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HFC-134A PHASE-OUT IN THE CHINESE LIGHT-DUTY MOTOR VEHICLE SECTOR

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EXECUTIVE SUMMARY

Hydrofluorocarbons (HFCs) are powerful greenhouse gases (GHG) that are widely used in mobile air conditioning (MAC) systems. China fully embraced HFC-134a in 2001 when it implemented its obligations under the 1987 Montreal Protocol to phase out ozone-depleting chlorofluorocarbons (CFC-12). Today the HFC-134a system remains the dominant MAC system in China and around the world.

While possessing zero ozone-depletion potential, HFC-134a can cause more than 1,500 times as much warming as an equivalent amount of carbon dioxide (CO_2). With the rapid expansion of the Chinese automobile industry and the near-100% penetration of MAC systems in the light-duty passenger vehicle market, emissions of HFC-134a from the MAC sector are estimated to have tripled between 2005 and 2010 and are expected to continue increasing as the Chinese economy grows. This translates into a rapidly increasing climate impact from future Chinese MAC.

Alternative MAC refrigerants have up to a 99% lower climate impact than HFC-134a. The European Union (EU), the United States, and Japan have established domestic policies that will require the phase-out of HFC-134a with these refrigerants by 2017, 2021, and 2024, respectively. With 24% of global MAC sales in 2015, China remains the largest vehicle market that still permits the indefinite use of HFC-134a.

Reducing refrigerant emissions from the MAC sector can contribute significantly to meeting Chinese climate goals. China has announced an intention to halt economy-wide GHG (or CO_2-equivalent) emissions growth around or before 2030, and to reduce carbon intensity per unit gross domestic product (GDP) by 65% in that same time frame. China has also stated its support for multilateral actions to phase down the production and consumption of HFCs. Phase-out of HFC-134a with alternative low global warming potential (GWP) refrigerants supports these goals.

This study evaluates the impacts and costs in China associated with transitioning light-duty vehicle MAC systems away from HFC-134a. This information will allow Chinese decision-makers to more fully evaluate national options and make an informed decision on how best to address light-duty vehicle MAC refrigerant in China.

The ICCT evaluated the benefits, costs, and policy timelines associated with transitioning light-duty vehicle MAC systems away from HFC-134a to three alternative low-GWP MAC refrigerants: HFO-1234yf, CO_2 (R-744), and HFC-152a. Baseline and alternative system emissions under a variety of different transition pathways were estimated using an ICCT model of MAC emissions in the passenger vehicle fleet.

This study finds that a transition to low-GWP refrigerants could reduce fleet-wide GHG emissions of mobile refrigerants by more than 95% compared with an HFC-134a baseline. This reduction applies to operation, service, and end-of-life scrappage. Cumulative emissions of up to about 1.5 billion metric tons (tonnes) of CO_2 equivalent (CO_2e) can be avoided through 2050.

The timing of transition is important in maximizing the climate benefit. Complete phase-out of HFC-134a is achievable by 2035–2040, which would require all new vehicles to stop using HFC-134a between 2020 and 2024.

The costs of transition are generally favorable relative to other available CO_2 reduction technologies for motor vehicles. The cost-effectiveness for HFO-1234yf declines from about 484 yuan per tonne (¥/mt) to about 312 ¥/mt by 2050, while that for CO_2 declines from about ¥832 to about 436 ¥/mt over the same period. For HFC-152a, the cost-effectiveness declines from ¥241/mt to ¥179/mt by 2050.

Costs per gram per kilometer of CO_2e reduced are attractive for all three alternatives relative to the cost of the "workhorse" engine technology package expected to be employed for fuel economy compliance in China.[1] These costs are also much lower compared with the EU penalty rate for CO_2e emissions, which effectively reflects the level of investment deemed not to be cost-effective in the EU. The United States allows vehicle manufacturers to obtain equivalent fuel economy (and GHG) credits with alternative refrigerants, which China could also adopt to facilitate transition.

Considering the social cost of CO_2e, up to 1 trillion RMB in costs required to address climate change can be avoided through 2050 by transitioning to low-GWP alternative MACs.

The competitiveness impacts of transition are expected to be minor and, because transition is already underway in the major US and EU markets, this transition cannot be avoided regardless of China's decision-making if Chinese manufacturers wish to compete globally. Joint-venture manufacturers are expected to possess little, if any, competitive advantage. MAC technology and equipment is generally of a commodity nature and is available through third-party suppliers to any vehicle manufacturer. China is already a leading producer of low-GWP refrigerants in MAC, although these refrigerants are primarily exported to meet requirements in the United States and Europe. The global movement toward low-GWP refrigerants ensures that China cannot minimize consumer cost impacts by maintaining and extending the service life of existing (HFC-134a) MAC technology.

Given the beneficial emissions and cost analysis, combined with China's previous experience transitioning away from CFC-12, there are no vehicle-production barriers preventing a complete phase-out of HFC-134a in the China light-duty vehicle fleet during the five-year period between 2020 and 2024. Such a requirement is relatively unaggressive, given that it includes up to three years of lead time and allows for a full five years of transition. A more aggressive schedule is possible, but the five-year period is generally consistent in the industry retooling cycle. This lead time provides both manufacturers and the service industry time to adopt appropriate transition policies.

1 Turbocharged and downsized gasoline direct injection engine with cooled exhaust gas recirculation (EGR).

INTRODUCTION

In response to the stratospheric ozone-depletion characteristics of chlorofluorocarbons (CFCs) and other ozone-depleting substances, the globally adopted 1987 Montreal Protocol (UNEP, 1987) effectively banned the continued production and sale of the then-predominant mobile air conditioning (MAC) refrigerant CFC-12 (dichlorodifluoromethane; generally known under its trade name Freon). As a result, automotive manufacturers began producing MAC systems utilizing chlorine-free HFC-134a (1,1,1,2-tetrafluoroethane) refrigerant in the mid-1990s. From an ozone-depletion perspective, this transition was tremendously successful as HFC-134a has an ozone-depletion potential of zero.[2] HFC-134a systems were (and remain) the dominant MAC systems in use throughout the global passenger vehicle fleet.

China first regulated MAC refrigerants in 1994 with the phasedown of CFC-12 and completely prohibited this refrigerant in new vehicles produced after 2001. As HFC-134a replaced CFC-12, the Chinese automobile industry has expanded from 1.5 million units produced in 1995 to 22 million units in 2013 (CATARC & CAAM, 2014). The penetration of MAC systems in the Chinese automobile market has grown rapidly, to the point where virtually all the cars produced since 2010 are equipped with MAC systems. This is supported by surveys conducted in China from 2004 to 2008 that show over 95% of passenger cars were equipped with air-conditioning systems. As in other geographic regions, MAC charge size has been decreasing and is expected to continue to decline as technology improves.

Emissions of HFC-134a from the Chinese MAC sector have tripled in just the five-year period between 2005 and 2010 (Hu, Wan, Li, Zhang, & Yi, 2010) and will continue to increase as the Chinese economy expands. Su et al. (2015) estimated that HFC-134a emissions from the MAC sector in China increased tremendously from 0.03 Gg in 1995 to 16.7 Gg in 2010, reflecting a tremendous average annual growth rate of 53.3%. This study projected that HFC-134a emissions under a business as usual (BAU) scenario will reach 89.4 Gg by 2030.

With the recognition of the global warming effects of various substances, HFC-134a has now become the focus of a second MAC refrigerant transition. With a 100-year global warming potential (GWP-100)[3] of 1,549[4] (Table 8.SM.16 in Myhre et al., 2013), one gram of HFC-134a possesses the same global warming potential as 1,549 g of carbon dioxide (CO_2). Although the most potent greenhouse gas (GHG) emitted by passenger vehicles, it is worth recognizing that the global warming effects of HFC-134a (on a unit

2 Tremendous insights can be gained with regard to global warming issues (and potential policy) by reviewing the historic record related to stratospheric ozone depletion (a respectable resource list for starting such a review can be found at https://www.epa.gov/ozone-layer-protection).

3 Global warming potential (GWP) is a metric developed to standardize characterization of the greenhouse effects associated with various substances. By definition, CO_2 is assigned a GWP of one, so that the GWP of any substance is the mass of CO2 that would produce the same warming effect as an identical mass of the given substance. Because different substances have differing atmospheric lifetimes, GWP is also measured over a standard time frame, typically 20, 100, or 500 years (although any standard time frame could be used). For convenience, the values cited in this paper are limited to 100-year or GWP-100 values, but GWP estimates for other time frames are available. The issues discussed and conclusions presented are insensitive to the time frame of the associated GWP, so that GWP-100 alone serves as an adequate metric for this paper.

4 Unless otherwise stated, the GWP values presented in this paper include both direct and feedback-related effects. Values independent of feedback effects are also available in a sensitivity analysis that can be found in Annex C, but they have no effect on either the issues discussed or conclusions presented. According to IPCC AR5 WG 1 Section 8.7.1.4, "Though uncertainties in the carbon cycle are substantial, it is likely that including the climate-carbon feedback for non-CO_2 gases as well as for CO_2 provides a better estimate of the metric value than including it only for CO_2." All cited global warming potentials adopt a 100-year time horizon (GWP-100).

mass basis) are approximately 87% lower than the effects that would be observed were CFC-12 (with a GWP-100 of 11,547) still the predominant MAC refrigerant. Nevertheless, substantial additional reductions in GWP can be achieved through a second phase transition away from HFC-134a. Xu, Zaelke, Velders, & Ramanathan (2013) predicted that regulating HFCs from all sectors can avoid as much as 0.5 degrees C global warming by the end of the century. Potential alternative refrigerants include (among others):

- HFC-152a (1,1-difluoroethane, GWP-100 = 167, providing an effective unit mass GWP-100 reduction of 89.2% relative to HFC-134a and 98.6% relative to CFC-12),
- HFO-1234yf (2,3,3,3-tetrafluoropropene, GWP-100 < 1, providing an effective unit mass GWP-100 reduction of more than 99.9% relative to both HFC-134a and CFC-12), and
- Carbon dioxide (CO_2, GWP-100 = 1, providing an effective unit mass GWP-100 reduction of more than 99.9% relative to both HFC-134a and CFC-12).

Both the United States (US) and the European Union (EU) have adopted requirements that either force (EU and US) or create incentives (US) for automotive manufacturers to move toward the use of lower-GWP refrigerants. The EU (European Commission, 2006) requires the industry to transition to MAC systems using refrigerants with a GWP-100 of 150 or less.[5] This transition began in 2008 by requiring low-leak systems in vehicles using refrigerants with a GWP-100 of more than 150, and is scheduled to be completed by 2017 when all new systems using refrigerants with a GWP-100 of more than 150 are prohibited. The United States has implemented a two-pronged low-GWP strategy. HFC-134a (GWP-100 = 1,549) is banned in light-duty vehicles beginning in vehicle model year (MY) 2021 (Protection of Stratospheric Ozone, 2015).[6] While this ban doesn't explicitly require the use of any specific alternative refrigerant or establish an explicit GWP ceiling, the fact that all MAC refrigerants in the *United States* must be approved under the Environmental Protection Agency's (EPA's) Significant New Alternatives Program (SNAP) effectively limits available alternatives to HFC-152a, HFO-1234yf, and CO_2 (US EPA, 2016). Additionally, under its Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards program for light-duty vehicles (US EPA, 2012), the United States provides CO_2e emissions-reduction compliance credits for various MAC system improvements, including the use of low-GWP refrigerant. These credits can be used in lieu of more expensive engine-efficiency improvement technologies.

In a number of countries, MAC refrigerant is included in more general hydrofluorocarbon (HFC) policies that either require the phasedown of usage or impose significant tax burdens designed to promote the cost-effectiveness of alternative refrigerants. For example, Japan has adopted requirements for the phasedown of HFCs across all economic sectors (METI, 2013), which include a 2023 target date to phase out HFC-134a from passenger vehicles. Various countries, including Australia and several EU member states, impose GWP-based taxes on HFCs, including those used in MAC systems (Thompson, 2013). In addition to these existing regional efforts, consensus is building within the global community to phase

5 Although this paper presents a GWP-100 value of 167 for HFC-152a, based on data from the 2013 Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Myhre et al., 2013), the EU directive relies on corresponding values from the 2001 Third Assessment Report from that same organization (EU 2006). The GWP-100 value for HFC-152a from the Third Assessment Report is 120 (Ramaswamy et al., 2001), which meets the legally permitted limit of 150.

6 Continued use of HFC-134a is allowed though 2025 for exports destined to markets with service industries that cannot adequately handle an alternative refrigerant.

down HFC production and consumption under the umbrella of an amended Montreal Protocol (UNEP, 2015).[7] The 197 parties to the existing Montreal Protocol are working together within the framework of the Protocol to finalize plans under an amendment for a global phasedown of HFCs. If adopted, such an amendment would largely standardize a global HFC phasedown strategy and largely resolve all issues associated with the global competitiveness impacts of regional solutions.

The Chinese government has taken some preliminary steps toward multilateral action on HFCs. In 2013, President Obama and President Xi jointly agreed to "phase down production and consumption of HFCs."[8] The United States and China will work together and with other countries through the expertise and institutions of the Montreal Protocol. This agreement provides high-level political support and an opening for mid-level regulatory effort to begin to explore how China could implement a global phasedown of HFCs.

To inform future actions to phase out HFC-134a in the Chinese auto sector, regulators will need information regarding the characteristics of the MAC sector, its emissions of HFC-134a, the cost of action, and the benefits to society. A number of studies (Clodic, Barrault, & Saba, 2010; Hu, Wan, Li, Zhang, & Yi, 2009; Hu et al., 2010; ICF International, 2012; Gloel et al., 2014; PKU, 2013; Su et al., 2015) have addressed these topics using various approaches. However, many of these studies were built on assumptions or estimates that were not specific to China, but rather developed on the basis of broad socioeconomic or geographic characterizations (e.g., developed vs. developing nations), which leads to uncertainty for the Chinese market. In addition, assumptions and estimates display large variability, increasing associated uncertainty. This study presents a new assessment for HFC-134a phase-out in the Chinese light-duty fleet based on the best available technical information available from China and the international community.

7 Throughout this document the term "phase-out" refers specifically to HFC-134a in the light-duty vehicle sector. We acknowledge that international negotiations around high-GWP HFCs are oriented around a different aim, which is a "phasedown" of HFC production and consumption.

8 "United States and China Agree to Work Together on Phase Down of HFCs." Accessed August 18, 2016, at https://www.whitehouse.gov/the-press-office/2013/06/08/united-states-and-china-agree-work-together-phase-down-hfcs.

MAC SYSTEMS IN CHINA

To understand the implications of a HFC-134a phase-out in the Chinese light-duty vehicle fleet, it is necessary to compile available China-specific data that can provide the technical underpinnings for this action.

This section describes the baseline and current options for MAC systems in China based on available data and published studies. The aim is to evaluate the data available for baseline refrigerants (primarily HFC-134a) in China and compile an associated set of input data for the ICCT refrigerant inventory model that will be the basis for cost and benefit estimates of alternative refrigerant systems.

PENETRATION OF MAC SYSTEMS

China first regulated CFC-12 use in MAC systems in 1994 by gradually reducing the production of vehicles equipped with CFC-12 systems. By the end of 2001, CFC-12 systems were completely banned in new vehicles. Beginning in 2009, refills of existing CFC-12 systems were restricted to recycled CFC-12 (CATARC, 2007). Light-duty passenger vehicles (equipped with air conditioning) in China are now predominantly equipped with HFC-134a MAC systems, and Chinese regulators have not issued any requirements for a transition away from HFC-134a to other alternatives. Therefore, discussion of baseline options primarily focuses on HFC-134a MAC systems.

The MAC industry in China started in the early 1990s, which is later than most developed countries. MAC penetration was initially low but has rapidly increased over the past two-plus decades (Hu et al., 2009). The availability of detailed data is limited, and a number of previous studies are based on assumptions and estimates rather than new data. The Japanese Automobile Manufacturers Association (JAMA, 2010) estimated that 66% of all vehicles sold in China during 2007 to 2009 were equipped with MAC systems. ICF International (2012) in a report submitted to the ICCT found this value to be a low estimate and instead proposed 83% for 2008 based on sales data provided by the China Association of Automobile Manufacturers (CAAM) in 2009. A report from Peking University and the Ministry of Environmental Protections of China (MEPC, 2003) (as cited by Hu et al., 2010) estimated that (on average) 71% of light-duty passenger vehicles were equipped with MAC systems between 1995 and 2002. A survey conducted in three Chinese cities from 2004 to 2008 indicated that over 95% of the more than 4,000 surveyed cars were equipped with MAC systems (SCEPA & THU, 2013).

Table 2-1 presents the fractions of new vehicles equipped with MAC systems from 1995 to 2002 based on data developed by CATARC & CAAM (2014) and Hu et al. (2010). As China completed the phase-out of CFC-12 over this time, the percentage of MAC-equipped vehicles increased steadily. MAC systems have become standard on all new vehicles in developing countries, including both China and India (Papasavva & Andersen, 2011). Su et al. (2015) assumes that 100% of new cars sold in 2010 were equipped with air conditioning, consistent with the earlier studies.

Table 2-1. Penetration of MAC systems from 1995 to 2002 in China (CATARC & CAAM, 2014 and Hu et al., 2010).

	1995	1996	1997	1998	1999	2000	2001	2002
Total vehicles produced	145	147	158	163	183	207	234	325
Total vehicles produced with MAC	42	46	56	58	71	83	96	140
% MAC production, %	29	31	35	36	39	40	41	43
Production based on CFC-12	37	36	40	27	20	16	10	0
% production based on CFC-12, %	88	78	71	47	28	19	11	0
Production based on HFC-134a	5	10	16	31	51	67	87	140
% production based on HFC-134a, %	12	22	29	53	72	81	89	100

1. All production data are in tens of thousands.
2. Data include all new vehicles (i.e., cars, buses and trucks).

Assumptions

For this analysis, assumptions of MAC system penetration were made to represent the current refrigerant options (primarily HFC-134a systems and existing CFC-12 systems). Table 2-2 summarizes these assumptions, which were developed based on previous China-specific studies and surveys (MEPC, 2003 as cited in Hu et al., 2010; Hu et al., 2010; PKU, 2013; Su et al., 2015). Because a comprehensive dataset that covers all the vehicle classes over an extended period of time is not yet available, Table 2-2 puts forward the best available assumptions from existing data.

The penetration of MAC systems steadily increased from the 1990s and reached 100% in 2010. MEPC (2003) (as cited in Hu et al., 2010) found that MAC penetration was about 71% of the vehicle fleet from 1995 to 2002. The share of the vehicle fleet with MAC before 2000 and of new vehicles with MAC sold in 2000 and 2001 was assumed to be 70%, 70%, and 72%, respectively. Using the ICF International's (2012) estimate (83% of the new sold vehicles in 2008 were equipped with MAC) as another anchor year, the remaining years between 2000 and 2010 were interpolated linearly.

Before 1994, there was only a small portion of vehicles (mostly imported) using HFC-134a-based MAC systems. However, this share increased dramatically from 1995 to 2002 as CFC-12 was completely phased out. China has not issued any additional regulations toward the phase-out of HFC-134a and the adoption of any substitute refrigerant. Therefore, light-duty vehicles sold from 2002 to 2015 are assumed to be solely HFC-134a-based. For 2000 and 2001, shares of the two refrigerants in total vehicles produced were adopted from Hu et al. (2010). We apply these shares to light-duty passenger vehicles assuming similar profiles across different vehicle classes. Shares of these two refrigerants for pre-2000 vehicle stocks were assumed based on the average profiles across 1995 to 2000 reported by Hu et al. (2010).

Table 2-2. Assumptions of share of light-duty vehicle sales with MAC systems (including stock before MY 2000) (Unit: %).

	< 2000	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	> 2010
share of light-duty vehicle sales with MAC systems												
	70	70	72	75	76.3	77.6	78.9	80.2	81.6	83	91.5	100
share of light-duty vehicle sales based on refrigerants												
CFC-12	60	19	11	0	0	0	0	0	0	0	0	0
HFC-134a	40	81	89	100	100	100	100	100	100	100	100	100

MAC CHARGE SIZE

An extensive literature review by ICF International (2012) suggested that MAC charge size fell in the range of 0.4 to 1.2 kg per MAC system globally (with charge size generally varying directly with vehicle size and age). As presented in Table 2-3, charge sizes reported or used specifically for China-related studies range from 0.536 kg to 1.1 kg. Both global and China-specific data suggest the evolution over time toward smaller MAC systems due to technological development, including better system seals, improved fittings, and higher evaporator temperatures. This trend will continue into the future. For example, Hu & Li (2003) (as cited in Clodic et al., 2011) reported a decrease in charge size from 1.1 kg in 1990 to 0.67 kg in 2006. Estimates from other China-specific studies are generally consistent. Based on Hu et al. (2010) estimated initial refrigerant fills of HFC-134a were 1.0 kg. Later studies assume 0.8 kg per unit (PKU, 2013 and Su et al., 2015), based on assumptions from the IPCC (2006) as a default value. Chen, Shi, & Zhao (2008) estimated that the average charge size for cars and light trucks decreased to 0.536 kg by 2006.

Table 2-3. Estimates of MAC system charge size in China.

Charge size, kg	Notes	Source
1.1	charge size in 1990	Hu & Li, 2003 (as cited in Clodic et al., 2010)
0.9	charge size in 2000	
0.67	charge size in 2006	
1.0	average charge size of cars; temporal range was not specified	MEPC, 2003 (as cited in Hu et al., 2010)
0.8	default charge size of cars suggested by IPCC	IPCC, 2006
0.536	charge size of cars since 2006	Chen et al., 2008

The Minnesota Pollution Control Agency (MPCA) in the United States requires vehicle manufacturers to submit air-conditioner leakage rate data to the MPCA, including model, leakage rate, and charge size.[9] This requirement applies to new motor vehicles sold in Minnesota on or after January 1, 2009. The leakage rates reported by these automakers also suggested a decreasing trend in the charge size. For passenger cars the average charge size (not sales weighted) dropped from 632 g in MY 2009 to 578 g in MY 2016.

9 The data is publicly available at: https://www.pca.state.mn.us/quick-links/climate-change-mobile-air-conditioners#leakdata.

Assumptions

Most of the available data for China was based on researchers' assumptions or modeled estimates instead of primary surveys and production reports. A recommended value by IPCC (2006) was commonly accepted by many of these studies. This study assumes a MAC charge size of 800 g prior to MY 2009 and 550 g for 2009 or later MYs. These are built from MPCA data and reconciled with estimates from China. Although the charge size is expected to be less dependent on regions and more associated with technology development, data obtained from actual measurements are desired to strengthen the assumptions made in this study. Furthermore, given data scarcity, it is important that Chinese regulators collect additional information by conducting surveys or obtaining production reports from industrial sources in China to validate the assumptions and minimize uncertainties.

REFRIGERANT EMISSIONS

Initial emissions

Several China-specific studies took into consideration emissions at initial system charging. Such emissions could be up to 0.5% of the MAC charge size (Hu et al., 2010; PKU, 2013; Su et al., 2015). Because these initial emissions are associated directly with financial losses to vehicle manufacturers, there exists a direct financial incentive for manufacturers to minimize such losses. Few sources have provided supporting evidence of the magnitude of emissions associated with initial charging, and therefore the validity of assumptions is still to be investigated. This study takes the view that this portion of emissions is not directly associated with vehicle operation. Therefore, we exclude such emissions from our initial analysis, also recognizing that 0.5% of a 500 g system equates to an uncertainty of only 2.5 g per vehicle.

Regular emissions

Regular operational emissions occur continuously over time. These emissions are a consequence of leaks from high-pressure MAC systems and the degradation of components such as seals and fittings during normal operation. Estimates of regular operational emissions are highly variable. An extensive investigation of studies conducted in multiple regions of the globe by ICF International (2012) indicated that annual losses for HFC-134a-based MAC systems ranged from 7% to 30% (of system charge size) per year averaged over a vehicle lifetime. Developing countries tend to show higher leakage rates due to insufficient maintenance. An investigation by Chen et al. (2008) estimated that the typical regular operational emission rate in China ranges from 50 g/yr to 150 g/yr (6.25 to 18.75% /yr for a 0.8 kg system). Su et al. (2015) assumes an average emission rate of 6.25% /yr.

Measurements of operational emissions in China are rare. Note that this is also an issue in other regions simply due to the difficulty associated with undertaking surveys. Because we expect operational emissions to decline as technology improves (e.g., better sealing and fittings), it is important to develop a profile of the expected temporal variation of operational emissions in China. However, because of the lack of publicly available data (both historical and current), determining the temporal profile is very challenging.

The EPA and the California Air Resources Board (CARB) have conducted a series of studies aiming to quantitatively understand the various types of emissions (Vincent, Cleary, Ayala, & Corey, 2004a, b; US EPA, 2010a). These US studies have, for example, estimated not only the initial emission rates associated with new MAC systems, but also the change in emission rates over time as systems age. Due to the more robust nature of the US assessments and higher associated confidence levels, refrigerant emission estimates for this analysis are primarily built on the methods and results from US studies as well as detailed emission data from MPCA, and they also incorporate some changes in parameters in order to better reflect common practices in China (for example, the disposal of MAC units for end-of-life vehicles may be different from that performed in the United States). The methodology is discussed in more detail in the section "Methodology to construct emissions rate estimates and assumptions."

