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Engineering assessment of refrigerant recovery and emission control in automotive air-conditioning maintenance and end-of-life vehicle management

Jia Wang[1], Qingyao Meng[1,*], Prieto G. Manuel[3], Yin Wang[4], Yingli Ren[1,2], Yueyan Zhu[1]

[1]China Automotive Technology and Research Center Co., Ltd., No. 68, Xianfeng East Road, Dongli District, Tianjin, China
[2] School of Materials Science and Engineering, Tianjin University, Tianjin 300350, China, P. R. China
[3] Seilerbahnweg 14 | 61462 Konigstein (Taunus), Germany
[4] German Development Cooperation GIZ office China

Abstract—Refrigerant emissions from passenger car mobile air-conditioning (MAC) servicing are an important but poorly quantified source of high-GWP greenhouse gases. This study collaborated with H Company's Guangzhou workshop to develop a standardized refrigerant recovery procedure, collect pre- and post-intervention field data, and estimate emission reduction potential under BAU, WS1, WS2, and MIT scenarios using IPCC-based calculations. Compared with BAU servicing, standardized recovery equipment use and technician training reduced direct workshop emissions by over 90%. At the Guangzhou scale, annual emissions were estimated to decline from 527,261 tCO_2eq under BAU to 165,772 tCO_2eq under the average workshop scenario and to 141,311 tCO_2eq under the mitigation scenario. Because the empirical dataset is based on one pilot workshop, the revised analysis treats the city-scale results as scenario-based estimates rather than statistically representative national averages, and adds uncertainty propagation and sensitivity tests for initial charge, leakage, service interval, recovery rate, fleet size, and GWP/emission-factor choices. The results show that marginal emission reduction plateaus at high workshop recovery rates because on-road leakage remains outside the boundary of workshop interventions. The study, therefore, demonstrates both the mitigation potential and the implementation limits of standardized refrigerant recovery, and highlights the need for multi - site validation before broader extrapolation. This study focuses on the engineering management of refrigerant recovery during automotive air-conditioning servicing and end - of - life vehicle dismantling, rather than solely assessing environmental impacts.

1.Introduction

Refrigerants used in mobile air-conditioning (MAC) systems are an important source of emissions with very high global warming potentials (GWP), particularly in countries with rapidly growing vehicle fleets such as China. Although the phase-down of HFCs under the Kigali Amendment and the strengthening of domestic environmental regulations have increased attention to refrigerant management, emissions from the automotive maintenance sector remain largely underestimated. During vehicle servicing, refrigerant leakage can occur through improper hose connections, inadequate recovery procedures, or insufficient filtration and storage. Such operational gaps contribute directly to atmospheric release of HFC-134a and other MAC refrigerants [1,2].

China hosts one of the world's largest automotive maintenance sectors, servicing hundreds of millions of vehicles annually. By the end of 2024, national motor vehicle ownership reached 453 million vehicles, including 353 million automobiles, and 96 cities had more than one million automobiles[14]. This high volume of MAC servicing creates substantial potential for refrigerant leakage when recovery practices are incomplete or inconsistent. The sector is also highly fragmented, with substantial variability in technician skill levels, equipment availability, and workshop procedures, resulting in significant differences in recovery performance. These structural characteristics make maintenance-related refrigerant emissions an important yet understudied component of China's overall HFC emission profile [3-6].

Existing literature focuses primarily on MAC system leakage during vehicle use, end-of-life recovery, or alternative refrigerants. However, very limited empirical research quantifies emissions originating from maintenance workshops, despite their significant mitigation potential. Furthermore, national and regional HFC emission inventories based on atmospheric observations have revealed discrepancies with reported emissions, highlighting the uncertainty associated with service-related emission sources[7-9]. In addition, few standardized operating procedures (SOP) have been widely adopted in China's repair industry, and technicians' skill levels vary considerably. This results in inconsistent

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*E-mail: mengqingyao@catarc.ac.cn

recovery performance, low equipment utilization, and poor compliance with environmental requirements[5].

The policy relevance of workshop-level refrigerant management has also increased. In 2026, China's Ministry of Ecology and Environment issued requirements for strengthened management of ozone-depleting substances (ODSs) and HFCs, covering production, sales, use, maintenance, end-of-life treatment, recovery, reclamation, and destruction[15]. This policy context supports the need to quantify emissions from the maintenance stage rather than limiting MAC assessments to vehicle-use leakage or end-of-life recovery.

To address these gaps, this study collaborated with a workshop operated by a large automotive maintenance enterprise in Guangzhou (hereafter referred to as H Company, to conduct a pilot intervention introducing standardized refrigerant recovery processes.

This research makes three key contributions:

- Empirical evidence: It provides one of the first quantified baseline datasets for refrigerant recovery performance in Chinese automotive workshops.
- Operational validation: It tests the effectiveness of standardized practices and structured technician training in improving recovery efficiency.
- Policy relevance: It offers actionable insights for national standard development and sector-wide climate mitigation planning, consistent with life-cycle climate performance (LCCP) and early mitigation frameworks proposed for MAC systems [10-12].

