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**Life cycle costs and benefits of mobile air conditioning systems
with low-global warming potential (GWP) refrigerants and
improved efficiency**

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Executive summary

Motor vehicle air conditioning systems, also known as mobile air conditioning (MAC) systems, are a significant source of greenhouse gas (GHG) emissions. The fuel used to run MAC systems has been estimated to be 3-7% of that used by the global light-duty fleet, but MAC use can account for up to 20% of fuel use in congested and hot, humid climates (Chaney et al., 2007; Yang et al., 2018). In fact, GHG emissions associated with MAC systems are dominated by indirect emissions, emissions of CO₂ associated with the energy required to run the AC system, which account for about 81% to 88% of the GHG emissions. The direct emissions that make up the rest are associated with leakage of the refrigerant used in the system—the leading refrigerant globally, R134a, has a global warming potential (GWP) 1300 times higher than CO₂. As MAC systems spread globally, as the world warms from climate change, and as vehicle fleets grow (with all three factors exacerbated in many regions that already have hot and humid climates), the importance of targeting GHG emissions from MACs becomes more critical.

The Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer, ratified in 2016, requires the phase-down of HFC refrigerants, including those still used in MAC systems, and also targets improvements in energy efficiency. On battery electric vehicles, climate control energy consumption represents a marked decrease in range. Thus, as governments seek to fulfil their climate goals and reduce emissions from the transport sector through electrification, improving MAC energy efficiency is necessary to ensure real-world benefits.

In the past, ICCT has focused on refrigerant switching, and its effect on direct emissions of refrigerant (Minjares, 2011; Baral et al, 2013; Du et al, 2016). For this paper, we collected recent

data and estimates available on alternative refrigerants—R744 (CO₂) and R1234yf, both with GWP of 1, and R152a, with a GWP of 138—as well as on technologies that reduce MAC energy requirements. We examined all three alternative refrigerants as well as the current leading refrigerant, R134a, in both direct expansion (DX) and secondary loop (SL) configurations, employing load reduction and powertrain optimization strategies, for use with single or multiple cooling points and in different climates. Secondary loop systems are an alternative configuration to the direct expansion systems in current use. While they reduce the overall system efficiency, SL configurations can provide other benefits including reduction of direct emissions and costs. And while all refrigerants were considered in both DX and SL systems for comparison sake, SL offers safety improvements which are assumed to be required for the more flammable R152a.¹

Combining these data, this paper examines MAC system lifetime costs and GHG benefits of switching to lower-global warming potential (GWP) alternative refrigerants *and* improving system efficiency. It became clear through this analysis that the benefits offered by different refrigerants and systems depends on ambient climate conditions. In temperate climates, R744 (CO₂) in a DX system offers the greatest GHG benefits. At higher ambient temperatures, the greatest benefits are offered by R1234yf (DX) or R152a (SL), both of which offer roughly equivalent emissions benefits. Of course, these latter two options each face potential issues in terms of climate goals. R1234yf systems can be illicitly recharged with the significantly cheaper R134a, all but eliminating the benefits of the refrigerant switch. R152a is a better refrigerant than R134a in terms of energy efficiency and GWP but does not achieve the extremely low GWP of R1234yf or R744.

As seen in Figure ES 1 and ES 2, changes in refrigerants along with other improvements in system efficiency can cut per-vehicle GHG emissions associated with MAC system use by up to 70% compared to older, non-enhanced systems, and approximately in half compared with enhanced systems already available throughout the world. MAC GHG emissions are almost three times greater in higher temperature climates (note the different scales in Figure ES 1 and Figure ES 2), and energy efficiency improvements become even more important under these conditions.

¹ The secondary loop system allows the refrigerant to be isolated from the passenger cabin, with a separate coolant used in the cabin.

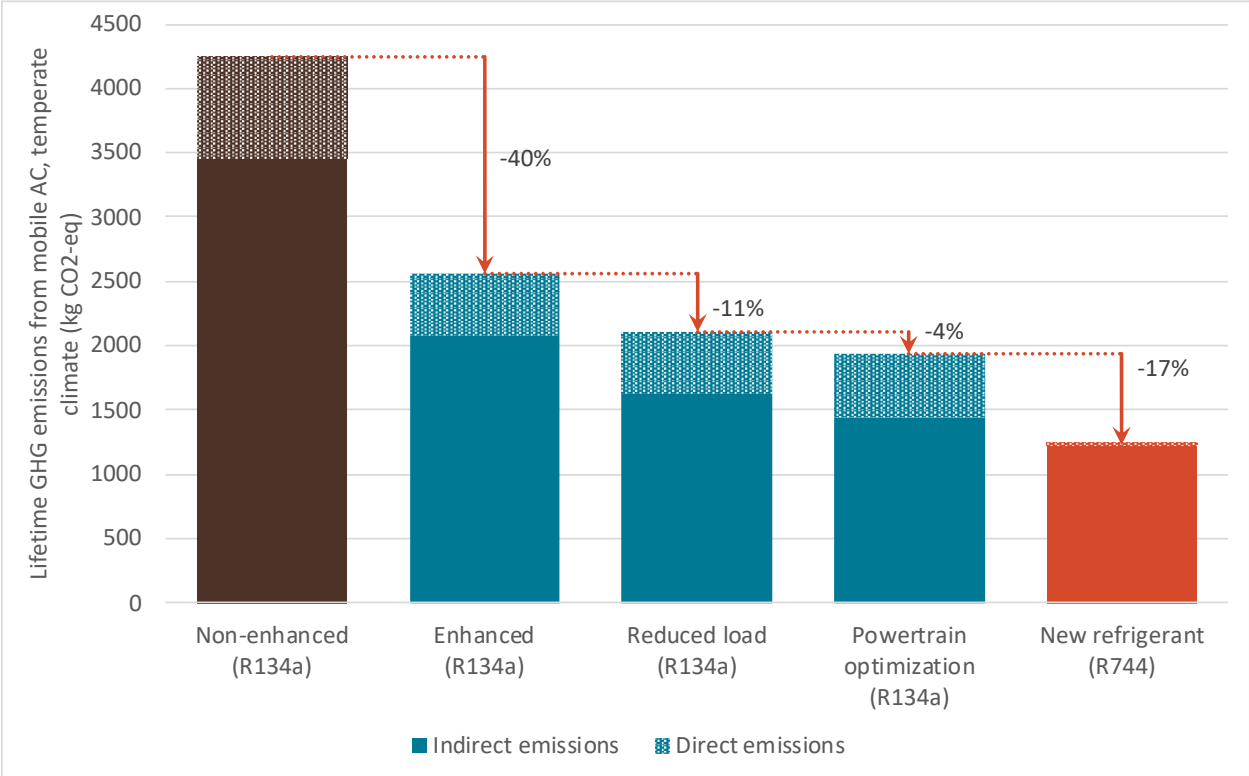


Figure ES 1. GHG reduction potential at temperate climate conditions

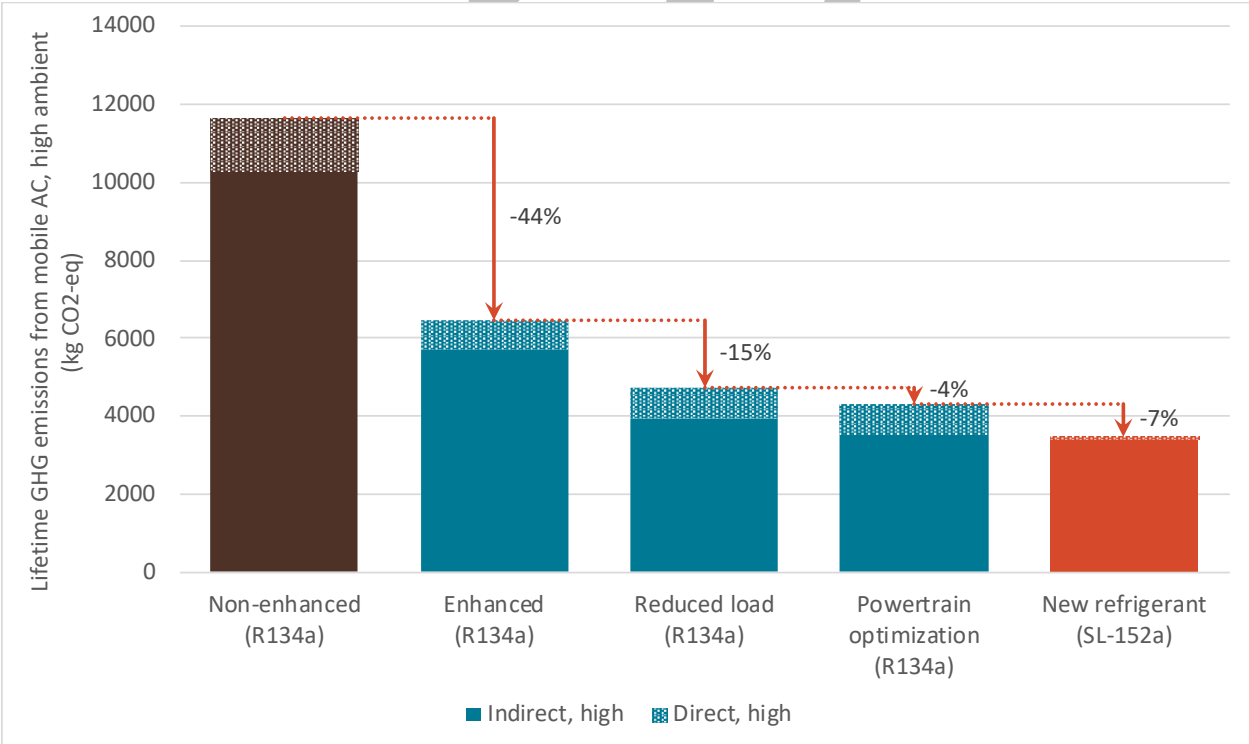


Figure ES 2. GHG reduction potential at higher average temperature conditions

A simple change to a refrigerant with much lower global warming potential (GWP) can almost eliminate the direct GHG emissions (12% to 19% of MAC system emissions): the alternative refrigerants assessed—R1234yf, R744, and R152a—provide a 90% to 99% reduction compared to R134a. Enhanced MAC systems that cut total emissions (both direct and indirect) by 40% or more are already prevalent in many markets. Additional load reduction technologies and system optimization can reduce indirect emissions another 15% to 19%, providing even greater GHG reductions in higher ambient temperatures.

While switching refrigerants and systems implies additional costs to vehicle manufacturers, more efficient MAC systems using alternative refrigerants with lower refrigerant leak rates offer more value to consumers. For any refrigerant, enhanced MAC systems clearly offer a tremendous payback through reduced fuel and refrigerant use. And alternative refrigerants and systems can offer still more value than R134a through reductions in fuel and refrigerant consumption, under both temperate and higher temperature climates. Consumers in hotter climates, where AC is used more frequently, realize the largest savings overall.

Because improved MAC systems benefit consumers and the environment, but modestly increase system cost to the manufacturer, policy action is needed to spur the introduction of these systems into the global fleet. The European Union, Canada and Japan have rules in place that ban the sale of vehicles using refrigerants with greater than 150 GWP. Widescale adoption of such policies can relatively easily require refrigerant substitution with low-GWP options, ideally moving much more quickly than required by the Kigali Amendment. However, in order to achieve the full benefits of improved MAC systems, policies must be adopted to also target the full MAC-system efficiency. While stand-alone policies on MAC system efficiency are possible, the more likely pathway is to incorporate MAC efficiency into vehicle GHG or fuel economy standards, either measuring real-world AC use on the test cycles or providing regulatory incentives for improved MAC efficiency or technologies. The paper concludes with an exploration of the policy paradigms in place to enact these changes.

I. Introduction

Until about 1990 in developed countries and about 2006 in developing countries, vehicle air conditioning systems worldwide used chlorofluorocarbon (CFC)-12 (R12) as the refrigerant. R12 is an ozone-depleting substance (ODS) with a global warming potential (GWP) of 10,200 that was

phased out of production and consumption by the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol), which was adopted in 1987 and entered into force in 1989.

All MAC systems worldwide transitioned from R12 to HFC-134a (R134a). While R134a is not an ODS, and its climate impact is reduced compared to R12, it has a relatively high GWP of 1300 (Myhre et al., 2013)². In 2006, the European Union (EU) passed Directive 2006/40/EC of the European Parliament, better known as the F-gas Directive, which requires that air conditioners sold on new vehicle models after 2010 and all vehicles sold in the EU after 2017 use refrigerants with a GWP of less than 150. When the Directive was published, the only publicly disclosed refrigerants satisfying this criterion were hydrocarbons (GWP ~3 to 5), CO₂ (R744) (GWP=1; the reference gas), and HFC-152a (R152a) (GWP=138). Within weeks of publication of the F-Gas Directive, half a dozen international chemical manufacturers, including Asahi, Arkema, DuPont, Honeywell, Ineos, and Sinochem, announced patents for the manufacture of hydrofluoroolefin-1234yf (R1234yf), which is ozone safe and has a GWP of less than 1 (Andersen, Halberstadt & Borgford-Parnell, 2013). All three of these possible alternative refrigerants are considered to be low toxicity and range from lower flammability to not flammable. The environmental and safety classifications of all the refrigerants referred to in this report are included in Appendix A.

The 2016 Kigali Amendment to the Montreal Protocol requires the global phase-down of the production and consumption of HFCs according to the schedule shown in **Error! Reference source not found.** in the regulatory section below. The HFCs now being phased down have served as replacements for about 15% of ODSs that the Protocol originally targeted. About 85% of ODSs have been replaced by not-in-kind (non-fluorocarbon) alternatives, minimized by reduced leakage and improved service, and in some cases eliminated by doing without (Seidel et al., 2016; Andersen, Sarma & Taddonio, 2007). With alternative low-GWP refrigerants and associated air conditioning systems available and in development, the potential exists to greatly diminish the direct climate change impacts associated with R134a leakage from mobile air conditioning (MAC) systems.

² GWPs cited in this report are based on the fifth assessment report from the Intergovernmental Panel on Climate Change (IPCC). The fifth assessment report (AR5) from the IPCC updates previous estimates of GWP, both including and excluding carbon-climate feedback effects (WG I Ch. 8 Table 8.A.1 & Ch. 8 Supplementary Material Table 8.SM.16). In line with regulations in place in Europe, the US, and elsewhere, we use GWP without feedback effects for this report. Feedback effects increase the 100-year GWP by 248 for R134a and by 30 for R152a, while R1234yf and R744 are unchanged. Section 8.7.1.4 states, "Though uncertainties in the carbon cycle are substantial, it is likely that including the climate-carbon feedback for non-CO₂ gases as well as for CO₂ provides a better estimate of the metric value than including it only for CO₂."

As we look toward the elimination of high-GWP refrigerants from MAC systems, it becomes clear that the total energy consumed through operation of the air conditioner in vehicles represents another, substantially greater source of GHG emissions. The fuel used by MACs has been estimated to be 3-7% of annual vehicle fuel consumption, as a global average, with considerable regional variation (IPCC/TEAP, 2005; Mock et al., 2013; Chaney et al., 2007; Rugh, Hovland, & Andersen 2003, Yang et al., 2018). MAC fuel consumption approaches 20% in very hot and humid climates that have traffic congestion, where more air-conditioned time is required to travel any distance (Chidambaram, 2010; Papasavva et al., 2009).

For conventional internal combustion vehicles, this energy demand results in CO₂ emissions as more fuel is burned. For electric vehicles, the additional energy demand results in indirect emissions of CO₂ via the electricity generated at fossil-fuel or biomass power plants. This energy consumption also decreases in the driving range of the battery. Of course, GHG emissions from AC power use are very small if electricity is entirely provided from geothermal, hydropower, nuclear, solar or wind. At maximum cooling settings, using the AC can reduce electric vehicle range by 30-50% (DOE, 2013; Leighton, 2015; Kreutzer et al., 2016). Thus, the MAC system presents an important opportunity to reduce the energy demand and GHG emissions associated with real-world vehicle operation.

Using the most recent data and estimates available, this paper examines lifetime costs and benefits of switching MAC systems to lower-GWP alternative refrigerants *and* improving system energy efficiency. Consideration of the full system raises the potential of alternative MAC systems that can aid in the implementation of national-level vehicle fuel efficiency and refrigerant standards, as well as assist international efforts to reduce emissions of GHGs. As vehicle fuel economy and GHG standards become increasingly stringent, the gap between measured emissions for vehicle certification and real-world vehicle emissions has been growing, and MAC use accounts for a large part of that difference (Fontaras et al, 2017; ICCT, 2017). As GHG emissions from vehicles decline overall, the life-cycle emissions of MAC systems become increasingly significant. As MAC-equipped vehicles spread around the globe and global warming increases temperatures, refrigerant emissions and energy demand from MAC systems will also grow.

While lower-GWP refrigerants, improved MAC system efficiency, and thermal load reduction strategies can reduce GHG emissions substantially, there are technical limits to the benefits of improved MAC systems. Systemic changes to the transportation system as a whole can offer

additional reductions in AC demand, with commensurate GHG benefits. For instance, altering driver behavior—e.g., parking in the shade, driving at times of lower solar insolation—further reduces AC cooling load within vehicles. Encouraging carpooling and shifting away from private vehicles and onto public transit can reduce the cooling load per capita. Examining the strategies and environmental impacts of these types of changes is beyond the scope of this paper, but such an exploration represents an additional research opportunity.

II. Background

This section first describes the design and environmental impacts of the most common MAC systems today: those based on R134a. These impacts include GHG emissions associated with refrigerant manufacture, in-use and servicing leakage, and end-of-life (EOL) emissions, as well as the indirect in-use CO₂ emissions due to increased fuel consumption associated with use of the MAC system. The costs of the system hardware and refrigerant, as well as the energy usage, are then explored. Finally, this section provides a brief overview of the alternative systems available—low-GWP refrigerants and techniques/technologies to improve energy efficiency and reduce AC load—which will be described in greater detail in the rest of the paper.

The most prevalent MAC system in passenger vehicles today operates on a direct-expansion (DX), subcritical, vapor-compression cycle. In this thermodynamic cycle, heat is extracted from the air in the vehicle cabin by evaporating a refrigerant (R134a) and is transferred to the ambient air via the condenser after being compressed (and consequently heated and pressurized) in a compressor. Transferring heat from the pressurized vapor causes it to condense back into a liquid. Finally, the pressure of the liquid is reduced through an expansion device, causing partial vaporization and lowering of the temperature of the refrigerant as it enters the evaporator. Cycling from liquid to vapor and back is an efficient cooling mechanism, since substantial latent heat can be absorbed (evaporation) and released (condensation) during isothermal phase changes.

This analysis also considers secondary loop systems, which use a subcritical, vapor-compression cycle coupled through a heat exchanger to a coolant flow loop.³ The thermodynamic cycle is the same, however the refrigerant is isolated within the engine bay, while the coolant circulates within the passenger cabin. Because the refrigerant stays in the engine compartment and only coolant circulates in the cabin area, a wider variety of refrigerants can be safely utilized in an SL-MAC

³ While secondary loop systems are not currently in commercial use, a pilot project in India, data for this paper came from a pilot project in India involving a major air conditioning system supplier (Mahle) and a vehicle manufacturer (Tata Motors). The project is described in detail in Andersen et al., 2018.

system than in a direct expansion system. This is especially critical for R152a, which has somewhat higher flammability than the other refrigerants considered. However, because the secondary loop system allows for use of less refrigerant and may have lower leakage rates, we investigated the climate and cost implications of use of secondary loop systems for all refrigerants.

To cool air, all alternative refrigerants go through a similar process of heat absorption, compression, heat expulsion, and expansion. For alternative refrigerants R152a and R1234yf, the process is qualitatively identical to R134a and R12 systems in that all steps are at temperatures and pressures below the critical point of the refrigerant. That is, the cycle never goes beyond the critical point at which the gas and liquid phases become indistinguishable. The CO₂ system, described later, is *supercritical*, because it does go beyond this point in a unique design unsuitable for R12, R134a or R1234yf.

