



# Development and application of a life cycle greenhouse gas emission analysis model for mobile air conditioning systems

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## HIGHLIGHTS

- Vehicle, mobile air conditioning (MAC) and refrigerants are combined for analysis.
- MAC-GHG-LCA Model is built to analyze life-cycle GHG emissions from MAC systems.
- LCA covers life-span refrigerant leakage and indirect GHG emissions in MAC system.
- EV technology is timely integrated to MAC systems GHG emissions analysis.
- Up-to-date fleet-level scenario analysis is taken on China's MAC system up to 2050.

## ARTICLE INFO

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## ABSTRACT

Mobile air conditioning (MAC) is potentially a huge source of greenhouse gas (GHG) emissions in China from a life cycle (LC) perspective as the vehicle population increases in the future. The MAC-GHG-LCA model is developed to calculate LC GHG emissions from MAC systems, covering life-span refrigerant leakage (direct emissions) and emissions caused by energy use in MAC system production and operation (indirect emissions). Using R152a and R1234yf as alternative refrigerants instead of R134a in MAC systems can decrease LC GHG emissions by 22–32% and 17–29%, respectively. Their GHG reduction benefits mainly result from their lower global warming potential (GWP) values though the indirect emissions are only slight lower or even higher than R134a. Using R744 can offer reduction in 2050 though it will cause an increase of 20% in 2020. Total LC GHG emissions from MAC systems of the whole light duty vehicle (LDV) fleet in China will be 159 million tonnes of CO<sub>2</sub>-equivalent in 2050 in the scenario where R134a will be the only refrigerant adopted, about 3 times that in 2015. It is found that alternative low-GWP refrigerants can help reduce LC GHG emissions from MAC systems effectively. The shift from conventional cooling and heating technology to advanced heat pump technology in electric vehicles (EVs) can reduce electricity use in MAC system operation and reduce LC GHG emissions from the MAC systems in EVs.

## 1. Introduction

It is urgent to control the greenhouse gas (GHG) emissions globally [1]. China's CO<sub>2</sub> emission has already reached about 9.9 billion tonnes in 2015, accounting for 28% of the world's total CO<sub>2</sub> emission [2]. It is crucial to slow down the growth of GHG emissions in China accompanied by future potential economic development [3–5].

Hydrofluorocarbons (HFCs) is one of the major contributors to GHG emissions nowadays [6] and has been regulated under the Montreal Protocol since 1987 [7]. Global HFC emission reached about 800 million tonnes of CO<sub>2</sub>-equivalent (Mt CO<sub>2,e</sub>), which is roughly equal to

2.5% of the total CO<sub>2</sub> emissions in 2015 [8]. China's HFC emissions were about 200 Mt CO<sub>2,e</sub> in 2014 [8].

Refrigerant emissions from mobile air conditioning (MAC) systems contribute significantly to HFC emissions in China currently. R134a has been the most widely-used MAC refrigerant in China and has flourished in recent decades. Its consumption increased from 25.52 thousand tonnes in 2007 to 75.05 thousand tonnes in 2015 with an average annual growth of 14% [9,10], benefited from the booming Chinese automobile market. The high global warming potential (GWP) of R134a [11] and its rising consumption have made HFCs emissions one of the most important driving forces for GHG emissions increase in China. The

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**Nomenclature****Abbreviations**

AVSM	Annual Vehicle Sale Module
CO	carbon monoxide
CO <sub>2,e</sub>	CO <sub>2</sub> -equivalent
COP	coefficient of performance
DEM	Direct Emission Module
EPCRM	Emission during Production, Conveyance and Recycling Module
EVs	electric vehicles
FMEPM	Future MAC Emission Projection Module
GHG	greenhouse gas
GWP	global warming potential
HFCs	Hydrofluorocarbons
ICEV	internal combustion engine vehicle
IEM	Indirect Emission Module
LC	life cycle
LCA	life cycle analysis
LDV	light duty vehicle
Mt	million tonnes
MAC	mobile air conditioning
MECM	MAC Energy Consumption Module
PTC	positive thermal coefficient

**Subscripts**

<i>k</i>	refrigerant type
<i>l</i>	different parts of the MAC system
<i>y</i>	age of MAC/vehicle
<i>m</i>	calendar year (from 2004) earlier than the year <i>t</i>
<i>r</i>	calendar year (from 2004) earlier than the year <i>m</i>
<i>t</i>	calendar year
<i>z</i>	sub-stage

