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Fuel-efficiency technology trend assessment for LDVs in China: Thermal management technology

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1 Background

Fuel-consumption standards drive down China's use of fuel by the on-road sector and encourage the uptake of advanced vehicle-efficiency technologies. Understanding the need for a policy roadmap and long-term strategies to provide certainty for long-term fuel consumption, technology advancement, and potential compliance costs for manufacturers, China is looking ahead to advance post-2020 standards for light-duty vehicles.

In its "Made in China 2025" strategic initiative (MIIT, 2015), China set a 2025 fleet efficiency target of 4 L/100 km for passenger cars, a 20% decrease from the 2020 target of 5 L/100 km. In the Technology Roadmap for Energy Saving and New Energy Vehicles published by the Society of Automotive Engineers of China (SAE China, 2016), a 2030 fleet efficiency target of 3.2 L/100 km was set. To evaluate whether and how these targets can be met, it is essential to understand what technologies will be available within the 2020-2030 timeframe and what the costs of applying those technologies in the Chinese market will be.

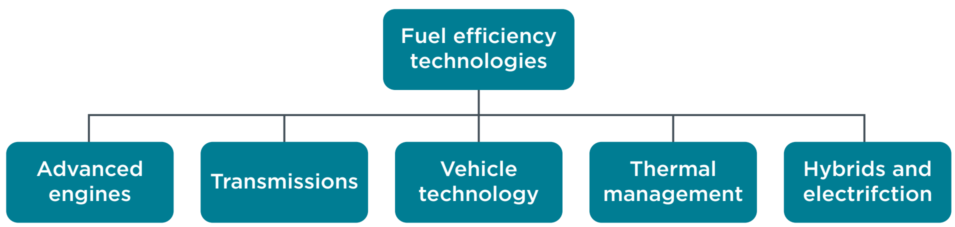

Figure 1 Categorization of fuel efficiency technologies in the working paper

This series of technical working papers aims to provide a comprehensive understanding of the current availability, effectiveness, and future market penetration of key fuel-efficiency technologies that manufacturers are likely to use in China by 2030. This information enables a more accurate, China-specific understanding of future technology pathways.

We group technologies into several categories: advanced engine, transmission, vehicle technologies, thermal management, and hybrids and electrification (Figure 1). The specific technologies we considered include those that are available today and others that are under development and expected to be in production in the next 5-10 years.

This research relies on information from publicly available sources, third-party databases, and information from the participating partners. Our approach includes:

- A detailed literature survey, including both Chinese and global regulatory documents, official announcements, and industry and academic reports.
- Analysis of databases from Polk and Segment Y.

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- Conversations with manufacturers, tier one suppliers, research entities, and domestic and international experts.

For each key technology, we discuss how it reduces passenger-car fuel consumption, its effectiveness in reducing fuel consumption, and its current level of application or potential application in the China market. Wherever applicable, we compare technology trends in China with those in the United States and the European Union to reflect potential technology pathways in the long term.

This working paper assesses progress and new developments in thermal management technologies.

2 Introduction

Thermal management technologies reduce vehicle fuel consumption and CO_2 emissions by improving powertrain efficiencies and reducing the amount of energy used to provide passenger comfort. Powertrain thermal management enables safe vehicle operation and includes engine and transmission thermal management, lubricant temperature control, and, more recently, thermal management of electrical systems and energy storage devices. We discuss powertrain thermal management technologies in the first working paper in this series on advanced engine technologies.

In this paper, we evaluate new thermal management technologies related to occupant comfort in the passenger cabin. Some thermal management technologies affect fuel consumption during the government type approval test drive cycles, whereas some technologies have significant real-world improvements that are not reflected on the test cycles. The later offer "off-cycle" benefits.

Passenger thermal comfort is conventionally achieved by regulating air temperature in the passenger cabin using high-powered heating, ventilation, and air-conditioning (HVAC) systems. Reductions in the amount of energy required to provide passenger comfort can be achieved by minimizing heat losses using such technologies as cabin insulation, solar reflective paints, and advanced window glazing. Further reductions in HVAC energy use can result from delivering heating and cooling directly to occupants from seats, interior panels, and other surfaces in close proximity to occupants. Passenger comfort technologies usually focus on consumer experience rather than fuel consumption. Evaluating fuel consumption in real driving conditions under which air condition (A/C) can consume as much as 9%–12% of fuel energy (Yang & Yang, 2018) has raised awareness of the impact on fuel economy of human thermal comfort management.

Thermal management technologies play an important role for both conventional and electric vehicles. For conventional vehicles, a suite of powertrain thermal management technologies can result in reductions of as much as 8% in fuel consumption and CO_2 emissions (ITB, 2015). As fuel-consumption standards grow more stringent, thermal management assumes greater strategic importance for improving vehicle efficiency. For electric vehicles, a suite of technologies including battery/electric system management and passenger comfort technologies can improve all-electric driving range by as much as 30% in hot or cold driving conditions (ITB, 2017). As electric vehicle demand rises quickly in China with government encouragement, thermal management is essential for expanding electric driving range, reducing charging times, and increasing energy efficiency.

