icct
THE INTERNATIONAL COUNCIL ON CLEAN TRANSPORTATION

Automotive Thermal Management Technology

Author: Sean Osborne, Dr. Joel Kopinsky, and Sarah Norton (The ITB Group); Andy Sutherland, David Lancaster, and Erika Nielsen (BorgWarner); Aaron Isenstadt and John German (ICCT)

Date: 21 September 2016

Keywords: Passenger vehicles, advanced technologies, fuel-efficiency, thermal management, technology innovation

INTRODUCTION

In 2012, the U.S. Environmental Protection Agency (EPA) and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) finalized a joint rule establishing new greenhouse gas and fuel economy standards for vehicles.[1] The standards apply to new passenger cars and light-duty trucks, model years 2012 through 2021. A mid-term review of the 2022–2025 standards is in progress and will be finished in 2018.

Assuming the fleet mix remains unchanged, the standards require these vehicles to meet an estimated combined average fuel economy of 34.1 miles per gallon (mpg) in model year 2016, and 49.1 mpg in model year 2025, which equates to 54.5 mpg as measured in terms of carbon dioxide emissions with various credits for additional climate benefits factored in. The standards require an average improvement in fuel economy of about 4.1 percent per year.

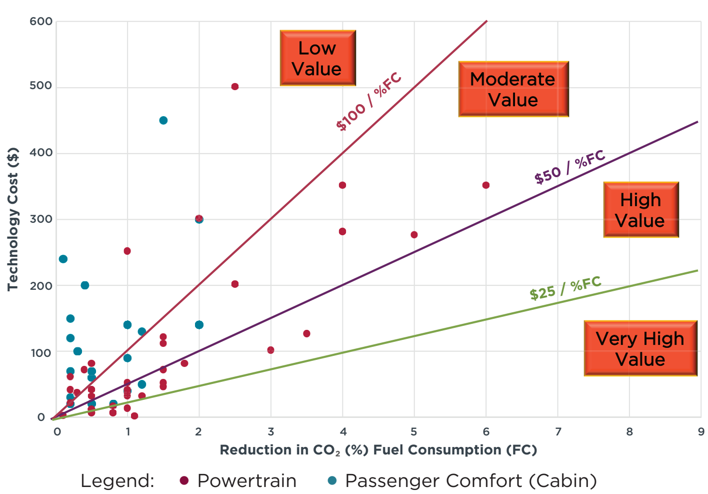
The technology assessments performed by the agencies to inform the 2017–2025 rule were conducted five years ago. The ICCT is now collaborating with automotive suppliers on a series of working papers evaluating technology progress and new developments in engines, transmissions, vehicle body design and lightweighting, and other measures that have occurred since then. Each paper will evaluate:

- How the current rate of progress (costs, benefits, market penetration) compares to projections in the rule;
- Recent technology developments that were not considered in the rule and how they impact cost and benefits;
- Customer acceptance issues, such as real-world fuel economy, performance, drivability, reliability, and safety.

This paper provides an analysis of thermal management technology development and trends. It is a joint collaboration between The ITB Group, BorgWarner, and the ICCT. The paper relies on data from publicly available sources and data and information from the participating automotive suppliers.

The essential takeaway is graphically summarized in figure 1. More than 60 thermal management technologies are currently in production or development. As the chart shows, over half of these technologies are projected to cost less than \$50 per percent fuel consumption reduction and will be of "high" or "very high" value to manufacturers. Furthermore, cabin technologies offer passenger comfort benefits in addition to the efficiency benefits. Thermal management can contribute on the order of 2% to 7.5% reductions in fuel consumption over the next ten years depending on a vehicle powertrain's base thermal management features.

Figure 1 Economic comparison of thermal management technologies.



1 U.S. EPA and NHTSA, (2012). EPA/NHTSA Final Rulemaking to Establish 2017 and Later Model Years Light Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards. Retrieved from https://www3.epa.gov/otaq/climate/regs-light-duty.htm#2017-2025.

