 0.49% per month and 5.8% per year. The 40% Line is intersected by as late as 82.1 months.

The annual normal rates of emission differ by more than 1% (ranging from 5.8 to 7.0) between the three brands of car. The 40% Line is intersected after 68 months by Brand 2, but not until after 82 by Brand 3.

VI. Car Manufacturer Specifications concerning Normal Leakage

Placed in relation to the average 825 gram charge of air-conditioning systems losing less than 40% refrigerant (see introduction to the present Chapter D), the annual average of 6.3% represents a <u>normal</u> (not total) refrigerant leakage level of <u>52 grams per year</u>.

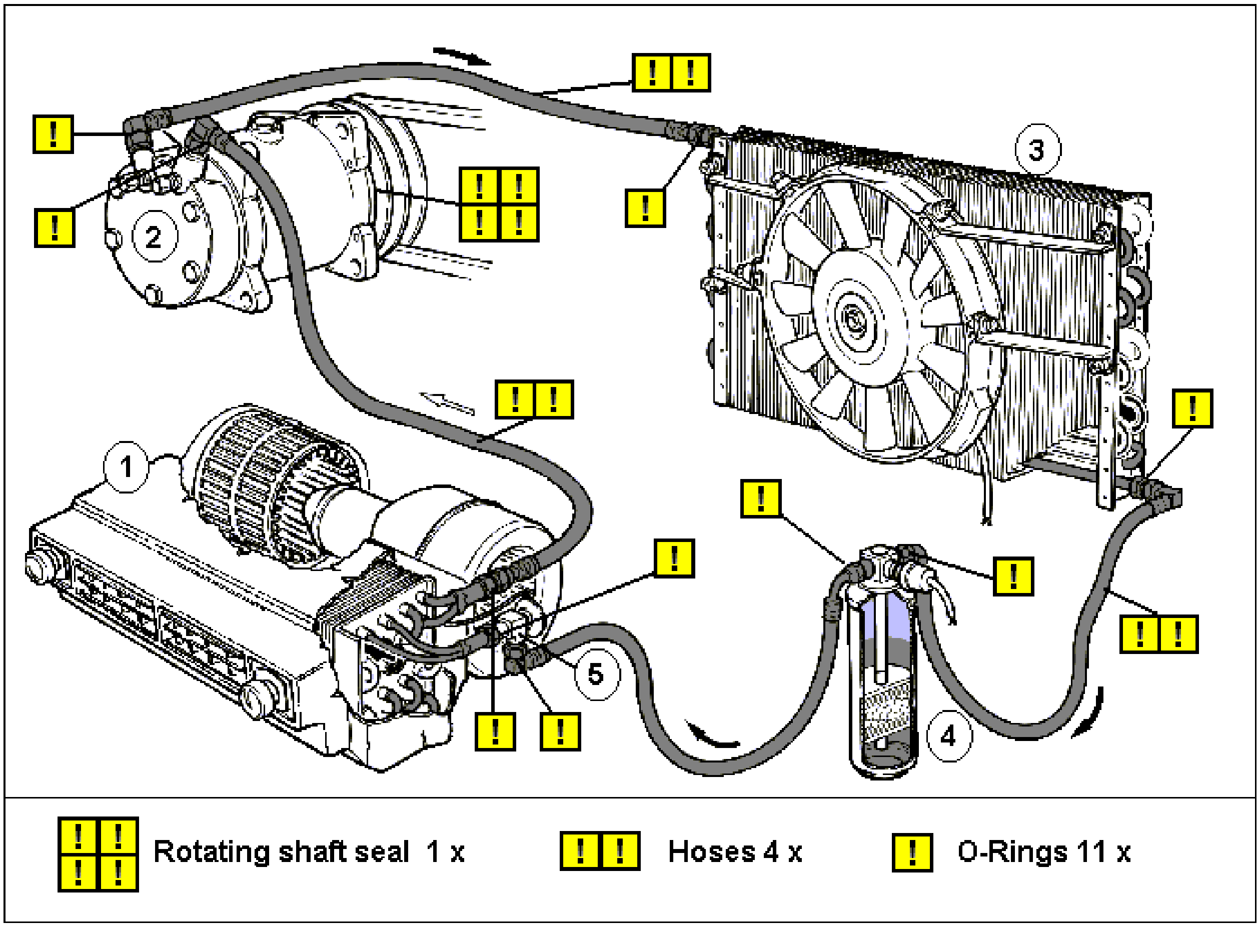

Fig. 3: Car air-conditioning system showing the principal points of R-134a emergence under the conditions of normal refrigerant leakage stipulated by the car manufacturers. An annual leakage of at most 10 to 30 grams is admissible from the shaft seal of the compressor (4 exclamation marks), altogether 10 to 20 grams (two exclamation marks each) from the hose system (the illustration shows four hoses), and 2 to 3 grams from each O ring (there are eleven such sealing rings in the illustration). Adding up the figures, annual losses of from 42 to 83 grams are considered "normal" in the system illustrated. The number of exclamation marks (!) stand for the relative importance of the particular source of leakage. Refrigerant circuit: 1 = evaporator; 2 = compressor; 3 = condenser; 4 = collector/dryer; 5 = expansion valve.

Source: WAECO (modified).

According to the suppliers of complete car air-conditioning systems (Air-Conditioning Conference - 2001), car manufacturers specify margins - for the leakage of refrigerant through seals and hoses - within which a car air-conditioning system will be accepted as "refrigerant-tight". Under these specifications, the annual loss of refrigerant must be kept within the following bounds:

- compressor shaft-seal: 10 to 30 grams,
- flexible hose lines: 10 to 20 grams, and
- each O ring at connections to components: 2 to 3 grams.

The number of connections to the components 'compressor', 'evaporator', 'condenser', 'dryer' and 'expansion' valve' (all of which can be dismantled), and therefore the number of O-ring seals, varies from seven to eleven according to system design. Accordingly, normal leakage through the O rings is allowed to vary between 14 and 33 grams.[19]

The annual loss of refrigerant accepted by the car manufacturers amounts to between 34 and 83 grams when all three sources are added together.