3 Current status

3.1 CONVENTIONAL VEHICLES

A variety of mature technologies are associated with vehicle thermal efficiency and have on-cycle and off-cycle benefits. The ITB Group identified more than 60 potentially beneficial thermal management technologies for conventional vehicles (Osborne et al., 2016). These technologies include power train-related and passenger comfort technologies that have a significant impact on reducing fuel consumption. These technologies lower fuel consumption by as much as 7.5% with costs ranging up to 3,000 RMB. Figure 2 illustrates the cost and benefit of each technology and categorizes them into four groups based on cost per 1% reduction in fuel consumption. The most cost-effective are powertrain technologies followed by some passenger comfort technologies.

On-cycle engine technologies include those that reduce frictional losses in the valve train, crankshaft, and pistons, such as low-friction lubrication, engine friction reduction, and cooled EGR. On-cycle transmission technologies include technologies that minimize losses associated with torque converter slip, such as high-efficiency transmissions. Table 1 lists the estimated benefits for fuel consumption of different on-cycle thermal technologies as estimated by the U.S. National Highway Traffic Safety Administration (NHTSA). The current status of these technologies is

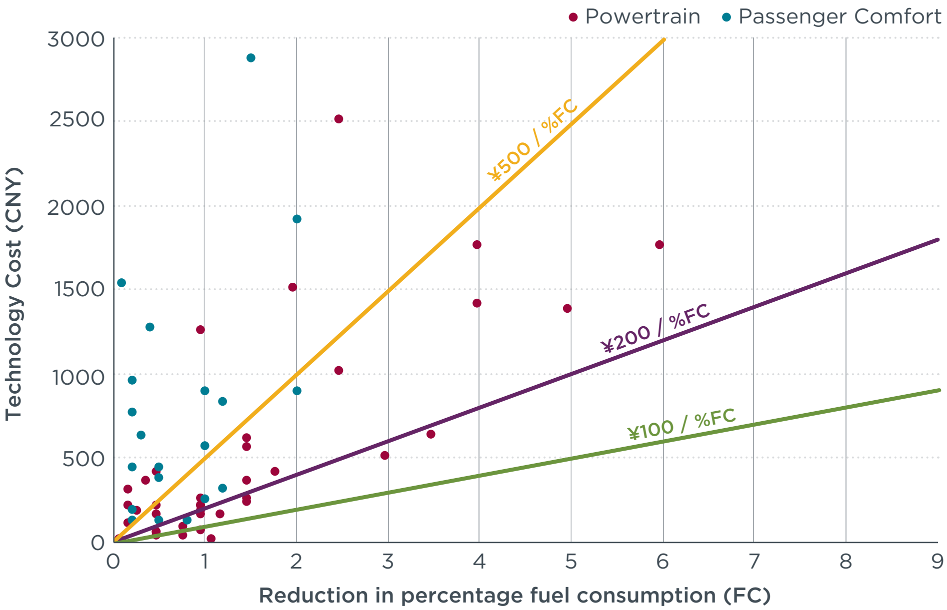

Figure 2 Economic comparison of thermal management technologies

Table 1 On-cycle thermal technologies estimated by NHTSA

Thermal Technology	Benefit (L/100 km)	Cost (RMB)[i]	Notes
Low Friction Lubrication	0.02	26	Low viscosity and advanced low friction lubricant oils
Engine Friction Reduction	0.07	365	Low-tension piston rings, roller cam followers, improved material coatings, more optimal thermal management, piston surface treatments, and others
Low Friction Lubrication + Engine Friction Reduction 2	0.03	384	Further development
Cooled EGR 1	0.09	1,594	24 bar
Cooled EGR 2	0.13	2,330	27 bar
Improved Accessories 1 (IACC 1)	0.03	480	High efficiency alternators and electrically driven water pumps and cooling fans
Improved Accessories 2 (IACC 2)	0.10	768	IACC 1 + a mild regeneration strategy and a higher efficiency alternator
High-efficiency transmission	0.07	1,293	Continuous improvement in seals, bearings and clutches; super finishing of transmission parts; and development in the area of lubrication

Color: cost per 0.1 L/100 km reduction	< 500	500-1000	1,000-1,500	1,500-2,000

[i] Exchange rate is 6.4 RMB to $1.

discussed in the working paper in this series on advanced engine technology (Xiao, Yang, & Isenstadt, 2018).

Off-cycle technologies reduce fuel consumption in real-world driving but are usually not captured by the current fuel-consumption test procedure. The China 2020 passenger vehicle standard has a list of technologies eligible for off-cycle credits that is capped at 0.5 L/100 km. One thermal management technology—efficient air conditioning—is so far captured in the off-cycle technology list. There are other technologies that provide off-cycle fuel consumption benefits, some of which are captured by the off-cycle U.S. credits as listed in Table 2 (EPA, 2012). The estimation is based on assumed typical vehicle in the U.S., thus may vary by different vehicle specifications. Note that the application of low-global warming power (GWP)/leakage refrigerant would reduce only green-house gas (GHG) emissions without reducing fuel consumption. Given the potential for synergistic management of fuel consumption and GHG in China, this is considered an effective technology in this working paper.

HVAC technologies can have a significant impact on fuel consumption and CO_2 emissions, though functionally these systems are intended to provide for passenger comfort. The baseline equipment is a central HVAC system that heats and cools the vehicle cabin.

