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INTEGRATING REFRIGERANTS WITH LOW GLOBAL WARMING POTENTIAL INTO INDIA'S LIGHT VEHICLE FUEL EFFICIENCY STANDARDS

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EXECUTIVE SUMMARY

Greenhouse gas (GHG) emissions from mobile air conditioning (MAC) systems are significantly higher in the hot and humid climates common in India than in cooler climates. Both heat and humidity increase refrigerant leakage and lead to much higher indirect emissions that result from the extra energy used to power the cooling system. MAC systems in India today commonly rely on R134a, a hydrofluorocarbon (HFC)-based refrigerant, and it has a significantly higher global warming potential (GWP) than other available refrigerants. India also has a growing passenger car market that is distinguished by an increasing demand for cooling.

At the same time, India has set ambitious goals to reduce GHG emissions as part of its commitment to the Paris Agreement and recently ratified the Kigali Amendment to the Montreal Protocol, pursuant to which it will phase out use of HFCs. Alternative refrigerants with low GWP include R1234yf, R744, and R152a, and these can dramatically reduce or virtually eliminate direct emissions from refrigerant leakage from MAC systems. The indirect emissions can also be reduced by improving system efficiency, either by enhancing the existing components or reducing the cooling load.

Many regions, including the United States and the European Union, have incentivized improvements in MAC systems, both efficiency improvements aimed at reducing indirect emissions and switching to refrigerants with low GWP. But air conditioning operation is not currently included in the official tests determining compliance with India's vehicle fuel consumption standards or in the credits offered under the standards for technologies not captured by the tests (i.e., the off-cycle credits system). India's standards thus ignore both the direct and indirect emissions. To help inform future regulations that can reflect the value of technology that reduces these emissions, this paper evaluates the emissions benefits and costs of four different improved MAC systems versus the current R134a systems: an enhanced R134a system with reduced leakage and improved efficiency, and systems that use R152a, R744, and R1234yf. We estimate the amount of GHG emission reductions from these with a focus on Indian driving conditions and consider the associated cost to customers and passenger car manufacturers.

Results show that R1234yf has the most potential for the Indian market. This is a near drop-in replacement for R134a and does not require any significant hardware change in MAC systems. The cost of R1234yf is currently an obstacle to widespread adoption, though, as it is 10 times higher than R134a and R152a due to protection from several patents that remain active in India, including those maintained by Honeywell and Chemours (Deo & Callahan, 2022).

The most significant reductions in lifetime GHG emissions are offered by using R1234yf in a direct expansion (DX) system or R152a in a secondary loop (SL) system. Both offer roughly equivalent benefits in terms of reductions in total direct and indirect emissions. However, R152a in SL systems has thus far only been demonstrated in India in a prototype vehicle and it has not been adopted in production vehicles anywhere in the world yet. R1234yf, meanwhile, is widely used in new vehicles in the United States, Europe, and Japan.

For all of the alternative refrigerants evaluated, lifetime emissions are about 50% lower than the baseline R134a system. For the enhanced R134a-based DX system, the direct emissions share of lifetime emissions is still estimated to be more than 50%; that is because of the high GWP of the refrigerant and because cars tend to be driven less in India than in other markets, which reduces the amount of indirect emissions in total emissions.

For vehicle owners, the most considerable expense is in-use fuel consumption, and that depends on MAC system efficiency, engine efficiency, and local fuel prices. This analysis estimates that lifetime fuel savings of approximately ₹40,000 are realized with alternative refrigerants in an average midsize passenger car over a 15-year vehicle life at 10,000 km driven per year. This result is primarily due to the increased efficiency assumed for all alternative refrigerants and the less frequent service of SL-MAC systems. Moreover, Figure ES1 shows that all low-GWP MAC systems are more cost-effective for manufacturers per g CO_2e emissions reduction per km than technologies that currently enjoy off-cycle credits in India's regulation.

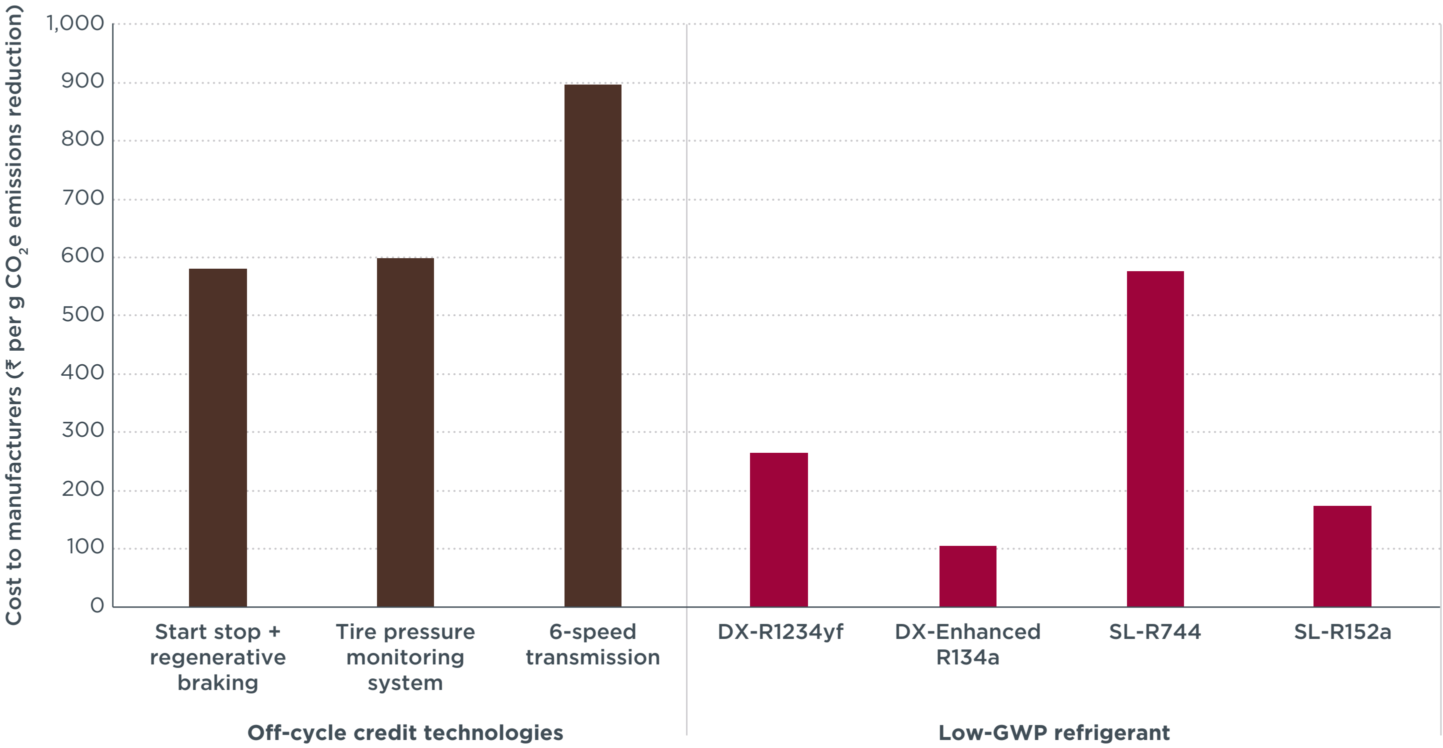

Figure ES1. Estimated cost per gram of CO_2e emissions reduction (direct emissions) of single-cooling-point MAC systems compared with technologies that currently qualify for off-cycle credits in India's fuel consumption standards.

From a vehicle manufacturing standpoint, the results suggest that future regulations in India need not distinguish between MAC systems using refrigerants with a GWP less than 150. R152a, R1234yf, and R744 can be effective in reducing emissions and are thus worthy of CO_2 credits for direct and indirect emissions reduction in India's fuel consumption standards. We suggest that direct emissions credits of up to 16 g CO_2/km would fit for R744 and R1234yf and that 15 g CO_2/km is appropriate for R152a. Direct credits of up to 6 g CO_2/km are also suggested as appropriate for enhanced R134a systems, although the benefits would need to be validated. Indirect emissions credits for improved MAC efficiency technology and cooling load reduction technology of up to 8% of the certified emission level for each vehicle would reflect the contributions of the technology. Note that indirect credits should be based on the percentage reduction in CO_2 emissions when accounting for MAC use during certified testing and not on a fixed g/km. Here, too, the credits should be confirmed using test procedures representative of real-world use like the U.S. Environmental Protection Agency's test procedure to validate indirect credits, AC17.

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1. INTRODUCTION

Thermal comfort has always been of high value to passenger car customers in India, mainly because of the hot and humid climate across large areas of the country. Cabin air cooling in cars is maintained by a mobile air conditioning (MAC) system. MAC systems use refrigerants that are responsible for greenhouse gas (GHG) emissions in two ways: (1) directly, through refrigerant leakage; and (2) indirectly, through increased fuel consumption to run the MAC system. Indeed, the energy consumed through MAC system operation is estimated to increase total fuel consumption by about 20% in India's high average yearly temperatures and humid climate (Chidambaram, 2010). This is almost three times more than the emissions increases from MAC operation in colder areas of North America and Europe.

MAC systems worldwide, including in India, once used chlorofluorocarbons (CFCs) such as dichlorodifluoromethane (R12, commonly known as freon). The Montreal Protocol agreement in 1987 acknowledged the harmful effects of CFCs and other ozone-depleting substances, and countries agreed to move away from R12. This refrigerant transition occurred in advanced economies in the early 1990s when hydrofluorocarbon (HFC)-based R134a, which has zero ozone depletion potential, replaced R12. The change to R134a in developing countries occurred later, during the 2000s, and today it is widely used in the MAC systems of passenger cars in India.