The average 52 grams the present study has defined as normal emission per year per air-conditioning system over a period of seven years in use comes about midway in relation to the manufacturers' overall allowance. Far from contradicting the car makers' stipulations, the study figure confirms how closely they approach reality.

Looking at matters in reverse, the allowances confirm how close to reality is the result arrived at from the selected workshops' Record Sheets, ranging as it does from 46 grams (Brand 1) to 58 grams (Brand 2) among the three car brands. The normal annual loss recorded for Brand 3 coincides with the average loss figure of 52 grams.

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[19] Integration of the dryer with the condenser, an approach already to be found at the present time, saves on two connections and therefore on sources of loss amounting to about 5 grams. The same can be said of integrating the expansion valve with the evaporator. Then the widely introduced reduction in the proportion of elastomer connection lines between components in favour of aluminium piping has also reduced normal leakage. However, there are limits to the replacement of hoses with pipes, in part because of the better heat and sound insulation provided by flexible elastomer lines. In fact, the single line most severely exposed to high pressure (up to 20 bar) and high temperature (the gas being "superheated" to above 100 °C), the pressure line from compressor to condenser, lends itself least to being replaced with a metal tube, because not only does it need to be very large in diameter and highly flexible, it must also be capable of compensating for the vibrations of the engine to which it is connected.

E. The Annual Rate of 'Irregular' Emission

The approach I took when determining the 'normal' rate of emission was an indirect one. The data obtained on refrigerant recoveries from car air-conditioning systems losing less than 40% served as a "workshop sample" of vehicles which, for the most part, had not in fact visited the workshop primarily because of a problem with their air-conditioning system. The situation is otherwise for 'irregular' emission, which makes itself felt in the form of obviously faulty behaviour or functional failure, readily noticeable to the driver when switching on. A visit to the workshop inevitably follows, even if after some delay which may indeed extend to several months in the colder part of the year (see diagram in Chapter A).

It has been taken as a starting point for the following series of estimates that, on principle, 'irregular' cases of emission (whose treatment necessarily calls for an opening - recovery and recharging - of the air-conditioning system) are dealt with by the originally designated workshop, which, where Record Sheets are kept, will also document the process. The 'non-normal' emissions contained in the Record Sheets (namely all refrigerant losses of over 40%, and those under 40% that were eliminated by the correction described in Chapter D) therefore directly represent the entirety of 'irregular' emissions from - basically - all vehicles making up the regular 'client fleet' of a particular workshop.

I. Inspections as Reference Quantity for Cases of Irregular Emission

In terms of volume, the 'regular client fleet' is understood to mean all the vehicles that would be brought to a particular workshop in the event of a fault in their air-conditioning system; in other words, all the vehicles belonging to regular customers - who are also referred to as "loyal" customers in the jargon of the motor industry. The question now arises of finding a suitable company 'figure' to account for these customers. A garage's registered daily throughput of vehicles would be too high, because it would include multiple countings of one and the same vehicle. The 'annual inspections' figure, of which garages also keep an account, would seem to be the most appropriate. Regular inspections include "major" and "minor" versions, which may also be referred to as 'maintenance' or 'after-care' services depending on the make of vehicle. Conveniently for our present purposes, on average every vehicle in Germany underwent approximately one (1.05) regular maintenance/inspection service in the year 2000 (DAT-Veedol 2001, 23 et seq.). In other words, we can take it that the number of annual inspections equals the number of vehicles constituting a garage's annual 'regular client fleet'.

All nine garages in our selected population provided us with figures on their number of vehicle throughputs and number of regular annual inspections during at least one whole year in which refrigerant records had been kept (years 1999 or 2000, or the twelve-month period May 2000 to May 2001) - see Table 4.

Table 4: Annual Vehicle Throughputs and Inspections by Brand of Car and "Irregular" Emissions from 1999 to 2001 in Nine Garages

	1. Throughput	2. Inspections	2. as % of 1.	4. Irregular Emissions	4. as % of 2
Brand 1	30,396	8,495	28%	113	1.3%
Brand 2	57,226	16,118	28%	200	1.2%
Brand 3	37,966	9,556	25%	167	1.7%
Total	**125,588**	**34,169**	**27%**	**480**	**1.4%**

Source: reports and refrigerant records from nine garages from 1999 to 2001.

As Table 4 indicates, 34,169 or 27% of 125,588 vehicle throughputs constituted 'regular annual inspections'. These 34,169 vehicles represent the permanent 'client fleet' of vehicles serviced by the study's nine 'authorised dealers'. Out of this 'client fleet', 480 air-conditioning systems producing 'irregular' emissions were opened during the period of one year, representing an average 1.4% of all three brands of car, all of whose individual percentages are in any case very alike. (Adding the 175 systems opened in connection with 'normal' emission, 655 systems were duly emptied and recharged, representing 1.9% of "regular customer cars".)

The cases of emission used in this chapter (480 in number) have been chosen as a function of whether or not the date of their detection (and entry in the records) falls within an 'inspection year' (reference period) at my disposal. For instance, where the 'inspection year' is the year 2000, I have eliminated emissions subsequent to January 2001 that I did in fact use in another connection - in the previous chapter for example. This confinement is in fact matched by a corresponding broadening of our scope: since our sole interest at this point is in the level of an emission and in the brand of vehicle producing same, we can also take account of cases in which the age of the vehicle or even its type proved impossible to determine.

The garages did often raise an obvious objection to the idea of using 'inspections' as a basis for our study of air-conditioning systems, claiming that the air-conditioning system does not belong to the normal work of routine maintenance and that most faults are actually reported by the customer himself, outside the ambit of an 'inspection'. This objection is not really relevant to our present purposes, since the 'inspections' serve solely as quantitative reference point for recorded emissions of refrigerant, concentrating in fact on their upper limit.