HVAC systems have traditionally been designed to maximize cooling capacity, not efficiency (Rugh & Farrington, 2008). Today, HVAC systems are designed with high capacities for extreme conditions, with 4 kW–9 kW for cooling and 5 kW for heating. Conventional air conditioning technology adds a parasitic load on the engine when vehicle occupants demand it, thus increasing fuel consumption. According to a study conducted by the American National Renewable Energy Laboratory (NREL), air conditioning use represents 5.5% of conventional light-duty vehicle fuel consumption in the United States (Rugh, Hovland, & Anderson, 2004). On-road testing of popular Chinese models by the ICCT found fuel-consumption increases of 9%–12% after turning on the A/C (Yang & Yang, 2018). Given the large penetration of A/C in the current passenger car fleet, its impact on the amount of fuel consumed is significant.

Heating has a lesser effect on conventional vehicles when engine heat is used for heating the cabin. However, improvements in engine efficiency mean that there is less heat available for warming the cabin. High-efficiency and diesel vehicles sold in cold climates come equipped with auxiliary heaters that are powered by either electricity or burning of fuel, thereby adding to overall vehicle CO_2 emissions. For electric vehicles, which operate without internal combustion engines, using electrical cabin heating will significantly reduce the battery range.

Figure 3 illustrates the composition of an HVAC system. Manufacturers can reduce HVAC energy use in several ways: by improving system and component efficiency and reducing refrigerant leaks, by targeting individual occupants in delivering heating or cooling, and by implementing distributed heating and cooling systems such as those integrated in seats. For example, most of the auxiliary engine load is due to operation of the air conditioning compressor. Reducing compressor size and operating time would lower energy consumption. This can be achieved by using more sophisticated sensors and control strategies to minimize compressor demand.

Table 2 Summary of off-cycle potential for reducing fuel consumption

Off-cycle vehicle technology	Benefit (L/100 km)	Off-cycle solar/ thermal technology*	Benefit (L/100 km)
Waste Heat Recovery (Scalable)	0.02 (100 watt)	**Glass or Glazing**	Up to 0.08
Active Engine Warm-Up	0.04	**Active Seat Ventilation**	0.03
Active Transmission Warm-Up	0.04	**Solar Reflective Paint**	0.01
Solar Panels (Battery Charging)	0.02	**Passive Cabin Ventilation**	0.05
Solar Panels (Battery Charging and Active Cabin Ventilation)	0.07	**Active Cabin Ventilation**	0.06
Active Aerodynamics	0.02	**(Solar/Thermal Total)**	(Up to 0.08)
Start-Stop	0.04	**Actively Cooled Seats**	0.11
Start-Stop (heater circulation system)	0.07		
High-efficiency A/C	0.13		
Low GWP/leakage refrigerant	0.37		

* Solar and thermal technologies are assigned up to 0.08 L/100km in total in the U.S. regulation.

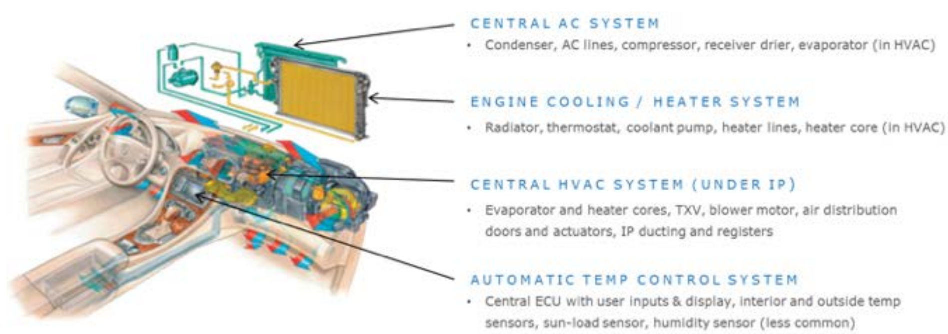

Figure 3 Illustration of HVAC system (provided by Gentherm)

A group of technologies that can reduce the energy drain of HVAC systems delivers cooling and heating directly to driver and passengers. These technologies target surfaces in contact with the human body or in close proximity to it. According to Gentherm, when a conventional HVAC system use 5 kW of energy, only about 150 W of it is used to condition the occupants; the rest cools the cabin. Technologies targeting occupants are active seat ventilation, actively cooled seats, convective heaters for the back and neck areas, actively heated seat surfaces, and heated interior panels and steering wheels.

Ventilated seats use fans or blowers to move cabin air through the seat to cool the surface. Actively cooled seats are an improvement on this, integrating cooling devices that reduce seat temperature below cabin air temperature. Providing additional cooling in the seat itself makes it possible to allow higher cabin air temperatures and reduce energy consumed by the HVAC (NREL, 2016). Based on an NREL study (Rugh, Chaney, Lustbader, and Meyer, 2007), ventilated seats can reduce A/C-related fuel consumption by 7.5%, or 0.03 L/100 km (converted from 1.0 g CO_2/mi). A separate study found that actively cooled seats allow for a 2.6°C increase in cabin temperature, reducing fuel consumption by 17.0% (Kreutzer, Rugh, Kekelia, & Titov, 2017). The EPA grants the same off-cycle credits to ventilated and actively cooled seating. American OEMs are increasingly aware of the performance difference, and GM is leading the way in urging the EPA to recognize it.[1]

Heated seats, steering wheels, and other interior surfaces have similar effects to cooled seats. In this case, surface temperatures are higher than cabin air temperature. The time required to deliver passenger comfort is shorter and is achieved by using less energy. Surface heating results in lower cabin air temperature and has a noteworthy effect on improving occupant thermal comfort while extending electrical vehicle (EV) driving range.