The standard metric of efficiency for AC systems, the coefficient of performance (COP), is the ratio of heat extracted from the cooled air to the work performed in order to extract the heat (mostly the compression of heated vapor, but also energy for condenser cooling fans that also cool the engine and for fans to circulate cool air in the cabin). It is quite possible for the amount of heat that is transferred to be higher than the energy consumed by the compressor, resulting in a COP greater than one, although energy must still be supplied to the compressor to drive the entire cycle. The COP of MAC systems vary based on system design and the refrigerant used, as well as with ambient conditions, as explained below.

Since heat can only be transferred from a hot source to a comparatively cold sink, the work required by the compressor, and thus the COP, is highly dependent on ambient and vehicle cabin conditions. As the temperature and humidity of ambient air increase, the amount of cycle-specific heat that can be transferred for a given system design decreases. To compensate, the system (compressor) must work harder to provide a given level of cooling. Because more work is required to produce a given level of heat exchange, the COP under demanding ambient conditions is lower. Condensing moisture from the inside air also reduces COP. As the temperature of air inside and outside a vehicle approach one another, less heat transfer is required, and less energy is used by the compressor, resulting in a higher COP. As explored below, one tactic to reduce the load on the AC system is to reduce the amount of cooling required by limiting heat buildup in the vehicle cabin with reflective glass and insulated surfaces.

Baseline R134a system

Within the last two decades, R134a systems have been improving, with system leakage decreasing and operating efficiency increasing. “Enhanced” R134a systems can reduce refrigerant leakage by 50% and fuel consumption of the system by at least 40%, resulting in a 39% to 44% reduction in overall GHG emissions compared to earlier systems (CARB, 2007; Science 2005; Rugh, 2005). While there are clear lifetime benefits for the vehicle owner associated with lower refrigerant leakage and more efficient systems, the incremental upfront cost of enhanced R134a systems may discourage automakers from upgrading systems in more price-sensitive vehicle markets. In this analysis, we assume that the added cost of an enhanced system is approximately \$10. This assumes the use of low or non-permeable hoses, leak-tight metal-to-metal seals, a variable displacement compressor, reduced refrigerant charge, and other improvements. As a result of the low price, a spectrum of energy efficiency and refrigerant performance from R134a systems exists in the new and existing vehicles in the world.

This section details assumptions related to GHG emissions and costs for DX R134a systems, including both older systems and the enhanced systems that are gaining market share.⁴ All GHG emissions estimates are converted into CO₂-equivalent emissions in order to facilitate comparisons with other refrigerant systems. GHG emission estimates include embodied emissions related to the production of the refrigerant, direct emissions related to leakage to the atmosphere, and indirect emissions related the energy required to run the MAC system.

provides the baseline assumptions for direct expansion R134a systems. The GHG emissions associated with the manufacture of R134a are low compared to the GHG emissions associated with direct refrigerant emissions to the atmosphere from system leakage during the vehicle’s usage, servicing, and retirement (Johnson, 2004).

Table 1. Summary of assumptions used to estimate direct emissions from non-enhanced R134a MAC systems

Emissions component	Assumptions used	Source
Emissions to atmosphere (GWP)	1300 kg CO ₂ -eq per kg of R134a	Myhre et al., 2013

⁴ Direct expansion systems are systems in which the air to be cooled is passed directly across the system evaporator. R134a can also be used as a refrigerant in secondary loop (SL) systems, in which a secondary fluid is cooled via a passage across the system evaporator and then serves as a heat sink for cabin air cooling.

Initial charge	0.5 – 0.9 kg	IPCC/TEAP, 2005; ICF International 2012
Manufacture emissions	5 kg CO ₂ -eq per kg of R134a	Baral et al., 2013
Annual leakage	30–82g/yr	Craig, 2018
Recharge amount	30%–50% of original charge	IPCC/TEAP, 2005; ICF International 2012
Service leakage	0.85% of original charge annually (average of 0.6%–1.1%)	ICF International, 2012
Service events	3 per 15-year lifetime	IPCC/TEAP, 2005; ICF International 2012
End of life	16% of total charge (average)	ICF International, 2012

The relatively high pressure and temperature of the refrigerant causes it to leak through flexible hoses, seals, and connectors. Refrigerant emissions of R134a can be estimated using the Society of Automotive Engineers (SAE) International standard J-2727. Recent benchmarking found that a typical, two-cooling point R134a system leaks at around 20 g/yr (Craig, 2018). Trends in MAC leakage benchmarking show that between 2009 and 2015, leakage rates have decreased by at least 20% (EPA, 2016). Steady progress on improving leak-tightness suggests a ~50% overall reduction in leakage since 2004 (SAE International, 2006). This analysis thus uses the range of 41–82 g/yr as the annual leakage rate for older R134a systems with more than one cooling point. Although this leakage rate is higher than the range of 2%–8% used in other studies (IPCC/TEAP 2005; ICF International, 2012; Atkinson, 2009), it correlates fairly well with the assumption that leakage rates increase with vehicle age and accounts for accident-related emissions from a portion of the vehicle fleet (EPA, 2012; Vincent, 2004). Recall that enhanced systems could effectively cut leakage levels in half. Single-cooling point DX systems are estimated to leak at 75% the rate of multi-cooling point DX systems (Atkinson, 2009), or 30–61 g/yr. At 1300 GWP, these leaks are equivalent to direct emissions of 53–106 kg CO₂ each year.

The fuel used by MACs in temperate climates has been estimated to be 3-7% of annual vehicle fuel consumption. But this range can vary considerably by regional climate and local weather, approaching 20% in very hot and humid climates (Chidambaram, 2010; Papasavva et al., 2009; Chaney et al., 2007; Rugh, Hovland & Andersen 2003). Furthermore, due to vehicle fuel efficiency standards around the globe that reduce fuel use other than for AC, fuel consumed by AC is likely

to hold a progressively greater share of total fuel consumption. Absolute AC usage will actually *increase* due to more vehicles sold in warmer and more humid climates and due to global warming worldwide as a consequence of climate change.

By the year 2000, approximately half of the light-duty vehicle fleet on the road was equipped with AC. In Europe, MAC penetration grew from approximately 10% in 1995 to more than 90% in 2010 (Clodic et al., 2006). As market penetration of MAC systems in new vehicles is now near 100% worldwide, the share of the global fleet equipped with AC is expected to continue to grow quickly (Andersen et al., 2013a).

Even if we were to assume that MAC usage was constant, improving vehicle efficiency implies that the fraction of the total vehicle energy used for cooling will grow. Since cooling levels depend on climate conditions and individual behavior, the absolute energy consumption of a MAC system is relatively independent of overall vehicle efficiency. In its 2012 rulemaking for model years 2017-2025, the US Environmental Protection Agency (EPA) conducted vehicle simulations that found the MAC increases emissions by 7.3–11 gCO₂/km (US EPA, 2012). More recent estimates find that the MAC system increases CO₂ emissions by 15 gCO₂/km (on average in the US). MAC usage in very hot and humid climates can increase emissions by over 34 gCO₂/km (Kreutzer et al., 2017a). Other estimates are higher, in part due to different ambient conditions and humidity levels: 9.4–41 gCO₂/km, with an average of 22 gCO₂/km (Meszler, 2004). Since the US contains many climates, the US average conditions (22 gCO₂/km) represent the temperate climate conditions reported here, and US high ambient temperature conditions (41 gCO₂/km) represent higher average temperature conditions. Under US average conditions, the fraction of driving time with the AC on is 34%, whereas the fraction is 50% under US high ambient temperature conditions.

In the US, drivers average about 18,520 km/year (US DOT, 2016). Using this value as the global average partially offsets any underestimated MAC fuel consumption in cities like Mumbai, which experience much higher MAC loads than the global average (Chaney et al., 2007).

Table 2 summarizes the emission estimation results for one cooling point non-enhanced and enhanced R134a systems. As can be seen, the emissions for the enhanced systems are already 40% to 44% lower than the non-enhanced systems. While emissions estimates would be higher, the trends illustrated in the table are the same for DX systems with two cooling points.

Table 2. Summary of CO₂-equivalent emissions from enhanced R134a MAC DX systems versus non-enhanced systems, both with one cooling point.

Emission type	Emission source	Emission total (kg CO ₂ -eq) (non-enhanced)	Emission total (kg CO ₂ -eq) (enhanced)
Direct or embodied	Initial charge manufacture	2.5–4.5	2.5–4.5
	Leakage	597–1,190	298–597
	Re-charge manufacture	2.3–3.8 (3 service events)	1.5–2.5 (2 service events)
	Service	83	83
	EOL	104	104
Direct subtotal ⁵		788–1,390	489–788
Indirect		3,460–10,300 (1,480–4,380 L of gasoline)	2,080–5,700 (890–2,430 L of gasoline)
Total		4,250–11,700	2,570–6,480

Note: Values rounded to three significant digits.

The hardware and performance for current R134a systems are assumed to be equivalent to those considered “enhanced” or “improved” in reports cited previously. These systems cost, in total, around \$200–\$250 (IPCC/TEAP, 2005; ICF International, 2012; Meszler, 2004). More recent ICCT estimates are closer to \$200 (Du et al., 2016), although even these estimates are from 2011.

A full R134a refrigerant charge is around \$4–\$7 (\$8/kg bulk wholesale price). Servicing is estimated to cost \$100 in labor per job, plus \$15/kg for refrigerant (retail price) (Andersen et al., 2017). Use of proper equipment by trained service staff can greatly reduce emissions during servicing and recharge, while home servicing, which is common in the US market (US EPA, 2013), can lead to significantly higher service emissions as well as emissions of leftover replacement refrigerant escaping from smaller consumer cans because do-it-yourself (DIY) home mechanics

⁵ Direct and embodied emissions of 788 kg CO₂-eq for a typical single-cooling point system for global average under ambient conditions assume a charge of 0.5 kg R134a (2.5kg CO₂), and three recharges at 30% each (2.3 kg CO₂), 41 g/yr leakage over 15 years (597 kg CO₂-eq), service leakage at an average of 0.85% g/yr of full charge (83 kg CO₂-eq), and 16% of a full charge leaked at end-of-life (104 kg CO₂-eq). For higher average ambient temperature conditions, leakage rates and recharge amounts are on the upper range.

rarely have access to the equipment necessary for leak detection, recovery and recycle, and accurate recharge.

During lifetime operation, using the enhanced MAC system causes around 2,100–5,700kg CO₂ to be emitted from fuel combustion, 900–2,400 liters of gasoline. As of this writing, the global average gasoline price is \$1.16/L (USD) (GlobalPetrolPrices, 2018). Thus, the MAC costs an additional \$1,000–\$2,800 in fuel costs to operate over 15 years, or about \$70–\$190 per year.

Table 3. Summary of lifetime costs for a single-cooling point, enhanced and non-enhanced R134a DX system, under temperate climate and higher average temperature conditions.

Cost type		Cost (USD)	Cost (USD)
		Non-enhanced	Enhanced
Direct manufacturing costs	System hardware	\$190–\$240	\$200–\$250
	Initial refrigerant charge	\$4–\$7	\$4–\$7
Total direct manufacturing costs		\$194–\$247	\$204–\$257
Ownership costs	Re-charge (total)	\$7–\$12	\$5–\$8
	Service labour (total)	\$300	\$200
	Fuel consumption	\$1,710–\$5,090 (temperate climate— higher ambient)	\$1,030–\$2,820 (temperate climate— higher ambient)
Total ownership costs		\$2,017–\$5,402	\$1,235–\$3,028
Total consumer costs (direct + ownership)		\$2,210–\$5,650	\$1,440–\$3,290

Note: Final values rounded to three significant digits.

As shown in Table 3, in total, fuel consumption costs represent roughly 70–90% of total cooling costs faced by consumers. Results for two cooling point systems are similar.

Alternative MAC systems: low-GWP refrigerants and improved energy efficiency

Before estimating and comparing the lifecycle costs and GHG emissions of improved alternative MAC systems, below is a brief overview of the refrigerants, systems, and technologies considered. Table 4 summarizes the potential benefits of the various strategies for reducing direct and indirect GHG emissions.

Table 4. Strategies for reducing GHG emissions from DX MAC systems

Strategy	Alternatives considered		Compared to R134a systems
Refrigerant replacement	Type	GWP*	Reduction in direct and embodied GHG emissions from refrigerants**
	R1234yf	<1	97.8%–98.3% lower than R134a
	R152a	138	89.7%–90.0% lower than R134a
	R744	1	99.8% lower than R134a
System improvement	System design strategy		Reduction in indirect GHG emissions from MAC system
	Enhanced systems		40%
	Powertrain optimization		3%–10%
	Load reduction		18%–31%

*GWP values come from the IPCC Fifth assessment report (Myhre et al., 2013).

**Includes system-specific charge size and leakage rates, which vary slightly by refrigerant.

Alternative refrigerants

HFO-1234yf (R1234yf) is a near drop-in replacement for R134a, but it requires an internal heat exchanger (IHx) or other re-design to make up for lower cooling capacity and lower COP. R1234yf has a GWP of less than one, a 99.9% reduction compared to R134a. Although R1234yf is slightly more flammable than the non-flammable R134a, both systems use flammable lubricant and thus engineers have already designed systems to mitigate flammability risk. While combustion of R1234yf leads to the production of two extremely toxic chemicals—hydrogen fluoride and carbonyl fluoride—the Society of Automotive Engineers and the Joint Research Center of the European Commission independently confirmed the safety of R1234yf even in the event of a vehicle collision (European Commission, 2014). R1234yf also readily degrades into

trifluoroacetic acid (TFA),⁶ producing five times as much as R134a but still at relatively low levels (Andersen et al., 2017; Luecken et al., 2010; Luecken et al., 2009).

R1234yf systems use a charge comparable to that used in R134a systems (ICF International, 2012; Du et al., 2016). Due to their similar physical properties, systems based on R1234yf and R134a generally use the same hardware except for the internal heat exchanger necessary in R1234yf systems to achieve comparable cooling capacity and efficiency.⁷ The similarities also imply that R1234yf systems could be improperly recharged with R134a, offsetting potential CO₂ benefits. R1234yf is currently covered by several application patents, which are held by Honeywell in the US and some foreign markets. As discussed in the cost section below, the Honeywell patents currently increase the refrigerant's price to manufacturers by a factor of two to six and to consumers by a factor of four to 15 compared to the production price (Sherry et al., 2017; Seidel and Ye, 2015). Potential compliance issues associated with recharging R1234yf systems with R134a are exacerbated by the current high price of R1234yf but could be reduced as the R1234yf patents expire and implementation of the Kigali potentially causes R134a prices to increase. Blends of R1234yf with R134a or other chemicals can reduce the cost of charging the system, although this cost benefit can come at the expense of reduced COP and increased GWP.

Other choices that satisfy the EU requirement of GWP<150 and are listed as acceptable by the United States Environmental Protection Agency (US EPA) under the Significant New Alternatives Policy Program (SNAP) are R152a and R744. HFC-152a (R152a), while still an HFC, has a GWP of 138 and less refrigerant is required overall, with R152a requiring 50% (for SL) to 80% (in DX systems) of the initial charge of R134a. This is an 89.4% reduction versus an equal volume of R134a, and 95% or greater reduction when the R152a MAC's lower refrigerant charge is taken into account. R152a also has a higher COP and does not produce TFA as a byproduct of atmospheric degradation (Du et al., 2016). R152a has higher flammability than R134a and R1234yf, which requires, for safety reasons, that it be used in a secondary loop system or, in a direct expansion system, be equipped with a reliable leak detection system and automatic venting outside the cabin to relieve refrigerant pressure (US EPA, 2012).

⁶ There is a special concern regarding the production of TFA because of possible effects on life in aquatic environments. While some studies suggest that the extensive use of some TFA source compounds could dramatically increase the amount of TFA in wetlands, the potential effects on associated ecosystems remains unclear. UNEP (2010) concluded that even when added to existing amounts from natural sources, risks from TFA (and the more toxic monofluoroacetic acid or MFA) from halocarbons to humans and organisms in the aquatic environment are judged to be negligible. Nonetheless, there remains significant uncertainty about the potential effects of TFA in the future environment.

⁷ Note that R134a systems can also use an internal heat exchanger to enhance system efficiency.

Secondary loop MAC (SL-MAC) systems, described in detail in the next section, “Hardware improvement and load reduction,” have a refrigerant loop in the engine compartment that chills an antifreeze-like coolant contained in a completely separate secondary loop that circulated within the passenger cabin. This liquid coolant transfers heat from the vehicle cabin to the refrigerant primary loop. The additional loop increases system cost and complexity. Energy consumption can also rise, due to two heat transfers (refrigerant to coolant and coolant to cabin air) and pumping requirements for the recirculating liquid coolant. However, the secondary loop requires less refrigerant and offers the built-in ability to generate and store cold during deceleration and the flexibility to maintain passenger comfort for a longer period while the engine is off and the compressor is not running, the benefits of which are discussed in the next section.

With a GWP of 1 (by definition), the climate forcing of CO₂ (R744) is 99.9% less potent than R134a, and effectively is 100% less potent if recycled from waste CO₂. R744 systems are unique among alternative MAC systems because they use significantly higher pressure to achieve the supercritical thermodynamic cycle required for CO₂ refrigeration. One consequence of the higher pressure and supercritical cycle is that over a wide range of conditions typical in Europe and North America, R744 systems are the most efficient because they transfer heat more effectively than R134a systems and with greater compressor efficiency (Meszler, 2004; Hafner et al., 2005). Of course, the higher pressures imply more robust hardware is needed for reliability and safety, and higher leakage rates are likely for any design of seals. Thus, service events may be slightly more frequent (2-4 times per lifetime, IPCC/TEAP 2005).

Load reduction

An important way to reduce the energy consumption of MACs is to lower the amount of cooling required in the first place. This can be achieved by modifying the properties of the vehicle to cut heat absorption or improve ventilation or insulation, or by using targeted cooling that directly cools a passenger without having to cool the entire vehicle cabin. Both strategies reduce fuel use for AC. Combined, the two strategies can reduce AC energy consumption 22%–31%, depending on climate.

Strategies to modify the vehicle to reduce cooling demand include:

- Several techniques that essentially block sunlight or heat transfer through the vehicle’s body and windows. Solar glazing is the installation of glass with lower solar transmittance, i.e., less thermal radiation through the windows. Window shades achieve the same effect.

Solar reflective paint is similar, but it prevents sunlight absorption on the exterior non-window surfaces of the vehicle.

- Insulation within doors and beams that supplement the effects of reflective paint and also reduce heat (or cold) losses through the walls when the AC is running.
- Active and passive cabin ventilation that allow cabin air that has been heated by soaking in the sun to escape the vehicle. This reduces both the actual temperature in a parked car and the perceived temperature when passengers enter. However, thus far the benefits appear to be small (Kreutzer et al., 2017b), particularly with current designs, where air intake vents are below the windshield at higher than ambient temperature or warmed by heating coils in the air distribution system.

Directly cooling passengers instead of cooling the full cabin allows the AC setpoint temperature to be higher, reducing the cooling load. While the actual temperature in the cabin may be higher, the perceived comfort meets the needs of occupants, which can be an effective strategy to moderate AC use and reduce energy demand overall. These strategies can confound common testing practices, which tend to focus on measuring system efficiency by setting the system to achieve a set cabin air temperature.

Cooling passengers directly, rather than full-cabin cooling, reduces cooling load by lowering the total amount of air that requires cooling, as well as by improving convective heat transfer. Climate controlled seating pushes or pulls air through the seat cushion and seat back, using either ambient cabin air (seat ventilation) to transfer heat away from a passenger, or air cooled by a thermoelectric device (active seat cooling) to directly cool the passenger. Overhead vents can reduce perceived temperature as well. Similar strategies use the ductwork already present in a vehicle to target particular parts of the body, especially the areas that dictate the thermal comfort of the rest of the body (wrists and neck, for example) (SAE International, 2009, Rugh 2005, Jeffers et al., 2015 and 2016, Kreutzer et al., 2017a).

