WORKING PAPER 2022-03

FEBRUARY 2022

Measures for reducing greenhouse gas emissions from motor air conditioning in China

Authors: Liuhanzi Yang, Hui He, Yihao Xie, and Shiyue Mao (International Council on Clean Transportation); Jiabao Ren and Chaoqian Wang (Automotive Data of China Co., Ltd.); Dong Ma, Jie Yin, and Qian Wu (Chinese Research Academy of Environmental Sciences)
Keywords: GHG emissions, motor air conditioning, refrigerants

Hydrofluorocarbons (HFCs) used in mobile air conditioning (MAC) and refrigeration equipment are an important contributor to greenhouse gas (GHG) emissions from motor vehicles. Estimates of emissions in China from the MAC refrigerant HFC-134a, conducted by Peking University, shows that they exceed 20 million tonnes of CO_2 equivalent per year (Hu Jianxin et al., 2018).

The international community attaches great importance to the reduction of GHG emissions from MAC. As major automotive producing regions, the United States and the European Union have implemented measures to reduce emissions of HFCs and other GHGs from MAC. Meanwhile, in October 2016, the Montreal Protocol on Substances that Deplete the Ozone Layer (Kigali Amendment) incorporated 18 HFCs into its list of controlled substances, with a goal of gradually reducing the production and consumption of HFCs over the coming decades. In June 2021, China announced its acceptance of the Kigali Amendment and became its 122nd contracting party. Further, this Amendment also addresses the issue of improving MAC energy efficiency. Recently, China announced the goal of a peak in carbon emissions by 2030 and carbon neutrality by 2060, and the Kigali

Acknowledgments: the authors hereby acknowledge Energy Foundation China and the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety for their support of this work. This publication is part of NDC Transport Initiative for Asia (NDC-TIA). NDC-TIA is part of the International Climate Initiative (IKI). The Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) supports the initiative on the basis of a decision adopted by the German Bundestag. For more visit: https://www.ndctransportinitiativeforasia.org. The views in this article represent the opinion and position of the authors only, not of the funders. The authors also appreciate the generous help and comments provided by external reviewers Jianxin Hu (Peking University), Qingfeng Xue (FAW), Lijin Zhao (SAE-China) and Jia Wang (CATARC). The authors also acknowledge the copy editing and design work provided by Gary Gardner and Valerie Sheckler.

Supported by:

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety

based on a decision of the German Bundestag

www.theicct.org

communications@theicct.org

twitter @theicct

THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

Amendment officially came into force on September 15, 2021 in China. It is urgent that China formulate policies that aim to reduce GHG emissions from MAC.

This report is organized as follows. The first section briefly describes the categories and sources of GHG emissions from MAC. The second section summarizes the measures to reduce GHG emissions from MAC, including the means to improve MAC energy efficiency. The third section analyzes the development status and challenges of advanced MAC technologies and refrigerants in China through a literature review and market research. The next section summarizes international experience and best practices, focusing on the regulatory systems and policies for reducing GHG emissions from MAC in the United States and Europe. The fifth section summarizes the existing measures and policy gaps in regulating GHG emissions from MAC in China. The last section provides policy recommendations for future regulation of GHG emissions from MAC in China, based on the previous analysis.

Overview of GHG emissions from MAC

GHG emissions from MAC include two types, direct emissions and indirect emissions. As shown in Figure 1, direct emissions refer to emissions related to the production, use, maintenance and scrappage of MAC refrigerants. Indirect emissions refer to the GHG emissions caused by the energy consumed during MAC operation, including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and black carbon. Indirect GHG emissions account for 81% to 88% of the total GHG emissions from MAC systems, while the remainder is direct emissions (Blumberg & Isenstadt, 2019).

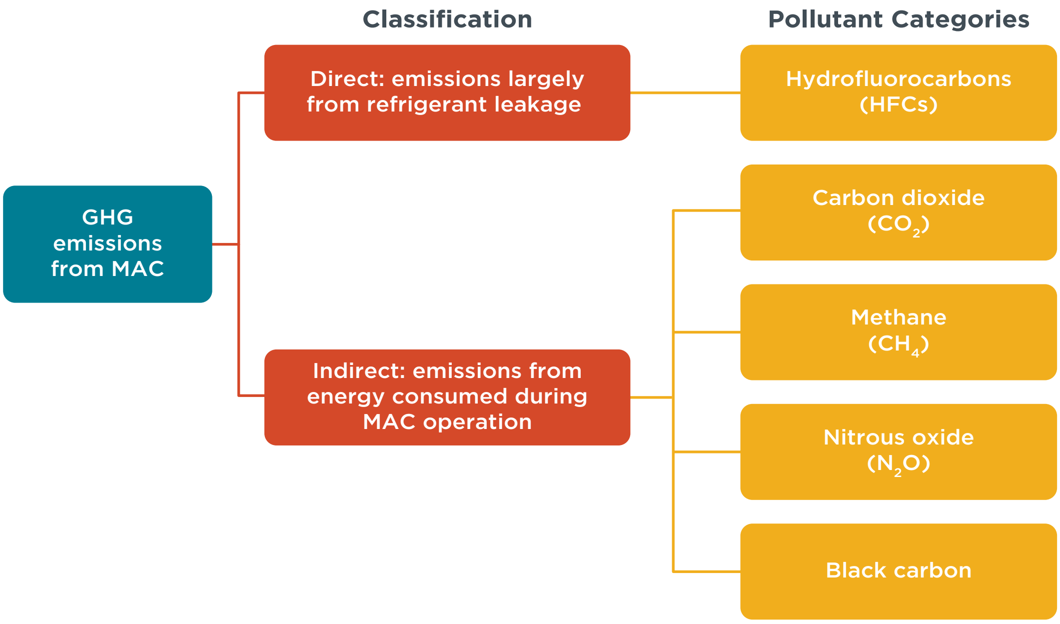

Figure 1. Composition of GHG emissions from MAC

Since the 1990s, the signatories to the Montreal Protocol have initiated actions to reduce the use of ozone-depleting refrigerants such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), replacing them with HFCs, which are now widely used. However, as potent GHGs, HFCs exhibit increasing climate impacts as their use has grown, so it is urgent to replace them with alternative refrigerants that have a synergistic control effect on climate change.

Global Warming Potential (GWP) is a metric designed to measure the influence of a GHG on global warming relative to CO_2, that is, the capacity of a GHG to absorb long-wave radiation reflected from the earth. Considering that various GHGs have different atmospheric lifetimes, the discussion of GWP is usually limited to a fixed time frame.

According to the Fifth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC), the most widely used MAC refrigerant on the market, HFC-134a, has a 100-year GWP of 1,430. If a shorter 20-year time frame is adopted, the global warming effect of one tonne of HFC-134a is 3,710, meaning that over a 20-year period, the GWP is 3,710 times higher than that of CO_2. Thus, reducing short-lived climate pollutants, including HFCs, can help to slow climate change.

In addition to direct emissions caused by the leakage of MAC refrigerant, the energy consumed by MAC operation also contributes to substantial GHG emissions. MAC systems account for 3% to 7% of the fuel consumed by light-duty fossil fueled vehicles in the world. In a hot and humid environment, this number can be as high as 20% (Chidambaram, 2010). Laboratory tests show that under the Worldwide Harmonized Light Vehicle Test Procedure (WLTP), the use of MAC in light-duty gasoline vehicles increases CO_2 emissions by approximately 10% (Yang & Yang, 2018). In real-world operation, more than 30% of the energy consumption of electric buses is related to the use of MAC systems (Basma et al, 2020). The impact on fuel consumption largely depends on vehicle speed and performance. As for battery electric vehicles, the use of MAC would reduce the driving range and increase energy consumption, thereby increasing upstream GHG emissions.

Measures for reducing GHG emissions from MAC

The reduction of GHG emissions from MAC systems can be achieved through various paths: 1) with regard to reducing direct emissions, by using low-GWP refrigerants and reducing the leakage rate of MAC systems; and 2) regarding reducing indirect emissions caused by MAC operation, by improving the energy efficiency of the MAC system (see Figure 2). This section briefly introduces the mainstream MAC technologies currently available on the market, the main alternative refrigerants, and the technologies that can improve MAC efficiency and their potential emission reductions.