The uptake of thermal seats is much lower in China than in other countries because of low average vehicle prices. The United States, the European Union, and Japan have higher penetration reflecting market maturity, demonstrated customer satisfaction, and common seat architectures that can easily adopt the technology. Actively heated seats have the highest penetration in China. In 2017, 19% of new cars were equipped with actively heated seats, compared with 38% in the United States, 30% in Europe, and 27% in Japan. Ventilated and actively cooled seats had a China market share of 3% in 2017, compared with the U.S. rate of 14%, Europe's 4%, and Japan's 7%. Actively heated and cooled seats, also called climate seats, have been available in the three mature markets since 2000, but the first climate seats in China were imported in 2007 by the luxury German brands Audi, BMW, and Mercedes. Domestic production of actively cooled seats began in 2012 with Chang'an Ford. FAW-VW, Dongfeng-Honda, Chang'an Ford, and SAIC-GM are pioneering climate seats mainly on their premium vehicles.

Other technologies are being developed to reduce cabin thermal loads: passive and active cabin ventilation, solar glass or glazing, and solar reflective paints.

Passive cabin ventilation opens windows or sunroofs and uses floor vents to supply fresh air to the cabin, whereas active cabin ventilation employs electric fans to pull heated air from the cabin. Passive ventilation reduces the impact of solar soaking by lowering cabin air temperatures by as much as 5.7°C, and active ventilation, by as much as 6.9°C (Rugh & Farrington, 2008). Lower cabin air temperature reduces the load on the A/C system. The EPA estimates a fuel saving of 0.01 L/100 km (converted from 0.3 g CO_2/mi) for cars for each degree centigrade of cabin air temperature reduction. Consequently, the agency grants off-cycle credits of 0.05 L/100 km for passive cabin ventilation and 0.05 L/100 km for active cabin ventilation (EPA, 2012). However, a 2017 NREL study questioned the benefits of these technologies and found that active and passive cabin ventilation have less impact on reducing thermal load than those off-cycle credits (Kreutzer, Kekelia, Rugh, & Titov, 2017). The factors that influence research results and real-world driving performance include the percentage of time that cabin ventilation is used and the duration of air flow and flow rate. Because of the uncertainty of the real-world benefit and its impact on future fuel-efficiency regulation, OEMs that historically took such off-cycle credits are evaluating their future CO_2 technology strategies.[2]

In 2016 in the United States, 94% of BMW cars were sold equipped with active cabin ventilation while almost all Fiat Chrysler cars came with passive cabin ventilation. All Fiat Chrysler cars imported to China should thus already be equipped with this technology. It is likely that cars sold by Brilliance-BMW, the joint venture of BMW in China, have also adopted active cabin ventilation technologies.

Thermal glass, or glazing with low thermal transmittance, and solar reflective paint improve passenger comfort by reducing cabin temperature when occupants enter a vehicle. As with active and passive cabin ventilation, lower initial cabin air temperature reduces fuel consumption by lowering HVAC energy use. NREL's study determined that cabin air temperature could be lowered by as much as 9.7°C with the use of glazing technologies on all windows (Rugh & Farrington, 2008). Thermal glazing receives U.S. off-cycle credit of as much as 0.08 L/100 km (converted from 2.9 g CO_2/mi), with the level of credit determined by the percentage of solar energy that passes through the glazing. Solar reflective paint is estimated to reduce cabin air temperature by 1°C and is granted off-cycle credit of 0.01 L/100 km (converted from 0.4 g CO_2/mi).

Thermal glazing has the highest U.S. fleet penetration among all off-cycle technologies at 50.7%. Some manufacturers, such as Fiat Chrysler, Ford, and JLR, equip almost all vehicles with at least one of these thermal management technologies. Solar reflective paint is used by several manufacturers including Toyota, GM, Ford, and Fiat Chrysler on as much as a quarter of their new car fleets. Penetration of these technologies in the Chinese

1 This application was recently made public by the EPA at https://www.gpo.gov/fdsys/pkg/FR-2018-02-26/pdf/2018-03846.pdf.

2 Based on communication with project partners.

market is unclear. If China grants off-cycle credits to these technologies, their market penetration is likely to be high because glazing and paint are relatively inexpensive to implement.

As vehicle technologies advance, cabin and seat thermal technologies also benefit vehicles with start-stop technology. When the engine stops, mechanical power to the vehicle is removed along with the ability to thermally condition the occupants. Thus, vehicles are likely to use electric heaters or cold storage evaporators to keep passengers comfortable when the engine is stopped. Electrically operated thermal components distributed strategically around the vehicle can provide thermal comfort and allow more frequent and longer engine-off time. The impact on performance of electric vehicles is even greater as such technologies can increase driving range compared with conventional central HVAC-equipped vehicles.