Not only is the ozone depletion potential of R134a zero, but its global warming potential (GWP) of 1,300 is lower than R12's GWP of 8,500.[1] However, R134a still has a relatively high GWP and recently there has been a lot of focus on the need to replace it with new refrigerants. In October 2016 in Kigali, Rwanda, more than 170 countries agreed to amend the Montreal Protocol and phase down the production and consumption of HFCs in stages. In the first stage, the United States, the European Union member states, the United Kingdom, Canada, and Japan agreed to phase down the production and consumption of HFCs starting in 2020 and then stop all HFC use by 2024. Pursuant to the same agreement, India will freeze HFC production and use at the 2028 level and then begin to phase down use 5 years after that.

Previous ICCT papers discussed alternative refrigerants suitable for use in countries with moderate and high average temperatures (e.g., Blumberg & Isenstadt, 2019). In countries with colder climates, the MAC system typically also serves to heat the passenger cabin during winter. In India, though, the MAC systems are generally only used for cooling, and this paper does not consider heating as a requirement.

China is a significant producer and exporter of HFCs and handles 70% of the global supply of refrigerants (Yang et al., 2022). Studies specifically focused on China have evaluated the costs of transitioning light-duty vehicle MAC systems away from HFC-134a (Du et al., 2016). China ratified the Kigali Amendment in 2021 and is set to freeze HFCs in 2024 and begin phasing down 5 years after that.

The objective of this paper is to understand the amount of GHG emissions reduction possible from low-GWP refrigerants and more efficient MAC systems in Indian driving conditions. We also explore the associated cost to customers and passenger car manufacturers and consider how regulations in India could be structured to incentivize their use. Section 2 gives a brief overview of the current MAC systems and how they work. It also highlights the advantages and disadvantages of using alternative refrigerants and discusses charge size and modifications required in MAC systems to accommodate alternative refrigerants. Section 3 explains the different refrigerant

1 The global warming potential (GWP) compares the warming impacts of different gases based on their ability to absorb energy and how long they stay in the atmosphere. It is defined as the energy absorbed by emissions of 1 ton of a gas relative to 1 ton of CO2 emissions over a given period. The time generally used for GWPs is 100 years. If a shorter, 20-year time frame is considered, the global warming effect is greater for many gases.

emission types and vehicle-level technologies that can reduce emissions. After that, Section 4 analyzes the cost of the alternative refrigerants and MAC hardware to car manufacturers during production and to customers during scheduled maintenance. Section 5 reviews the off-cycle credits of refrigerants and MAC technologies in Europe, the United States, and China, and considers the amount of CO_2 credits that could reasonably be given to manufacturers for direct and indirect emissions reduction in India. We conclude in Section 6.

2. OVERVIEW OF MAC SYSTEMS AND REFRIGERANTS

MAC systems are primarily divided into direct expansion systems and secondary loop systems, but the latter are only a concept right now. Both systems have standard components such as the condenser, compressor, expansion device, and the evaporator, and secondary loop systems need additional piping, hoses, and sensors.

2.1. DIRECT EXPANSION MAC SYSTEMS

Direct expansion (DX) MAC systems in passenger vehicles use a vapor-compression cycle that goes through compression, heat rejection, expansion, and heat absorption. The low-pressure refrigerant vapor is compressed in a compressor and condensed into a liquid by cooling it in condenser tubes using ambient air. The cooler liquid refrigerant passes through the evaporator and absorbs heat from the vehicle cabin to change its state from liquid to vapor. Most vehicles use a thermal expansion valve that controls the refrigerant flow in the evaporator and ensures complete evaporation of the refrigerant. The essential components are the compressor, condenser, expansion device, and evaporator.

2.2. SECONDARY LOOP MAC SYSTEMS

Secondary loop (SL) systems also use a vapor-compression cycle, but the refrigerant is kept within the engine bay by a separate system and a coolant (water-glycol mixture) circulates within the passenger cabin. These systems require a heat exchanger, called a chiller, between the primary and secondary loops and this reduces the coefficient of performance (COP) by 5%–12% (Andersen et al., 2017).[2] A wider variety of refrigerants can be safely utilized in an SL system than in a DX system because the refrigerant stays in the engine compartment and only coolant circulates in the cabin. An SL system is generally necessary when using alternative refrigerants that are either potentially flammable or dangerous for passengers, but it also requires different sensors to detect leakage into the passenger cabin.

An SL system requires fewer recharges over a vehicle's service and maintenance life, especially in two-cooling-point systems, and can use thermal ballast to maintain passenger cabin comfort for a longer period.[3] SL can also be used for battery pack cooling in plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs).

Intending to develop an efficient, affordable, and low-GWP option for Indian climatic conditions, the Institute for Governance & Sustainable Development (IGSD) collaborated with Tata Motors Limited and Mahle to build a prototype of an SL system using R152a. A technology demonstration was developed on a Tata Aria 2.2L Dicor and the study used optimizations like switching off the compressor during stop-start and regenerative cooling during deceleration (Andersen et al., 2017).

2.3. MAC REFRIGERANTS

Several studies and research projects (e.g., Minjares, 2011) have identified different alternatives to the R134a refrigerant. Because refrigerants, if leaked, can collect in the passenger cabin, it is essential to identify if the alternative refrigerant is more toxic or flammable than the existing refrigerant. Some of the other factors that are critical for the selection of alternative refrigerants are development costs, energy efficiency, packaging space, and serviceability.

2 The coefficient of performance (COP) measures the efficiency in converting energy into cooling.

3 Vehicles generally carry only one evaporator. It is placed in the front of the vehicle to provide cooling in the passenger cabin and is called a single or one cooling point. Large cars such as sport-utility vehicles offer passengers front and rear air conditioning for additional thermal comfort. Such MAC systems have front and rear evaporators to cool the cabin air and these are called two-cooling-point systems.

By the early 2000s, R134a had replaced all R12 MAC systems in India's passenger car segment. R134a was close to a drop-in solution for the R12 MAC systems, but the transition necessitated some design modifications in the condenser, expansion valve, and rubber components. Analysis done in this paper was narrowed to alternative refrigerants that use the vapor compression system used with R134a. We considered the fluorinated gases 2,3,3,3-tetrafluoropropene (R1234yf) and 1,1-difluoroethane (R152a) and carbon dioxide (R744), which are currently the best contenders to replace R134a in India. Refrigerant properties such as flammability, ozone depletion potential and GWP, atmospheric lifetime, and efficiency (COP) of some of the alternative refrigerants are given in Table 1. Note that all four refrigerants have zero impact on ozone depletion.

Table 1. Properties of the three alternative refrigerants considered in this study and of the currently dominant R134a.

Passenger car refrigerant	Global warming potential [a]	Atmospheric lifetime	Impact on ozone depletion	Flammability	Patent	System	Toxicity	COP relative to R134a[c]
R134a	1,300	13.4 years	None	No	No	DX	Low	Baseline
R152a	138	1.5 years	None	Moderate	No	SL	Low	6%–19%
R1234yf	1	10.5 days	None	Low	Yes	DX	Low	2%–5%
R744	1	100 years	None	No	No	SL	Moderate	Depends on ambient temperature[b]

a. Myhre et al. (2013). The GWP of refrigerants is calculated by including and excluding carbon-climate feedback effects. However, because there are uncertainties involved in the carbon cycle of the refrigerants, GWP values without carbon feedback are used in this study; this aligns with regulations in place in Europe and the United States. Feedback effects increase the 100-year GWP by 250 for R134a and by 29 for R152a, while R1234yf and R744 are unchanged.
b. The COP of R744-based MAC depends on temperature, as CO_2 systems perform well at low ambient temperatures due to advantageous heat-transfer properties. However, this advantage declines as temperature increases, so performance at very high ambient conditions (i.e., near or above about 45 ºC) can be less efficient than R134a systems.
c. The coefficient of performance measures machine efficiency in converting energy into cooling. The source for the COP values is Andersen et al. (2017).

R152a

R152a is a colorless gas with low molecular weight and a GWP of 138. Its GWP is higher than that of R1234yf and R744, but still much lower than R134a. R152a is designated as an A2 refrigerant with minimal toxicity and moderate flammability.[4] Because additional safety sensors are required to detect high concentrations during accidents, SL systems are typically necessary when this refrigerant is used in passenger cars. One advantage of R152a is that it requires a 25% lower charge size (in grams) due to its low density. Also, the COP of HFC-152a is the highest in the ambient temperature range of 37.8 °C to 54.4 °C, a temperature range common in most parts of India.

Unlike R134a and R1234yf, R152a does not degrade in the atmosphere into trifluoracetic acid (TFA). However, the need for more leak-proof piping; safety and space concerns in a densely packed engine compartment; and the higher implementation costs of an SL system have inhibited manufacturers from widely using R152a. Additionally, while the European Union currently allows use of any refrigerants with GWP lower than 150, major global automakers have not expressed great interest in R152a partly because of concerns about potential stricter regulation and control in the future. There are currently no manufacturing patents on R152a.

R1234yf

R1234yf is an unsaturated fluorinated hydrocarbon (hydrofluoroolefin) with moderate flammability and is designated as an A2 refrigerant. The thermodynamic properties of R1234yf are slightly different from those of R134a, as it has a somewhat higher

4 As designated by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE).

molecular weight and thus requires more charge. R1234yf is a nearly drop-in substitute for R134a because of its comparable cooling capacity and COP relative to R134a under similar conditions.