By bridging practical workshop operations with scientific emission accounting, this study contributes to advancing refrigerant lifecycle management and supporting China's long-term HFC phase-down strategy.

Therefore, this study aims to establish a workshop-level engineering assessment framework for refrigerant recovery and emission control in automotive air-conditioning maintenance. The focus is placed on operational scenarios, recovery efficiency, management feasibility, and end-of-life refrigerant handling, which are closely aligned with environmental engineering and pollution control practices.

2.Methods

In accordance with one of the objectives of the project, a methodology was developed for calculating the baseline emissions. This methodology follows the IPCC Guidelines[1] for National Greenhouse Gas Inventories[13]. First, the baseline is calculated for the workshop where the data collection took place and extrapolated to all other workshops operated by H Company and to the Guangzhou region. Second, different scenarios were developed to estimate the total emission reduction potential in the mobile air conditioning (MAC)[2] sector in Guangzhou as well as in the workshops operated by H Company. The emissions calculated for each scenario are compared in the results chapter to study the impact of the use of refrigerant recycling machines, proper training and other measures that can be applied in the MAC sector in China. In this study, the MAC sector includes only passenger cars for private use.

2.1.Pilot Design and Study Setting

The pilot study aimed to develop and test a standardized refrigerant recovery procedure for automotive maintenance workshops and compare its effectiveness against baseline “business-as-usual” practices. The intervention consisted of selecting a representative workshop, developing a structured data-collection protocol, training technicians, and conducting two rounds of field measurements to capture pre- and post-intervention performance.

A demonstration workshop operated by H Company in Guangzhou was selected as a high-volume urban pilot site rather than as a statistically representative sample of all Chinese workshops. The site was chosen for three practical and analytical reasons:

(1) contextual relevance—the facility reflects the operating conditions of a formal urban automotive maintenance chain, but it does not capture the full diversity of small, independent, and rural workshops in China;

(2) operational capacity—the workshop conducts a high volume of MAC servicing necessary for obtaining sufficient sample size, and

(3) practical feasibility—warm climate during the study period ensured continuous air-conditioning maintenance activities.

The Guangzhou site was therefore chosen over the initially considered Tianjin workshop, where seasonal conditions limited air-conditioning service demand during the pilot timeline.

2.2.Data Collection Instruments and Protocol

A structured data-collection system was developed, comprising:

- As shown in Figure 1, a Word form for technicians, used at the workshop to record individual service cases.
- A centralized Excel summary sheet for researchers, used to compile and analyze the collected records.

The technician form included two components:

(1) Instructions, providing definitions of all variables recorded (e.g., refrigerant mass recovered, process steps followed, equipment used),

(2) Data fields, completed by workshop staff during each MAC recovery operation.

The Excel summary sheet consolidated all individual records for statistical analysis and cross-validation. Both tools were iteratively refined through pilot testing to ensure clarity, usability, and consistency with the methodological requirements of the study.

Data collected across both rounds included: Vehicle and MAC system characteristics, Estimated refrigerant

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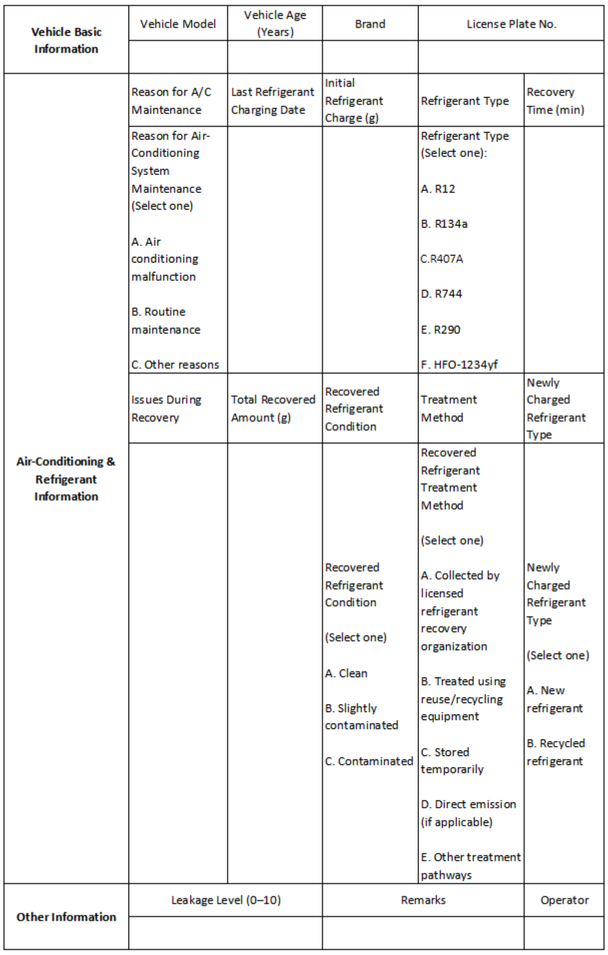
[1] https://www.ipccnggip.iges.or.jp/public/2006gl/index.html.