Policies to encourage the adoption of alternative refrigerants and AC load-reducing technologies generally occur at the national level. However, local regulators can assist in the effort by encouraging driver behavioral changes. For example, driving earlier in the morning and later in the evening can reduce the cabin air temperature below its maximum point throughout the day. Providing shaded parking, or encouraging parking indoors also greatly reduces cabin air warming

due to solar absorption. (Of course, nothing reduces MAC fuel consumption like getting more people to ride public transit or take alternate modes to work.)

Powertrain optimization

Improving system energy efficiency can be achieved by optimizing the powertrain and system hardware and by reducing the overall cooling load. There are many options for both. Together, powertrain optimization and load reduction can realize a 24%–38% reduction in AC energy requirements, depending on climate and technology combinations.

Taken in combination, enhanced hardware can increase efficiency by around 40% (US EPA, 2012). Opportunities to directly increase system efficiency through use of improved hardware include:

- Reducing leakage rates by using low permeability hoses, leak-tight fittings and connectors, and an improved compressor shaft seal (US EPA, 2012). Less leakage reduces direct climate forcing from higher-GWP refrigerants. At the same time, less leakage allows the system cooling capacity to be maintained, which improves efficiency for all MAC systems regardless of the refrigerant, while also improving reliability and reducing servicing costs.
- Variable displacement compressors can reduce or eliminate over-cooling of air that in some system designs requires re-heating to maintain the temperature desired by the driver and passengers. Improved controls for blowers and the fan motor can also provide increased efficiency. Ejector-expansion or electronic expansion devices, which replace typical throttling devices, reduce the amount of work required by the compressor (saving fuel) while enhancing evaporator efficiency, which improves the COP (Denso, 2012; Kawamoto et al., 2017; Li et al, 2004; Zhu et al., 2016).
- Recirculating air by default (rather than by continuously diluting already cooled air with unconditioned ambient air) allows more effective and faster cooling (although too much recirculation can cause concerns for in-cabin air quality). Similarly, using an internal heat exchanger to transfer heat from the high-pressure liquid in an R1234yf system (or vapor, for R744 systems) exiting the condenser (gas cooler, for R744 systems) to the low-pressure vapor entering the compressor reduces the amount of work required by the compressor.
- Improving the performance of the air-to-refrigerant heat exchangers, through better design and with oil separation, can increase the cooling ability of the heat exchangers.

Improvements to MAC systems can enable greater use of other efficiency technologies, for example stop-start technology, which is used in conventional (internal combustion) vehicles to reduce/eliminate the burning of fuel while idling. Such systems turn off the engine completely while idling and re-start when acceleration is requested (by depressing the accelerator or lifting off the brake pedal). Since the AC compressor in non-electric vehicles is driven off the engine, stopping the engine also halts cooling when the AC is on and the compressor is engaged. Although some cooling can be maintained due to heat transfer to liquid refrigerant remaining in the evaporator, to prevent passenger discomfort, stop-start systems are either disabled while the AC is on, or when the evaporator exhausts its thermal ballast. However, there are several techniques that can maintain steady-state cooling for a short period of time while the engine is off. Adopting these techniques would allow stop-start to be active more of the time in urban driving conditions, reducing fuel consumption further. These technologies can reduce energy consumption by 10%–11% (as calculated from Andersen et al., 2018 and Ghodbane, 1999; see footnote 8).

Examples of technologies with the ability to maintain cooling with the compressor off (or to store cooling energy in one way or another) include: coolant recirculation used in secondary loop systems; phase change materials within the evaporator, which can continue to absorb heat from the cabin air while the refrigerant is not circulating; and mild hybrid systems, which can power the compressor electrically with the substantial advantage of controllable compressor speeds and recuperate energy from braking. More advanced techniques allow selective operation of the compressor so as to avoid adding load to the engine when it is least efficient (e.g. during acceleration) or increasing the load on the engine to a more efficient operating point (for low-load conditions). Examples of such strategies include regenerative or deceleration cooling, idle-off coasting, and compressor shut-off during peak acceleration. Integrating these techniques into MAC system design will reduce fuel use for conventional vehicles and will extend battery and driving range for plug-in hybrid and electric drive vehicles.

Perhaps the most straightforward to maintain cooling during engine off is an electric compressor: one that can run exclusively off electricity supplied by the battery. Though used on hybrid, plug-in and fully electric vehicles, this option can be cost prohibitive for conventional vehicles and alone may not offer the full optimization benefits associated with other technologies. Incorporating a phase change material (PCM) into the evaporator also allows cooling to be maintained, and the compressor to be off, for about 60 seconds (Kowsky et al., 2014; Özbek et al., 2018). The phase

change material saves energy compared to a conventional MAC system, despite the small amount of energy required to cool the phase change material. This is because the phase change material allows the compressor to remain off for about 60 seconds while maintaining cooling. Decoupling compressor use from cooling demand enables energy savings by allowing the compressor to be turned on when it is most efficient to do so (see Figure 15, Kowsky et al., 2014).

Another option is secondary loop systems, in which the coolant acts as built-in thermal ballast. The secondary loop contains heat transfer fluid that can be circulated (using an electric pump) even while the engine is off. One study estimates the net energy savings of idle-off cooling when accounting for re-cooling the fluid and running the pump (Weissler, 2015): by shutting off the compressor at idle, the secondary loop of an R152a system showed a reduction in total fuel consumption (with AC running, within and without compressor shut off) of 3% over the Federal Test Procedure (@ 28C), 4% over the New European Drive Cycle (@ 28C), and 5% over the EPA Supplemental Federal Test Procedure SC03 cycle (@ 33C). Interestingly, AC fuel consumption was cut by 38%, 77%, and 73%, respectively, when the compressor was allowed to shut off at idle and during acceleration. This benefit occurs due to using the compressor more at times when adding such a load to the engine increases its fuel efficiency. Testing of secondary loop systems with the compressor shut off in India suggests a 3% reduction in fuel consumption is possible at both high ambient temperatures and in highly urban conditions (Andersen et al., 2018). In conditions such as these, AC operation consumes nearly 20% of overall annual fuel (Chidambaram, 2010). The thermal ballast provided by the secondary loop system can maintain cooling for minutes at a time, which clearly expands the range over which the compressor can be shut off. To achieve a 3% net benefit when the secondary loop reduces efficiency by 8.5% (Table 7), the actual improvement due to secondary loop benefits was estimated to be up to 10.6%.⁸

Lastly, mild hybrid systems, which use start-stop and/or electric drive technologies, have the capability to maintain engine-off climate control (McKay, 2016). This type of hybridization is substantially cheaper than full hybridization but enables many benefits that conventional 12V electrical systems cannot provide. Examples of such benefits include more robust stop-start, regenerative braking, and acceleration assist. Although any of these technologies can be used on a mild hybrid, the mild hybrid system alone can couple to a conventional AC compressor to capture the same benefits as either a secondary loop or a cold storage evaporator. Due to the

⁸ Secondary loop benefits were calculated by solving for the benefit required in order to achieve a 3% reduction in fuel consumption with an 8.5% energy penalty: $(100\% - 3\%) = 100\% * (100\% + 8.5\%) * (100\% - \text{SL-benefit})$.

wide range of additional benefits available on a mild hybrid, it may have greater cost-effectiveness than the other technologies presented above, especially if automakers use mild hybrid systems to meet fuel economy standards around the world. (Though their cost is lower compared to the full cost of a hybrid, in general secondary loops and cold storage evaporators are only useful when the AC is running.)

A related concern is that without excess waste heat available to heat the cabin, highly efficient engines and electric vehicles have challenges in producing sufficient heating. One method involves running the AC system in heat pump mode. This strategy may be best suited for R744-based AC systems (Meszler, 2004). As with cooling, significant energy savings come from targeted/direct heating. That is, particular surfaces are heated (seats, steering wheel, floor mats), or vents more directly target occupants. This analysis does not consider these co-benefits, but they are sizeable. Targeted heating is estimated to reduce heating energy by 28% (Jeffers et al., 2016). Solar glazing can reduce heating energy by 3%. When combined with insulation in all cabin surfaces, the total reduction is about 18%. For plug-in and fully electric vehicles, these savings lead to increased range during cold weather.

III. Lifecycle GHG emissions comparison

Life Cycle Climate Performance (LCCP) is the comprehensive metric that accounts for direct refrigerant GWG emissions, indirect GHG emissions from fuel use, and embodied GHG emissions from the manufacture of refrigerant and system components, service, and recovery and recycle of all materials and chemical substances at the end of a MAC system's life. It also considers the impacts of substituting alternatives for ODSs (Papasavva and Andersen, 2010; Papasavva, Hill & Andersen; Papasavva, Hill & Brown 2008). In the early 2000s, a global team of mobile air conditioning experts developed best practices and a method for estimating CO₂-equivalent emissions called GREEN-MAC-LCCP (Global Refrigerants Energy and EnVironmental – Mobile Air Conditioning – Life Cycle Climate Performance), which became SAE Standard J-2766_200902 (SAE International, 2009). SAE periodically reviews and revises SAE J-2766 to account for the latest improvements in MAC technology. As of this writing, an update is currently in progress to better account for recent MAC innovation.

This section estimates the lifecycle GHG emissions for alternative MAC systems but does not strictly adhere to SAE J-2766. As indicated in Table 4, all alternative refrigerants slash direct

emissions. Whereas indirect emissions associated with R134a represent around three quarters of total lifetime emissions, they constitute more than 97% of alternative refrigerant systems because of the lower GWP of the refrigerants. Thus, regardless of the MAC system used, as the number of low-GWP systems increases worldwide and their relative importance grows, there is increasing focus on indirect emissions—the emissions associated with the energy demand of the system.

Direct and embodied emissions

Table 5 summarizes the low-GWP system assumptions used to estimate direct emissions. The basis for the tabulated values is presented in the discussion that follows.

Table 5. Summary of assumptions used to estimate direct emissions

Temperate climate		R1234yf		R152a		R744	
		DX	SL	DX	SL	DX	SL
GWP		<1	<1	138	138	1	1
Initial charge (kg)	1 cooling point	0.48	0.32	0.36	0.24	0.39	0.26
	2 cooling points	0.96	0.64	0.72	0.48	0.78	0.52
Manufacture emissions (per kg of refrigerant)		13.5kg CO ₂ -eq		5kg CO ₂ -eq		0.5kg CO ₂ -eq	
Recharge amount (% of original charge)		30%		30%		30%	
Service annual leakage (% of original charge)		0.85%		0.85%		1.02%	
End of life (% of original charge)		16%		16%		16%	
Annual leakage (g/yr)	1 cooling point	15.3	8.5	15.3	8.5	18.4	10.2
	2 cooling points	20.4	8.5	20.4	8.5	24.5	10.2
Number of lifetime recharges		2	1	2	1	3	2
Higher average temperature		R1234yf		R152a		R744	
		DX	SL	DX	SL	DX	SL
GWP		<1	<1	138	138	1	1
1 cooling point		0.48	0.32	0.36	0.24	0.39	0.26

Initial charge (kg)	2 cooling points	0.96	0.64	0.72	0.48	0.78	0.52
Manufacture emissions (per kg of refrigerant)		13.5kg CO ₂ -eq		5kg CO ₂ -eq		0.5kg CO ₂ -eq	
Recharge amount (% of original charge)		50%		50%		50%	
Service annual leakage (% of original charge)		0.85%		0.85%		1.02%	
End of life (% of original charge)		16%		16%		16%	
Annual leakage (g/yr)	1 cooling point	30.6	17.0	30.6	17.0	36.8	20.4
	2 cooling points	40.8	17.0	40.8	17.0	49.0	20.4
Number of lifetime recharges		2	1	2	1	3	2

Table 6 summarizes the level of total direct emissions associated with each alternative system. As expected, due to the significantly lower GWP of all alternatives, each system reduces direct emissions dramatically relative to a R134a system: R1234yf and R744 by 98%-100% and R152a by about 91% to 96%, depending on the number of cooling points and the number of refrigerant circuit fittings. The values in Table 6 are averages for direct expansion and secondary loop systems, with one or two cooling points.

Table 6. Summary of average direct GHG emissions of enhanced R134a and alternative refrigerant systems compared to non-enhanced R134a

Emission source	enhanced R134a	R1234yf		R152a		R744	
	DX	DX	SL	DX	SL	DX	SL
Initial charge manufacture	0%	+174%	+82%	-24%	-49%	-92%	-95%
Leakage (annual)	-42%	-99.9%	-99.9%	-95%	-97%	-99.9%	-99.9%

Re-charge manufacture	-17%	+76%	-42%	-43%	-84%	-91%	-97%
Service	0%	-99.9%	-99.9%	-92%	-95%	-99.9%	-99.9%
EOL	0%	-99.9%	-99.9%	-92%	-95%	-99.9%	-99.9%
Total Direct Emissions	-10%	-98%	-99%	-94%	-96%	-99.9%	-99.9%

Embodied upstream & manufacturing emissions

Upstream refrigerant emissions are primarily from the manufacture of the refrigerants. They are relatively small compared to the direct emissions of R134a or R152a but can become relatively more significant for refrigerants with very low GWP, such as R1234yf with its more complex and energy-intensive manufacture (Sherry et al., 2017). For R744-based systems, the refrigerant is mainly available from scavenging chemical processes but may also come from well sources or the dedicated combustion of fossil fuel. As of 2004 calculations, the emissions associated with capture, refining, compression, and transportation of CO₂ were 0.5kg CO₂ per kg CO₂ produced (Johnson, 2004).

R1234yf production requires the processing of several chemical precursors, as well as modest emissions due to process energy (Baral et al., 2013). R1234yf production releases about 10.4 kgCO₂-eq of climate-forcing chemicals per kg R1234yf produced. Emissions due to energy consumption are about 3.1kgCO₂ per kg produced. Thus, the manufacture of R1234yf contributes 13.5kg CO₂-eq per kg produced. Upstream emissions of R152a are still under investigation but are lower than R134a as a result of the simpler manufacturing process. Additionally, R152a uses a slightly smaller charge of 0.4-0.7kg, which lowers the impact (ICF International, 2012; Du et al., 2016).

Due to lack of data, it is assumed that embodied emissions due to hardware manufacture are all roughly comparable. Hardware includes not just pipes, hoses, connectors, and heat exchangers, but also any additional hardware used to improve efficiency and reduce AC load. R744 MACs require more robust hardware to contain high pressure refrigerant. SL-MAC systems require additional hardware including a heat exchanger, pump, and reservoir, but use shorter refrigerant hoses and fewer refrigerant fittings.

Leakage

As described above, estimates for leakage rates vary considerably in the literature. Early estimates put annual leakage rates around 4%-8% of the original refrigerant charge (IPCC, 2005; ICF, 2012). SAE standard J-2727 and SAE test procedure J-2763 can be used to estimate and calculate annual emissions rates at the time of manufacture (before materials have deteriorated with age). Recent benchmarking using J-2763 found a direct expansion R134a two-cooling point system to leak at 20.4g/yr, and a secondary loop R152a system to leak at 8.5g/yr; using J-2727, the leakage rates for the same DX and SL systems were estimated at 21.8 g/yr and 12.1 g/yr (Craig, 2018). These values fall on the low end of the range of annual leakage rates quoted in earlier estimates and reflect efforts by manufacturers to improve MAC reliability and environmental performance. Even for multiple cooling points, the SL-MAC effectively has the same minimum number of hoses and fittings as the minimum for a single cooling point DX system. Its hoses are shorter than even a single cooling point DX system, and it has a smaller charge than a DX system of similar capacity. These factors contribute to the lower leakage rate for SL-MACs. Due to similar pressures and hardware, the J2763 leakage rates (20.4 g/year for direct expansion and 8.5 g/year for secondary loop) are assumed to apply to all two-cooling point systems in this analysis, except CO₂, which uses higher pressure (Andersen et al., 2017). Typical single cooling point direct expansion systems are assumed to leak 25% less than two-cooling point direct expansion systems.

R744 systems, which operate at higher pressures than other MACs, may leak at a rate 20% higher (Meszler, 2004; Du et al., 2016). This corresponds with other, possibly outdated estimates of R744 leakage rates of around 18-23g/yr (Hafner et al., 2005). Even if the R744 system required a service recharge every year for its entire lifetime, the direct emissions would still be over 99% lower than those from non-enhanced R134a systems (indirect emissions would be higher). However, these service events would add to the lifetime cost of the system and would also reduce system efficiency.

Other studies have estimated increasing rates of leakage as vehicle age increases (US EPA 2012; Vincent et al., 2004). However, vehicles sold much more recently show a 20% decrease in leakage relative to their predecessors, based on J-2727 scores (US EPA, 2016).

In terms of HFC reductions, switching refrigerants to any of the alternatives discussed here could provide a substantial portion of the HFC reductions required by the Kigali Amendment to the Montreal Protocol (Du et al., 2016).⁹

Maintenance

Although estimates of service emissions/leakage rates vary (Du et al., 2016), the average of a range of values considered appropriate by experts for the annual average leakage due to service is 0.85% of the original charge (ICF International, 2012). All low-GWP refrigerants deliver substantial service emissions reductions compared to baseline R134a systems. R1234yf and R744 services losses represent a >99% reduction in CO₂-eq emissions compared to the losses of a non-enhanced R134a system. R152a service losses are about 92% to 95% lower CO₂-eq emissions than R134a losses.

Worldwide, the high cost of R1234yf and continued availability of R134a for servicing poses a potential problem, as vehicle owners or service technicians might be motivated to recharge these systems with much cheaper R134a (Atkinson, 2009; Minjares, 2011; Atkinson & Hill, 2016). The climate impacts of such an activity depend on the number of recharges during which improper recharge occurs, which relates to the level of inspection and enforcement present in a given country. The GWP of R134a means that any recharging with R134a would increase CO₂-eq emissions from both leakage and service by hundreds of times compared to R1234yf. In the United States, topping off or refilling a MAC system designed for R1234yf with any refrigerant other than R1234yf is considered by US EPA to be tampering with a vehicle emissions-control device and is a violation of Section 203 of the Clean Air Act. The Clean Air Act prohibits the retrofit of a system designed to use R1234yf for use with any other refrigerant, including R134a. In Europe as of 2018, the F-gas regulation has constrained R134a supply and increased R134a servicing prices, reducing the cost differential between refrigerants.

End of Life

All systems are assumed to have the same portion of their remaining refrigerant recovered at end of life (EOL) as R134a (16% of original charge) (ICF, 2012). If none of the CO₂ is recovered from R744 MACs, EOL emissions may be in the range of 0.1–0.2kgCO₂.

⁹ In Du et al., 2016, MACs were estimated to account for 24% of CO₂e HFCs globally. Analysis was conducted for three regions: North America, EU, and India. Although an interim target was set only for North America (20%) and the EU (24%) based on 2015 proposals put forward during discussions of the Kigali Amendment, the net reduction in HFCs due to alternative MACs is similar across all three regions (10%-13%).

Because the current price of R1234yf used for servicing is so high (\$143 – \$192 per kg, 14-19 times higher than R134a), recovery rates may be significantly higher than the 16% recovery rate for R134a. However, intellectual property issues currently driving up the price of R1234yf may be close to resolution by the time a significant number of R1234yf vehicles require service, which could cut current prices in half (Sherry et al., 2017).

Indirect emissions

With many clear options available to drastically reduce the CO₂-eq direct emissions through preventing leaks and switching to alternative refrigerants, the major challenge in reducing overall MAC-system GHG emissions lies in indirect/operational emissions. While fuel efficiency and GHG regulations are driving down the overall fuel consumption of passenger vehicles in many markets, the energy consumed by MAC systems is generally not accounted for in regulatory test cycles and thus is not a high priority for efforts by automakers to improve efficiency. Thus, as vehicle efficiency increases, the relative energy consumption of the AC system tends to increase as a fraction of total vehicle energy consumption. Both relative energy consumption of the AC system itself, and strategies to reduce AC load, contribute to cutting total operational energy consumption.

