Technology Demonstration of Low Global Warming Potential (GWP) High Efficiency Mobile Air Conditioning
Final Report
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Institute for Governance & Sustainable Development

Abstract

The Institute for Governance & Sustainable Development (IGSD), in collaboration with Automobile Manufacturer Tata Motors Limited (TML) based in Pune, India, and the Technology System Supplier, MAHLE Behr Troy Inc. (formerly Delphi) based in Stuttgart, Germany, demonstrated an innovative technology called secondary loop mobile air conditioning (SL-MAC), which is also called an indirect system. This demonstration project designed, tested and validated an SL-MAC system that achieved energy-efficient operation in high ambient air temperatures, such as those in India, when compared to existing direct expansion (DX) mobile air conditioners. The project tested SL-MAC systems using two different refrigerants with 100-year global warming potential (GWP) under 150: HFO-1234yf (GWP<1) and HFC-152a (GWP=138). The cooling performance of both refrigerants was demonstrated while cooling vehicles in the challenging Indian climate, but both had a deficit in cooling capacity compared to the baseline DX system due to project constraints that can be overcome in new designs. HFC-152a was shown to have superior performance. The vehicle using the HFC-152a SL MAC saved 1.9% to 2.6% of fuel on the India Drive Cycle compared to the baseline HFC-134a DX system, used half the amount of refrigerant, and reduced direct refrigerant emissions by over 95% (on a CO_2-eq basis). In addition to superior climate performance, the SL-MAC system, if commercialized, would save car owners money on fuel and AC service: the SL-MAC system is expected to require service only half as often as the DX-HFC-134a system, with savings of $50 or more per instance, depending on localized costs of service and refrigerant. In addition, the fuel savings demonstrated by this SL-MAC system could save individual owners 20-40 liters of diesel fuel per year (worth USD $20-$50 per year at today's fuel prices), depending on driving habits and AC usage. Additional fuel savings could be realized by integrating the demonstrated compressor control algorithm in a vehicle equipped with fuel-saving stop-start technology, as the superior cold storage available with the SL-MAC system can allow these vehicles to remain in engine-off mode for up to two minutes without needing to turn on the engine to operate the AC. These outcomes will encourage global implementation to phase down high GWP hydrofluorocarbons (HFCs), a short-lived climate pollutant (SLCP), under the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol).

Introduction

The project partners' hypothesis was that an SL-MAC system using low-GWP refrigerants could (1) achieve climate, energy, and consumer cost savings benefits relative to a direct expansion system using HFC-134a, and (2) provide a viable, cost-effective alternative for manufacturers relative to a DX-MAC system using HFO-1234yf at today's refrigerant prices. Since about 20% of motor vehicle fuel consumption in India is used to power MACS, and about 25% of total HFC use nationwide in India is for MACs, an affordable, efficient, low GHG refrigerant is needed.

This hypothesis was informed by prior research and engineering experience on SL-MAC systems, combined with recent advances in MAC technology and controls. Currently, most mobile air conditioners (MACs) installed in vehicles are configured as traditional DX systems, in which refrigerant enters the passenger compartment to provide cooling. This traditional configuration has several drawbacks:

- DX-MAC systems were not designed to isolate the refrigerant from the passenger compartment. This limits refrigerant choice to low or non-flammable refrigerants, which often have a high global warming potential or significantly higher cost.
- DX-MAC systems have more fittings and longer refrigerant lines, requiring a larger refrigerant charge and increasing likelihood of leaks. This results in greater emissions and more frequent service needs.
- When modern vehicles are idling or stopped in traffic or at a light, the engines are increasingly designed to turn off and run on battery to save fuel (this is sometimes referred to as "stop-start" or "idle stop" technology). However, with DX-MAC, the engine often must turn on to run the AC compressor, defeating fuel-efficiency features and increasing urban pollution on warm and hot days.

A modern SL-MAC system solves many of these problems:

- SL-MACs are designed so that only an antifreeze coolant, not refrigerant, enters the passenger cabin. This increases refrigerant choice: flammable refrigerants can more safely be used because they are kept out of the passenger compartment. This has environmental benefits because some flammable refrigerants have very low GWP and excellent energy efficiency.
- SL-MACs also retain cold in the coolant reservoir during stops, so the engine does not have to turn on during idle stop to operate the AC. Chilled air is quickly available after stops, enhancing passenger comfort and saving fuel by delaying engagement of the compressor during acceleration.
- Fewer fittings and shorter refrigerant lines mean that less refrigerant is used and there is less likelihood of refrigerant leaks. This reduces refrigerant emissions and saves vehicle owners money on avoided repair costs.