Service emissions

Service emissions occur when the system requires maintenance, repair, or refill. Here we include so-called irregular emissions in this category. Irregular emissions occur during improper vehicle servicing or during a vehicle accident that damages the system and allows a partial or complete escape of the refrigerant. Such emissions can vary considerably, depending on the specific service practices employed. Service done by MAC owners may be associated with more emissions due to a lack of expertise and absence of proper recycling capabilities as compared with similar service performed by professional technicians. As a result, service emissions are highly variable by global geographic region. Relative to developed countries, we expect that vehicle owners in developing countries will perform a greater proportion of service activity than professional technicians. Service emission rates are thus expected to be higher in developing countries.

Robust service emission-rate estimates are not yet available in China. Su et al. (2015) assumed a service rate of 30%, presumably on an annual basis (240 g/yr for a 0.8 kg system). This estimate is significantly higher than corresponding data for other regions. For example, the EPA estimates the average lifetime emissions attributable to service events at 8.8%, or 68 g/yr (US EPA & NHTSA, 2012) and Henne et al. (2012) assumed a yearly loss caused by servicing events to range from 2.92 g/yr to 29.2 g/yr.

End-of-life emissions

End-of-life emissions are emissions associated with the scrappage and disposal of a vehicle equipped with air conditioning and will primarily depend on two effects: the amount of refrigerant remaining in the MAC system at the time of disposal and the refrigerant recovery practices (if any) employed during disposal. It is commonly assumed that less than 50% of the system charge size remains in the MAC system at the time of disposal due to pre-disposal operational losses (ICF International, 2012). However, there is considerable variability in the end-of-life emission rates across studies in different geographic regions. Assuming an initial charge size of 0.8 kg, estimates of remaining refrigerant at the end of vehicle life vary from 20% to 60% (Henne et al., 2012; Oko-Recherche et al., 2011; ICF International, 2011; Vincent et al., 2004a). Most studies for China have adopted the IPCC default (40%) (IPCC, 2006) value or calculated the remaining charge based on the operational emissions rate. For example, Hu et al. (2010) and PKU (2013) assumed 40% of the initial charge remaining based on the IPCC default value, whereas Su et al. (2015) calculated this value by taking into account an operational emissions rate that results in 25% of the initial charge remaining. China-specific data on the remaining amount of refrigerant is unavailable.

End-of-life recovery efficiency is generally considered to be higher in developed countries compared with developing countries because of better technologies and compliance. However, the disposal of refrigerant is difficult to monitor and enforce. In addition, treatment of contaminated refrigerant for reuse purposes and destruction of the refrigerant from the end-of-life vehicles are usually costly (ICF International, 2012). As a result, even in some developed countries the overall recovery efficiency is relatively low. For example, Vincent (2004b) estimated that only 50% of the remaining charge was recovered in California.

China has adopted regulations on reducing the emissions of CFC-12 from end-of-life vehicles by distributing CFC-12 recovery devices to designated car scrappage companies and setting up storage stations for recycled CFC-12 (CATARC, 2007). However, a survey conducted in Shandong Province by the Shandong Circular Economy Promotion Association (SCEPA) and Tsinghua University (THU) (2013) found that on average only 10% of the refrigerant (CFC-12) remaining in the MAC system is collected and recycled. The survey found that owners removed most MAC units before they were sent to scrappage facilities. In those remaining vehicles with MAC units, this survey found that only 20%~30% of them still contained refrigerant. For HFC-134a, there currently is no regulatory requirement for recovery in China (PKU, 2013). This study assumes that end-of-life recovery efficiency is 0%, which means that all remaining refrigerant is released to the environment (Hu et al., 2010; PKU, 2013; Su et al., 2015).

Methodology to construct emissions rate estimates and assumptions

While studies and publications specifically related to the Chinese passenger vehicle fleet are indicative, considerable data gaps remain (see Annex C). Due to these limitations, this study constructs emission estimates using data inputs generated from systematic studies by government agencies in the United States. These refrigerant-specific inputs supplement China-specific fleet data already contained in the ICCT Refrigerant Inventory Model.

Regular refrigerant operational leakage occurs through all components of the MAC system, such as hoses, fittings, compressors, etc., which wear with age and exposure to harsh environmental conditions. Therefore, the EPA assumes a linearly increasing emissions rate for regular MAC emissions (US EPA, 2010a), such that the regular operational emission rate for new vehicles is 18 g/yr at age zero, but averages 59 g/yr over the MAC system lifetime (average emission/new vehicle emission = 3.28). Emissions due to servicing and maintenance are modeled as 1.17 times the regular operational emissions (based on the relationship between estimated regular and service emissions for new vehicles). Using these two relationships along with new vehicle emission rates reported to the MCPA by vehicle manufacturers, average regular operational and servicing emission rates are estimated for MY 2009 through 2016. This study assumes that vehicles of a MY prior to 2009 emit on average 80 g/yr due to regular operational leakage based on test results from Vincent et al. (2004a, b). For MYs after 2016, this study assumes that emission rates will not change.

It is reasonable to assume that only one service event occurs during the entire vehicle lifetime since after nine years owners are less likely to continue servicing the MAC systems (MACS, 2008 as cited in ICF International, 2012). The service events typically occur after the first six or seven years of the vehicle's lifetime (Vincent et al., 2004a, b). This study assumes that on average the service event occurs in the sixth year.

This study assumes that only 50% of end-of-life vehicles still have MAC units, based on a survey in China (SEPA & THU, 2013). Units removed from vehicles were mostly sold or traded in at service stores or auto dealers. Recovery from these units is assumed to be zero. Considering compliance rates, this study assumes that 50% of the refrigerant is recovered at scrappage stations. The amount of refrigerant that remains in the MAC system is calculated from the years between the assumed last service event and the modeled end of life.

Since MY 2012, vehicle manufacturers in the United States have been able to obtain additional credits toward GHG emission compliance by incorporating low-leak technologies into MAC systems. However, due to the lack of such incentives in China, it is likely that the reduction in emission rates is comparably less than in the United States, especially in recent years. A “high emission assumptions” case in this study was created that assumes regular operational and servicing emissions will not be further reduced after 2011. A “low emission assumptions” case does assume reductions in operational and servicing emissions beyond 2011.

Limitations

MAC leakage in developing countries tends to be higher than in developed countries due to the relatively poor maintenance of equipment and inadequate enforcement of refrigerant recovery programs (ICF International, 2012). Emission estimates derived from the United States and applied to China are very likely to result in an underestimation of the emissions in China. These estimates should be considered a lower bound on China fleet-wide emissions, given the fact that China-specific refrigerant emission data were mostly limited to best estimates from large-scale studies or surveys. Greater investment in China-specific MAC research is necessary to avoid producing estimates that by their nature must be conservative.

VEHICLE LIFETIME AND ACTIVITY

The IPCC (2006) estimates an average passenger vehicle lifetime of 12 years in China, which may be equal to the useful lifetime of MAC units. Several China-specific studies adopt this assumption (PKU, 2013; Hu et al., 2010; Su et al., 2015). Other global studies that include China have adopted a lifetime of 15 years (ICF International, 2012; Gloel et al., 2014). Based on the literature and data adjusted for this study, we assumed that MAC units have a useful lifetime of 12 years.

ICCT developed and maintains an emissions inventory model for China called the China Transportation Roadmap model (Shao & Wagner, 2015; Façanha et al., 2012). This model was designed to help Chinese policymakers isolate trends and evaluate policy options for vehicle emissions control. The model uses socioeconomic forecasts in which population, gross domestic product (GDP), and fuel prices inform estimates of future transportation activity and mode share. The China Roadmap model takes data for key variables from Chinese governmental agencies, which are processed to provide vehicle distance traveled, vehicle sales, vehicle stock, and vehicle scrappage rates for the years 2000 through 2050 (in five-year intervals). Exponential interpolation generates an annual time series for these parameters. Together with the refrigerant emissions data describe above, these activity data are used to generate estimates of refrigerant emissions under various scenarios.

Table 2-4 summarizes key assumptions for MAC in China following the methodology described in this section.

Table 2-4. Summary of assumptions for baseline (CFC-12 and HFC-134a) MAC systems.

	Pre-2000	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Post-2016
Share of light-duty vehicle sales with MAC systems (%)																			
	70	70	72	75	76.3	77.6	78.9	80.2	81.6	83	91.5	100	100	100	100	100	100	100	100
Share of light-duty vehicle sales by refrigerant (%)																			
R12	60	19	11	0															
R134a	40	81	89	100															
MAC charge size (g)																			
800											550								
MAC useful lifetime (yr)																			
12																			
Low emission assumptions																			
Regular operational emission (g/vehicle/yr)																			
80											49.5	47.9	48.2	47.5	41.6	43.3	41.3	38.0	38.0
Service emission (g/vehicle/yr)																			
93.3											57.7	55.8	56.2	55.4	48.6	50.5	48.2	44.4	44.4
End-of-life emission (g/vehicle)																			
240.0											189.8	197.2	195.7	198.6	225.2	217.8	226.7	241.4	241.4
High emission assumptions																			
Regular operational emission (g/vehicle/yr)																			
80											49.5	47.9	48.2						
Service emission (g/vehicle/yr)																			
93.3											57.7	55.8	56.2						
End-of-life emission (g/vehicle)																			
240.0											189.8	197.2	195.7						

BENEFITS OF HFC-134A PHASE-OUT IN CHINA

This section provides an assessment of the climate benefits of a HFC-134a phase-out in the Chinese light-duty vehicle fleet based on scenarios developed from international best practices.

Both EU and US regulations are performance based, meaning they set a performance target that allows automobile manufacturers to determine which alternative refrigerant to use. These alternatives must meet specifications given in the EU MAC rule and the US light-duty vehicle GHG standards. In the United States they must also be included in the list of chemicals approved under the EPA Significant New Alternatives Program (SNAP), which reviews the flammability, toxicity, and environmental damage of all alternative refrigerants to ensure that they are no more harmful than HFC-134a. Refrigerants that have approval under the EPA SNAP and meet US light-duty vehicle GHG specifications include HFO-1234yf, HFC-152a, and R-744. All three are climate-friendly, with zero ozone-depleting effects and significantly reduced global warming impacts. Each of these has been recognized as low-GWP refrigerants by the European Commission as well.

Because the US and EU markets account for about 40% of global light-duty vehicle sales, automakers competing in both markets have a strong incentive to choose alternative refrigerants that are allowed in both of these regions. This incentive extends to China, which accounts for an additional 25% of the global automobile market. Under this assumption, therefore, this study will assess the potential benefits in China of MAC systems using HFO-1234yf, HFC-152a, and R-744 (CO_2) refrigerants.

Modeling of GHG emissions for each alternative refrigerant was performed using the ICCT Refrigerant Inventory Model v3. Assumptions were developed for each alternative MAC system regarding charge size, regular operational emissions, servicing emissions, and end-of-life emissions. Potential policy pathways for HFC-134a phase-out were explored to quantify the total mitigation potential of each alternative refrigerant against the baseline system.

ALTERNATIVES TO HFC-134A

The three primary alternative refrigerants to HFC-134a have undergone a series of evaluations on their properties and performance when used in MAC. This section describes the characteristics of these refrigerants.

R-1234yf (HFO-1234yf)

2,3,3,3-tetrafluoropropene (HFO-1234yf) is hydrofluoroolefin, or an unsaturated HFC. The Fourth Assessment Report of the IPCC (Forster et al., 2007) recommended a GWP-100 value of 4, which is currently used in many regulatory documents (US EPA, 2010b; US EPA, 2015). The more recent IPCC Fifth Assessment Report revised this value downward to 1 or less, reflecting improved scientific understanding of its lifetime (Myrhe et al., 2013).

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) designated HFO-1234yf as an A2L refrigerant, which indicates low toxicity under low or moderate concentrations and very low flammability. The generation of hydrofluoric acid (HF) during a vehicle fire has raised some concerns for suitability in MAC systems (BAM, 2010) and was a motivating factor for Daimler to delay its introduction of such systems in Europe. The EPA has determined that the hazard of exposure to HF associated with HFO-1234yf is not greater than that of HFC-134a, given proper precautions (US EPA, 2015). Additionally, SAE International (2009) and Lewandowski (2013) administered two Cooperative Research Program (CRP) studies to evaluate the risk associated with the use of HFO-1234yf as an alternative refrigerant in MAC systems, with the second study performed specifically to address the Daimler claims. Both studies confirmed through extensive lab testing that the risk associated with HFO-1234yf is well below commonly accepted risk levels in the United States. HFO-1234yf is nearly a "drop in" substitute for HFC-134a due to the similarity of thermophysical properties (including vapor pressure) between the two refrigerants. An experimental assessment conducted by DuPont (Leck, 2009) showed that HFO-1234yf displays a slightly lower but very comparable cooling capacity and coefficient of performance relative to HFC-134a under working conditions. Minor modifications to current MAC systems are needed to promote similar performance (Koban, 2009).

Currently, Honeywell holds the patent on the application and use of HFO-1234yf as a MAC refrigerant. In 2010, Honeywell and DuPont made arrangements for joint development, licensing and production.[10] Other manufacturers are required to purchase a license to use HFO-1234yf in the refrigeration market.

HFO-1234yf is being used in cars on the road today in the United States and in Europe. A 2014 survey conducted by the Alliance of Automobile Manufacturers and the Association of Global Automakers found that automobile manufacturers plan to transition 90% of light-duty vehicle models sold in the United States to HFO-1234yf by or before MY 2021 (US EPA, 2015).

R-744 (CO_2)

CO_2, designated by ASHRAE as R-744 when used as a refrigerant, is a colorless and odorless gas under atmospheric conditions. CO_2 has, by definition, a GWP of 1. The EPA approved the use of R-744 as a substitute for HFC-134a in MAC systems in 1994 and later proposed further conditions to R-744 systems to minimize passenger exposure in cases of leakage (US EPA, 2016). Carbon dioxide is an A1 refrigerant, which is associated with no flammability and minimal toxicity.

R-744 MAC systems normally operate at pressures five to 10 times higher than HFC-134a systems. Therefore, improvements to the MAC system to sustain higher pressures are needed, including modifications to the compressor, hoses, and other components (Minjares, 2011). As safeguard measures, CO_2 sensors in the cabin may need to be installed to activate ventilation systems in case of refrigerant leakage. In addition, a secondary loop system that isolates CO_2 in the engine compartment is another commonly proposed design. Under a secondary loop configuration, CO_2 cools a mixture of water and glycol, which directly cools the passenger cabin.

Evaluations of the relative efficiency of R-744 systems have been mixed. Some studies of R-744 systems have shown less efficient performance at high ambient temperature compared with HFC-134a systems. All studies to date have been conducted on demonstration systems, so the real-world performance of commercially available systems has yet to be demonstrated. With the deployment of commercially available

10 "Patents." Accessed on February 3, 2016, at https://www.1234facts.com/about-us/patents/.

R-744 systems in MY 2017 E-class and S-class Mercedes-Benz vehicles,[11] real-world testing of R-744 systems will be able to compare against previous demonstration models. R-744 systems are already widely used in urban bus fleets in Europe and in retail refrigeration systems.

R-152a (HFC-152a)

1,1-difluoroethane (HFC-152a) is a colorless gas under atmospheric conditions. Its GWP-100 value is 138 (167 with climate-carbon feedback), which is greater than corresponding values for HFO-1234yf and R-744 but still much lower than that of HFC-134a. The EPA approved the use of HFC-152a in the SNAP program as an alternative refrigerant with special use conditions to address the associated safety issues.

HFC-152a is designated as an A2 refrigerant with minimal toxicity and moderate flammability. To address the safety considerations associated with this mild flammability, a secondary loop system is commonly proposed to avoid direct interaction between the unit and the passenger cabin.

In spite of R&D activities to commercialize HFC-152a in the MAC market, technical obstacles to its broader uptake include its higher flammability and the space constraints of a secondary loop system in a densely packed engine compartment (S. O. Andersen, Institute for Governance & Sustainable Development, personal communication, April 2016). A higher global warming potential than other alternatives further reduces its attractiveness to most automakers (UNEP RTOC 2010). Safeguard measures needed for the manufacturing and servicing infrastructure (including proper training for personnel), might further add to the implementation costs of HFC-152a. In light of major global automakers preferring a single global refrigerant that can act as a drop-in replacement for HFC-134a, these companies have not expressed great interest in HFC-152a.

DATA AND ASSUMPTIONS

System Charge Size

Because of the similarity in thermophysical properties between HFO-1234yf and HFC-134a, the charge size for HFO-1234yf will be comparable to that of the baseline system. UNEP RTOC (2010) estimated that R-744 systems would be 20%–30% smaller than HFC-134a MAC systems. This study assumes a 30% smaller charge size. UNEP RTOC (2010) estimated HFC-152a systems to be 50~75% the size of HFC-134a systems. This study assumes a 45% reduction. The specific assumptions regarding system charge size are:

- HFC-134a (Baseline):550 g
- HFO-1234yf: 550 g
- R-744: 385 g
- HFC-152a: 300 g

Because this study evaluates the phase-in of alternative refrigerants no earlier than 2016, and because system charge sizes are assumed to be constant from 2011 through 2050, no changes in assumed charge size for earlier MAC are made in this study.

11 http://media.daimler.com/deeplink?cci=2695000.

Operational emissions

In general, the leakage rates of HFO-1234yf systems are similar to HFC-134a because HFO-1234yf is essentially a drop-in replacement for HFC-134a. A report produced by ICF International (2012) indicated that higher leakage rates through seals and other connections may be expected for this new refrigerant, but high molecular weight and viscosity can lower permeation rates through system hoses. SAE standard J2727 (2012) suggests that the leakage rate is proportional to the molecular weight of the refrigerant and inversely proportional to the dynamic viscosity of the refrigerant vapor (except for hose permeation). Researchers in France (Yu & Clodic, 2007) found in a series of experimental tests that the operational leakage rate is proportional to the term of (P_{system}^2-$P_{ambient}^2$). The technical advisory committee to this study estimated based on these findings that the leakage rate for an HFO-1234yf system is 108% of an HFC-134a system (on an absolute weight basis). Thus, an operational emission rate that is 1.08 times of the baseline HFC-134a system is assumed.

In the absence of actual tests for HFC-152a systems, and based on the same methodology, this study assumes that the operational emissions from an HFC-152a system are 57% of the original HFC-134a system on an absolute weight basis. Thus, this study assumes the operational leakage of an HFC-152a system is 57% of an HFC-134a system.

For R-744 systems, leaks could occur under higher system operating pressure if not addressed through proper component design. This study assumes the annual operational emission rate is 20% higher (on a fraction of charge basis) than that of an HFC-134a system, which is consistent with an earlier study by ICF International (2012).

Servicing emissions

Methodology similar to that used to determine the service emissions for baseline systems was adopted to estimate service emissions for alternative systems. Based on the current situation in China, no recovery at service events was assumed.

End-of-life emissions

Under the baseline HFC-134a scenario, this study assumes that only 50% of vehicles at end of life still have MAC units. Many vehicle owners will choose to remove these systems and resell them to service facilities before sending the vehicle for scrappage (SEPA & THU, 2013). For those vehicles with intact MAC systems, this study assumes that only 50% of the remaining refrigerant is recycled. Even if recovery is required, this study assumes weak enforcement. For MAC systems removed before scrappage, this study assumes all remaining refrigerant was emitted. These same assumptions were employed for HFO-1234yf and HFC-152a. The assumption of poor recovery could potentially lead to an overestimate of the end-of-life emission. For R-744 systems, no recovery was assumed according to ICF International (2012). However, uncertainty may exist because of the lack of availability of public data.

The lifetime of alternative MAC systems is assumed to be identical to baseline systems, which is 12 years. Table 3-1 summarizes assumptions under high and low emission pathways.

Table 3-1. Summary of the assumptions of system refrigerant emissions.*

	Operational emissions	Servicing emissions	End-of-life emissions
Low emission			
HFC-134a	38.0	44.4	241.4
HFO-1234yf	41.1	47.9	227.7
R-744	31.9	37.3	145.0
HFC-152a	21.7	25.3	127.5
High emission			
HFC-134a	48.2	56.2	195.7
HFO-1234yf	52.0	60.7	178.3
R-744	40.5	47.2	106.6
HFC-152a	27.5	32.0	101.4

**Units are g/vehicle/yr for operational and service emission and g/vehicle for end-of-life emission.*

PHASEDOWN SCENARIOS

Multiple scenarios representing various policy pathways for the transition to alternative refrigerants were evaluated. As shown in Figure 3-1, these scenarios include a range of time frames associated with a transition between specific refrigerants. For each scenario, this study explored the effect if each alternative refrigerant were used to fully replace HFC-134a. MY 2018 was considered the earliest start year for any auto manufacturer to realistically begin to phase out HFC-134a. The modeling of various phase-out scenarios extends through MY 2050. GWP-100 values (listed below) used in this modeling were based on the IPCC Fifth Assessment Report with consideration of climate-carbon feedback (Myrhe et al., 2013). These GWP values provide a more representative picture of climate impacts of these refrigerants. Currently, the EU and the United States regulate refrigerants based on outdated GWP-100 values from earlier IPCC assessment reports and without climate-carbon feedback.

GWP-100 values used in the benefit modeling:

- CFC-12: 11,550
- HFC-134a: 1,549
- HFC-152a: 167
- HFO-1234yf: 1
- R-744: 1

The policy drivers for different HFC-134a phase-out scenarios proposed in this analysis range from the adoption of regulations similar to those issued in the EU or the United States to timelines put forward in recently proposed amendments to regulate HFCs under the Montreal Protocol. The implementation timelines for these scenarios are represented in Figure 3-1. Linear phase-in of alternative refrigerants was assumed between any two years with designated targets. In a BAU scenario, China continues to allow the use of HFC-134a in MAC systems without any further regulation.

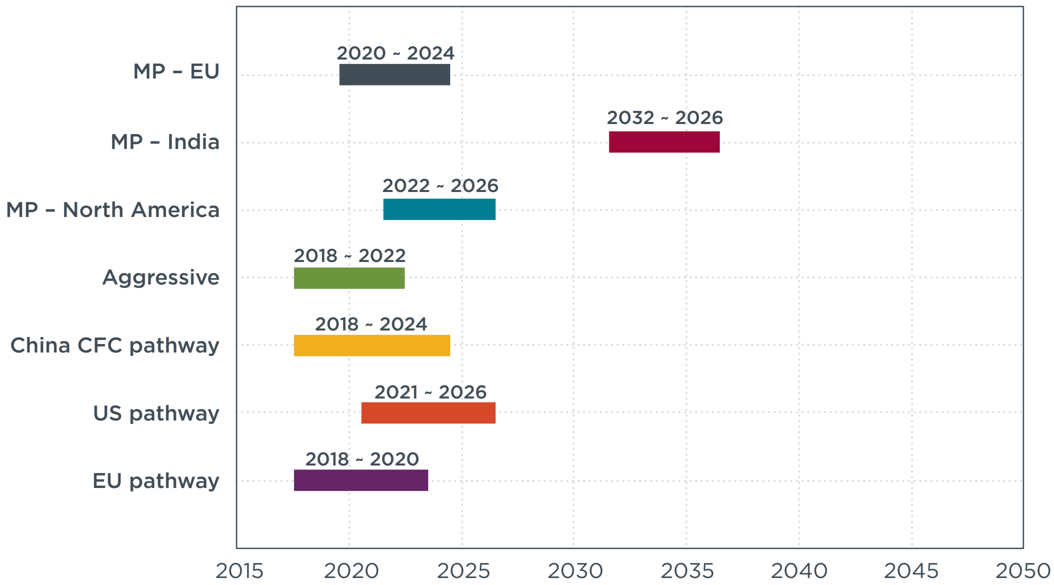

Figure 3-1. Overview of action years for scenarios proposed in this benefit analysis.

Scenario 1 – EU pathway
China starts to phase out HFC-134a immediately after the EU completes its transition to MAC systems containing refrigerants with GWP lower than 150 in 2017. The time frame for the transition is six years, consistent with the time frame that was required under the EU MAC directive.

Scenario 2 – US pathway
China starts to phase out HFC-134a immediately after the United States completes a similar transition in 2021. A six-year transition period was assumed.

Scenario 3 – China CFC pathway
China completes the transition from HFC-134a by following the same pace and seven-year length of transition used during China's earlier phase-out of CFC-12.

Scenario 4 – Aggressive
China adopts MAC regulations in 2018 and phases out HFC-134a in all new vehicles within five years. Modification to any existing vehicular system to accommodate regulatory requirements takes five years based on the standard development cycle for new vehicle models. This scenario represents a case where China chooses to phase out HFCs in 2016 and allows automakers two years to prepare for this phase-out.

Scenario 5 – HFC Amendment to Montreal Protocol
Phase-out of HFC-134a follows timelines for Article 5 countries as suggested by multiple recent proposals to amend the Montreal Protocol. Thus far, five proposals to amend the Montreal Protocol have been released, with four of them containing specific timelines and targets to reduce the production and consumption of HFCs. The main purpose of these scenarios is to demonstrate how a transition to low-GWP MAC systems can help China toward compliance with any future Montreal Protocol amendment.

Table 3-2 compares the 2015 Montreal Protocol amendment proposals. For Scenario 5, we assume that the HFC-134a in the MAC sector will be phased out first to meet these new obligations. Therefore, it is assumed that China will phase out HFC-134a in the MAC sector within the first five years of the suggested control periods, based on a standard five-year cycle for new vehicle design.

In order to incorporate the timelines reflected in the recent proposals to amend the Montreal Protocol, Scenario 5 was further divided into three sub-scenarios:

- Scenario 5a – MP-North America: China follows the timeline proposed by North America. The transition starts in 2022 with a time frame of five years.
- Scenario 5b – MP-India: China follows the timeline proposed by India. The transition starts in 2032 with a time frame of five years.
- Scenario 5c – MP-EU: China follows the timeline proposed by the EU and the Island States. The transition starts in 2020 with a time frame of five years.

Table 3-2. Comparison of the 2015 Montreal Protocol Amendment proposals for Article 5 countries.

