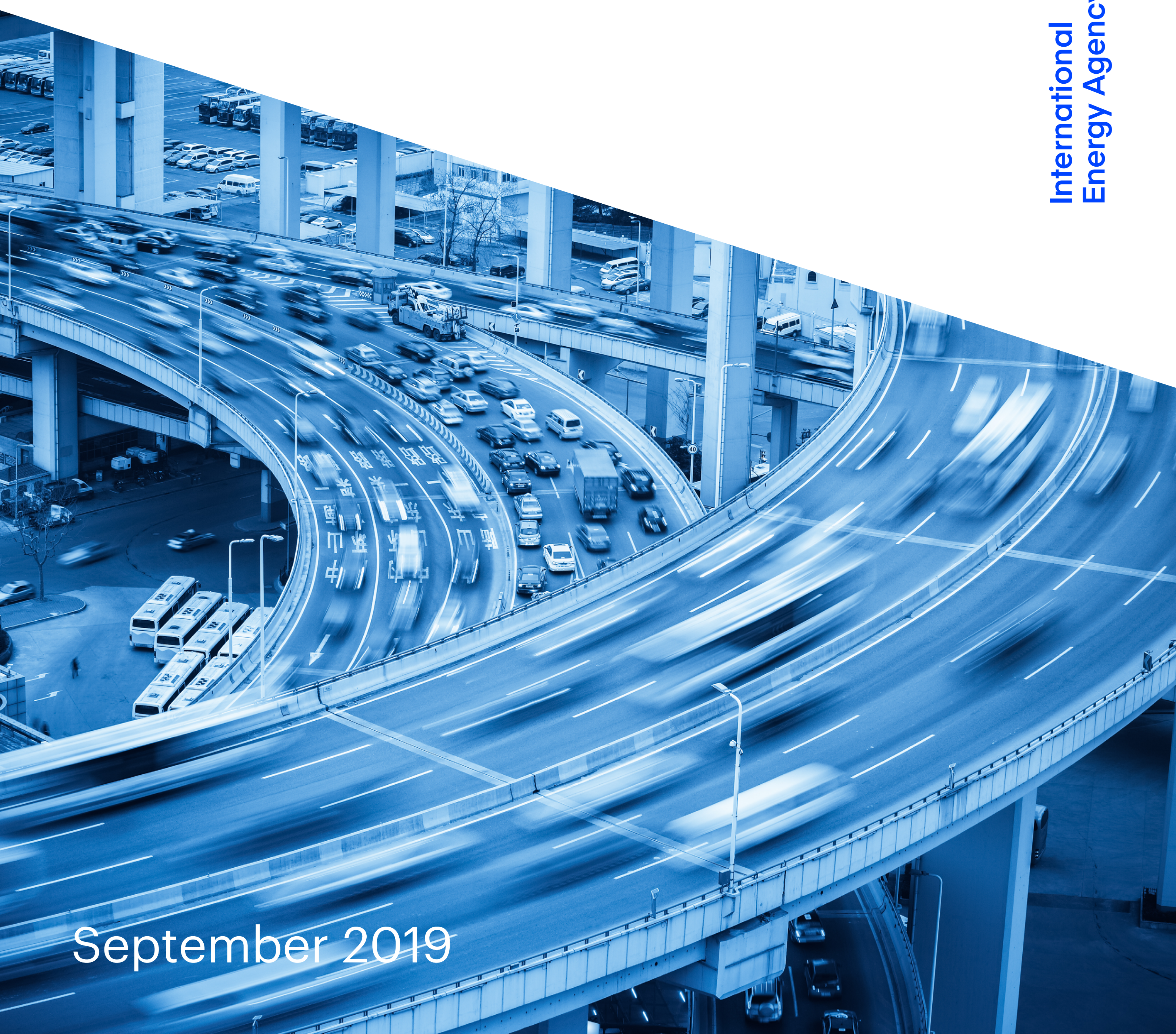
Cooling on the Move

The future of air conditioning in vehicles

International Energy Agency



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Abstract

Air conditioners in passenger cars, vans, buses and freight trucks – collectively known as mobile air conditioning – consume large amounts of energy. The fuel they use and their leaks of refrigerant are also responsible for a significant amount of greenhouse gas emissions.

This report explores the current global energy consumption from mobile air conditioning systems, along with the resulting greenhouse gas emissions from the energy consumption and the leaking refrigerants. With no further policy action, energy use from mobile air conditioning may almost triple to over 5.7 million barrels of oil equivalent per day by 2050. At the same time, annual combined emissions from energy consumption and refrigerant leakage could more than triple to 1 300 million tons of CO_2 equivalent.

The report provides a summary review of the technical opportunities for improving the efficiency of mobile air conditioning. This is complemented with a review of the different types of alternative cooling refrigerants, and their potential impact on global warming. These two analyses are combined to develop a scenario of high efficiency and low global warming potential. The report's analysis is based on a study of the literature and makes use of the IEA's Mobility Model, which provides insights into the current and expected future stock of road vehicles.

Finally, the report explores the role government policy can play in supporting the development and installation of more efficient mobile air conditioning systems.

Highlights

- **Air conditioners in passenger cars, vans, buses and freight trucks – collectively known as mobile air conditioning (MAC) – consume almost 2 million barrels of oil equivalent per day (Mboe/d).**

- **Greenhouse gas (GHG) emissions from MAC stand at around 420 million tonnes of CO_2 equivalent ($MtCO_2$-eq), more than 1% of global energy-related CO_2 emissions.** Energy consumption is responsible for around 70% of these emissions, while GHG emissions from refrigerant leakage account for 30%.

- **The proportion of annual vehicle fuel consumption used by MAC varies by country, ranging between 3% in colder climates and 20% in hotter climates.** Though over shorter timescales, MAC can peak at over 40% in warm climates and congested traffic. For electric vehicles, MAC can reduce driving range by up to 50% on hot and humid days.

- **Without further policy intervention, MAC energy consumption may rise to over 5.7 Mboe/d by 2050.** This near tripling of consumption is driven by an increase in the number of passenger cars on the road, from around 1 billion today to over 2 billion, with a greater proportion of the increase in warmer climates. The overall expected increase in global ambient temperatures will drive further air conditioning demand. Without further policy intervention, GHG emissions resulting from energy use and refrigerant leakage in 2050 could triple to 1 300 $MtCO_2$-eq.

- **In an Efficient Cooling Scenario, improvements in energy efficiency could limit energy consumption to 2.8 Mboe/d.** With low-global warming potential (GWP) refrigerants included in this scenario and partial electrification of the vehicle fleet, GHG emissions by 2050 would be 20% lower than today at 320 $MtCO_2$-eq.