SL-MACs are vapor compression refrigerant systems coupled with a coolant flow loop to provide cooling for passenger comfort, window defogging, thermal control of batteries and other components. Figure 1 shows the basic components of the SL-MAC system and how they are arranged.

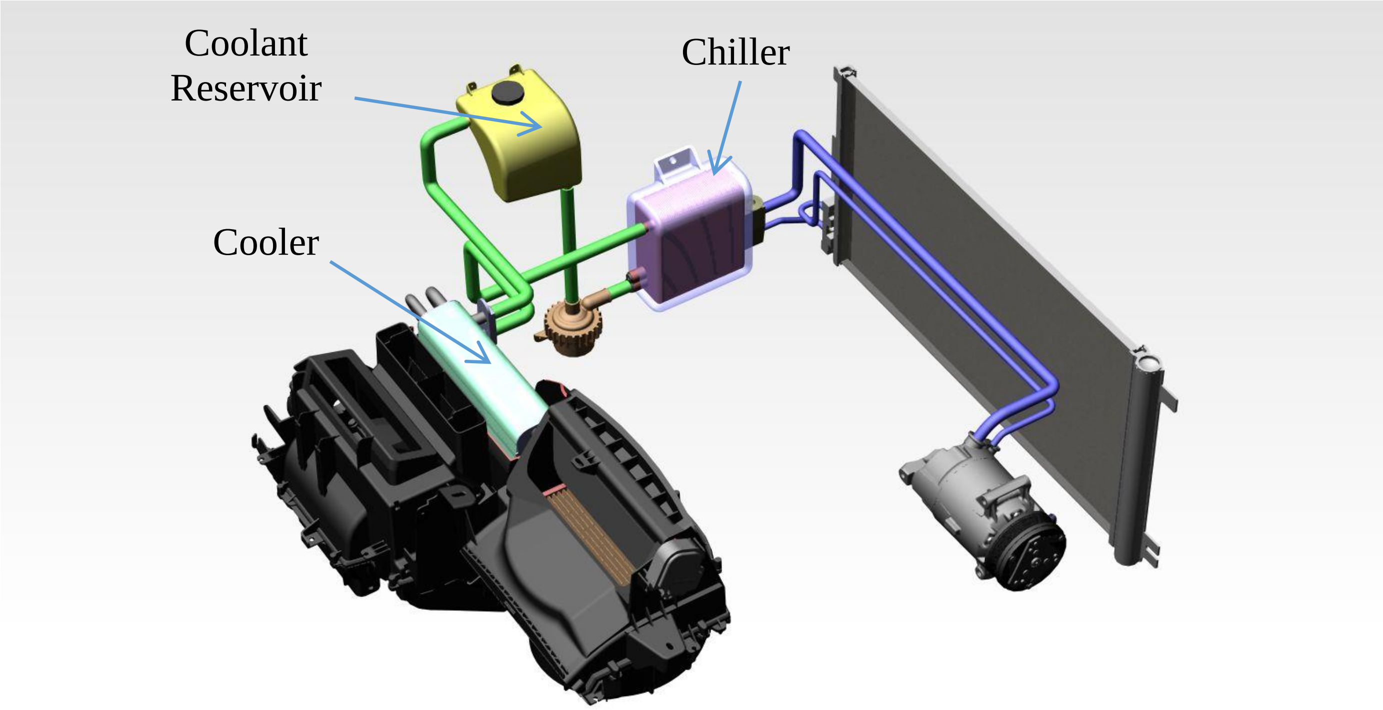

Figure 1: Secondary Loop Mobile Air Conditioning System Configuration. The refrigerant is contained within the engine bay (shown in purple) and the coolant (shown in green) fills the secondary loop, which circulates between the chiller/internal heat exchanger and the cooler, the latter located within the passenger cabin. In a traditional (DX-MAC system, refrigerant enters the passenger compartment. In SL-MAC systems refrigerant does not enter the passenger compartment. This provides an added margin of safety and enables use of a wider variety of refrigerants.