Efficiency & COP

Taking a standard direct expansion system as the baseline, the GHG emissions of AC use will vary depending on the physical and thermal performance of the refrigerant used and the COP achieved with the selected components and controls. The COP can vary depending on ambient temperature and the cabin temperature sought by vehicle occupants. SL-MACs are less efficient because the systems require two rather than one heat exchange, and the coolant pump adds to energy consumption, but they will more than overcome that inefficiency with gains from deceleration cooling, prolonged stop-start with cooling comfort, and ballast that allows powered cooling to be constrained to times when the engine is most efficient.

Although the literature lacks consensus on COPs for the various systems, estimates generally contend that alternative MAC system COPs are within 10% of R134a systems (KATECH 2012). One experimental study indicated that R1234yf systems operate at 0.88-0.95 the COP of R134a, R152a at 0.90-1.02 the COP of R134a, and R744 at 0.85-0.91 the COP of R134a (KATECH 2012). As with all subcritical AC systems, the COP and cooling capacity of R1234yf can be improved with the addition of an internal heat exchanger. Such an addition adds cost to the

system, but, due to the properties of R1234yf, is necessary to bring R1234yf efficiency back on par with R134a (Sherman et al., 2017). R152a achieves up to 10% greater efficiency over R134a with efficiency increasing relative to R134a as ambient temperature increases (Sherman et al., 2017; Baker et al., 2003, Meszler, 2004). The COP of R744 systems at higher ambient temperatures declines below that of R134a, but it equals or exceeds R134a refrigerants' COPs at lower ambient temperatures (Meszler, 2004; Gloël et al., 2014; Hafner et al, 2005). For all refrigerants, a secondary loop reduces overall effectiveness, due to the need for additional cooling to transfer heat between the refrigerant and coolant (Andersen et al., 2018; Ghodbane, 1999) and the need to power a coolant pump. As explained later, this reduced COP can be offset by improvements in deceleration cooling, thermal ballast, prolonged stop-start with comfort, and AC controls that cool with power when the engine is most efficient, leading to overall fuel savings.

For this assessment, Table 7 lists the assumed efficiencies of the various systems.

Table 7. Fuel efficiency assumptions. (All values rounded to three significant digits.)

	Enhanced R134a		R1234yf		R152a		R744	
	temperate	higher	temperate	higher	temperate	higher	temperate	higher
Climate conditions								
DX fuel consumption (g/km)	22	41	21 (-2%)	42 (+2%)	20 (-10%)	37 (-10%)	19 (-15%)	45 (+10%)
SL fuel consumption penalty (without advanced controls, etc.)	8.5%		8.5%		8.5%		8.5%	
AC-on fraction	34%	50%	34%	50%	34%	50%	34%	50%
Annual VKT	18,520		18,520		18,520		18,520	
DX lifetime fuel consumption (kg CO ₂ -eq)	2,080	5,700	2,030	5,720	1,870	5,130	1,770	6,260
SL lifetime fuel consumption (kg CO ₂ -eq)	2,260	6,180	2,200	6,210	2,030	5,560	1,920	6,800

Load reduction

Various technologies have emerged that do not involve changes to the MAC system but instead allow for a reduction in the load and demand on that system and/or improvements in heat transfer efficiency.

Directly cooling passengers promises some of the highest reductions in AC load of all load-reducing strategies. A study by NREL used by US EPA estimated that seat ventilation reduces AC energy usage by 7.5% (Kreutzer et al., 2017a). While active seat cooling, even accounting for the energy consumption of the active cooling device, this strategy can reduce AC energy usage by 12-22%, with an average of 17% (Kreutzer et al., 2017a).

NREL also recently estimated the benefits of four other AC load reduction technologies: active and passive cabin ventilation, solar glazing, and solar reflective paint (Kreutzer et al., 2017b). The impact estimates presented in Table 8 are based on the conditions in the US during which the AC is used. Thus, locations with different climate conditions may experience different effectiveness.

Cabin ventilation—ambient air circulated into the cabin while in park and soaking in the sun—had a small effect, in the range of 0.4–0.8% reduction in AC fuel use. Passive ventilation uses naturally occurring airflow through vents and windows to pass air through the cabin. Active ventilation forces air into the cabin with a fan/blower. The energy required to operate the fan can reduce the effectiveness of active cabin ventilation. Different strategies of ventilation can result in varying levels of cabin air replacement, leading to differing degrees of load reduction (Jeffers et al., 2015).

Solar glazing on the vehicle windows blocks some of the solar radiation from entering the vehicle and warming the cabin. It reduces AC fuel consumption by an estimated 8%. Similarly, solar reflective paint prevents the absorption of a wider range of the solar spectrum from the vehicle's painted surfaces. Its estimated AC fuel consumption reduction is 3%.

Combined, these thermal control technologies lead to a net AC fuel consumption reduction of about 11%. Overall, reducing AC load with localized conditioning (e.g., actively cooled seats) and thermal control can lead to a 22–31% reduction in AC fuel usage. These results are tabulated in

Table 8.

Table 8. Load reduction technology effectiveness

AC load reducing technology	% reduction in AC fuel consumption
Seat ventilation	7.5%
Actively cooled seats	12–22%
Cabin ventilation	0.4–0.8%
Solar glazing	8%
Solar reflective paint	3%
Total load reduction (including ventilated & cooled seats)	22–31%
Total load reduction (including ventilated seats)	18%

The predicted load reductions cited above combine both transient and steady-state cooling phases. The transient phase occurs when the AC system is under the highest burden: cooling from maximum cabin temperature (hot soak) to the setpoint temperature. Steady-state cooling maintains setpoint temperature once it is reached. Transient cooling requires more power in order to quickly reach the setpoint temperature. Due to the higher power demands of transient cooling, the total energy consumed in the transient phase is higher than in a steady-state phase of the same duration. Though data is lacking on full-system/combined transient cooling load reductions, one recent study found some promising results (Kreutzer et al., 2017c):

- Ventilated/cooled seats reduce transient cooling energy by 25–45%
- Solar glazing can reduce transient cooling energy 23–42%
- Solar paint reduces transient cooling energy by 5%

A combination of two, or more, of the above-listed technologies is likely to reduce transient cooling energy by 25–45%. Real-world benefits depend on trip duration, the duration or soaking time, and intensity of the solar radiation loading prior to the trip. Trip duration affects the fraction of total cooling energy consumed during the transient phase (which could be more than 50% for short trips). Soaking time affects how hot the cabin interior feels, and how much cooling is demanded during transient cool-down. Solar radiation loading will vary depending on latitude, elevation, climatic conditions and parking location.

Powertrain optimization

Enhanced systems have already realized an approximately 40% reduction in GHG emissions through improvements to the hardware and controls of the MAC system. Relative efficiency estimates given in this assessment are compared to an enhanced R134a system that already has numerous improvements built in. The improvements already present in an enhanced system include an externally controlled variable capacity compressor, default recirculation controls, an internal heat exchanger, and improved evaporators, condensers, and expansion valves, resulting in a 40–50% (up to 60% under higher temperature conditions) reduction in MAC energy consumption under temperate climate conditions (Meszler, 2004; US EPA, 2012).

Further system optimization requires better integration with the powertrain, especially with new technology options intended to improve efficiency overall. Strategies to optimize control of the AC compressor were described in the background section. These include regenerative or deceleration cooling, idle-off coasting, and compressor shut-off during peak acceleration. More advanced strategies include mild hybridization and the use of a secondary loop system, both expected to reduce AC energy consumption by 3%–11% (Andersen et al., 2018; Ghodbane et al., 1999).

Summary of emissions

Figure 1 through Figure 4 show how switching refrigerant and improving efficiency affects estimated lifetime CO₂-eq emissions (direct and indirect emissions, respectively). As the figures illustrate, secondary loop systems have lower direct emissions, which is most apparent for higher GWP refrigerants. However, all systems benefit fairly uniformly from load-reducing technologies and powertrain optimization.

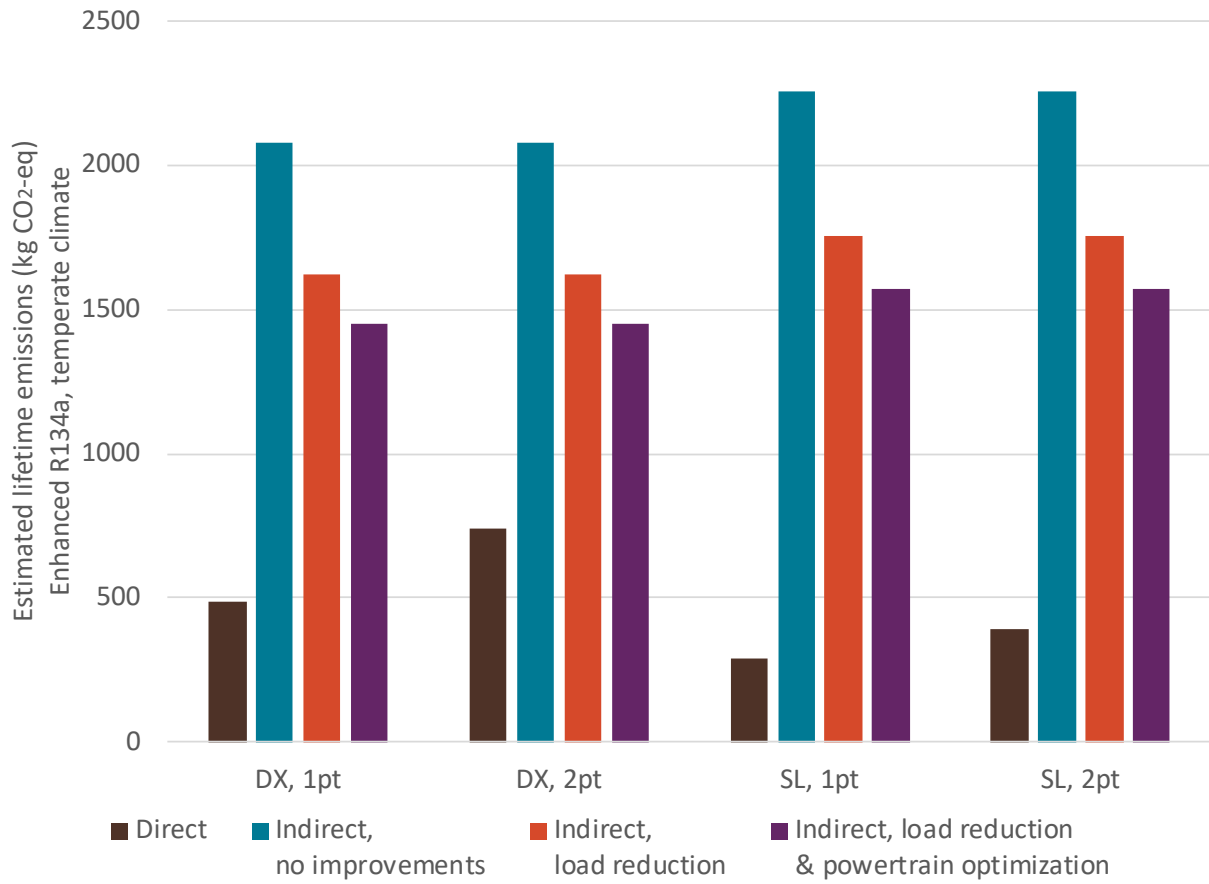


Figure 1. R134a estimated lifetime emissions under temperate climate conditions

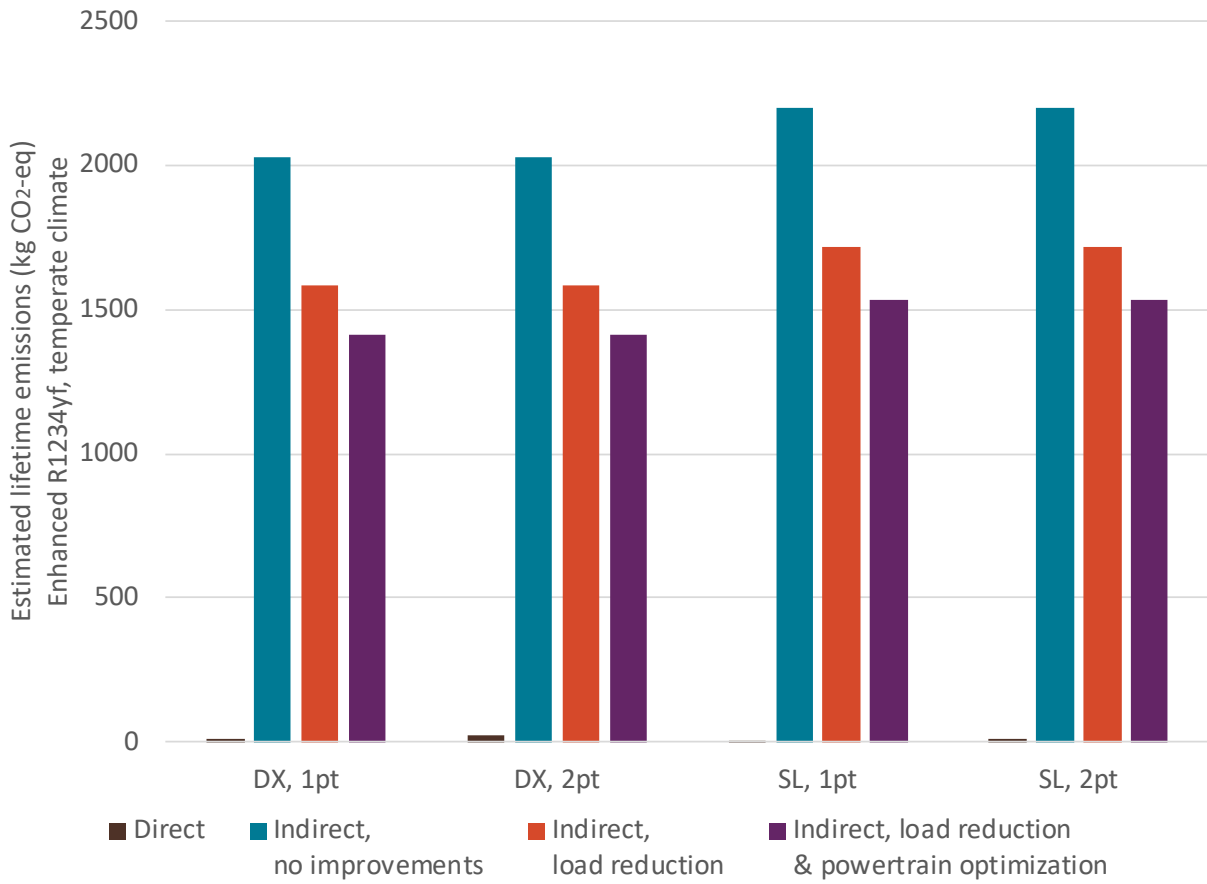


Figure 2. R1234yf estimated lifetime emissions under temperate climate conditions

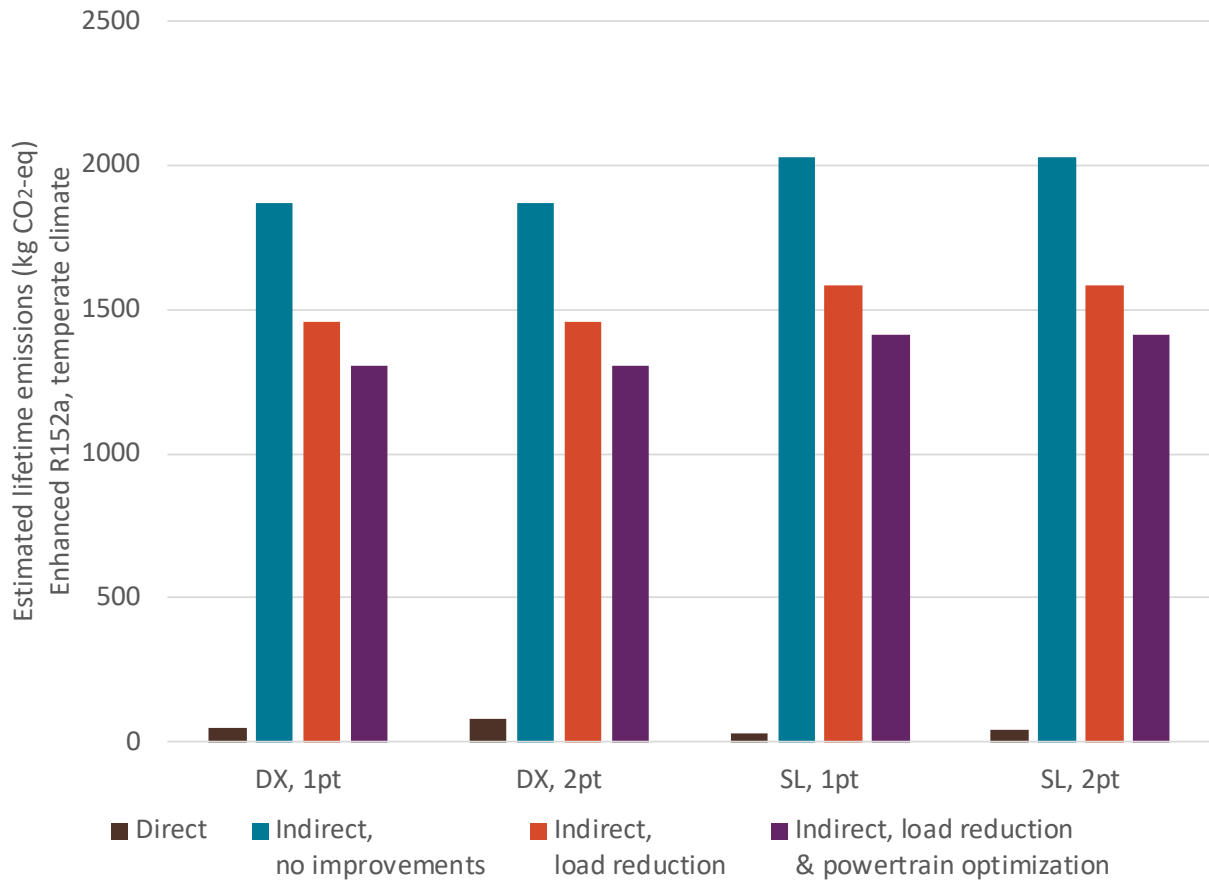


Figure 3. R152a estimated lifetime emissions under temperate climate conditions

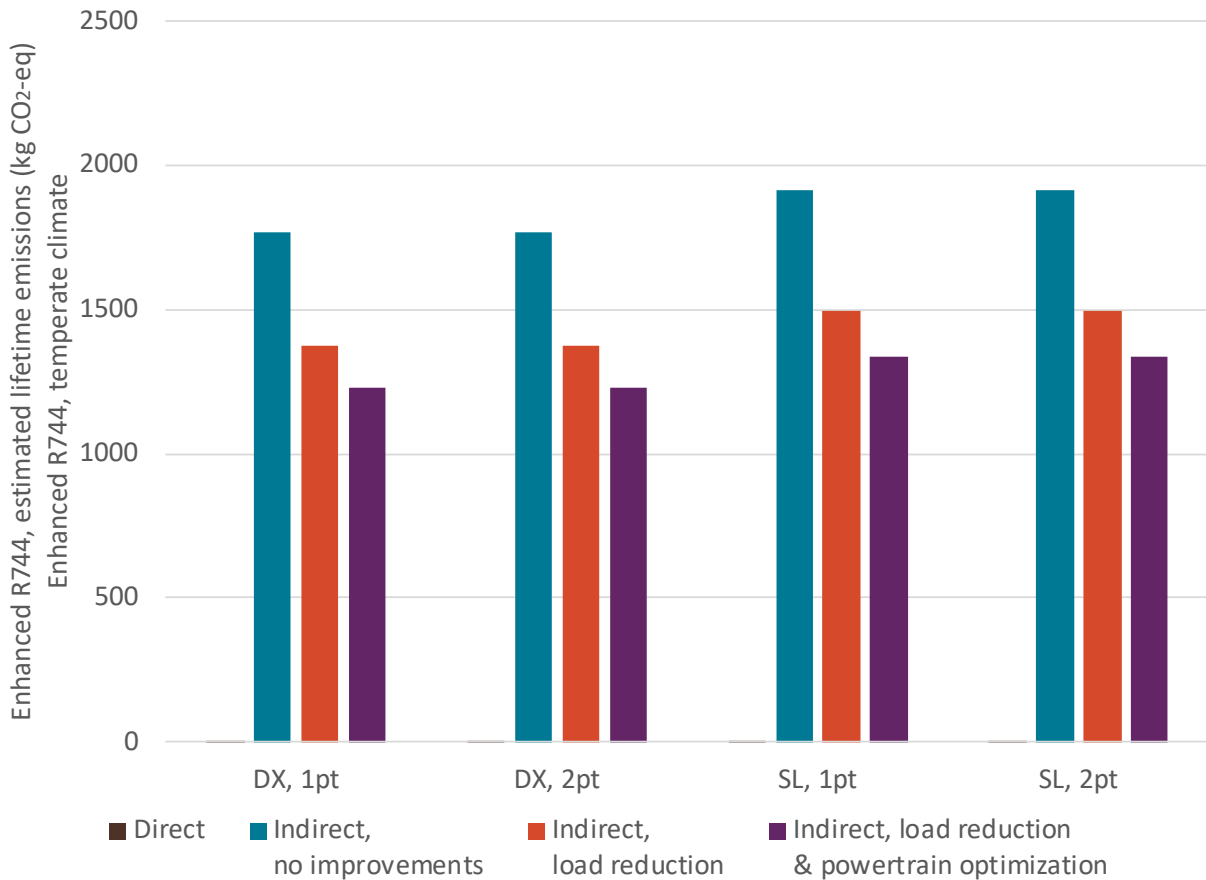


Figure 4. R744 estimated lifetime emissions under temperate climate conditions

Figure 5 and Figure 6 compare the lifetime emissions of alternative MAC refrigerants in temperate and higher temperature climates. These graphs assume the highest level of indirect emission improvements (i.e. MAC fuel efficiency improvements through indirect, load reduction and powertrain optimization strategies). While the figures show results for all refrigerants using both direct expansion (DX) and secondary loop (SL) MAC systems, it is likely that for R152a secondary loop systems will be used due to flammability concerns.