- **Policy will play a critical role in limiting growth in emissions from MAC.** MAC energy consumption could be included in existing fuel economy standards, expanded vehicle testing methods and/or minimum performance standards for specific air-conditioning components.

Executive summary

Air conditioners in passenger cars, vans, buses and freight trucks – collectively known as mobile air conditioning (MAC) – currently consume over 1.8 million barrels of oil equivalent per day (Mboe/d). This represents more than 1.5% of current global oil consumption.

Estimates from the literature reveal that around 6% of the annual global energy consumed by cars is used for MAC, varying by country between about 3% and 20% depending on climate, driving patterns and traffic congestion. It can peak at over 40% in warm climates and congested traffic. This equates to around 1.2 Mboe/d consumed by MAC units in cars alone, with other road vehicles adding another 0.6 Mboe/d. For electric vehicles, MAC can reduce driving range by up to 50% on hot and humid days.

In 2015 total carbon emissions from MAC amounted to approximately 420 million tonnes of carbon dioxide equivalent ($MtCO_2$-eq). Of this, around 70% was due to fuel use, whilst greenhouse gas (GHG) emissions from refrigerant leakage were responsible for the other 30%.

This study adopts two scenarios to explore different futures of MAC energy consumption and emissions to 2050. The Baseline Scenario assumes no further policy intervention. In this scenario, the average global energy efficiency improves slowly – the only improvements are made by the switch to electric vehicles and in those countries with MAC policies in place. No changes in refrigerant use are included beyond those already mandated. It foresees energy consumption almost tripling to 5.7 Mboe/d by 2050. This is driven by the large increase in activity: there will be more than 2 billion cars and another 450 million other road vehicles globally, nearly all of which will have MAC installed. The uptake of vehicles with MAC will be greater in countries with warmer climates such as Indonesia and India, while at the same time the expected increase in global ambient temperatures will drive further MAC demand in more moderate climates.

Potential efficiency gains for cooling in vehicles can be achieved through better MAC technology, improving other components of the vehicle, such as thermal insulation, reflective windows and body paint that reduce heat load, and optimising power trains. If applied in combination, best-in-class technologies could reduce MAC energy demand by up to 67%, halving energy-related MAC emissions. In the Efficient Cooling Scenario the efficiency potential of MAC is fully realised, limiting energy consumption to 2.8 Mboe/d – less than half of the Baseline Scenario in 2050.

Alternative refrigerants already available on the market would eliminate most direct emissions from MAC. Historically CFC-12 was the most common refrigerant used in MAC, a chlorofluorocarbon ozone-depleting substance (ODS) with a global warming (GWP) 10 200 times that of CO_2, and high ozone depleting potential (ODP). Since the adoption of the Montreal Protocol, this has shifted globally to the hydrofluorocarbon HFC-134a, with no ODP but still a high and unsustainable GWP 1 300 times that of CO_2. Alternatives with no ODP and low GWP now exist.

Improving the energy efficiency of MAC and transitioning to refrigerants with a GWP of less than 1 would avoid more than 950 $MtCO_2$-eq in overall MAC-related GHG emissions, or the equivalent of almost 1% of global energy-related CO_2 emissions. Further emission reductions could come from decarbonising vehicle fuel supply and through greater electrification of the vehicle stock, especially if coupled with low-carbon electricity.

Significant GHG emission reductions are therefore available from the use of more efficient MAC and switching to low-GWP refrigerants. Governments have an essential role in ensuring GHG emissions from MAC are limited.

No country currently has a policy of directly regulating the energy efficiency of MAC. However, several countries award efficiency bonus credits to manufacturers for the inclusion of energy-efficient MAC technologies, which can be used towards meeting their efficiency or fuel-related carbon emissions targets.

The use of this approach could be extended; though ideally, the energy consumption and energy efficiency of MAC systems within vehicles would be identified through the use of a low-cost, reliable and reproducible standard testing procedure, either as part of the overall vehicle energy test or for the MAC component alone. This would open up multiple policy opportunities to influence the efficiency of MAC. Further research and international collaboration are needed to develop such testing standards for vehicles.

For limiting refrigerant emissions, the European Union, Japan and Canada have introduced restrictions on the maximum GWP of the refrigerants used in MAC, while the United States encourages the same low-GWP technology with credits toward carbon emission reductions. The wider use of limits on the allowable GWP of refrigerants in MAC would dramatically reduce the direct GHG emissions from refrigerants globally.

Further research is needed to provide more robust estimates of GHG emissions from MAC equipment, and extended to go beyond road vehicles.

Analysis

Introduction

The global population is travelling further and more frequently, with the total number of passenger kilometres expected to more than double by 2050 (IEA, 2019a). The energy consumed for this relates not only to motive power, but also increasingly to creating a comfortable environment inside the vehicle by air conditioning. This report examines the impacts of mobile air conditioning (MAC) in road vehicles, specifically the expected increase in energy use and greenhouse gas (GHG) emissions should countries not take further action to address MAC. It compares this against a scenario where countries take comprehensive action to reduce the impacts of MAC.

The growing use of MAC – and other auxiliary equipment – may also partly explain the growing gap between tested fuel consumption and actual fuel consumption on the road (IEA/ICCT, 2019).

This study examines the use of MAC in all road vehicles (cars, vans, trucks and buses), although it does not include cooling in refrigerated freight in the broader cold chain. It also briefly addresses MAC in other forms of passenger transport.

The concept of fitting MAC to cars dates back more than 80 years (Popular Science, 1933), and the first vehicles with optional MAC were made by Packard in 1940 in the United States. By 1953 MAC was factory-installed on Buick, Cadillac, Chrysler, Oldsmobile, Packard and Nash (Bhatti, 1999). Since then, MAC has gone from a luxury option to a standard feature in many markets, and an increasing share of vehicles globally have MAC installed as standard today (Andersen, Halberstadt and Borgford-Parnell, 2013).

MAC in road transport relies on the use of refrigerants, and these have historically had an adverse impact on the environment due to their ozone depletion potential (ODP) and their global warming potential (GWP). Parties to the Montreal Protocol have already phased out most ozone-depleting refrigerants worldwide, and the 2016 Kigali Amendment to the Montreal Protocol requires the phase-down of hydrofluorocarbon (HFC) refrigerants (currently the most commonly used) while also targeting improvements in energy efficiency. These measures will support efforts to meet GHG emission reductions agreed by parties to United Nations Framework Convention on Climate Change at their 21st Conference of Parties (COP 21) in Paris in 2015.

How does MAC work?