BACKGROUND

Automakers are applying new powertrain technologies in order to meet government regulations. Thermal management techniques can improve powertrain and passenger comfort system efficiencies and are also important for the implementation of powertrain technologies like start-stop and coasting systems.

Examples of powertrain thermal management include engine and transmission lubrication, electrical systems, and coolant subsystems. These subsystems include hardware and software to regulate powertrain thermal condition. Passenger comfort (or cabin) thermal management includes technologies to regulate the temperature within the passenger cabin such as heating, ventilation, and air-conditioning (HVAC) systems, glazing, and others. Advancements of these technologies generally refine thermal control and reduce energy losses.

In the past decade there has been a proliferation of thermal management technological solutions. Automotive suppliers have developed and commercialized new products, such as electric pumps and valves. At the same time, lower cost variable mechanical solutions that offer many of the benefits of electrified devices have been commercialized. Devices such as grille shutters offer the ability to dynamically control air flow based on powertrain thermal needs. Individual components are being combined into system sets for application to specific vehicles. This state of flux is expected to continue for the next ten years, as components and systems are refined to provide CO_2 benefits at reduced costs.

Thermal management technologies have a role to play in improving both conventional and electrified powertrain vehicles. Thermal technology advances may reduce parasitic losses, but more importantly such technologies make engines, transmissions, and HVAC systems more efficient. For conventional powertrains, a primary technology metric is the impact on fuel consumption versus the cost of the technology, from both a piece-cost and development-cost perspective. In electrified powertrains the benefit of thermal management is different, and value stems from improving electric powertrain range, reduced charging times, and enabling reductions in size, mass, and cost of the powertrain subsystem (e.g. motor, power electronics or battery). Benefits of thermal management are not limited to energy savings, but also have a positive consumer impact when they improve passenger comfort.

The rising importance of thermal innovation can be demonstrated by the *Automotive News* annual PACE awards. A PACE award recognizes automotive product innovations with potentially high industry impact. The awards are intended as a general evaluation rather than an absolute measurement of the technology itself. Since 2014, there have been 57 awards given, and 10 of them were specifically related to thermal management. For the 2016 PACE awards, there were 28 finalists, of which 7 involved thermal and fluid management. These technologies were from BorgWarner, Bosch, Dana, FTE Automotive, Hanon, Röchling, and Valeo.[2] This paper outlines the range of thermal technologies being commercialized and the potential impact and cost of various solutions. Thermal management technologies are expected to complement other vehicle energy consumption reduction technologies to achieve future fuel consumption and emissions requirements in a cost-effective way. Thermal management improvements are important for both electrified and conventional powertrain vehicles.

EPA/NHTSA 2017–2025 PROJECTIONS

As preparation for the initial GHG rulemaking, EPA and NHTSA conducted extensive investigations of the cost and fuel consumption impact of technologies. Some technologies were shown to affect fuel consumption during the government certification test drive cycles. Other technologies were found to not have significant impacts during the test cycles, but to have significant real-world improvements during conditions that are not included on the test cycles. One of these key factors is thermal ambient conditions and the benefits of rapidly warming the powertrain.

Listed in table 1 are technologies associated with vehicular thermal effects. For each of these technologies thermal effects are only a portion of the total cost and benefit. For example, IACC1 includes an electric water pump and cooling fan thermal changes, but also a high efficiency electrical system (alternator).

As part of the initial rulemaking, processes were developed to grant off-cycle credits for technologies which provide benefits beyond those measured by federal driving test cycles (on-cycle benefits). A large portion of these technologies are related to thermal management. Table 2 lists the technologies and shows estimates of the four value categories, as assessed by The ITB Group.