II. Confinement of Inspections to Vehicles with Air-Conditioning System

It should go without saying that refrigerant emission would not be examined in relation to all inspected vehicles, but just to those of them duly equipped with an air-conditioning system.

Several intermediate steps were required in the process of confining the registered 'inspections' to those conducted on air-conditioned vehicles (and specifically those with an original R-134a system), none of the garages having classified their inspections under the headings of vehicles with and without air-conditioning system.

Every year since 1993, the percentage of new cars equipped with air-conditioning system has been growing at a very substantial rate, and the point of saturation is not yet in sight. Consequently, the percentage of vehicles equipped with air-conditioning is different not only for each brand of car, but also for each 'year of registration' of each car, quite apart from further differences existing between the numerous types of a particular brand.

The two main steps to be taken in determining a brand-tied garage's quota of air-conditioning systems in a given 'inspection year' (the year 2000, for instance) are

- firstly, arrangement of the garage's total number of vehicle inspections into their individual 'years of registration' (obtaining the 'age pattern'), and

- secondly, determination of the specific quota of air-conditioning systems (MAC Quota) in each of a particular car brand's 'years of registration'.

The MAC quota for an 'inspection year' is first arrived at by relating the MAC Quotas of specific years to the proportion (in terms of quantity) of cars from those years that call to a garage in the current 'inspection year'. In making this calculation, we do have to take on board a measurement error attributable to the fact that MAC Quotas for specific years are only obtainable for

Germany as a whole, so they may differ to a greater or lesser degree from the 'quotas' of the vehicles serviced by a particular garage.

1. Model of Age Patterns in Annual Inspections

What interests a garage most in respect of a 'year of registration' is the percentage of vehicles from that year that actually come into the garage for inspection (thereby demonstrating loyalty to the company). Apart from garage records, there is also a more general body of data available on these visits, as well as on the declining tendency to avail of an 'authorised dealer' workshop as a vehicle becomes older - for instance, the DAT-Veedol 2001 survey. The number of annual inspections categorised by age of vehicle is another question, one not normally investigated by the garages even though associated with their first interest.

Working together with a number of service managers and the regional sales department of one German manufacturer, we developed a model of the age pattern emerging in annual inspections, which, at least for the year 2000, probably comes very close to the reality of the situation in authorised-dealer workshops. This is because expert estimations for the year 2000 were supported, in three of the garages (covering two car brands), by the company computer which ran a program selecting inspected vehicles by the year of their first registration. Our model is reproduced in Diagram 10.

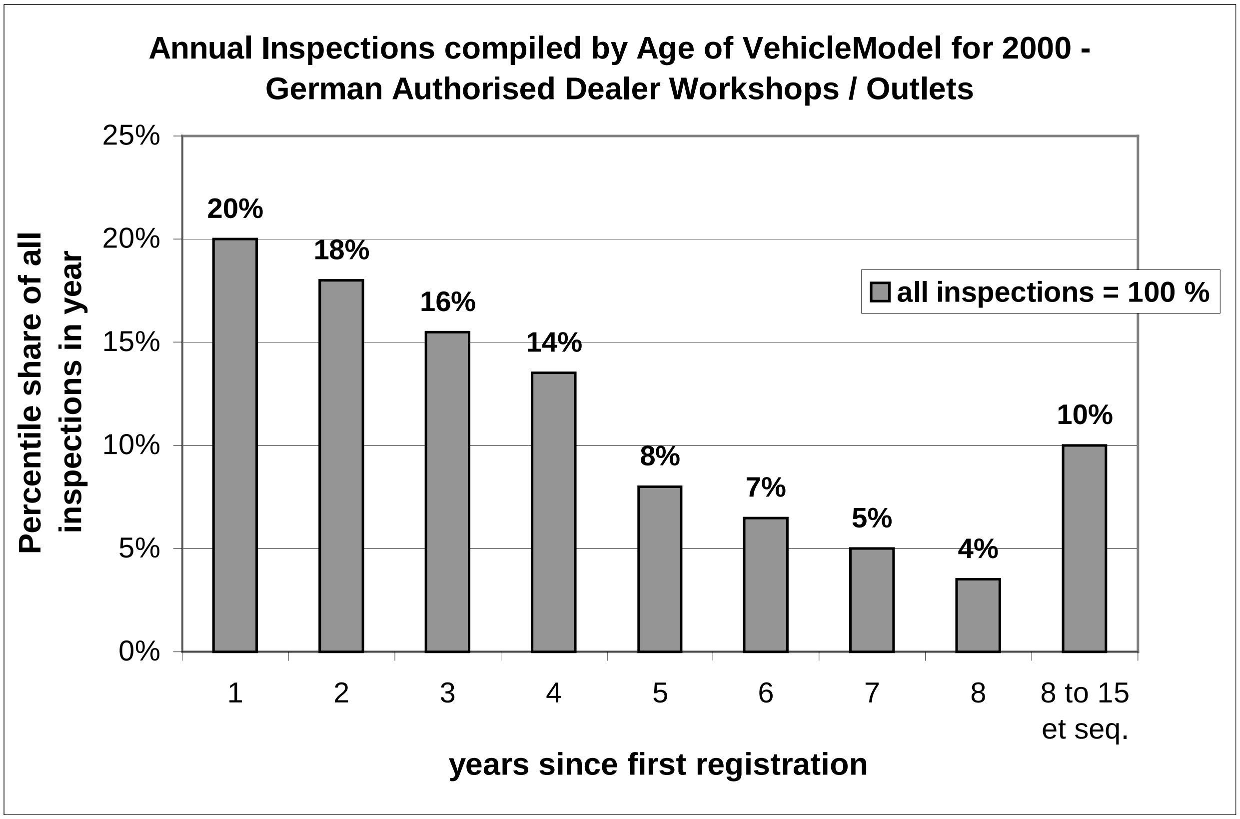

Diagram 10: Annual inspections compiled by age of vehicle. Model for 2000, authorised dealer workshops/outlets. More than two thirds of all inspections are concentrated within the first few years of a vehicle's age, older vehicles accounting for less than a third of the total.