MAC systems work by using power to remove heat and moisture from the air inside the vehicle by transferring it outside. Most cars make use of a direct expansion vapour-compression cycle in which heat is extracted from the cabin via an evaporator using a refrigerant, and is then transferred to the ambient (outdoor) air via a condenser. The pressure of the compression cycle causes the refrigerant to condense back to a liquid, lowering the temperature of the refrigerant and beginning the cycle again (Blumberg et al., 2019).

The power capacity of modern MAC units in cars and vans ranges between 2 and 5 kilowatts (kW) (Farrington and Rugh, 2000), where electrical components represent 20-30% of the energy they consume and mechanical components 70-80% (Nielsen, Uddheim and Dalenbäck, 2016). The typical size of MAC units in cars is around 4 kW. This is comparable to the size of a standard room air conditioner in many countries, although the volume of air cooled in a typical car is considerably smaller. Part of this is explained by the need for rapid removal of heat from vehicles on hot days, although this also means units are generally oversized, which affects their energy consumption. While running, MAC typically uses between 3% and 50% of the vehicle's fuel consumption, depending on the outside temperature and driving conditions (Haniu and Matsuura, 2013). However, MAC systems do not run at high capacity for most of the time, leading to a more modest impact on annual fuel consumption.

Buses with MAC often have power capacities of between 8 and 25 kW (Basile, 2019; Göhlich et al., 2015). The larger size is necessary in order to cool a larger volume of space and to account for higher passenger occupancy (where passengers also generate heat inside the vehicle). Occupancy affects the cooling energy consumption per capita, which can be substantially lower than in cars, although many urban buses also operate with frequent stops, which requires higher energy consumption to maintain cool temperatures as doors are opened and closed (more warm air can enter the bus, which needs to be cooled).

Medium and heavy freight trucks, with MAC typically in the driver cabin, often have similar capacities to cars and vans, typically ranging between 1.2 kW and 4.5 kW (Delgado, Rodriguez and Muncrief, 2017). However, trucks generally drive for longer periods during the day when cooling is required, resulting in more annual energy being consumed than an average car. MAC systems in heavy trucks are also used when drivers rest alongside the road, although some truck stops provide electric connections to reduce fuel consumption by auxiliaries (CARB, 2017; Millard-Ball, 2009; US DOE, n.d.).

Typical direct expansion MAC units in cars require charging with around 0.5-0.9 kilogrammes (kg) of refrigerant to operate (EC, 2011). Adding additional cooling points (i.e. "dual evaporator" systems) increases the refrigerant charge. Emissions from refrigerants come from different phases of the vehicle's life. The manufacturing process typically emits 5 kg of carbon dioxide (CO_2) equivalent per kg of HFC-134a (the primary refrigerant used in most MAC systems today), whilst at end of life around 16% of the initial charge is typically lost. MAC systems are not fully sealed, so small quantities of refrigerant leak during operation. Annual leakage rates account for around 30-82 grammes (g) of refrigerant per year (Blumberg et al., 2019).

Trucks require around 1.1 kg of refrigerant charge and have leakage rates between 60 g and 100 g of refrigerant per year (EC, 2007a). Buses require a larger charge and have much higher leakage rates, as much as 2.4 kg per year (EC, 2007b).

Other studies have used different leakage rates for manufacturing, stock and disposal (Gschrey et al., 2011; Velders et al., 2015; EC, 2011).

Drivers of MAC impacts

The main drivers of GHG emissions from MAC are:

- Climate, including cooling degree days (CDDs) and relative humidity.
- Penetration of MAC in the vehicle fleet and vehicle design (e.g. window size and vehicle colour).

- The refrigerant used in, and energy efficiency of, the MAC technology.
- Travel patterns and traffic congestion (requiring more cooling per trip if congested).

Climate conditions

Climatic conditions, including local temperatures and humidity, influence the overall need for MAC. CDDs and the relative heat index (which takes into account humidity) are widely used to predict cooling loads and are a useful indicator of potential MAC demand (see annex, "Cooling Degree Days"). A degree day measures how cold or warm a given location is, comparing the mean of high and low outdoor temperatures recorded each day to a standard temperature (18°C in this study).

Penetration of MAC in the vehicle fleet and vehicle design

MAC is becoming ubiquitous across the road vehicle fleet, affecting total energy consumption. The MAC installation rate in the fleet of existing vehicles is close to 100% in advanced economies and more limited data suggest that MAC penetration in emerging countries is around 60% (Blumberg et al., 2019; Kumar, 2018), with near 100% of new road vehicles (excluding 2- and 3-wheelers) including MAC as standard equipment.

The need for vehicle occupants to operate their MAC can be reduced by a range of vehicle features, for example reflective paints (particularly colours white and silver) and glazing, occupancy sensors and additional thermal insulation.

MAC refrigerants and energy efficiency

The GHG emissions resulting from the use of MAC are directly from the leakage of refrigerant (during manufacturing, charging, recharging and disposal) where the refrigerant has a significant GWP, and indirectly via the energy used to power the MAC system, which is typically from the combustion of gasoline or diesel. Life cycle climate performance (LCCP) is the metric that calculates the carbon equivalent total GHG emissions from direct refrigerant leakage, indirect fuel consumption, and embodied energy for manufacturing, servicing and recycling at the end of product life (Papasavva, Hill and Brown., 2008; Papasavva, Hill and Andersen, 2010). The LCCP method and model are available in SAE standard J-2766 (SAE, 2009).

MAC equipment in cars is generally oversized to ensure sufficient output capacity to quickly cool the interior when it is hot. A typical 4 kW MAC unit in a car is able to provide a blast of cold air to provide near-immediate cooling comfort – for instance, dropping indoor temperatures from 50°C to 25°C in around five minutes on a very hot day (Atkinson and Hill, 2011). This oversizing of MAC equipment is partially necessary as cars generally heat up much more quickly than the interior of buildings, but this means MAC units operate at very low part-loads once the initial blast of cooling is complete. This can dramatically affect operational energy performance (Cheng, 2018).

Travel patterns and congestion

The average distance that road vehicle users cover each year and the timing (seasonal and time of the day) when trips are made have a direct impact on the use of MAC – the lengthening of average commuter distances, for example, has the effect of increasing emissions from fuel used to run MAC. Travel patterns in Europe, the United States and India suggest that the time when the MAC is running ranges between 20% and 85%, with higher usage in hotter climate, seasons and daytime travel (Chaney et al., 2007). Congestion, particularly in hot countries, increases MAC usage as journeys of the same length take longer, sometimes much longer, as congestion is increasingly being observed in countries with burgeoning car ownership (Wen et al., 2019). Similarly, the near-universal fitting of MAC as standard equipment on new road vehicles is having the greatest impact in developing countries.