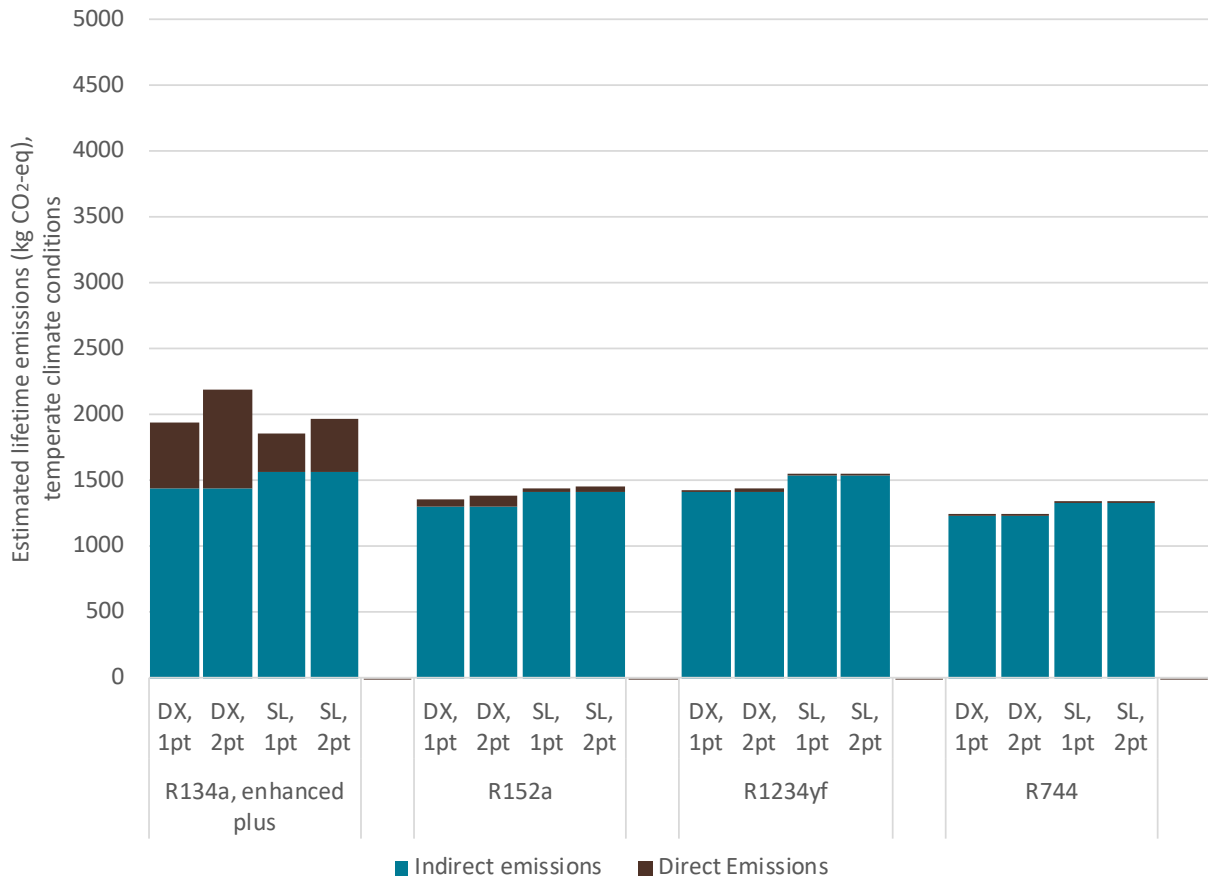


Figure 5. Comparison of estimated lifetime emissions under temperate climatic conditions. Indirect emissions assume application of all currently available efficiency-improving technology.

In temperate climates, all alternative refrigerant MAC systems have lower climate impacts than enhanced R134a systems. We estimate that enhanced R134a DX systems produce 1,940–2,190 kg CO₂-eq emissions over their lifetime. By comparison, R152a, R1234yf, and R744 systems produce an estimated 1,350–1,460 kg CO₂-eq; 1,430–1,550 kg CO₂-eq; and 1,230–1,340 kg CO₂-eq, respectively.

In comparison to enhanced direct expansion R134a MACs, secondary loop MACs using R152a, R1234yf and R744 in temperate climates equaled or reduced indirect emissions resulting from fuel consumption. Secondary loop MACs using R152a also equaled or reduced indirect emissions compared to direct expansion MACs using R1234yf in temperate climates.

In temperate climates, both R152a and R744 systems exhibit slightly lower estimated lifetime emissions than R1234yf, the low-GWP refrigerant currently in use. R152a and R744 MACs are

also less likely to be improperly recharged with high-GWP R134a as a cost saving measure, since R152a and R744 refrigerants are inexpensive in comparison to R1234yf.

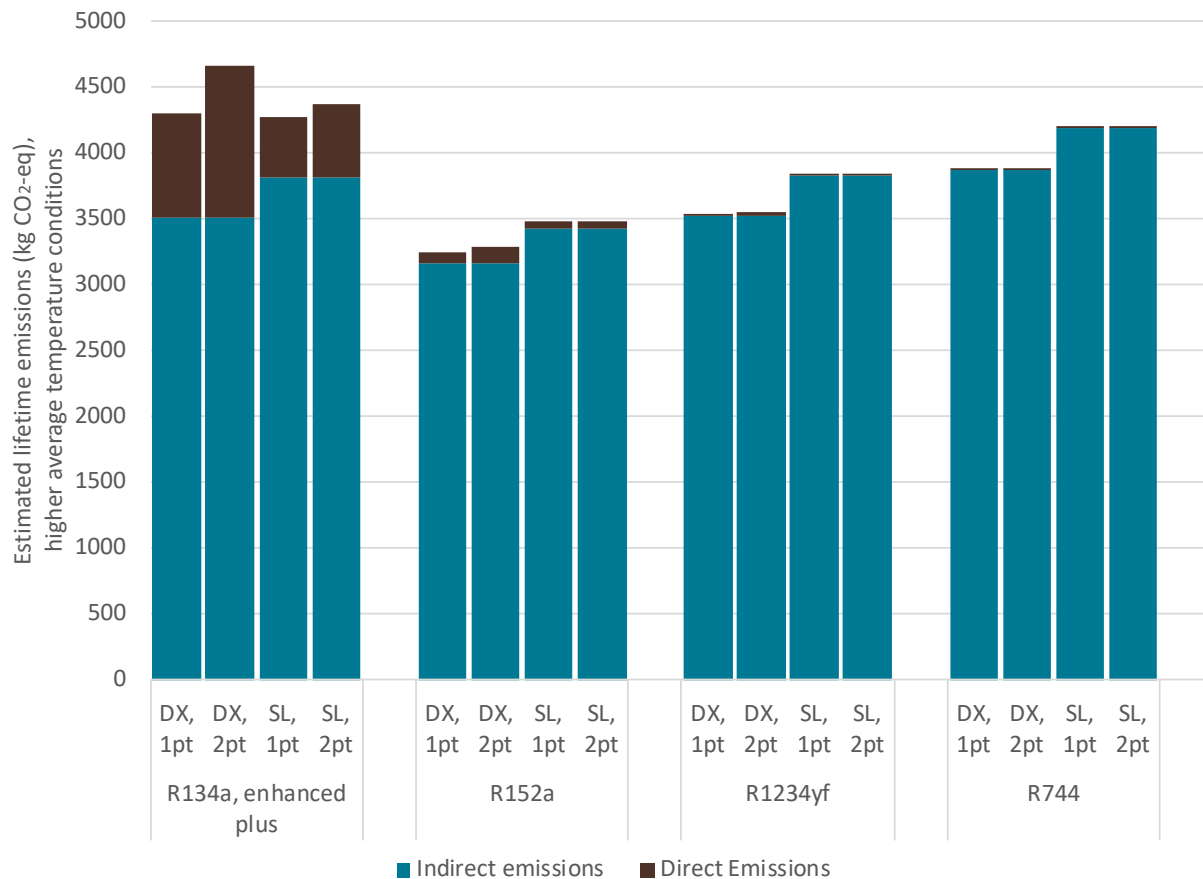


Figure 6. Comparison of estimated lifetime emissions under higher average temperature conditions. Indirect emissions assume application of all currently available efficiency-improving technology.

In high ambient temperatures, alternative refrigerant MAC systems maintain lower climate impacts when compared to enhanced R134a systems, but notable differences between alternatives emerge. Enhanced R134a MACs have the highest estimated lifetime emissions under higher average temperature conditions, generating 4,270 to 4,650 kilograms of CO₂-eq emissions, and thereby exceeding the emissions of low-GWP alternative MACs by as much as 1500 kilograms of CO₂-eq.

Emissions from R152a SL and R1234yf DX MAC systems have approximately equal lifetime emissions in higher average temperature conditions, approximately 3,500 kilograms of CO₂-eq emissions, with slightly lower emissions from the R152a SL system. (Use of R152a in a DX system

would be even lower, but due to safety concerns this is unlikely unless highly reliable active leak detection systems are developed.) SL-MACs using R152a exceed the efficiency and climate performance of SL-MACs using R1234yf, R744, or R134a. SL-MACs using R152a also exceed the efficiency and climate performance of enhanced direct expansion R134a or R744 MACs.

While R1234yf costs remain higher than R134a, there is an incentive for consumers to recharge with R134a. (Even as patents expire, the production costs of R1234yf are expected to continue to be higher than R134a.) In a direct expansion MAC this would erase much of the climate benefit compared to the R134a systems. Some authors have suggested that secondary loop configurations could reduce the likelihood of re-charge with lower-cost but higher-GWP R134a. Due to secondary loop MAC systems' smaller refrigerant charge and lower leak rates, SL MAC systems using R1234yf are expected to have about 7% higher lifetime emissions than direct expansion systems using the same refrigerant, but could still produce climate benefits compared to enhanced R134a systems in high ambient temperature regions where compliance and enforcement of proper system servicing is expected to be low (Andersen et al., 2017, Andersen et al., 2018).

R744 is a less compelling refrigerant option in regions with higher average ambient temperatures. While fuel use related CO₂ emissions are higher, it still offers a significant climate benefit compared to R134a, due to much lower GHG emissions from the refrigerant. However, in the case of leaky R744 systems in need of annual recharging, efficiency could be reduced by 20%, with a corresponding increase in fuel consumption, erasing all climate benefits of this low-GWP refrigerant.

Figures 7 and 8 show the lifetime emission reduction potential from adoption of all described efficiency and refrigerant strategies in temperate and higher temperature climates. As seen in these figures, changes in refrigerants along with other improvements in system efficiency can cut per-vehicle GHG emissions associated with MAC system use by 70% compared to older, non-enhanced systems, and then approximately in half compared to the enhanced systems already available throughout the world.

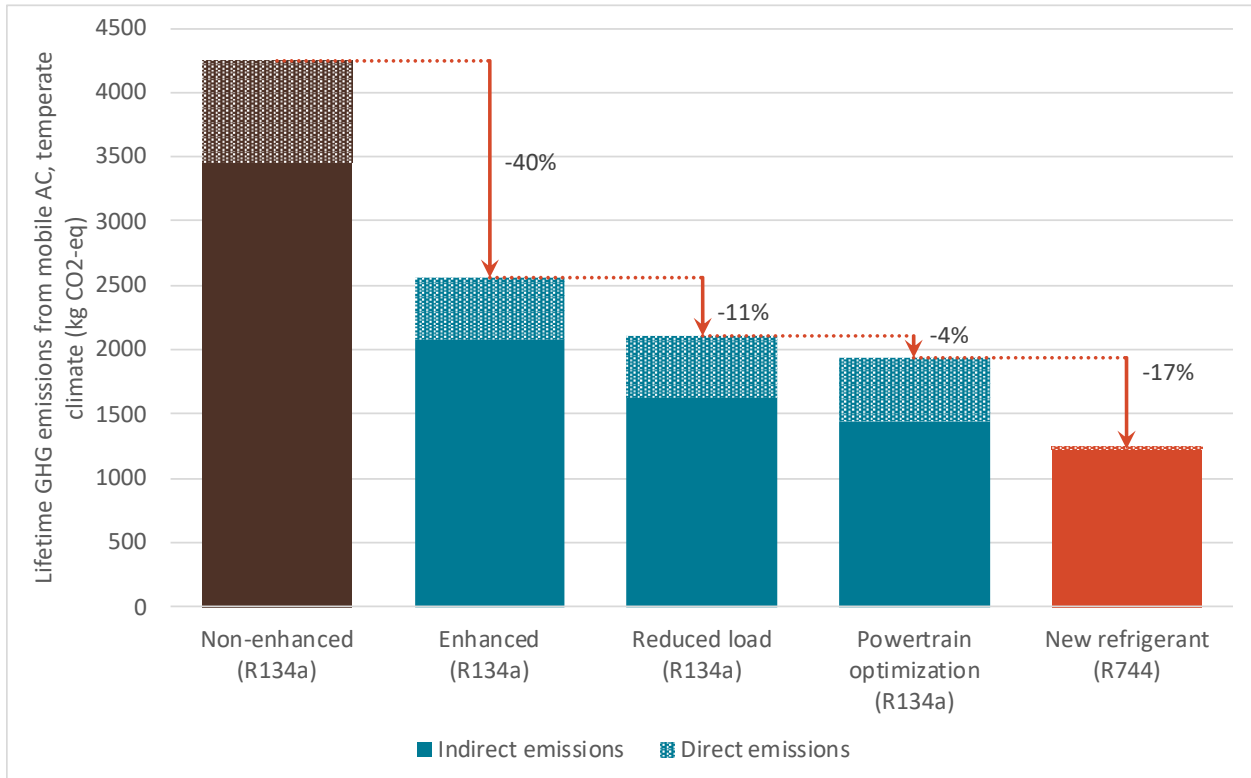


Figure 7. GHG reduction potential of efficiency and refrigerant strategies in temperate climates

Figure 7 demonstrates the GHG reduction potential of the different strategies discussed above, including the R744 DX MAC system, which has the lowest overall estimated lifetime emissions in temperate climates. As demonstrated in Figure 7, after the transition to enhanced systems, moving to an alternative refrigerant offers the most substantial emissions reduction opportunities at lower ambient temperatures.

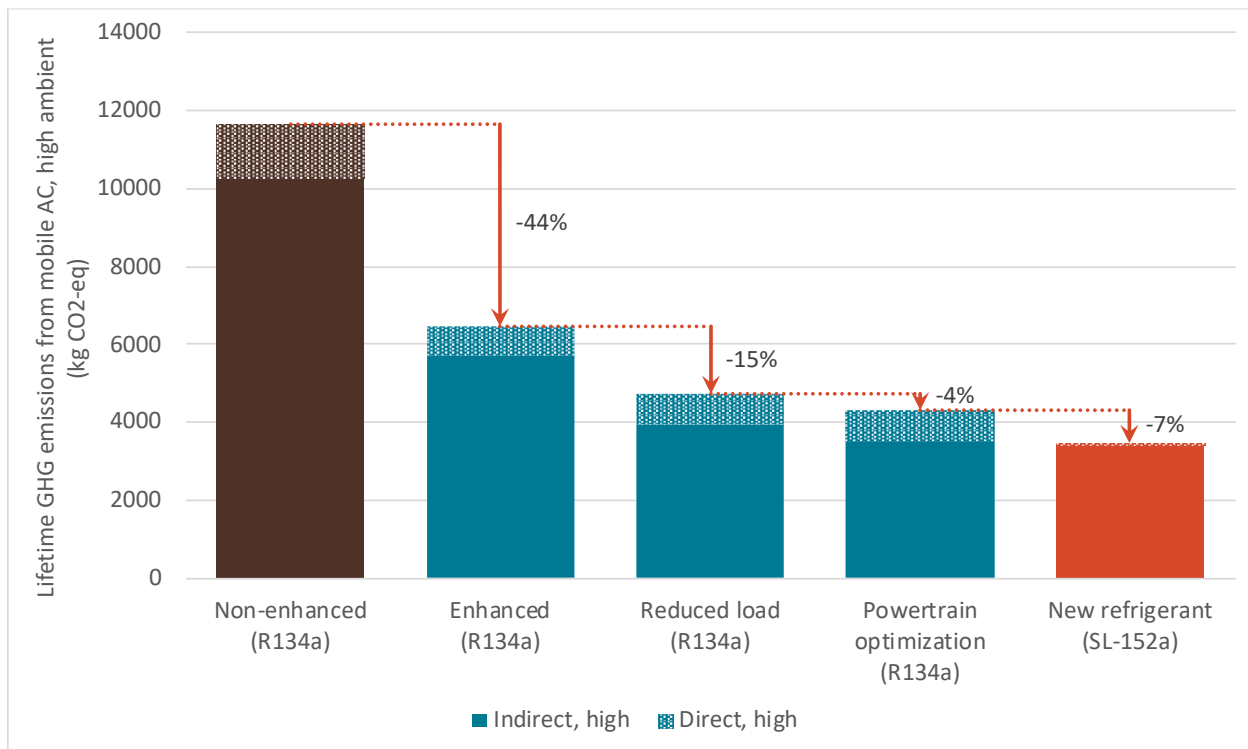


Figure 8. GHG reduction potential of efficiency and refrigerant strategies in higher average temperature conditions

MAC GHG emissions are almost three times greater in higher average temperature conditions, and system efficiency improvements become more important under these conditions. At higher ambient temperatures, the greatest benefits are offered by use of R1234yf in a DX system or R152a in a SL system, both of which offer roughly equivalent emissions benefits. When the ambient air is at a higher temperature on average, all three alternative systems produce less than 4,000 kilograms of CO₂-eq emissions when coupled with thermal load reduction and powertrain optimization strategies, whereas a non-enhanced R134a system produces three times as much pollution (nearly 12,000 kilograms of CO₂-eq). Refrigerant change offers similar absolute emissions benefits in temperate and higher average temperature climates, while the benefits from other strategies increase substantially at higher temperatures.