Experts have long recognized that SL-MAC holds great potential to improve energy efficiency, reduce climate impacts, and save vehicle owners money. For example, the US Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) recognized the added value of SL-MAC's cold storage ability when strengthening US fuel economy and GHG standards, stating: "Secondary loop systems have added value in that they have the ability to store cooling within the loop, which in turn allows for 'free' cooling to occur during deceleration events, and then [be] delivered to the cabin during engine idle off conditions" (EPA and NHTSA, 2012). In the last two decades, several secondary loop systems have been designed and tested by MAC suppliers, automobile manufacturers, and research institutes. However, none of these demonstrations had the benefits of the advanced components and control algorithms used in this demonstration. Examples of prior demonstrations include the following:

- In 1999, Delphi and General Motors developed a prototype 152a SL-MAC system using R-152a. Testing at the SAE (formerly Society of Automotive Engineers) Phoenix Forum showed equal passenger cooling comfort compared with a standard DX R-134a system (Andersen et al 2014).
- In 2003, Delphi and Volvo partnered to test SL-MAC technology. They installed SL-MAC in a Volvo SC90 sport utility vehicle, which showed superior energy and cooling performance. Passengers found that although initial cabin cool down was slightly slower, the reservoir of coolness (a.k.a thermal ballast) stored within the SL system allowed the car interior to stay cooler during brief stops and provided quicker cool-down once the car was re-started (Andersen et al 2014).

- In 2007, Delphi participated in a major study—partly financed by the US EPA—to demonstrate the production viability of SL-MAC systems using HFC-152a. This study used two identical vehicles, one equipped with a standard DX-MAC and another equipped with SL-MAC. The study's results showed equivalent A/C system capacity and equal perceived passenger comfort in ride tests (Andersen et al 2014).
- In 2009, the European Union sponsored the Thermal Systems Integration for Fuel Economy (TIFFE) project, which tested SL-MAC on two vehicles. Conducted from 2009-2012, this project involved two major car manufacturers (Fiat and Ford), two leading suppliers (Denso and Maflow), and two European research institutions (SINTEF and the University of Braunschweig). Compact refrigerant units with coolant loops were installed on two vehicles: a gasoline passenger car with stop and start functionality, and a diesel light commercial vehicle with a hybrid power train system. The project demonstrated a new generation of compact fluid-to-fluid heat exchangers, and used innovative coolants (nanofluids) to improve performance. The compact refrigeration units were designed to be compliant for use with low GWP refrigerants including R-744 and flammable refrigerants R-152a and R-1234yf. The researchers succeeded in reducing system cost, size, and improved AC-on fuel economy (Malvicino and Riccardo, 2010). The project results summary stated that "results are very promising, showing a fuel economy increase of up to 5%" (European Commission, 2018).

With the commercial introduction of low-GWP HFO-1234yf, many manufacturers in Europe and North America paused research and development on SL-MAC systems. The passage of the 2016 Kigali Amendment to the Montreal Protocol phasing down HFCs, coupled with recent advancements in automotive technology and controls and the high price of HFO-1234yf, reignited interest in developing affordable, efficient SL-MAC systems.

With support of the Climate and Clean Air Coalition (CCAC), for the first time ever, the project partners were able to design, build, test and demonstrate commercially-viable, energy efficient SL-MACs utilizing low-GWP refrigerants and specifically tailored to the Indian climate and market.

Methods

The project partners designed, developed, installed, and tested SL-MAC systems using two different low-GWP refrigerants and compared their performance to that of a baseline 'control' DX-MAC using HFC-134a. All systems were tested on the same vehicle: the Tata Aria. Project technical targets are summarized in Table 1, and project steps and timeline are summarized in Table 2.

Target / Parameter	**Baseline**	**Target**
Refrigerant (GWP)	R-134a (1300)	R-152a (138) HFO-1234yf (<1)
Charge Quantity	800 g (±20 g)	40% reduction
Average Cabin Temperature at 25th min in 35^{0}C 40%RH Solar Load 1000W/m2	21.8°C	21±1
Average Cabin Temperature at 25th min in 45^{0}C 40%RH Solar Load 1200W/m2	28.9°C	28±1

Compressor Power Consumption	5.5 kW at 2400 engine rpm	5-8% reduction
Rise in Grill temp – City Cycle Tests	≤ 4^0C	≤ 2^0C
Fuel Economy -Indian Drive Cycle (ARAI) with AC ON	12.55Kmpl	~3% Improvement

Table 1: Project technical targets

The project partners targeted a ten-fold (or better) reduction in refrigerant GWP by selecting a low GWP alternative to HFC-134a. We also sought to reduce charge size by at least 40% due to the SL-MAC system's shorter refrigerant hoses and refrigerants' qualities. To demonstrate adequate performance, we targeted a similar average cabin temperature to that which would have been achieved in testing by HFC-134a. To save fuel, we sought to improve the compressor controls so that the AC operated when optimal to do so from a fuel-efficiency standpoint, utilizing the built-in thermal reservoir of chilled coolant to provide cabin comfort without wasting fuel. Additional non-technical project targets focused on consumer and manufacturer savings and life-cycle climate performance. We concurrently completed a life cycle cost analysis to evaluate whether the SL-MAC system could save consumers money relative to a DX MAC using HFC-134a, assessed whether the SL-MAC system could be implemented for similar or lower price to a DX-MAC using HFO-1234yf, and evaluated life cycle climate performance.