Options to reduce MAC impacts

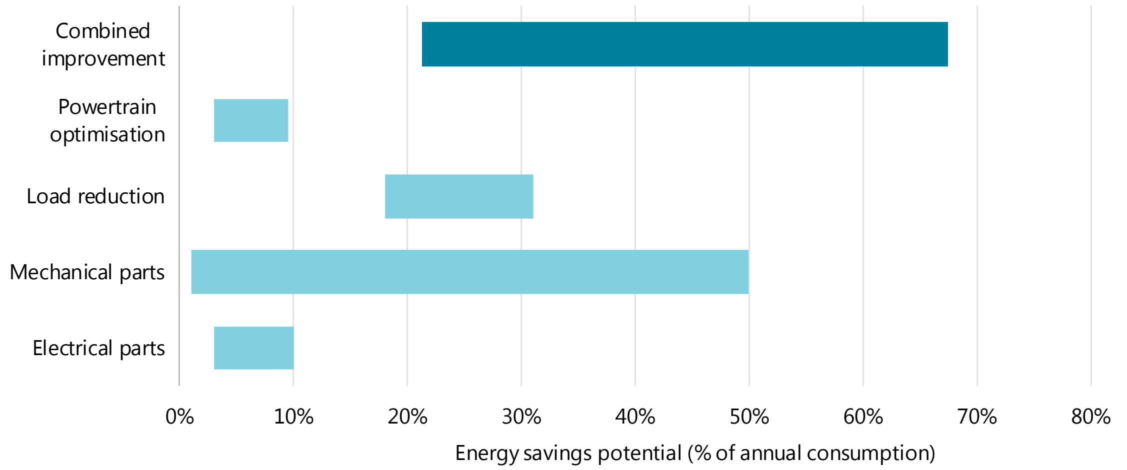
Energy efficiency potential

Energy efficiency improvements in MAC systems can be achieved in several ways:

- **Improve MAC systems** through changes to electrical and mechanical components.
- **Reduce cooling load (load reduction)** through changes to vehicle components and characteristics, such as improved insulation, window coatings and reflective paints.
- Take indirect measures in the form of **powertrain optimisation.**

These combined energy efficiency improvements could reduce the energy consumed by MAC systems in cars and vans by as much as 67%, depending on the mix of measures applied (Figure 1).

Figure 1. Efficiency improvement potential of MAC in cars and vans



Sources: Analysis based on Blumberg et al., (2019), *Mobile Air Conditioning*, www.theicct.org/publications/mobile-air-conditioning-cbe-20190308; Nielsen, Uddheim and Dalenbäck et al., (2016), "Potential energy consumption reduction of automotive climate control systems", www.sciencedirect.com/science/article/pii/S1359431116308158?via%3Dihub; Weilenmann, Alvarez and Keller (2010), "Fuel consumption and CO_2/pollutant emissions of mobile air conditioning at fleet level – new data and model comparison", https://pubs.acs.org/doi/10.1021/es903654t; Subiantoro, Ooi and Stimming (2014), "Energy saving measures for automotive air conditioning system in the tropics", https://docs.lib.purdue.edu/cgi/viewcontent.cgi?referer=https://www.ecosia.org/&httpsredir=1&article=2360&context=iracc.

MAC efficiency could be improved by up to two-thirds, with the highest potential improvements in mechanical components, such as the compressor.

Encouraging **behavioural change**, such as parking under shading and pre-cooling of vehicles, could reduce energy consumption by 20-30% of the total or up to 10% of the combined efficiency improvement (Weilenmann, Alvarez and Keller, 2010).

MAC system improvements

Individual measures relating to the MAC system can improve the efficiency of electrical components by up to 46%, with the highest potential through improvements to the efficiency of the blower (Nielsen, Uddheim and Dalenbäck, 2016). Mechanical improvements such as upgrades to more efficient compressors can yield improvements as high as 36%. For hot and humid regions in particular, efficient dehumidification could reduce compressor energy use by 50% (Subiantoro, Ooi and Stimming, 2014).

Buses have an energy savings potential similar to cars, with an estimated improvement potential of 50-60% (Göhlich et al., 2015). For heavy freight trucks, MAC efficiency could be improved by around 40% (Silvas et al., 2013).

Reductions in cooling load

Beyond the electrical and mechanical improvements, additional savings can be achieved through load reduction, such as limiting solar gain in the vehicle or raising the default temperature for MAC. These load reduction strategies separately could reduce energy consumption by 20-30% (Blumberg et al., 2019).

As noted above, MAC equipment in cars is generally oversized to ensure rapid cooling when it is hot. As operating at very low part-loads can significantly affect efficiency, effort is needed to address equipment performance in typical conditions versus extreme operating conditions. Solving this issue may require innovative technical solutions that ensure high operational performance at different cooling load profiles. For instance, several MAC equipment suppliers have developed solutions designed to address part-load performance, such as variable speed compressors. US government sources estimate that available technologies like properly calibrated externally controlled variable-displacement compressors could improve MAC efficiency in cars by 42% compared to a baseline system (US EPA and NHTSA, 2012).

Powertrain improvements

Powertrain improvement measures could reduce MAC energy consumption even further, with estimates ranging between 3 and 7% (Blumberg et al., 2019). Waste heat reduction from better engine performance (e.g. hybridisation) improves the efficiency of auxiliary systems, such as MAC.

Although there are many opportunities to improve the efficiency of MAC systems in vehicles, they are not being introduced into most vehicle product lines. The main reasons for the lack of efficiency improvement include: the higher initial cost for switching to more efficient components, MAC energy consumption not being included in testing procedures, coupled with the lack of credit received in most regulations and perceived consumer benefit. The main sector where this is not the case is for electric vehicles where range is an issue, and subsequently a great incentive to reduce the auxiliary load on batteries.

Improved refrigerants

Direct GHG emissions from MAC can be improved by better control and handling of the refrigerants (reducing leaks) and importantly by employing refrigerants with a low GWP. The primary refrigerant used in most MAC systems today is HFC-134a, which is not an ODS, although it still has a relatively high GWP of 1 300 times that of CO_2. Under the Kigali Amendment to the Montreal Protocol, which entered into force on 1 January 2019, there will be a phase-down of HFCs, which means the use of HFC-134a will be reduced in coming years.

A variety of low-GWP refrigerants are available that can equal or exceed the energy efficiency and performance of HFC-134a MAC systems, with proper adjustments. The hydrofluoroolefin HFO-1234yf (also known as R-1234yf) is the most widely used low-GWP refrigerant, already fully replacing HFC-134a in the European Union and penetrating markets in the United States, Canada, Japan, Korea, South America and Africa (Schaeber, 2019). It is already used in 18 million vehicles worldwide and all car manufacturers are shifting to HFO-1234yf, with the exception of Audi and Daimler, which plan to offer CO_2 systems (Bjørnåvolda and van Passelab, 2017). At the moment, costs and supply of this refrigerant are the main issues limiting its increased use, especially in developing countries (Purohit et al., 2016).