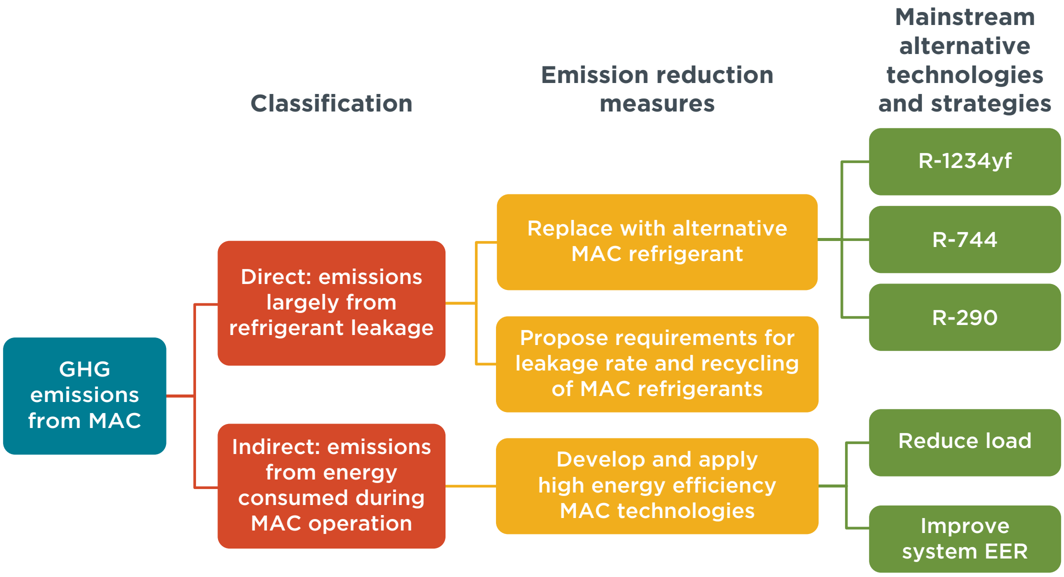

Figure 2. MAC GHG emission reduction strategies and technology pathways

Currently, **HFC-134a** (R-134a) is the most popular refrigerant for passenger cars, trucks and buses sold in China. Because electric buses experience greater demand for heat in the winter, some electric buses with heat pumps use refrigerants with better heating performance, including **R-407C** (23%HFC-125, 25%HFC-32, 52%HFC-134a) and **R-410A** (50%HFC-125, 50%HFC-32). MAC systems should be designed to adapt to these and other types of refrigerants. Table 1 shows the GWP values of commonly used MAC refrigerants.

Table 1. Commonly used MAC refrigerants and their GWP values

Refrigerant name	R-134a	R-410A	R-407C
GWP	1430	2100	1700

Four MAC technologies are in common use today: cooling conditioners, heat pumps, positive temperature coefficient (PTC) heaters, and fuel heaters.

A classic **cooling conditioner** is a technology whose sole function is to provide cooling; it is mostly used in passenger vehicles, trucks, and buses that have waste heat sources. The cooling air conditioner is a vapor compression refrigeration system, composed of an internal heat exchanger, an external heat exchanger, high-pressure/low-pressure pipelines, compressors, receiver dryers, expansion valves and sensors. The cooling air-conditioning refrigeration cycle includes 4 phases: *compression*, *heating*, *throttling*, and *heat absorption*.

Heat pump conditioners can generate heat in cold temperature and are thus suitable for pure electric vehicles that do not have engine waste heat. Heat pump-type air conditioners are equipped with two modes—cooling and heating—and have a more complicated structure than cooling conditioners. The heat pump cooling cycle is identical to that of the cooling conditioner. When heating, the refrigerant runs in the reverse direction through the four-way valves and other valves. The fan blows low-temperature air through the condenser and the air is heated. After the refrigerant exits the condenser, it enters the evaporator through the expansion valve. The expanded refrigerant in the evaporator exchanges heat with an external heat source, and then is sucked into the compressor again for the next round of the work cycle.

PTC heaters provide heat for automobiles by means of electric-heat conversion; they do not use a refrigerant and are suitable for heating battery electric vehicles. The PTC heater offers reliable performance, but its heating efficiency is less than 1. Using a PTC heater increases the depth of discharge of the traction battery, thus reducing the driving range of electric vehicles and reducing battery life.

Fuel heaters provide heat for automobiles through the combustion of fuels such as diesel and ethanol; it does not use a refrigerant and is used for heating battery electric vehicles in extremely cold regions where heat pump conditioners and PTC technologies cannot provide sufficient heat. Because the fuel heater is not driven by the traction battery, it would not reduce driving range, but its energy conversion efficiency is only about 70%, which is lower than that of PTC and heat pump systems. In addition, it would produce CO_2, $NO_{X,}$ and other pollutants[1], which are harmful to the environment.

Currently, alternative refrigerants with relatively low GWPs include:

HFO-1234yf (2,3,3,3-tetrafluoropropene, R-1234yf) has a GWP of less than 1, a 99.9% reduction compared to R-134a. R-1234yf is nearly a drop-in substitute for R-134a due to the similarity of charge size and physical properties between the two refrigerants; thus the hardware in which R-1234yf and R-134a are used is substantially the same. Although R-1234yf is slightly more flammable than the non-flammable R-134a, the methods to mitigate the flammability risk have been considered in the design of the MAC systems because both MAC systems use flammable lubricant. Combustion of R-1234yf would produce two extremely toxic chemicals, i.e., hydrogen fluoride and carbonyl fluoride, but the Society of Automotive Engineers (SAE) and the Joint Research Center of the European Commission independently confirmed the safety of R-1234yf, and R-1234yf is considered to be safer even in the event of a vehicle

1 Those pollutants are not covered by the scope of vehicle exhaust after-treatment system.

collision (Blumberg & Isenstadt, 2019). In addition, R-1234yf is readily degraded into trifluoroacetic acid, producing trifluoroacetic acid at five times the level of R-134a, but still in relatively low amounts. Currently, R-1234yf has been used in more than 100 million vehicles around the world, and the penetration rates of R-1234yf in new passenger cars in Europe, USA, and Japan have reached 100%, 70% and 30%, respectively. Some Chinese automakers also have experience in the application of R-1234yf. However, at low temperatures, the R-1234yf system performs poorly in the heat pump heating cycle, which is the main reason the R-1234yf systems are not universally adopted.

CO_2 (R-744) has a GWP of 1, and its climate forcing is 99.9% less potent than R-134a, and 100% less potent if R-744 is recycled in the scrapping process. Due to a higher heating energy efficiency ratio (EER) at low temperatures, R-744 is suitable for use in the heat pump system of electric vehicles. However, the cooling efficiency of the R-744 system is poor, so further technical research is needed. In addition, the R-744 system requires higher pressure to achieve the supercritical thermodynamic cycle required for R-744 refrigeration. Under high pressure and a supercritical cycle, the R-744 MAC system delivers highly efficient heating under normal environmental conditions. Of course, higher pressure requires more robust hardware for reliability and safety, and air-tightness must be ensured. Therefore, this system would need more frequent maintenance, with checks two to four times throughout its useful life. The R-744 system is currently in use in passenger cars and buses in small batches. For example, Volkswagen has launched an ID.4 electric vehicle model equipped with the R-744 system, and BYD has also applied the R-744 system to some bus models for export.

R-290 (propane), with a GWP of 3, is a refrigerant with a higher EER for refrigerating and heating that is suitable for cooling and heat pump MAC. However, the R-290 refrigerant has a safety grade of A3, which is extremely flammable. In order to reduce the flammability risk of the R-290 system, some Chinese enterprises are developing R-290 modular MAC systems and secondary loop systems, aimed at reducing the refrigerant charge size and preventing R-290 leakage into the driver's cab, so as to ensure safety even in the event of vehicle collision. Currently, an electric bus model, developed by the European enterprise AURORA, has adopted the R-290 system, while the R-290 system for passenger cars is still under research and development and has not been deployed commercially.

HFC-152a (1,1-difluoroethane, R-152a) is also an experimental alternative refrigerant, still in the HFC family, and with a GWP of 138. Relative to the initial charge size of R-134a, the overall usage amount of R-152a refrigerant is significantly reduced (the charge size is 50%-80% of R-134a). This is an 89.4% reduction compared to an equal volume of R-134a, and a 95% or greater reduction when the R-152a MAC's lower refrigerant charge is taken into account. In addition, R-152a has a higher EER and does not produce trifluoroacetic acid, a byproduct that damages the atmospheric environment. R-152a is more flammable than R-134a and R-1234yf, which requires, for safety reasons, that it be used in a secondary loop system or, if in a direct expansion system, that it be equipped with a reliable leak-detection system and automatic venting outside the cabin to relieve refrigerant pressure. Currently, the R-152a system is in the experimental stage and has not been commercialized. Furthermore, HFC-152a is one of the 18 HFCs regulated under the Kigali Amendment, so it is not considered a mainstream alternative refrigerant technology.

Table 2 summarizes the characteristics, costs and market status of R-134a and the four alternative refrigerants just discussed. Currently, the price of in-use refrigerants and alternatives in the auto sector ranges between 20 and 300 CNY/kg. The prices of alternative refrigerants, other than R-1234yf, are lower than those of in-use refrigerants, mainly because the production process of R-1234yf is more complicated than that of R-134a, and the patent on its application is limited. The price of R-1234yf is expected to decrease gradually as its use increases, and once the patent limitation expires.