	North America	India	EU	Island States
Grace period*	2 years	15 years	none	3 years
Control period & length	2021–2046 25 years	2031–2050 19 years	2019–2040 20 years	2019–2040 20 years
Control Measures for HFC production and consumption	2021 – 100% 2026 – 80% 2032 – 40% 2046 – 15%	2031 – 100% 2050 – 15%	2019 – 100% 2040 -15%	2020 – 85% 2025 – 65% 2030 – 45% 2040 – 10%

**Grace period beyond non-Article 5 countries control period.*

RESULTS

The per-vehicle reduction in lifetime CO_2e emissions (including operational, servicing, and end-of-life emissions) relative to an HFC-134a system is displayed in Figure 3-2. All three alternatives are capable of reducing per-vehicle GHG emissions by more than 90%, with HFO-1234yf and R-744 systems achieving greater than 99% of reduction. The lower GWP values of these alternatives, which are about 1/10 to 1/1000 of that of HFC-134a, are the drivers of these reductions. The results are very similar under a "high emission" case (see Annex A).

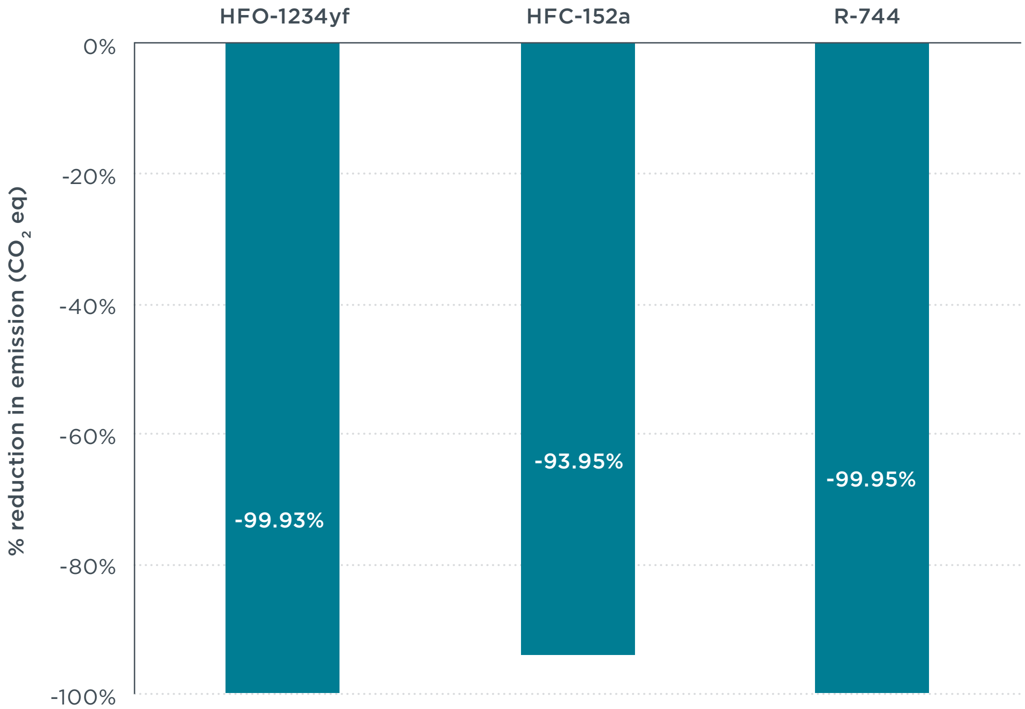

Figure 3-2. Lifetime reduction of GHG emissions relative to a HFC-134a MAC system under low emission assumptions.

Figure 3-3 shows refrigerant emissions under a low emission case for BAU and alternative scenarios from 2000 to 2050. Results under a high emission case are presented in Annex A, Figure A1. Without any control strategies, total refrigerant CO_2e emissions are expected to reach 80 (low emission) to 95 (high emission) trillion grams (Tg) per year, which is about four times the emissions levels in 2015. Baseline emissions ramp up quickly after 2010 due to the rapid growth of the auto industry and penetration of MAC systems in China.

Figure 3-4 compares the cumulative refrigerant (CO_2e) emission reductions achieved through 2050 under low emissions. Both HFO-1234yf and R-744 are able to achieve a comparable amount of reductions. The cumulative reduction achievable using HFC-152a is lower than for the other two alternatives because of its higher GWP. This reduction reaches approximately 1,500 Tg (1,800 Tg under high emission) by 2050 using HFO-1234yf and R-744 under scenarios featuring relatively aggressive strategies (Scenarios EU pathway, China CFC pathway and Aggressive), corresponding to more than 70% reduction relative to cumulative emissions under the BAU scenario.

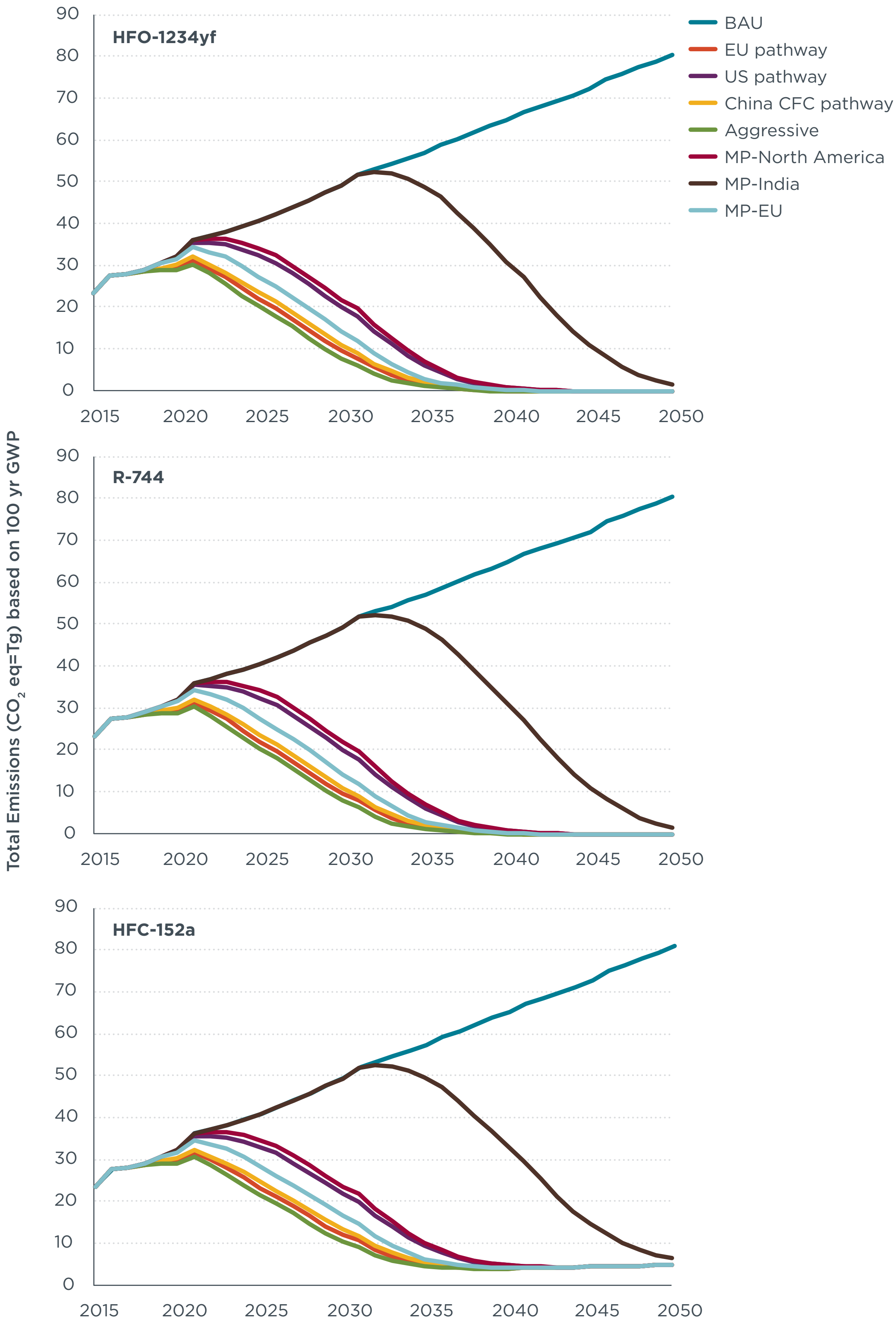

Figure 3-3. Time series of total refrigerant (CO_2e) emissions for (a) HFO-1234yf, (b) R-744, and (c) HFC-152a by scenarios (with low emission assumptions).

Assuming China follows the timelines proposed by India for a Montreal Protocol amendment, cumulative reductions through 2050 are expected to be approximately 50% of the other phase-out scenarios. Cumulative emission reductions relative to the baseline scenario were less than 40% for all three alternative refrigerants, which is the lowest reduction among all the scenarios. Scenario 4, which assumes an implementation year of 2018 with complete phase-out over five years, results in the highest level of GHG emission reductions by 2050 and earliest phase-out of HFC-134a. Modeling of the high emission case suggests very similar results (see Annex A).

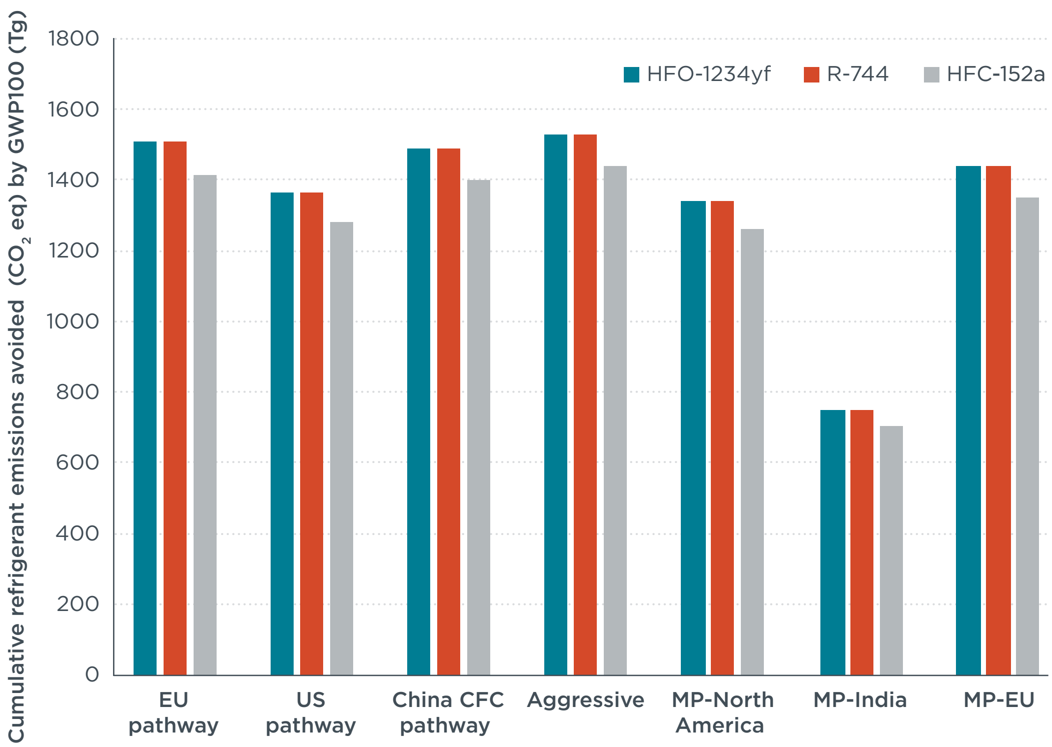

Figure 3-4. Cumulative refrigerant emissions avoided (CO_2 eq) by 2050 under all scenarios with low emission assumptions.

This analysis demonstrates that the penetration of alternative refrigerants could significantly reduce GHG emissions, but the pace and timing of transition strategies play key roles in the reductions achieved by 2050. Scenarios MP-North America, MP-India, and MP-EU, all of which feature an extended transition period, achieve the least reduction by 2050. The most aggressive transition policies phase out HFC-134a in new vehicles over a five-year period, begin this phase-out in 2018, and completely phase out HFC-134a from all vehicles by 2035 or 2040.

SOCIAL BENEFIT OF REDUCED GHG EMISSIONS

In this study, global social cost of carbon (SCC) equivalent is applied to monetize the climate benefits of alternative refrigerants. SCC is used by many agencies such as the EPA to estimate the economic damages associated with an increase of CO_2 emissions. This also quantifies the climate benefits of new rulemakings that directly or indirectly affect GHG emissions. The SCC is a comprehensive estimate of climate damages and includes changes in agricultural productivity, human health, and property damages from increased flood risks, among other economic damages. The SCC also incorporates change in energy consumption, for example increased use of air conditioning and reduced used of heating due to global warming. The EPA, collaborating with an interagency working group comprising experts from the White House and other federal agencies, assessed climate models, economic models, and the interactions between the two to model the SCC. More technical details are included in a technical support document (US Government, 2015).

Economic models estimate the cost of climate damage over time. Those estimates are discounted using three different discount rates (2.5%, 3%, and 5%). Average costs are then calculated for each discount rate. Additionally, the 95th percentile cost at a 3% discount is used to characterize the general uncertainty of the cost estimation process.

The SCC, according to these four discount rates in each year from 2015 to 2050, was used for this analysis. Costs expressed in 2007 dollars were converted to 2015 dollars using a GDP price inflator of 1.14 derived from GDP price index data produced by the US Bureau of Economic Analysis. A factor of 6.5 was applied to convert US dollars to Chinese yuan. SCC used in this analysis is tabulated in Table 3-3.

Table 3-3. Social cost of CO_2 (¥/mt CO_2)[12]

Year	2016	2020	2025	2030	2035	2040	2045	2050
5% avg	82	89	104	119	133	156	170	193
3% avg	282	311	341	371	408	445	474	511
2.5% avg	422	459	504	541	578	622	659	704
3% 95th Percentile	800	911	1023	1126	1245	1356	1438	1571

Figure 3-5 shows the total SCC avoided through year 2050 relative to a BAU scenario. The range of avoided SCC using each SCC discount rate is captured for each refrigerant and scenario. All avoided SCC are expressed in 2016 present dollars (NPV).

Phasing out HFC-134a under Scenario 4 leads to the greatest climate benefit with up to more than 1,000 billion yuan (nearly 1,200 billion under a high emission case) avoided compared with the BAU scenario. A delayed action (e.g., described by Scenario MP-India) of transition is likely to result in additional social cost up to 557 billion dollars relative to Scenario 4. This additional cost will be even greater under a high emission trajectory, reaching approximately 654 billion (Figure A6). In general, the inter-refrigerant variability is less than the inter-scenario variability in the social cost avoided, which reinforces the fact that the timing of transition plays a central role in the achievable climate benefits and total social cost avoided.

12 Conversion rate of 6.5 to 1 for yuan (renminbi) to USD were used in this analysis.

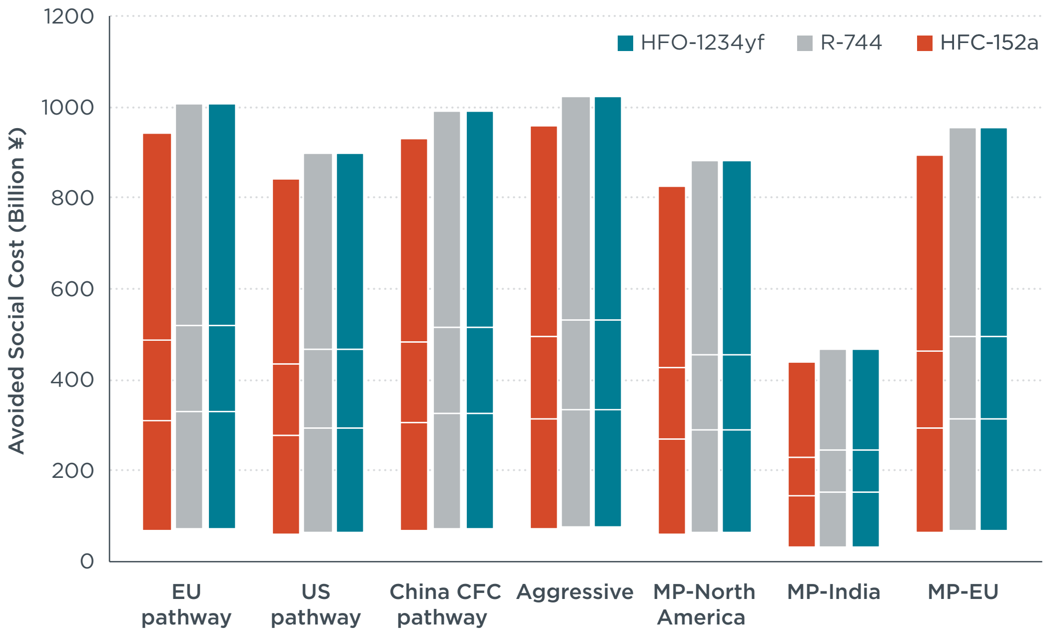

Figure 3-5. Total avoided global social cost till 2050 induced by transitioning in China to alternative MAC refrigerants under conservative emission assumptions.[13] The lower end of the bar is the 5% average SCC estimate, the lowest white line the 3% average SCC estimate, the upper white line the 2.5% average SCC estimate, and the upper end of the bar the 3% 95th percentile SCC estimate.

Potential uncertainties with the analysis may include the following:

» The models used to develop social cost estimates do not cover all the important physical, ecological, and economic impacts of climate change due to the lack of precise information (US Government, 2015).

» Emission rate estimates, even under a high emission case, may still underestimate emissions of the Chinese fleet. However, a deeper understanding of such information would be facilitated by more comprehensive and systematic studies on the MAC sector in China.

» The cost prediction for future years is primarily based on learning curves, which do not capture other potential sources of cost savings.

IMPLICATIONS FOR MONTREAL PROTOCOL AMENDMENTS

Scenarios MP-North America, MP-India, and MP-EU were based on 2015 proposals put forward by parties to the Montreal Protocol in recent discussions around an HFC amendment. Any one of these would require reductions in the consumption and production of HFCs across the economies of signatories to the Montreal Protocol. HFCs in the MAC sector account for about 24% of CO_2e HFCs consumed globally (US EPA, 2010c). The contribution may be even greater in China, accounting for about 33% of total HFC consumption (Hu, 2013). With large reduction potential, HFCs in the MAC sector could be the low-hanging fruit for China to mitigate GHG emissions.

13 Total avoided global social cost through 2050 induced by transitioning to alternative refrigerants under high emission assumptions is shown in Annex A.

What effect does a HFC-134a phase-out in the MAC sector have on obligations under an amended Montreal Protocol to phase down consumption of HFCs? The two major contributions to the consumption of HFCs in MACs are initial charge to the system and refill at the service. Based on ICCT estimates, six-year-old vehicles account for approximately 10% of the vehicle stock. Assuming a service refill every six years per vehicle, on average 10% of the vehicle stock needs a refill each year. Based on this amount of HFC consumption in the legacy fleet, Table 3-4 summarizes the reduction in HFC consumption toward compliance with interim phasedown targets under each scenario taken from Montreal Protocol proposals. These reflect changes at either the first interim target given under each proposal, or the end of the MAC transition period compared with the year before the transition. Note that the proposals from individual parties/groups included both HFCs and hydrochlorofluorocarbons (HCFCs) in the target. Given the small proportion of HCFCs compared with HFCs in the total consumption, this analysis makes a comparison solely on HFCs.

Table 3-4. Progress toward HFC consumption phasedown targets by transitioning to low-GWP refrigerants in the China MAC sector.

	MP-North America	MP-India	MP-EU
Baseline year	2021	2031	2019[1]
Interim target	- 20%	Not applicable[2]	- 24%
HFO-1234yf, %	- 10%	- 14%	- 13%
HFC-152a, %	- 10%	- 13%	- 12%
R-744, %	- 11%	- 14%	- 13%

1. The proposal from the Island States requires a reduction of HFCs before the start of the control period. For demonstration purposes, 2019 was selected as the baseline year as was suggested by the EU proposal.
2. The India proposal did not specify any interim targets.

COSTS OF HFC-134A PHASE-OUT IN CHINA

Low-GWP refrigerants could result in additional cost compared with HFC-134a systems. This includes not only the cost of the refrigerant itself, but also changes to hardware necessary to accommodate different refrigerants.

In this analysis, the cost of transition to alternative MAC systems was broken down into two categories: one-time cost incurred by manufacturers, and ownership cost incurred by consumers. Cost induced by facility upgrade at service stations is considered to be fully passed on to consumers and will be reflected in labor rates. Disposal cost was assumed to be negligible and was not calculated.

DATA AND ASSUMPTIONS

One-time costs incurred by manufacturers

One-time costs incurred by manufacturers include both initial manufacturing cost and cost of the initial refrigerant charge.

HFC-134a systems

Oko-Recherche et al. (2011) estimated that the cost to manufacture and initially charge an HFC-134a MAC system is ¥1,184–¥1,258 ($182-$193). The bulk price for HFC-134a refrigerant fluctuates with market supply and demand and currently averages around ¥40/kg (about $6/kg)[14],[15] in China. Initial charge costs about ¥22 for a car with a 550 g MAC system.

Based on this information, this study assumes that the upfront manufacturing cost of the unit and the initial refrigerant charge of an HFC-134a system is about ¥1,235 ($190).

Technology related to HFC-134a systems is relatively well-developed, so very limited reduction in technology cost is expected. This study assumes that all costs associated with HFC-134a systems are unchanged in all future scenarios.

HFO-1234yf systems

Previous assessments of the incremental cost associated with transitioning to HFO-1234yf MAC systems are reasonably consistent. Fiat estimated an incremental cost of $68 relative to a baseline HFC-134a system (Malvicino, 2008). The EPA estimated capital cost of an HFO-1234yf system at approximately $66 for developing countries, including incremental refrigerant costs and hardware changes (US EPA, 2013). General Motors (GM) produced a corresponding estimate of $76 (Milnes, 2013). In the technical support document for its 2017–2025 light-duty vehicle GHG emission standards, the EPA estimated the retail-level cost of HFO-1234yf refrigerant (exclusive of required hardware changes) at $120 per kg (2015$, US EPA & NHTSA, 2012). A similar analysis by CARB for their LEV III rulemaking used a corresponding retail-level price of $138 per kg (2015$, ARB 2011). For a 550 g system, these EPA and CARB estimates equate to an HFO-1234yf refrigerant cost of $66 and $76, respectively.

14 In this cost analysis, all US dollars are converted to 2015 USD unless otherwise noted. Conversion rates of 6.5 to 1 for yuan (renminbi) to USD and 7.4 to 1 for yuan to euro are used.

15 "China Industry Online." Accessed on March 16, 2016, at www.chinaiol.com.

Other less formal estimates of the price of HFO-1234yf refrigerant cover a substantial range. Consultation with a confidential US industrial source indicates an expected price range of $110–$130 per kg for auto service providers. Prices for automotive system manufacturers would be correspondingly lower. Conversely, confidential industrial sources in China indicate much higher price expectations, in the range of $200–$300 per kg.

Given that HFO-1234yf MAC systems are in current production, the refrigerant is available to both original equipment manufacturers (OEMs) and service facilities today. Unfortunately, current prices are influenced by relatively low-volume production and supply constraints. Substantial new production capacity coming on line in the United States, China, and India as well as continuing increases in demand are expected to reduce prices from current levels. Unfortunately, current OEM supply contracts are confidential. However, current aftermarket prices can be determined with accuracy. Mopar is selling HFO-1234yf under part number 68224028AA, priced at about $8 per ounce ($282 per kg).[16] In contrast, GM sells the same product under part number 19260234, priced at about $750 per 10 lb cylinder ($165 per kg).[17] Independent outlets exhibit similar price ranges. For example, O'Reilly Auto Parts currently retails HFO-1234yf priced at $1,279 per 10 lb cylinder ($282 per kg),[18] while Refrigerant Depot sells the identical 10 lb cylinder for $750 ($165 per kg) and offers volume discounts.[19] All suppliers are marketing either Dupont's OpteonYF or Honeywell's Solstice brand-name products. Price differentials merely reflect the current sparsity of the HFO-1234yf market.

While it is not possible to foresee with clarity the near-term future price of HFO-1234yf in a high-volume scenario, we see no reason that such prices would be greater than those of currently available product. Thus, we estimate the current service-sector price at $165 per kg. We further assume that service-sector prices reflect a 20% premium over OEM retail-level prices, and thus derive an OEM retail price estimate of $138 per kg, identical to the retail-level price assumed by CARB in their LEV III analysis (updated to 2015$). We consider these estimates to be quite conservative (on the high side) for the high-volume production scenario that would occur under a committed industry transition away from HFC-134a. We especially note that these estimates are 25%–50% *higher* than those suggested by confidential industrial sources. We think it highly likely that we are overstating the future costs of HFO-1234yf, but deem this appropriate given current pricing uncertainty in the face of ongoing patent deliberations. We have employed this same methodology to estimate costs for this analysis.

In the 2017–2025 light-duty passenger vehicle GHG emission standards, the EPA adopted a systematic approach to break down total cost to manufacturers of new technology into direct manufacturing cost (DMC) and indirect cost (IC). DMCs primarily account for the costs of the components of the unit while other costs such as facility-related cost, utilities, and R&D are covered by IC. The methodology is discussed in more

16 See http://www.moparpartsoverstock.com/p/___/REFRIGERANT-R1234YF-1-Ounce-HA0--XFC--HAA-OR-HAF--XFC--HAB--XFC--HAD-OR-HAF--XFC--HAF--XFC/10245887/68224028AA.html. Many other sites offer similar availability and pricing.