Note that these standard values can be claimed by automakers if the technology is applied to a vehicle meeting the definition specified in the NHTSA ruling. Some credit values are based on specific calculation formulas. If a technology permutation can provide higher value than the standard credit, then an automaker may apply to receive

2 Boudette, Neal E, “21 Suppliers Named PACE Award Finalists,” *Automotive News*, 12 Oct. 2015.

Table 1 On-Cycle Thermal Technologies NHTSA Estimates

Thermal Technology	Benefit (g CO_2/mi)				ITB Value Estimate*
	Car	Truck	Cost Estimate Car	Cost Estimate Truck	
Low Friction Lubrication 1	0.7	0.7	$4	$4	Very High
Engine Friction Reduction 1 (EFR 1)	2.6	2.4	$57	$118	High
Low Friction Lubrication + EFR Level 2	1.3	1.2	$60	$122	Moderate/Low
Cooled EGR 1	3.5	3.6	$249*	$305*	Moderate
Cooled EGR 2	4.9	4.8	$364*	$885*	Moderate/Low
Improved Accessories 1 (IACC 1)	1.2	1.6	$75	$89	Moderate
Improved Accessories 2 (IACC 2)	3.6	3.8	$120	$143	High
High efficiency transmission gearbox	2.7	3.7	$202	$251	Moderate

Very high: < $25 per percent fuel consumption reduction

High: $25 to $50 per percent fuel consumption reduction

Moderate: $50 to $100 per percent fuel consumption reduction

Low: > $100 per percent fuel consumption reduction

Table 2 Off-Cycle Credits for Thermal Control Technologies

Thermal Control Technology	Credit (g CO_2/mi)		ITB Value Estimate
	Car	Truck	
Waste Heat Recovery (Scalable)	0.7 at 100 W	0.7 at 100 W	Moderate
Glass or Glazing	Up to 2.9	Up to 3.9	Low
Active Seat Ventilation	1	1.3	Low
Solar Reflective Paint	0.4	0.5	Moderate
Passive Cabin Ventilation	1.7	2.3	High
Active Cabin Ventilation	2.1	2.8	High
Active Engine Warm-Up	1.5	3.2	High
Active Transmission Warm-Up	1.5	3.2	Very High
Solar Panels (Battery Charging Only)	0.7	0.7	Low
Solar Panels (Active Cabin Ventilation and Battery Charging)	2.5	2.5	Low
Active Aerodynamics	0.6	1	Very High
Engine Idle Start-Stop (w/ heater circulation system)	2.5	4.4	Low
Engine Idle Start-Stop (w/o heater circulation system)	1.5	2.9	Low

Very high: < $25 per percent fuel consumption reduction

High: $25 to $50 per percent fuel consumption reduction

Moderate: $50 to $100 per percent fuel consumption reduction

Low: > $100 per percent fuel consumption reduction

Table 3 Examples of Thermal Management Technology Fuel Consumption Benefits[3]

Technology	Benefit on FTP at 75°F	Benefit on Other 5-Cycle tests	Benefit Off-Cycle	Off-Cycle Credit Available?
Intelligent Coolant Pumps	Yes	All Cycles	Yes	Limited
Electric Coolant Control Valve	Yes	All Cycles	Yes	Limited
Heated Stat + Position Sensor	Yes	All Cycles	Yes	Limited
Transmission Oil Bypass Valve	Yes	FTP at 20°F	Yes	Limited
Exhaust Heat Recovery System	Yes	FTP at 20°F	Yes	Limited
Thermoelectric Generator	Limited	HWY, US06	Most Benefit	Yes (Capped)
Organic Rankine Cycle	Limited	HWY, US06	Most Benefit	Yes (Capped)
Pre-Conditioning				
Thermal Storage	Yes	FTP at 20°F	Most Benefit	No
Block Heater	Limited	FTP at 20°F	Most Benefit	No
Traditional Remote Start	N/A	N/A	Negative	N/A

Table 4 Percent of 2014 Model Year Vehicle Production Volume with Credits from the Menu, by Manufacturer and Technology (%)