Table 2. Comparison of performance, cost, and market status of alternative refrigerants for MAC systems

Type	GWP-100	Relative EER	Cost (CNY/kg)	Maintenance frequency over lifetime	Safety	Market status
Current refrigerant R-134a	1430	/	30	2	A1, non-flammable	Mainstream refrigerant
R-1234yf	<1	Equivalent	300	2	A2L, slightly flammable	Commercialized widely
R-152a	138	Increased by 10%	18	2	A2, flammable	Experimental
R-744	1	The heating EER is higher at low temperatures, but the refrigerating EER is lower at high temperatures	6	2-4	A1, non-flammable	Applied to passenger cars and buses in small batches
R-290	3	Increased by about 20%	20	2	A3, extremely flammable	Commercialized in an electric bus model, but no known commercialized application in passenger cars.

Many countries have set clear deadlines for phasing out the use of high-GWP refrigerants. However, most have not proposed policies to reduce indirect emissions through improved energy efficiency of MAC. Although the fuel consumption of passenger cars obtained from laboratory tests has gradually improved as regulations on fuel consumption and GHG emissions are tightened, MAC energy consumption has not been covered by laboratory testing procedures in most countries. In other words, MAC energy consumption would not affect whether a vehicle is compliant in terms of fuel consumption. Therefore, automakers are not motivated to improve MAC energy efficiency. One result is that MAC energy consumption as a share of a vehicle's overall energy consumption increases as vehicle efficiency improves.

There are two main pathways to improve the MAC energy efficiency: load reduction and powertrain optimization.

The key to reducing MAC load is to reduce the use of air-conditioning through other temperature control means. Specific measures include: applying a solar reflective coating to the vehicle body and installing window glass with lower solar light transmittance to reduce the effect of heat radiation to the interior from external sunlight; providing additional thermal insulating layers within the doors and beams to further enhance the effect of reflective coating and to reduce the cooling losses through the inner body walls when the MAC is operating; directing cooled air to passengers rather than circulating it throughout the interior, thus reducing the need for refrigeration; and using climate-controlled seating which pushes or pulls air through the seat cushion and seat back, using either seat ventilation to transfer heat away from a passenger, or air cooled by an electric device to help passengers feel cool. These technologies can reduce the fuel consumption of MAC, achieving a combined 18%–31% reduction in energy consumption of MAC for passenger cars under different climatic conditions (Blumberg & Isenstadt, 2019).

In addition to load reduction, it is possible to reduce the compressor load by **improving the efficiency of the MAC system** and improving system hardware, thus improving the system's energy efficiency. Measures to improve energy efficiency include: reducing the refrigerant leakage using low-permeability hoses, leak-resistant fittings and connectors, and an improved compressor shaft seal (even if the effect of refrigerants is not considered, less leakage can also contribute to maintaining the refrigerating capacity of the MAC system, which improves the energy efficiency of the MAC system, while also improving the reliability of the MAC system and reducing the servicing cost); reducing or eliminating the over-cooling of air by using variable displacement compressors, and by improving the controls for blowers and the fan motor; using internal circulation instead of external circulation whenever possible, provided that access to fresh air is ensured, to prevent the cooled interior air from being diluted by external air; and improving the performance of air-to-refrigerant heat exchangers through better design and with oil separation. In addition, with respect to the vehicle models with start-stop technology, certain air-conditioning technologies can maintain stable refrigerating performance for a short period when the engine is turned off. Vehicles equipped with these technologies can allow the automatic start-stop device to be active more frequently in urban driving conditions, reducing fuel consumption further.

Table 3 summarizes the main means of improving the energy efficiency of the MAC for passenger cars and the potential for reducing GHG emissions. Combined use of these technologies can reduce indirect GHG emissions from the MAC of passenger cars by about 40% (Blumberg & Isenstadt, 2019).

Table 3. The main means of improving energy efficiency of MAC systems in passenger cars, and GHG emission reduction potential

Indirect emission reduction scheme	Main technological means	Potential for reducing indirect GHG emissions from MAC systems
Load reduction	Reduce heat absorption and heat insulation, and directional delivery of cooled air	18%–31%
Improving the efficiency of MAC system	Improve compressor shaft seal, improve controls for blowers and fan motors, improve the performance of the air-to-refrigerant heat exchangers	3%–10%

Development status and challenges of MAC and refrigerants in China

As consumers seek ever-greater driving comfort, the penetration rate of MAC is increasing in China. According to industry research and related literature review results (State Environmental Protection Administration, 2001; Hu Jianxin et al., 2013), the penetration rates of the MAC for various vehicle categories in China are shown in Figure 3. Passenger cars is the vehicle category for which the MAC is popularized first. The MAC penetration rate for passenger cars was greater than 90% in 2000 and reached 100% around 2013. Since 2000, MAC penetration rates for buses and trucks have increased gradually. Currently, the MAC penetration rate for buses has reached nearly 100%, and the MAC penetration rate for trucks has reached about 90% overall, and 100% for medium- and heavy-duty trucks.

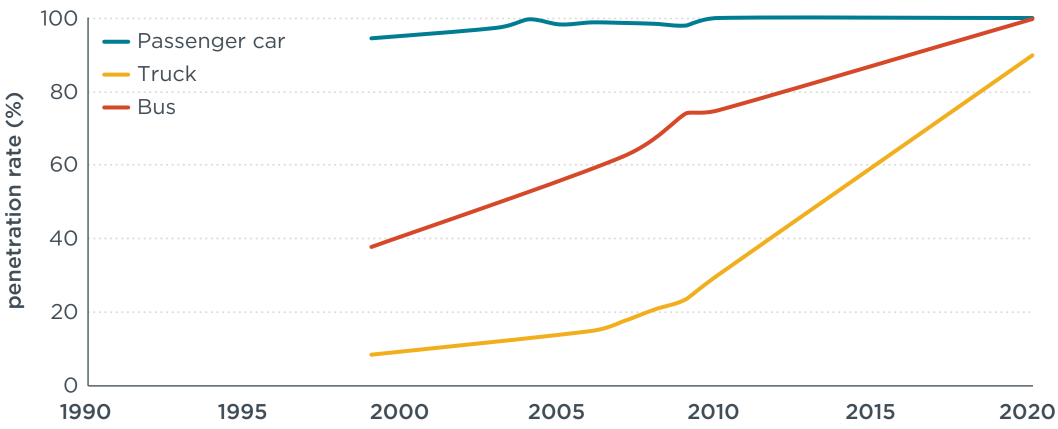

Figure 3. MAC penetration rate in China by year

Current situation of the MAC technology market in China

Internal combustion engine vehicles, whether passenger cars, trucks, or buses, rely mainly on the residual temperature of the engine coolant to generate heat; basically they all use cooling conditioners.

With respect to electric passenger cars, the residual heat of the electric motor is not sufficient for heating, so most electric vehicles must generate heat with the aid of PTC technology. Regarding electric passenger car models, 95% use a combination of a cooling conditioner with PTC technology, while the remaining 5% use a combination of heat pump and PTC. In order to maximize the driving range of electric passenger cars, some passenger car manufacturers also use fuel heaters to generate heat for vehicles. Only one Weltmeister vehicle model uses the combination of heat pump with fuel heater, accounting for less than 1% of market sales.

Electric trucks in China are primarily used for cargo transfer at ports, cargo transfer in logistics parks, materials transfer at construction sites, and other functions with short operating distances and complete charging facilities. Therefore electric trucks have little demand for extended range. Currently, nearly all electric trucks in China use a combination of cooling conditioner and PTC.

With respect to electric buses, the ambient temperature conditions across China's vast territory vary greatly, leading to significant differences in demand for bus cooling and heating in different regions, and the technologies used are also different. Currently, cooling conditioners are mainly used in Hainan and the Pearl River Delta where the annual minimum temperature is higher than 10°C. Heat pumps, cooling conditioner + PTC, and heat pump + PTC are used in the central and northern regions where the ambient temperature is lower in winter. In extremely cold regions such as Northeast China, electric buses with fuel heaters would be purchased, or additional fuel heaters would be installed after the purchase of electric buses. Electric bus models available today use a combination of heat pump with PTC in 76% of cases, cooling conditioners and the combination of cooling conditioners with PTC in 20%, and fuel heater technology in about 4%. However, in extremely cold regions such as Northeast China, fuel heater technology accounts for more than 50% of electric buses. The limited heating/refrigerating capacity of the current MAC is also one of the important factors for the slow development of electric vehicles in extremely cold and extremely hot regions.