R1234yf might cause a cooling performance loss of 5%, but using an internal heat exchanger or a condenser with a higher sub-cooling area can compensate for that (Andersen et al., 2017). The IPCC Fifth Assessment Report (Myhre et al., 2013) showed that R1234yf has a GWP of 1 and a short atmospheric lifetime. Honeywell and Chemours currently hold patents on the refrigerant in India, and auto manufacturers must purchase a license to use R1234yf in their MAC systems. This leads to high cost: R1234yf is about 10 times more expensive than R134a (Papasavva & Moomaw, 2014). The patents have been defended and would be expected to expire (Seidel & Ethridge, 2016) in the 2023–2025 time frame, except that the companies have filed newer divisional applications in several countries, including in India. Given this, it is difficult to predict when other manufacturers might be able to produce and sell in India, which would bring the cost down. Currently, R-1234yf is widely used in more than 100 million vehicles worldwide, especially in Europe, the United States, and Japan (Yang et al., 2022).

R744 (CO_2)

R744, refrigerant-grade CO_2, is a colorless and odorless refrigerant with a GWP of 1. It is an A1 refrigerant associated with no flammability and minimal toxicity. It is also a low-cost refrigerant, and there is no need to recycle it at the end of life. When used in MAC systems, CO_2 sensors are needed in the passenger cabin to activate ventilation systems in case of refrigerant leakage. Because R744 can displace a significant amount of oxygen and cause headaches and dizziness in vehicle occupants, it is generally used with SL systems so that direct refrigerant contact with the passenger cabin air is avoided. Studies show that R744 systems perform well at low ambient temperatures like in Northern Europe, due to advantageous heat transfer properties, and this advantage declines as temperature increases. The reason is the low critical temperature of CO_2, 31 °C. At ambient temperatures higher than that, there will be no phase change when heat is removed from the condenser, and this lowers the overall efficiency to less than that of R134a systems. Therefore, R744 systems are less suitable for countries with typically high ambient temperatures like India.

Additionally, R744 has low efficiency during idling and under high-load conditions. Further, compared to medium or large cars, compact vehicles are generally at a disadvantage due to space constraints, which limit condenser and evaporator sizes; the increase in compressor power consumption can even hurt vehicle drivability and fuel economy. Also, higher pressure in the MAC system creates a higher leakage rate and requires more service (Blumberg & Isenstadt, 2019).

2.4. MAC REFRIGERANT CHARGE SIZE

Refrigerant charge size directly affects initial cost, refill cost, and the chances of leakage; leakage is of most concern in the case of flammable or toxic refrigerants. The two primary ways to significantly reduce refrigerant charge size are refrigerant choice and optimum design of the internal volume of components, such as the evaporator and receiver. Studies suggest that globally in the past decade, MAC initial refrigerant charge has dropped to 0.4 kg from 1.2 kg per MAC system, and the necessary size generally varies directly with vehicle size (Du et al., 2016). Estimates from India-specific studies show that refrigerant charge ranges from 0.4 kg to 1.0 kg, depending on the vehicle's capacity and number of cooling points (K. & Singh, 2020). The various refrigerant charge sizes for low-GWP refrigerants are listed in Table 2. Our analysis assumes a 33% lower charge size in SL systems and that the MAC's useful lifetime is 15 years for all systems.

Table 2. Refrigerant charge for one-point MAC systems in a compact segment vehicle.

Refrigerant	Amount of refrigerant charge compared with baseline	Charge (g) direct expansion (DX)	Charge (g) secondary loop (SL)
R134a (baseline)	1.00	480	320
R1234yf	1.00	480	320
R744	0.80	390	260
R152a	0.75	360	240

Source: Du et al. (2016)

3. TYPES OF REFRIGERANT EMISSIONS

Direct emissions from MAC systems are the direct leakage of refrigerant from the hoses and pipe fittings during regular operation, servicing, and scrappage at the end of life. Indirect emissions happen because the MAC system increases overall vehicle fuel consumption, both to power the MAC unit and because of its additional weight. A third kind of emissions are called embodied emissions, and these happen during the production and manufacturing of the refrigerant units.

3.1. DIRECT EMISSIONS

The total climate warming effect of direct emissions is expressed in terms of CO_2 equivalent (CO_2e) emissions. There is also some irregular refrigerant leakage during charging in a production plant or during accidents. Due to a lack of data about these emissions and because they are minimal in amount, these are assumed to be zero in our analysis. Improvements in safety and crashworthiness might also further reduce these emissions over time.

During operations

Direct emissions are continuous during operation due to leaks from high-pressure systems and the degradation of components such as seals and fittings. Studies show these emissions are highly variable: Annual losses for MAC systems using R134a ranged from 7% to 30% of system charge size per year, averaged over the vehicle's lifetime. Lab tests in Figure 1 (Yingzhong & Clodic, 2010) showed that the operational leakage rate is proportional to $P_{system}{}^2$-$P_{ambient}{}^2$, where P system is the pressure developed due to compression of the refrigerant and $P_{ambient}$ is the atmospheric pressure.

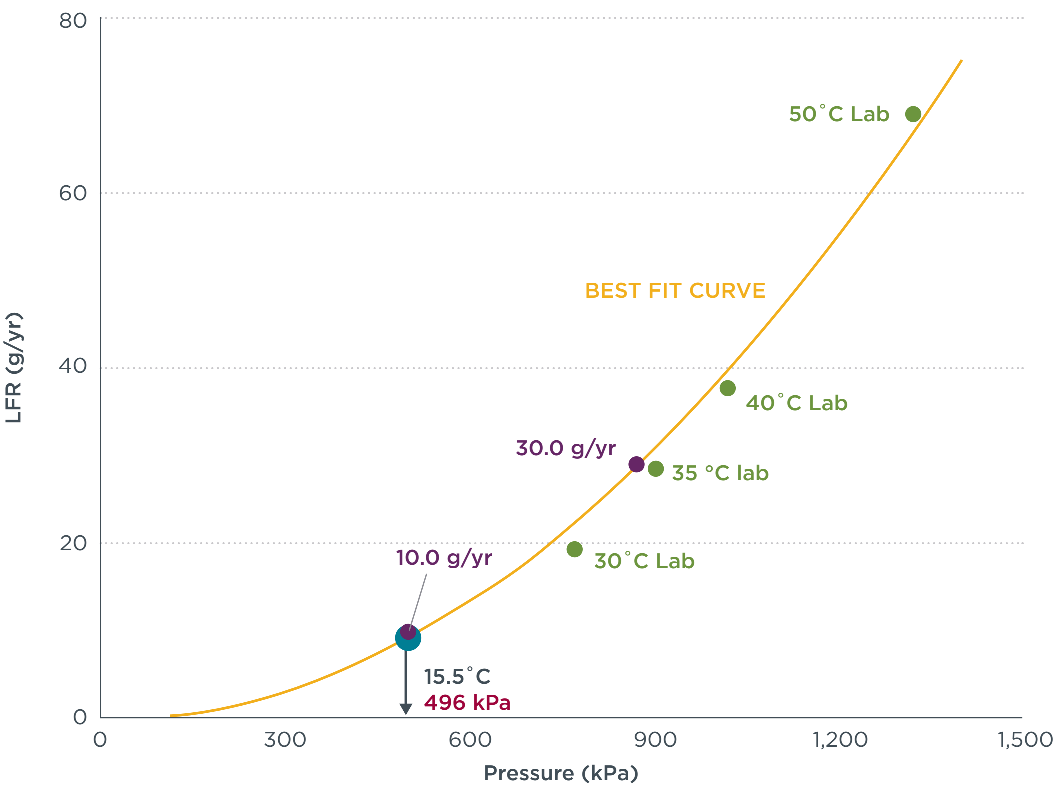

Figure 1. Annual leak flow rate according to MAC system pressure.

Source: Yingzhong and Clodic (2010).

The trend line in Figure 1 shows that at the higher operating pressure of the MAC system caused by higher ambient temperature, leakage rates of 30 g per year can be expected in the first year in ambient temperatures around 35 °C. For the emissions estimates in this analysis, we used a range of 32–38 °C because the data were available; still, higher temperatures are common in many parts of India. There is an additional leakage of 20% per year due to system wear and tear. This averages to 72 g per year over the 15-year MAC system lifetime at 35 °C.

Because two-cooling-point systems have a higher number of refrigerant fittings, they are assumed in this analysis to have 25% higher leakage rates. Additionally, because SL systems have fewer refrigerant fittings, we assumed leakage rates are 45% lower than DX systems. R1234yf is a near drop-in replacement for R134a; therefore, the leakage rates of R1234yf systems are similar to R134a. This study assumed that the operational emissions from an R152a system are 45% lower than the emissions from R134a in an SL system. The leakage rate of R744 is 20% higher (Blumberg & Isenstadt, 2019) because of the higher operating pressure than in an R134a system. Note that high leakage in the system could become a reason to replace or repair the AC compressor and lines. If this occurs, it will reduce leakage emissions and thus our analysis, which assumes a 15-year life, is a worst-case analysis.