The diagram clearly shows the preponderance of inspections in the earliest years (68% in total), which is hardly surprising given the four-year loyalty-maintaining attraction of warranty and goodwill arrangements. Vehicles more than four years old (the time when changes of ownership begin to occur) together make up only one third of the inspections total. The two bars on the far right of the diagram deserve particular attention - in the year 2000, 14% of inspected vehicles were eight and more years old, meaning that this 14% of vehicles are very likely not to have been fitted ex-works with an R-134a air-conditioning system, which first really came into general use in 1993 or 1994.

The 'age pattern model' is based on the inspections carried out in all three of the reference periods in question, namely years 1999 and 2000, and the twelve months from May 2000 to May 2001.

2. Air-conditioning quotas in inspection periods 1999, 2000 and 2001

All six German mass-producers of passenger cars reported the number of each of their passenger-car types (ranging from five by BMW and Audi, to fifteen by Ford) equipped ex-works with an air-conditioning system and sold in Germany in 1999 and 2000. They also provided specific information on types during the complex changeover phase from R-12 to R-134a, that lasted from mid 1991 to the end of 1993. Drawing as well on the data held in ÖKO-Recherche archives for the years 1994 to 1998, we then duly worked out the brand-specific quota of air-conditioning systems (the MAC Quota), in each calendar year, from the type-specific data in our possession.

Table 5: Percentage Air-Conditioned of New Cars sold in Germany (German brands only, from 1995 to 2000)

Brand	**2000**	**1999**	**1998**	**1997**	**1996**	**1995**
A	97%	93%	84%	84%	75%	71%
B	97%	93%	91%	81%	75%	57%
C	94%	90%	87%	75%	67%	58%
D	80%	74%	63%	46%	24%	20%
E	82%	78%	64%	55%	40%	19%
F	82%	75%	66%	55%	17%	11%

Table 5 reproduces these quotas without giving the names of the car brands, so that the identify of the three brands of car actually chosen for our study cannot be inferred from the brand-specific air-conditioning quota for the inspection periods - which itself is based on the quotas of 1992 to 2000 et seq. (see below).

The final step was to <u>weight</u> the MAC Quota for each year with the percentile share each 'year of registration' enjoyed in the annual inspection total, as illustrated in Diagram 10.

A total of nine MAC Quotas were arrived at in this way, three for each of the three chosen car brands: one for Inspection Year 1999, one for 2000 and one for May 2000 to May 2001.

Table 6: Air-Conditioning Quotas (MAC Quotas) in the three Inspection Periods 1999 to 2001 by Brand of Car

Period	Brand 1	Brand 2	Brand 3
Inspections in 1999	64%	37%	68%
Inspections in 2000	73%	47%	75%
Inspections from 5/2000 to 5/2001	78%	53%	80%

As a result of the general increase in MAC Quotas over time, the MAC Quota for inspections in the period May 2000 to May 2001 is distinctly higher than that in the year 1999. These quotas are likely to continue growing for the foreseeable future.

Brand 3's MAC Quota of 75% for "Inspections in 2000" (Table 6, last column, second last line) indicates that of the vehicles undergoing annual inspection in the year 2000, 75% were equipped ex-works with an R-134a air-conditioning system.

3. 'Workshop Rate' of air-conditioned vehicles

Eighteen times in total we were able to relate whole-year 'irregular' emissions from the three car brands to the respective 'inspection periods' in which they had been detected - four times for the full calendar year 1999, ten times for full calendar year 2000, and four times for the period May 2000 to May 2001. On summing up our individual calculations and arranging our figures by brand of car, we obtain the percentage of 'irregular' emissions encountered in workshop inspections of vehicles having an air-conditioning system. I have called this percentage the 'Workshop Rate' (Table 7).

Table 7: The 'Workshop Rate' ('Irregular' Emissions) of Air-Conditioned Vehicles of the Three Brands in 1999 to 2001 (Nine Garages)

	All inspections	Average MAC Quota	Inspections of MAC cars	Irregular emissions	Workshop Rate
Brand 1	8,495	73%	6,202	113	1.8%
Brand 2	16,118	48%	7,772	200	2.6%
Brand 3	9,556	77%	7,370	167	2.3%
Total	**34,169**	**62%**	**21,344**	**480**	**2.2%**

During the same period in which the nine garages detected and recorded 480 'irregular' cases of emission, they inspected a total of 21,344 air-conditioned vehicles (not their air-conditioning systems!). The number of inspections of vehicles having an air-conditioning system ('MAC cars') has been calculated here through multiplying the total number of inspections by the MAC Quota for the specific brand. This MAC Quota adds up to an average of 62% for the three brands of car, being at its lowest for Brand 2 (48%) and its highest for Brand 3 (77%). The (mathematical) percentage of 'irregular' emissions found when inspecting 'MAC cars' - or the 'Workshop Rate of MAC Cars' - averages out at 2.2% for all three brands.

III. The Annual Rate of 'Irregular' Emission

The rate of 'irregular' emission is arrived at by weighting the 'workshop rate of MAC cars' with the rate of refrigerant loss discovered on opening air-conditioning systems. These loss rates, obtained from the Record Sheets, were available as percentages and as absolute figures for all 480 vehicles in question, and are entered in Table 8 along with the resultant brand-specific annual rates of irregular emission.

Table 8: The Annual Rate of Irregular Emission from Air-Conditioning Systems of the three Brands of Car in 1999 to 2001 (Nine Garages)

	Irregular emissions	Workshop Rate	Refrigerant loss in kg	Rate of loss*	Annual rate of irregular emission
Brand 1	113	1.8%	67.0	82%	1.5%
Brand 2	200	2.6%	147.3	85%	2.2%
Brand 3	167	2.3%	133.1	84%	1.9%
Total	**480**	**2.2%**	**347.4**	**84%**	**1.9%**

* percentile relationship of "refrigerant loss in kg" to the sum of standard charge quantities of 81.4 kg (Brand 1), 173 kg (Brand 2) and 158.5 kg (Brand 3), adding up to 412.9 kg.