17 See http://www.gmpartsdirect.co/oe-gm/19260234. Many other sites offer similar availability and pricing.

18 See http://www.oreillyauto.com/site/c/detail/FRE1/1234YF/N1782.oap.

19 See http://www.refrigerantdepot.com/hfo-1234yf-699-per-cylinder-while-supplies-last-2/. Current pricing confirmed via telephone on April 26, 2016.

detail in the technical support document to the EPA rule making (US EPA, 2012). The costs described in the paragraphs that follow are primarily expressed in terms of DMC, but we apply IC estimates to each to derive retail-level cost estimates (as presented in summary Tables 4-1 through 4-4).

The EPA and NHTSA (2012) constructed a projection of future costs of HFO-1234yf systems through 2050, taking into account learning effects. In its technical support documents (US EPA, 2010a; US EPA, 2012), the EPA employed a methodology to predict cost variations during different stages of technology development. The methodology, referred as the "learning curve," includes three portions:

1. Steep portion: The learning effects are greatest in this portion of the curve and current cost relative to original cost declines rapidly. The EPA is using an "every two years" learning progression, assuming costs are reduced by 20% every two years.
2. Flat portion: The learning effects are less pronounced in this portion of the curve. EPA assumes the costs are reduced at 3% per year for the first five years, 2% for another five years, and 1% for the last five years.
3. No-learning portion: There is no more learning effect on costs occurring in this phase of the curve, and the cost will remain the same throughout this stage.

The majority of research and development activities related to low-GWP MAC systems are performed by international manufacturers. Because all major international vehicle manufacturers are active in China, it is reasonable to assume costs will be no different for China than for any other country that currently has access to this technology (see below for discussion of economic competitiveness impacts on China). This study therefore adopts an incremental DMC for HFO-1234yf refrigerant charge of ¥397 ($61) and ¥104 ($16) for hardware modifications. These were adopted based on the EPA's and CARB's assumptions and methodologies.

The EPA (2012) considered HFO-1234yf to be on the steep portion of the learning curve because it is a newly developed chemical that is used in a limited number of vehicles. Although DuPont and Honeywell own a patent for HFO-1234yf production, Honeywell has recently expanded its production via partnerships with local producers in China.

Following the EPA's methodology described in the joint technical support documents for the EPA's 2012–2016 and 2017–2025 MY rules, this study assumes that refrigerant cost will decline by 20% every two years from 2016 MY though 2020 MY, 3% per year thereafter through 2026 MY, 2% per year through 2031, and 1% per year through 2036, assuming it enters the flat portion of the learning curve. Starting from 2036, it is assumed that this technology reaches a plateau and has very limited potential of further cost reduction. Therefore, the cost will remain constant through 2050. HFO-1234yf has dropped by about 30% since 2011, according to a knowledgeable industrial source, which is consistent with estimates based on the learning curve.

In contrast to refrigerant cost, the cost of hardware modification is not entirely new and considered to be in the flat portion of the learning curve. Therefore, it is assumed that this cost will be reduced by 2% each year through 2021, 1% each year through 2026, and will remain constant through 2050.

HFC-152a systems

The R&D and penetration of HFC-152a as an alternative MAC refrigerant is limited compared with the other alternative refrigerants. A previous study estimated the incremental cost of such a system relative to an HFC-134a system at approximately ¥143 ($22) for direct expansion systems and ¥429 ($66) for secondary loop systems (Hill, 2003). The cost of an HFC-152a system is estimated to be less than an HFO-1234yf system, according to an industrial source consulted by ICF International (2012). The bulk price for this refrigerant is approximately ¥40/kg ($6/kg) in China.[20] For a full system charge based on a 300 g charge size, ¥13 ($2) is needed for the refrigerant.

For this analysis, it is assumed that the incremental DMC for an HFC-152a system hardware is ¥358 ($55), based on a secondary loop design. The initial charge will cost approximately ¥13 ($2). Indirect costs are calculated following the same method described above. The technology of a secondary loop system is not entirely new, so it is assumed to be in the flat portion of the learning curve. Similarly to an HFO-1234yf system, the cost will decline by 3% each year through 2021, 2% each year through 2026, 1% each year through 2031, and finally stay at a flat rate through 2050. The cost of the refrigerant is assumed to remain the same because HFC-152a has been fully commercialized for over a decade.

R-744 systems

The hardware modification to accommodate R-744 is considered to be relatively costly at present due to limited commercialization. Eustice (2008) from GM estimated the incremental cost of an R-744 system to be ¥2,275 ($350). The EPA & NHTSA (2012) estimated that accommodating R-744 will require an additional ¥910 ($140) to ¥1,365 ($210). The cost of the refrigerant R-744 is considerably less compared with the other alternative refrigerants, and the cost is primarily associated with storage and transportation. It is reported by a global study that this cost ranges from approximately ¥6.5/kg ($1/kg) to ¥32.5 ($5/kg) (Oko-Recherche et al., 2011).

For this analysis the DMC for hardware modification is assumed to be ¥1,300 ($200) and the DMC for refrigerant cost is assumed to be ¥6.5/kg ($1/kg) or ¥2.6/kg ($0.4/kg) for a full charge. Because R-744 systems are still emerging, it is reasonable to assume the technology to be in the steep portion of the learning curve for the first few years. The same learning curve applied to HFO-1234yf systems is used. It is assumed that the refrigerant cost will remain at the current level through the end of 2050 due to its relative availability. Indirect costs are estimated following the same methodology described above.

Recurring costs incurred by consumers

Recurring costs include the cost of refrigerant filled at service events and resulting labor costs. Based on assumptions used in the previous sections, MAC systems will be serviced once in their useful lifetime.

HFC-134a systems

A survey for the Chinese auto service market estimated that one refill at service costs about ¥35 ($5) for refrigerant. One standard service job that includes system recharge takes about one hour. Based on ¥60 (~$10/hr) for the labor rate, the cost incurred by

20 "China Industry Online." Accessed March 16, 2016, at www.chinaiol.com.

consumers for an HFC-134a system during its lifetime is estimated to be around ¥100 (~$15) (Si & Zhang, 2012). Because the market for HFC-134a is fully developed, it is assumed that the cost will remain the same in the future years. The labor rates may vary with a battery of factors such as GDP, inflation, and economy. Therefore, for simplicity in this analysis, the labor rate is assumed to remain the same through 2050.

HFO-1234yf systems

As a conservative estimate, we assume that service center cost of refrigerant is 1.2 times bulk cost to OEMs with the same learning effects incorporated into price change over time. Due to similarities between the HFO-1234yf system and the baseline HFC-134a system, average time spent at servicing is assumed to be the same.

HFC-152a systems

The refrigerant cost at service stations is assumed to be 1.2 times the bulk cost for OEMs, which is equal to ¥19. Labor cost is identical to the baseline system, which remains at ¥60 ($10)/service job.

R-744 systems

The refrigerant cost at service stations is assumed to be 1.2 times the bulk cost for OEMs, which is equal to ¥9. Labor cost is identical to the baseline system, which remains at ¥60 ($10)/service job.

Table 4-1. Summary of cost estimates for baseline HFC-134a systems.

2016	2020	2025	2030	2035	2040	2045	2050
One-time cost incurred by manufacturers, ¥							
1,235	1,235	1,235	1,235	1,235	1,235	1,235	1,235
Recurring cost incurred by consumers, ¥							
Number of service jobs							
1	1	1	1	1	1	1	1
Refill cost, ¥/service job							
35	35	35	35	35	35	35	35
Labor cost, ¥/service job							
60	60	60	60	60	60	60	60
Total cost, ¥							
1,330	1,330	1,330	1,330	1,330	1,330	1,330	1,330

Table 4-2. Summary of cost estimates for alternative HFO-1234yf systems.

2016	2020	2025	2030	2035	2040	2045	2050
One-time cost incurred by manufacturers, ¥							
1,860	1,702	1,648	1,623	1,611	1,609	1,609	1,609
Recurring cost incurred by consumers, ¥							
Number of service jobs							
1	1	1	1	1	1	1	1
Refill cost, ¥/service job							
592	418	361	332	318	315	315	315
Labor cost, ¥/service job							
60	60	60	60	60	60	60	60
Total cost, ¥							
2,253	2,047	1,972	1,937	1,926	1,924	1,924	1,924

Table 4-3. Summary of cost estimates for alternative HFC-152a systems.

2016	2020	2025	2030	2035	2040	2045	2050
One-time cost incurred by manufacturers, ¥							
1,695	1,653	1,602	1,585	1,583	1,583	1,583	1,583
Recurring cost incurred by consumers, ¥							
Number of service jobs							
1	1	1	1	1	1	1	1
Refill cost, ¥/service job							
19	19	19	19	19	19	19	19
Labor cost, ¥/service job							
60	60	60	60	60	60	60	60
Total cost, ¥							
1,760	1,719	1,668	1,651	1,648	1,648	1,648	1,648

Table 4-4. Summary of cost estimates for alternative R-744 systems.

2016	2020	2025	2030	2035	2040	2045	2050
One-time cost incurred by manufacturers, ¥							
2,857	2,384	2,226	2,148	2,109	2,103	2,103	2,103
Recurring cost incurred by consumers							
Number of service jobs							
1	1	1	1	1	1	1	1
Refill cost, ¥/service job							
9	9	9	9	9	9	9	9
Labor cost, ¥/service job							
60	60	60	60	60	60	60	60
Total cost, ¥							
2,915	2,441	2,284	2,206	2,167	2,161	2,161	2,161

INCREMENTAL COSTS OF HFC-134A PHASE-OUT

Based on the total cost for each alternative MAC system summarized in Tables 4-2 through 4-4, the R-744-based systems display the highest per unit incremental cost followed by HFO-1234yf systems. HFC-152a systems display the least incremental cost among the three refrigerant systems.

The incremental cost to reduce each CO_2e ton per vehicle is shown in Figure 4-1. The cost-effectiveness of HFO-1234yf declines from ¥484/mt CO_2e in 2016 to ¥312/mt CO_2 in 2050 while the cost-effectiveness for R-744 systems declines from ¥832/mt CO_2 to ¥436/mt CO_2 in 2050. In comparison, the cost-effectiveness of HFC-152a systems shows relatively small change.

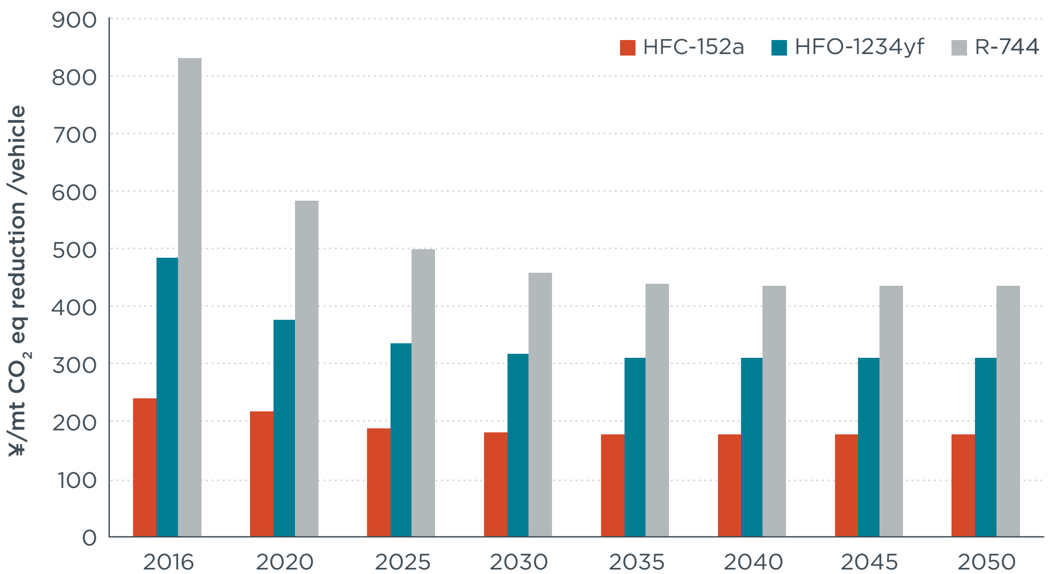

Figure 4-1. Cost-effectiveness of alternative MAC systems under low emission assumptions. Cost incurred during the MAC useful lifetime were discounted back to the first year using a discount rate of 3%.[21]

Using vehicle activity data extracted from the ICCT Roadmap model, MAC system mass emission reductions can be converted into units of grams per kilometer, which allows for direct comparison with other vehicle CO_2 reduction technologies. Generally, cost estimates for engine technologies are available for the 2020–2025 time period, so MAC estimates for this same period are used for comparison. Figure 4-2 presents two comparisons, one a bounding comparison based on the EU penalty rate for noncompliance with vehicle CO_2 standards and one based on the "workhorse" engine technology package expected to be used for compliance with fuel economy standards in China.

The workhorse technology package is a package that consists of a turbocharged and downsized gasoline direct injection engine with cooled EGR. This technology package was selected as the basis for comparison as it represents the most cost-effective solution for manufacturer compliance with a 5 liter per 100 kilometer fuel economy

21 Cost-effectiveness of alternative MAC systems under a "high emission" case is shown in Annex A.

standard. This determination was made as part of a detailed ICCT study on 2020–2025 fuel economy technology in China (Meszler, Tu, He, & Bandivadekar, 2015). That study included detailed vehicle simulation modeling to derive CO_2 impact estimates and detailed tear-down evaluations of technology costs. It reflects state-of-the-science methodologies and is expected to provide best-estimate costs and benefits. It does not reflect conservatively high engine technology costs and thus serves an informative, unbiased comparative reference.

The EU comparison is intended to reflect an upper-bound technology cost estimate. The EU imposes a penalty of €95 per gram CO_2 per kilometer on vehicle manufacturers that fail to meet CO_2 standards. While not indicative of the cost of all complying technologies, the penalty serves as an effective upper bound on the cost-effectiveness of CO_2 reduction technology. Once a technology reaches the penalty level of cost, it is cheaper to pay the penalty than install the technology. Thus, it serves as a convenient benchmark against which to judge the relative costs of alternative MAC systems.

The higher price for HFO-1234yf refrigerant is the driving factor behind its cost. Meanwhile, hardware is a major contributor to total cost of R-744 systems. Because both refrigerants are on the steep portion of the learning curve, the cost for both systems is expected to decline rapidly over the coming years. For example, from 2016 to 2050 these costs should fall by about 38% for HFO-1234yf systems and 48% for R-744 systems. The low cost of HFC-152a systems can be explained by widely available production of the refrigerant and by broad access to technology necessary to implement a secondary loop design needed to implement this refrigerant system. Overall, we expect the costs of all three alternative MAC systems to decline over the next few decades, resulting in smaller differences among the three systems.

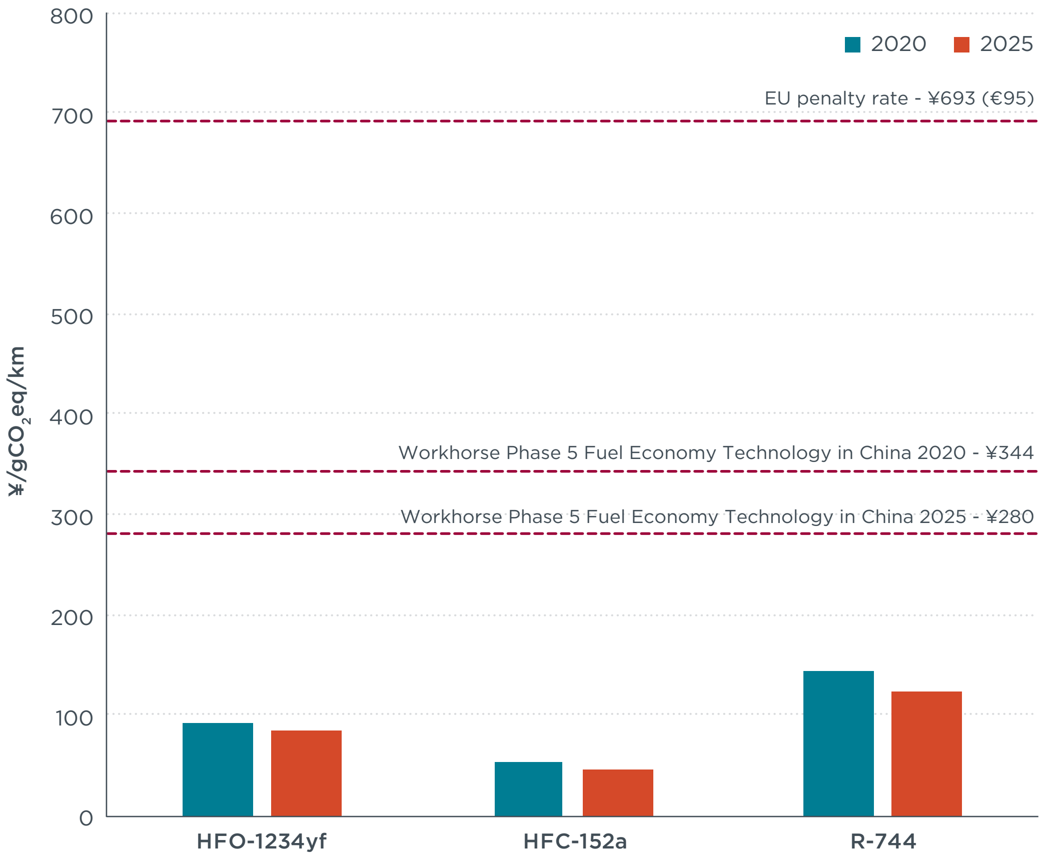

Figure 4-2. Cost-effectiveness of alternative MAC systems (under low emission assumptions) as compared with both EU CO_2 emission penalties and with costs of technology to comply with next-phase Chinese fuel economy standards. Costs during the useful lifetime of a MAC were discounted with a rate of 3%.[22]

MAC system costs are about 80% lower than the EU penalty rate of ¥693 (€95), so low-GWP MAC systems are well below the cost at which manufacturers would be economically justified not to adopt new technology. MAC system costs are roughly 30% to 50% of the cost of technology to be widely adopted to comply with Chinese fuel economy standards. This demonstrates that MAC technology is quite cost-effective relative to other light-duty vehicle CO_2 reduction technology.

A discussion of uncertainties in the cost of alternative refrigerant systems and their effect on this analysis can be found in Annex B.

22 Annex A gives cost-effectiveness of alternative MAC systems under a "high emission" case.

IMPACTS OF HFC-134A PHASE-OUT ON THE ECONOMIC COMPETITIVENESS OF THE CHINESE AUTO SECTOR

OVERVIEW OF THE AUTOMOTIVE MARKET

In recognition of the mounting pressure to move away from HFC-134a, significant R&D activity has been, and continues to be, undertaken on this topic. This includes, for example, the development of HFO-1234yf production capacity in China as well as ongoing development discussions between refrigerant suppliers and Chinese automotive manufacturers. Thus, there is already considerable activity going on to provide fundamental support to any transition to low-GWP refrigerant.

Figure 5-1 shows the distribution of global light-duty vehicle (passenger cars and light truck) sales across regional markets (ICCT, 2015). As indicated, the combined US and EU markets that are currently in transition from high- to low-GWP refrigerant account for a bit over a third (36.2%) of current light-duty sales. China itself accounts for another 24% of sales, so that these three regions together reflect about 60% of global sales. Due to growth expected in India between now and 2030, the combined China/US/EU sales share is expected to decline modestly to about 54% by 2030, but the three regions together will continue to dominate the global market for the foreseeable future. The four regions (China/US/EU/India) sales share is expected to account for 70% of total global sales by 2030. Thus, while sales in other areas of the globe are significant and nonetheless important from an economic standpoint, China must, to be a globally competitive player in the automotive manufacturing market, continue to develop and maintain a presence in the US, EU, and India markets.

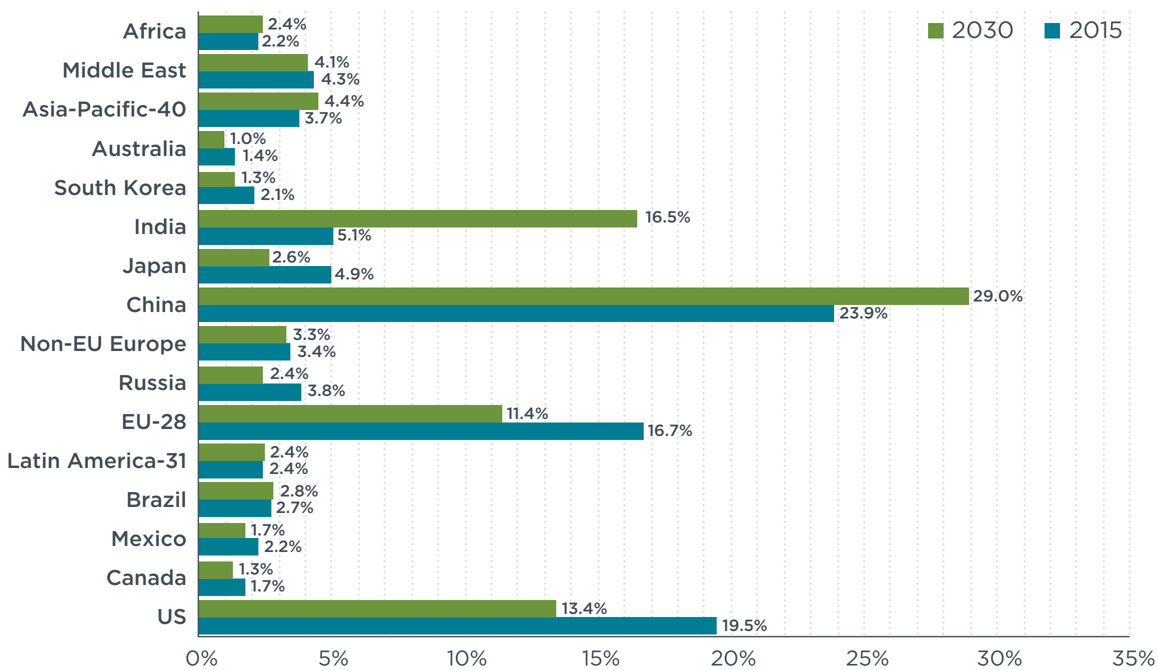

Figure 5-1. Global light-duty vehicle sales shares.

The importance of such presence is amplified when one considers that many of the other regional markets look to either the United States or the EU for leadership when developing their own regional standards. Exclusive of China, over 85% of vehicle production in G20 nations is subject to either EU or US-derived emission standards (Kodjak, 2015). This means that over 75% of global production is subject to such standards, even if not a single non-G20 nation required EU- or US-derived compliance.[23] However, even this may be too limited a view. For example, both the Kingdom of Saudi Arabia and the United Arab Emirates have adopted, or are in the process of adopting, US light-duty vehicle fuel economy standards, including their associated credit allowances for low-GWP MAC systems. Many of the countries that currently rely on EU or US vehicle emission standards could easily extend that reliance to CO_2 efficiency and MAC system standards. Thus, the footprint of the US and EU regulatory programs expands well beyond their respective geopolitical borders, influencing markets and vehicle sales across the globe. The global expansion of US and EU regulatory influence is not expected to diminish over the foreseeable future, so global competitiveness dictates an ability to manufacture vehicles in compliance with the requirements of EU and US standards.

The domestic Chinese automotive market can be roughly split into two components: one composed of independent domestic manufacturers and one composed of domestic manufacturers that have aligned themselves with one or more extra-national manufacturers. These latter joint ventures represent the only way that extra-national manufacturers are allowed to compete in the domestic Chinese market and comprise a substantial fraction of the domestic market. For example, the top 18 automotive manufacturers capture about 80% of the domestic market, with joint ventures capturing about 70% of that share (He & Tu, 2012). Because participation in a joint venture obligates extra-national manufacturers to share technology with their domestic partners, there is some concern that domestic manufacturers that do not participate in such ventures are at a competitive disadvantage relative to those domestic manufacturers that do. The sections that follow include an evaluation of the extent to which any transition to low-GWP refrigerants could exacerbate such an advantage.

GLOBALLY OPTIMUM INDUSTRY RESPONSE

In the absence of confounding issues, the globally optimum automotive industry response to efforts to reduce the GWP of MAC systems would be to simply select the most cost-effective low-GWP refrigerant and transition the industry en masse toward universal replacement. MAC systems are essentially a commodity for manufacturers. Generally, vehicles either have a MAC system or they do not (and today, almost all vehicles are MAC-equipped). While there are functional aspects of climate control systems, such as multi-zonal controls that are used as distinguishing marketing features, the basic functionality of the underlying refrigeration system is essentially common across manufacturers. Thus, from a standardization perspective, the use of a single common refrigerant minimizes not only equipment procurement and assembly line requirements, but also refrigerant production and aftermarket service and training requirements. Of course, there will be a need to retain an HFC-134a infrastructure throughout the phase-out period of existing systems, but the industry would optimize that phase-out by selecting a single replacement.

23 Note that this includes countries, such as India, that adopt their own standards based on those of the EU or the United States. Additionally, not all such countries require compliance with the most recent EU or US standards. There is often a lag time between adoption of more stringent standards in the EU or the United States and corresponding adoption in a “referencing” country.