3.2 PLUG-IN VEHICLES

As China is encouraging a significant increase in production of electric vehicles, the benefits of thermal management advances can reduce losses to electric powertrain performance and lower the amount of energy used for passenger comfort. In Figure 4, ITB (2017) summarizes the impact of different technologies on electric range and technology cost. Different technologies can extend vehicle electric range by as much as 18% at a cost of less than $240 a car.

Focal points for powertrain thermal management include advanced technologies related to batteries, electronic power inverters, and electric motors. Improved battery chemistry and greater efficiency for electric drives and DC/AC converters will result in lower energy use during charging and reduced energy losses during operation. These measures can extend driving range while maintaining vehicle performance.

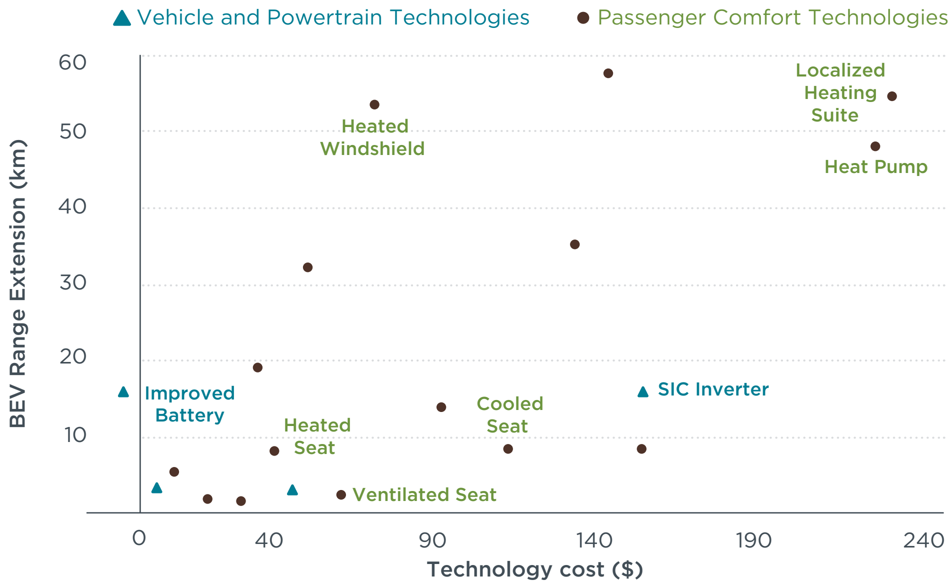

Figure 4 Technology cost versus range extension in battery electric vehicles (BEVs) (ITB, 2017)

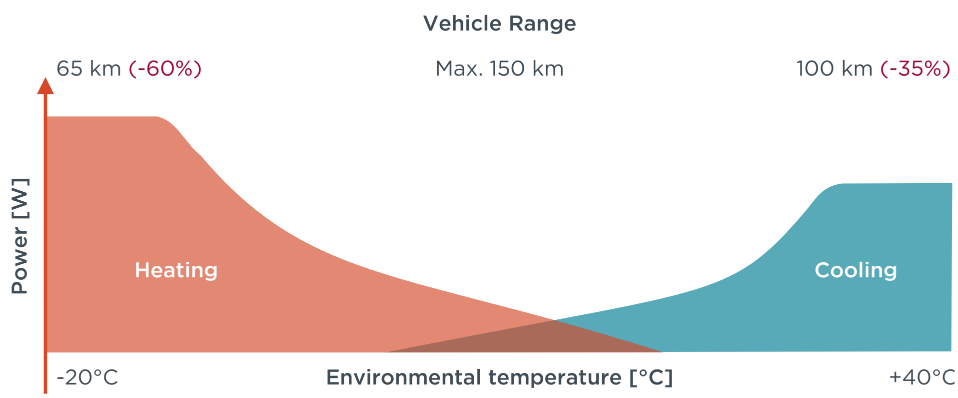

Figure 5 Illustration of impact of heating and cooling on driving range of battery electric vehicles (provided by Gentherm)

Cabin thermal technologies have a huge impact on EV energy consumption. The only source of energy is the battery, and it is shared by the propulsion and HVAC systems. A study by NREL (Robb, Brooker, Ramroth, Rugh, & Smith, 2010) found that conventional HVAC technologies typically reduce EV range by 20%–30%, and a hottest or coldest day trip can reduce range by as much as 50%. Heating during cold operation has a significantly greater impact than that of A/C during hot operation (Rask, 2014), as shown in Figure 5, which illustrate the impact of heating and cooling on driving range of battery electric vehicles.

Most electric vehicles use a positive temperature coefficient (PTC) heater when no engine exhaust heat is available. The PTC heats air or water, which is then used to heat the cabin. The heater draws energy from the same battery that power the vehicle, therefore reducing driving range. Automating control of the PTC heater or preheating the cabin while the vehicle is connected to the grid are approaches adopted to reduce the impact of heating on driving range, but these technologies have limited effectiveness. Because improving heating in cold conditions and reducing EV range anxiety are both important, alternatives are under development, including heat pumps, high fractional recirculation, and localized heating.