The annual rate of irregular emission is lower than the 'workshop rate' (averaging 2.2%), being only **1.9%** because of the loss-rate of less than 100%, namely 84%.

Among the three car brands, this annual rate varies from 1.5% (Brand 1) to 2.2% (Brand 3)., being about one third as high as the rate of 'normal' emission (6.3% according to our study).

The measurement error referred to in Chapter B - "omitted entry" of the recovery operation - is seen to produce only a very slight 'absolute' increase in the emission rate. Assuming 5% forgotten entries and a correspondingly 5% higher irregular loss of refrigerant, the annual rate of irregular emission would rise from 1.9 to barely 2.0 %, in other words, by just 0.1% in absolute terms.

F. The Annual Total Rate of Emission for Air-Conditioning Systems at most Seven Years old

I. The Calculated 8.2% Rate of Emission

The average annual rate of emission is arrived at by adding the rate of 'normal' emission to the rate of 'irregular' emission.

The annual rate of normal emission is 6.3% on average, while the annual rate of irregular emission is 1.9% on average, so the annual total rate of emission runs out at **8.2%.**

This means that passenger cars having an ex-works R-134a air-conditioning system lose over eight percent of their refrigerant charge every year. Placed in relationship with the average charge quantity of 856 g, that percentage represents **70 grams** per annum. Which is not to say that all of the corresponding refrigerant is topped up again, this hitherto only being done for a portion of the air-conditioning systems found to have irregular losses and defects. Most air-conditioned vehicles simply produce 'normal' emission and have not yet reached the critical charge-limit (around 60%) because they are still too young to have done so.

An important reservation should be mentioned at this point, to the effect that our emission rates apply only to vehicles in operation for at most seven years from the date of their first registration. Older vehicles (more than 84 months) are not included in our determination of the rate of normal emission. R-134a air-conditioning systems have only been on the market to any large extent since 1993. It is impossible to predict at this stage whether the rate of loss will continue to rise linearly as the ageing process proceeds, or if - as some experts fear (Holdack-Janssen, 2000) - the rate of normal emission might in fact accelerate.

Finally, with regard to our total rate of emission, it should also be borne in mind that (for the very reason that the study vehicles are not yet sufficiently old) neither the 6.3% figure (normal rate) nor the 8.2% figure (total rate) as yet makes any allowance for possible emission on the occasion of disposing of an old car.

Despite the limited amount of information obtainable due to the small number of cases involved, our study still provides us with a picture of the way in which emission rates vary from one to the other of the three different brands of vehicle. What for me is the most important finding out of Table 9 is not so much the fact that Brand 2 has the highest figures for both the 'normal' and the 'irregular' rate of emission (indeed it also comes highest under the heading of loss in grams per vehicle), as the actual existence of a difference of any kind between the brands that is not to be seen when they are viewed as a whole - because this difference suggests the need to leave a little latitude above and below our duly determined average annual rate of emission of 8.2%.

Table 9: Annual Rates of Emission and Loss in Grams per Vehicle for the Three Brands of Car

Vehicle	Normal Emission	Irregular Emission	Total Emission	Grams per Year*
Brand 1	6.2	1.5	7.7	57
Brand 2	7.0	2.2	9.2	79
Brand 3	5.8	1.9	7.7	72
All brands	**6.3**	**1.9**	**8.2**	**70**

* The respective refrigerant charges are 734 g (Brand 1), 857 g (Brand 2) and 932 g (Brand 3).

II. Margins of Error in determined Quantities

Our study could be criticised on fundamental statistical grounds for not being sufficiently representative and its limited informative value. It is fair to say that our selection of examined air-conditioning systems is too small, and that it does not represent a systematically collected random sample - a fact which is obvious from the outset given our concentration on 'authorised dealer' workshops, which only service some out of the total stock of air-conditioned vehicles, and furthermore only the 'younger' of them (note the preponderance of vehicles less than four years old).

Acknowledging these shortcomings, in my defence I would say that any more representative a survey could not have been completed within the terms of reference provided.

That having been said, however, the study does contain some inherent sources of error, to allow for which certain correcting factors and margins of error did need to be introduced.

While completing the study, one important source of error emerged in Chapter D in connection with determining the 'normal' rate of emission. Right from the first diagram (Diagram 2), putting "regular" refrigerant loss on a par with "less than 40% refrigerant loss" proved to give an unduly 'black-and-white' picture of the situation, given that a substantial portion of refrigerant losses under 40% are not actually attributable - as initially thought - to 'regular' , but to 'irregular' events. The 'irregular' events were eliminated by a criterion ('more than four times the average') the author felt to be plausible at the time, but which proved in the end to be rather arbitrary and could not guarantee that the selection 'corrected' in this manner would then really only include systems experiencing 'normal' leakage of refrigerant. This source of error is necessarily associated with the adopted procedure of evaluating Refrigerant Record Sheets 'after the event', and in the author's opinion, its influence on the result of the study is impossible to quantify. The error would be avoidable by employing another, in fact far more complex and more time-consuming, empirical approach involving the surveyor's own controlled measurement and analysis of the refrigerant charges in intact vehicle air-conditioning systems.

1. Errors in recording recovery and recharging operations

The general readout-error probability of plus or minus 25 grams works in both directions - upward and downward - by up to 15%.

As discussed in Chapter B, the 50-gram rounding practised when writing Record Sheets can give a false impression of emission by an amount of 25 grams above or below reality. Without exception, refrigerant loss of less than 40% is deemed to be 'normal' emission. That 40% is at most 340 grams of the average 850 gram charge quantity. Then, when it is put in relationship with the mid-point between 0 and 40% (therefore with 170 grams), the '25 gram allowance' is in fact 15%.