During service

Service emissions occur when the MAC system requires maintenance, repair, or recharge. During maintenance, most refrigerant leakages occur when a technician's skill level for operating recycling and recovery equipment is low and/or the work is done at an unauthorized service center. Relative to developed countries, vehicle owners in India perform MAC repairs at unauthorized service centers far more frequently (Ozone Cell, Ministry of Environment, Forest & Climate Change, India, 2019). Thus, we assumed that approximately 50% of the remaining charge is lost during each service event. We also assumed that service is needed and performed when the refrigerant charge drops to 50% of the initial charge due to leakage. The net result is that about 7% of the initial charge size is lost due to service emissions each year.

At end of life

End-of-life emissions are emissions associated with the scrappage and disposal of a vehicle. The amount of refrigerant remaining in the MAC system at the end of its life and the refrigerant recovery practices govern the extent of these emissions. This study evaluated end-of-life emissions by calculating the difference between the total amount of service recharges, including initial charge, and the sum of annual leakages. End-of-life recovery efficiency is generally lower in India because of lack of advanced technologies and compliance. However, best practices for refrigerant disposal are challenging to implement and monitor even in countries that have robust compliance mechanisms. Our analysis assumed that almost all refrigerant charges are released at the end of life and that no recovery is carried out.

Direct emissions summary

Table 3 summarizes the assumptions used to estimate the direct emissions. The thermophysical properties of R1234yf and R134a are similar; therefore, the charge size for both DX and SL systems that use R1234yf is identical to that of the baseline system. For R744 and R152a, studies estimate that the charge size would be smaller by 20%–30% than it is for R134a systems (United Nations Environment Programme, 2010). Enhanced R134a systems are designed with improved fittings and tubing to reduce leakage, so the Initial operational leakage rate is half that of the standard R134a system. Such enhancements are not used for the other refrigerants because they have much lower GWP.

Table 3. Summary of assumptions used to estimate direct emissions.

Parameters		R134a (Baseline)		R134a (Enhanced)		R1234yf		R152a		R744	
		DX	SL	DX	SL	DX	SL	DX	SL	DX	SL
Initial charge (g)	1 cooling point	480.0	320.0	480.0	320.0	480.0	320.0	360.0	240.0	390.0	260.0
	2 cooling point	960.0	640.0	960.0	640.0	960.0	640.0	720.0	480.0	780.0	520.0
Initial operational leakage rate (g)	1 cooling point	30.0	16.7	15.0	8.3	30.0	16.7	30.0	16.7	36.1	20.0
	2 cooling point	40.0	16.7	20.0	8.3	40.0	16.7	40.0	16.7	48.1	20.0
Leakage deterioration rate per year (%)		20%	20%	20%	20%	20%	20%	20%	20%	20%	20%
Average annual operational leakage (g/yr)	1 cooling point	72.0	40.0	36.0	20.0	72.0	40.0	72.0	40.0	86.6	48.0
	2 cooling point	96.0	40.0	48.0	20.0	96.0	40.0	96.0	40.0	115.5	48.0
Recharge amount (% of original charge)		50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
Number of lifetime recharges	1 cooling point	4.0	3.0	2.0	1.0	4.0	3.0	5.0	4.0	5.0	4.0
	2 cooling point	2.0	1.0	1.0	0.0	2.0	1.0	3.0	2.0	3.0	2.0
Service recovery efficiency (%)		50%	50%	50%	50%	50%	50%	50%	50%	50%	50%
Average annual service losses (g/yr)	1 cooling point	32.0	16.0	16.0	5.3	32.0	16.0	30.0	16.0	32.5	17.3
	2 cooling point	32.0	10.7	16.0	0.0	32.0	10.7	36.0	16.0	39.0	17.3
End of life (g)	1 cooling point	360.0	200.0	420.0	180.0	360.0	200.0	180.0	120.0	66.2	60.0
	2 cooling point	480.0	360.0	720.0	340.0	480.0	360.0	360.0	360.0	218.2	320.0
End of life recovery efficiency (%)		0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Average annual end-of-life losses (g/yr)	1 cooling point	24.0	13.3	28.0	12.0	24.0	13.3	12.0	8.0	4.4	4.0
	2 cooling point	32.0	24.0	48.0	22.7	32.0	24.0	24.0	24.0	14.5	21.3
Total average annual losses (g/yr)	1 cooling point	128.0	69.3	80.0	37.3	128.0	69.3	114.0	64.0	123.5	69.3
	2 cooling point	160.0	74.7	112.0	42.7	160.0	74.7	156.0	80.0	169.0	86.7

3.2. INDIRECT EMISSIONS

During MAC operation, the blower motor and the compressor draw power from the engine, which increases CO_2 emissions from the tailpipe of an internal combustion engine vehicle and electricity consumption in a BEV. Studies show that the compressor and its associated drive belt consume 77%–89% of the additional fuel consumed while operating a MAC system. This is followed by other components: blower, 6%–12%; cooling fan, 4%–10%; and compressor clutch, 0.7%–2% (Lee et al., 2013).

Indirect emissions depend primarily on the in-cabin cooling load and efficiency of the MAC system. New technologies can both improve system efficiency and reduce the overall cooling load, and these can provide a more than 45% reduction in indirect GHG emissions (Blumberg & Isenstadt, 2019). Though system mass is also a significant cause of indirect emissions, we assumed that all the new systems will be similar in mass.

Reducing emissions through MAC hardware improvements

The efficiency of MAC systems can be enhanced by making use of the latest advances in evaporator and condenser effectiveness and compressors, by implementing evaporator superheating and condenser subcooling, and by exercising control over cabin recirculation air. Efficient compressors and control strategies reduce the energy required to operate the MAC system. In a fixed displacement design, which has been common for years, compressors do not have much control over refrigerant volume and are either employed or disengaged to meet the passenger cabin cooling requirement. Variable displacement and variable speed compressors adjust the refrigerant volume according to the cooling requirement and significantly reduce engine load; variable displacement compressors are powered by the engine, while an independent electric motor generally powers variable speed compressors. Electric compressors are used on electric vehicles and the large battery pack supplies the electrical energy required by the MAC system.

Reducing emissions through vehicle body and in-cabin improvements

Reducing the amount of cooling required in a vehicle minimizes the power needed for the engine or battery to run the compressor and hence reduces the fuel consumption. This can be achieved by applying insulating materials like solar glazing on windows and solar reflective paint on the non-window surfaces of the vehicle's exterior, as they reduce heat absorption when under the sun (Lutsey & Isenstadt, 2018). Targeted in-cabin cooling through directly cooling passengers instead of cooling the entire cabin allows the temperature set on the AC to be higher while the occupants' comfort needs are still met, and this reduces the energy demand. Climate-controlled seating circulates air through the seat cushion and seatback such that heat is transferred away from the passenger and the passenger is directly cooled. Other strategies for cabin air ventilation include ambient air circulation into the cabin using naturally occurring airflow through vents and windows (Jeffers et al., 2015). Active and passive cabin ventilation allows cabin air heated by parking under the sun to escape the vehicle (Kreutzer et al., 2017). Table 4 is a list of technologies that reduce MAC cooling demand in a vehicle.

Table 4. MAC load-reduction technologies.

Improvements	Technology	MAC CO_2 emissions reduction (%)
MAC hardware	Variable displacement compressors	20%
	Improved controls for blowers and the fan motor	15%
	Control of cabin recirculation air	30%
	Internal heat exchanger	20%
	Improved evaporator and condenser effectiveness	20%
	Coolant recirculation (thermal ballast) used in SL systems	10%–11%
Vehicle body and in-cabin improvements	Solar glazing, and solar reflective paint combined with insulation in all cabin surfaces	18%
	Active and passive cabin ventilation	0.4%–0.8%
	Seat ventilation	7.50%
	Active seat cooling	12%–22%

Source: U.S. Environmental Protection Agency and National Highway Traffic Safety Administration (2010); and Blumberg and Isenstadt (2019). Note that MAC CO_2 emissions reductions are not additive due to overlapping benefits and because the baseline is reduced every time additional technology is applied.

Reducing emissions through powertrain optimization

Powertrain optimization reduces indirect emissions by operating compressors during deceleration and engine-off coasting and by shutting off compressors during peak acceleration. Mild hybrid systems can also provide the power required for electric compressors and there are substantial advantages associated with controllable compressor speeds. Compressors can be selectively loaded to the engine when the latter is at a more efficient operating point. Integrating these techniques into MAC system design will reduce fuel use for conventional vehicles and extend the battery range of PHEVs and BEVs.

3.3. EMBODIED EMISSIONS

A small number of emissions are generated during the manufacturing of refrigerants and hardware components. These can be relatively more significant for alternative refrigerants that are more complex and energy-intensive to manufacture, such as R1234yf (Sherry et al., 2017). For each kg of R1234yf produced, about 10.4 kg of CO_2e

emissions are emitted during chemical processing (Baral et al., 2013) and there are 3.1 kg of CO_2e from energy consumption, totaling 13.5 kg CO_2e per kg. The manufacturing process of R152a is more straightforward and not energy-intensive. Thus, it is assumed that R152a production emits similar upstream emissions as R134a – 5 kg CO_2e per kg produced. Charge size also impacts embodied emissions and the smaller charge of R152a lowers its impact (Du et al., 2016).

In R744-based MAC systems, the refrigerant is created using existing chemical processes or through dedicated combustion of fossil fuel. The emissions associated with capture, refining, compression, and transportation of CO_2 were found to be 0.5 kg CO_2 per kg of refrigerant produced (Johnson, 2004). Our analysis assumed that the embodied emissions from hardware manufacturing, including pipes, hoses, connectors, and heat exchangers, are all roughly comparable among the refrigerants studied.

Table 5. Data used to estimate embodied emissions in this analysis.