Unfortunately, there are confounding issues. Different manufacturers have different opinions on the optimum replacement refrigerant. Issues with regard to refrigerant safety, and decomposition products are not fully resolved. Potential cost premiums associated with HFO-1234yf patent claims are of concern.[24] And, the differential cost of refrigerant-specific technology, both at installation and during in-use service life, is not known with certainty. Thus, manufacturers have not reached consensus. While the overwhelming majority of automotive manufacturers appear to be committed to an HFO-1234yf future, there are some that continue to pursue CO_2 systems as a preferred solution. While the exact number of HFO-1234yf systems in production is not known with certainty, it is clear that the number is significant. One researcher, for example, estimates that there were, as of December 2015, at least 30 manufacturers producing at least 83 models with HFO-1234yf systems for sale in the EU and at least 17 manufacturers producing at least 47 models with HFO-1234yf systems for sale in the United States (Andersen & Sherman, 2015).[25] These vehicles are manufactured in at least 11 countries, including China. Actual certification data suggests the number of systems is much higher. In Germany alone, HFO-1234yf systems were available on at least 101 vehicle models (reflecting a production volume of over 350,000) in 2015, up from 64 models (representing a production volume of over 200,000) in 2014, and 41 models (representing a production volume of just under 100,000) in 2013.[26] This is most significant when one recognizes that it is German automakers in particular that favor CO_2 systems. Regardless of whether or not some domestic manufacturers favor CO_2, there are, and will be, substantial numbers of HFO-1234yf systems in operation in Germany.

CHINA: GLOBAL VERSUS NATIONAL FOCUS

In the absence of global agreement on the control of HFCs, China can, in all likelihood, nurture a robust *national* automotive manufacturing industry for the foreseeable future without regard to MAC refrigerant. The Chinese market is sufficiently large to allow for the development of parallel MAC system technologies, one based on extra-national requirements and demands that are satisfied by industry responses independent of the Chinese market and a second based solely on industry responses tailored specifically to China. As long as China maintains sufficient national assembly capacity and associated supply chains, the national market is more than large enough to operate in accordance with whatever national requirements Chinese regulators opt to impose (or not impose should the transition away from HFC-134a be viewed as deleterious). However, there are costs associated with either action (i.e., transitioning to lower GWP refrigerants) or inaction (i.e., not transitioning).

Should China elect to defer transition while extra-national markets are actively moving toward a low-GWP refrigerant future, the ability for Chinese automakers to develop

24 Patent issues related to HFO-1234yf are currently being investigated in the EU, where the EU is conducting antitrust proceedings against the patent holders (European Commission, 2011). Although it is not currently possible to comment on the final outcome of this investigation, the EU has issued a formal statement of objections notifying the patent holders of suspected violations of EU antitrust rules (European Commission, 2014). Patent holders have the opportunity to respond before a final decision is rendered.

25 Due to the fact that not all manufacturers sell vehicles in both regions and not all common manufacturers sell the same models in both regions, the differential in manufacturer and model counts should not be interpreted as an indication of more or less progress in either region. Instead, the counts are merely indicative of the fact that manufacturers are generally moving forward with HFO-1234yf systems.

26 German Environmental Aid Association (DUH). (2016, January). Vehicle Type Certification Statistics for Germany, private correspondence.

export markets will be substantially inhibited.[27] Chinese manufacturers will be required to maintain separate assembly and supply chains for vehicles produced for the domestic and export markets, in effect subjecting expansion- minded domestic manufacturers to the same dual system requirements that would face non-Chinese manufacturers wishing to do business in China. However, while the non-Chinese manufacturers have the advantage of leveraging joint venture relationships to access Chinese manufacturing plants and suppliers, the opposite may be much more difficult for Chinese manufacturers expanding into smaller, more diverse markets. This will put manufacturers interested in developing foreign markets at a competitive disadvantage relative to their purely domestic counterparts not burdened with satisfying differential extra-national requirements.[28] Although the major destinations of export vehicles from China are *currently* less-regulated third-world markets,[29] the increasing penetration of low-GWP MACs produced in other countries would nevertheless pose challenges to Chinese automobile manufacturers due to the possible higher cost in maintaining a separate service infrastructure. Moreover, the Chinese manufacturing market would be indefinitely constrained to such markets as HFC-134a systems will not be compliant with the largest global markets. As more areas adopt the requirements of the United States and the EU, the export market will continually shrink. Chinese automobile part manufacturers already export to a number of countries, including those with MAC regulations. Phasing out HFC-134a domestically would promote the economic efficiency of this industry by expanding the production of parts compatible with vehicles fitted with low-GWP MACs. Moreover, as HFC-134a is phased out outside of China, it may become necessary for China to establish domestic production plants to meet national demand. Due to the size of the Chinese market, there would be sufficient demand to make such production economically viable, but production constraints will need to be addressed should extra-national production shift to other refrigerants.

A decision to transition to low-GWP refrigerant would carry the inherent incremental costs of the alternative MAC system (as described in the discussion above on costs), but would also bolster the ability of the domestic industry to expand globally. Additionally, the size of the Chinese market would likely reduce incremental costs due to high-volume efficiencies of scale. While such costs would be borne equally by both globally minded manufacturers and manufacturers content to compete only domestically, neither would be at any additional disadvantage (vis-à-vis current market forces in play). Domestic manufacturers participating in joint ventures with foreign manufacturers might find transitioning to low-GWP refrigerants less disruptive than independent Chinese manufacturers, but it is expected that any advantage would be minor. MAC system components are generally manufactured by independent suppliers willing to satisfy purchase commitments from any automotive manufacturer. The systems themselves are relatively low tech as compared with evolving engine and associated management

27 Throughout this discussion it is assumed that there is a financial incentive for maintaining HFC-134a production if China elects not to transition to low-GWP refrigerant. Without such incentive, Chinese manufacturers wishing to develop extra-national markets will transition to low-GWP refrigerant regardless of national decision-making in this regard. Under such a scenario, any global competitiveness issues are inherently resolved. Thus, this paper assumes that there is a financial incentive to continue HFC-134a production.

28 Here again, it should be recognized that should there be drivers unrelated to air-conditioning that would require dual production regardless of Chinese decision-making related to low-GWP refrigerants, then any global competitiveness issues related to the refrigerant decision-making are inherently resolved because the dual production of air- conditioning systems could be accommodated within an existing dual production system. Thus, it is necessarily assumed that an external dual system driver does not exist.

29 In 2015, the 10 importers of vehicles from China were: Iran, Vietnam, Venezuela, Chile, Egypt, Colombia, Algeria, Peru, Saudi Arabia, and Bangladesh (http://www.cinn.cn/xw/caij/353428.shtml, accessed July 1, 2016).

technologies.[30] While evolutionary improvements to MAC systems are ongoing, most systems consist of relatively few and generally standardized parts (actuation controls, a compressor, a condenser, one or more evaporators, pressure regulating devices, hoses, and seals). For all but CO_2 systems (due to refrigeration cycle operating differences), the functionality of MAC system components is largely unaffected by the choice of refrigerant (although individual components may be redesigned to better accommodate the properties of any specific refrigerant). Even for CO_2, where the condenser is replaced by one or more gas coolers and the remaining components redesigned for the higher-pressure operating characteristics of a CO_2 system, the general function of the various system components remains generally unchanged. Most important, these components are available from independent automotive suppliers and generally do not require automotive manufacturer design and development activities beyond those already associated with HFC-134a systems (primarily related to system integration into overall vehicle design). Given this relative standardization and the competitive nature of the automotive supplier market, it is not expected that independent domestic manufacturers would be put at a competitive disadvantage due to any transition to low-GWP refrigerants.

From a vehicle service perspective, economic efficiency would also dictate a single universal MAC refrigerant. Regardless of national decision-making, China is almost certain to see some penetration of refrigerants other than HFC-134a in the national fleet – either through importation of extra-national vehicles or through the sales of joint venture manufacturers that simply find it advantageous to offer the same MAC technology across their entire market. For *some* global manufacturers selling in either the EU or US markets, a homogeneous technology slate will almost assuredly include refrigerant other than HFC-134a. Others may find the cost of low-GWP MAC systems sufficiently high to continue offering technology tailored to individual markets, but some low-GWP systems will almost certainly penetrate the Chinese fleet. This means that the China service industry will either have to invest in new equipment designed to service low-GWP systems or service such systems inefficiently (and ineffectively) using HFC-134a (and bypassing refrigerant-specific service fittings while simultaneously voiding any MAC system warranties). It is possible that HFO-1234yf systems will perform adequately with HFC-134a, but any penetration of CO_2 systems into the market will necessitate the procurement of CO_2 service technology. Thus, even in the absence of an affirmative decision to transition to low-GWP refrigerants, the Chinese service industry will still need to develop procedures to undertake repairs on low-GWP systems, including (ideally) the proper training of service personnel and the purchase of appropriate equipment. To the extent that such systems comprise only a fraction of the China fleet (as they might under a decision not to transition domestically), the cost-effectiveness of such training and equipment would be substantially compromised due to both a lower vehicle population over which to spread costs and the continuing requirement to simultaneously and indefinitely maintain high-GWP service equipment and expertise. Conversely, an affirmative decision to transition to low-GWP refrigerant allows the service industry to minimize equipment costs (by spreading those costs over a larger affected population and reducing the associated equipment acquisition payback period) and focus on developing efficient service

30 The terminology "low tech" is not intended to diminish either the great strides that have been made and will continue to be made with regard to either MAC system performance and design, or the componentry that facilitate that performance. It is simply intended to distinguish the complexity of the (quasi-) independent closed-cycle MAC system from that of the more complex propulsion system around which vehicles are constructed.

methodologies and expertise. Moreover, this expertise would be transferrable to any global market should such an opportunity arise. In short, developing and maintaining a focus on the latest MAC technology would pave the way for a substantially more robust domestic service industry.

Finally, the same efficiency that dictates a single MAC refrigerant from a global competitiveness standpoint carries over to the minimization of consumer costs (as consumers will bear the added cost of any inefficiencies in both the automotive production and service industries). While HFO-1234yf is currently more expensive than HFC-134a, that premium will decline as production volume increases.[31] The added costs of maintaining service equipment capable of addressing a multi-refrigerant fleet and, possibly, a multi-refrigerant production infrastructure will be passed on to consumers should China elect not to transition to low-GWP refrigerant. This cost would *only* be minimized under a streamlined single refrigerant response. The fact that global movement is toward a low-GWP future ensures that China *cannot* minimize consumer cost impacts by maintaining and extending the service life of MAC technology that is not consistent with the transition of the largest global automotive markets. In the end, both national efficiency and global competitiveness dictate movement away from the current MAC refrigerant.

HFC-134A PHASE-OUT TIMING

China phased out the use of CFC-12 as a MAC refrigerant over an eight-year period between 1994 and 2001 (Hu et al., 2010). The duration of that phase-out roughly matches the seven-year phase-in (2011 through 2017) of low-GWP refrigerant requirements in the EU, but the EU schedule also included a five-year lead time so that there was a 12-year period between adoption of the phase-out requirements and the complete prohibition of HFC-134a (European Commission, 2006). The lead time requirement of the EU phase-out is roughly consistent with typical four- to six-year industry redesign cycles for individual vehicle models, essentially providing manufacturers with the opportunity to incorporate MAC system redesign into their normal product planning. While a number of automakers already have experience transitioning away from HFC-134a (as indicated by the HFO-1234yf penetration statistics presented above), it would still be advantageous for China manufacturers (as well as for the Chinese service industry) if a lead time allowance was built into a decision to phase out HFC-134a in China. Even with such an allowance, it is still possible to constrain the length of the overall phase-out period to roughly seven or eight years, consistent with the previous CFC-12 phase-out. Assuming manufacturers redesign roughly 20% of their models in any given year (i.e., each model is redesigned roughly every five years), an eight-year HFC-134a phase-out schedule could be developed along the lines of the example presented in Table 5-1.

31 Note that the terminology “costs” as discussed here does not include offsetting savings associated with health and environmental effects that would be avoided due to a reduction on global warming effects. These health and environmental effects are “hidden” costs associated with the continued use of HFC-134a and “hidden” benefits that accrue through any transition to low-GWP refrigerant.

Table 5-1. Proposed phase-in schedule for low-GWP MAC refrigerant.

Adoption Year Plus (years)	0	1	2	3	4	5	6	7
Example Year	2017	2018	2019	2020	2021	2022	2023	2024
Minimum Low GWP Fraction of Models	0%	0%	0%	20%	40%	60%	80%	100%

Such a schedule should accommodate existing industry redesign plans as well as facilitate global competitiveness by allowing those manufacturers exploring extra-national markets to focus their refrigerant compliance efforts in China in a fashion consistent with any refrigerant requirements existing in the target extra-national markets. The schedule also facilitates service industry training and development, allowing repair facilities sufficient time to garner appropriate knowledge and procure equipment. Given the importance of the Chinese automotive market and the volume-scale opportunities created by such market size, we see no reason why Chinese manufacturers cannot establish a competitive global-scale presence. To accomplish such expansion, however, China will need to foster technological advances that are at least as aggressive as those currently underway in the major extra-national markets (e.g., the EU, the United States) currently served by global-scale players. Transitioning to low-GWP MAC refrigerant should be an integral element of such an expansion effort.

As noted above, China successfully accomplished the transition away from CFC-12 over a time frame similar to the schedule presented in Table 5-1. Other notable examples of automotive technology introduction over similar (or more aggressive) time frames include:

- The transition of the entire US light-duty vehicle fleet to so-called Tier 1 emission standards during the six-year period following adoption of the US Clean Air Act Amendments of 1990 (US Government, 1990).
- The implementation of more aggressive light-duty vehicle fuel economy standards in the US over a seven-year period following a 2009 release of a notice of intent to implement such standards (US EPA, 2010b).

Note that these transitions were more complex than envisioned in any movement away from HFC-134a, both in terms of scope and the initial state of technology development. Technology developers and suppliers generally indicate the possibility of more aggressive transitions. For example, Honeywell, one of the developers of HFO-1234yf, believes that a three- to six-year transition period is possible.

SUMMARY AND RECOMMENDATIONS

In response to the globally adopted 1987 Montreal Protocol, the refrigerant used in MAC systems was transitioned away from the stratospheric ozone-depleting chlorofluorocarbon CFC-12 to the zero ozone-depleting hydrofluorocarbon HFC-134a. China completed its transition from CFC-12 in 2001. The HFC-134a system remains the dominant MAC system in China and around the world.

While possessing zero ozone-depletion potential, HFC-134a is a potent GHG. As a result, it too has become the focus of transitional efforts. One gram of HFC-134a possesses the same global warming potential as 1,549 grams of CO_2. Although potent, it is worth noting that this potential is about 87% lower than that of CFC-12. Nevertheless, substantial additional reductions can be achieved through a transition away from HFC-134a. Potential alternative refrigerants include HFC-152a (with a warming potential of 167, 89.2% lower than that of HFC-134a), HFO-1234yf (with a warming potential of less than one, 99.9% lower than that of HFC-134a), and carbon dioxide (with a warming potential of one, 99.9% lower than that of HFC-134a).

The United States, the EU, and Japan have adopted requirements to phase out HFC-134a. The EU transition for light-duty vehicles is slated to be complete by 2017. HFC-134a is banned from US light-duty vehicles beginning in MY 2021. Japan will transition away from HFC-134a in light-duty vehicles by 2023. In a number of countries, MAC refrigerant is included in more general hydrofluorocarbon (HFC, which includes both HFC-134a and HFC-152a) policies that either require the phasedown of usage or impose significant tax burdens designed to promote the cost-effectiveness of alternative refrigerants. For example, Japan has adopted requirements for the phasedown of HFCs across all economic sectors, while various countries, including Australia and several EU members, impose global warming-based taxes on HFCs. Consensus is also building within the global community to address HFC emissions under the umbrella of an amended Montreal Protocol.

The Chinese automobile industry has expanded from 1.5 million units produced in 1995 to 22 million units in 2013. Almost all light-duty vehicles now produced in China (and globally) include air-conditioning systems. Emissions of HFC-134a from the MAC sector are estimated to have tripled in just the five-year period between 2005 and 2010 and will continue to increase as the Chinese economy expands.

The Chinese government has taken some preliminary steps toward multilateral action on HFCs. Chinese President Xi and US President Obama jointly agreed (in 2013) to “phase down production and consumption of HFCs.” This agreement provides high-level political support and an opening for mid-level regulatory efforts to explore how China could implement a national HFC phasedown. This analysis estimates the GHG reduction benefits associated with a transition away from the use of HFC-134a in China as a MAC refrigerant and qualitatively evaluates the effects of such a transition (or alternatively, the effects of a decision not to undertake such a transition) on the global competitiveness of the Chinese automobile industry.

A variety of previous Chinese studies and data sources were reviewed to develop an accurate analysis dataset. Developed data include China-specific data on light-duty vehicles sales and stock, the share of vehicles equipped with MAC systems, MAC system refrigerant charge sizes, typical refrigerant leakage rates (both during regular vehicle operations and during irregular events such as vehicle accidents that result in catastrophic system releases), and typical end-of-life emissions associated with vehicle scrappage and disposal.

Most of the data used in previous China studies are based on researchers' assumptions or modeled estimates rather than surveys and production reports. In many cases, "default" values developed by global researchers are used in lieu of China-specific data. While this study attempts to improve on these methods, it is also recommended that China researchers continue to develop local data sources though local surveys, and obtain and evaluate available production reports from local industry. Such data will be invaluable to validate analysis assumptions and minimize estimation uncertainty.

For this analysis, we generally combine data derived from China-specific studies with more robust data developed to support air-conditioning system analysis in the United States to develop a complete analysis dataset.

To evaluate the emission impacts associated with a transition away from HFC-134a, we also developed a set of corresponding MAC system data for three alternative refrigerants: HFC-152a, HFO-1234yf, and CO_2 (R-744). HFC-152a is a colorless gas under atmospheric conditions, with minimal toxicity and moderate flammability. Because of potential flammability concerns, a secondary loop MAC system is commonly proposed to isolate the HFC-152a refrigerant circuit from the vehicle passenger cabin. HFC-152 has a higher global warming potential (167) than either HFO-1234yf (<1) or CO_2 (1). HFO-1234yf is designated as an A2 refrigerant, indicating unidentified toxicity under low or moderate concentrations and mild flammability. Daimler cited potential flammability and toxicity concerns as a rationale for not producing HFO-1234yf systems in Europe, supported by the German government[32] and local German non-governmental organizations (NGOs). However, extensive lab testing conducted for projects administered by SAE International (Lewandowski, 2013) demonstrated that the risk associated with the use of HFO-1234yf was well below generally accepted levels. HFO-1234yf is nearly a drop-in substitute for HFC-134a. CO_2, designated as R-744 when used as a refrigerant, is a colorless and odorless gas under atmospheric conditions. It is designated as an A1 refrigerant, indicating no flammability and minimal toxicity. CO_2 MAC systems operate at pressures five to 10 times higher than HFC-134a systems, and therefore demand more durable system components. German automaker Daimler recently announced it would commercialize a CO_2 MAC system in their luxury Mercedes E and S Class vehicles starting in MY 2016.

Based on the similarity of the thermophysical properties of HFO-1234yf and HFC-134a, this analysis assumes that MAC system charge sizes will be comparable. HFC-152a and CO_2 systems are assumed to be 45% and 30% smaller, respectively, than comparable HFC-134a systems. On the basis of their respective thermophysical properties, this analysis assumes a leakage rate for HFO-1234yf that is 8% higher than that of HFC-134a. Through a similar thermophysical analysis, the leakage rate of HFC-152a is estimated to be 43% lower than an equivalent HFC-134a system. Leakage rates for CO_2 systems are not easily estimated given differential system performance parameters and a lack of currently operating systems, but system operating pressures hint at higher emissions

32 The European Commission has referred the German government to the European Court of Justice for type-approving Daimler vehicles that did not use low-GWP refrigerant. See http://europa.eu/rapid/press-release_IP-15-6290_en.htm.

potential. For this analysis, it is assumed that leakage rates for CO_2 systems will be 20% higher (per unit charge) than the corresponding rates for an HFC-134a system.

Multiple scenarios representing various possible policy pathways for the transition to alternative refrigerants were evaluated. MY 2018 was considered as the earliest year that is realistic for any policy to be implemented given the current date and regulatory circumstances. Modeling of the various scenarios extends through MY 2050. In the BAU scenario, it is assumed that China continues to allow the use of HFC-134a in MAC systems without any further regulation. The policy drivers for alternative future scenarios range from the adoption of regulations similar to those issued in the EU or the United States to the proposed timelines put forward in recently proposed amendments to regulate HFCs under the Montreal Protocol. The implementation timeline for these scenarios is represented in Figure 6-1.

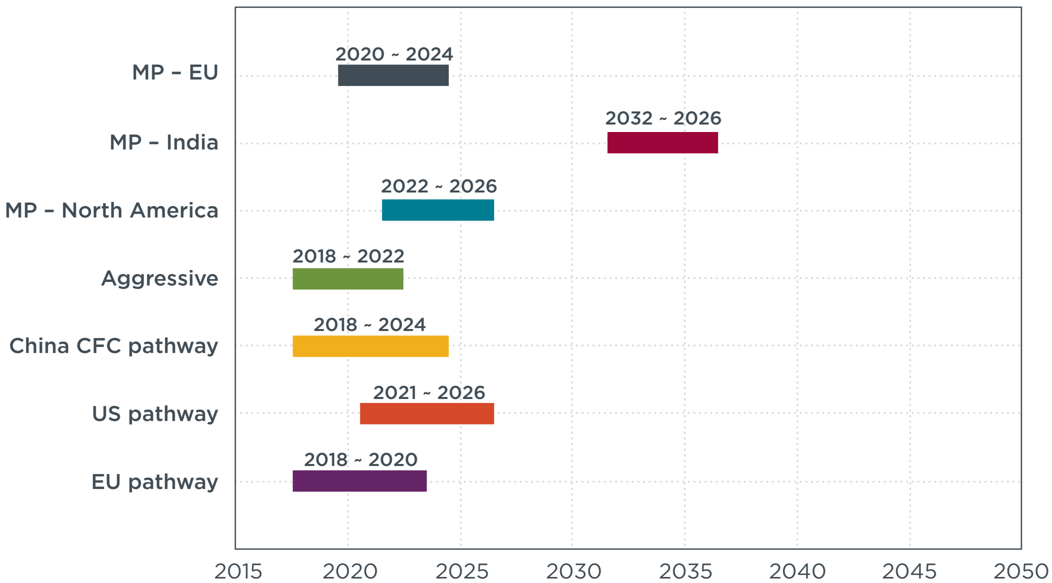

Figure 6-1. Overview of evaluated HFC-134a transitional policy scenarios.

The EU pathway scenario assumes that China begins a six-year transition from HFC-134a immediately after the EU completes its transition to low-GWP MAC systems in 2017. The US pathway scenario assumes that China begins a six-year transition from HFC-134a immediately after the United States completes its transition away from HFC-134a MAC systems in 2021. Under the China CFC pathway scenario, it is assumed that China implements a seven-year transition beginning in 2018, analogous to its earlier transition away from CFC-12. The Aggressive scenario also begins transitioning in 2018, but accomplishes that transition in a shorter five-year time frame intended to mimic a typical five-year vehicle redesign schedule. The MP scenarios are based on the transitional schedules of recent Montreal Protocol proposals. MP-North America and MP-India are based on the proposals from North America and India, respectively, while MP-EU is consistent with the proposals from the EU and the Island States. In all cases, it is assumed that the MAC sector will be among the first targets and that MAC HFC-134a will be phased out over no less than a five-year period to reflect the standard design cycle for new vehicles.

Figure 6-2 shows the refrigerant emissions estimates under low emission analysis assumptions. Under a baseline HFC-134a future, refrigerant CO_2e emissions are expected to reach 80 Tg per year by 2050, an approximate fourfold increase from 2015. Alternative refrigerants can significantly reduce GHG emissions, but the timing of the transition plays a critical role in the cumulative emission reductions achieved by 2050. The most aggressive transitional policies are able to completely phase out HFC-134a by 2035 or 2040.

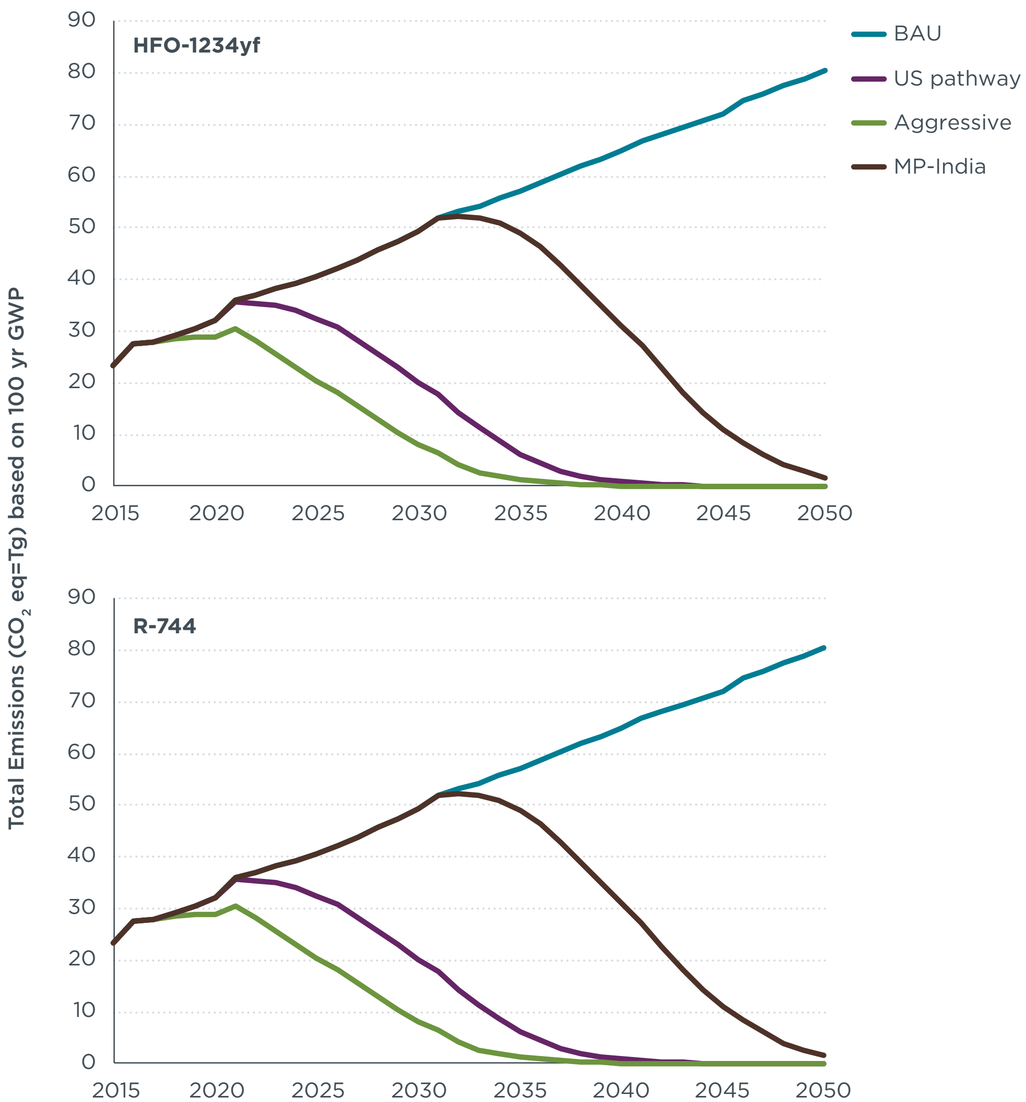

Figure 6-2. CO_2e emissions of HFO-1234yf and R-744 by policy scenario.