[2] In this case the sector consists of only passenger cars.

charge, Recovered refrigerant mass, Recovery duration and procedural steps, Equipment settings and operation details, Technician notes on deviations and errors.

This framework provided a robust basis for evaluating baseline emissions, post-training improvements, and the effectiveness of standardized procedures.



Vehicle Basic Information	Vehicle Model	Vehicle Age (Years)	Brand	License Plate No.	
Air-Conditioning & Refrigerant Information	Reason for A/C Maintenance	Last Refrigerant Charging Date	Initial Refrigerant Charge (g)	Refrigerant Type	Recovery Time (min)
	Reason for Air-Conditioning System Maintenance (Select one) A. Air conditioning malfunction B. Routine maintenance C. Other reasons			Refrigerant Type (Select one): A. R12 B. R134a C.R407A D. R744 E. R290 F. HFO-1234yf	
	Issues During Recovery	Total Recovered Amount (g)	Recovered Refrigerant Condition	Treatment Method	Newly Charged Refrigerant Type
			Recovered Refrigerant Condition (Select one) A. Clean B. Slightly contaminated C. Contaminated	Recovered Refrigerant Treatment Method (Select one) A. Collected by licensed refrigerant recovery organization B. Treated using reuse/recycling equipment C. Stored temporarily D. Direct emission (if applicable) E. Other treatment pathways	Newly Charged Refrigerant Type (Select one) A. New refrigerant B. Recycled refrigerant
Other Information	Leakage Level (0–10)		Remarks		Operator

Figure 1. Automotive Refrigerant Recovery Data Collection Form.

2.3. Scenarios

Four scenarios are considered for comparing results and calculating the baseline. These are Business as Usual (BAU), Workshop Scenario 1 (WS1), Workshop Scenario 2 (WS2) and Mitigation Scenario (MIT). WS 1 and 2 are based on the actual conditions of the workshop where the data collection campaigns (Phase 1 and 2) took place. While BAU is based on the actual conditions of a regular auto repair shop in the country and MIT is based on workshops following international best practices for refrigerant management. The scenarios are characterized by the following practices and conditions:

BAU scenario: As is common in China and many other countries around the world, workshops do not have refrigerant recycling machines. Therefore, the refrigerant recovered from the MAC unit of a serviced vehicle is assumed not to be recycled for reuse, but instead to be collected in cylinders and sent for proper disposal, while the unit is recharged with virgin refrigerant to the full charge level. Thus, in this scenario, the annual emission of a car is assumed to be equal to the initial charge divided by the frequency of service.

WS1 reflects the conditions of the workshop at the time of the **first data collection campaign**. These conditions were that the workshop had refrigerant recycling machines, however, no training had been conducted for the technicians to learn how to operate the machines. This led to irregular use of the machines depending on the technician. In addition, when the recycling machines were not in use, the refrigerant was vented.

WS2 reflects the workshop conditions at the time of the **second data collection campaign**. At this time, all technicians were trained in the proper use of the refrigerant recycling machines. Therefore, it is assumed that in all cases the refrigerant was recycled whenever possible. Only in cases where the refrigerant was too polluted to be recycled was it vented.

MIT scenario: The MIT assumes that no refrigerant is vented in the workshops. Instead, all refrigerant is recycled and/or collected for reclamation if recycling is not an option. This is an ideal scenario where direct refrigerant emissions from the workshop are zero.

2.3.1. Baseline and Emissions Calculations.

The baseline (BL) is calculated under the assumption of the BAU scenario in order to see all the potential emissions that can be reduced by introducing refrigerant recycling machines to passenger cars servicing workshops and conducting proper training. For the calculation of the BL all the data collected was used. Instead, emissions for other the WS1 and WS2 scenarios were calculated using data from only one of the data collection campaigns. All the variables calculated are presented in Table 1, followed by the methodology presented for the calculation of emissions in the workshop and in the Guangzhou region separately. The text follows a logical calculation process where the workshop's emissions are upscaled to the region using parameters and information from Guangzhou. To calculate the emissions in carbon dioxide equivalent units (CO_2eq), the kilograms of refrigerant are multiplied by the Global Warming Potential[3] (GWP) of each refrigerant. The average charge of the cars surveyed in this study is 0.8 kg. In this case only the refrigerant HFC-134a is considered. This HFC has a GWP value of 1530 kgHFC-134a/kgCO_2eq (IPCC, 2022).