Rounding errors have some part to play in the rate of 'irregular' emission too, even if to a very much lesser degree because we are dealing here with 'total' loss. On top of this come the omitted entries of refrigerant loss, which I estimated to account for at least 5% (Chapter B, Section II, Paragraph 5).

2. Differences between the three brands of car

Comparing the three brands of car, both the 'normal' and the 'irregular' rates of emission vary either upward or downward by more than 15% from the average.

III. The Annual Rates of Emission with Margins of Error

The emission rates duly determined include 'fault tolerances' of at least 25% above and below to allow for inaccuracies of measurement and to account for the different figures from the three different car brands in our study. These margins are illustrated graphically in Diagram 11.

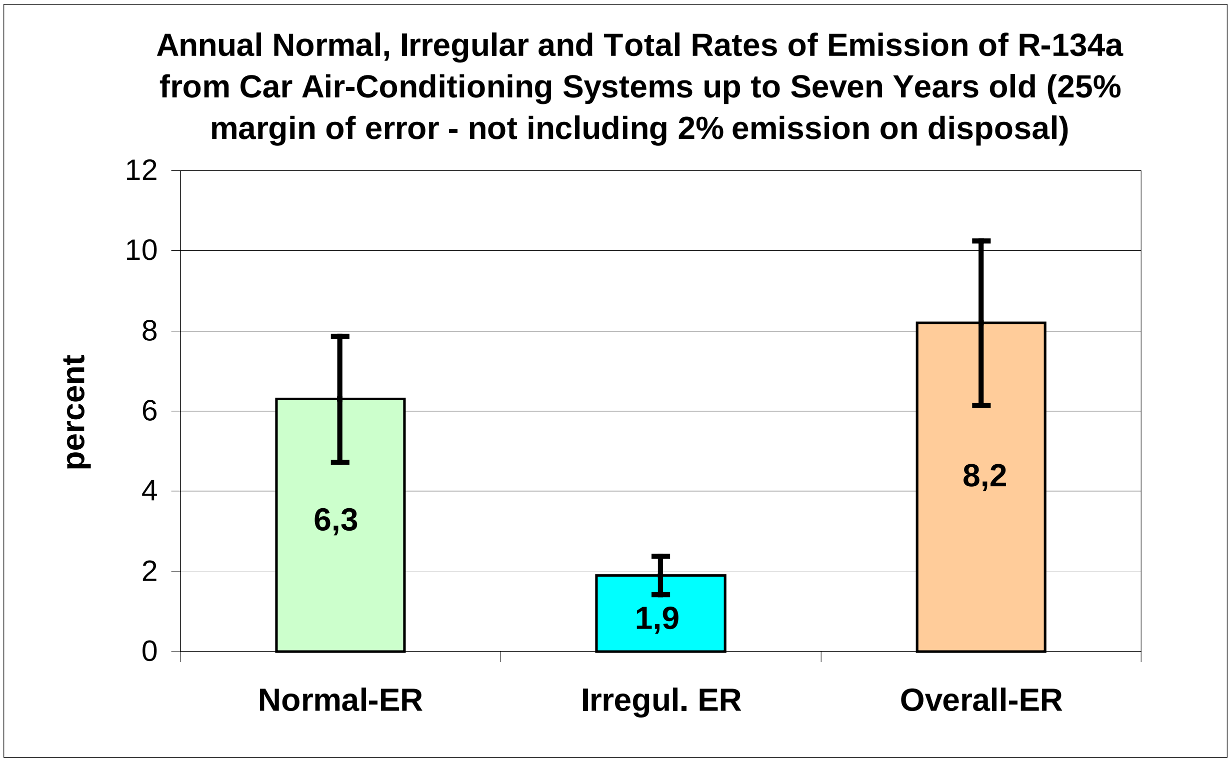

Diagram 11: Annual rates of 'normal', 'irregular' and 'total' emission from car air-conditioning systems at most seven years old - with 25% margin of error and excluding an approximately 2% annual rate of emission on disposal. The total rate of 8.2% is made up of the 'normal' rate (6.3%) and the 'irregular' rate of emission (1.9%) added together. Our examination proved the need to allow a 25% margin of error above and below, so the 'total' rate fluctuates within the region of 6.2 to 10.3%.

Allowing for the necessary 25% margin of error above and below the line, the 'total' rate for air-conditioning systems up to seven years old varies (without including loss on disposal) between 6.2% and 10.3%. Current total emission of R-134a from car air-conditioning systems in the year 2000 can be confined within the limits of 685 and 1,140 tonnes, these different figures depending on whether an emission rate of 6.2% (the minimum) or 10.3% (the maximum) is assumed for the 11,500 tonnes of refrigerant in circulation in passenger cars in Germany. These 11,500 tonnes are based, in turn, on the assumption of 13 million air-conditioned passenger cars (30% of the total population being thus equipped) having an average R-134a charge of 850 g.

IV. Emission on Disposal raises the Annual Rate by 10%

It is worth remembering at this point that an annual rate of emission extending over the first seven years of a system's use will be quite different (lower, in fact) from an annual emission rate calculated over the whole life of a system. Factors to be mentioned in this connection would first of all include the age-related acceleration of normal system leakage feared by some experts (Holdack-Janssen - 2000, and others), an aspect neither examined nor quantified within the confines of the present study in which the rate of normal emission remains at 6.3%.

A more important aspect is the loss associated with the scrapping of old cars. Weaknesses in this respect do not lie with German recyclers of old cars, who by this stage are very largely equipped with proper refrigerant recovery stations. Indeed, the situation is likely to improve even further over the coming years, thanks to national and EU regulation. The weak point is the fact that the approximately 1,400 recyclers in Germany receive not even the half of the 1.3 to 1.5 million old cars taken out of circulation (Arge Altauto 2000, 34). About half of the cars from any original German 'year of registration' are first exported as used cars to countries outside of the EU (Arge Altauto 2000, 48). I know nothing about refrigerant recovery in the importing countries, but it probably does not carry any great weight in practice, an assertion which would admittedly need to be examined. An investigation of this kind is called for, in that evidently "all western European states" (ibid.) are faced with this export problem.