Current status of refrigerant production and consumption in the Chinese auto sector

Passenger cars, trucks and buses sold in China mainly use R-134a as the refrigerant for MAC. Because electric buses have a large demand for heat, some electric buses that use heat pumps use R-407C and R-410A refrigerants that have better heating performance. In addition, passenger cars exported to Europe and the United States use R-1234yf refrigerant to meet local regulations banning the use of high-GWP refrigerants.

In response to the requirements for phasing down HFCs under the Kigali Amendment, passenger car and bus manufacturers in China are evaluating alternative refrigerants. Some automakers have already incorporated the design and application capabilities of the R-1234yf MAC system, and brands such as Tesla, FAW, Geely, and Great Wall have already exported vehicle models equipped with R-1234yf. Enterprises such as Sanhua, Dongfeng, SAIC, NIO, Yutong, BYD, and Valeo have also carried out research and development on heat pump systems for refrigerants such as R-744 and R-290. Currently, the R-744 system has been applied to passenger cars and buses in small batches; for example, Volkswagen has launched an ID.4 electric vehicle model equipped with the R-744 system, and BYD has also applied the R-744 system to some bus models for export. In terms of R-290 system application, the European enterprise AURORA has launched an electric bus model with the R-290 system, while the R-290 system for passenger cars is still under research and development, so no commercialized application case is available.

Consumption of MAC refrigerant includes two parts: the initial charge and the maintenance charge. Due to the lack of refrigerant sales data at servicing shops, this study estimates the consumption of HFCs in the auto sector in 2020 based on refrigerant charge size, vehicle population, and maintenance rate. Specific baseline data for estimates are as shown in Table 4. Passenger cars and trucks have a smaller refrigerant charge size with an average charge size of less than 1kg, while the larger size of the MAC system in buses requires a charge size between 1kg and 10kg. Further, new vehicles exported from China to the EU are filled with R-1234yf refrigerant in China, so consumption of R-1234yf refrigerant is estimated based on passenger car export data and the refrigerant charge size for a single vehicle in 2020 (see Table 5). In 2020, consumption of HFCs (R-134a, R-407A, R-407C, R-404A) in the auto sector reached about 32,000 tonnes (including 18,000 tonnes for initial charge and 14,000 tonnes for maintenance charge), whereas consumption of R-1234yf was about 67 tonnes. With the phase-down of HFCs in China, the demand for R-1234yf refrigerant will increase gradually, and the demand for R-1234yf in the Chinese auto sector is expected to increase to more than 20,000 tonnes in 2030.[2]

Table 4. Baseline data for estimating the consumption of HFCs refrigerant in the Chinese auto sector in 2020

Vehicle type	Production in 2020 (ten thousands)	Vehicle population in 2020 (ten thousands)	Refrigerant charge size (kg)
Passenger cars	1999.4	24800	0.6
Trucks	477.8	3134	0.9
Conventional buses	37.4	206	2.1
Electric and plug-in hybrid buses	7.9	44	5
Refrigerated truck (Refrigerated Cabinet)	7.2	25	0.5
Parking air conditioner	97.5	312	0.5

2 Currently, R-1234yf is the technology that is most mature. We assume that the R-134a used for new vehicles is replaced completely by R-1234yf.

Table 5. Consumption of main refrigerants in the Chinese auto sector in 2020

Refrigerant type	Refrigerant consumption in 2020 (tonne)
R-134a	32055
R-410A	22.7
R-407C	432.1
R-404A	44.8
R-1234yf	67

China is the world's largest producer and exporter of HFCs, accounting for about 70% of global production, of which more than 50% is for export. In 2020, the production capacities of the R-134a, R-32, and R-125 refrigerants in China was more than 238,000 tonnes, 272,000 tonnes and 106,000 tonnes, respectively, which fully met demand for HFC refrigerant in the Chinese auto sector. Figure 4 shows the HFC refrigerant supply chain in the Chinese auto sector. 80% of HFC refrigerant consumed in the Chinese auto sector comes from large-scale production enterprises, e.g., Sinochem Lantian, Zhejiang Juhua, Zhejiang Sanmei, Bluestar, Mecichem, and Chemours, while the remaining 20% comes from other small and medium-sized refrigerant manufacturers. Large-scale refrigerant manufacturers supply their products to authorized service providers and agents, who sell refrigerants to automobile manufacturers. Small and medium-sized refrigerant manufacturers sell their refrigerant to auto service shops through agents and distributors, while a small share of refrigerants is sold to individuals who refill and repair their own MVACs.

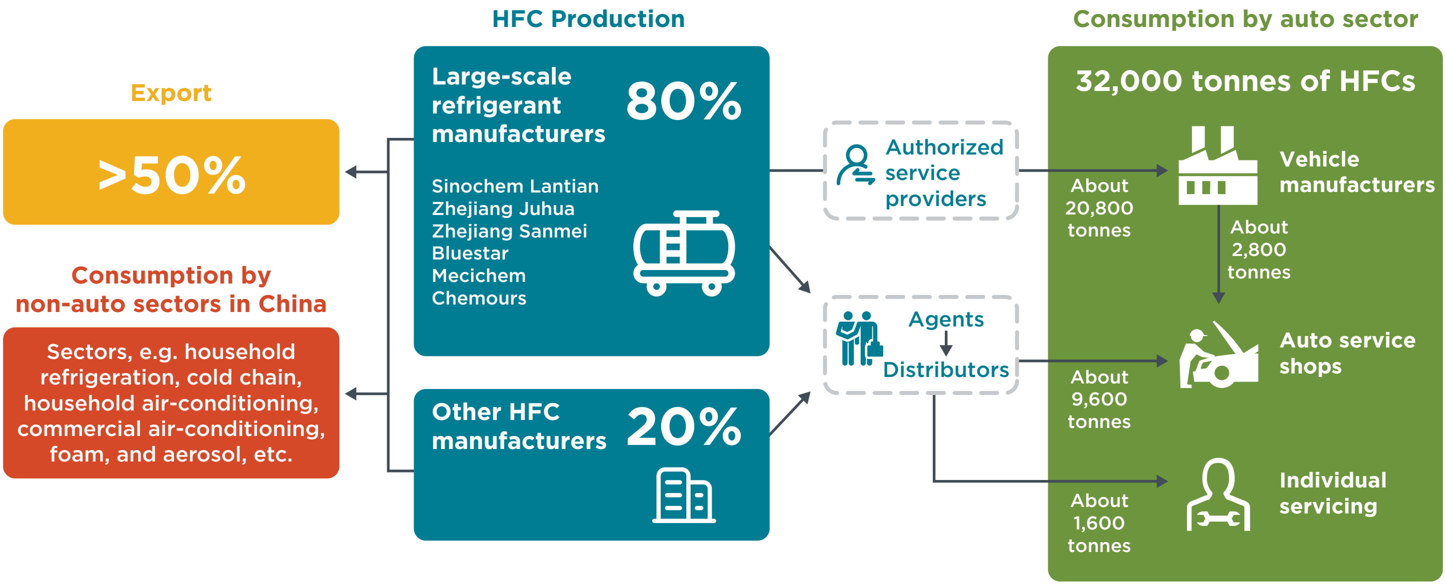

Figure 4. Schematic diagram of the HFC refrigerant supply chain in the Chinese auto sector

As for alternative refrigerants, China has capacity to manufacture R-1234yf, R-152a, R-290, and R-744. Enterprises such as Honeywell, Chemours and Huanxin Fluorine have production capacity of about 20,000 tonnes of R-1234yf, which can meet the current demand for alternative refrigerants. As HFCs phase down in China, refrigerant manufacturers such as Chemours and Honeywell will rapidly expand the production of R-1234yf and other alternative refrigerants, so as to meet the new demand.

The use of alternative refrigerants needs to match particular MAC systems. While R-1234yf can use most parts of the R-134a system, the matching system for other refrigerants must be significantly adjusted, and the cost will increase accordingly. Therefore, when considering the cost of alternative refrigerants, it is necessary to take into account not only the different charge sizes for different refrigerants, but also the cost increment of the corresponding matching system. Table 6 analyzes the cost variation per vehicle when different refrigerants are used.

Table 6. Cost variation per vehicle for refrigerant replacement and system matching in the Chinese market (positive values indicate an increase, negative values a decrease)

Vehicle type [a]	Variation	R-1234yf	R-744	R-152a	R-290
Passenger cars	Refrigerant charge size (kg)	0.57	0.35	0.38	0.16
	Refrigerant cost increase (CNY)	152	-17	-12	-16
	Matching system cost increase (CNY)	About 100	About 9,000	About 180	NA[b]
Buses [c]	Refrigerant charge size (kg)	NA[d]	6	NA[d]	1.5
	Refrigerant cost increase (CNY)	NA	-96	NA	-102

[a] Cost information about alternative refrigerants and the corresponding matching system for trucks is not available currently.