2.3.2. Methodology of Baseline Emissions Calculations in the Workshopy.

The refrigerant recycled is calculated for a 4-week period by summing all relevant data collected during each of the

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[3] The GWP values used for the calculation are taken from the IPCC Sixth Assessment Report.

campaigns. This is calculated using **Equation 1**, which is the sum of all the refrigerant recycled that was reported by the technicians. In the equation “n” is the total number of cars serviced in the workshop during the data collection period and “i” is each entry.

$$\text{Equation}\quad R_{rcy}=\sum_{i=1}^{n} R_{recycled,i} \qquad (1)$$

Similarly, Equation 2 and Equation 3 are used to calculate the refrigerant vented and the VR used in the workshops. All three variables are calculated in kilograms for each data collection campaign, corresponding to the WS1 and WS2 scenarios, described above. To calculate these variables for a 1-year period, the total number of vehicles serviced in the workshop during this period is used. This data was provided directly by H Company.

$$\text{Equation}\quad R_{vent}=\sum_{i=1}^{n} R_{vented,i} \qquad (2)$$

$$\text{Equation}\quad VR=\sum_{i=1}^{n} R_{virgin,i} \qquad (3)$$

The refrigerant emissions (Em) are calculated using Equation 4. This variable is calculated for a period of 4 weeks (corresponding to the duration of a data collection campaign) and then extrapolated to have the emissions of 1 year using the total number of cars services at the workshop. The emissions in the workshop equal the refrigerant vented, as it can be seen on the equation.

$$\text{Equation}\quad Em= R_{vent}\times GWP \qquad (4)$$

As explained above, the calculated emissions for the BAU scenario are considered as the baseline (BL). In this scenario, it is assumed that all the refrigerant contained in the vehicles is vented in the workshops and replaced with new refrigerant. The baseline is calculated using Equation 5, where Q_{ref}, the amount of refrigerant vented, is multiplied by the GWP value of the refrigerant. in this case by 1530 kg HFC-134a/kgCO$_2$eq. It is important to note that the emissions that occur on the road (leakage) are not considered, nor are emissions from leakage during the handling of refrigerant in the workshop.

$$\text{Equation}\quad BL_{BAU}=Q_{ref}\times GWP \qquad (5)$$

In addition, the avoided emissions (AvEm) are calculated using Equation 6, which compares the baseline emissions (BL_{BAU}) with the emissions calculated for each scenario (Em). This calculation makes it possible to determine the effectiveness in terms of emission reduction of each measure that was taken during the project[4]. The equation also serves to estimate the impact of best practice (MIT scenario), where all refrigerant is recycled or recovered.

$$\text{Equation}\quad AvEm = BL_{BAU} - Em_{scenario} \qquad (6)$$

Lastly, Equation 7 is used to calculate all the refrigerant that could be recovered from the workshops. Currently, the workshops do not have the capacity to recover and store refrigerant for safe disposal or reclamation, they can only recycle in-situ. This always some refrigerant left that could not be recycled due to poor quality. However, if sector best practices are followed, all the used refrigerant in the workshops will be recycled, reclaimed or properly disposed of (destroyed).

$$\text{Equation}\quad PR_{rcov}=R_{vent} \qquad (7)$$

2.3.3. Methodology of Baseline Emissions Calculations in the Guangzhou Metropolitan Area.

As it was previously mentioned, some of the variables that are calculated for the workshops operated by H Company are also calculated for the Guangzhou region. This is by using the parameters shown in Table 2. The initial charge and the leakage rate were calculated using the data collected during the campaigns and compared with the data provided by the participating enterprise. These two parameters are an average of the non-commercial passenger cars in the region, which are the type of vehicles serviced at the workshops of H Company. The number of cars and the frequency of servicing were provided by H Company.

Equation 8 is used to estimate the baseline emissions in the BAU scenario. Here it is assumed that the of cars emit their entire initial refrigerant charge (IC) during the Servicing frequency-period (S_y), which in this case is 6.5 years. This is based on the assumption that any refrigerant that has not been leaked on the road during the 6.5-year period is then vented in the workshop.

$$\text{Equation}\quad BL_{mac}=n_c\times\frac{IC_{avg}}{S_y} \qquad (8)$$

In the WS1 and WS2, some of the emissions are avoided through the recycling of refrigerant at the workshops during the servicing of the cars. Equation 9 is used to calculate the emissions of the passenger cars in the Guangzhou metropolitan area for these scenarios. This equation is the sum of the emission that occur on the road due to refrigerant leakage. (Em_{road}) and in the workshops when the refrigerant is vented (Em_w). Equation 10 uses the initial charge (IC), the leakage rate (LR) and the total number of vehicles (n) to estimate the annual emissions that occur on the road. This differs from previous emissions calculated in the last subchapter, where the special boundary was restricted to the workshops.

$$\text{Equation}\quad Em_{mac}=Em_{road}+Em_w \qquad (9)$$

$$\text{Equation}\quad Em_{road}=n_c\times IC_{avg}\times LR \qquad (10)$$

Em_w are the emissions that occur in the workshops during the servicing of the vehicles. These emissions are zero on the MIT scenario and are calculated for the WS1 and WS2 scenarios using Equation 11, where all the potential refrigerant available for recycling (PRRmac) is multiplied by a factor expressed as a percentage. This factor is calculated by dividing the total refrigerant recycled during the 4-week data collection period by the total amount of used refrigerant handled in the workshops. This total is the refrigerant recycled plus the vented one[5]. Moreover, the potential refrigerant for recycling is calculated using Equation 12. This is all the refrigerant left in the vehicles when they arrive in the workshop, and it is calculated by estimating the number of vehicles that are serviced every year n_c/s_y times all the refrigerant that they contained.

$$\text{Equation}\quad PRR_{mac}Em_w=PRR_{mac}\times\left(\frac{R_{vent}}{R_{cyl}+R_{vent}}\right) \qquad (11)$$

$$\text{Equation}\quad PRR_{mac}=\frac{n_c}{S_y}\times\left(IC_{avg}-IC_{avg}\times E_r\right) \qquad (12)$$

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[4] Measures applied during the pilot project include introducing refrigerant recycling machines and conducting training for their proper use.