HFC-152a in secondary-loop MAC designs has demonstrated the lowest life cycle carbon footprint in hot climates, matching the air-conditioning performance and manufacturer cost of optimised direct-expansion HFO-1234yf systems, but with significant savings for consumers compared with systems using more expensive HFO-1234yf (Taddonio, Sherman and Andersen, 2019; Andersen et al., 2018; Blumberg et al., 2019). Some automotive MAC experts in China have also begun evaluating the use of hydrocarbons (R290) in a secondary loop, but these systems are not evaluated in this study (Chen, Shi and Dandong, 2018).

Table 1 provides a summary of the refrigerants used in MAC systems.

Table 1. Properties of refrigerants used in MAC systems

MAC gas	ODP	GWP	Flammability	Toxicity	Comment
CFC-12	1	10 200	1 (not)	A (lower)	• Used until about 1994 and 2010 in developed and developing countries, respectively.
HFC-134a	0	1 300	1 (not)	A (lower)	• Introduced in 1994/5 to replace CFC-12.
HFO-1234yf	0	1-4	2L (mildly flammable)	A (lower)	• Similar cooling properties to HC134a, although some initial supply and cost issues.
R744 (CO_2)	0	1	1 (not)	A (lower)	• Slightly higher cost (e.g. 16% higher for buses, EC 2007b), and currently used in limited number of German automobiles.
HFC-152a	0	138	2 (lower)	A (lower)	• More flammable, requiring alternative circulation system in MAC.

Notes: CFC = chlorofluorocarbon; ODP = ozone depletion potential; GWP data from the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5) for a 100-year time horizon (IPCC, 2014). Flammability and toxicity on ASHRAE scale.

Sources: IEA analysis based on IPCC (2014) AR5, www.ipcc.ch/report/ar5/syr/; and Blumberg et al. (2019), *Mobile Air Conditioning*, www.theicct.org/publications/mobile-air-conditioning-cbe-20190308.

Existing policy

No country has a requirement to directly measure or limit the energy consumption of MAC systems. Energy efficiency regulations for vehicles are based on standard testing drive cycles, which in most cases do not cover auxiliary energy consumption such as the energy used by MAC equipment. Only Brazil has a requirement to test the energy consumption of vehicles with any MAC equipment running for its pollutant emissions standard (Dallmann and Façanha, 2017).

One reason for this gap in policy coverage of MAC is the lack of an appropriate and widely applied international test method to measure MAC energy consumption as a contributor to the running vehicle energy consumption. There are also differences to consider in simulating MAC use, for instance only measuring MAC systems while operating at a constant ambient temperature, solar incidence and speed, or following a test cycle at various temperature settings. To date, the only approach to address MAC efficiency has been to give manufacturers credit for including technologies that are considered good practice in improving MAC energy efficiency, such as stop-start (idle stop) or to reduce refrigerant leakage. These are called off-cycle credits and are used mainly in North American markets (Table 2). For example, the United States allows credits towards fuel standard targets based on manufacturers introducing MAC-related technologies from a technology menu. The combined credits can add up to 4.5 g of CO_2 per kilometre (km), or nearly one-third of the average emissions of a car in the United States (Kreutzer et al., 2017). The European Union is expected to allow efficient MAC as part of Eco-Innovation within their 2030 fuel economy standard from 2025 (OJEU, 2019).

Fuel economy regulations for heavy-duty vehicles do include auxiliary system use (including MAC) as an input in the simulation tools used for test standards, such as the VECTO (Vehicle Energy Consumption Calculation Tool) in the European Union and GEM (GHG Emissions Model) in the United States (EC, 2018; Zhang, 2018).

Regulations to limit the use of non-ozone-depleting and encourage the use of low-GWP refrigerants in MAC are relatively simple to implement, although they are not yet widespread. Only the European Union, Japan and Canada have successfully introduced regulations to cap the GWP of refrigerants used in new vehicles (GWP < 150, Table 2). The US EPA may reinstate rules that allow manufacturers to apply for off-cycle credits for the use of low-GWP alternatives to HFC-134a.

Table 2. MAC system policy requirements in vehicle regulations

Country	MAC use in test cycle	Off-cycle credits	GWP limit
United States	No	Yes, under revision	No
Canada	No	As United States	GWP < 150 from 2021
Mexico	No	As United States	No
European Union	No	No, but Eco-Innovation from 2025	GWP < 150 from 2017
Australia	No	No, but under consideration	No
Japan	No	Require MAC in top runner vehicles	GWP < 150 from 2023

Country	MAC use in test cycle	Off-cycle credits	GWP limit
China	No	Yes, but not implemented	No
India	No	No, but under consideration	No
South Korea	No	Yes (efficiency); potential for thermal technology	No
Saudi Arabia	No	Yes, adjusted for local conditions	No
Brazil	Emissions standards only	No	No

Note: Off-cycle credits are bonuses given to manufacturers towards meeting targets for measures not covered under a testing cycle.
Sources: Based on Blumberg et al. (2019), *Mobile Air Conditioning*, www.theicct.org/publications/mobile-air-conditioning-cbe-20190308; OJEU (2019), Regulation (EU) 2019/631, https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0631&from=EN.

With regard to the control of HFC-134a emissions from MAC, there are several regulations at the regional (e.g. EU F-gas regulations EC 842/2006, EC 517/2014, MAC Directive) and national level (e.g. in the United States and Japan). Implementation of good practices when MAC is in use and/or at end of life/disposal is already in place in the European Union and other developed countries (Japan, United States, Canada, etc.).

Vehicle electrification

MAC use can have a significant impact on the energy consumption of electric vehicles (EVs). It reduces the vehicle range, which with current battery technology is perceived as a key performance limitation of battery electric vehicles (BEVs) relative to similar internal combustion engine (ICE) vehicles. EVs also require additional cooling for thermal management of the battery, which is often linked to the MAC system (Kiss and Lustbader, 2014). On warm days, MAC usage can reduce EV range overall by more than 50% (Jeffers, Chaney and Rugh, 2015; Subiantoro, Ooi and Stimming, 2014; Noyama and Umezu, 2010; Rugh, Hoveland and Andersen, 2004; Li et al., 2018).