Refrigerants	Source of embodied emissions	DX, 1 point (kg CO_2e)	DX, 2 point (kg CO_2e)	SL, 1 point (kg CO_2e)	SL, 2 point (kg CO_2e)
R134a	**Initial**	2.5	4.5	1.7	3.0
	Recharge	5.0	10.0	2.5	4.5
R134a, enhanced	**Initial**	2.5	4.5	1.7	3.0
	Recharge	2.5	5.0	0.8	1.5
R152a	**Initial**	1.8	3.6	1.2	2.4
	Recharge	4.5	12.5	2.4	4.8
R1234yf	**Initial**	6.5	13.0	4.3	8.6
	Recharge	13.0	27.0	6.0	13.0
R744	**Initial**	0.2	0.4	0.1	0.3
	Recharge	0.5	1.3	0.3	0.5

4. RESULTS

4.1. LIFETIME GHG EMISSIONS

Figure 2 shows our estimates of lifetime GHG emissions from MAC for the baseline and the four alternative refrigerants, including direct emissions from leakage into the atmosphere and indirect emissions from the energy required to run the MAC system; for all this includes 45% improvement in MAC efficiency technology. Note that while embodied emissions are not included in the figure, they are small compared to indirect emissions: a maximum of 27 kg CO_2e for 1234yf compared with about 1,000 kg CO_2e from indirect emissions.

As the figure illustrates, the most significant climate benefits are provided by using R1234yf in a DX system or R152a in an SL system; both offer roughly equivalent emissions benefits. R744 is a less compelling option for India's higher average temperatures due to higher indirect emissions and fuel consumption. (Recall, also, that we assumed a temperature range of 32–38 °C because that data was available.) However, R744 still offers significant climate benefits compared to baseline R134a due to much lower lifetime direct GHG emissions.

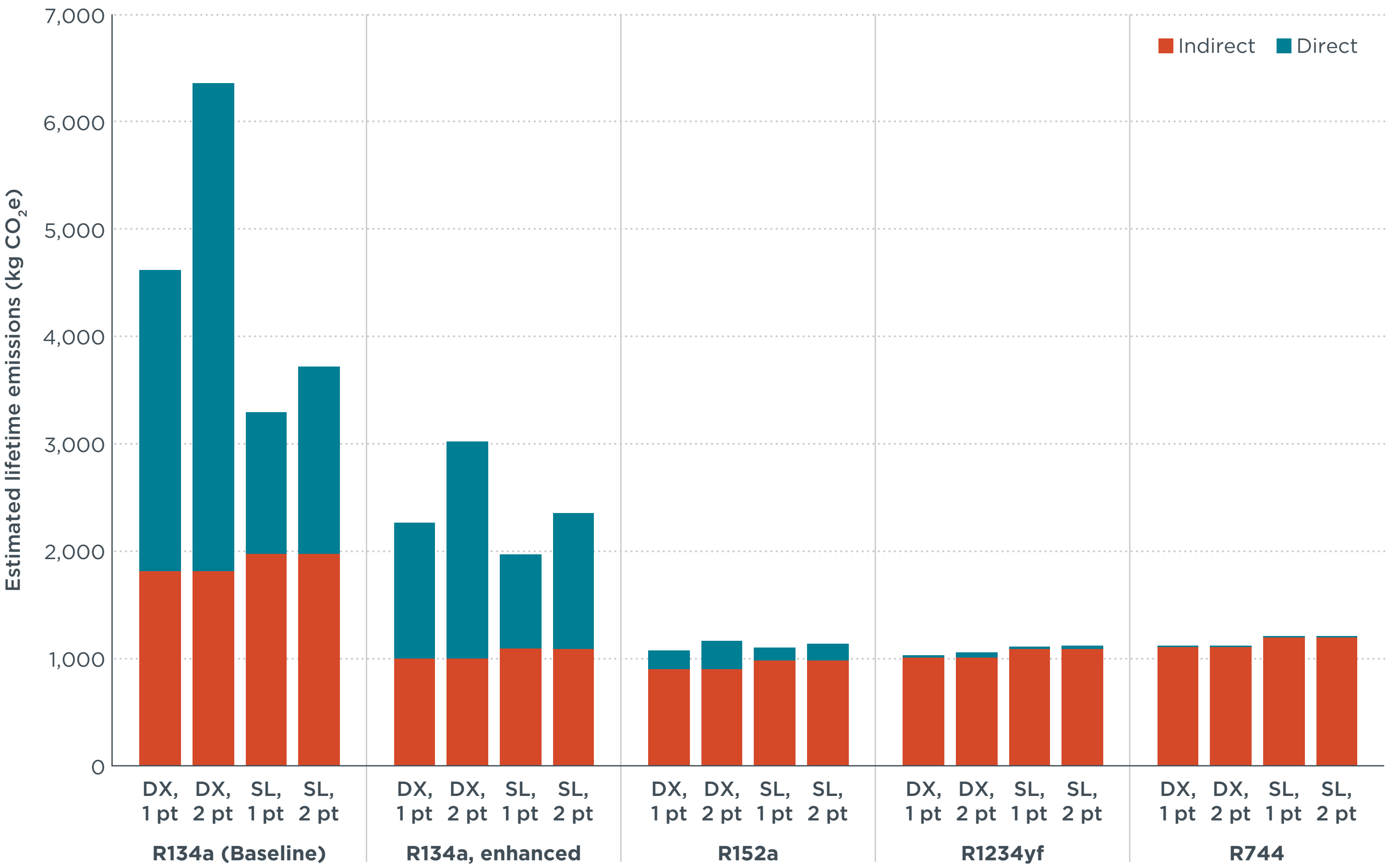

Figure 2. Estimated lifetime MAC emissions for baseline R134a and the alternative refrigerants assuming a temperature range of 32–38 °C.

Note: 45% MAC efficiency improvement technologies included for all four alternative systems.

Direct emissions are more than 50% of lifetime emissions for R134a-based DX systems, including the enhanced R134a system. This is because of the high GWP of the refrigerant (1,300) and the lower vehicle kilometers traveled in India.

For all alternative refrigerants, we find that lifetime emissions are lower by 3,500–5,500 kg of CO_2e, or 75%–85%. The sharp reduction is because these have such low GWP that they virtually eliminate direct emissions. Recall that SL MACs have lower direct emissions than DX MACs simply because of lower refrigerant charge size; this reduces the climate impact of R134a and R152a SL systems but has virtually no effect on R1234yf or R744 systems because the direct emissions of the latter two refrigerants are already quite low.

Indirect emissions from R152a, R744, and R1234yf systems are approximately equal over the 15-year lifetime, around 1,000 kg CO_2e emissions. According to COP figures, R152a performs better than R134a by 6% to 19% (Andersen et al., 2017). Therefore, a smaller charge size of R134a in SL configurations would not be expected to provide the required cooling performance and that could reduce the likelihood of customers recharging with R134a during service events.

Note, too, that because temperatures in India are generally higher than the range assumed for this analysis, the indirect emissions are expected to be much higher than shown, especially for R744-based MAC systems. While the impacts of the higher temperatures cannot be illustrated here because of lack of data, the physical properties of R744 would lead to higher indirect emissions at higher temperature.

Figure 3 shows the direct emissions reduction estimates for single cooling point systems relative to an R134a system. This is derived from the blue portions of the columns in Figure 2 and recall that SL systems are needed in R744- and R152a-based MACs to protect passenger safety. R1234yf and R744 systems have very low GWP and achieve a greater than 99% reduction; R152a reduces these emissions by more than 90% and the enhanced R134a system reduces emissions by only 37.5%.

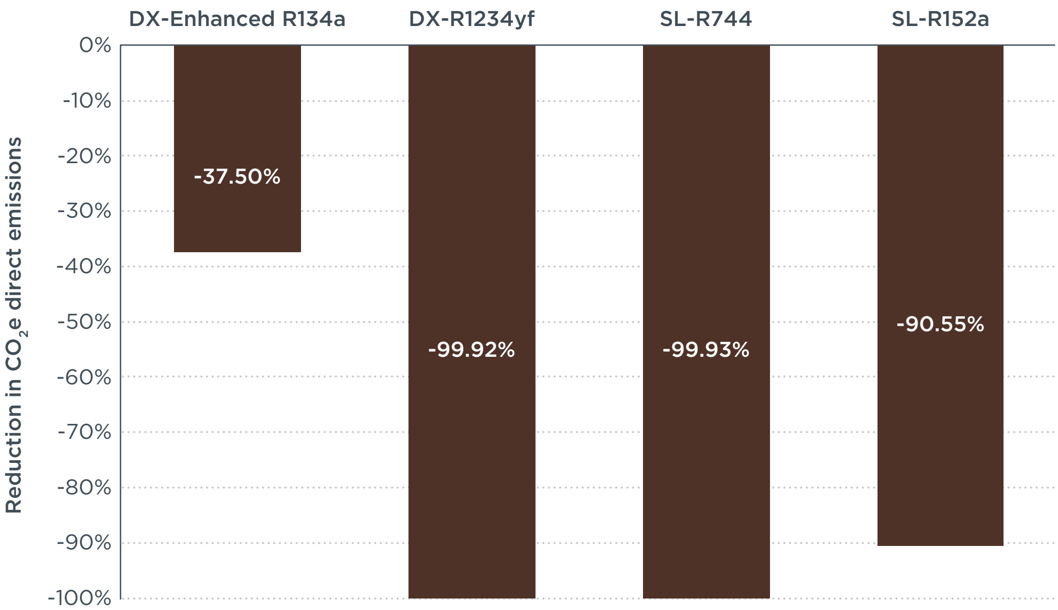

Figure 3. Estimates of direct GHG emissions reductions relative to baseline R134a for single cooling point MAC systems.