Given the relative uncertainty in the emission rates associated with alternative MAC systems, a sensitivity analysis was conducted that doubled the emission rates for the HFO-1234yf, HFC-152a, and CO_2 MAC systems (see Annex A). The resulting change in the cumulative emission reductions for both HFO-1234yf and CO_2 was less than 0.05% (both refrigerants reduce unit-mass CO_2e emissions by over 99.9%, so changes in overall CO_2e emission reductions to even large – but still realistic – changes in emissions of either refrigerant are exceedingly minor). Because HFC-152a has a higher global warming potential, emission reductions are somewhat more sensitive to emission rates, but the difference is still less than 5%. Thus, while there continues to be uncertainty with regard to the precise level of refrigerant emissions, there is only minor uncertainty in the significance of the emission reductions associated with a transition away from HFC-134a.

As with any alternative technology, there will be costs associated with low-GWP refrigerant MAC systems. Such costs accrue not only from the refrigerant itself, but also from modifications to the MAC system to accommodate the different chemical and physical characteristics of the refrigerants. Figure 6-4 presents associated cost per metric tonne of CO_2e emission reduction. While HFC-152a is the most cost-effective alternative, that cost-effectiveness is based on lesser emission reductions than either HFO-1234yf or CO_2. Although HFC-152a has a substantially lower warming potential than HFC-134a, it is still substantially higher than that of HFO-1234yf and CO_2, so that future efforts to further reduce warming emissions might ultimately target even HFC-152a for reduction. There is, therefore, the continuing risk of future investment beyond that indicated here.

The cost-effectiveness for HFO-1234yf declines from about 484 yuan per tonne (¥/mt) to about 312 ¥/mt by 2050, while that for CO_2 declines from about ¥832 to about 436 ¥/mt over the same period. For HFC-152a the cost-effectiveness declines from ¥241/mt to ¥179/mt by 2050. To put such costs in perspective, it is convenient to express them in terms of euros per grams reduced per kilometer (€/g/km), as such a metric can be more easily compared with alternative CO_2 reduction technology being implemented on light-duty vehicles in Europe. The equivalent cost for HFO-1234yf declines from about 16 €/g/km to about 11 €/g/km by 2050, while that for CO_2 declines from about 28 to about 15 €/g/km over the same period. HFC-152a has the lowest equivalent cost, declining from €8/g/km to €6/g/km by 2050. The costs for HFO-1234yf, HFC-152a, and CO_2 are cheaper than engine technologies being widely deployed for CO_2 reduction both globally and in China. As shown in Figure 6-4, the technology package expected to be employed on a widespread basis for fuel economy compliance (turbocharged and downsized gasoline direct injection engine with cooled EGR and an advanced transmission), is estimated to cost about ¥280 gCO_2e/km in 2025, as compared with costs ranging from ¥46 to ¥123 gCO_2e/km for refrigerant replacement.

All three alternatives become even more attractive when the social costs associated with the additional CO_2 emissions that would occur if a transition was not made away from HFC-134a are considered. Figure 6-5 shows the avoided SCC through 2050 under the seven scenarios modeled in this report, equal to up to more than 1,000 billion yuan. Differences in the avoided SCC under each of the scenarios reinforces the importance that the overall timing of the transition on the benefits.

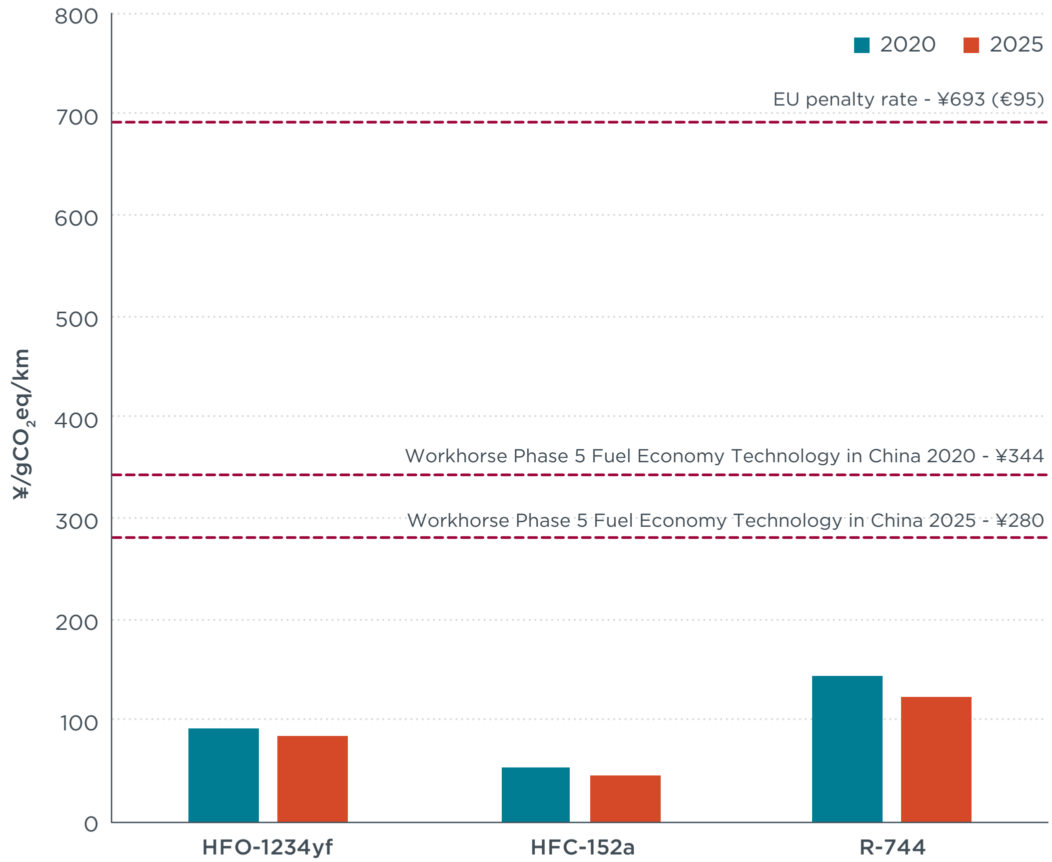

Figure 6-4. Cost-effectiveness of alternative MAC systems in the context of major CO_2 reduction technologies.

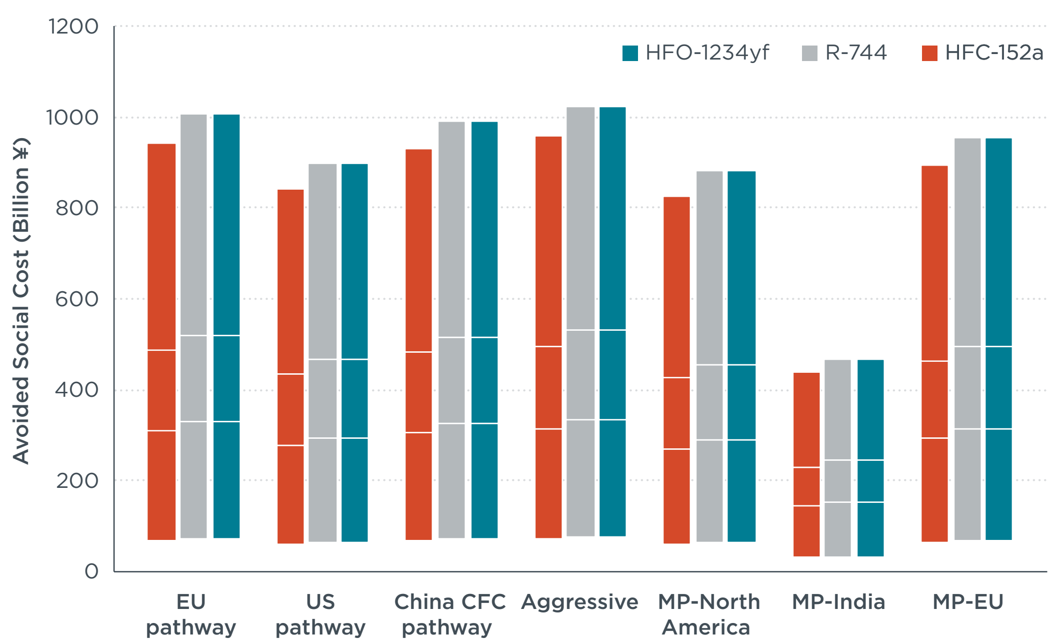

Figure 6-5. Avoided SCC by transitioning to low-GWP MACs in the Chinese passenger vehicle fleet under low emission assumptions through 2050.

Ultimately, a decision to (or not to) transition away from HFC-134a MAC systems will impact the global competitiveness of the Chinese automotive industry. In many respects, China cannot be isolated from the effects of such a transition regardless of national decision-making simply because transitions are already underway in the EU, Japan, and the United States. As shown in Figure 6-6, the combined US and EU markets account for a little over a third (36.2%) of current light-duty sales, while China itself accounts for another 24%. Thus, while sales in other areas of the globe are significant and nonetheless important from an economic standpoint, China must, to be a globally competitive player in the automotive manufacturing market, continue to develop and maintain a presence in the US and EU markets. The importance of such a presence is amplified when one considers than many of the other regional markets look to either the United States or the EU for leadership when developing their own regional standards. The footprint of US and EU regulatory programs expands well beyond their respective geopolitical borders.

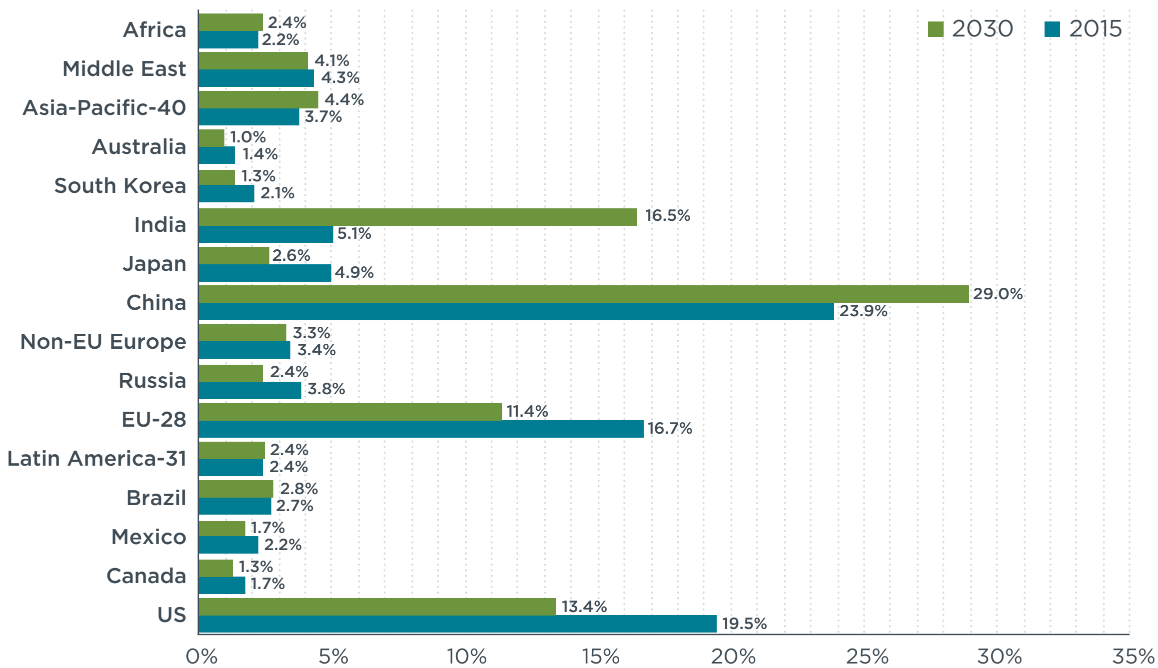

Figure 6-6. Global light-duty vehicle sales shares.

In the absence of confounding issues, the globally optimum automotive industry response to efforts to reduce the GWP of MAC systems would be to simply select the most cost-effective low-GWP refrigerant and transition the industry en masse toward universal replacement. MAC systems are essentially a commodity for manufacturers. Generally, vehicles either have a MAC system or they do not (and today, almost all vehicles are MAC-equipped). While there are functional aspects of climate control systems, such as multi-zonal controls that are used as distinguishing marketing features, the basic functionality of the underlying refrigeration system is essentially common across manufacturers. Thus, from a standardization perspective, the use of a single common refrigerant minimizes not only equipment procurement and assembly line requirements, but also refrigerant production and aftermarket service and training requirements. Of course, there will be a need to retain an HFC-134a infrastructure throughout the phase-out period of existing systems, but the industry would optimize that phase-out by selecting a single replacement.

Unfortunately, there are confounding issues. Different manufacturers have different opinions on the optimum replacement refrigerant. Issues with regard to refrigerant safety and decomposition products are not fully resolved. Potential cost premiums associated with HFO-1234yf patent claims are of concern. And, the differential cost of refrigerant-specific technology, both at installation and during in-use service life, is not known with certainty. Thus, manufacturers have not reached consensus. While beyond the scope of this study, such issues are ripe for future analysis. The overwhelming majority of automotive manufacturers appear to be committed to an HFO-1234yf future, but there are some that continue to pursue CO_2 systems as a preferred solution. Interest in HFC-152a waned in recent years due to a variety of issues, including safety concerns regarding its flammability, relatively high-GWP values that might become a concern under future regulations (UNEP RTOC, 2012), more burdensome redesign requirements associated with the need to fit a larger secondary loop system into an already crowded engine compartment (S. O. Andersen, Institute for Governance & Sustainable Development, personal communication, April 2016), and the inherent “inertia” of an automobile industry that has accepted HFO-1234yf on the basis of extensive R&D aimed at commercializing this drop-in refrigerant (Z. Tao, California Air Resources Board, personal communication, April 2016).

In the absence of global agreement on the control of HFCs, China can, in all likelihood, nurture a robust *national* automotive manufacturing industry for the foreseeable future without regard to MAC refrigerant. The Chinese market is sufficiently large enough to allow for the development of parallel MAC system technologies, one based on extra-national requirements and demands that are satisfied by industry responses independent of the Chinese market and a second based solely on industry responses tailored specifically to China. As long as China maintains sufficient national assembly capacity and associated supply chains, the national market is more than large enough to operate in accordance with whatever national requirements Chinese regulators opt to impose (or not impose should the transition away from HFC-134a be viewed as deleterious). However, there are costs associated with either action (i.e., transitioning to lower-GWP refrigerants) or inaction (i.e., not transitioning).

Should China elect to defer transition while extra-national markets are actively moving toward a low-GWP refrigerant future, the ability for Chinese automakers to develop export markets will be substantially inhibited. Chinese manufacturers will be required to maintain separate assembly and supply chains for vehicles produced for the domestic and export markets, in effect subjecting expansion- minded domestic manufacturers to the same dual system requirements that would face non-Chinese manufacturers wishing to do business in China. However, while the non-Chinese manufacturers have the advantage of leveraging joint venture relationships to access Chinese manufacturing plants and suppliers, the opposite may be much more difficult for Chinese manufacturers expanding into smaller, more diverse markets. This will put manufacturers interested in developing foreign markets at a competitive disadvantage relative to their purely domestic counterparts not burdened with satisfying differential extra-national requirements.

A decision to transition to low-GWP refrigerant would carry the inherent incremental costs of the alternative MAC system, and would also bolster the ability of the domestic industry to expand globally. Additionally, the size of the Chinese market would likely reduce incremental costs due to high-volume efficiencies of scale. While such costs would be borne equally by both globally minded manufacturers and manufacturers content to compete only domestically, neither would be at any additional disadvantage (vis-à-vis current market forces in play). Domestic manufacturers participating in joint ventures with foreign manufacturers might find transitioning to low-GWP refrigerants less disruptive than independent Chinese manufacturers, but it is expected that any advantage would be minor. MAC system components are generally automotive commodities manufactured by independent suppliers willing to satisfy purchase commitments from any automotive manufacturer.

From a vehicle service perspective, economic efficiency would also dictate a single universal MAC refrigerant. Regardless of national decision-making, China is almost certain to see some penetration of refrigerants other than HFC-134a in the national fleet – either through importation of extra-national vehicles or through the sales of joint venture manufacturers who simply find it advantageous to offer the same MAC technology across their entire market. For *some* global manufacturers selling in either the EU or US markets, a homogeneous technology slate will almost assuredly include refrigerant other than HFC-134a. Others may find the cost of low-GWP MAC systems sufficiently high to continue offering technology tailored to individual markets, but some low-GWP systems will almost certainly penetrate the Chinese fleet. This means that the China service industry will either have to invest in new equipment designed to service low-GWP systems or service such systems inefficiently (and ineffectively) using HFC-134a (and bypassing refrigerant-specific service fittings while simultaneously voiding any MAC system warranties). Thus, even in the absence of an affirmative decision to transition to low-GWP refrigerants, the Chinese service industry will still need to develop procedures to undertake repairs on low-GWP systems, including (ideally) the proper training of service personnel and the purchase of appropriate equipment. To the extent that such systems comprise only a fraction of the China fleet (as they might under a decision not to transition domestically), the cost-effectiveness of such training and equipment would be substantially higher due to both a lower vehicle population over which to spread costs and the continuing requirement to simultaneously and indefinitely maintain high-GWP service equipment and expertise.

Finally, the same efficiency that dictates a single MAC refrigerant from a global competitiveness standpoint carries over to the minimization of consumer costs (as consumers will bear the added cost of any inefficiencies in both the automotive production and service industries). This cost can *only* be minimized under a streamlined single-refrigerant response. The fact that global movement is toward a low-GWP future ensures that China *cannot* minimize consumer cost impacts by maintaining and extending the service life of MAC technology that is not consistent with the transition of the largest global automotive markets. Both national efficiency and global competitiveness dictate movement away from HFC-134a.

China phased out the use of CFC-12 as a MAC refrigerant over an eight-year period between 1994 and 2001. The duration of that phase-out roughly matches the seven-year phase-in (2011 through 2017) of low-GWP refrigerant requirements in the EU, but the EU schedule also included a five-year lead time so that there was a 12-year period between adoption of the phase-out requirements and the complete prohibition of HFC-134a (European Commission, 2006). The lead time requirement of the EU phase-out is roughly consistent with typical four- to six-year industry redesign cycles for individual vehicle models, essentially providing manufacturers with the opportunity to incorporate

MAC system redesign into their normal product planning. With such an allowance, it is still possible to constrain the length of the overall phase-out period to roughly seven or eight years, consistent with the previous CFC-12 phase-out. An implementation schedule such as that shown in Table 6-1 would accomplish a complete phase-out of HFC-134a in Chinese MAC systems by 2024.

Table 6-1. Proposed phase-in schedule for low-GWP MAC refrigerant.

Adoption Year Plus (years)	0	1	2	3	4	5	6	7
Example Year	2017	2018	2019	2020	2021	2022	2023	2024
Minimum Low-GWP Fraction of Models	0%	0%	0%	20%	40%	60%	80%	100%

Such a schedule should accommodate existing industry redesign plans and facilitate global competitiveness by allowing those manufacturers exploring extra-national markets to focus their refrigerant compliance efforts in China in a fashion consistent with any refrigerant requirements existing in the target extra-national markets. The schedule also facilitates service industry training and development, allowing repair facilities sufficient time to garner appropriate knowledge and procure equipment. Given the importance of the Chinese automotive market and the volume-scale opportunities created by such market size, we see no reason why Chinese manufacturers cannot establish a competitive global-scale presence. To accomplish such expansion, however, China will need to foster technological advances that are at least as aggressive as those currently underway in the major extra-national markets (e.g., the EU, the United States) currently served by global-scale players. Transitioning to low-GWP MAC refrigerant should be an integral element of such an expansion effort.

REFERENCES

Andersen, S. O., & Sherman, N.J. (Institute for Governance & Sustainable Development). (2015). [HFO-1234yf Automobile Penetration]. Unpublished raw data.

California Air Resources Board (CARB). (2011). *LEV III greenhouse gas non-test cycle provisions – technical support document.* Retrieved from http://www.arb.ca.gov/regact/2012/leviiighg2012/levappr.pdf.

Bundesanstalt für Materialforschung und -prüfung (BAM). (2010). *Ignition behavior of HFO-1234yf. Final Test Report, 22* (BAM Reference No. II-2318/2009 I). Retrieved from https://www.umweltbundesamt.de/sites/default/files/medien/419/dokumente/test_report_hfo1234yf_2010_06.pdf.

Chen, J., Shi, J., & Zhao, Y. (2008). International latest development of the automotive air-conditioning system. *Journal of Chemical Industry and Engineering, 59*(S2): 9-13 (in Chinese).

China Automobile Technology and Research Center (CATARC). (2007). 报废汽车回收拆解经营规范专题研究 （汽车空调CFC-12制冷剂回收）[Research report on the management and administration of vehicle scrappage (Recycling of CFC-12 from MAC)] (prepared for Foreign Economic Cooperation Office of the Ministry of Environmental Protection China and Department of Market System Development Ministry of Commerce of the People's Republic of China). November 2007.

China Automobile Technology and Research Center (CATARC) & China Association of Automobile Manufacturers (CAAM), (2014). 中国汽车工业年鉴 [China Automotive Industry Yearbook] (2014 Edition). Beijing, China: China Machine Press.

Clodic, D., Barrault, S., & Saba, S. (2010). *Global inventories of the worldwide fleets of refrigerating and air-conditioning equipment in order to determine refrigerant emissions – The 1990 to 2006 updating* (Research report). Retrieved from Mines ParisTech, Center for Energy Efficiency of Systems website: http://www.ces.mines-paristech.fr/Donnees/data06/653-Short-report-complete.pdf

European Commission. (2006, May 17). Directive 2006/40/EC of the European Parliament and of the Council of 17 May 2006 relating to emissions from air-conditioning systems in motor vehicles and amending Council Directive 70/156/EEC. *Official Journal of the European Union*, *L161,* 14.6.2006, Page 12.

European Commission. (2011, December 16). *Antitrust: Commission opens proceedings against two manufacturers of refrigerants used in car air conditioning* (Press Release). Retrieved from http://europa.eu/rapid/press-release_IP-11-1560_en.htm?locale=en.

European Commission. (2014, October 21). *Antitrust: Commission sends Statement of Objections to Honeywell and DuPont regarding cooperation on new refrigerant used in car air conditioning systems* (Press Release). Retrieved from http://europa.eu/rapid/press-release_IP-14-1186_en.htm.

Eustice, H. (2008, June). *General Motors Corporation Assessment of Alternative Refrigerant for EU Regulations*. Presented at SAE Alternative Refrigerant and System Efficiency Symposium, Scottsdale, AZ. Retrieved from http://www.sae.org/events/aars/presentations/2008/harryeustice.pdf.

Façanha, C., Blumberg, K., & Miller, J. (2012). *Global transportation energy and climate roadmap: The impact of transportation policies and their potential to reduce oil consumption and greenhouse gas emissions*. Retrieved from http://www.theicct.org/sites/default/files/publications/ICCT%20Roadmap%20Energy%20Report.pdf.

Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., & Van Dorland, R. (2007). *Changes in Atmospheric Constituents and in Radiative Forcing.* In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, & H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Gloel, J., Colbourne, D., Oppelt, D., Hasse, V., Hu, J., & Langebach, R. (2014). *Mitigation of GHG emissions through the use of natural refrigerants for mobile air conditioning in cars in China*. Paper presented at 11th IIR Gustav Lorentzen Conference on Natural Refrigerants, Hangzhou, China.

He, H., & Tu, J. (2012). *The New Passenger Car Fleet in China, 2010 Technology Assessment and International Comparisons*. Retrieved from http://www.theicct.org/sites/default/files/publications/ICCT_New_Passenger_Car_Fleet_China_2010.pdf.

Henne, S., Shallcross, D.E., Reimann, S., Xiao, P., Brunner, D., O'Doherty, S., & Buchmann, B. (2012). Future emissions and atmospheric fate of HFC-1234yf from mobile air conditioners in Europe. *Environ. Sci. Technol. 46* (3): 1650-1658.