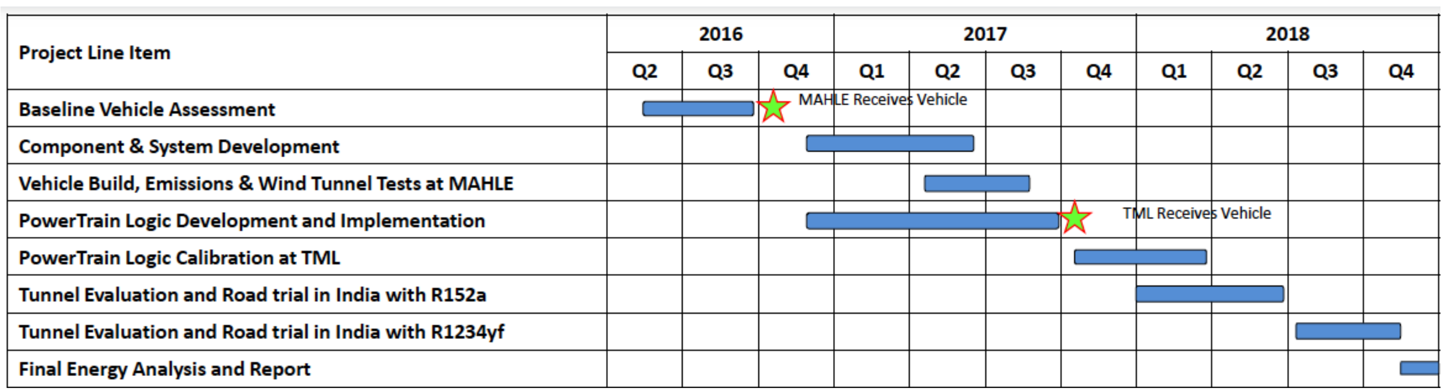

Table 2: Project steps and timeline.

Summary[1] of project technical steps:

1. First, TML evaluated the baseline DX-MAC using HFC-134a on the Aria vehicle in a TML India facility, then shipped the vehicle to MAHLE USA to be fitted with the SL-MAC system.
2. Next, MAHLE designed and retrofitted the SL-MAC system in consultation with TML. TML provided all the required electronic controls and wiring harness.
3. Then, MAHLE completed the preliminary AC system evaluation and shipped the vehicle back to TML India.

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[1] A detailed description of each project step, sub-step, and key milestones was submitted to UNEP in TML Project Milestone 4 by authors and TML employees Sangeet Kapoor, Prasanna Nagarhalli, Maneesh Arora, and Javendra Meena dated 28 December 2018 and submitted to CCAC in the first quarter of 2019. As this report contained certain confidential information, TML requests that interested parties contact Mr. Sangeet Kapoor (sh_kapoor@tatamotors.com) for additional technical details and obtain approval before information contained therein is released to the public.

4. Once TML received the vehicle equipped with the SL MAC system, TML tested AC performance, power consumption, fuel economy, and road trials with both low-GWP refrigerants, R-152a and R1234yf.