[b] Because there are few commercialized cases of the R-290 matching system, its cost information is not available.

[c] 10m-long buses are an example.

[d] The commercialized system suitable for bus models is not available currently for this refrigerant.

Although some Chinese automakers have accumulated experience in research & development and the application of alternative refrigerant systems, and although the production capacity for alternative refrigerants can meet market demand, several challenges remain for the wide application of alternative refrigerants:

1. Long transition time: Transition to a new refrigerant needs to be matched with vehicle model development, system matching, and emissions verification. An average transition period of 5 years is required for automakers to apply an alternative refrigerant.
2. High cost of transition: Refrigerant transition requires the transformation of vehicle production lines and maintenance lines, which entails additional costs of more than 3 million CNY for a single production line.
3. Patent limitations on application of alternative refrigerant technology for ICE vehicles: R-1234yf is an ideal alternative refrigerant for ICE vehicles, but the patent on its application is held mainly by Honeywell and Chemours. Chinese refrigerant manufacturers do not have sales rights to R-1234yf, and Chinese automobile manufacturers are required to purchase R-1234yf only from Honeywell, Chemours, and their authorized companies.
4. Alternative refrigerant technology for new energy vehicles (NEV) is not mature: Due to its poor heating capacity, the R-1234yf system needs to use PTC heaters for supplementary heating, which seriously reduces the driving range of electric vehicles. Although the R-744 system and R-290 system have high heating energy efficiency, they are currently produced only in small batches, and in R&D stages, respectively, so they are not ready for large-scale application. In addition, insufficient mass production of the R-744 system components results in a higher price for the R-744 system. The current price of the R-744 system is 1.3–5 times the price of the existing system.
5. Absence of relevant policies and standards: China has not yet issued specific requirements for phasing down HFCs in the auto sector, so the enterprises have low willingness to replace the refrigerant and the system autonomously. Further, a series of standard specifications related to alternative system design, system safety limitations, and refrigerant testing and certification is required for the replacement of MAC refrigerants, but currently the relevant standard system in China is not complete.

International experience in regulating GHG emissions from MACs

The Kigali Amendment officially embraced by China in 2021 is an important measure for regulating and controlling the direct emissions of refrigerants, and it imposes restrictions on the production and consumption of HFCs throughout the economy. In addition, regional and national policies or laws across the globe also regulate the types, leakage rates, and recycling of MAC refrigerants. On the other hand, the development and wide application of energy-efficient MAC technologies can be effectively advanced by incorporating incentive credits for energy-efficient MAC into standards for automobile fuel consumption or CO_2 emissions (see Figure 5). This section will briefly introduce the Kigali Amendment and summarize the experience of the United States and the European Union (EU) in regulating GHG emissions from MACs.

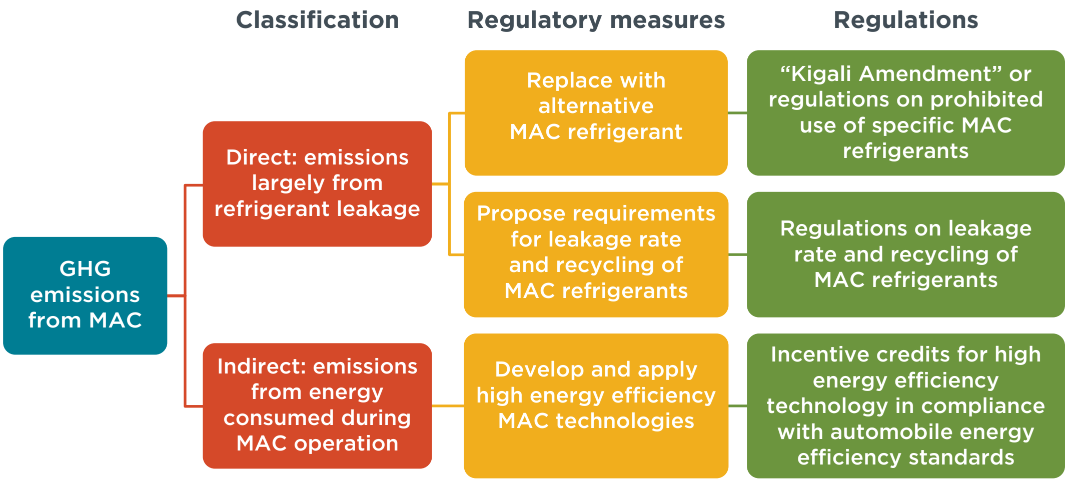

Figure 5. Summary of measures for regulating GHG emissions from MAC systems

Kigali Amendment

The Kigali Amendment provides for different schedules for phasing out HFCs, based on country categorizations (see Table 7). Most developed countries, i.e., Group 1 of the non-A5 countries, initiated the phase-out of HFCs in 2019, while five initiated the phase-out in 2020. According to Article 5 of the Montreal Protocol, developing countries, i.e., A5 countries, were granted more time to achieve the phase-out of HFCs. Most developing countries, including China, will freeze production and consumption of HFCs at the baseline level in 2024. Some A5 countries will start to phase down HFCs in 2028. The Kigali Amendment went into effect in China on September 15, 2021.

Table 7. Phase-down schedules for HFCs under the Kigali Amendment

	A5 Parties: Group 1	A5 Parties: Group 2[1]	Non-A5 Parties: Group 1	Non-A5 Parties: Group 2[2]
Baseline Years	2020-2022	2024-2026	2011-2013	2011-2013
Freeze Year	2024	2028		
Step 1	2029: 90%	2032: 90%	2019: 90%	2020: 95%
Step 2	2035: 70%	2037: 80%	2024: 60%	2025: 65%
Step 3	2040: 50%	2042: 70%	2029: 30%	2029: 30%
Step 4			2034: 20%	2034: 20%
Final step	2045: 20%	2047: 15%	2036: 15%	2036: 15%

[1] Bahrain, India, Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia and United Arab Emirates

[2] Belarus, Kazakhstan, Russia, Tajikistan and Uzbekistan

Studies show that the climate mitigation benefits of the HFC phase-down could be doubled if matched with complementary measures to improve the energy efficiency of air conditioning and refrigeration (Blumberg & Isenstadt, 2019). Therefore, contracting parties to the Kigali Amendment also agreed to take steps to maintain and/or enhance the energy efficiency of low- or zero-GWP alternative technologies and equipment when phasing down HFCs.

United States

The United States has one of the strongest and most comprehensive programs to reduce GHG emissions from MAC systems. It regulates the MAC system of light-duty vehicles (LDV) as a whole system, has set multidimensional incentive credits for reducing GHG emissions from MAC in its CO_2 standards for LDVs, and provides relatively systematic measures for administering its regulations. Manufacturers have the option of obtaining generous GHG emission reduction credits by reducing leakage of refrigerants, switching to lower-GWP refrigerants, improving the efficiency of MAC systems, and reducing cooling demand. In the CO_2 emission standards for LDVs in the United States, off-cycle incentive credit is one of the strategies used to help manufacturers meet stringent CO_2 fleet-average standards, and the specific technologies and list of credits are as shown in the Appendix. Under the current administrative policy, automakers or AC parts enterprises would seek to optimize the refrigerant matching system, cooperate to achieve direct emission reduction of HFCs and indirect emission reduction of CO_2, and reduce costs reasonably.

In addition, the Significant New Alternatives Policy Program (SNAP) issued by the United States also specifies the categories of MAC refrigerants. According to the Clean Air Act (CAA), the SNAP program was originally intended to reduce the use of ozone depleting substances (ODS) throughout all sectors of the economy. In 2015, the United States updated requirements for certain refrigerant substitutes under the SNAP program, which stipulate that their climate impacts shall be taken into consideration as well. That policy required the complete phase-out of R-134a from 2021 for all LDVs in the United States; under the stringent provisions on consumption limits, until 2025 R-134a is allowed in vehicles exported to countries lacking infrastructure for servicing alternative refrigerants; starting in 2026, R-134a would not be allowed in any vehicles newly manufactured in or imported into the United States.

Refrigerant leakage from MAC servicing is significantly higher in the United States than in most other countries because a large number of vehicle owners service their vehicles themselves. EPA has also adopted regulations intended to reduce leakage of refrigerants to the atmosphere during servicing. These regulations include: (1) prohibition of intentional release or venting of refrigerants to the atmosphere[3]; (2) requirements for technician training and certification for repair of MAC systems at servicing shops, and for use of certified equipment; and (3) safe disposal requirements at the end of life of the MAC system or vehicle. California also adopted restrictions on sales of small cans of refrigerant used in home servicing of MAC systems.