Manufacturer	Grille Shutters	Passive Cabin Ventilation	Active Cabin Ventilation	Active Seat Ventilation	Glass or Glazing	Solar Reflective Surface Coating	Active Engine Warm-Up	Active Transmission Warm-Up	Engine Idle Stop-Start
BMW	0.0	0.0	85.1	2.5	2.9	0.0	78.5	0.0	0.0
Fiat Chrysler	16.4	99.3	0.0	1.8	99.3	1.3	58.0	11.7	0.0
Ford	38.4	0.0	0.0	12.8	97.2	12.5	9.6	16.2	3.4
GM	6.7	0.0	0.0	13.3	52.3	15.6	0.0	0.0	6.7
Honda	0.0	0.0	0.0	0.9	0.0	0.0	0.0	58.5	0.0
Hyundai	2.1	0.0	0.0	12.1	84.4	0.0	0.0	16.7	0.0
JLR	0.0	0.0	0.0	62.6	98.1	0.0	0.0	0.0	93.0
Kia	1.8	0.0	0.0	15.8	76.1	0.0	0.0	22.7	0.6
Mercedes	0.0	0.0	0.0	8.7	3.9	0.0	0.0	0.0	65.3
Nissan	4.6	0.0	0.0	4.9	0.0	0.0	19.5	55.7	0.9
Subaru	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Toyota	0.0	11.4	0.0	13.5	52.9	25.5	9.2	53.8	12.5
Fleet Total	**9.8**	**15.0**	**2.1**	**9.6**	**50.7**	**8.7**	**14.2**	**23.2**	**5.5**

3 BorgWarner, "Examples: Thermal Management Off-Cycle Technology," received via email communication, May 2016.

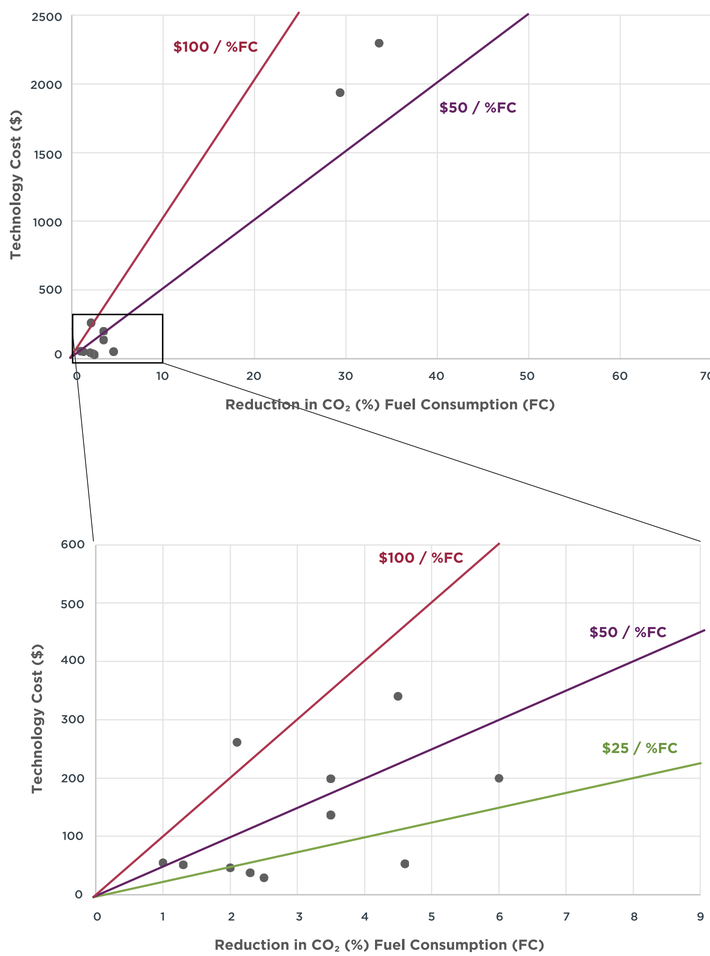
higher credit for an off-cycle technology than shown in the ruling.