Additional operational energy efficiency measures could improve the range of electric cars by 11-33% (Jeffers, Chaney and Rugh, 2015). Key options are "just-in-time" pre-cooling and ventilation, cutting energy consumption in the first 20 minutes of cool-down by more than 30%. Pre-cooling could occur when the car is parked and plugged, as most charging takes place at home or at work (IEA, 2019a). Furthermore, load reduction strategies, such as reflective windows and body colour, could reduce initial energy consumption by up to 50% (Jeffers, Chaney and Rugh, 2015). Another measure is targeted zonal cooling, potentially reducing energy consumption in the start-up phase by 7-41%.

The range of electric buses can also drop rapidly when the MAC system is running at high loads, cutting range by 30-50% (Basile, 2019; ADB, 2018). Several electric bus operations in hot climates already struggle to meet their daily range (Citylab, 2019). One study examining buses in a cooler climate (Germany) found that shifting towards a heat pump system using low-GWP refrigerant (R744) could reduce energy consumption for heating and cooling a bus by 50% compared with an HFC-134a unit coupled with a positive temperature coefficient (PTC) or diesel heater. However, payback costs are high due to the substantial capital costs of such efficient heating and MAC systems (Göhlich et al., 2015; EC, 2011).

The large impact that MAC consumption has on EV range incentivises vehicle manufacturers to deploy more efficient MAC systems relative to ICE vehicle counterparts.

MAC in non-road vehicles

Energy consumption for the heating, ventilation and air conditioning of trains can be as high as 15-20%, levels that can generally be attributed to cooling in regions with a hot climate (UIC, 2016; Kumar, 2018). Even in more temperate climates, the train MAC system is running for most of the time. In Europe, several regulations determine the temperature and air replenishment for urban trains (NEN 14750), non-urban trains (NEN 13129) and driving cabs (NEN 14813). Passenger-based ventilation – targeting cooled air on passengers rather than seeking to cool the entire vehicle – offers the largest energy efficiency potential, reducing energy demand by as much as 15% (UIC, n.d.; UIC, 2016). Insulation norms have not changed in the past 30 years, which if implemented would be able to reduce the cooling load by 2-5% (UIC, n.d.). A wider set of efficiency measures could improve efficiency by 40%.

Air conditioning is the second-highest energy use for cruise ships, accounting for 30-40% of all fuel use (Danfoss, 2015). Several energy efficiency improvements, such as improved valve controls, could reduce energy consumption by up to 30%.

MAC capacity in aircraft can be up to several hundred kilowatts (Sikorski, 2010). Nevertheless, the MAC share of total aviation energy consumption is more modest than road and rail transport, increasing fuel use by approximately 2-3%. As nearly all of the cooling takes place while aircraft are at the airport, ground-based cooling can be applied. Many airports limit the use of kerosene for cooling and offer electric connections. Various airlines opt to limit cooling while stationary to save costs.

Energy and emissions outlooks

For this study, the first scenario is a **Baseline Scenario** to show the likely increase in energy consumption and emissions if there are no further improvements to MAC efficiency or changes in refrigerant use. This serves as a reference against which to measure and track future MAC improvements. The second scenario is an **Efficient Cooling Scenario**, which explores the likely impact if the energy efficiency of MAC systems is maximised and low-GWP refrigerants are employed across the entire vehicle stock. Non-road vehicles are not included in these scenarios.

In both scenarios, the number of vehicles in the global stock and the total distance travelled are expected to grow. The numbers used are consistent with the latest New Policies Scenario (NPS) of the IEA Mobility Model (MoMo) – what is expected to happen without any additional policy development (IEA, 2019a). It is assumed that all vehicles will have a MAC system by 2050.

Fuel consumption emissions are based on a well-to-wheel (WTW) basis, including the emissions from power generation for EVs and refining for ICE vehicles. The emission factors for power generation are based on the New Policies Scenario for the *Global EV Outlook 2019* (IEA, 2019b).

In the reference Baseline Scenario, MAC energy efficiency and refrigerants used in MAC systems are considered to be the same as those in use today.

By contrast, the Efficient Cooling Scenario increases MAC energy efficiency by 67% in countries that currently have no MAC regulations, with a 33% improvement rate in countries that already have regulations. It also includes the introduction of refrigerants with a GWP of 1 for the remaining majority countries that do not currently have minimum GWP requirements for refrigerants.

Table 3. Summary of the Baseline and Efficient Cooling Scenarios

		2050 Baseline	2050 Efficient Cooling	Comment
Stock of all road vehicles (million)	In line with IEA Mobility Model New Policies Scenario (MoMo NPS).			
Vehicle kilometres (vkm) driven	In line with IEA MoMo NPS.			
CDD	CDD 18°C heat index.	Projected CDD 18°C heat index.		See Annex I: Cooling degree days
MAC penetration	95% in advanced economies. 60% in emerging economies	100% in all regions		
MAC efficiency improvement	–	No improvement in non-regulated countries. Regulated countries have 50% of stock with efficient MAC, excluding load reduction and behaviour change. EVs already use efficient MAC.	All stock achieves maximum efficiency improvement: 67% (cars and vans) in unregulated countries. 33% (cars and vans) in regulated countries. 50% (buses and trucks).	In 2015 half of all vehicles sold in regulated countries were already equipped with more efficient MAC.
MAC energy consumption cars (global average)	0.59 Lge/100 km	0.57 Lge/100 km	0.26 Lge/100 km	Based on literature values for key countries in 2015 converted to Lge/100 km from real-world fuel consumption in the IEA MoMo, where other countries are scaled based on the CDD values for the year of analysis. 2050 dependent on efficiency improvement and expected CDDs.

		2050 Baseline	2050 Efficient Cooling	Comment
Emission factors	Well-to-tank emissions based on IEA MoMo. Tank-to-wheel emissions based on IEA (2018a).	Well-to-tank (including power generation) emission factors from IEA MoMo NPS in IEA (2019a). Tank-to-wheel emissions based on IEA (2018a).		Based on the mobility model regions.
Refrigerant GWP use	67%: GWP of 1 300 (HFC-134a). 33%: GWP of 1 (HFO-1234yf).	80%: GWP of 1 300. 20%: GWP of 1.	100%: GWP of 1	In 2015 half of all vehicles sold in regulated countries were already equipped with MAC with a GWP of 1.
Leakage (global average) for cars	97 g of refrigerant/year	89 g of refrigerant/year	41 g of refrigerant/year	Higher share in countries with high leakage rates in Baseline Scenario.

Notes: Lge = litre of gasoline equivalent; MAC energy consumption for trucks and buses are converted based on their typical performance and air conditioner size relative to vans and cars.

Sources: IEA (2019a), *Mobility Model Partnership*, www.iea.org/topics/transport/mobilitymodelpartnership/; IEA (2018a), *CO_2 Emissions from Fuel Combustion 2018*, https://webstore.iea.org/co2-emissions-from-fuel-combustion-2018.