Sanhua Group, the supplier of 60% of vehicle refrigeration valves in China, has developed an electronic expansion valve (EXV) that is superior to the thermal expansion valve (TXV) in regulating the amount of refrigerant flow in an air conditioning system. TXV has inherent difficulty controlling saturated or low superheat conditions in dynamical circumstances. EXV allows quicker response to changes in operating conditions and flexibility in superheat regulation, thereby optimizing internal heat exchanger efficiency and contributing to greater system efficiency. Testing under the SAE J2765 mobile air conditioning standard has shown that EXV can improve the refrigerant system coefficient of performance for a typical passenger vehicle by more than 10%. EXV has been applied on EV models of BYD, Daimler, NIO, and a major North American automaker.

Heat pumps are becoming more common for battery electric vehicles, including the Nissan Leaf, BMW i3, VW eGolf, Kia Soul EV, and Daimler B-Class EV. The performance of first-generation heat pump systems varies greatly. Toyota was the first OEM to introduce a second-generation vapor-injection (VI) heat pump on the 2017 Prius PHEV. The Prius PHEV VI heat pump conditions the cabin and forced air used for battery thermal management. Air International Thermal Systems (Shanghai) is also developing a VI heat pump system. Notably, GM and Tesla have not yet commercialized heat pumps. Because of the physical limitations of refrigerant fluids, heat pumps on EVs usually work at temperatures above 0°C but at lower temperatures are less efficient than PTC heaters. Developments of improved heat pumps with better performance at low temperature (-15°C ~ 0°C) are underway (Wang, Wei, Guo, & Zhao, 2016).

Table 3 Energy reduction of thermal technologies during transient and steady-state phases

	Transient phase	Steady-state phase
Solar control glazing	43%	13%
Solar reflective paint	5%	16%
Ventilated/cooled seats	25%–46%	10%–17%
Heated seat and surface	-1%– -2%	29%–59%

Advanced HVAC technologies such as improved cabin air recirculation systems and heat pumps are not yet employed in passenger vehicles in China and are considered too costly to commercialize. However, development of heat pumps for new-energy vehicles in China has begun. Kinglong, BYD, and BAIC Foton have already adopted heat pumps on some electric coaches (Songz, 2017).

For passenger vehicles, manufacturers in China are likely to skip the first-generation heat pump designs and introduce second-generation VI heat pump systems. Sanhua Group has developed the R134a heat pump which has passed chassis tests and shows effectiveness in real-world test driving. Starting in 2019, Sanhua's heat pump will be applied in production EVs in China. Moving forward, Sanhua Group envisions that its R290 and R744 heat pumps would be the best options for new-energy vehicles (Zhao, 2017). Heat pumps offer the greatest benefits and value for battery electric vehicles, where they are expected to be introduced first. Geely, BYD, and likely others are developing VI heat pumps. Sanhua is also developing CO_2 refrigerant to improve heating performance of heat pumps at low temperatures.

Technologies that focus on delivering heating and cooling directly to occupants, such as thermal seats and other distributed heating and cooling technologies, effectively reduce energy required by HVAC systems by as much as 17%. The potential of these technologies was best evaluated in a 2017 NREL study using a Hyundai Sonata PHEV (Kreutzer, Rugh, & Tomerlin, 2017). The tests recorded energy consumption during the transient phase, or entry into vehicle and vehicle start, and the steady-state phase.[3] As Table 3 shows, reflecting the reduced time to achieve whole body sensation for the occupant and the reduced need for cooling the cabin, solar reflective glazing, solar reflective paint, and ventilated/cooled seats contributed to reducing energy consumption by 5%–46% during the transient phase and 10–17% during the steady-state phase. The energy saving from adopting heated seats and surfaces was also significant during the steady-state phase. The study is subjective because it uses occupant body sensation as a measurement, but it does illustrate the feasibility of various thermal technologies in reducing thermal load for electric vehicles. A 2015 NREL study (Jeffers, Chaney, & Rugh, 2015)

3 The transient phase is the time between the end of a vehicle soaking period and entry of an occupant into vehicle until the time when the occupant determines that target thermal comfort is achieved. In the steady-state phase, the occupant adjusts cabin temperature to achieve comfort level.,

found a similar range of energy saving from cabin pre-ventilation, solar control glazing, and distributed occupant cooling that included driver vents, overhead vents delivering cool air to the face, and lap vents delivering cooling to chest areas.

As energy used to thermally manage vehicle interiors could be as significant as energy used for vehicle propulsion, improving energy efficiency for human thermal comfort will continue to be one of greatest challenges in development of EVs. As consumers become more sophisticated and require higher levels of comfort, energy demand increases.

4 Further development pathways

There has been a proliferation of thermal management technological solutions in the past decade in major vehicle markets (Osborne et al., 2016). These mature and commercialized products have the potential to be applied on Chinese cars. If the rest of the world is a guide, then HVAC efficiency measures and solar glazing will be commercialized first, since they are quite mature. However, if the effects of these technologies will not be reflected in the fuel-consumption type-approval test procedure in China in the post-2020 regulations, they might need to be recognized for off-cycle credits to offset costs.