[5] This factor is calculated using the average of the two data collection campaigns.

As explained before Equation 8 and Equation 9 calculate the total refrigerant lost by the vehicles on the road and in the workshops (emissions). Any refrigerant emitted would have to be replaced with (VR) in the workshops. Therefore, Equation 13 (a) is valid for the BAU scenario and Equation 13 (b) for the other three WS1, WS2 and MIT.

$$Equation \quad VR_{BAU}=BL_{mac} \qquad (13(a))$$

$$Equation \quad VR=Em_{mac} \qquad (13(b)$$

Finally, Equation 14, similar to Equation 6, is used to calculate the emissions avoided in each of the scenarios by comparing them to the baseline emissions (BL_{mac}) produced by the passenger cars in the Guangzhou region.

$$Equation \quad AvEm_{mac}=BL_{BAU}-Em_{mac} \qquad (14)$$

2.3.4. Data and Calculations Uncertainties.

In accordance with the IPCC Guidelines for National Greenhouse Gas Inventories [6] for the calculation of emissions in the refrigeration and air conditioning (RAC) sector, uncertainties related to the data and the calculations are presented here.

During the data collection errors can occur when entering information into the spreadsheets, as well as due to misunderstandings on the use of the templates. However, to avoid errors and reduce uncertainties the data collection process was refined through a 4-week trial in which the template and the data collected were reviewed and modifications to the process were made. On the other hand, there is an uncertainty associated with the data collection because of the short period surveyed (4-weeks). This data collection process could miss changes in seasonality and temperature. For example, the number of cars serviced in workshops is expected to fluctuate with the need for air conditioning and therefore with ambient temperature. It is also important to note that the leakage (not the venting) during the handling of refrigerant in the workshops is not considered. Therefore, workshop emissions might be slightly underestimated, as this source is not included. Finally, the parameters (e.g. initial charge, leakage rate) used for calculating the variables for the Guangzhou metropolitan area are based on data from H Company and the surveys, which mainly services larger, higher-end European cars, which are more expensive in China than other brands. This is a potential data—error source as H Company does not service all passenger cars in the metropolitan area, and other parameters like the total number of cars there are estimates.

3.Uncertainty and Sensitivity Analysis

To respond to the uncertainty associated with the transition from a single pilot workshop to city-scale estimates, the revised analysis treats the workshop data as an empirical anchor for scenario construction rather than as a statistically representative mean for the whole sector. The upscaling calculation was therefore supplemented with one-at-a-time sensitivity analysis and uncertainty propagation of the main emission-factor parameters.

For each scenario, the effective annual refrigerant emission factor per vehicle was expressed as a function of the initial charge (IC), servicing frequency (Sy), road leakage share during the service interval (Er), workshop recovery/recycling rate (RR), and GWP. In simplified form, EF_{BAU} = IC/Sy x GWP; EF_{WS} = [IC/Sy x Er + IC/Sy x (1 - Er) x (1 - RR)] x GWP; and EF_{MIT} = IC/Sy x Er x GWP. City-scale emissions were then calculated as the product of the passenger-car stock and the scenario-specific emission factor.

The deterministic values in Table 5 were retained as the central estimates. Sensitivity ranges were then tested for IC (+/-20%), Sy (5.2-7.8 years), Er (20-34% of initial charge over the service interval), RR (85-98%), and Guangzhou passenger-car stock (+/-10%). The GWP conversion was retained at the IPCC AR6 central value for HFC-134a, while GWP-related uncertainty is discussed separately because it rescales CO_2eq results but does not change the refrigerant mass balance. These ranges do not replace multi-site empirical validation, but they show which assumptions most strongly affect the city-scale extrapolation and prevent the results from being interpreted as a simple linear scaling of one workshop.

The main limitation remains the single-workshop design. Multi-site validation should include at least three workshop types: large authorized service chains, medium independent urban workshops, and small community/rural repair shops. For each site, future surveys should record refrigerant charge, recovered mass, vented mass, refrigerant quality, equipment type, technician training status, and seasonal service volume. The present pilot provides the data-collection protocol and first-order emission factors needed to design such a stratified validation study.

4.Results of the calculations: baseline and emissions

This chapter presents the results of the calculations, differentiated for the workshops and the Guangzhou metropolitan area. A comparison is made between the baseline emissions (BAU scenario) and those of the WS1 and WS2 and the MIT. However, to avoid redundancy the MIT scenario is not shown for the workshop emissions. For the metropolitan area of Guangzhou an average of the WS1 and WS2 is presented.