Hill, W. (2003, February). *HFC-152a as the alternative refrigerant.* Presented at the MAC Summit 2003, Brussels, Belgium. Retrieved from http://ec.europa.eu/environment/archives/mac2003/pdf/hill.pdf

Hu, J. (2013). *HFC management in China: challenges and opportunities*. Presented at ClimateWorks Non-CO_2 Summit, Dubrovnik, Croatia.

Hu, J. & Li, C. (2003). Growing markets of MAC with HFC-134a in China. Peking University and China Association of Automobile Manufacturers, Beijing.

Hu, J., Wan, D., Li, C., Zhang, J., & Yi, X. (2009). 中国汽车空调行业HFC-134a需求和排放预测 [Forecast of consumption and emission of HFC-134a used in the mobile air-conditioner sector in China]. *Adv. Clim. Change Res. 5*(1), 1-6.

Hu, J., Wan, D., Li, C., Zhang, J., & Yi, X. (2010). Forecast of consumption and emission of HFC-134a used in the mobile air-conditioner sector in China. *Adv. Clim. Change Res. 1*, 20-26.

ICF International. (2011). *Development of the GHG refrigerant and air conditioning model* (Prepared for U.K. Department of Energy and Climate Change). Retrieved from https://www.gov.uk/government/uploads/system/uploads/attachment_data /file/48250/3844-greenhouse-gas-inventory-improvement-project-deve.PDF.

ICF International. (2012). *Comparative lifecycle cost assessment of alternative mobile air conditioning systems in the light-duty vehicle sector* (Prepared for International Council on Clean Transportation). May 2, 2012.

International Council on Clean Transportation (ICCT). (2015). *Global Transportation Roadmap Model* [July 27, 2015 Version]. Model and documentation available at http://www.theicct.org/global-transportation-roadmap-model.

IPCC. (2006). *Good practice guidance and uncertainty management in national greenhouse gas inventories.* Retrieved from IPCC website: http://www.ipcc-nggip.iges.or.jp/public/gp/english/.

JAMA. (2010). *Regarding refrigerants used in car air conditioning.* Retrieved from www.meti.go.Jp/committee/materials2/downloadfiles/g100729b03j.pdf.

Japan Ministry of Economy, Trade, and Industry (METI). (2013). *Cabinet Decision on the Bill for the Act for Partial Revision of the Act on Ensuring the Implementation of Recovery and Destruction of Fluorocarbons Concerning Designated Products.* Retrieved from http://www.meti.go.jp/english/press/2013/0419_01.html

Koban, M. (2009, April). *HFO-1234yf low GWP refrigerant LCCP analysis*. Presentation at SAE 2009 World Congress, Detroit, MI.

Kodjak, D. (2015). *Policies to Reduce Fuel Consumption, Air Pollution, and Carbon Emissions from Vehicles in G20 Nations.* Retrieved from ICCT website: http://www.theicct.org/sites/default/files/publications/ICCT_G20-briefing-paper_Jun2015_updated.pdf.

Leck, T. (2009, June). *Evaluation of HFO-1234yf as a potential replacement for R-134a in refrigeration applications*. Presentation at 3rd IIR Conference on Thermophysical Properties and Transfer Processes of Refrigerants, Boulder, CO.

Lewandowski, T. (2013). *Additional risk assessment of alternative refrigerant R-1234yf* (Prepared for SAE International). Retrieved from SAE International website: http://www.sae.org/standardsdev/tsb/cooperative/crp_1234-4_report.pdf

Mobile Air Conditioning Society (MACS). (2008). From Montreal to Kyoto: Two decades of change in the mobile A/C industry. Lansdale, PA. Mobile Air Conditioning Society.

Malvicino, C. (2008, June). *The 4 Fiat Pandas Experiment and other considerations on refrigerants.* Presented at the SAE Alternative Refrigerant Systems Symposium, Phoenix, Arizona.

MEPC. (2003). Ministry of Environmental Protection of China, 2003. 中国制冷维修行业CFCs的淘汰战略 [Strategy for CFCs phase-out in refrigeration servicing sector in China].

Meszler, D., Tu, J., He, H., & Bandivadekar, A. (2015). Development of 2020-2025 fuel efficiency technology cost curves for Chinese passenger cars. Draft Report.

Milnes, J. (2013). *US car giant GM publicly backs HFO-1234y*. Retrieved from Refrigeration and Air Conditioning Magazine: http://www.racplus.com/news/us-car-giant-gmpublicly-backs-1234yf/8640815.article?blocktitle=Latest-news&contentID=2332.

Minjares, R. (2011). *Refrigerants for light-duty passenger vehicle air conditioning systems* (Working paper No. 2011-3). Retrieved from the ICCT website: http://www.theicct.org/sites/default/files/publications/ICCT_refrigerant_workingpaper_2011_0.pdf.

Myhre, G., Shindell, D., Breon, F.-M., Collins, Fuglestvedt, W., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., & Zhang, H. (2013): *Anthropogenic and Natural Radiative Forcing.* In: Climate Change, 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Oko-Recherche, Oko-Institute, HEAT International, Danish Technological Institute, Re-phridge, Karlsruhe University of Applied Sciences, Estonia Environmental Research Centre, Ammonia Partnership. (2011). *Preparatory study for a review of Regulation (EC) No 842/2006 on certain fluorinated greenhouse gases* (Prepared for the European Commission). Retrieved from the European Commission website: http://ec.europa.eu/clima/policies/f-gas/docs/2011_study_en.pdf.

Papasavva, S. & Andersen, S. O. (2011). Green-MAC-LCCP: Life-cycle climate performance metric for mobile air conditioning technology choice. *Env. Progress & Sustainable Energy, 30* (2): 234-247.

Peking University (PKU), College of Environmental Science and Engineering. (2013). 控制管理氢氟碳化物(HFCs)影响研究 – 机遇与挑战 [*The control and management of HFCs – opportunities and challenges*]. Retrieved from Energy Foundation China website: http://www.efchina.org/Attachments/Report/reports-20130122-zh/reports-20130122-zh.

Protection of Stratospheric Ozone: Change of Listing Status for Certain Substitutes Under the Significant New Alternatives Policy Program, 80 Fed. Reg. § 138 (final rule Jul. 20, 2015) (to be codified at 40 C.F.R. Part 82).

Ramaswamy, V., Boucher, O., Haigh, J., Hauglustaine, D., Haywood, J., Myhre, G., Nakajima, T., Shi, G.Y., & Solomon, S. (2001): *Radiative Forcing of Climate Chang. In: Climate Change 2001: The Scientific Basis*. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change [Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, X. Dai, K. Maskell, & C.A. Johnson (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 881pp.

SAE International, 2009. *Industrial evaluation of the low global warming potential refrigerant HFO-1234yf* (Presentation). Retrieved from SAE International website: https://www.sae.org/standardsdev/tsb/cooperative/crp1234-3.pdf

SAE International 2012. *Mobile air conditioning system refrigerant emission charts for R-134a and R-1234yf*. Available at http://standards.sae.org/j2727_201202/

Shandong Circular Economy Promotion Association (SCEPA) & Tsinghua University (THU). (2013). 低速电动车市场状况、车用电池和报废车辆空调制冷剂回收状况调研报告 [*Research on the recycling of batteries from low-speed electrical motorcycle and refrigerants from MAC*]. August 23, 2013

Shao, Z. & Wagner, D.V. (2015). *Costs and benefits of motor vehicle emission control programs in China.* Retrieved from http://www.theicct.org/costs-and-benefits-motor-vehicle-emission-control-programs-china.

Si, B. & Zhang, J. (2012). 浅谈汽车空调维修行业现状-假冒伪劣制冷剂的应对措施 [Discussion on the current status of mobile air conditioning servicing sector – measures to address counterfeited refrigerants]. 汽车维修与保养 [Automobile Repair and Maintenance] 5:548-549.

Su, S., Fang, X., Li, L., Wu, J., Zhang, J., Xu, W., & Hu, J. (2015). HFC-134a emission from mobile air conditioning in China from 1995 to 2030. *Atmospheric Environment 102*, 122-129.

Thompson, M. (2013). *Climate Change Regulation and the Next Generation of Refrigerants.* Retrieved from http://www.trane.com/commercial/uploads/pdf/cso/138/Refrigerants.pdf.

US Government Publishing Office. (1990). 42 U.S.C., Chapter 85, Subchapter II, "Emission Standards for Moving Sources," Part A, Section 7521, *Emission Standards for New Motor Vehicles or New Motor Vehicle Engines*, as adopted in 1990. Available at https://www.gpo.gov/fdsys/pkg/USCODE-2013-title42/html/USCODE-2013-title42-chap85-subchapII-partA-sec7521.htm.

United Nations Environment Programme (UNEP), Ozone Secretariat. (1987). *The Montreal Protocol on Substances that Deplete the Ozone Layer.* Accessed Aug 11 2016 at http://ozone.unep.org/en/treaties-and-decisions/montreal-protocol-substances-deplete-ozone-layer.

United Nations Environment Programme (UNEP), & Refrigeration, Air Conditioning and Heat Pump Technical Options Committee (RTOC) (2010). *2010 Report of the Refrigeration, Air Conditioning and Heat Pump Technical Options Committee (RTOC)*. Retrieved from http://acdb-ext.gsfc.nasa.gov/Documents/O3_Assessments/Docs/WMO_2010/2010assessment/RTOC_2010_Assessment_Report.pdf.

United Nations Environment Programme (UNEP), UNEP News Centre. (2015). *Montreal Protocol Parties Devise Way Forward to Protect Climate Ahead of Paris COP21*. Accessed Aug 11 2016 at http://www.unep.org/newscentre/Default.aspx?DocumentID=26854&ArticleID=35543.

United States Environmental Protection Agency (US EPA). (2010a). *Final rulemaking to establish light-duty vehicle greenhouse gas emission standards and corporate average fuel economy standards – regulatory impact analysis (EPA-420-R-10-009)*. Retrieved from US EPA website at: https://www3.epa.gov/otaq/climate/regulations/420r10009.pdf.

United States Environmental Protection Agency (US EPA). (2010b). Light-duty vehicle greenhouse gas emission standards and corporate average fuel economy standards; Final rule. *Federal Register, 75*(88), 25324-25728.

United States Environmental Protection Agency (US EPA). (2010c). *Transitioning to low-GWP alternatives in MVACs.* Accessed March 30 2016 at: https://www.epa.gov/nscep.

United States Environmental Protection Agency (US EPA) & National Highway Traffic Safety Administration (US NHSTA). (2012). *Joint technical support document: final rulemaking for 2017-2025 light-duty vehicle greenhouse gas emission standards and corporate average fuel economy standards (EPA-420-R-12-901).* Retrieved from: https://www3.epa.gov/otaq/climate/documents/420r12901.pdf.

United States Environmental Protection Agency (US EPA), Office of Atmospheric Programs. (2013). *Global mitigation of non-CO_2 greenhouse gases: 2010-2030 (EPA-430-R-13-011).* Retrieved from: https://www3.epa.gov/climatechange/Downloads/EPAactivities/MAC_Report_2013.pdf.

United States Environmental Protection Agency (US EPA). (2016). Significant New Alternatives Policy (SNAP). *Acceptable Substitutes in MVAC: Passenger Air Conditioning in Light-Duty, Medium-Duty, Heavy-Duty and Off-Road Vehicles.* Accessed March 20, 2016 at: https://www.epa.gov/snap/acceptable-substitutes-mvac-passenger-air-conditioning-light-duty-medium-duty-heavy-duty-and.

United States Government, Interagency Working Group on Social Cost of Carbon. (2015). *Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866*. Retrieved from https://www.whitehouse.gov/sites/default/files/omb/inforeg/social_cost_of_carbon_for_ria_2013_update.pdf.

Vincent, R., Cleary, K., Ayala, A., & Corey, R. (2004a). *Emissions of HFC-134a from light-duty vehicles in California.* Presented at the 6th SAE Automotive Alternate Refrigerant Systems Symposium, Scottsdale, AZ. Retrieved from http://www.sae.org/events/aars/presentations/2004-vincent.pdf.

Vincent, R., Cleary, K., Ayala, A., & Corey, R. (2004b). *Emissions of HFC-134a from Light-Duty Vehicles in California* (SAE Technical Paper 2004-01-2256).

Xu, Y., Zaelke, D., Velders, G.J.M., & Ramanathan, V. (2013). The role of HFCs in mitigating 21st century climate change. *Atmos. Chem.Phys.,13*, 6083-6089.

Yu, Y. & Clodic, D. (2007). *Measurement of Leak Flow Rates of Mobile Air Conditioning (MAC) Components – How to Reach a Generic Approach* (SAE Technical Paper 2007-01-1186).

ANNEX A: SENSITIVITY OF COSTS AND BENEFITS TO HIGH EMISSION ASSUMPTIONS

BENEFITS

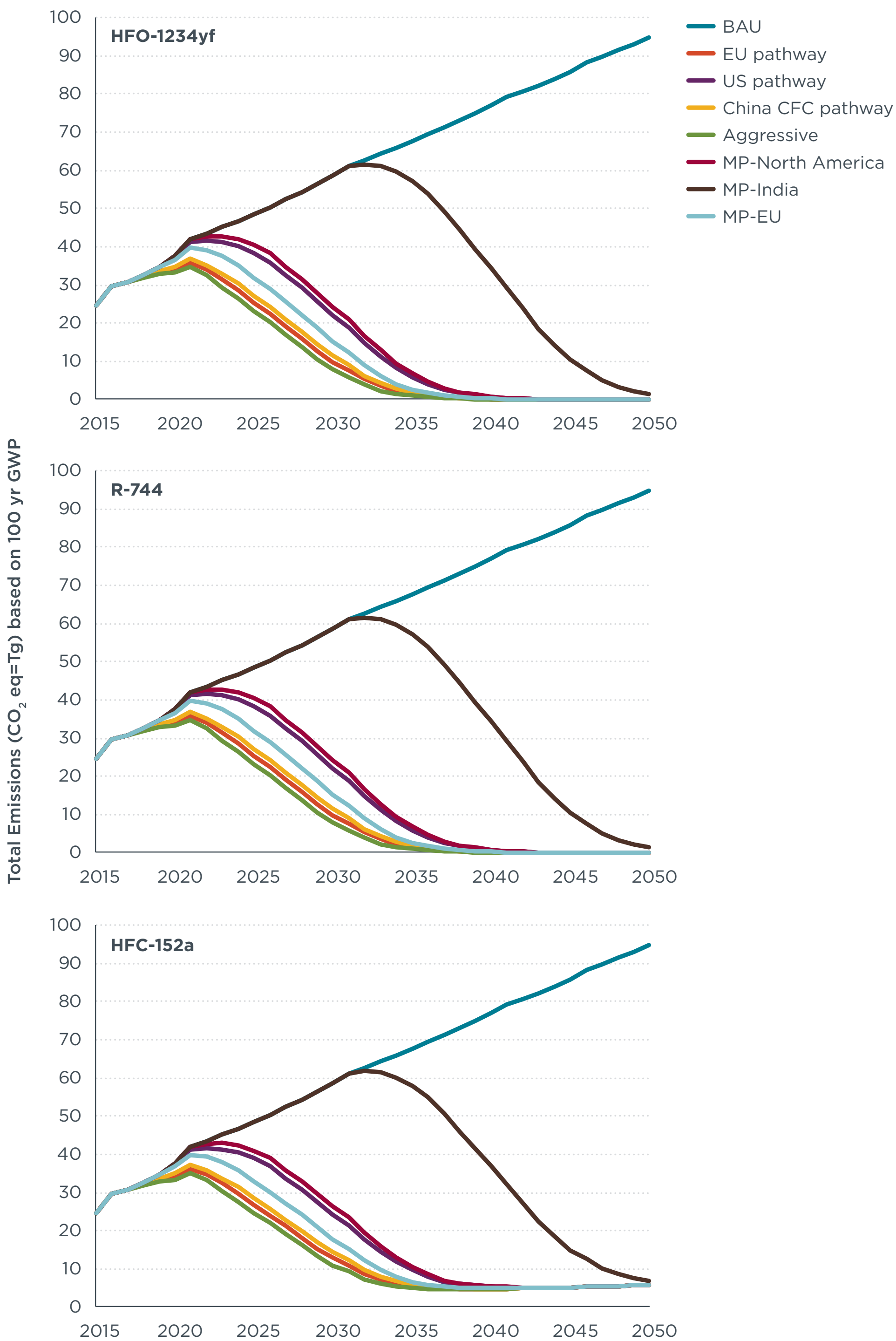

Figure A1. Time series of total refrigerant (CO_2e) emissions for (a) HFO-1234yf, (b) R-744, and (c) HFC-152a by scenarios (with high emission assumptions).

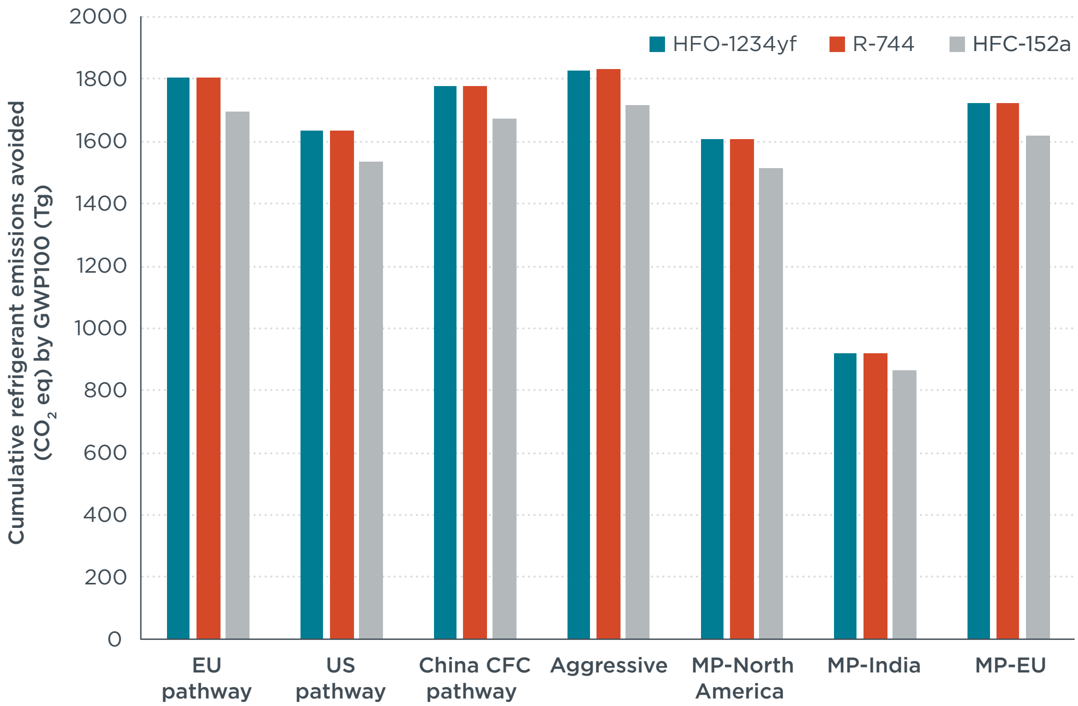

Figure A2. Cumulative refrigerant emissions avoided (CO_2 eq) by 2050 under all scenarios with high emission assumptions.

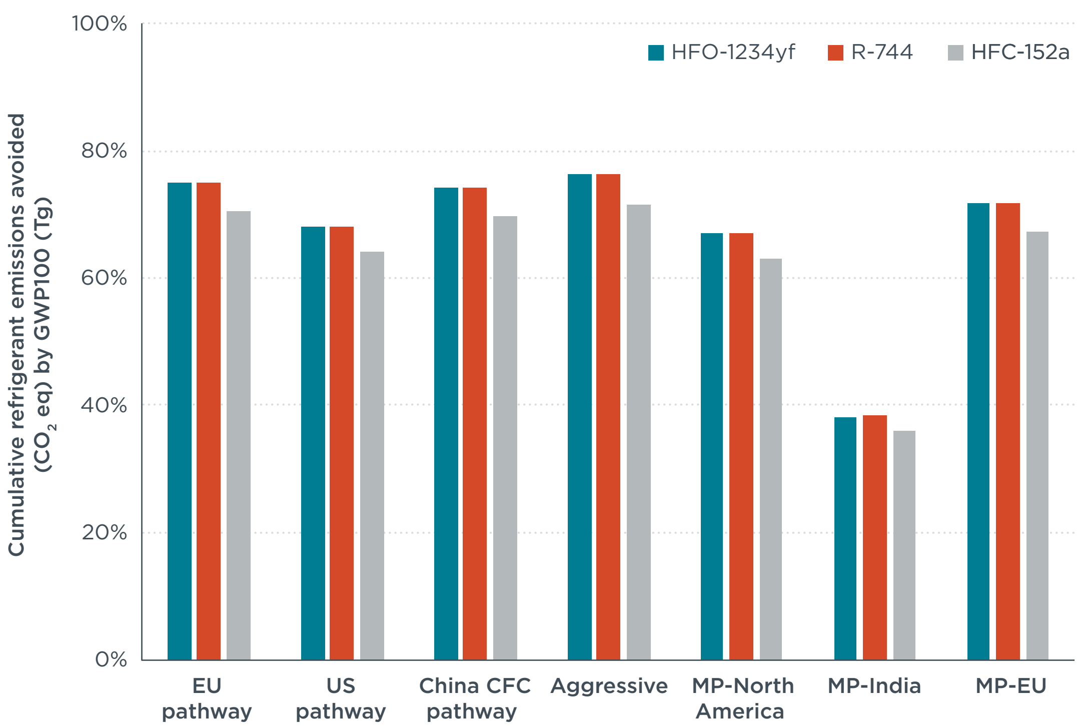

Figure A3. Cumulative refrigerant emissions avoided (CO_2 eq) relative to cumulative emission under the baseline scenario by 2050 with hight emission assumptions.

COSTS

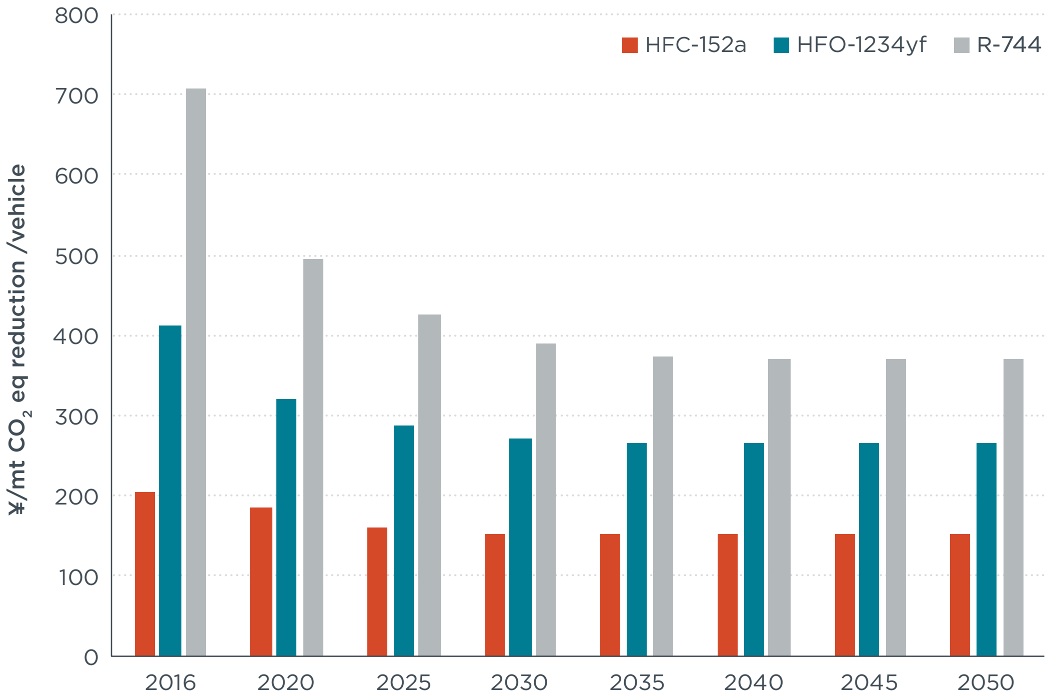

Figure A4. Cost-effectiveness of alternative MAC systems under high emission assumptions. Cost incurred during the MAC useful lifetime were discounted back to the first year using a discount rate of 3%.

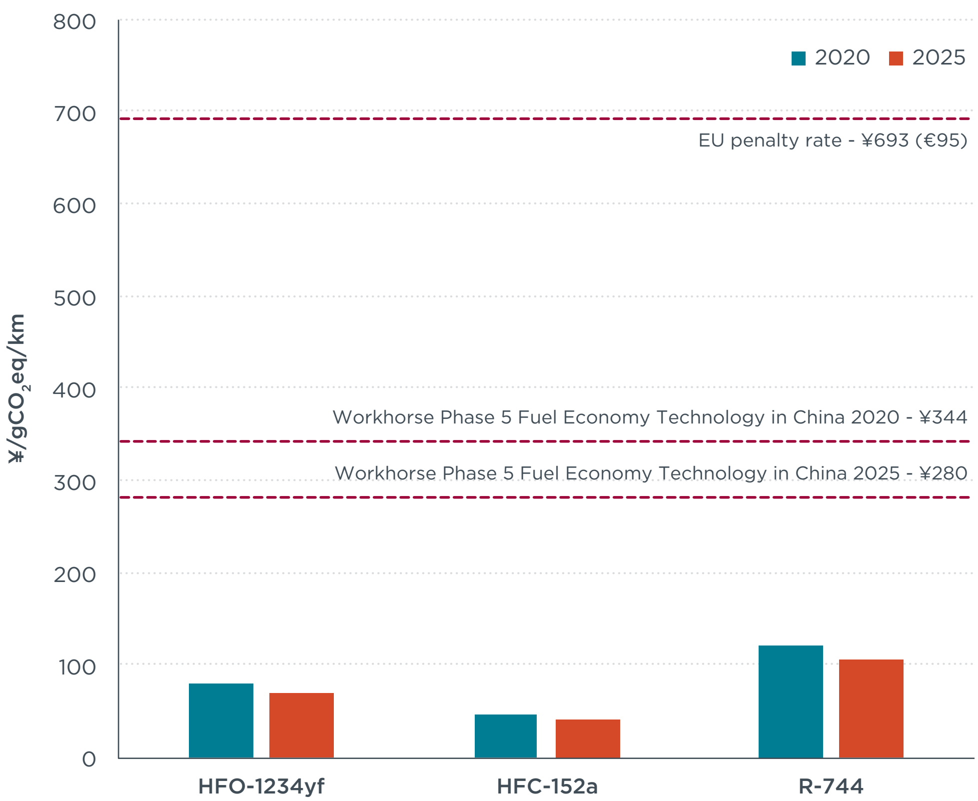

Figure A5. Cost-effectiveness of alternative MAC systems under high emission assumptions.