Seat heating and other technologies providing distributed thermal comfort will continue to increase but likely at a slower rate than the other technologies. In more mature markets, customer demand for heated, ventilated, and actively cooled seats is high. As the China market matures and consumers become increasingly familiar with thermal comfort products, technology uptake rates will increase.

The thermal seat penetration estimated by Gentherm in Figure 6 reflect an organic growth scenario and an electrification scenario.[4] By 2030, the China market will see significant thermal seat penetration reflecting the desire to electrify the entire Chinese fleet. The availability of thermal seats is projected to increase nominally from 2017 to 2023. Beyond 2023, the market will see significant increases in thermal seat content because of the push for electrified powertrains. Thermal seat installations of 3% in 2017 will increase to 33% by 2030. Vehicles with no thermal seat options will decline from 79% in 2017 to 45% in 2030. Small, low-cost vehicles will have some thermal seats while larger, more expensive vehicles will be fitted with thermal seats to meet the comfort expectations of a more discriminating consumer.

In a future dominated by electric vehicles, ventilated, cooled, and heated seats and other distributed heating and cooling technologies will become a standard part of the complete vehicle climatization strategy. Personalized microclimate systems are expected to be standard equipment for localized heating and cooling – focusing on delivering energy close to the occupant, or seat-centric comfort. Increased electrification of climate systems will enable remote pre-conditioning even in vehicles

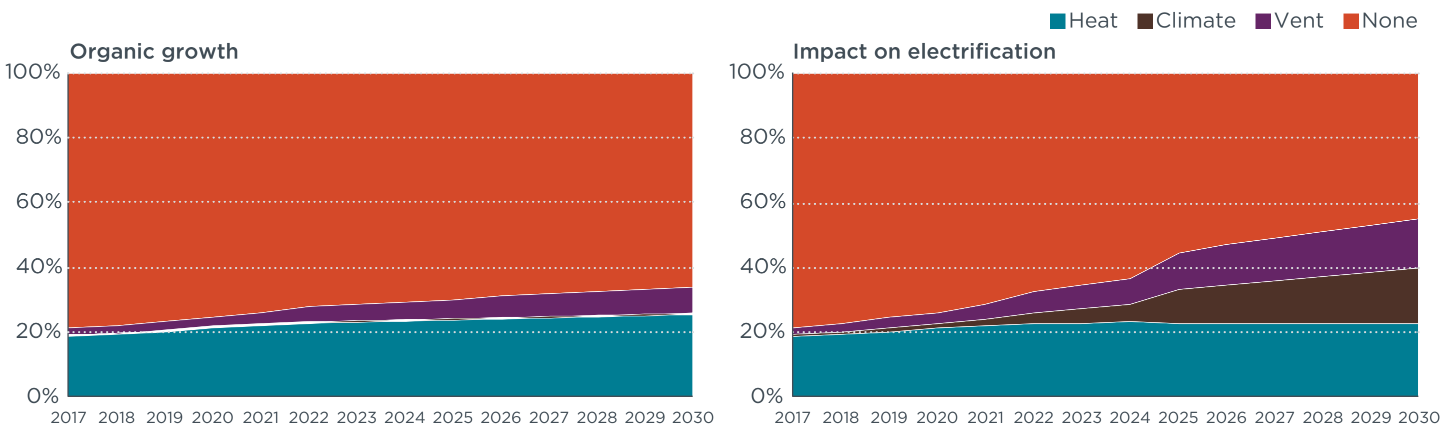

Figure 6 China thermal seat penetration estimates 2017–2030

4 The estimate assumes that EV penetration will increase from 1.4% in 2017 to 57% by 2030 (higher than the 40%–50% projection by CATARC) and differentiates the different uptake rates of climate seats by segment.

equipped with conventional internal combustion engines.

There are many advanced powertrain thermal management technology options that will enter the market, such as split-engine cooling, cooling fan improvement, variable or switchable water pump. However, some technologies are not mature even in more advanced markets. For example, because of the high cost ratio and an immature product development status, Rankine Cycle and thermoelectric exhaust heat recovery systems are not likely to be available in the United States by 2025 (Osborne et al., 2016). There is some possibility for these technologies to be commercialized in the longer term as their costs decline with continued development.

There are more opportunities for developing thermal management technologies to reduce fuel consumption. Future vehicle systems require more electronic devices, which enable more precise control under dynamic situations. Advancements in engineering and materials will allow better durability. Improvements in engine technologies will contribute to thermal-related improvement. The continued challenge for thermal management breakthroughs would be strategic system integration and optimization. This must be realized by development of more complex control algorithms as engine, electronics, and occupant thermal management systems are starting to overlap.

This working paper finds that a wide range of thermal management technologies are being developed worldwide to help vehicles meet fuel-consumption standards. Some Chinese joint ventures are following in the application of advanced thermal management technologies, and domestic manufacturers have also started to introduce commercialized technologies. Given that none of the thermal management technologies is currently listed to receive off-cycle credits, the policy incentives for manufacturers to invest in such technologies are mild. Therefore, the cost-effectiveness of thermal management technologies becomes a critical factor for manufacturers to integrate innovative technologies in their decision making.