If we were to say that an air-conditioned old car still contains 50% of its standard charge of refrigerant, and if we were then to assume, crudely speaking, a figure of 100% recovery of refrigerant under German recycling conditions and none at all for exported vehicles, then 25% of the refrigerant associated with a whole 'year of registration' would remain un-recovered.

Interestingly, Pettersen/Hafner published 75% as a maximum level of recovery from R-134a air-conditioning systems as early as 1996, a figure that has not been refuted to date. Tujibayashi arrived at something in the same order of magnitude (70%) for the island state of Japan in 1999, as a goal to be aspired to by the year 2010.

Distributed over a car air-conditioning system life of twelve to thirteen years, loss at disposal produces an increase of 2% in the annual total rate of emission. That rate therefore fluctuates within the region of 10% unless the situation should change substantially within the medium term.

The risk of an incorrect estimate increases very considerably once the 'first seven years' period has elapsed.

In any case, precise figures are not the goal of the present study, and never were, the prime purpose having been to arrive at the order of magnitude of emission from ex-works R-134a air-conditioning systems which are seven years old at the most.

I feel the study has duly achieved its aim by localising this order of magnitude within the region of 6 to 11%, or, including emission on disposal, 8 to 13%.

G. The Question of Reducing Emission by Regular System Inspection

All manufacturers of air-conditioning systems recommend regular maintenance (Air-Conditioning Conference - 2001). However, these systems are not included in the scope of the vehicle inspections specified by the car manufacturers. Preventive maintenance is carried out on a voluntary basis and therefore rarely, although many garages do offer the service of checking an intact air-conditioning system along the lines of the description in the box below.

> Air-Conditioning System Check (as recommended by WAECO)
>
> Every twelve months
>
> Function check: high and low pressure readings, condenser fan, temperature of air blown into passenger compartment.
> Visual inspections: soiling of or damage to the condenser, fault location on air-conditioning system using leak indicator unit.
>
> Every twenty-four months
>
> Replace dryer
> Recover and clean refrigerant, dehumidify system at same time.
> Recharge up to standard level.

I. Maintaining an Air-Conditioning System increases Operational Reliability

Checks in which the refrigerant circuit is not opened can provide clues to faults and may improve the efficiency of a system where a contaminated condenser is cleaned in the process, for example. Attention of this kind to the condenser may reduce fuel consumption, thus contributing to climate protection. Severe loss of refrigerant may well be suspected if pressure levels are too low or if the temperature of the air leaving the evaporator is too high, but the problem cannot be rectified for as long as the system remains unopened. There is little sense in looking for leaks in a closed, intact system, because normal emergence of refrigerant through hoses and seals will neither be detected nor eliminated in the process. In turn, a check of this kind is unnecessary in respect of irregular leaks, because lack of refrigerant will already have brought the system to a standstill.

Checks in which the refrigerant circuit is opened in an intact system make more sense from the technical point of view. The refrigerant is duly cleaned (dehumidified, that is) in the recovery/recharging station, and the emptied system is dehumidified by vacuum at the same time. The dryer may be changed to ensure continued absorption of diffusing humidity once the system is closed up again. Finally, recharging prevents operational faults attributable to loss of refrigerant. Provided no irregular damage occurs, the cleaning and recharging of refrigerant does help to improve functional reliability.

However, the possibility that measures of this kind might prevent effective emission of refrigerant is quite another question.

II. Regular Maintenance generally does not reduce Emission

This question needs to be examined individually with regard to the different forms of emission.

Emission on disposal can only be avoided where the refrigerant is properly removed when a car is scrapped - the question of reduction by means of regular maintenance with a top-up of refrigerant does not apply to this class of emission (rather more the reverse, in fact, since an air-conditioning system which is not properly pumped dry during the scrapping process will emit more if it had been topped up and remains full, than it would if it were half empty).

The same applies to **irregular emission** caused by an accident or by stone impact, since regular maintenance will not prevent external damage to the air-conditioning system accompanied by abrupt emergence of refrigerant.

Normal emission consists mainly in leakage of refrigerant through seals, a factor inextricably linked with the present-day design of air-conditioning systems whose compressor is driven by the vehicle's engine (see Chapter D, Section 6). Regular refrigerant top-ups (calling for the system to be opened) may recurringly put off the day on which refrigerant shortage begins to cause operational problems, but they do not help to reduce emission.

III. Partial Prevention of Irregular Emission - Minimal

Nonetheless, suppliers of recovery/recharging stations have put forward two examples demonstrating how they think that emission could be reduced by maintaining a system regularly and checking it for leaks (Recovery/Recharging Station Conference - 2001). Both of these examples relate to 'irregular' emission.

1. Two examples showing how emission may be reduced by maintenance

Example 1: where the refrigerant is not regularly cleaned, penetrating moisture may overcome the absorbent capacity of the dryer and mix with fluorinated refrigerant to produce corrosive acids (HF) which cause internal corrosion and leaks in metal components.

Example 2: a leak, whether attributable to internal or external causes, may initially be so small that the amount of refrigerant escaping is still too slight to be noticeable as a fault. Over time, however, the leak grows and grows in size and may eventually become sufficiently large to let through the whole charge of refrigerant. This emergence of refrigerant would be confined by checking for leaks in good time.

2. Internal corrosion by acid refrigerant is unlikely

The experts have dismissed the first example (Air-Conditioning Systems Conference - 2001), stating firstly that the capacity of the dryer is designed so that, for the whole life of the system, it will absorb the moisture that penetrates under normal operation, and secondly, that any irregular admission of moisture to the refrigerant circuit to produce a non-evaporating liquid

would so severely damage the compressor by 'liquid shock' that this component would fail well before acid could form. Rather than a release of refrigerant, the outcome would be a visit to the workshop to have the refrigerant circuit opened with a view to replacing the compressor.