IV. Life cycle cost comparison

This section estimates the life cycle costs of the enhanced R134a and three alternative systems. Costs consist primarily of hardware costs (direct manufacturing costs plus consumer markup) and ownership costs (fuel consumption and servicing costs, including refrigerant). Absolute component costs are given, or estimated, where available, but the focus here is on relative cost

differences. Similarly, since load reduction strategies apply to all systems (including R134a), they contribute the same amount to hardware costs. What's most important regarding those costs is that any regulation seeking to reduce AC fuel consumption should set a value for these improvements that approaches the real-world value, either by direct testing of AC fuel consumption, or in terms of percent reduction in fuel consumption.

Direct manufacturing costs

The *enhanced* R134a system costs \$200-\$250. This system includes a higher-efficiency evaporator, an internal heat exchanger, an externally-controlled compressor, and other hardware and software improvements. That cost includes \$4-\$6 per full refrigerant charge.

R1234yf currently has a significantly higher cost than R134a and R152a (see Table 9). As R744 is considered to be a waste gas with negligible cost, it was not included in Table 9. While the manufacturing costs of R1234y, at \$13-\$39, is higher than the wholesale or consumer cost of other refrigerants, the price is further inflated due to protection by Honeywell patents (Sherry et al., 2017; Seidel et al., 2016).¹⁰ Consequently, the costs paid by automakers for R1234yf are \$75-\$80 per kilogram, while at the time of this writing R1234yf is available in bulk to consumers for around \$143/kg - \$192/kg (Sherry et al., 2017; Refrigerant Depot, 2018).

Table 9. Refrigerant costs per kilogram (U.S. market, 2018)

	Manufacturing	Automaker	Consumer
R1234yf	\$13-\$39	\$75-\$80	\$143-\$192
R134a	\$2-4*	\$8	\$15
R152a	\$2-4*	\$5	\$10
R744	<\$1	\$1	\$1

*Bulk pricing substituted where manufacturing costs not available (Alibaba, 2018)

While the current costs for R134a are much lower than R1234yf, the cost difference could diminish substantially in coming years. Due to the substantial markup from Honeywell's monopoly, as patent/application claims become invalidated/rejected or as granted patents themselves expire

¹⁰ IGSD communications with chemical manufacturers this year (2018) quoted the cost of R1234yf at \$12/kg; similar to the low end of the range estimated in Sherry et al., 2017. This may indicate that manufacturing process improvements have indeed succeeded in lowering the production costs of R1234yf.

by 2023-2025, the costs for R1234yf could easily halve, or more. While the status of current patents and applications remains uncertain, many claims have been rejected in the US, EU, and Japan, which could affect filings in other countries. Even if some claims are upheld, most of the patents expire between 2023-2025, which is around the time when the first R1234yf systems will require servicing. At the same time, as higher-GWP refrigerants are restricted in supply in certain markets, the prices for R134a are expected to increase in those markets. In Europe, R134a prices have increased by 350% in 2017, the year after the F-gas regulation started to limit HFC supply (Öko-Recherche, 2018). Current consumer prices for R134a are around \$40 per kg, significantly higher than the price in the U.S. market (Elgra, 2018). Thus, the price difference could continue to vary from market to market depending upon the sales restrictions in place.

In addition to higher refrigerant costs, R1234yf hardware is estimated to cost somewhat more than R134a hardware due to the necessity of an added internal heat exchanger to make up for the lower cooling capacity. **Error! Reference source not found.** provides the full hardware costs, which includes the initial refrigerant charge.

R152a systems utilize many hardware components similar to those used for R134a and R1234yf. Since the primary loop of the presumed SL system uses a smaller refrigerant charge and shorter refrigerant hoses, some cost reductions may be possible. Current refrigerant prices are on the order of \$2-4/kg for manufacturers (Alibaba, 2018), and \$10/kg retail (Andersen et al., 2017). Due to R152a flammability, the additional safety hardware needed (e.g., leak sensors, evacuation valves) is estimated to cost \$23 (Meszler, 2004). The additional secondary loop hardware has been estimated to cost \$30–\$40. Importantly, these costs account for one- and two-cooling points, as the secondary loop system does not require additional refrigerant hoses, evaporator, and fittings as would a two-point direct expansion system (hoses, cooler, and fittings are needed for coolant, but these are less expensive). Each additional cooling point adds just insulated low-pressure coolant tubing, low-pressure coolant-to-air heat exchanger, and controls.

R744 system cost estimates vary widely. The significantly higher pressures of the R744 system require more robust components, and the different thermodynamic cycle uses slightly modified heat transfer hardware. The US EPA estimated in its 2012 rulemaking that R744 systems cost \$150-\$230 more than equivalent R134a systems (US EPA, 2012). Other estimates, adjusted for inflation, range from \$105-\$145 extra (Meszler, 2004), \$120 extra (ICF, 2012), to 1.5–2.0 times the cost of a 2009 R134a system (Malvicino et al., 2009). Due to much higher operating pressure,

replacement parts for R744 systems are more expensive than for R152a systems, and there is a safety risk if parts designed for R152a or R134a are utilized in repair.

As mentioned earlier, since the thermal load-reducing technologies are a consumer feature and improve passenger comfort, they may be highly valued by manufacturers. The value would be even greater if manufacturers are granted credit towards fuel efficiency or GHG standards for using them. The broad usage of thermal- and solar-control technologies on millions of vehicles in the US supports this conclusion (Lutsey et al., 2018). Due to the higher cost-effectiveness of these technologies, robust data (such as national humidity and temperature with AC on) would be advantageous in quantifying their full fuel efficiency and GHG benefit. In US regulations, which provide credits for specific technology adoption (as described in the next section), some thermal credit values are overestimated (Kreutzer et al., 2017b).

An anonymous supplier provided the following cost ranges for AC load reducing technologies discussed above:

- Ventilated seats: \$40-\$60 per seat
- Actively cooled seats: \$40-\$70 per seat
- Heated steering wheel: \$10-\$25
- Heated surfaces: \$4-\$40 per surface

Except for R744 system costs, the costs presented in this section assume full commercial-scale production levels. As manufacturers gain experience in a variety of alternative systems and load-reducing technologies, these costs will likely decrease. Additionally, as patents begin to expire (or are invalidated), the use of the previously protected intellectual property will spread. This is especially true for 1234yf-based systems—these will first require service within the time-frame of application patent expiration (2023-2025), which should substantially reduce refrigerant servicing costs.

Ownership costs

Service costs vary around the world. Estimates vary from \$50 to \$100 for labor per service (ICF, 2012; Andersen et al., 2017). In general, labor costs do not significantly affect the results of the cost analysis. However, for a high-pressure R744 system—which may require annual servicing—these costs actually make up a major portion of ownership costs.

The biggest ownership expense is in-use fuel consumption, costs of which depend on both AC system and engine efficiency as well as local fuel prices. The price of gasoline (petrol) varies considerably across the globe, but the global average is about \$1.16 per liter (as of April 2018).

Costs summary

Combining the direct manufacturing costs with ownership costs leads to the results shown in Figure 9, Figure 10, and Table 10. While not shown below, we estimate that non-enhanced R134a systems under temperate and higher average temperature conditions have a lifetime cost of \$2,200–\$5,700 due to significantly higher fuel energy demand. All the alternative systems with thermal load-reducing improvements are substantially lower in cost and highly cost effective by comparison. All the options considered here cut lifetime costs in half compared to non-enhanced R134a systems. Additionally, if the costs of R1234yf plummet to just \$13 per kg (as is possible when patents expire), lifetime costs for R1234yf could drop by \$37-\$219, or less than 10%. This would make R1234yf slightly less expensive in total than R744 under temperate conditions, although R744 maintains its advantage over all refrigerants in terms of fuel consumed.

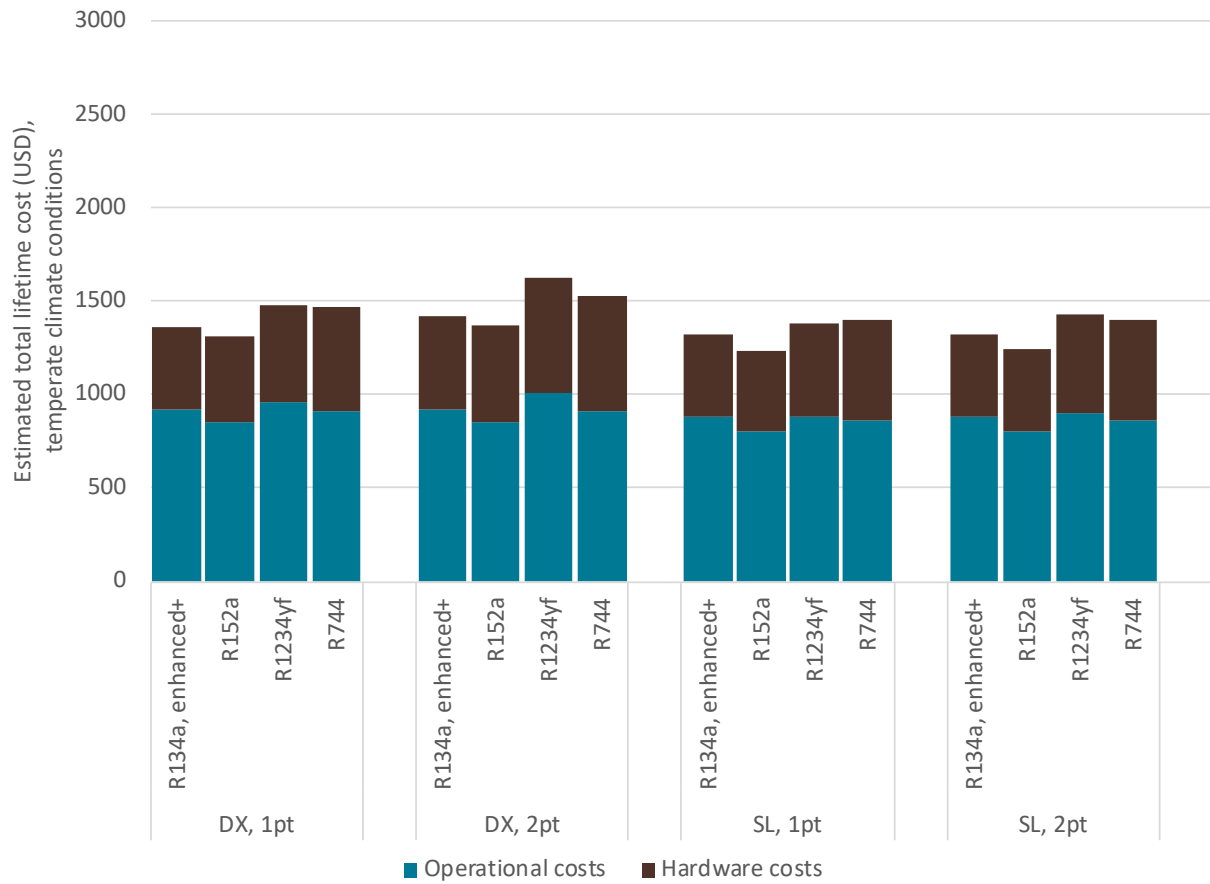


Figure 9. Estimated total lifetime costs under temperate conditions. Assumes application of all currently available efficiency-improving technology for all systems.

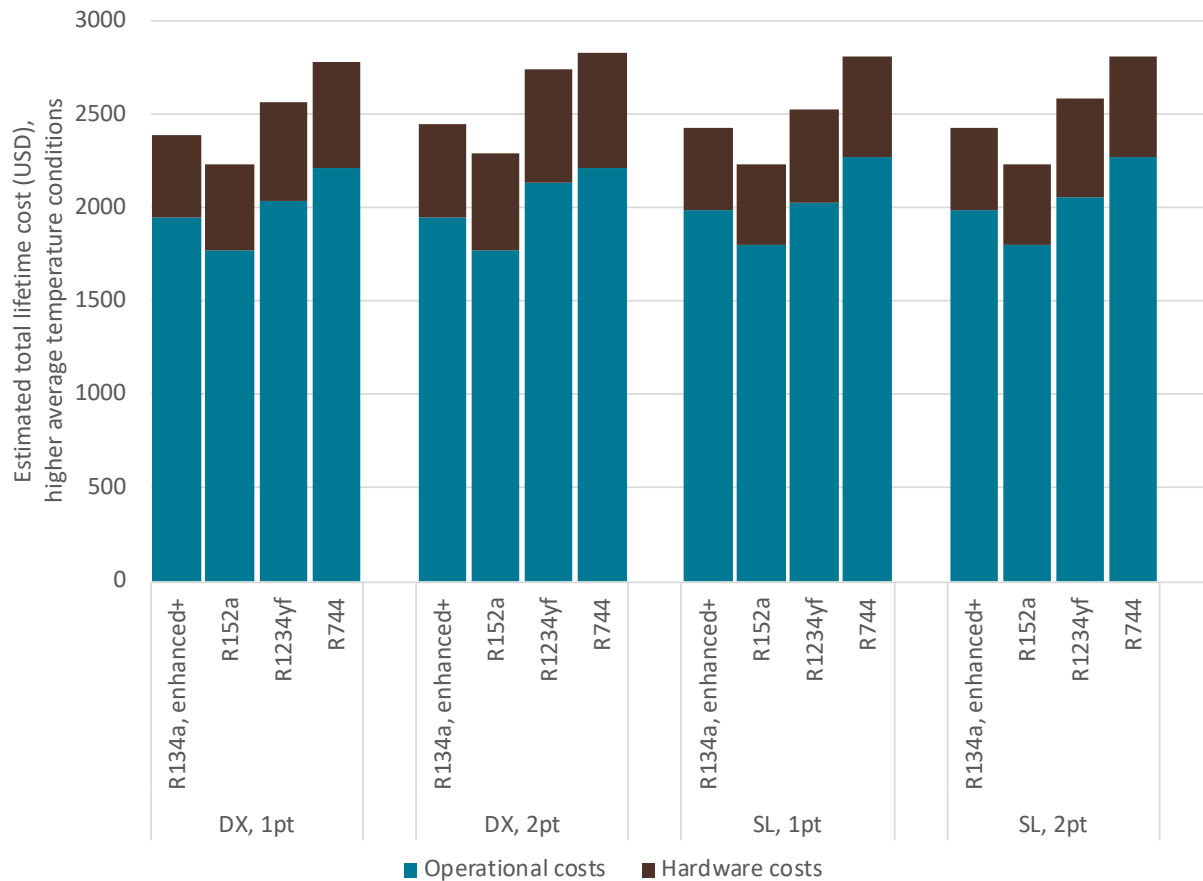


Figure 10. Estimated total lifetime costs under higher average temperature conditions. Assumes application of all currently available efficiency-improving technology for all systems.

Table 10. Total consumer cost comparison

Cost source		Enhanced R134a	R152a	R1234yf	R744
Hardware costs		\$200–\$250	\$201–\$277	\$271–\$372	\$300–\$374
Load reducing technology costs*		\$240	\$240	\$240	\$240
Lifetime recharges**	Temperate	\$102–\$208	\$101–\$204	\$118–\$311	\$200–\$300
	Higher temperature	\$103–\$214	\$101–\$207	\$131–\$384	\$200–\$301
Fuel consumption	Temperate	\$717–\$778	\$645–\$700	\$700–\$759	\$609–\$661
	Higher temperature	\$1,740–\$1,890	\$1,560–\$1,700	\$1,750–\$1,860	\$1,910–\$2,070
		\$1,320–\$1,420	\$1,240–\$1,370	\$1,380–\$1,620	\$1,400–\$1,520

Total consumer costs	Higher temperature	\$2,390–\$2,430	\$2,230–\$2,290	\$2,530–\$2,740	\$2,780–\$2,820
Total savings vs non-enhanced R134a***	Temperate	\$850–\$952	\$902–\$1,030	\$650–\$845	\$741–\$876
	Higher temperature	\$3,160–\$3,220	\$3,360–\$3,420	\$2,910–\$3,070	\$2,780–\$2,840

* Assumes a direct manufacturing cost of \$200 for actively cooled seats, cabin ventilation, solar glazing, solar paint, and \$40 for a secondary loop or cold storage evaporator or a 48V system (only a portion of the cost of 48V is applied to the MAC system).

** Assumes 1–2 recharges for all alternatives except R744, which undergoes 2–3 recharges.

*** Non-enhanced R134a costs assume direct expansion and one cooling point (\$2,214-avg., \$5,590-high) or two cooling points (\$2,273-avg., \$5,652-high)

The results of the cost comparison are broadly similar across alternative systems. Lifetime savings of \$650–\$1,000 are realized under temperate climate conditions. Lifetime savings of \$2,800–\$3,400 are realized in climates with higher average ambient temperatures. These results suggest that, conservatively, alternative MAC systems with improved efficiency offer at least as much value to consumers as an enhanced R134a system, at substantially reduced GHG emissions.

Under the efficiency and cost assumptions listed previously, all alternative systems—with full adoption of thermal load-reducing technologies—show payback within 3-6 years, as compared to a non-enhanced R134a system. This result is primarily due to the increased efficiency assumed for all alternatives and the less frequent service of SL-MAC systems. The primary benefit of such rapid payback is that the first owners of the new MAC system will see savings within their ownership period. Even if load-reducing costs were double the assumed estimates, drivers in higher temperature climates would still see a 3- to 6-year payback period.

Both consumers and the environment benefit from lower GWP systems with enhanced AC load reducing technologies. Since consumers face the brunt of AC costs, policies should be designed to advocate for, and reward, the use of more efficient and less harmful technologies. Setting incentives and policies early allows the most efficient strategies to reach economies of scale and levels of understanding faster. This early adoption, in turn, leads to important benefits for a global fleet and can also support fleet electrification.

V. Regulatory approaches for low-GWP, efficient MAC systems

MAC systems have been regulated primarily in two ways:

1. Targeting direct refrigerant emissions: The Montreal Protocol Kigali Amendment requires phasedown in production and consumption of HFCs. Regional and national regulations or legislation, such as the European Union MAC f-gas Directive, requires refrigerants with $GWP < 150$. While these changes will have an important impact on greenhouse gases (GHGs) through elimination of high-GWP HFCs, they have only a small and incidental impact on full MAC system energy efficiency.
2. Targeting vehicle air conditioning systems, including direct and indirect emissions: While no country currently directly captures the efficiency impacts of MAC systems as part of regulatory test procedures, light-duty vehicles standards in California, the US and Canada offer credit-based incentives for more efficient MAC systems and refrigerant switching. Credits reduce direct refrigerant emissions through substitution and leakage reductions and incentivize improved MAC system efficiency and reduced cooling load.

While requirements to reduce the climate impact of HFCs are now global via the Kigali Amendment, policies to implement this global commitment have only been implemented in a handful of countries. Regulations that require or inspire efficiency improvements from MAC systems are also rare. Nearly 80% of global light-duty vehicles are now subject to fuel economy or GHG standards, and additional large markets are in the process of developing standards. Unfortunately, compliance with standards is measured using test cycles run without AC, and only a few regions provide any regulatory incentive to improve AC efficiency, even though there is a substantial return on the investment to vehicle users. In general, air conditioning is considered to be one of the most important factors in the growing gap between CO₂ regulations and emissions in the real world (Fontaras et al, 2017; ICCT, 2017).

This section provides an overview of the Kigali Amendment to the Montreal Protocol, as well as detailed descriptions of national refrigerant and vehicle regulations pertaining to MAC-related GHG emissions in place or upcoming around the world. Additional policies to reduce GHG emissions from refrigerant leakage through servicing and at the end of the vehicle life are not covered exhaustively, but some best practices are described. The section concludes with an overview of the regulatory approaches employed by all regions.

Kigali Amendment

The phasedown schedule of HFCs under the Kigali Amendment to the Montreal Protocol (see **Error! Reference source not found.**) will achieve an 85% reduction in warming from HFCs in the 2036 to 2047 timeframe. Developed countries (Non-Article 5 (A5) Parties) will mostly begin the phasedown in 2019, with just five countries waiting until 2020 (UNEP, 2016a). The developing countries, which were granted more time to achieve the phasedown under Article 5 of the Protocol, are required to freeze consumption and production of HFCs and then begin the phasedown five years later. Most of the developing countries have agreed to freeze HFCs by 2024, while a minority of A5 Parties from regions with higher temperature climate conditions will wait until 2028.