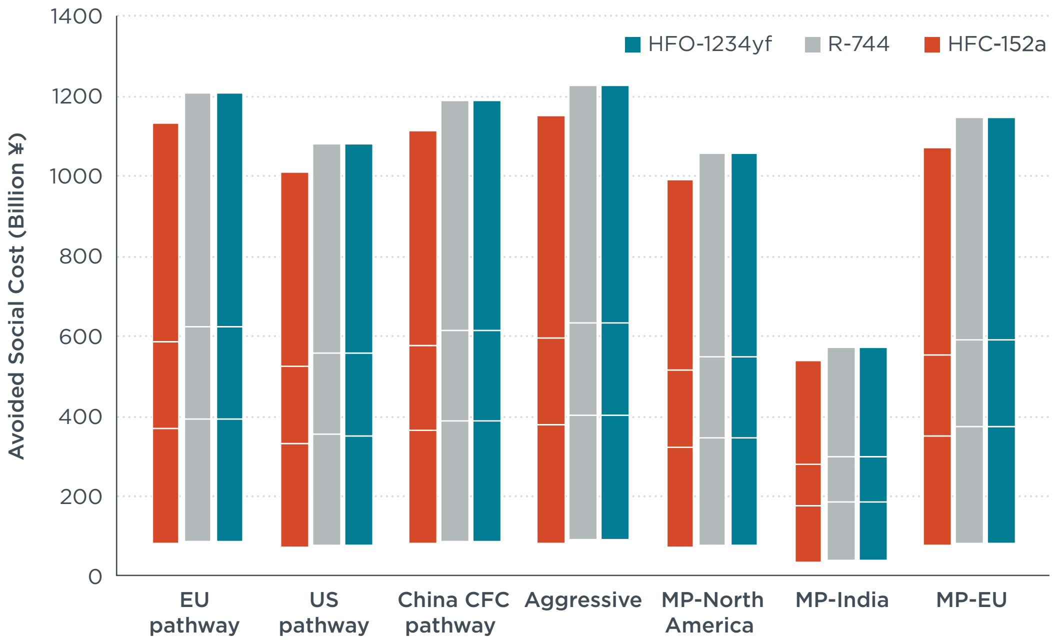

Figure A6. Total avoided social cost until 2050 induced by transitioning to alternative refrigerants under high emission assumptions.

ANNEX B: SENSITIVITY ANALYSIS OF KEY INPUT PARAMETERS

This annex provides an evaluation of some of the uncertainties in the main analysis. Uncertainties identified in this study include GWP values, emissions factor estimates, and cost estimates for alternative MAC systems. Note that in all cases, the main analysis uses best-estimate data derived from the most credible sources. As a result, the estimates presented in this section are meant to quantify potential sensitivities and not serve as alternative best estimates.

GWP VALUES

In the report, GWP values with climate-carbon feedback were used for both baseline and alternative refrigerants. However, the technical advisory group to this report highlighted that uncertainties remain in these GWP values based on our understanding of the carbon cycle. Therefore, GWP values without climate-carbon feedback are explored here to understand the sensitivity of our results and conclusions to these uncertainties. Table B1 compares the GWP values with and without carbon feedback for both the baseline and alternative refrigerants.

Table B1. GWP values for baseline and alternative refrigerants.

	GWP with carbon feedback	GWP without carbon feedback
HFC-134a	1,549	1,300
HFO-1234yf	1	1
R-744	1	1
HFC-152a	167	138

Cumulative refrigerant (CO_2e) emissions relative to the BAU scenario calculated using GWP values without climate-carbon feedback are almost identical to those calculated with climate-carbon feedback (see Figure B1). Although not shown graphically, the cumulative reduction of CO_2e mass is greater by roughly 19% for all three alternative refrigerants when considering climate-carbon feedback. This is because CO_2e emissions of HFC-134a are about 19% higher when climate-carbon feedback is considered.

GWP values with climate-carbon feedback have a marginal impact on the relative reductions in estimated GHG emissions. They do not necessarily alter any of the conclusions reached in the report.

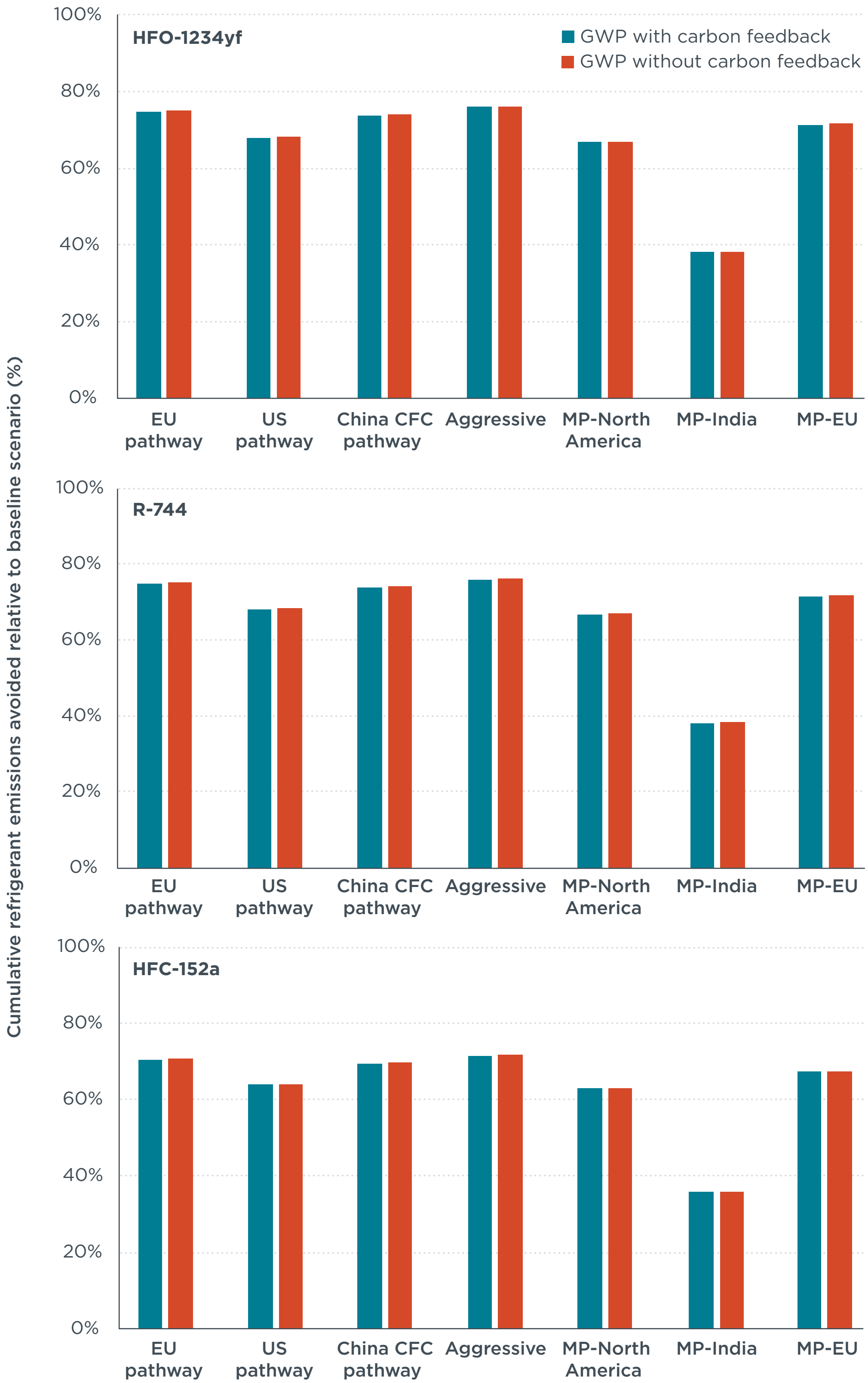

Figure B1. Comparison of cumulative refrigerant emissions avoided relative to the BAU scenario by using GWP values with and without carbon feedback for (a) HFO-1234yf, (b) R-744, and (c) HFC-152a.

By applying GWP values without climate-carbon feedback, the cost of reducing CO_2 emissions on a g/km/vehicle basis increases by about 16%. With cost of transition unchanged, the cost per unit CO_2e is higher. However, this increase is insignificant compared with the overall cost. Figure B2 gives the sensitivity of cost-effectiveness estimates to GWP values with and without climate-carbon feedback.

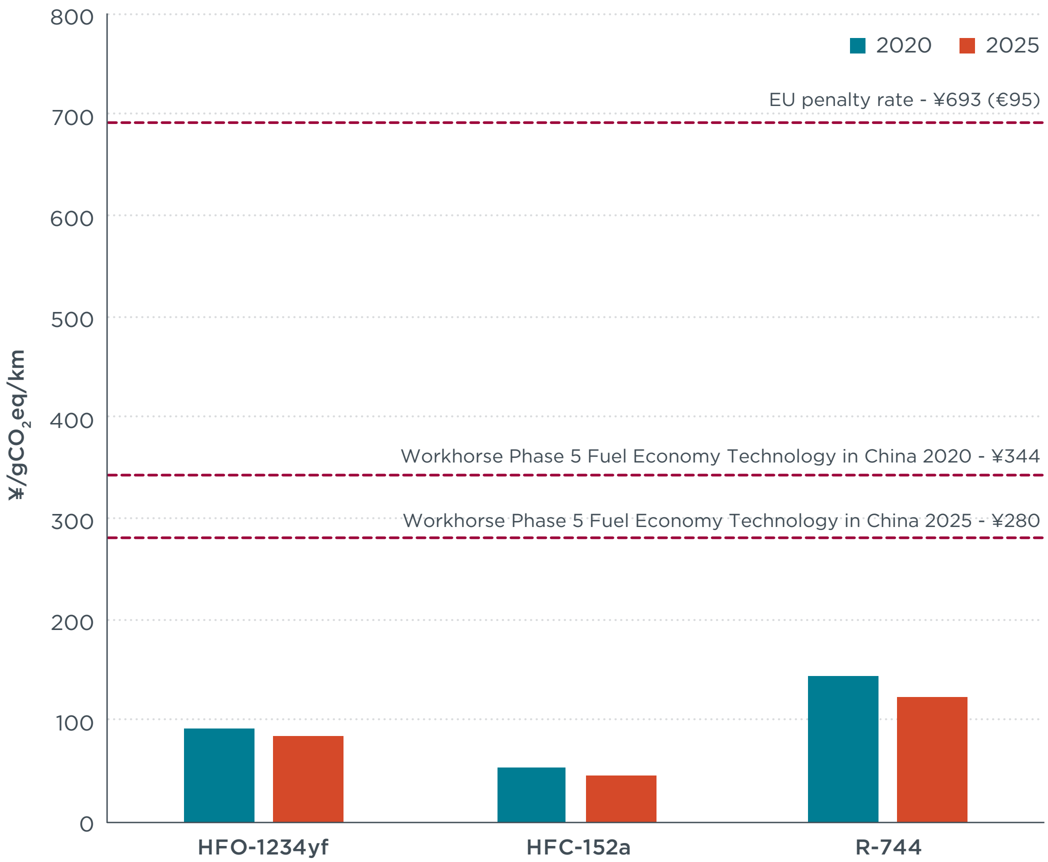

Figure B2. Sensitivity of cost-effectiveness to GWP values without climate-carbon feedback under low emission assumptions.

EMISSIONS FACTORS

Because emissions factors are based on EPA and MPCA datasets, uncertainties with emission factors exist due to possible discrepancies between MAC sectors in the United States and China. In order to further validate the benefits resulting from the use of alternative refrigerants and different phase-out policies in China, we conducted sensitivity analyses of emission rates by doubling MAC regular emission rates and service emission rates. The end-of-life emission rate was also adjusted to be twice as high in order to test the sensitivity of modeled climate benefits to these emission rates.[33] Figure B3 shows the results of the sensitivity analysis.

The increased emission rates produced a small change in cumulative emission reductions. For HFO-1234yf and R-744, the change in cumulative emission reductions relative to the baseline was less than 0.05%. For HFC-152a, differences were slightly

33 This only serves the purpose of a sensitivity analysis and is not intended to represent any real emission scenarios.

larger but typically less than 5%. These results confirm that the primary driver of emission benefits is the near-100% reduction in GWP. In other words, emissions would have to increase by orders of magnitude to have any significant influence on overall CO_2e reductions. Emission rate uncertainty is not a major factor in evaluating the release of alternative MAC refrigerants. Given its comparatively higher GWP, this assessment is less precise for HFC-152a than it is for HFO-1234yf and CO_2, but the same general rationale holds. The use of low-GWP refrigerants and the implementation of regulations for transition are the major drivers of benefits.

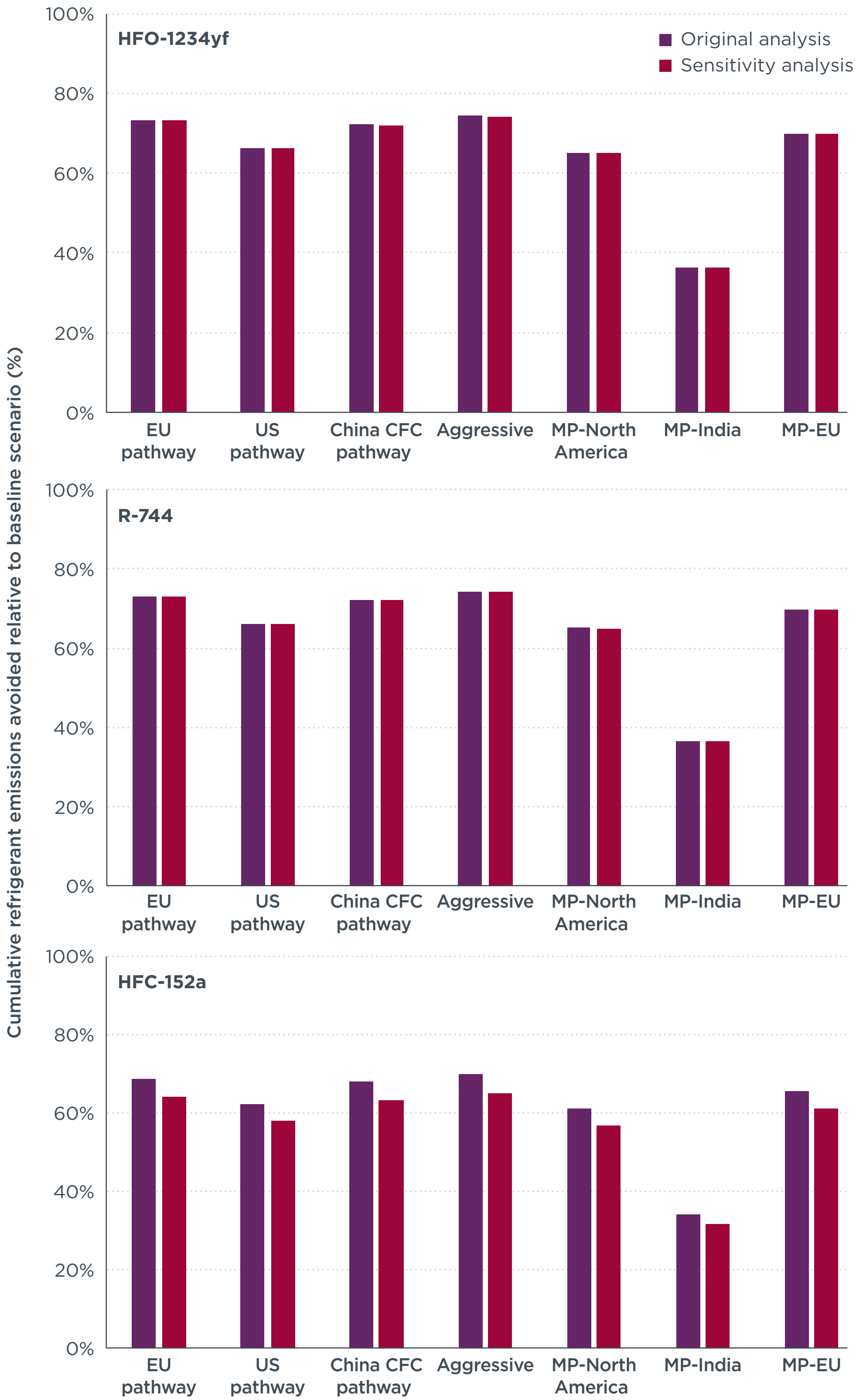

Figure B3. Comparison of the cumulative refrigerant emissions avoided for original analysis and sensitivity analysis (doubling the regular emission, service emission rate, and end-of-life emission rates) for (a) HFO-1234yf, (b) R-744, and (c) HFC-152a.

COST OF ALTERNATIVE MAC SYSTEMS

Due to relatively low penetration of alternative MAC systems in the global marketplace, this study faced a high degree of uncertainty with regard to the incremental costs of refrigerants and hardware. These costs depend on a variety of factors, such as present and future production, present and future demand, and regional differences in these projections. In this report, our approach to uncertainty was to choose values we believe are biased conservatively high.

In order to quantify uncertainty based on a range of costs we found, we present below the effect of a lower bound cost range on our results. For an R-744 system, the EPA estimated in its technical support document to its 2017-2025 light-duty vehicle GHG emission standards that the incremental cost for R-744 hardware modification ranges from ¥988–¥1482 ($152–$228) per vehicle. This sensitivity analysis presents the effect of the EPA's lower bound hardware cost estimate of ¥988 ($152). The uncertainty in R-744 refrigerant cost is not evaluated here because we did not find the same degree of uncertainty in cost estimates.

For an HFO-1234yf system, our central source of uncertainty is the cost of the refrigerant. According to HFO-1234yf refrigerant cost estimates contained in the LEV III regulation adopted by the California Air Resources Board, the incremental cost of HFO-1234yf is ¥494 ($76). A confidential industrial source indicates that the price of HFO-1234yf sold to auto service centers could be as low as about ¥715 ($110) per kilogram. Here we present the latter estimate as a lower bound on the cost of the HFO-1234yf system. We do not assess uncertainties in system components for HFO-1234yf because the technology is relatively well known and we consider the uncertainties to be low.

Figure B4 shows the range of costs to reduce one gCO_2e/km by transitioning to low-GWP MACs. The range of uncertainty for either the HFO-1234yf or the R-744 system suggests that the cost-effectiveness of reducing GHGs through either system is well below the EU penalty rate for compliance with its CO_2 standard on motor vehicles.

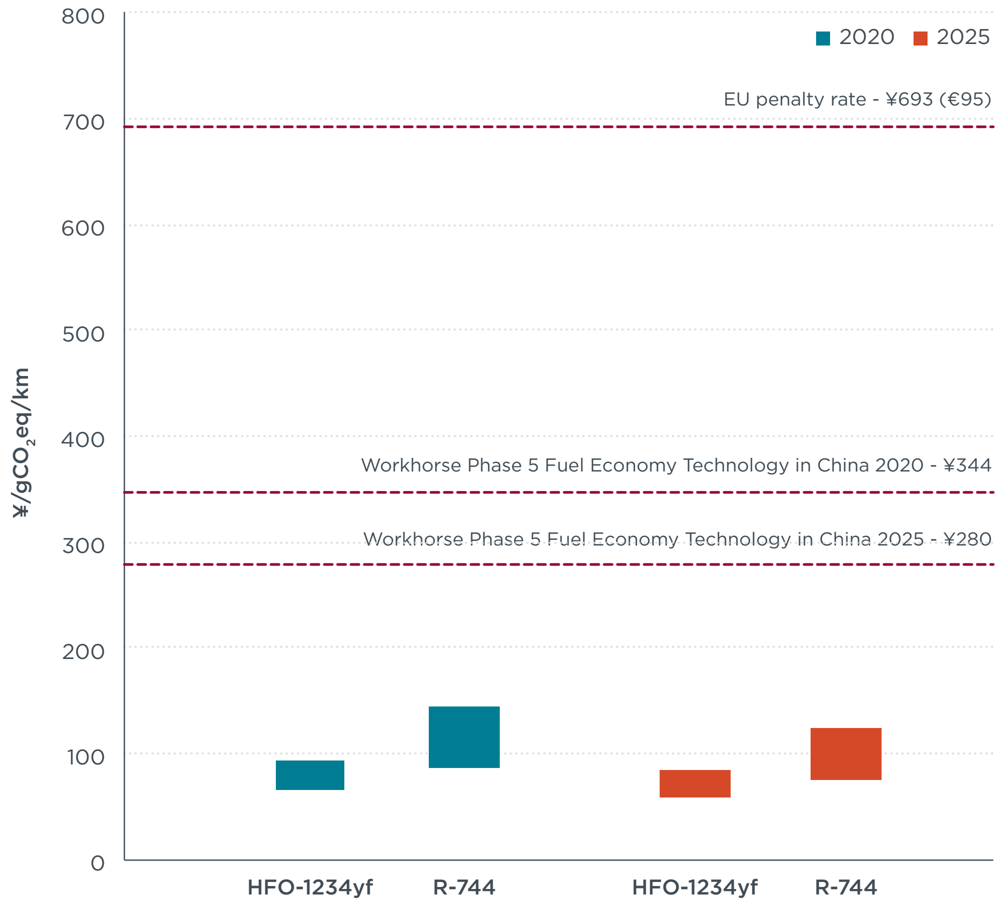

Figure B4. Sensitivity analysis of cost-effectiveness to uncertainties in system costs in costs in 2020 and 2025.

ANNEX C: CHINA DATA SUMMARY

Table C1. Summary of MAC information collected from publications and studies that focus on the China vehicle fleet.

MAC penetration		
% cars with A/C	**Notes**	**Source**
100%	Cars with MAC since 2006	Su et al., 2015
MAC charge size		
Charge size, kg	**Notes**	**Source**
1.1	charge size in 1990	Hu & Li, 2003 (as cited in Clodic et al., 2010)
0.9	charge size in 2000	
0.67	charge size in 2006	
1	average charge size of cars; temporal range was not specified	MEPC, 2003 (as cited in Hu et al., 2010)
0.8	default charge size of cars suggested by IPCC	IPCC, 2006
0.536	charge size of cars since 2006	Chen et al., 2008
Operational emissions		
	Notes	**Source**
30%	operational loss during lifetime concluded from refill at service	MEPC, 2003 (as cited in Hu et al., 2010)
50 ~ 150 g/yr		Chen et al., 2008
6.25%	calculated using the estimates from Chen et al. (2008) assuming a charge size of 0.8 kg	Su et al., 2015
Service emissions		
	Notes	**Source**
30%	annual service leak rate	Su et al., 2015
End-of-life emissions		
	Notes	**Source**
40%	initial charge remaining; assuming recovery efficiency of zero	Hu et al. 2010
80%	initial charge remaining; assuming recovery efficiency of zero	PKU, 2013
25%	initial charge remaining; assuming recovery efficiency of zero	Su et al., 2015
Lifetime		
	Notes	**Source**
12 yr	IPCC default value	IPCC, 2006; Hu et al., 2010; Su et al., 2015
15 yr	lifetime estimates	Gloel et al., 2014

Table C1 lists the data regarding MAC retrieved from studies and publications that specifically focused on the China vehicle fleet. In general, the publicly available data is still sparse. Most of the information is retrieved from a limited number of studies, which also cross-reference each other or share similar sources. Specifically to each aspect:

1. MAC penetration in China passenger fleet: Many publications assumed 100% penetration of MAC in the new China passenger vehicles. While this may be well justified based on the communication with automobile manufacturers, direct sales and manufacturing data are preferred but were not available.
2. MAC charge size: A previous global study (ICF International, 2012) suggested variability of MAC charge size across different markets. Based on China-specific studies, there is limited information to explain how average system charge size in China compares with other markets. Most China-specific studies assume charge size from global studies.
3. MAC emissions: Emission data used in China-specific studies are mostly adopted from studies in other markets, particularly from Europe and the United States.

In summary, the scarcity of publicly available data and the limited number of research activities on MAC in China posed challenges to this study and to similar studies that have already been conducted in China. Major data gaps still exist, particularly on MAC penetration, MAC charge size, and emissions.

We encourage studies and surveys to be performed in China to collect baseline information that is already available in North American and European markets. Normally, such activity would be critical to tailoring Chinese policies to the Chinese vehicle market, but our analysis has shown that the benefits of transitioning to low-GWP refrigerants are insensitive to the precise quantification of these parameters. This is unique and is largely driven by the inherent GWP differences of the alternatives themselves, and these differences are independent of any particular vehicle market. Thus, while we continue to encourage efforts to better characterize the Chinese fleet, we do not believe that such efforts will affect the conclusions of this work in any way.