4.2. DIRECT MANUFACTURING COST

ICCT previously studied the cost of phasing out R134a with low-GWP refrigerants in China (Du et al., 2016) and for temperate and hot climates (Blumberg & Isenstadt, 2019). Both studies found that when compared with baseline R134a systems, low-GWP refrigerants require some additional cost due to the cost of the refrigerant and changes to hardware to accommodate different refrigerants. Two categories of costs were identified: (1) the one-time cost to manufacturers during vehicle production and (2) the cost to the owner during the vehicle's lifetime. Here we present our estimates of these costs for typical vehicles in India. We assumed that the disposal of refrigerants does not incur any cost or the cost is negligible and thus it is not included.

R134a (the baseline)

The cost to manufacture an R134a MAC system in 2021 was previously estimated to be $190 or ₹14,212 (Blumberg & Isenstadt, 2019). The retail price for R134a fluctuates with market supply and demand and by late 2021, it averaged around $6/kg or ₹450/kg in India (Indiamart, 2021). In this analysis, we calculated the refrigerant cost to vehicle manufacturers using a retail markup of two (i.e., the manufacturer's cost is half of the retail price). The initial charge cost for a car with a 480 g MAC system was assumed to be about $1.6 (₹120) in 2021. Combining the upfront manufacturing cost of the unit and the initial refrigerant charge added up to about $192 or ₹14,330. Because R134a systems are a mature technology and have been used in vehicles for many years, only minimal reduction in future technology costs is expected. It was assumed for this analysis that costs associated with R134a systems will remain the same in 2025.

For the refill cost of refrigerants at the service center, we assumed that the cost of the refrigerant is about two times the bulk cost to manufacturers, about $2.9 or ₹217 for the refrigerant. One standard service job that includes system recharge takes about 1 hour. Moreover, service costs in India are cheaper than in developed countries; the labor rate is fixed for refilling and varies between ₹2,000–₹3,500, depending on the vehicle. Here we estimated $30 (₹2,244) in labor cost for each service event (TeamBHP, 2021). As mentioned in Table 3, a DX system with one cooling point is estimated to need four refill service events during its lifetime due to coolant leakage. Total lifetime service costs for labor and refrigerant are thus $126 (₹9,425). Note that only about half of the refrigerant is replaced during a service event, so the higher cost of the refrigerant is primarily offset by the smaller refill amount.

Table 6, below, presents a summary of total estimated costs for R134a and the other alternatives.

R152a

Although current use of R152a is limited, many of the hardware components that would be used in an SL R152a system are similar to those being used today for R134a and R1234yf systems. The primary loop of the SL system for R152a should use a smaller refrigerant charge and shorter piping, thus reducing some cost. In the case of two cooling points, the SL system does not require additional refrigerant hoses, evaporators, and fittings as a two-point DX system would. Recall that SL systems are still only a concept. In this analysis, the cost to manufacture SL systems is estimated as $35 (₹2,625) for one cooling point and $70 (₹5,250) for two cooling points. The technology cost of an SL system was assumed to decline by 2% each year through 2030, then 1% each year through 2035; after that the cost was assumed to remain flat.

The retail price for this refrigerant was assumed to be similar to that of R134a in 2021 at approximately $5.7/kg or ₹426/kg. Using a retail markup of two, a total system charge size of 360 g for the refrigerant would cost the manufacturer $1.2 (₹90). This analysis assumed that R152a costs will drop by 3% each year until 2025 (Du et al., 2016). The incremental DMC for R152a system hardware relative to baseline R134a in 2021 is ₹4,370 for SL systems. Labor cost is identical to the baseline system, which is ₹2,244 per service job.

R1234yf

R1234yf's refrigerant cost is 10 times higher in India than it is for R134a and R152a due to protection by patents, including those held by Honeywell and Chemours (Papasavva & Moomaw, 2014). After the patent claims expire, the cost difference is expected to drop substantially, as a result of the economy of scale achieved with more producers involved (Seidel & Ethridge, 2016).

R1234yf hardware is estimated to cost somewhat more than R134a hardware due to the need for an internal heat exchanger to compensate for the lower cooling capacity. As the R1234yf system is a nearly drop-in solution, the average time spent for servicing is assumed to be the same as the baseline R134a system.

The U.S. Environmental Protection Agency (2012) estimated approximately $120/kg for incremental refrigerant costs and hardware changes for R1234yf. A similar analysis by the California Air Resources Board (CARB, 2011) used a retail price of $138/kg. The studies resulted in an R1234yf refrigerant cost to the manufacturer of $76–$87 on a 480 g system. According to Indiamart (2021), the commercial cost of the refrigerant to the manufacturer was $7/kg (₹5,909/kg). The hardware incremental cost was estimated to be $47 (₹3,516) in 2021. We conservatively assumed that the service cost of the refrigerant is two times the bulk cost to manufacturers. We also assumed that refrigerant and incremental hardware costs drop by 3% each year until 2025, by 2% per year through 2030, and by 1% per year through 2035 before becoming flat. Bulk and retail prices are expected to drop because of the economy of scale achieved with more producers involved and cheaper labor cost in India. Also, the labor cost of ₹2,244 per service job is used.

R744 systems

An R744 system requires about six to eight times higher operating pressures than an R134a system (Minjares, 2011). The new design, high tooling costs, and safety system costs of an R744-based MAC system relative to other refrigerant systems means it is likely to have limited commercialization in India. The EPA and the National Highway Traffic Safety Administration (2012) estimated that accommodating R744 would require an additional $140 to $210. The refrigerant cost of R744 is considerably less than the other alternative refrigerants and its price is primarily associated with storage and transportation. The retail cost of R744 ranges from approximately $1/kg to $5/kg (Blumberg & Isenstadt, 2019). In this analysis, the hardware DMC cost incremental to baseline R134a was assumed as $133 (₹9,948) and the refrigerant cost to the manufacturer was assumed to be $0.33 (₹25) on a 390 g system in 2021 for a one-point cooling system. Because R744 systems are still emerging, it is reasonable to assume the technology is in the steep portion of the learning curve for the first few years, and the same learning curve applied to R1234yf systems was used. The refrigerant cost at service stations was assumed to be two times the bulk cost for manufacturers, and once more, the labor cost is identical to the baseline R134a system.

Table 6. Summary of direct manufacturing cost estimates for R134a (baseline) and the alternative refrigerant systems.

Refrigerant	Hardware cost (₹)	2021				2025			
		DX, 1 pt	DX, 2 pt	SL, 1 pt	SL, 2 pt	DX, 1 pt	DX, 2 pt	SL, 1 pt	SL, 2 pt
R134a (baseline)	**Initial charge (₹)**	110	221	74	147	110	221	74	147
	Hardware (₹)	14,212	17,952	14,212	14,212	14,212	17,952	14,212	14,212
	Total cost (₹)	**14,322**	**18,173**	**14,286**	**14,359**	**14,322**	**18,173**	**14,286**	**14,359**
R152a	**Initial charge (₹)**	77	155	52	103	68	137	46	91
	Hardware (₹)	16,332	20,072	17,103	19,352	16,089	19,829	16,771	18,762
	Total cost (₹)	**16,409**	**20,227**	**17,155**	**19,455**	**16,157**	**19,966**	**16,817**	**18,853**
R1234yf	**Initial charge (₹)**	1,425	2,850	950	1,900	1,262	2,523	841	1,682
	Hardware (₹)	17,746	21,486	19,994	22,243	17,340	21,080	19,331	21,322
	Total cost (₹)	**19,171**	**24,336**	**20,944**	**24,143**	**18,602**	**23,603**	**20,172**	**23,004**
R744	**Initial charge (₹)**	25	50	17	33	22	44	15	30
	Hardware (₹)	22,757	26,497	25,005	27,254	21,777	25,517	23,767	25,758
	Total cost (₹)	**22,782**	**26,547**	**25,022**	**27,288**	**21,799**	**25,561**	**23,782**	**25,788**

4.3. CONSUMER OWNERSHIP COSTS

Fuel consumption depends on the MAC system and engine efficiency. Most of the ownership expense of a vehicle is from in-use fuel consumption. The price of gasoline varies considerably and recently reached its highest price ever in India. For the analysis of ownership costs across the alternative MAC systems here, the gasoline price assumed for India was ₹100 per liter. As Table 7 shows, by comparison, refrigerant and service costs have a relatively small effect on lifetime cost, and fuel savings of approximately ₹40,000 are realized by using alternative refrigerants over the 15-year life at the 10,000 km per year assumed, which is based on annual distance traveled by an average midsize car. The total lifetime cost estimates are illustrated in Figure 4.