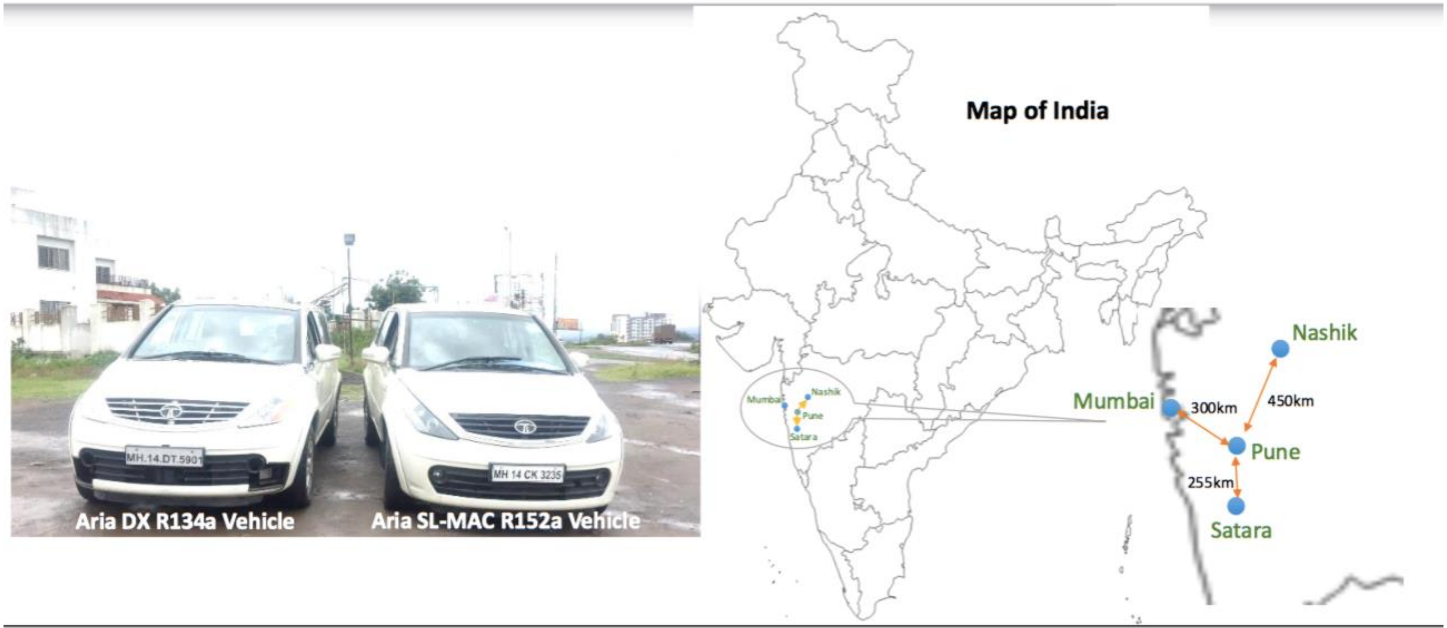

Figure 2: The baseline and SL-MAC R152a road-test vehicles and the test route in India.

Results

Technical results are summarized in Table 3. Findings related to consumer and manufacturer cost savings are summarized in Table 4. Life cycle GHG savings opportunities are summarized in Figure 3.

Target / Parameter	**Baseline**	**Target**	**SL HFC-152a Results**	**SL HFO-1234yf Results** (without IHX)
Refrigerant (GWP)	R-134a (1300)	R-152a (138) HFO-1234yf (<1)	Direct emissions reduced >95%	Direct emissions reduced >99%
Charge quantity	800 g (±20 g)	40% reduction	46% reduction 430 g	34% reduction 530 grams
Average Cabin Temperature at 25th min in 35^{0}C 40%RH Solar Load 1000W/m2	21.8°C	21±1	23.8°C - Needs normal development	27°C – Needs improvement
Average Cabin Temperature at 25th min in 45^{0}C 40%RH Solar Load 1200W/m2	28.9°C	28±1	31.5°C - Needs normal development	36°C – Needs improvement
Compressor Power Consumption	5.5 kW at 2400 engine rpm	5-8% reduction	9.6% reduction 5.0kW at 2400 erpm	4.9% increase 5.0kW at 2400 erpm
Rise in Grill temp – City cycle tests	≤ 4^{0}C	≤ 2^{0}C	< 2.0°C	< 2.0°C

Fuel Economy -Indian Drive Cycle (ARAI) With AC ON (without idle-stop)	12.55Kmpl	~3% Improvement	1.9% to 2.6% improvement, mix of city & highway	1.3 to 4.7% reduction, can be improved with IHX

Table 3: Technical results

MAC System Type:	***Direct Expansion R134a***	***Direct Expansion R1234yf***	***Secondary Loop R152a***	***Secondary Loop R1234yf***
Refrigerant *charge* *Tonnes CO_2-eq (initial charge)*	*HFC-134a 800 g* *1.04*	*HFO-1234yf 750 g* *<0.01*	*HFC-152a 430 g* *<0.1*	*HFO-1234yf 530 g* *<0.01*
Added manufacture cost	*Baseline*	*$65 [1]*	*$36 [2]*	*$71 [1]*
Service cost *(lifetime)* *Estimated savings & service frequency in India*	*$114-$171* *$57 [4] every 3-5 years*	*$240-$360* *$120 [5] every 3-5 years*	*$54 [6]* *$54 every 6-10 years*	*$200-$300* *$100 [5] every 3-5 years*
Annual fuel savings *(Assumes 2.6% savings)* *Savings with SL MAC* *Tonnes CO_2 over 10 years*	*Not applicable*	*Not applicable*	*Saves up to 37 litres[8]* *$37 at $1 per litre* *1 tonne +*	*Similar to R134a baseline*

Table 4: Illustrative consumer and manufacturer cost savings.