European Union

The EU has formulated the F-gas Regulation for all sectors and the MAC Directive for automotive air conditioners. The original F-gas Regulation was adopted by the EU in 2006. In 2014, EU Regulation No. 517/2014 updated the relevant regulations and was implemented in 2015. As required by the new regulation, F-gas consumption shall be reduced to one-third of its 2014 level by 2030. The F-gas Regulation limits the total amount of F-gas in the EU by assigning F-gas quotas to

3 R-744 as a refrigerant is exempt from this rule

producers and importers. Currently, the European Commission is studying the next steps and will propose a new regulation on F-gas by the end of 2021.

In 2006, the EU adopted the first policy for use of refrigerants in MAC systems, Directive 2006/40/EC "MAC Directive". According to this Directive, from 2017, the use of refrigerant with a GWP higher than 150 is banned in all new vehicles for sale in the EU. New vehicles with MAC systems using these gases shall not be registered, sold, or entered into service in the European Union. According to the F-gas regulation mentioned above, the supply of R-134a for servicing in in-use vehicles is also limited.

While the European Union has demonstrated leadership in the phase-out of high-GWP refrigerants, the EU LDV CO_2 emission standards to date have not provided any incentive credits for the use of low-GWP refrigerants or any requirements for improving the energy efficiency of MAC systems, nor does it include use of air conditioning in the official test cycle or measure the impact of air conditioning use on vehicle CO_2 emissions. This lack of accounting for energy consumption from LDV AC systems is considered to be one of the important reasons behind the growing gap between the real-world CO_2 emissions of LDVs and the type-approved CO_2 emissions in the EU. ICCT's analysis concludes that the divergence between official laboratory testing for type approval and real-world CO_2 emissions data has grown from 8% for model year 2001 to 37% for model year 2017 (Tietge et al, 2019).

The European Commission's proposal for post-2025 standards will allow improvements to air conditioning systems to be counted as "eco-innovations" for the first time. Eco-innovations are innovative technologies that provide verifiable CO_2 benefits not covered by the standard test cycle. To gain access to these credits, automakers must submit to the European Commission verification reports provided by certified third-party agencies. Eco-innovation credits are currently capped at 7 g/km, but the proposal for post-2025 standards has opened the possibility of revising this cap.

The European Commission's fuel economy and CO_2 emission standards for heavy-duty vehicles (HDV) have not provided any regulations on improving MAC system efficiency by means of incentive credits. EU Regulation No. 2019/1242 stipulated the CO_2 emission reduction targets for four types of trucks. Manufacturers are required to reduce the CO_2 new fleet-average emissions by 15% compared to the baseline level by 2025, and by 30% by 2030. The baseline is determined according to the certified CO_2 emissions of vehicles registered in the second half of 2019 and in the first half of 2020. The certification for CO_2 emissions from European commercial vehicles relies on the vehicle energy consumption calculation tool known as VECTO. In the VECTO model, the air-conditioning system is classified as auxiliary equipment. VECTO calculates the energy consumption of auxiliary equipment by analyzing technologies in the test vehicle, with input values drawn from a predetermined technology list. The certification rules do not have any regulations on testing, family, or conformity of production.

In addition to the United States and the European Union, other countries have introduced regulations aimed at reducing GHG emissions from MAC. Table 8 summarizes the regulatory measures for GHG emissions from MAC adopted by 11 countries and regions.

Table 8. Regulatory measures for reducing GHG emissions from MAC adopted by various countries

Country/region	MVAC requirements in emission standards			Policies for reducing HFCs emissions from MAC
	AC testing	Credits	Comments	
United States	For credit only	Credits for AC energy efficiency technology, thermal management technology, use of alternative refrigerants, and low leakage rates	Credits offered based upon a technology list and real-world testing results	Ban HFC-134a (2021)
Canada				Ban refrigerants with GWP>150 (2021)
Mexico	Not included	Credits for efficient AC technology, refrigerant replacement, and system with low leakage rates	No regulatory mechanism for compliance	N/A
Brazil	Included in emission testing only	No credits	N/A	N/A
European Union	Not included	No credits	HDV CO_2 model has an option of high-efficiency AC	Ban refrigerants with GWP>150 (2017)
Australia	Not included	No credits	Under consideration	N/A
Japan	Not included	N/A	N/A	Ban refrigerants with GWP>150 (2023) Regulations on scrappage and recycling
China	Not included	Credits for high-efficiency AC for LDVs to be implemented in 2022	N/A	N/A
India	Not included	No credits	National high efficiency cooling action plan under development	N/A
South Korea	Not included	Credits for high efficiency AC included, potential credits for thermal management technology	N/A	N/A
Saudi Arabia	Not included	Credits for high efficiency AC and thermal management (based on U.S. standards)	Specific credits were adjusted	N/A

Current regulatory measures for GHG emissions from MAC and policy gaps in China

Currently, China regulates refrigerants and AC energy efficiency separately, rather than regulating the MAC as a whole system, so it is difficult to reflect the impact of the MAC system on GHG emissions and pollutants from the vehicle.

Regulatory measures for direct emissions

As part of its implementation of the Kigali Amendment, China has formulated and implemented the "Regulation on the Administration of the Ozone Depleting Substances (ODSs)". This is the first national regulation derived from the international environmental convention, and serves as the legal basis and work foundation for China to achieve its phase-out goals for ODSs. Similarly, in response to the issuance and implementation of the Kigali Amendment, the Ministry of Ecology and Environment (MEE) is revising the "Regulation on the Administration of the Ozone Layer Depleting Substances (ODSs)" by including HFCs as one of the regulated substances, by fully learning from China's successful experience in eliminating and regulating ODSs and effectively leveraging on existing regulatory laws & regulations and systems. The name of the regulation will be changed to to "Regulation on the Administration of the Ozone Layer Depleting Substances (ODSs) and Hydrofluorocarbons (HFCs)". Currently, this regulation has been publicly solicited for comments and is being further revised. The draft regulation proposes that China will, by taking measures in the areas of finance, taxation, price, and government procurement, encourage and support the scientific research, technology development, and application of HFC alternatives and alternative technologies, as well as detection and monitoring technologies and methods, and encourage recovering, recycling, and transforming HFCs. Meanwhile, the MAC systems that use HFCs as a refrigerant will be included in the national comprehensive industrial policy catalogue based on their phase-down progress. Also, China plans to establish and improve the data and information management system of HFCs, and to collect, summarize, and release the data and information about their production, use, import, and export. The revision and implementation of the regulation will provide important guidance for the phase-down of HFCs, including the MAC refrigerants.

With respect to the regulation of refrigerant leakage, China has published two recommended technical standards associated with MACs, and another standard is under development. The standards issued and implemented include GB/T 21361-2017 “Motor vehicle air-conditioning unit” (State Administration for Market Regulation, 2018a), which was implemented on February 1, 2018, and GB/T 37123-2018 “Electrically driven motor vehicle air-conditioning unit” (State Administration for Market Regulation and Administration, 2018b), implemented in July 2019. In addition, a group standard “Test Methods and Limits for Leakage of Automotive Air-Conditioning Refrigerant (R-134a)” has been approved for initiation by China Association for Standardization, and is under development.

“Motor vehicle air-conditioning unit” is used to describe the air-conditioning units intended for motor vehicles other than battery electric vehicles. “Electrically driven motor vehicle air-conditioning unit” is used to describe the electrically driven motor vehicle air-conditioning units, which include not only electric vehicles, but also the electrification of conventional vehicles. “Motor vehicle air-conditioning unit” specifies two test methods of sealing performance. One is to test according to the operating procedure specified in SAE J1628; under this test method, the evaporator assembly and condenser assembly shall not exhibit any leakage. The other is to seal the opening when the unit is charged with dry nitrogen to reach its maximum operating pressure; under this test method, the leakage rate shall be less than 5g per year. “Electrically driven motor vehicle air-conditioning unit” also stipulates that, when testing is carried out according the operating procedure specified in SAE J1628, no refrigerant leakage shall occur to any part of the refrigerating system. Because the two national standards are recommended, rather than mandatory, the implementation results are not satisfactory. “Test Methods and Limits for Leakage of Automotive Air-Conditioning Refrigerant (R-134a),” which is under development, refers to the European Commission Regulation No. 706/2007, and stipulates the test procedures and limits for R-134a leakage, but it has not been issued and implemented. The test procedure specified in the draft standard is as shown in Figure 6.