5 Summary

Figure 7 summarizes the key thermal management technologies, especially off-cycle technologies, as discussed in this working paper. The adoption status of each technology in the China market is marked before the name of each technology. The pie chart is shown to reflect the market penetration of commercialized technologies in China. The start sign indicates that it is a technology applied on only a couple of models in China. The blue question mark is used for technologies without sufficient market penetration information. Because of the lack of data, we do not have a comprehensive summary of the application of most technologies.

The percentages following each technology summarize its potential for reducing fuel consumption. In most cases, the fuel-consumption reduction potential is compared with baseline vehicles without certain technologies.

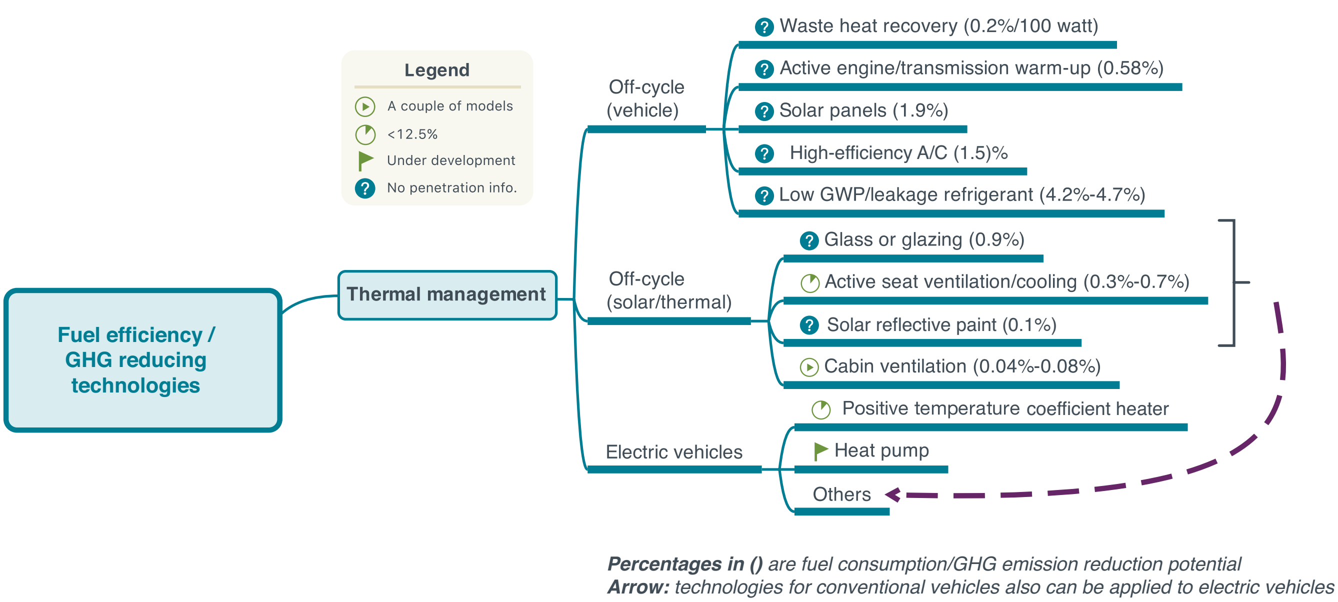

Figure 7 Thermal management technology map for passenger cars in China

The percentage is based on the absolute fuel-consumption saving potential listed in Table 2 divided by the fuel consumption of the baseline vehicles evaluated in the same EPA report (EPA, 2012). The numbers represent an average impact or impact range considering the differences in baseline vehicles' segment, specifications, and other factors.

Based on the application status of thermal technologies in China, we group the technologies into three categories:

Commercialized technologies. Technologies that are already adopted at least on several production models in China and could be applied widely through the fleet.

Emerging technologies. Technologies that are available on passenger cars sold in the Chinese market but are adopted only by a couple of models, such as variants of flagship models, or luxury models that target high-end users.

Table 4 Thermal management technologies at different development stages in China

With commercialized technologies	With additional emerging technologies	With additional underdeveloped technologies
• Off-cycle credit for thermal management technologies accounts for 3% of fleet average fuel consumption	• Off-cycle credit for thermal management technologies accounts for 6% of fleet average fuel consumption	• Off-cycle credit for thermal management technologies accounts for 9% of fleet average fuel consumption

Underdeveloped technologies. Technologies that have been adopted in other markets but currently are not available on cars produced in China, or technologies that have been announced by manufacturers or suppliers and are likely to be adopted on production passenger cars in the near future.

Because of a lack of comprehensive data, it is challenging to sort each thermal management technology by category based on our definitions as we have done for other types of technologies in this working paper series. Considering that the technologies under discussion are off-cycle technologies, we assume three average application levels to differentiate development phases. As Table 4 shows, we assume that the off-cycle credit for thermal management technologies will account for 3% of fleet average fuel consumption after application of commercialized technologies, 6% after the additional application of emerging technologies, and 9% after the additional application of underdeveloped technologies. As a reference, the allowable off-cycle credit to achieve the China Phase IV fuel consumption target in 2020 is 0.5 L/100 km, 10% of the fleet average target. The assumption in Table 4 is a rough estimate to illustrate the potential effect of thermal management technologies that are likely to have off-cycle impact. This information is used to estimate fuel-saving potential of all efficiency technologies in the summary working paper in this series.

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