Table 4 Notes:

1. Includes added cost of refrigerant plus components such as internal heat exchanger (IHX) or SL-MAC components.
2. Includes added cost of SL-MAC components and slight refrigerant savings due to lower charge.
3. Included added cost of SL-MAC components and increased refrigerant cost.
4. Equals $50 labor cost plus cost of ½ charge of refrigerant at $16.90/kg HFC-134a.
5. Equals $50 labor cost plus cost of ½ charge of refrigerant at $187/kg HFO-1234yf.
6. Equals $50 labor cost plus cost of ½ charge of refrigerant at $16.90/kg HFC-152a.
7. Equals $50 labor cost plus cost of ½ charge of refrigerant at $187/kg HFO-1234yf.
8. Assumes 18000 km/year, 2.6% improvement over 12.55 km per litre for SL MAC; diesel price of 68 rupees ($1 USD) per litre. Also assumes that fuel use can be comparable to HFC-134a with the addition of an IHX.

Table 4 assumptions:

Refrigerant charge size (2 cooling points):

DX HFC-134a: 800 g

DX HFO-1234yf: 750 g (~93.5% of HFC-134a charge)

SL HFO-1234yf: 530 g
SL HFC-152a: 430 g

Refrigerant prices:

HFC-134a manufacturer price: $6 per kg (various industry sources)
HFC-134a service price: $16.90 per kg (source: O'Reilly Auto Parts, based on 30 lbs at $230)
HFC-152a manufacturer price: same as HFC-134a
HFC-152a service price: same as HFC-134a
HFO-1234yf manufacturer price: $70 per kg (price has come down since 2018)
HFO-1234yf service price: $187 per kg (source: Autozone, based on $850 per 10-lb container)

Exchange rate: 1 USD = 68 Rupees
1 litre diesel in India = 68 Rupees
1 litre diesel = 2.6676 kg CO_2 emissions