Table 11. Phasedown schedules for HFCs under the Kigali Amendment

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

*Bahrain, India, Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, and United Arab Emirates

**Belarus, Kazakhstan, Russian Federation, Tajikistan, and Uzbekistan

The phasedown of production, consumption, imports, exports, and emissions as well as consumption baselines of HFCs are calculated and expressed in carbon dioxide equivalent (UNEP, 2016b). As a result, moving to HFCs with significantly lower global warming potential (GWP) can also achieve the terms of the agreement. The Kigali Amendment will reduce GHG emissions by 80 gigatonnes of CO₂-equivalent (80 Gt CO_{2e}) by 2050 and will avoid nearly 0.5 degrees Celsius of warming by 2100.

Parties also agreed to take steps to maintain and/or enhance the energy efficiency of low or zero-GWP replacement technologies and equipment when phasing down HFCs. The agreement includes energy efficiency in guidelines for financing the HFC phasedown, in the work of the Montreal Protocol's Technology and Economic Assessment Panel, and more (Montreal Protocol Decisions, 2016 & 2017). This is especially important as research indicates that the climate mitigation benefits of an HFC phasedown could be doubled if matched with complementary measures to improve the energy efficiency of refrigeration and air conditioning (Shah, 2015).

United States

The US program was until recently considered one of the strongest and most comprehensive programs to reduce GHG emissions from MAC systems. Unfortunately, the two major component policies in place may be eliminated or undermined, one through court rulings and the other through administrative action. At the time of this writing, implementation of the policy to phase out higher GHG refrigerants, specifically, by removing R134a from the Significant New Alternatives Policy Program (SNAP) list of acceptable refrigerants, was barred due to a court decision, which the US Supreme Court declined to reverse, despite appeals from US states and industry. At the same time, the current administration has proposed changes that would substantially weaken federal light-duty vehicle GHG standards and eliminate credits for reducing refrigerant GHG emissions (DOT and EPA, 2018). While the credit structure addressing MAC system efficiency is not a target for revision, all credits would be devalued as the overall stringency of vehicle GHG standards is reduced. It is unknown whether the US automobile industry will stay the course on eliminating R134a out of concern for climate protection and to simplify compliance with regulations outside the USA, which will adhere to the Kigali Amendment.

California regulations maintain vehicle GHG standards to 2025 as originally adopted, although they are under siege by the federal administration. As the state has sought to replace the overturned SNAP rules for other sectors, the California Air Resources Board (CARB) has stated that it may also adopt a limit of 150 GWP for MAC refrigerants (CARB, 2018). California has also adopted additional policies to reduce GHG emissions associated with MAC servicing, adding to the federal regulations on MAC servicing and vehicle end-of-life, which remain in place.

Refrigerant policy history and status

Under Section 612 of the Clean Air Act (CAA), the EPA's SNAP program was originally intended to provide protection from ODSs throughout all sectors of the economy. In the 2015 rule updating the status for certain substitutes under the SNAP program, EPA extended the rulemaking to require consideration of climate impact in the substitution of ODSs. That update required the complete phase-out of R134a by 2021 for all vehicles manufactured in the US, with an exemption allowed until 2025 for vehicles manufactured for use in countries that do not have infrastructure in place for servicing with other acceptable refrigerants. Starting in 2026, R134a would not be allowed in any vehicles newly manufactured in or imported into the US. Certain other refrigerant blends were also banned starting in 2017.

Three manufacturers impacted by SNAP challenged the rule and it was consolidated in 2015 into a single court case heard in the U.S. federal District of Columbia (D.C.) Circuit. The rulemaking, *Mexichem Fluor, Inc. v. EPA*, decided August 8, 2017, states that “Section 612 [of the CAA] requires manufacturers to replace *ozone-depleting substances* with safe substitutes.” The opinion written by D.C. Circuit Judge Kavanaugh, states that because the previously approved R134a is not an ODS, it cannot be subject to Section 612, although EPA could change the classification of HFCs currently considered to be a safe substitute for ozone-depleting chemicals. The ruling vacates the portion of the 2015 update to the SNAP rule that requires manufacturers to replace HFCs that had been previously approved by EPA (US Court of Appeals, 2017). A petition by the Natural Resources Defense Council (NRDC), Honeywell International, and the Chemours Company¹¹ to appeal the case was denied by the D.C. Circuit in January 2018 (US Court of Appeals, 2018). The case was appealed to the Supreme Court supported by a half dozen leading US manufacturers of heating, ventilation, air conditioning and commercial refrigeration equipment, as well as seventeen states and the District of Columbia. The appeal asserted that the D.C. Circuit’s decision had “torn up” a “well-established and reasonable path toward new, environmentally safer alternatives” and “created enormous uncertainty and associated costs,” but review of the case was denied (US Supreme Court, 2018 a, b and c).

The reduction of the SNAP program’s authority brings uncertainty to the refrigerant market in the US, which is exacerbated by the proposed changes to light-duty vehicle GHG standards. The SNAP program offered clear limits on the use of R134a, and credits for use of lower GWP refrigerants were expected to move the automotive industry towards refrigerants with lower climate impacts. With neither provision certain at the federal level, California plans to maintain credits for lower-GWP refrigerants in state vehicle standards and may seek to limit MAC refrigerants to 150 GWP in the future (CARB, 2018).

Passenger vehicle regulatory structure

Until recently, GHG standards for light-duty vehicle were aligned in the US, California, Canada, offering a relatively comprehensive regulatory approach to address GHG emissions and energy demands from MAC systems. The standards were intended to give manufacturers the option to obtain generous GHG emission reduction credits by reducing leakage of refrigerants, switching to lower-GWP refrigerants, improving the efficiency of MAC systems and reducing cooling demand. Credits could then be used as part of a manufacturer’s overall compliance with stringent

¹¹ Honeywell and Chemours are manufacturers of R1234yf, while NRDC is a nonprofit environmental organization.

CO₂ fleet-average standards. Under the current administration, the US has proposed to eliminate credits associated with reducing direct GHG emissions from refrigerants and will also greatly reduce the overall stringency of standards, thus reducing the value of credits associated with MAC system efficiency and load reduction.

US standards rely on credits to incentivize MAC efficiency improvements and load reductions, because the official US federal test procedure (FTP) used for regulatory purposes is not conducted with the air conditioning running. However, other test procedures include AC use to support emission standards, fuel economy labeling, and off-cycle credit calculation. In addition to the two (city and highway) official fuel economy regulatory test cycles, three supplemental test cycles are integrated into a five-cycle test used for fuel economy labeling and emissions standards. One of these is the SC03 cycle, a test run at high ambient temperatures to specifically measure the impact of the air conditioning system. The EPA more recently introduced the AC17 cycle, which is required to verify credit applicability for MAC systems and thermal technologies (SAE International, 2014). The AC17 cycle, a variant of the SC03, is run under high solar loading, high ambient temperature, and high humidity conditions.

While the current federal proposal would eliminate credits for refrigerant switching and reducing leakage, California standards maintain these credits. As seen in

Table 12, credits for leakage reduction depend on compressor technology, but are offered regardless of the refrigerant used. EPA uses a leak score derived from SAE's J-2727 scoring system. For systems that use low-GWP refrigerants, there is a high-leak penalty of up to 1.8 g/mi for any systems with a leak rate higher than the average of the initial charge per year. While leakage of low-GWP refrigerants may not have a direct GHG impact, EPA reasoned in the original rulemaking that substantially reducing leakage lowers the risks associated with the potential for consumer recharge with higher-GWP refrigerants (EPA, 2012).

Table 12. Leakage and refrigerant credits (g/mi)

Maximum credits	Belt-driven compressor, R134a	Electric motor-driven compressor, R134a	Maximum credit, with GWP=1 refrigerant
Cars	6.3	9.5	13.8

Trucks	7.8	11.7	17.2
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Credits for more efficient MAC systems and technology to reduce cooling load are offered under California standards and are also maintained in federal regulations. A menu of technologies available and credits offered for each is provided in the applicable regulations and reproduced here as Tables 11 and 12 below. In order to gain access to the credit menu, manufacturers must demonstrate the benefits of the technologies in laboratory test conditions. Depending on the test results, manufacturers may gain full or partial access to the defined credits.

The maximum credit available for improved MAC efficiency is limited to 5 g/mi for cars and 7.2 g/mi for trucks, even if additional technologies from the menu are present and could otherwise add up to a higher total credit value. As with other off-cycle credits, a manufacturer can use the alternative credit approval process to justify higher credits for individual technologies. However, the maximum level of credit allowed for MAC efficiency will remain as is under all circumstances.

Table 13 shows the credit menu for MAC efficiency technologies that reduce energy demand on the vehicle associated with the MAC system. The incorporation of design features included here can be verified visually. EPA recently approved additional technology credits for MAC systems based upon application by automakers: 1.1 g/mi for use of the Denso SAS compressor or 1.4 g/mi for Denso SAS compressor with variable crankcase suction valve technology (EPA, 2017). Credit limits still apply for any additional credits approved.

Table 13. Air conditioning efficiency credits offered under EPA regulations

Technology	MAC CO ₂ emissions reduction	Car AC credit (g/mi)	Truck AC credit (g/mi)
Reduced reheat, with externally controlled, variable-displacement compressor	30%	1.5	2.2
Reduced reheat, with externally controlled, fixed-displacement or pneumatic variable displacement compressor	20%	1	1.4
Default to recirculated air with closed-loop control of the air supply (sensor feedback to control interior air quality) whenever the outside ambient temp is 75 °F or higher (variations allowed with engineering analysis)	30%	1.5	2.2

Default to recirculated air with open-loop control of the air supply (no sensor feedback) whenever the outside ambient temp is 75 °F or higher (variations allowed with engineering analysis)	20%	1	1.4
Blower motor control that limits wasted electrical energy (e.g. pulse width modulated power controller)	15%	0.8	1.1
Internal heat exchanger (or suction line heat exchanger)	20%	1	1.4
Improved evaporators and condensers (engineering analysis indicating COP improvement >10% compared to previous)	20%	1	1.4
Oil separator (internal or external to compressor)	10%	0.5	0.7
Maximum credit		5	7.2

Additional credits are available for thermal management technologies designed to reduce MAC demand or load. To access the credits described in

Table 14, benefits must also be verified on defined test cycles, which include the solar loading.

Table 14. Credits for thermal technology

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

Individual credits only apply if that technology is installed on the vehicle. The full credit can only be accessed if the delta between AC off and AC on is equal to or greater than the maximum credit value. The cabin temperature of the vehicles during testing is required to confirm that the MAC system is working better than or at the level of the comparative baseline vehicle. To limit the testing burden, testing is not necessary on more than one vehicle from each platform for each model year.

MAC servicing regulations

EPA has adopted regulations intended to reduce leakage of refrigerants to the atmosphere during servicing. These regulations include:

1. Restrictions on intentional release or venting of refrigerants to the atmosphere (CO₂ as a refrigerant is exempt from this rule);
2. Requirements for technician training and certification for repair of MAC systems at servicing shops, including use of certified equipment, proper handling of refrigerants during servicing, and keeping records for refrigerant handling equipment; and
3. Safe disposal requirements for end of life of the system or vehicle.

California adopted restrictions on sales of small cans of refrigerant used in home servicing of MAC systems. Leakage from servicing is significantly higher in the US than in most other parts of the world because of the large number of people who service vehicles themselves rather than seeking professional help. California regulations were adopted in 2009 and last amended in 2017. They require: a self-sealing valve on all refrigerant containers, which is intended to reduce leakage of the refrigerant left in the can after servicing; improved labeling instructions; a consumer education program, as overfilling can damage the compressor, reduce the system efficiency, and potentially increase leakage; a \$10 deposit per container; and a recycling program for used containers, intended to recapture the refrigerant left in cans and reduce leakage (CARB, 2017).

Canada

Canada adopted in 2016 economy-wide regulations, the *Ozone-depleting Substances and Halocarbon Alternatives Regulations*, to enable compliance with the Montreal Protocol. These regulations were amended in 2017 to include a requirement that any MAC system on vehicles imported into or manufactured in Canada from model year 2021 on must contain and be designed for a refrigerant with GWP of 150 or less (Government of Canada, 2017).

Canada light-duty vehicle GHG standards are explicitly aligned with the US and directly cite the US Code of Federal Regulations. Canada has begun consultations on light-duty vehicle standards and may consider decoupling from US standards if the current US proposal is adopted (Government of Canada, 2018).

Mexico

In 2012, Mexico's Secretary of Environment and Natural Resources (SEMARNAT), the Secretary of Economy, and the Secretary of Energy jointly adopted fuel economy and CO₂ standards for new light-duty passenger vehicles. Those standards were based on US National Highway Traffic Safety Administration (NHTSA) standards, although the primary compliance metric is gCO₂/km

(rather than miles). Credits are offered for manufacturers who reduce CO₂-equivalent emissions from MAC systems. To access this credit, manufacturers must demonstrate that 80% or more of their vehicles sold: 1) reduce CO₂-equivalent emissions of refrigerants, either through substitution of refrigerants or through low-leak systems; and 2) are equipped with more efficient technologies relating to the MAC system (SEMARNAT, 2013). The technology list included was drawn directly from US regulations. There is no requirement for verification testing of system efficiencies. The U.S. FTP is the only test cycle referred to in the regulation; no supplemental cycles are described or cited. While the standard was adopted for model years 2014-2016, the standard for model year 2016 was extended to 2017 and 2018.

Unfortunately, the new SEMARNAT proposal for GHG standards out to 2025 incorporates higher crediting for MAC systems, combined with even less rigor in assuring benefits are realized. In total, the AC and off-cycle (including thermal technologies) credit allowances in the proposal would cut the expected GHG benefits associated with the standard in half. The proposal was published in the Mexico federal register on September 28, 2018. Given that the new administration begins just a few days after the close of the 60-day public comment period it is unlikely to be finalized by the current administration (SEMARNAT, 2018).

The proposal is based loosely on US standards, but without the critical details, safeguards and compliance mechanisms, it allows any technology within the credit category (e.g. off-cycle or AC efficiency) to be awarded what would be the maximum credit allowance under the US program. Furthermore, there are no requirements for submission of test results to confirm that the technology provides any actual benefits in the real world. As a result, a manufacturer could make use of an oil separator to improve AC efficiency—a technology that provides a 0.3 g/km benefit—and claim the full 6.82 g/km credit for the vehicle. In this way, the proposal awards credits for thermal technologies, AC efficiency, and low leakage that could be more than 30 times greater than the GHG benefits associated with the actual technology applied to the vehicle. Only the credit for refrigerant substitution is likely to be within 20% of the actual benefit provided by the change. Table 13 compares the credit allowances under the original US standards and SEMARNAT's 2018 proposal.

Table 15. Credit allowances under SEMARNAT GHG emissions proposal

US credit allowances (maximum)		Mexico credits (any technology)
PV	LT	PV & LT

	g/km		g/km
Off-cycle (includes thermal technologies)	6.2		6.25
AC efficiency	3.1	4.5	6.82
Belt-driven R134a (Electric R134a)	3.9 (5.9)	4.8 (7.3)	4.12
Leakage and refrigerant change	8.6	10.7	9.04

Brazil

Brazil's emissions standards, administered by the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA), an agency of the Ministry of Environment (CONAMA), include some testing provisions related to air conditioning (CONAMA, 2009). However, the fiscal incentive program administered by the Ministry of Development, Industry and Commerce (MDIC), which targets vehicle efficiency, does not include any testing provisions related to air conditioning or credits related to more efficient AC systems. Discussion of updates to the MDIC program and new proposals on CO₂ standards from CONAMA currently do not include any provisions to incentivize more efficient AC systems and lower GWP refrigerants.

European Union

In 2006, the EU adopted the first and one of the most ambitious policies for use of refrigerants in MAC systems, Directive 2006/40/EC (European Parliament, 2006). Known as the MAC Directive, this rule banned the use of refrigerants with GWP of higher than 150. The Directive included the following requirements:

1. From 2008, for approval of new vehicle types, and from 2009, for all vehicles sold in the EU containing a MAC system, the following apply: for systems containing gases with a GWP higher than 150, leakage is less than 40 grams of the refrigerant per year for systems with one evaporator and less than 60 grams/year for systems with two evaporators.
2. From 2011, air conditioning systems in all new vehicle types approved must use a refrigerant with a GWP of 150 or less.
3. From 2017, the use of fluorinated greenhouse gases with a GWP higher than 150 is totally banned in all new vehicles put on the EU market. New vehicles with MAC systems using these gases may not be registered, sold, or able to enter into service in the EU.

While now fully implemented, the rule was challenged early on by automakers and early enforcement of the Directive by EU member states was not consistent. Daimler AG, an automaker based in Germany, argued in 2012 that R1234yf, the low-GWP refrigerant being widely utilized in compliance with the MAC Directive, was not safe. Daimler claimed they needed more time to develop MAC systems using R744 as the refrigerant and, in the meantime, refused to discontinue use of R134a and claimed that Daimler engineers did not know how to safely use R-1234yf. In 2013, the German market surveillance authorities, Kraftfahrt Bundesamt (KBA), found that there was not “sufficient supporting evidence of a serious risk that would entail the intervention of the authorities” (European Commission, 2014b). Nonetheless, German authorities continued to allow Daimler vehicles equipped with MAC systems that ran counter to the European directive to be placed for sale in the EU market.

In 2014, the European Commission released a memo regarding the safety of R1234yf for use as refrigerant in MAC systems, summarizing the research by SAE International, KBA, the Joint Research Commission (JRC) of the European Commission and others. The memo found that there was no evidence to support Daimler’s safety claims (European Commission, 2014b). In December of 2015, the European Commission referred Germany to the EU Court of Justice over failure to enforce this directive (European Commission, 2018). Daimler began using R1234yf that same year but pledged to continue work on R744 (Cooling Post, 2015). In 2016, Mercedes-Benz announced that they would offer, at added expense, R744 MAC systems as an alternative to the standard R1234yf system in S-Class and E-class automobiles sold in the EU starting with model year 2017, making them the first series-produced passenger cars utilizing R744 in mobile air conditioning systems (Mercedes-Benz, 2016).

The overall supply of R134a for servicing in existing vehicles is also limited as part of the European F-gas regulation, originally adopted in 2006 and updated in 2014, which limits the total amount of F-gases that can be sold in the EU and requires proper servicing and recovery of F-gases for equipment that use them (European Parliament, 2014). As a result of limited supply, along with strengthened servicing requirements, R134a prices in Europe have risen by 350% in 2017 (Öko-Recherche, 2018).

While the European Union has demonstrated leadership in the phaseout of high-GWP refrigerants, the EU light-duty vehicle CO₂ standards to date have not provided any incentive to improve AC systems overall. Indeed, the lack of accounting for energy demand from light-duty AC systems is considered to be one of the most important reasons behind the growing gap

between the real-world CO₂ emissions of vehicles in use and certified CO₂ emissions. ICCT's analysis concludes that the divergence between type approval values and this one source of real-world CO₂ emissions data has grown from 8% for model year 2001 to 40% for model year 2015 (Tietge et al., 2016).

Europe is in the process of transitioning from the New European Driving Cycle (NEDC) to the World Harmonized Light Vehicle Test Procedure (WLTP). The WLTP is considered to be more representative of real-world driving conditions than the NEDC and reduces some of the loopholes widely utilized during testing under NEDC. For example, under the WLTP, vehicle models must be tested with equipment such as AC systems installed, which will influence the vehicle weight. Nonetheless, the WLTP still does not require AC use during testing. Japan, South Korea, China, India and Australia have all committed to adoption of the WLTP in the coming years (Alphabet, 2018).

The European Commission's proposal for post-2025 standards will allow improvements to air conditioning systems to be counted as "eco-innovations" for the first time (Dornoff et al., 2018). Eco-innovations are innovative technologies that provide verifiable CO₂ benefits not covered by the standard test cycle. To gain access to these credits, the automaker must submit a report, including a verification report by an independent and certified body, to the Commission (European Parliament, 2009). Eco-innovation credits are currently capped at 7 g/km, but the proposal for post-2025 has opened the possibility of revising this cap (Dornoff et al., 2018).