This study focuses on values that align as closely as possible with the average annual energy consumption of MAC systems in use today. These values are sometimes expressed as a percentage, which is converted to Lge/100 km based on on-road fuel consumption from the IEA MoMo (IEA, 2019a). A split is made between urban vehicles and non-urban vehicles, with a higher MAC consumption in urban conditions (Fontaras, Zacharof and Ciuffo, 2017). MAC consumption per country is based on conservative estimates of annual average energy values sourced from literature for Europe, the United States and India (Chaney et al., 2007; Papasavva, Hill and Andersen, 2010; Rugh, Hoveland and Andersen, 2004; Rugh, 2018), ranging between 3% and 20% of annual fuel consumption. The share of MAC energy consumption is converted to absolute values (Lge/100 km) from 2000 stock fuel economy levels per country as a base efficiency level. Other countries and regions are scaled based on their average annual heat index CDDs at 18°C.

It is assumed that the entire stock of road vehicles has MAC by 2050, given that nearly 100% of new road vehicles (excluding 2- and 3-wheelers) currently have MAC as standard equipment. These will filter through the stock of owned cars over the coming decades. It is also assumed that all vehicles that have MAC will use it according to their country-specific conditions. MAC energy consumption for other vehicle categories (i.e. trucks and buses) is converted based on their typical MAC size relative to cars and vans. The level of refrigerant leakage and GWP of the refrigerants are based on literature, taking into account existing and announced policies (Blumberg et al., 2019).

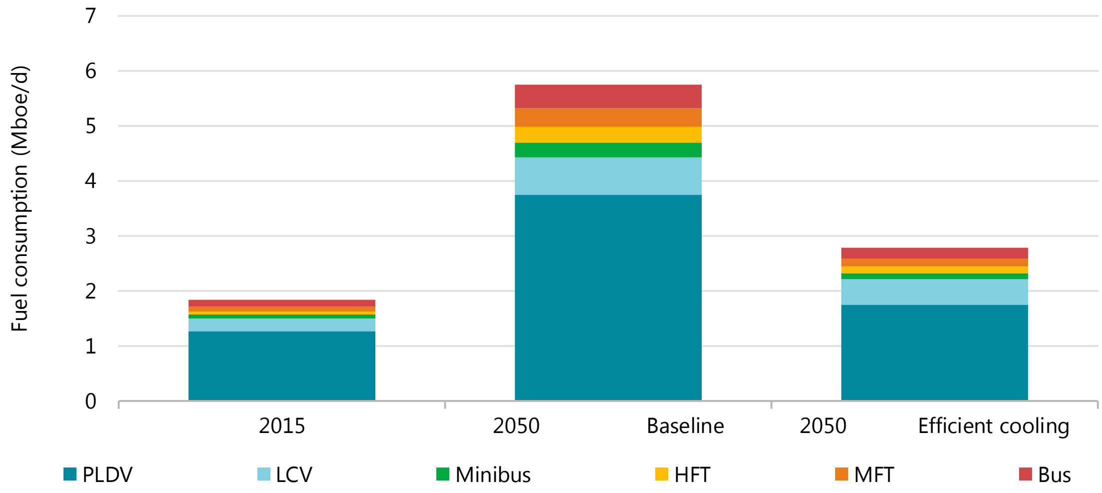
Energy

In 2015 the energy consumption of MAC in road vehicles totalled 1.8 million barrels of oil equivalent per day (Mboe/d), equivalent to the annual oil production of Nigeria in 2018 (IEA, 2019c). Cars represented more than 65% of that consumption, followed by vans and buses (Figure 2).

Without energy efficiency improvements, the energy consumption of MAC in the Baseline Scenario could reach 5.7 Mboe/d in 2050, that is more than tripling. In the Efficient Cooling Scenario, maximising energy efficiency improvements leads to energy consumption that only grows to 2.8 Mboe/d, up by 50%. This is in the context of the global car fleet rising from nearly 1 billion to 2.3 billion in 2050, alongside more prevalent MAC ownership and usage in warmer climates.

The United States had the highest MAC energy consumption in 2015, representing nearly one-third of the global total. By 2050, India will have surpassed US MAC energy consumption in the Baseline Scenario, while China follows closely. Expected economic growth and corresponding vehicle ownership will drive up MAC usage in other warm climates, such as South America, Africa and the Middle-East.

Figure 2. MAC energy consumption by vehicle category



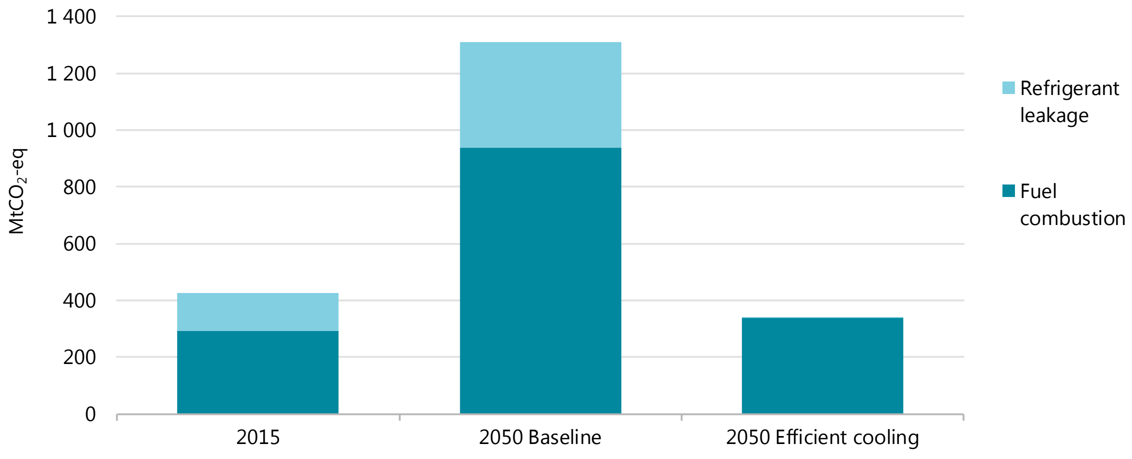
Notes: Rail, aviation and shipping have been omitted. PLDV = passenger light-duty vehicle (cars); LCV = light commercial vehicle (vans); HFT = heavy freight truck; MFT = medium freight truck.

Key point: Energy consumption of MAC is set to more than triple by 2050 without energy efficiency improvements, whereas efficient MACs could limit growth to less than 50%.