**Variables**

<i>DE</i>	direct life-span refrigerant leakage emissions occurred in Stage 1
<i>DE</i> <sub>1</sub>	direct emissions of refrigerant leakage during Sub-stage 1.1(the assembly of MAC system)
<i>DE</i> <sub>2</sub>	direct emissions of refrigerant leakage during Sub-stage 1.2 (MAC system operation)
<i>DE</i> <sub>3</sub>	direct emissions of refrigerant leakage during Sub-stage 1.3 (MAC system repairing and refrigerant recharging)
<i>DE</i> <sub>4</sub>	direct emissions of refrigerant leakage during Sub-stage 1.4 (Recycling and disposal of refrigerant)
<i>DE</i> <sub><i>m,k</i></sub>	direct life-span refrigerant leakage emissions of the vehicle sold in the year of <i>m</i> and adopting refrigerant type <i>k</i>
<i>DEPY</i> <sub><i>m,k</i></sub>	average annual direct refrigerant leakage per year for the vehicle sold in the year of <i>m</i> and adopting refrigerant type <i>k</i> .
<i>EM</i> <sub>leakage</sub>	refrigerant leakage from MAC system of vehicle fleet
<i>EM</i> <sub>energy</sub>	GHG emissions related to energy use in MAC system operation of vehicle fleet

<i>EM</i> <sub>embodied</sub>	embodied GHG emissions from the MAC system production and recycling of vehicle fleet
<i>EM</i> <sub><i>m,k</i></sub>	life-span embodied GHG emissions from the MAC system production and recycling of the vehicle sold in the year of <i>m</i> and adopting refrigerant type <i>k</i>
<i>EMP</i>	embodied GHG emissions for the production of each part of MAC system per mass
<i>EMR</i>	embodied GHG emissions for the recycling of each part of MAC system per mass
<i>EMPY</i> <sub><i>m,k</i></sub>	embodied GHG emissions from the MAC system production and recycling per year for the vehicle sold in the year of <i>m</i> and adopting refrigerant type <i>k</i>
<i>ENR</i>	energy demand amount for MAC system operation per km for the vehicle
<i>ER</i> <sub>pro</sub>	CO <sub>2</sub> emission resulted from the energy use for refrigerant production
<i>ER</i> <sub>conv</sub>	CO <sub>2</sub> emission resulted from the energy use for refrigerant conveyance
<i>ER</i> <sub>rec</sub>	CO <sub>2</sub> emission resulted from the energy use for refrigerant recycling
<i>GE</i>	GHG emission factor of the energy used in MAC system operation
<i>I</i>	initial charge size of refrigerant adopted in MAC system
<i>IDE</i>	indirect GHG emissions during Stage 2
<i>IDE</i> <sub>1</sub>	indirect GHG emissions during Sub-stage 2.1 (refrigerant production)
<i>IDE</i> <sub>2</sub>	indirect GHG emissions during Sub-stage 2.2 (refrigerant conveyance)
<i>IDE</i> <sub>3</sub>	indirect GHG emissions during Sub-stage 2.3 (refrigerant recycling)
<i>IDE</i> <sub>4</sub>	indirect GHG emissions during Sub-stage 2.4 (MAC system production)
<i>IDE</i> <sub>5</sub>	indirect GHG emissions during Sub-stage 2.5 (MAC system operation)
<i>IDE</i> <sub>6</sub>	indirect GHG emissions during Sub-stage 2.6 (MAC recycling)
<i>LCE</i>	the life cycle GHG emissions per vehicle
<i>LCEF</i>	life cycle GHG emissions of vehicle fleet
<i>leak</i> <sub>1</sub>	proportion that the life-span refrigerant leakage accounts for of the initial charge size during Sub-stage 1.1
<i>leak</i> <sub>2</sub>	proportion that the annual refrigerant leakage accounts for of the initial charge size during Sub-stage 1.2
<i>leak</i> <sub>3</sub>	proportion that the annual refrigerant leakage accounts for of the initial charge size during Sub-stage 1.3
<i>leak</i> <sub>4</sub>	proportion that the life-span refrigerant leakage accounts for of the initial charge size during Sub-stage 1.4
<i>LS</i>	average life-span of LDVs
<i>MEC</i>	MAC system life-span energy consumption
<i>NS</i>	vehicle new sale
<i>SUR</i>	survival rate function
<i>VMT</i>	annual distance traveled per vehicle in a specific year
<i>VP</i>	vehicle population
<i>VPN</i> <sub><i>m,k,t</i></sub>	vehicle population in the year of <i>t</i> of the vehicles registered in the year <i>m</i> adopting refrigerant type <i>k</i>
<i>w</i>	mass of each part in the MAC system

global HFCs emissions can be equal to 9–19% of total CO<sub>2</sub> emissions in 2050 under different scenarios if there is no action in its control [12]. R134a was included in the phase-out schedule under the Montreal Protocol. The parties of the Montreal Protocol passed the Kigali amendment to phase-out HFCs usage by October 2016 [13]. China has always strived to reduce HFCs emissions in recent years and president Xi Jinping promised to adopt concrete actions to restrict HFCs use as

stated in China-U.S. Joint Presidential Statement on Climate Change in 2015 [14]. It is therefore urgent to find refrigerants with lower GWP to replace R134a.

There are some studies that analyze suitability of different types of refrigerants for future MAC systems in China based on several considerations including safety, GWP, efficiency and economics [15–21]. They found that three types of refrigerants (R1234yf, R152a and R744)

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