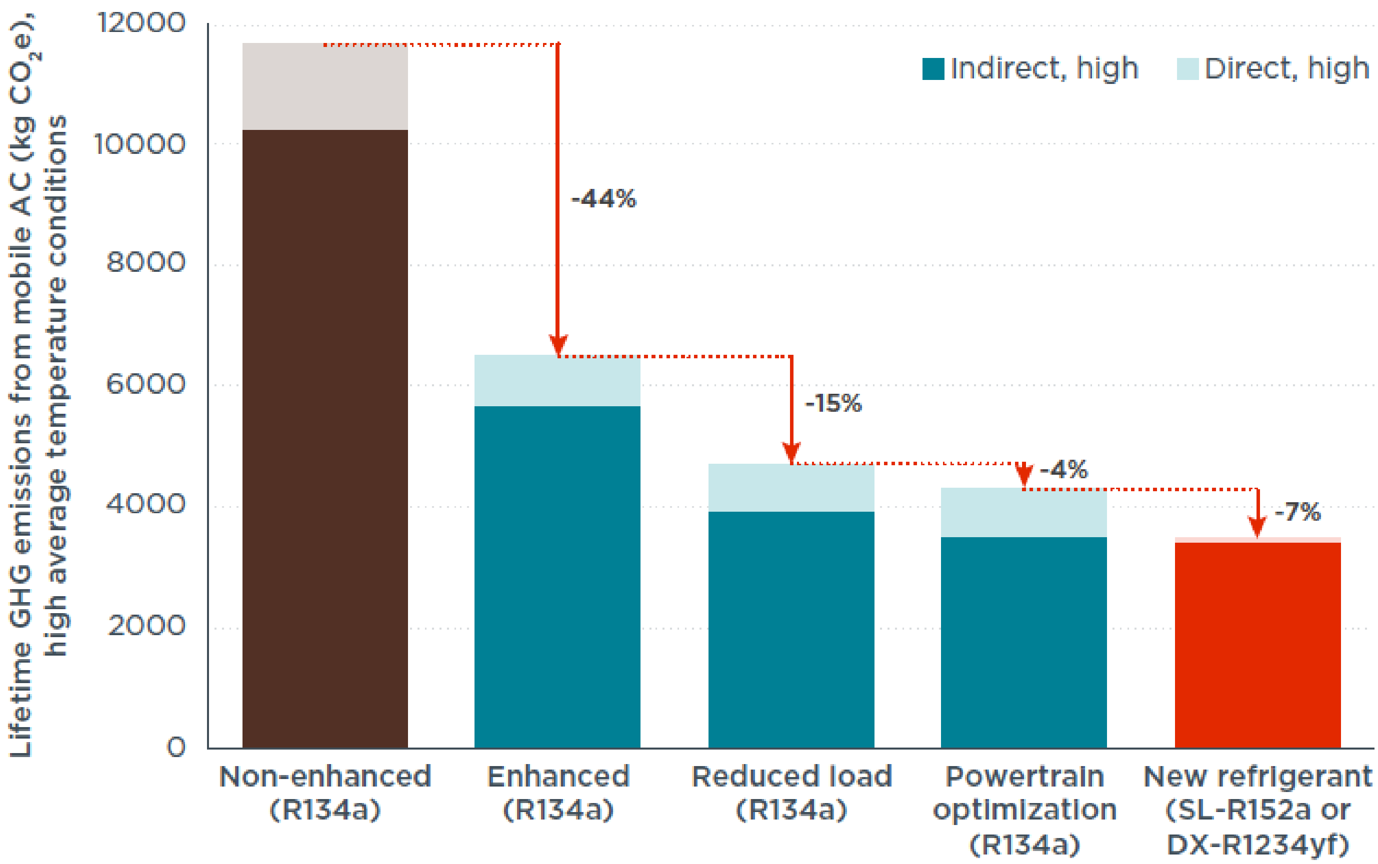

Figure 3: GHG reduction potential of improved MACs in climates with higher ambient temperature (Blumberg et al, 2019)

Discussion & Conclusions

The project partners' hypothesis was that an SL-MAC system using low-GWP refrigerants could (1) achieve climate, energy, and consumer cost savings benefits relative to a direct expansion system using HFC-134a, and (2) provide a viable, cost-effective alternative for manufacturers relative to a DX-MAC system using HFO-1234yf at today's refrigerant prices. To test these hypotheses, the project team project tested SL-MAC systems using two different refrigerants with 100-year global warming potential (GWP) under 150: HFO-1234yf

(GWP<1) and HFC-152a (GWP=138). The vehicle using the HFC-152a SLMAC exhibited superior climate performance, saving 1.9% to 2.6% of fuel compared to the baseline HFC-134a DX system. The HFC-152a system used half the amount of refrigerant and reduced direct refrigerant emissions by over 95% (on a CO_2-eq basis). In addition to superior climate performance, the SL-MAC system, if commercialized, is also estimated to save car owners money on fuel and AC service compared to DX-MAC using R-134a. Under typical operational conditions, the SL-MAC system using R-152a is estimated to require service only once over the vehicle's lifetime at an estimated cost of USD $54, compared to 2 or more services for an HFC-134a DX-MAC, costing an estimated $114-$171. Assuming 2.6% fuel savings, drivers of the Aria with the HFC-152a SL-MAC may also expect to save $20-$50 USD per year compared to the baseline HFC-134a MAC, depending on driving habits and AC usage, with estimated savings of $37 per year for a vehicle driven 18,000 km per year. Additional fuel savings could be realized by integrating the demonstrated compressor control algorithm in a vehicle equipped with fuel-saving stop-start technology, as the superior cold storage available with the SL-MAC system can allow these vehicles to remain in engine-off mode for up to two minutes without needing to turn on the engine to operate the AC. The R-152a SL-MAC is also estimated to be a cost-effective low-GWP alternative to DX HFO-1234yf systems for manufacturers: an SL-MAC using HFC-152a has an estimated incremental price increase of $36 over HFC-134a MACs, whereas the DX-R1234yf MAC is estimated to cost $65 more than DX HFC-134a MACs, largely as a result of the high price of HFO-1234yf.

Opposite the project objectives, the HFO-1234yf SL-MAC system showed a 1.3 to 4.7% reduction in fuel economy over HFC-134a. This reduction in fuel economy is not inherent in the technology, but results from the boundary conditions of this demonstration project. For example, limited heat exchanger re-design did not allow for the addition of an internal heat exchanger, which would have improved the fuel efficiency and performance of the HFO-1234yf SL-MAC. Building an SL-MAC system from the ground up (*ab initio*), would allow for a larger heat exchanger for the HFO-1234yf system, would eliminate the extra power needed by the compressor, and, therefore, increase fuel efficiency. Both systems showed a slight reduction in cooling performance, which could be offset by a higher capacity compressor. This would slightly reduce fuel efficiency, but additional strategies—such as integration of the compressor control with a stop-start system—could yield much greater fuel savings. Estimated impacts are presented in Figure 4.