Emissions

MAC in road vehicles emitted GHG emissions equivalent to approximately 420 million tonnes of CO_2 equivalent ($MtCO_2$-eq) in 2015, or over a million tonnes per day (Figure 3). This is equivalent to about 1% of global energy-related CO_2 emissions. More than two-thirds of these emissions originated from fuel combustion, while the rest were from estimated direct refrigerant leakage. In the Baseline Scenario, emissions nearly quadruple to almost 1 300 $MtCO_2$-eq in 2050, roughly keeping the same balance between fuel combustion and refrigerant leakage. In an Efficient Cooling Scenario, emissions could be reduced by over 20% while the vehicle fleet doubles. Compared with the 2050 Baseline Scenario, fuel combustion emissions could be more than 60% lower in the Efficient Cooling Scenario, while refrigerant emissions could be 99% lower (reflecting the almost universal use of refrigerant with a GWP of 1).

Figure 3. Global GHG emissions from direct refrigerant leakage and fuel combustion for MAC in road vehicles



Note: Includes the GHG emissions from fuel combustion at power plants to charge EVs.

Key point: Global GHG emissions could triple by 2050 without serious action to improve MAC performance. Improved efficiency and switching to low-GWP refrigerants could stabilise MAC GHG emissions.

Policy recommendations

Governments have an essential role to play in ensuring refrigerant and energy-related GHG emissions from MACs are minimised. Significant GHG emission reductions are available from the use of more efficient MAC and switching to low-GWP refrigerants.

Ideally, the energy consumption and energy efficiency of MAC systems within vehicles would be identified through the use of a low-cost, reliable and reproducible standard testing procedure, either as part of the overall vehicle energy test or for the MAC component alone. This would open up multiple opportunities for influencing their efficiency and allow manufacturers, vehicle buyers and regulators to identify and prefer the best-performing systems. To better represent real-world behaviour, further research and international collaboration are needed to develop such testing standards for road vehicles.

Without a robust MAC-specific testing standard (either standalone or as part of a whole vehicle test), policy choices to improve energy efficiency are limited, although they do include the targeting of individual components or aspects of the system. The main policy option currently used is to provide off-cycle credit (bonus credit outside the test standard, usable towards fuel standards) to manufacturers for using accredited high-efficiency MAC components and systems. As a starting point, other countries should consider the use of such credits to complement fuel efficiency standards, which are themselves strengthened in response to the technically and economically feasible MAC refrigerant and efficiency upgrades. Providing too large an incentive – without increasing the stringency of the overall standard – could reduce the cost of compliance without taking advantage of next-generation MAC technology.

The use of credits could be extended to include the benefits of other load-reducing technologies. For example, credits could be applied for the use of reflective paints and glazing, occupancy sensors, and additional thermal insulation. Separate assessments would be needed, as would a mechanism to validate and approve suitable technologies.

Besides off-cycle credits, minimum energy performance standards (MEPS) could be considered for some energy-using components, such as the compressor, fans and heat exchangers.

Governments can also remove barriers to new technology and approve new refrigerants on a priority basis under regulations such as the US EPA Significant New Alternatives Policy (SNAP) Program and the EU Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) programme.

Limiting the use of high-GWP HFCs can be done through simple regulation, such as that put in place in the European Union, Canada and Japan, and will be globalised under the Kigali Amendment to the Montreal Protocol. Placing a limit on the GWP of the refrigerant allowable in MAC systems (e.g. GWP below 150) would substantially reduce the GHG emissions from leaking refrigerants.

During the phase-down of HFCs, there will be a cohort of vehicles with high GWP refrigerant that will require disposal. Governments need to ensure good practice (as found in the European Union, Japan, the United States and others) is followed to collect and dispose of these refrigerants so as to ensure compliance.

Finally, further research is warranted to enable more robust estimates of the GHG emissions from MAC equipment to be undertaken, and given additional data, this analysis could be extended to include other forms of MAC beyond road vehicles.

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General Annexes

Annex I. Cooling degree days

Cooling degree days (CDDs) measure how much the mean temperature exceeds a standard temperature (such as a temperature a building thermostat would normally be set to) each day over a given period (e.g. a week in the summer or the entire year). For example, say a standard temperature is 18°C. A day with a high temperature of 30°C and a low of 20°C, and thus a mean temperature of 25°C, has 7 CDDs (25-18=7). If the next day has a mean temperature of 28°C, it has 10 CDDs (28-18=10.). The total for the two days is therefore 17 CDDs. Normally CDDs are calculated according to the dry bulb temperature (the temperature of the air measured by a thermometer freely exposed to the air, but shielded from radiation and moisture).

CDDs tend to be correlated with latitude, but there are exceptions. Some regions with cold or even very cold winter climates, such as the Northeast and Midwestern United States, as well as parts of Canada and the Russian Federation, can also have a very hot summer lasting several weeks, resulting in relatively high CDD levels and large cooling demands.

To account for the influence of humidity, a heat index[1] can be used that corrects CDDs by combining air temperature and relative humidity in order to determine the temperature as perceived by humans. Relative humidity – that is, how saturated with moisture the air is – can make it difficult for the body to perspire and lose heat, and can therefore make it feel hot even when dry temperatures are not that high. For example, if the dry temperature is 30°C and the relative humidity is 50%, then it will feel like 31°C; but if the relative humidity reaches 100%, then it would feel like 44°C. In other words, the humidity makes it "sweltering hot". The higher the relative humidity, the higher the temperature actually feels and the higher the corrected CDDs. For instance, the average annual number of CDDs in Indonesia is around 3 400, but when humidity is taken into account, that number is about 10% higher on average. The resulting number of CDDs is weighted by population across a country or region and the entire year. This report uses the CDD heat index to model cooling demand in the MAC projections (IEA, 2018b). The CDDs are aggregated per model region via a weighted average based on vehicle ownership (IEA, 2019a).

[1] www.nws.noaa.gov/om/heat/heat_index.shtml.

Abbreviations and acronyms

BEV	battery electric vehicle
CFC	chlorofluorocarbon
CDD	cooling degree day
CO_2	carbon dioxide
EV	electric vehicle
GHG	greenhouse gas
GWP	global warming potential
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
ICE	internal combustion engine
IEA	International Energy Agency
LCCP	life cycle climate performance
MAC	mobile air conditioning/mobile air conditioner
MoMo	Mobility Model (IEA)
NHTSA	National Highway Traffic Safety Administration
NPS	New Policies Scenario
ODP	ozone depletion potential
ODS	ozone depleting substance
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals (EU)
SNAP	Significant New Alternatives Policy program (US EPA)
US EPA	United States Environmental Protection Agency

Units of measure

°C	degree Celsius
g	gramme
kg	kilogramme
km	kilometre
kW	kilowatt
Lge	litre of gasoline equivalent
Mboe/d	million barrels of oil equivalent per day
$MtCO_2$-eq	million tonnes of CO_2 equivalent

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