Australia & New Zealand

Neither Australia nor New Zealand currently have regulations directly targeting HFC or CO₂ emissions from mobile air conditioning, but both countries are on track for federal legislation phasing down HFCs in line with the requirements of the Kigali Amendment to the Montreal Protocol.

In 2014, Australia repealed their tax on carbon, which had included a tax on the carbon equivalent for HFCs. This fiscal approach was replaced by a mandatory phase-down of HFCs as part of the *Ozone Protection and Synthetic Greenhouse Gas Management Legislation*. The 2017 amendment requires a phase-down for HFCs, gradually reducing the amount of bulk HFCs permitted to be imported into Australia (Department of Energy and Environment, 2018). The legislation went into effect January 1, 2018, with only residual amounts allowed after 2036.

The legislation impacts only bulk imports of HFCs and does not alter the import of equipment pre-charged with HFCs, including mobile air conditioners. In addition, R134a will still be available for vehicle servicing of all existing and new vehicles designed for it. The phase-down would, however, impact MAC systems in vehicles produced within Australia.

As the current phase-down law does not actually require vehicle manufacturers to switch to lower GWP refrigerant systems, an additional regulation would be needed to limit the GWP in refrigerants of new vehicles imported into the country. While R134a is already banned for use in new vehicles sold in Europe, there is no guarantee that vehicles imported to Australia and other countries will be equipped with the same advanced refrigerants and air conditioning systems.

New Zealand is expected to adopt legislation in the second half of 2018 to phase down HFC consumption by 80% by 2036, in line with the Kigali Amendment. Adoption is anticipated in the second half of 2018, with entry into force on January 1, 2019 (Ministry of the Environment, 2017).

Japan

The Act on the Rational Use and Proper Management of Fluorocarbons regulates economy-wide use of HFCs. Like Europe, Japan's Act sets a limit of 150 for the GWP of refrigerants in mobile air conditioning systems. MACs are required to use refrigerants complying with the 150 GWP limit starting in 2023 (Ministry of Environment, 2016).

While Japan does not specifically address refrigerants or AC efficiency in new light-duty vehicle fuel economy standards, the end-of-life vehicle recycling law, which entered into force in 2005, mandates that automakers or importers are responsible for the recovery, recycling and proper disposal of fluorocarbons used in mobile air conditioning (Ministry of Economy, Trade and Industry, 2006).

All Japanese vehicles sold in the EU and some sold in the US and Canada are equipped with R1234yf MACs.

China

China is the largest producer of light-duty vehicles, the largest market for vehicles, and the largest producer and consumer of HFCs in general (OICA, 2017; EIA, 2016). Vehicle efficiency is regulated through Corporate Average Fuel Consumption (CAFC) standards promulgated by the

Ministry of Industry and Information Technology (MIIT). The Phase 4 standards in force since 2016 offer off-cycle credits for efficient air conditioning systems (up to a maximum off-cycle credit of 0.5L/100km for three different technologies, including AC). However, implementation documentation specifying how those credits could be accessed has yet to be published (ICCT, 2014). The light-duty vehicle (LDV) test cycle used under MIIT's standard does not include the use of AC.

Although there are currently no regulations requiring or promoting a transition to lower-GWP refrigerants for mobile air conditioners, under its expanded regulatory authority, the Ministry of Ecology and Environment (MEE)—previously called the Ministry of Environmental Protection (MEP)—could promulgate either economy-wide or targeted vehicle regulations requiring the phase-down of high GWP HFCs in the coming years and could also implement separate GHG standards relating to AC efficiency and refrigerants for vehicles.

India

India has in place CO₂ standards for new light-duty vehicles applicable for model years 2017 through 2022 (Yang and Bandivadekar, 2017). Current standards use the European test cycle, NEDC. India was involved in the development of the WLTP, which incorporated data from vehicle use in India and is expected to transition to that cycle for the next regulatory phase. Currently, there is no mechanism in place for incentivizing more efficient air conditioning systems or lower-GWP refrigerants for MAC systems imported into or manufactured in India. However, The Government of India's Ministry of Environment, Forest and Climate Change (MoEFCC), is developing a National Cooling Action Plan (NCAP), due for publication later this year, which will address low-GWP refrigerant alternatives for the AC sector, including MAC (AEEE, 2018). All Jaguar and Land Rover vehicles (manufactured by TATA Motors Limited) sold in the EU, US and Canada are equipped with R1234yf MACs.

South Korea

As part of the GHG and energy efficiency standards for new light-duty vehicles, promulgated jointly by South Korea's Ministry of Environment and Ministry of Commerce, Industry and Energy, credits are available for transitioning to low-GWP refrigerants and improved AC efficiency. In order to gain access to the credits, manufacturers must demonstrate efficiency and GHG savings. The ministries will determine the credits to be applied. Credits for model years 2016-2020 are capped at 10 gCO₂/km total for four technologies: air conditioning refrigerant and performance

improvement and three other defined technologies. Another 4 g/km credits could be applied for “other technologies that manufacturers prove to be effective” (Ministry of Environment, 2014). These other off-cycle credits could, in theory, include thermal management to reduce AC demand. All South Korean vehicles sold in the EU and some sold in the US and Canada are equipped with R1234yf MACs.

Saudi Arabia

The Kingdom of Saudi Arabia (KSA) adopted a fuel economy regulation effective beginning in 2016 that is patterned off the US NHTSA standards. The regulation adopts the US test cycles and offers air conditioning efficiency credits adjusted for the higher temperature and cooling load expected in the region (ICCT, 2014). As the regulation concerns fuel economy and not GHG emissions, refrigerant switching and leakage is not considered.

Overview of regulatory approaches

While legislation specifically targeting HFCs appears to be one of the simplest approaches to reducing MAC GHG emissions, the European Union MAC Directive was relatively contentious, and the US SNAP regulation has been overturned. Nonetheless, as the technology and replacement refrigerants become more widespread, it should become much more straightforward for countries to replicate the approach of setting a 150 GWP limit for MAC refrigerants, either as a part of economy-wide regulation (as in Canada and Japan) or a stand-alone directive (as in the EU). Table 14 includes the limits currently in place for GWP from MAC refrigerants.

Table 16. Economy-wide legislation or regulation requiring refrigerant substitution

Country	Phase out of R134a	Target value (GWP)
US	Overtuned (was 2021)	Not applicable
Canada	2021	150
EU	2017	150
Japan	2023	150

Incentivizing MAC system efficiency and addressing refrigerant emissions in light-duty vehicle fuel economy or GHG standards can be more complex. However, as the regulatory framework becomes established in many regions, this is another approach that makes sense. It is important to verify that system benefits are real, a task made more challenging by the lack of an adopted methodology or test cycle in most countries to demonstrate the real-world impact of improved MAC systems. Table 17 briefly describes how MAC systems are addressed in vehicle regulations currently in place or under development. There are immediate opportunities to consider adding

AC efficiency credit provisions, possibly along with refrigerant switching, to proposals under development in Mexico, Brazil, Australia, and China.

Table 17. How MAC systems are addressed in vehicle regulations

Country	How MAC systems are handled in vehicle regulations			Other provisions to reduce HFC emissions
	AC use in test cycle	Credits	Comments	
US	For credit verification only	Proposal to eliminate refrigerant switching and low leak provisions. AC efficiency and thermal management provisions remain.	Credits offered based upon a technology menu, must verify efficiency benefits through testing.	No GWP limit for MAC refrigerants (SNAP regulation overturned)
Canada				MAC refrigerant 150 GWP limit
Mexico	Not included in test cycle	Credit given for 80% adoption of some AC efficiency technology with refrigerant switching or low leak.	New proposal further weakens credit provisions, without the detail, safeguards or compliance mechanisms needed to ensure real benefits.	N/A
Brazil	Emissions standards only	No credits	Not currently included in the regulations under development.	N/A
European Union	Not included in test cycle	No credits	Proposal to allow credits for MAC system efficiency as an eco-innovation post 2025.	MAC refrigerant 150 GWP limit
Australia	Not included in test cycle	No credits	Could be considered regulations under development.	Bulk HFC phase down does not apply to vehicles.
Japan	Not included in test cycle	Require AC in top runner vehicles.		MAC refrigerant 150 GWP limit; Vehicle end-of-life HFC regulations.
China	Not included in test cycle	Standards mention AC efficiency credits, provide no implementation path.	Could be considered in the next phase of standards.	N/A

India	Not included in test cycle	No credits	National Cooling Action Plan under development	N/A
South Korea	Not included in test cycle	AC efficiency credits specified, potential off-cycle credits for thermal technology.		N/A
Saudi Arabia	Not included in test cycle	AC efficiency and thermal technology credits, based on US standards.	Credits were adjusted for local conditions.	N/A

VI. Conclusions

Large climate and consumer benefits are possible by transitioning to low-GWP refrigerants while improving MAC system efficiency

Worldwide, as the global vehicle fleet grows, more consumers are purchasing AC-equipped vehicles, mostly equipped with relatively high-GWP R134a systems. As fuel efficiency standards across the globe make the global fleet increasingly fuel-efficient, AC will account for a growing percentage of vehicle fuel use. Warmer temperatures due to climate change also will increase the fuel use for MACs.

Changes in refrigerants and improvements in system efficiency can cut per-vehicle GHG emissions associated with MAC system use by up to 70% compared to older MAC systems. Enhanced systems that have cut GHG emissions by 40% already dominate the global market. Fortunately, cost-effective alternate, low-GWP refrigerants and technology to improve MAC system efficiency can reduce GHG emissions by another 50%.

MAC GHG emissions are almost three times greater in higher temperature climates, making system efficiency improvements even more important in warmer regions. Low-GWP R1234yf and R152a refrigerants can achieve substantial reductions in direct refrigerant and indirect fuel GHG emissions in all climates, while low-GWP R744 refrigerant can achieve even higher reductions in direct refrigerant and indirect fuel GHG emissions in temperate climates. New regulatory incentives and policies are needed to accelerate the transition to cleaner MAC systems.

Low-GWP R1234yf, R744, and R152a alternative refrigerant systems eliminate the majority of direct GHG emissions

If implementation of the Kigali Amendment to the Montreal Protocol is successful, lifetime GHG emissions from MACs will decline by ~7% to 17%, due to the reduction in direct GHG emissions from the switch in refrigerants.

The GHG impact of MACs depends both on the global warming potential of the refrigerant utilized and the efficiency of and demand on the system. As the world transitions to low-GWP refrigerants in compliance with the Kigali Amendment, the energy demand due to AC use will become the target of the GHG emissions associated with MAC systems.

Improved system hardware and load-reducing technologies reduce indirect emissions

While automakers offer increasingly global products, the efficiency and effectiveness of MAC systems depends to no small degree on ambient conditions, including temperature, humidity, and solar loading. Driving conditions also matter, with stop-start traffic putting a greater strain on the system. Improved MAC system designs will become increasingly important in the context of advanced vehicle technologies.

This review finds that there are substantial benefits in terms of GHG and lifecycle costs to be gained in the transition to thermal control technologies and enhanced MAC systems. Thermal control technologies and powertrain optimization represents nearly half to approximately three-quarters of the remaining GHG reductions possible.

Alternative refrigerants all offer substantial GHG benefits, with variation depending on ambient temperatures

In temperate climates, all alternative refrigerant MAC systems with improved system hardware and load-reducing technologies have significantly lower climate impacts than enhanced R134a systems. With a single cooling point, a traditional enhanced R134a system produces 1,940 kg CO₂-eq emissions over its lifetime. All alternative systems reduce GHG emissions by one quarter to a third. The R744 system offers the greatest GHG benefit under temperate climate conditions: lifetime emissions of 1230 kg CO₂-eq, a 37% reduction compared to R134a. SL-MACs using R152 and DX-MACs using R1234yf offer similar benefits in temperate climates, approximately a 26% reduction in GHG emissions compared to R134a.

MAC GHG emissions are almost three times greater at high ambient temperatures, and system efficiency improvements become more important at under these conditions. In higher average temperature conditions, an enhanced R134a system equipped with all currently available

efficiency-improving technology produces 4270 kilograms of CO₂-eq emissions for a single cooling point. With lifetime emissions of approximately 3500 kg CO₂-eq, R152a used in a SL system and R1234yf used in a DX system offer approximately equal benefits, an 18% reduction in lifetime emissions compared to R134a. With lifetime emissions of 3900 kg CO₂-eq, R744 systems are less efficient in high temperature and high humidity conditions, although they still offer a 9% benefit compared to R134a.

Alternative MAC systems offer similar value to vehicle owners as enhanced R134a systems and greater value in clean air and climate protection

Lifetime costs are broadly similar across enhanced R134a systems and the three alternatives considered. All systems offer substantial savings compared to non-enhanced R134a systems, in the range of almost 1000 to 3000 US dollars over the lifetime of the vehicle. Lifetime costs for alternatives range from very similar to the current enhanced R134a systems, to hundreds of dollars in savings realized. These results suggest that alternative MAC systems with improved efficiency offer similar and possibly much more value to consumers as enhanced R134a systems, with dramatically reduced GHG emissions. The SL systems offers cost savings for all refrigerants as a result of reduced servicing costs related to lower refrigerant charging and leakage, with R152a SL-MACs offering the lowest total lifetime costs.

As these changes will have an upfront cost to the manufacturer, while any benefits in reduced fuel costs would be realized by the consumer, policy action can help spur the introduction of these systems into the global fleet. Since thermal load-reducing technologies tend to increase passenger comfort, manufacturers may be eager to add them as desirable features, especially if policies reward them for doing so.

Performance-based standards are needed to drive improvements in MAC systems

Effective policies can relatively easily require refrigerant substitution with low-GWP options, ideally moving much more quickly than the Kigali Amendment requires. While the MAC Directive in Europe and the SNAP rule in the US were both challenged, now that alternative refrigerants and systems are becoming far more widespread, such policies are much less likely to run into implementation complications or strong opposition. So far only the European Union, Canada and Japan have rules in place that ban the sale of vehicles equipped with refrigerants of greater than 150 GWP. Although now overruled, the SNAP rule of the US took the further step of not allowing vehicles manufactured in the US for export to other countries to use higher GWP refrigerants, a framework that should be considered by countries that are major manufacturers.

In order to get the full benefits of improved MAC systems, light-duty vehicle GHG or fuel economy standards in each country need to incorporate incentives for improved MAC systems or technologies. Currently, incentives are in the form of a credit program added to the general GHG emissions or fuel economy standards. A more accurate program would not use credits but would instead measure CO₂ directly with the AC running. Using realistic test cycles, including use of AC, would help to demonstrate the benefits that these technologies could bring.

Consumers and the environment will benefit from alternative refrigerants and improved MAC systems

In many of the rapidly growing car markets of the developing world, AC systems are increasingly standard equipment on new vehicles. Many of these markets, situated in warmer climates, will see the greatest benefits in real-world fuel and GHG savings. These countries need be able to demonstrate the benefits of improved MAC technology, as well as thermal technologies to reduce AC load and incentivize their adoption.

It is technically and economically feasible to rapidly transition to low-GWP refrigerants and efficient MAC systems throughout the world. Both consumers and the environment will benefit from lower GWP systems with enhanced AC load reducing technologies. Since consumers face the brunt of AC costs, policies should be designed to advocate for, and reward, choosing the more efficient and less harmful technologies. Doing this early allows the most efficient strategies to reach levels of understanding and economies of scale faster. This early adoption, in turn, leads to important benefits for a global fleet.

Acronyms

A5 Parties	Parties covered under Article V (Article 5) of the Montreal Protocol
AC	air conditioning or air conditioner
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
C	Centigrade/Celsius
CAA	Clean Air Act (US)
CAFC	Corporate Average Fuel Consumption (China)
CARB	California Air Resources Board
CCAC	Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants
CFC	chlorofluorocarbon
CO ₂	carbon dioxide
CO ₂ -eq	carbon dioxide equivalent
CONAMA	Ministry of Environment (Brazil)
COP	coefficient of performance
DIY	do-it-yourself
DOT	Department of Transportation (US)
DX	direct expansion
EOL	end-of-life
EPA	Environmental Protection Agency (US)
EU	European Union
F-Gas	fluorocarbon
FTP	federal test procedure (US)
GHG	greenhouse gas
GWP	global warming potential
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
IBAMA	Brazilian Institute of Environment and Renewable Natural Resources
JRC	Joint Research Commission (of the European Commission)
ICCT	International Council on Clean Transportation
IMAC	Improved Mobile Air Conditioning
IPCC	Intergovernmental Panel on Climate Change
KBA	Kraftfahrt Bundesamt
KSA	Kingdom of Saudi Arabia

LCCP	Life-Cycle Climate Performance
LDV	light-duty vehicle
MAC	Mobile Air Conditioner or Motor Vehicle Air Conditioner
MACS	Mobile Air Conditioning Society Worldwide
MEE	Ministry of Ecology and Environment (China)
MIIT	Ministry of Industry and Information Technology (China)
MLF	Multilateral Fund (of the Montreal Protocol)
MoEFCC	Ministry of Environment, Forest and Climate Change (India)
NCAP	National Cooling Action Plan (India)
NEDC	New European Driving Cycle
NGO	non-governmental organization
NHTSA	National Highway Traffic Safety Administration (US)
Non-A5	Parties not covered under Article V (Article 5) of the Montreal Protocol
NRDC	Natural Resources Defense Council
ODP	ozone depletion potential
ODS	ozone-depleting substance
PCM	phase change materials
R-12	CFC-12 (CCl ₂ F ₂)
R-134a	HFC-134a (CH ₂ FCF ₃)
R-1234yf	HFO-1234yf (CF ₃ CF=CH ₂)
R-744	carbon dioxide (CO ₂) as a refrigerant
RACE	Refrigeration and Automotive Climate under Environmental Aspects
SAE	Society of Automotive Engineers International
SAP	Scientific Assessment Panel (of the UNEP Montreal Protocol)
SEMARNAT	Secretary of Environment and Natural Resources (Mexico)
SL-MAC	secondary-loop mobile air conditioner
SNAP	Significant New Alternatives Policy Program (US EPA)
TEAP	Technology and Economic Assessment Panel (of the UNEP Montreal Protocol)
TFA	trifluoroacetic acid
UN	United Nations
UNE	United Nations Environment
UNEP	United Nations Environment Programme
US	United States
USD	United States Dollar
USSR	Union of Soviet Socialist Republics

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Appendix A. Environmental and Safety Classification of MAC Refrigerants

The American Society for Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) assesses the flammability and toxicity of refrigerants. The following table provides the ozone depleting potential, 100-year global warming potential, the high temperature efficiency, atmospheric lifetime, flammability, toxicity, and whether or not TFA is produced when the refrigerant is burned. All alternative refrigerants are compared to refrigerants in current use (R134a) and now phased out by the Montreal Protocol (R12).

Table 18. Environmental and Safety Classification of MAC Refrigerants

Refrigerant	ODP	GWP (100-yr)	High Temp Efficiency	Atmospheric Lifetime	ASHRAE Flammability	ASHRAE Toxicity	TFA
R12	1.0	10200	Excellent	100 years	1 (not)*	A (lower)	Yes
R134a	0.0	1300	Good	13.4 years	1 (not)	A (lower)	Yes
R152a	0.0	138	Excellent	1.5 years	2 (lower)	A (lower)	No
R1234yf	0.0	<1	Good	10.5 days	2L (mildly flammable)**	A (lower)	Yes
R744	0.0	1	Poor	Infinite***	1 (not)	A (lower)	No

Sources: Minjares, 2011; Taddonio, 2010.

*ASHRAE 1 refrigerants have no flame propagation.

**ASHRAE 2L refrigerants have a burning velocity of less than 10 cm/s, lower than the ASHRAE 2 designation

***Between 65% and 80% of CO₂ is absorbed into the ocean over a period of 20–200 years; 20% to 35% remains in the atmosphere for hundreds to many thousands of years. There is no net climate impact if the CO₂ that would otherwise be emitted is scavenged from sources that would otherwise be emitted.