So with regard to Example 1, while regular dehumidification (and recharging) of the refrigerant is undoubtedly a good way of enhancing a system's reliability, regular inspection does not prevent 'irregular' penetration of moisture. Where moisture does penetrate 'irregularly', the occurrence makes itself felt not through loss of refrigerant, but as (non-emissive) component defect, interfering with the air-conditioning system's operation and therefore causing it to be opened in the workshop in any case.

3. Detection of slowly growing small leaks

The second example gives rise to the fundamental question of how large a leak has to be before it can be found in the course of a regular examination.

The principal form of emission - normal emergence of refrigerant through intact seals - is too slight to be found by manually operated leak detector on an unopened system. The detector will only respond to larger-scale leaks, by which stage the operation is generally too late. The only reliable way of looking for leaks is to open the system first. There are two methods of location when this is done.

The first method is to charge the emptied system with liquid nitrogen, metered by pressure reducer from a gas cylinder (kept under 200 bar pressure) into the system, where it develops pressure of up to 20 bar and higher in order to simulate extreme conditions. The leak detector then has a chance of locating leaks which otherwise, under normal workshop conditions, would let out too little refrigerant to be perceptible.

The second method - more frequently used because less complex - is to add a contrast medium or 'tracer' when recharging the system with refrigerant (see Chapter B, Section III, Paragraph 2). The pressure in the system does not rise as high as when adding nitrogen, so if the leak is not immediately revealed by a coloured stain (visible under ultraviolet illumination), the driver is asked to call again at an appointed date, when his air-conditioning system is run under practical conditions and the source of emission becomes clear to see.

To return to Example 2, neither the nitrogen method nor the tracer method[20] are suitable means of finding 'normal' leakage through intact seals. There would also be little sense in replacing intact seals, new ones would not necessarily reduce the pace of refrigerant emergence. However, both methods lend themselves to the detection of "irregular" sources of emission.

Irregular leaks, responsible for just under 2% of annual emission from air-conditioning systems (at most seven years old), are generally associated with abrupt rather than 'creeping' emergence of refrigerant. Within less than a month of being damaged on the outside by a thrown stone, a condenser will have begun to leak so badly because of pitting that hardly any refrigerant will be left in the system (Haussmann, 2001). Refrigerant emerges abruptly in any case after a frontal collision involving body damage. Accidents and stone impact are by far the most frequent causes of 'irregular' loss of refrigerant (see Chapter C, Section I). Generally, too, where other components develop leaks for irregular reasons (compressors, evaporators, dryers), the pattern of damage will be fast-acting to precipitate by nature, for instance when a compressor breaks or a dryer cracks.

It can indeed arise that a hole will enlarge continuously but so slowly that it fails to interfere with the system's operation by the time of the next regular inspection, which may be six months away or as far as two years into the future. However, such a situation is the exception to the rule among cases of 'irregular' damage, which for the most part cause refrigerant loss in such a short space of time that established maintenance intervals of two or four years will intervene either too early or too late in time. The vehicle has to be brought into the workshop without delay.

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[20] Since the tracer dye bonds to the refrigerant oil, not the refrigerant itself, no stain will form where a leak is so small that only gas can pass through, not oil.

4. Emissions prevented or caused by maintenance are approximately equal in magnitude.

It may be broadly assumed that 15% of cases of 'irregular' emission comprise leaks of a slowly developing nature which do not interfere with system operation before an inspection, but which are nonetheless found during the inspection. Under this assumption, the emission prevented in the process comes to about 0.2% of the total annual loss of refrigerant. That percentage, related to the 11,050 tonnes of refrigerant in circulation in the year 2000 (13 million R-134a air-conditioning systems each containing 850 grams of refrigerant), corresponds to at most 22 tonnes of emission prevented per annum.

Against that there is the enormous effort and expenditure of opening 6.5 million air-conditioning systems per year where regular maintenance is arranged once every two years (the interval cannot afford to be any longer if leaks of this kind are to be located in good time).

It should be duly noted that the 2 grams of recharging loss normally accompanying each maintenance service (see Chapter B, Section III, Paragraph 1) adds up to 13 tonnes per annum, on top of which service-related losses in the order of 0.1%[21] or 10.4 tonnes may arise where a leak is not found during the first visit to the workshop.

<u>Consequently, the level of emission which maintenance prevents is almost exactly the same as the level it produces.</u>

<u>As overall outcome</u>, regular maintenance generally does not prevent direct emission of refrigerant, although it may enhance a system's operational reliability and save on fuel consumption. At a more detailed level, our study describes two particular, conceivable cases demonstrating that regular maintenance either does not prevent refrigerant loss, or does so only at the price of emissions of just the same magnitude attributable to the maintenance operation itself.

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[21] This percentage rate is derived from the present study, based on the figure of 20.5 kg (from 29 cars) in relation to 21,300 inspections of air-conditioned cars by the nine garages.

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Note on unnamed sources

Unfortunately, the study's most important sources of information could not be named without revealing the identity of the three selected brands of car. This is a pity, in so far as our study has really been based not only on the Record Sheets, but also - indeed above all - on the experience of the air-conditioning mechanics from our nine garages. Service managers, environmental and safety officers, trainers and sometimes managing directors were as much involved as the apprentices who transferred the necessary data from the garage computers. The assistance provided by the sales departments of the three car manufacturers was just as indispensable, as were the information and suggestions originating from company head offices. While extending my heartfelt thanks to each and every one of my sources, I really must mention four particular contributors at this point, even if in abbreviated form: Mr F. and Mr S of Garage L, Mr P of Garage V, and Dr. M representing one of the three manufacturers.

The author himself must of course accept full responsibility for the actual content of this study.

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