Table 7. Estimates of 15-year lifetime operational costs for new cars sold in 2021 using the different MAC refrigerants in India

Refrigerants	Type, number of cooling points	Fuel consumption cost (₹)	Recharge cost (₹)	Service cost (₹)	Operational + service cost (₹)	Recharge events needed
R134a (Baseline)	DX, 1 pt	76,333	442	8,976	85,750	4
	DX, 2 pt	76,333	883	8,976	86,192	2
	SL, 1 pt	82,821	221	6,732	89,774	3
	SL, 2 pt	82,821	442	6,732	89,994	1
Enhanced R134a	DX, 1 pt	29,182	221	4,488	33,891	2
	DX, 2 pt	29,182	442	4,488	34,111	1
	SL, 1 pt	28,306	74	2,244	30,624	1
	SL, 2 pt	28,306	147	2,244	30,697	0
R1234yf	DX, 1 pt	29,310	5,700	8,976	43,986	4
	DX, 2 pt	29,310	11,400	8,976	49,686	2
	SL, 1 pt	28,431	2,850	6,732	38,013	3
	SL, 2 pt	28,431	5,700	6,732	40,863	1
R152a	DX, 1 pt	26,264	450	11,220	37,934	5
	DX, 2 pt	26,264	900	11,220	38,384	3
	SL, 1 pt	25,475	240	8,976	34,691	4
	SL, 2 pt	25,475	480	8,976	34,931	2
R744	DX, 1 pt	32,100	76	11,220	43,396	5
	DX, 2 pt	32,100	152	11,220	43,471	3
	SL, 1 pt	31,137	40	8,976	40,153	4
	SL, 2 pt	31,137	81	8,976	40,193	2

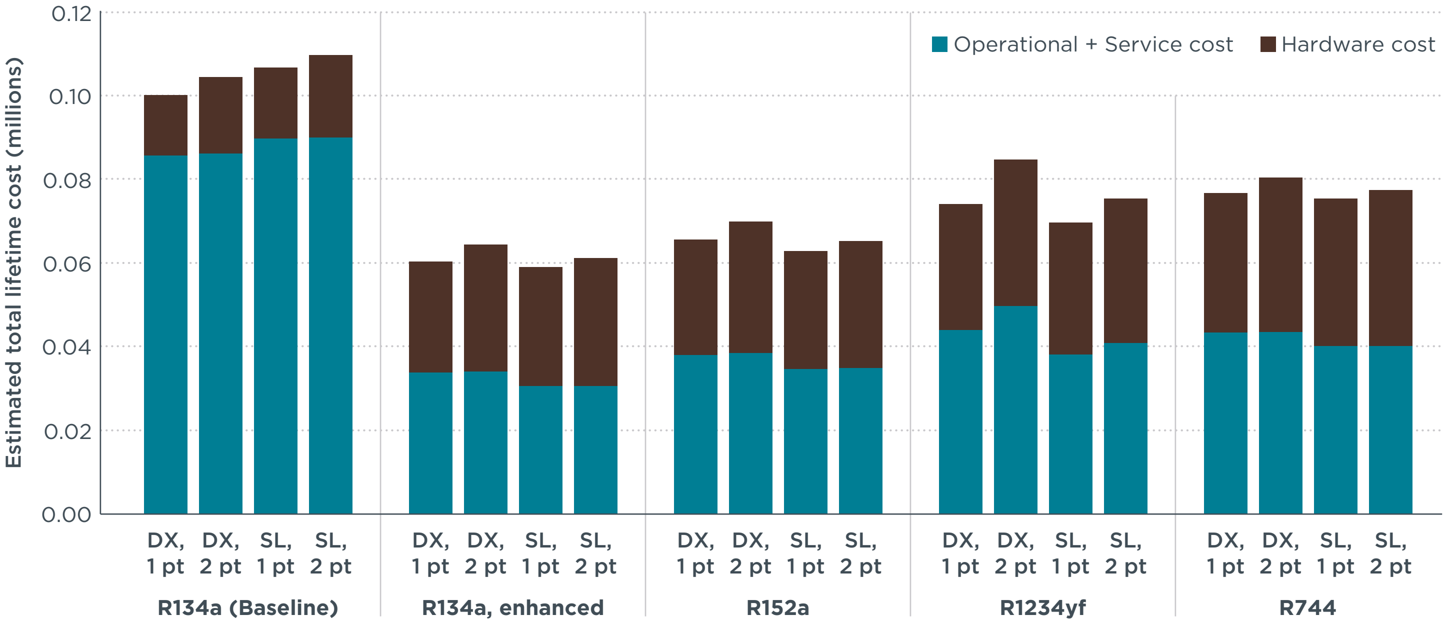

Figure 4. Estimated total lifetime cost for the different MAC refrigerants in India.

Note that the analysis Table 7 and Figure 4 assumes that all currently available efficiency-improving technologies are incorporated for each of the alternative MAC systems. Hardware costs include load reduction technologies for actively cooled seats, cabin ventilation, solar glazing, solar paint, and cold storage evaporator.

These results suggest that, conservatively, alternative MAC systems offer at least as much fuel savings to consumers as an enhanced R134a system, with substantially reduced GHG emissions. This is primarily due to the increased efficiency for all alternatives and the less frequent service of SL-MAC systems, and it means that the first owners of the new MAC systems would be expected to see savings within their 5 to 7 years of ownership. Even if the cost of reducing the cooling load were double the assumed estimates, drivers would still be expected to see payback before the end of the first ownership of the vehicle. Thus, both consumers and the environment benefit from low-GWP systems with alternative refrigerants.

Recall that our analysis of emissions is based on ambient temperatures between 32 and 38 °C because there is data available for that range. In the higher ambient temperatures common in India, the lifetime costs for R744 systems will be higher than shown in the chart. Also, the high hardware cost is a significant contributor to the higher total cost of R744 systems. The system needs much higher compression pressure than the baseline system and this will also increase the indirect CO_2 emissions, because of the higher load on the engine to power the compressor. For R1234yf systems, the price of the refrigerant is currently the main reason for its higher cost. R1234yf can be expected to remain costly in India until the patents expire, are set aside by the patent holders, or are legally defeated/invalidated. Until the upfront price comes down, R1234yf is not likely to be applied by manufacturers in any cost-competitive vehicle segments in India and, at best, might only be used in premium models (Deo & Callahan, 2022).

5. CONSIDERATIONS FOR MAC OFF-CYCLE CREDITS

Because the MAC system has been identified as one of the most critical factors in the growing gap between CO_2 regulations and real-world emissions performance (Fontares et al., 2017), it is important that India start including MAC operations in its fuel consumption standards. Manufacturers will face higher DMC costs for new hardware development when they switch to alternative refrigerants (shown in Table 6), and thus policies should be designed to reward the use of more-efficient and low-GWP refrigerants. Setting off-cycle credits for these would help the most-efficient strategies to reach economies of scale faster, with substantial benefits for the climate. This section reviews MAC efficiency improvement regulations adopted in various countries and then recommends off-cycle credits for India.

5.1. MAC OFF-CYCLE CREDITS IN MAJOR AUTO MARKETS

United States

The United States proactively implemented comprehensive norms that incentivize MAC efficiency improvements and load reductions by granting credits for reducing GHG emissions from MAC systems. These are independent of the fuel consumption standards because the EPA's Federal Test Procedure (FTP) used for vehicle regulatory purposes is conducted without the AC running. To verify that vehicles qualify for credits for their MAC systems and thermal technologies, the EPA introduced test cycle AC17, which runs under high solar loading, high ambient temperature, and high humidity conditions. The maximum credit available for passenger cars for high MAC efficiency is 3.1 g/km, and for low-GWP refrigerant it is 8.6 g/km (Yang & Bandivadekar, 2017).

European Union

The July 2021 proposal from the European Commission for post-2025 CO_2 standards for new passenger cars and vans allows improvements to AC systems to be counted as "eco-innovations" (European Commission, 2021). The credits are only for indirect efficiency improvements, as the European Union already limits the GWP of refrigerants. To qualify for these credits, the automaker must submit a report, including a verification report by an independent and certified body. Eco-innovation credits are currently capped at 7 g/km, but the regulatory agency is empowered to adjust the cap from 2025 onward (Dornoff et al., 2021).

China

China also regulates refrigerants and MAC efficiency technologies. China's MAC off-cycle credits regulation for indirect efficiency improvements, implemented in May 2022, allows up to a maximum credit of 0.2 L per 100 km (Yang et al., 2022). As this is part of China's corporate average fuel consumption standards, it applies only to conventional combustion engine passenger cars and not to electric vehicles.

5.2. COMPARISON OF LOW-GWP REFRIGERANT COSTS WITH EXISTING OFF-CYCLE CREDITS IN INDIA

Under India's current vehicle type-approval compliance provisions, manufacturers can use off-cycle credits for four technologies: regenerative braking, start-stop systems, tire-pressure monitoring systems (TPMS), and 6-speed or more transmissions. MAC energy consumption is not yet covered by laboratory testing procedures in India. It also has no bearing on whether a vehicle is fuel-efficient during the laboratory tests and therefore automakers are unmotivated to increase MAC energy efficiency. Table 8 shows that the CO_2 savings from using low-GWP refrigerants are significant when compared with the CO_2 benefits of existing off-cycle credit technologies, and the cost per g CO_2 saved by using alternative refrigerants is significantly lower than the present technologies. Moreover, the fuel consumption of passenger cars has steadily improved since India's fuel consumption standards were first implemented. As vehicle efficiency is expected to continue to improve, MAC energy consumption as a percentage of total energy consumption will rise further; this makes this technology even more important for CO_2 reduction.

Table 8. Comparison of CO_2 savings from low-GWP refrigerants and technologies that currently qualify for off-cycle credits in India.

		DMC cost (₹)	CO_2 savings (g)	₹ / gCO_2
Off-cycle credits	Start stop + regenerative braking	3,517	6.1	581
	Tire pressure monitoring system	1,799	3.0	600
	6-speed transmission	2,151	2.4	896
Low-GWP refrigerant	R1234yf (DX)	4,390	16.6	264
	Enhanced R134a (DX)	653	6.2	105
	R744 (SL)	9,570	16.6	576
	R152a (SL)	2,605	15.1	173

Regarding the efficacy of the existing credits, TPMS could be regarded more as safety requirement, as it is in the United States and the European Union. Additionally, regenerative braking, start-stop, and 6-speed (automated transmissions) already contribute during standardized test procedures. These technologies could be removed from off-cycle credits and replaced with technologies that are making significant contributions in real-world conditions not captured by the test procedures.