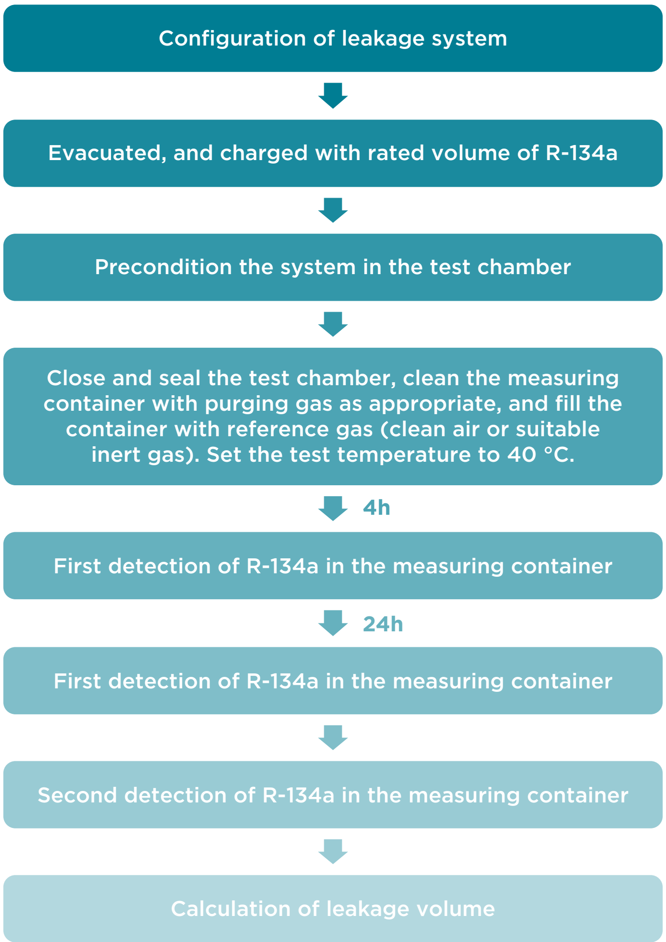

Figure 6. Proposed R-134a leakage test procedure in China

Regulatory measures for indirect emissions

Currently, the Chinese standards of passenger car fuel consumption provide additional energy-saving incentives for off-cycle technologies/devices. Off-cycle technologies/devices refers to technology or devices verified to have significant energy-saving effects in practical application but this effect cannot be embodied or incompletely embodied through existing test methods. The high-efficiency MAC is included in the off-cycle technology/device. For vehicles using high-efficiency MAC, when calculating the Corporate Average Fuel Consumption (CAFC), the fuel consumption of a vehicle model can be reduced accordingly based on its energy-saving effect. The standard "Off-cycle technology/device energy saving effects evaluation methods for passenger cars - Part 3: Automotive air conditioner" was issued on October 11, 2021, and will be implemented on May 1, 2022 (State Administration for Market Regulation, 2021). This standard only applies to fuel passenger cars and doesn't apply to commercial vehicles and electric vehicles.

In order to test the contribution of AC system improvements to actual fuel saving, this standard uses the vehicle chassis dynamometer method. The test procedures include: vehicle preparation, preconditioning (90 km/h), soak (30 min), AC on test, data analysis, preconditioning (90 km/h), AC off test, and data analysis. Specifically, prior to testing, the vehicle is exposed to simulated solar radiation for 30 minutes to imitate the process of parking the vehicle outdoors in summer. During the vehicle chassis dynamometer test, vehicle fuel consumption is tested with the AC on and off. The increase in fuel consumption after the AC is turned on is compared with the target value of fuel consumption for the vehicle model. If the fuel consumption from use of the air conditioner is greater than or equal to the corresponding target value, the air conditioner of this vehicle model is deemed not to have an energy-saving effect. If the fuel consumption is less than the corresponding target value, the energy saving effect of the air conditioner is calculated proportionately, and a corresponding premium is granted when calculating the CAFC. In order to promote the simultaneous development of multiple energy-saving technologies, incentives for high-efficiency AC technology are capped at 0.2 L/100 km.

Table 9 summarizes the international experience in reducing GHG emissions from MAC and China's policy gaps. Generally speaking, China lacks concrete policy solutions and even fundamental data and information to effectively reduce high-GWP refrigerant consumption and improve the efficiency of A/C systems in the motor vehicle industry. In terms of direct emissions, China has not formulated regulatory policies for GHG emissions from MACs; in terms of indirect emissions, China has established the fuel consumption incentive credits for high-efficiency air conditioners for passenger cars, but they have not yet been applied to commercial vehicles and electric vehicles.

Table 9. Analysis of international best practices and China's policy gaps

International best practices	Policy gaps in China
The air conditioner is regulated as a whole system in automobile CO_2 emission standards.	China has not yet regulated MVAC GHG emissions from a whole-system perspective, and has not formulated regulations on the prohibition and substitution of MAC refrigerants. The country lacks technical information on new vehicle AC refrigerants and AC systems, and statistics on production, use, and maintenance.
Incentive credits are granted to vehicle models that use low-GWP refrigerants, deliver low rates of refrigerant leakage, improve MAC system efficiency, and reduce cooling demand. Under these regulatory measures, automakers or AC parts enterprises would seek to optimize the refrigerant matching system, cooperate to reduce direct emission of HFCs and indirect emissions of CO_2, and reduce costs reasonably.	The fuel consumption incentive credits for high-efficiency AC for passenger cars have been issued, but they have not yet been applied to commercial vehicles and electric vehicles.
There are specific regulations for MAC servicing, recycling and scrappage.	China lacks relevant regulations for MAC servicing, recycling, and scrappage.

Recommendations for China's next step in regulating GHG emissions from MACs

The phase-down of HFCs and the improvement of energy efficiency associated with MAC in China face various opportunities and challenges. China was one of the first countries to produce low-GWP refrigerants, and its production capacity can meet the needs of the alternative refrigerant market. Although relatively costly in the initial stage of emission reductions, the cost of low-GWP refrigerants per gram of CO_2 reduction is lower than the cost of GHG reduction technologies in other non-auto sectors; with large-scale production of substitutes and with technological progress, the cost of emission reductions will gradually decrease. In addition, the use of low-GWP AC refrigerants can create a new, low-cost GHG emission reduction pathway for the automotive industry. On the other hand, many countries and regions in the world have banned the use of high-GWP refrigerants in MAC. Accelerating the development of vehicle models with low-GWP refrigerants will induce Chinese manufacturers to produce vehicles that meet the import standards of other countries. It is an important step for China to enter the ranks of the world's automotive powers.

However, China still faces many challenges in reducing GHG emissions from MAC systems in the auto sector. For example:

» refrigerant replacement needs to be matched with vehicle model development, system matching, and emission verification, so the transition period is long;

- there are additional refrigerant emissions resulting from refrigerant leakage and absence of regulatory measures for refrigerant recycling;
- additional investment is needed because refrigerant replacement requires the transformation of vehicle production lines and maintenance lines;
- the alternative refrigerants and MVC technologies for new energy vehicles (NEV) are not mature; R-1234yf could not meet the heating demand of NEVs, while the R-744 technology with favorable heating performance at low temperatures is not sufficiently mature for large-scale application.

Based on international experience with MAC and the current situation in China, we recommend the following policies for regulating GHG emissions from MAC in the auto sector:

1. **Incorporate MAC information into the motor vehicle environmental protection information disclosure management system, and collect the refrigerant consumption data and AC technology information**. China has established a full life-cycle environmental compliance regulatory system for motor vehicles, which includes ex-ante information disclosure, intermediate compliance supervision, and ex-post environmental recall. It is recommended that information about MAC systems and refrigerants be incorporated into the information disclosure platform and the configuration list, so as to strengthen public participation and supervision. Relevant information includes refrigerant type, AC technology, leakage rate, AC energy efficiency, and GHG emission data with AC on.
2. **Develop a MAC emission standard and systematically reduce GHGs and pollutants from MAC**. It is recommended that China regulate the MAC as a whole, systematically handle the reduction of direct and indirect emissions from MAC systems, formulate vehicle GHG emission standards, and incorporate the AC testing into emission testing procedures. It is recommended that AC testing procedures be incorporated into emission standards, and that the impact of activated AC on GHGs and pollutants be quantified. In the emission standards, it is important to establish the credit management system, and provide incentive credits to vehicle models with low-GWP refrigerant, low leakage rate, and high efficiency AC technologies. Through the provision of incentive credits policymakers can encourage manufacturers to develop and apply alternative refrigerants, alternative refrigerant AC systems, and high-efficiency AC technologies to promote the development and large-scale application of new technologies. Governments should guide the automotive industry to carry out technical research on model design, production line transformation, recycling technology and other countermeasures, to integrate industry resources, and to use supply chain advantages to reduce costs.
3. **Establish the MAC emission regulatory system and strengthen control of MAC emissions throughout life cycle**. It is recommended that regulators establish MAC refrigerant and GHG emission testing, and an information disclosure and supervision system, based on the motor vehicle environmental protection compliance regulatory system. When checking the conformity of production for new vehicles and in-use compliance for in-use vehicles, GHG emission testing with the AC on should be included, AC technology and refrigerant type should be verified, and the AC maintenance data should be collected. Authorities should establish penalties for nonconformity issues identified during production of new vehicles and the in-use compliance testing according to the Law of the People's Republic of China on the Prevention and Control of Atmospheric Pollution, and impose environmental recall for non-compliant vehicles. They should also strengthen the responsibility of manufacturers, establish an extended producer responsibility system, and strengthen refrigerant management during the life cycle. In addition, they might formulate policies related to MAC servicing,

scrappage and recycling, formulate the technical specifications for MAC servicing, strengthen the training and certification for MAC technicians, and strengthen the regulation and punishment for the use of counterfeit and shoddy refrigerants in the auto maintenance industry, so as to reduce the refrigerant leakage emissions during MAC servicing. Finally, they should formulate a regulation for Recycling and Handling Refrigerant from End-of-Life Vehicles, and give full play to the responsibility of automobile manufacturing and import enterprises in refrigerant recovery, recycling and proper disposal.