4.1.Workshop baseline and emissions

As explained in the methodology, results were standardized using the average daily and 4 - week number of cars serviced in the workshop, shown in Table 3. They were divided by the total number of cars used in emission calculations for each scenario and then multiplied by 19 (the 4 - week average number of cars).

In Table 4, the baseline emissions for the BAU scenario are 9.5 kg of R134a, equivalent to 14.481 $kgCO_2eq$. This scenario assumes zero recycled refrigerant, which is common in most MAC - servicing workshops in

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[6] https://www.ipccnggip.iges.or.jp/public/2006gl/index.html.

China. A total of 13.1 kg of VR is needed to service all cars in 4 weeks. In contrast, in WS1, 9.3 kg of refrigerant is recycled, resulting in only 0.5 kg of emissions (776.3 kgCO$_2$eq). In WS2, 8.5 kg of R134a is recycled, with a total emission of 0.7 kg (1051.2 kg CO$_2$eq).

Table 1. Variables calculated in the pilot project

No.	Variables	Name	Units	Special Boundaries	Temporal Boundaries	Sources
1	R_{rcyl}	Refrigerant recycled	kg	Workshop	4 weeks, 1 year	Data collection campaigns
2	R_{vent}	Refrigerant vented	kg	Workshop	4 weeks, 1 year	Data collection campaigns
3	VR	Refrigerant consumption (Virgin)	kg	Workshop	4 weeks, 1 year	Data collection campaigns
4	Em	Refrigerant emissions	CO$_2$eq	Workshop	4 weeks, 1 year	Data collection campaigns
5	BL_{BAU}	Baseline emissions	CO$_2$eq	Workshop	4 weeks, 1 year	Estimation based on data
6	AvEm	Total avoided emissions	CO$_2$eq	Workshop	4 weeks, 1 year	Estimation based on data
7	R_{rcov}	Refrigerant recovered	Kg	Workshop	4 weeks, 1 year	Theoretical variable for MIT scenario
8	BL_{mac}	Baseline emissions	kg, CO$_2$eq	Guangzhou	1 year	Extrapolation using data from H Company
9	Em_{mac}	Refrigerant emissions	kg, CO$_2$eq	Guangzhou	1 year	Extrapolation using data from H Company
10	PRR_{mac}	Potential refrigerant to be recycled	kg	Guangzhou	1 year	Extrapolation using data from H Company
11	VR_{mac}	Virgin gas needed for servicing	kg	Guangzhou	1 year	Extrapolation using data from H Company
12	$AvEm_{mac}$	Total avoided emissions	kg	Guangzhou	1 year	Extrapolation using data from H Company

Table 2. Parameters for upscaling variables to the Guangzhou region

No.	Parameters	Name	Value	Units	Source
1	IC	Initial refrigerant charge	0.8	kg	Estimated using the data collected and data provided by the participating enterprise
2	LR	Annual leakage rate	4.1	%/year	Estimated using the data collected and data provided by the participating enterprise
3	n_c	Number of passenger cars in Guangzhou	2,800,000	Number of unites	H Company
4	S_y	Servicing frequency	6.5	Years	H Company
5	Er	Emissions on the road relative to the initial charge Leakage during the servicing frequency period (6.5 years)*	27	%	Estimated using the data collected and data provided by the participating enterprise

* This parameter represents the emissions during the servicing frequency period (Sy) and is used to calculate the annual leakage rate (LR) by dividing it by Sy.

Table 3. Standardizing Parameters

No.	Name	Value	Units	Source
1	Number of cars serviced per day in the workshop	0.67	Number of unites	Estimated using the data collected
2	Number of cars serviced in a 4-week period in the workshop	19*	Number of unites	Estimated using the data collected

* This value is calculated based on the data collected and therefore does not represent an annual average. During the survey period (May to August) the number of vehicles serviced is higher than the annual average as these are the warmer months when air conditioning is most commonly used. The average number of vehicles that are serviced at this workshop per month is 15.

Table 4. Baseline and emissions results for the H Company workshop

Variable	BAU Scenario (Baseline)	WS1	WS2
Start date	09.05.2024	27.05.2024	08.07.2024
End date	04.08.2024	23.06.2024	04.08.2024
Number of days	88	28	28
Number of weeks	12.57	4.00	4.00
Number cars surveyed	59	13	24
Cars surveyed per day	0.67	0.46	0.86

Standardized results			
Refrigerant recycled (Rrcyl)	0 kg	9.3 kg	8.5 kg
VR (VR)	13.1 kg	3.8 kg	4.6 kg
Refrigerant emissions (Em) or Potential refrigerant for recovery (PRrcov)*	9.5 kg	0.5 kg	0.7 kg
Refrigerant emissions (Em)	14,481 kgCO$_2$eq (BL)	776.3 kgCO$_2$eq	1,051.2 kgCO$_2$eq
Total avoided emissions (AvEm)		13,705 kgCO$_2$eq	13,430 kgCO$_2$eq