5.3. SUGGESTED MAC OFF-CYCLE CREDITS FOR INDIA

The second phase of India's fuel consumption regulations began on April 1, 2022. The fuel consumption standard could be amended at any time to include a provision that allows manufacturers to earn credits for implementing technologies that reduce direct and/or indirect emissions from MAC.

Offering credits for reducing direct emissions would yield climate benefits that are significant and cost-effective. In Figure 5, the credits are shown in terms of g/km saved, in other words, the difference between the total lifetime emissions of alternative refrigerants and R134a over total kilometers traveled in a vehicle's assumed life of 15 years. As SL systems are currently only a concept and have not been applied in any production vehicles, the analysis focused only on a DX system. As you can see, one credit given for each gram of direct emissions avoided in a system with a single cooling point can mean total credit of up to 16 g CO_2/km for R1234yf and R744 refrigerants and 15 g CO_2/km for R152a refrigerant. The credits are somewhat higher for systems with two cooling points.

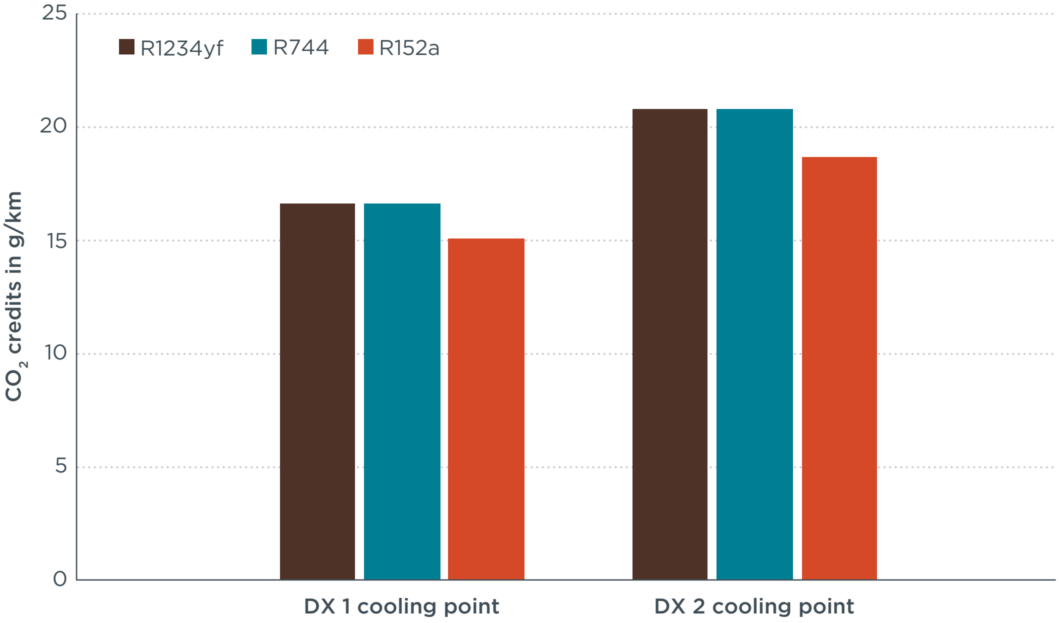

Figure 5. Average direct CO_2 emissions reduction from alternative refrigerants, with each g of CO_2 avoided counting as one credit.

Introducing off-cycle credits in India could also spur changes to the current R134a MAC systems. Engineering leak-tight fittings is a cost-effective measure that can be implemented immediately to reduce direct emissions by 38%, or up to 6 g CO_2/km. Credits for leak-tight designs are offered in other markets for all refrigerants, proportional to the refrigerant's GWP, and they depend on compressor technology and pipe and hose designs. In the United States, the EPA uses a leak score derived from SAE's J-2727 scoring system to determine the off-cycle credits (EPA & NHTSA, 2012). For systems that use low-GWP refrigerants, there is a high-leak penalty of up to 1.1 g/km for any designs with a leak rate higher than the average of the initial charge per year.[5] While leakage of low-GWP refrigerants does not have much impact on direct emissions, substantially reducing leakage means less need to recharge and therefore lower risk of consumers recharging with higher-GWP refrigerants (EPA, 2012).

Adding credits for improving MAC efficiency to reduce indirect emissions can be done irrespective of the refrigerant. The MAC efficiency improvement technologies listed above in Table 4 have the potential to reduce indirect emissions by 45%. To consider indirect emissions reduction credits for India, our analysis started from the fleet average value of 121.3 gCO_2/km for passenger vehicles in India in FY 2020–21 as the baseline. Recall that fleet average tests are conducted over standardized test cycles during which the MAC is not switched on. Additionally, the fuel used by MAC is more than 20% higher in hot and humid climates like India (Chidambaram, 2010). Using efficiency and coolant-load-reduction technologies, it is expected that MAC CO_2 consumption can be reduced by up to 8% of the certified emission level for an individual vehicle. Note that this 8% credit is based on percentage reduction in CO_2 emissions from the certified emissions of individual vehicles and is not a fixed g/km adjustment.

While reductions in direct emissions are simply a function of the GWP, when offering credits for reduction of indirect emissions, it is important to validate that the efficiency improvements actually achieve reductions in emission during real-world driving. For this, the EPA developed the AC17 cycle explicitly to test MAC systems and vehicle-load-reduction technologies to verify credit applicability. As mentioned above, the AC17 cycle is run under high solar loading, high ambient temperature, and

5 The grams per mile is converted to grams per kilometer by using conversion factor 1 mile = 1.609 kilometer

high humidity conditions. Any indirect credits offered by India could be validated with a similar procedure.

Table 9 is a summary of suggested CO_2 credits for both alternative refrigerants and high-efficiency MAC systems.

Table 9. Summary of MAC credits suggested for India's fuel consumption standards.

MAC system	Direct credits	Indirect credits
R744, R1234yf	Up to 16 g CO_2/km	Up to 8% of certified emission level (should be validated on the AC17 cycle or an equivalent cycle)
R152a	Up to 15 g CO_2/km	
Enhanced R134a	Up to 6 g CO_2/km (should be validated)	

6. CONCLUSION

India's passenger vehicle fuel consumption standards do not currently consider the GHG emissions from refrigerants, but they can be amended to do so, and many other large vehicle markets already do this. Any new regulatory incentives for reducing these emissions should be able to provide maximum benefits at an affordable cost, however, and this is not necessarily straightforward. Focusing on incentivizing efficiency alone might neglect the significant environmental impact of refrigerant leakage, and at the same time, focusing on low-GWP refrigerants alone might result in less-efficient systems that mean higher indirect emissions and higher fuel costs over the vehicle's lifetime. To help, this paper analyzed the direct and indirect emissions and manufacturing and operational costs of alternative low-GWP refrigerants in MAC systems over a 15-year operating lifetime in India.

For all of the alternative refrigerants considered, their low GWPs mean that direct emissions were virtually eliminated compared to the currently dominant R134a. This is important in India, where direct emissions are a significant share of lifetime MAC emissions because vehicles tend to be driven less than in other major vehicle markets. Additionally, vehicle manufacturers like Maruti Suzuki and Hyundai are already exporting vehicles made in India to the United States, the European Union, and Japan, where regulations allow only low-GWP refrigerants. This means that the know-how and infrastructure necessary to produce low-GWP refrigerants are already in India.

Based on this analysis, R152a in SL systems and R1234yf in DX systems are the two most advantageous alternatives for the Indian market. Recall, though, that SL systems are still a concept. Given that, R1234yf currently holds the most promise. While the R744 refrigerant also significantly reduces direct CO_2 emissions, the much higher compression it requires in India's climatic conditions substantially increases both its hardware cost and the amount of fuel consumption and indirect CO_2 emissions.

An SL system is proposed for R152a because of flammability concerns, as the system isolates the refrigerant circuit from the vehicle's passenger cabin. SL MAC systems also have the advantage of having shorter loops of high-pressure refrigerants passing through pipes and hoses. R1234yf, meanwhile, is a near drop-in substitute for R134a, but currently has a high cost in India because of patents. The patents are due to expire in the 2023 to 2025 time period, but any expectations of future price drop must be considered tentative because there are patents pending that would last several years more than that (Center for Science and Environment, n.d.).

Manufacturers can reduce indirect emissions through a variety of strategies and we estimated that total reductions can be as high as 45%. Therefore, Indian regulators should consider incentivizing manufacturers by providing off-cycle CO_2 credits for indirect emissions reduction technologies of up to 8%. To prevent gaming, though, indirect credits should be validated on a test procedure similar to the AC17 used by the EPA.

Finally, results show that low-GWP refrigerants are more cost-effective in reducing CO_2 emissions than the technologies that currently qualify for off-cycle credits in India. The cost-effectiveness of per gCO_2/km reduction just for direct emissions through low-GWP refrigerants is lower than start-stop, regenerative braking, TPMS, and 6-speed transmission. Based on this analysis, we suggest that granting CO_2 credits of 16 gCO_2/km for R744 and R1234yf refrigerants, 15 for R152a, and up to 6 for enhanced R134a would be reflective of the emissions reductions achieved.

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