4. **Expedite the development and revision of standards for MAC parts to reduce emissions from MAC units**. Based on the technical characteristics of alternative refrigerants and AC systems, regulators should revise existing standards for MAC and its parts as soon as possible, and include essential safety requirements. Further, the standards for purity identification and application of alternative refrigerants should be developed.

5. **Formulate the economic incentive policies for efficient MAC and accelerate the promotion and application of low-emission MAC**. In accordance with the development levels of low-GWP refrigerants, energy efficiency improvement technologies, and their costs, incentives, subsidies and tax reductions should be provided to the manufacturers that eliminate high-GWP refrigerants and adopt high-efficiency AC technologies in advance. China should strengthen R&D support for NEV refrigerants and AC technologies, guide manufacturers to increase investment, promote pilot implementation programs, and boost the application of mature technologies. Regulators should incorporate MAC with low-GWP refrigerant and low leakage rates into the green product environmental labeling and green government procurement systems, and encourage enterprises, institutions and consumers to purchase low-emission vehicle models.

Appendix

In the CO_2 emission standards for LDVs in the United States, incentive credit is one of the strategies used to help manufacturers meet stringent CO_2 fleet-average standards. Table 10 presents the credits for **reducing refrigerant leakage**. EPA uses a leak score derived from the SAE J-2727 scoring system. For systems that use low-GWP refrigerants, there is a high-leak penalty of up to 1.8 grams per mile (g/mi) for any systems with a leak rate higher than the average of the initial charge per year. While leakage of low-GWP refrigerants may not have a direct GHG impact, EPA also considered the potential risk associated with consumers potentially recharging with higher-GWP refrigerants.

Table 10. Maximum leakage and refrigerant credits in the United States (g/mi)

Vehicle type	Belt-driven compressor, HFC-134a	Electric motor-driven compressor, HFC-134a	Maximum credit, with GWP=1 refrigerant
Cars	6.3	9.5	13.8
Light-duty trucks	7.8	11.7	17.2

Table 11 shows the credit menu for MAC efficiency technologies that reduce energy demand in vehicles associated with the MAC system. The latest fuel economy standard expands the technologies included in the credit list for MAC efficiency technologies, e.g., an advanced air-conditioning compressor with variable crankcase suction valve, and simplifies the procedure through which automakers apply for off-cycle credits.

The maximum credit available for improved MAC efficiency is 5 g/mi for cars and 7.2 g/mi for trucks, even if additional technologies from the menu are present and could otherwise add up to a higher total credit value. As with other off-cycle credits, a manufacturer can use the alternative credit approval process to justify higher credits for individual technologies. However, the maximum level of credit allowed for MAC efficiency will remain as it is under all circumstances. Individual credits only apply if that technology is installed on the vehicle. The full credit can only be accessed if the difference in CO_2 emissions between "AC off" and "AC on" is equal to or greater than the maximum credit value.

Table 11. CO_2 emission reduction effects of MAC efficiency technologies and their credits in the United States

Technology	MAC CO_2 emission reduction	Car AC credit (g/mi)	Light-duty truck AC credit (g/mi)
Reduced reheat, with externally controlled variable displacement compressor	30%	1.5	2.2
Reduced reheat, with externally controlled fixed displacement or pneumatic variable displacement compressor	20%	1.0	1.4
Default to recirculated air with closed-loop control of the air supply (sensor feedback to control interior air quality) whenever the outside ambient temperature is 24°C or higher	30%	1.5	2.2
Default to recirculated air with open-loop control of the air supply (no sensor feedback) whenever the outside ambient temperature is 24°C or higher	20%	1.0	1.4
Blower motor control that limits wasted electrical energy (e.g. pulse with modulated power controller)	15%	0.8	1.1
Internal heat exchanger (or suction line heat exchanger)	20%	1.0	1.4
Improved evaporators and condensers [coefficient of performance (COP) improvement >10%]	20%	1.0	1.4
Oil separator (internal or external to compressor)	10%	0.5	0.7
Advanced and efficient air-conditioning compressor technology by using an additional variable crankcase suction valve		1.1	1.1
Maximum credit		5	7.2

Additional credits are available for **thermal management technologies** designed to reduce MAC demand or load. Table 12 summarizes these technologies and their credits.

Table 12. Credits for MAC thermal management technologies in the United States

Technology	Maximum car AC credit (g/mi)	Maximum light-duty truck AC credit (g/mi)
Glass or glazing	≤2.9	≤3.9
Active seat ventilation	1	1.3
Solar-reflective paint	0.4	0.5
Passive cabin ventilation	1.7	2.3
Active cabin ventilation	2.1	2.8
Maximum credit	3.0	4.3

References

Basma, H., Mansour, C., Haddad, M., Nemer, M., & Stabat, P. (2020). Comprehensive energy modeling methodology for battery electric buses. *Energy*, 207, 118241. https://doi.org/10.1016/j.energy.2020.118241

Blumberg, K., & Isenstadt, A. (2019). *Mobile air conditioning: The life-cycle costs and greenhouse-gas benefits of switching to alternative refrigerants and improving system efficiencies*. International Council on Clean Transportation. https://theicct.org/publications/mobile-air-conditioning-cbe-20190308

Chidambaram, S. (2010). India's mobile air-conditioning (MAC) study [slides]. India Policy Workshop on the Status of MAC Replacement Technologies, New Delhi, India. Retrieved from https://www.slideshare.net/ozonaction/indias-mobile-air-conditioningmac-study-pdf

Tietge, U., Díaz, S., Mock, P., Bandivadekar, A., Dornoff, J., & Ligterink, N. (2019). *From laboratory to road: A 2018 update*. International Council on Clean Transportation. Retrieved from https://theicct.org/publications/laboratory-road-2018-update

Yang, Z., & Yang, L. (2018). *Evaluation of real-world fuel consumption of light-duty vehicles in China*. International Council on Clean Transportation. https://theicct.org/publications/real_world_fuel_consumption_ldv_China

Hu Jianxin, Zhang Jianbo, Wu Jing, Fang Xuekun, Su Shenshen, Hu Xia, and Han Jiarui. (2013*). Research on the Impact of Control and Regulation of Hydrofluorocarbons (HFCs) - Opportunities and Challenges*. College of Environmental Science and Engineering, Peking University. http://scholar.pku.edu.cn/sites/default/files/jianxin_hu/files/the_economics_of_f-gases_management_in_china-_challenges_opportunities20130122.pdf

Hu Jianxin, et al. (2018). *Green Paper on Reducing HFCs Refrigerant Emissions from Automotive Air Conditioning.* College of Environmental Science and Engineering, Peking University. http://scholar.pku.edu.cn/sites/default/files/jianxin_hu/files/green_book_for_mac_0.pdf

State Environmental Protection Administration. (2001*). Plan for the Replacement of CFCs in the Chinese Automotive Air Conditioning Sector [M]*. Tianjin, China Automotive Technology and Research Center, 1-254

State Administration for Market Regulation. (2018a) Motor vehicle air-conditioning unit: GB/T 21361-2017. http://c.gb688.cn/bzgk/gb/showGb?type=online&hcno=711D263FC1C112BDC11C4C559BAB0A6E

State Administration for Market Regulation. (2018b). Electrically driven motor vehicle air-conditioning unit: GB/T 37123-2018. http://c.gb688.cn/bzgk/gb/showGb?type=online&hcno=5D5DFC6259B0020D7FC1B3E9E0969CA0

State Administration for Market Regulation. (2021). Announcement on Approval for Issuing the "Maximum allowable values of energy efficiency and energy efficiency grades for data centers" and 602 Other National Standards and 1 National Standard Amendment. http://www.samr.gov.cn/bzjss/tzgg/202110/P020211011403907260642.pdf

Ministry of Ecology and Environment. (2020). Regulation on the Administration of the ozone layer depleting substances (ODSs) and hydrofluorocarbons (HFCs) (Proposal). http://www.mee.gov.cn/xxgk2018/xxgk/xxgk06/202005/t20200521_780130.html