Overall, the results are very promising. The SL-MAC results with R-152a validated the hypothesis that an SL-MAC system using a low cost low-GWP refrigerant could (1) achieve climate, energy, and consumer cost savings benefits relative to DX-MACs using HFC-134a, and (2) provide a viable, cost-effective alternative for manufacturers relative to a DX-MAC system using HFO-1234yf at today's refrigerant prices.

Future opportunities include demonstrating the SL-MAC system on a stop-start equipped vehicle for greater fuel savings, testing in trucks and commercial vehicles, and/or a full-scale fleet demonstration.

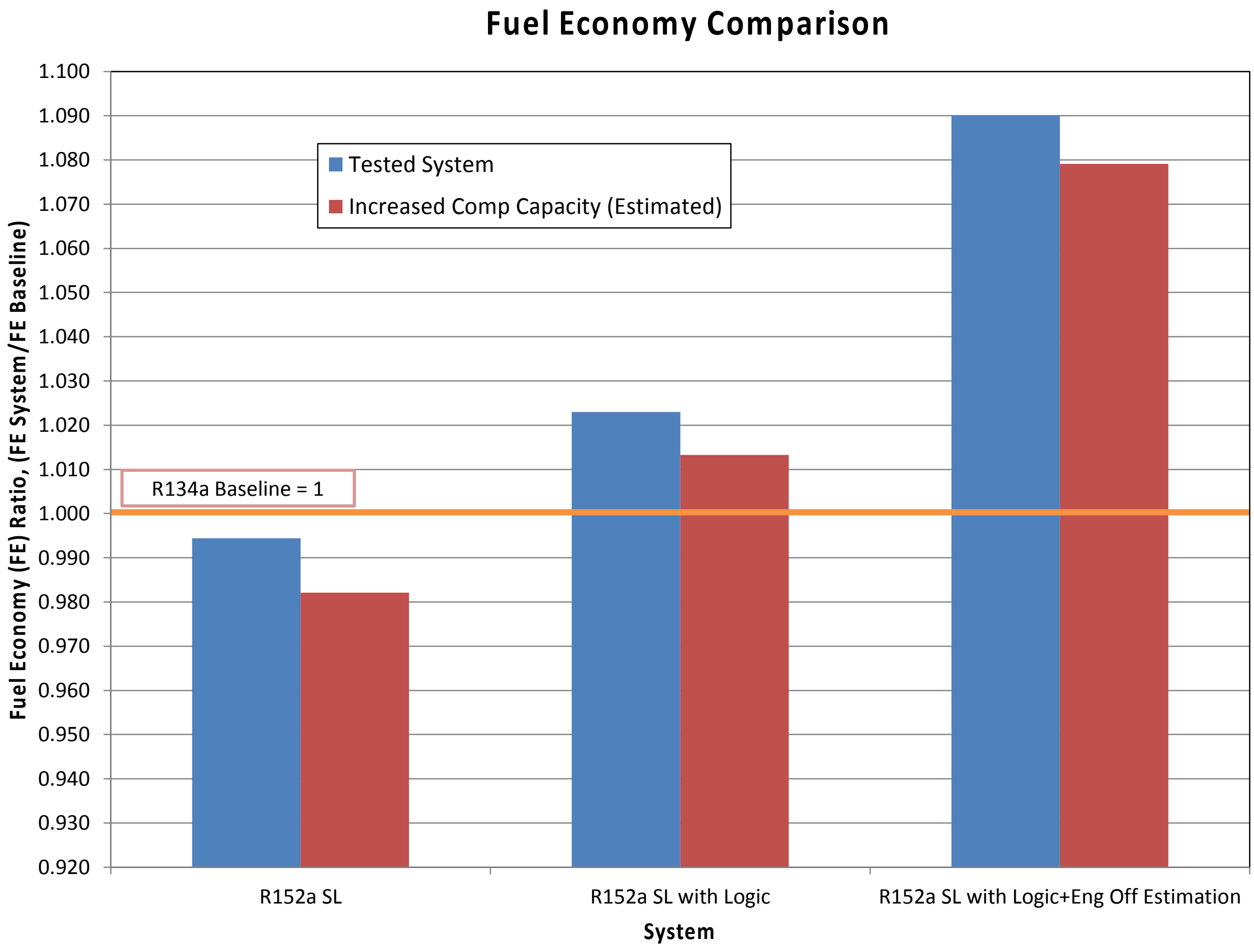

Figure 4: Estimated fuel economy impacts of increased compressor capacity and integration with stop-start (engine off) enabled vehicle.

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Additional Resources

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