* The refrigerant emissions (Em) equal the potential refrigerant for recovery (PRrcov), because, in this case the emissions are counted only as the vented refrigrant in the workshop, and this is exactly the refrigerant that can be recovered. (See Equation 7)

Table 5. Baseline and emissions results for the metropolitan area of Guangzhou

Variable	BAU Scenario (Baseline)	Workshop Scenarios 1 & 2 (average)	MIT
Refrigerant recycled (Rrcyl)	0 kg	236,268 kg	252,255 kg*
Refrigerant emission in the workshops Emw	252,255 kg	15,988 kg	0 kg
Refrigerant emission on the road Emroad	92,360 kg	92,360 kg	92,360 kg
Refrigerant emissions (Emmac) or VR (VR)**	344,615 kg (BL)	108,348 kg	92,360 kg
Refrigerant emissions (Emmac)	527,261 tCO$_2$eq (BL)	165,772 tCO$_2$eq	141,311 tCO$_2$eq
Total avoided emissions (AvEmmac)	-	361,489 tCO$_2$eq	385,950 tCO$_2$eq

* This number also represents the refrigerant that is reclaimed in cases where recycling in-situ is not possible.
** As shown in Equation 13 the refrigerant emissions (Emmac) equal the VR (VR).

The WS1, as mentioned, above uses the data collected on the first campaign when the workshop had already access to new refrigerant recycling machines. However, the emissions are slightly lower than in the WS2 which occurred after the technicians had received proper training. In total, of the 13 vehicles serviced during the first data collection campaign only the refrigerant of one of them was vented. This can be compared to the 24 vehicles serviced during the second data collection campaign, where the refrigerant of two of them was vented. One possible explanation for the venting of refrigerant is that, in these three cases, the refrigerant was too polluted to be recycled. In addition, it should be considered that the first data collection campaign happened a month after the data collection process started. The first 4 weeks were used to refine the templates and make sure all technicians knew how to collect the data properly. This period, consequently, allowed the technicians to learn how to (informally) use the machines properly which resulted in an outstanding rate of refrigerant recycling from the beginning of this pilot and the data collection process.

4.2.Guangzhou metropolitan area baseline and emissions

The baseline and the emissions for the metropolitan area of Guangzhou are presented in Table 5 for the BAU, WS 1 & 2 and MIT scenarios. The annual emissions from all passenger cars in Guangzhou are estimated to be 527.261 tCO$_2$eq (344.615 kg). This total figure is the result of 92.360 kg of refrigerant leakage on the road (27%) and 252.255 kg of refrigerant vented in the workshops (73%). This figure clearly shows that the emissions that occur in the workshops, due to the venting of refrigerant, are more than two times higher than the refrigerant leakage on the road. Therefore, the most critical point for reducing refrigerant emissions of passenger cars in China is by addressing the refrigerant servicing practices of the workshops. Moreover, the emissions on the WS 1 & 2 are 165.772 t CO$_2$eq (108.348 kg) which is slightly less than a third of the baseline. This reduction of emissions is achieved thanks to the amount of refrigerant recycled (236.268 kg) on the scenarios WS 1 & 2.

The MIT scenario assumes that all refrigerant that arrives in the workshops is recycled or reclaimed. Thus, in this scenario the emissions only occur on the road equivalent (as explained above) to a total of 141.311 tCO$_2$eq emitted every year. It is important to mention that the MIT scenario is theoretical and that some refrigerant might be also too polluted to be reclaimed. However, it shows that if all workshops in the metropolitan area of Guangzhou reach the high rates of refrigerant recycling seen during the data collection campaigns, the reduction will be very significant, as the difference of emissions between WS 1 & 2 and MIT is only 6%.

5.Additional analysis: uncertainty, plateau behavior, and economic feasibility

The following text-based analysis responds to the concern that the transition from one measured workshop to Guangzhou-scale estimates may appear overly linear. Instead of adding new figures, the robustness of the results is clarified through uncertainty interpretation, literature benchmarking, and explicit discussion of the boundary conditions of the scenario model.

Representativeness and multi-site validation. The empirical results should not be interpreted as a national average. The Guangzhou pilot is valuable because it records actual recovery and venting behavior under controlled pre- and post-training conditions, but China's maintenance market is much broader. At the end of 2024, China had 353 million automobiles and 96 cities with more than one million automobiles[14], implying large differences in climate, workshop scale, technician certification, equipment age, vehicle age, and refrigerant mix. International MAC studies have therefore used multigarage sampling designs; for example, a European Commission study measured HFC-134a leakage in 300 vehicles across 19 garages in Germany, Portugal, and Sweden to capture climatic and operational differences[16]. Therefore, the present results are best treated as a pilot-derived emission factor and a methodological template, while future validation should use stratified sampling across authorized 4S/chain workshops, independent urban workshops, and small community or county-level repair shops.

Text-based sensitivity analysis. Using the central values in Table 5, BAU emissions are 527,261 tCO_2eq , the WS1/WS2 average is 165,772 tCO_2eq , and MIT is 141,311 tCO_2eq . One-at-a-time sensitivity tests show that the city-scale estimate is mainly controlled by five assumptions: initial charge (IC), service interval (Sy), road leakage share (Er), workshop recovery rate (RR), and passenger-car stock. Increasing IC or fleet size changes all scenarios almost proportionally; shortening Sy increases annual emissions because vehicles enter the service cycle more frequently; increasing Er raises the residual emission floor; and reducing RR increases the workshop-venting component in WS scenarios. However, these changes do not alter the core conclusion that standardizing recovery practices sharply reduces workshop emissions before broader economic and operational limits are encountered.

Plateau explanation. The apparent emission-reduction plateau in Scenario 4/MIT is caused by the boundary of the intervention rather than by a technical failure of recovery equipment. Workshop controls can reduce or eliminate venting during servicing, but they cannot remove refrigerant that has already leaked during vehicle operation. In Table 5, the observed WS1/WS2 average already recycles 236,268 kg out of the 252,255 kg of refrigerant potentially available for recovery; therefore the additional gain from moving from WS1/WS2 to MIT is only 24,461 tCO_2eq, compared with 361,489 tCO_2eq 1 from BAU to WS1/WS2. The remaining 141,311 tCO_2eq in MIT corresponds to on-road leakage. Thus, at very high workshop recovery rates, additional workshop-level controls exhibit diminishing marginal returns, and further reductions require upstream measures such as lower-leakage MAC design, improved maintenance of hoses and connectors, refrigerant containment during vehicle use, or transition to lower-GWP refrigerants.

Emission-factor uncertainty. The CO_2eq results use the IPCC AR6 100-year GWP value of 1530 for HFC-134a[17]. This factor affects the absolute CO_2eq magnitude but not the mass balance of recovered or vented refrigerant. Therefore, uncertainty in the GWP value should be reported separately from operational uncertainty in IC, Er, Sy, and RR. This distinction is important because a different GWP convention would rescale all scenario emissions, whereas operational uncertainty changes both total emissions and the relative contribution of road leakage versus workshop venting.

Economic feasibility. The economics should also be interpreted in two stages. The first-stage transition from BAU to routine recovery is likely to be the most feasible because it captures most avoidable workshop emissions through equipment availability, technician training, standardized checklists, calibration, and management supervision. The second-stage transition from a high recovery rate to MIT is more costly per additional tonne avoided because it requires not only better operation of recovery machines, but also refrigerant quality testing, separate storage, logistics to reclamation or destruction facilities, documentation, and compliance management. This is consistent with China's recent policy emphasis on full-chain management of controlled ODSs and HFCs, including sales, use, maintenance, end-of-life handling, recovery, reclamation, and destruction[15]. For small or independent workshops, these costs may be a barrier unless supported by shared recovery networks, enterprise alliances, certification and training programs, or deposit-return and producer-responsibility mechanisms.

Accordingly, the policy implication should be framed as a phased approach: first, expand equipment use and technician training to eliminate routine venting; second, develop regional recovery and reclamation logistics and data-reporting systems; third, conduct multi-site validation to establish city- or climate-zone-specific emission factors. This framing addresses generalizability without overstating the single-workshop pilot.

6.Conclusion

This study shows that maintenance workshops are a critical intervention point for reducing refrigerant emissions from China's passenger-car MAC systems. Using a Guangzhou pilot workshop operated by H Company, we quantified baseline emissions and evaluated the impact of introducing standardized recovery procedures, technician training, and better equipment utilization. Results show that BAU servicing causes substantial avoidable emissions. At the workshop level, adopting recovery equipment, standardized procedures, and technician training cut direct refrigerant emissions by over 90% compared with the baseline. In the Guangzhou area, improved practices reduced estimated annual MAC-related emissions from 527,261 tCO_2eq to 165,772 tCO_2eq, while an ideal high-recovery scenario could further reduce emissions to 141,311 tCO_2eq. The revised text clarifies that these city-scale values are scenario estimates anchored in one pilot workshop rather than statistically representative national averages. The main limitation remains the single-workshop design; therefore, future work should conduct stratified multi-site validation across different workshop types, regions, seasons, vehicle segments, and refrigerant-handling practices. The apparent mitigation plateau under the high-recovery scenario is explained by the residual on-road leakage that remains outside the boundary of workshop intervention. Economically, the transition from BAU to standardized recovery is likely to deliver the largest low-cost mitigation benefit, whereas the move from high recovery to full MIT-level recovery requires additional investments in testing, storage, reclamation logistics, data reporting, and compliance management. These findings support phased policy action: strengthen technician training and certification, standardize recovery workflows, improve equipment requirements, build regional recovery and reclamation networks, and develop more representative emission factors for China's diverse automotive maintenance sector.

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Data Availability Statement

The datasets generated and analyzed during the current study are not publicly available due to enterprise confidentiality restrictions but are available from the corresponding author upon reasonable request.

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