As shown in table 3, some thermal management technologies have both on-cycle and off-cycle benefits. In some cases the off-cycle benefits may be limited by the technology as defined in the off-cycle credit menu. This limitation could be overcome by applying for credit for a specific thermal management technology, but the benefits may be difficult to generalize across powertrains. Validation of thermal technologies beyond the menu credits could be quite costly, although these additional thermal technologies could offer additional benefits and should be considered for off-cycle credits.

CURRENT THERMAL MANAGEMENT TECHNOLOGY USE

Table 4 shows the percentages in which different manufacturers are currently incorporating different types of thermal management technologies. For instance, a high percentage of BMW vehicles have active cabin ventilation (85.1%) and active engine warm-up (78.5%). Automakers are taking very different approaches. In contrast to BMW, FCA focuses on passive cabin ventilation and glazing technologies, as well as active engine warm-up. The 2014 Model Year Manufacturer Performance Report[4] specified that the technologies vary by manufacturer and that each vehicle can have more than one technology. Thus, each of the technologies and the vehicles are a many-to-one relationship. Active seat ventilation is a very common technology, but generally has a low penetration rate across the fleet average (9.6%) with the exception of JLR (62.6%). Glass or glazing is a relatively high percentage (50.7% fleetwide).

Figure 2 Economic Comparison of Vehicle and Powertrain Fuel Efficiency Technology Value vs. Cost of CO_2 Reduction (NHTSA)



VEHICULAR AND POWERTRAIN TECHNOLOGY VALUE

In order to assess the potential cost-effectiveness of thermal management technologies, it is instructive to examine the value of vehicle and powertrain technologies that were incorporated into the 2017–2025 rulemaking. As shown in figure 2 and table 5, based on NHTSA estimates, the values of 16 vehicle and powertrain technologies vary widely. The values of vehicle architectures like strong hybrids, advanced diesel, and 48V hybrid vehicles fall near a $100 per percent CO_2 reduction. Other conventional powertrain technologies may provide higher value, with costs below $25 or $50 per percent CO_2 reduction, but provide a smaller amount of CO_2 reduction. Note that automakers combine technology sets into packages, which achieve targeted improvement goals. Furthermore, the entire automotive value chain is focused on reducing the costs of these technologies. As discussed in ICCT's working paper on naturally aspirated engines, start-stop system costs have been significantly reduced in the past five years, shifting this technology downward and increasing its value.[5]

4 United States Environmental Protection Agency, "Greenhouse Gas Emission Standards for Light-Duty Vehicles: Manufacturer Performance Report for the 2014 Model Year," EPA-420-R-15-026 (2015), https://www3.epa.gov/otaq/climate/ghg-report.htm.

5 Aaron Isenstadt, John German, and Mihai Dorobantu, "Naturally aspirated gasoline engines and cylinder deactivation," ICCT working paper 2016-12 (2016), http://www.theicct.org/naturally-aspirated-gas-engines-201606.

Table 5 Economic Comparison of Vehicle and Powertrain Fuel Efficiency Technology Value vs. Cost of CO_2 Reduction (NHTSA)

Very High	High	Moderate	Low
Less than $25 / % CO_2 reduction	Between $25 and $50 / % CO_2 reduction	Between $50 and $100 / % CO_2 reduction	Greater than $100 / % CO_2 reduction
Dual Cam Phasing	SI Adv. Lubrication + Friction	Continuously Variable Valve Lift	12V Start-Stop
8 Speed AT vs. 6 Speed AT	CVT vs. 6 Speed AT	Cooled EGR – 50% Downsizing	
8 Speed DCT vs. 6 Speed AT	10% Mass Reduction	HP + LP EGR	
Adv. Reduction in Tire Rolling Resistance		Advanced Diesel	
10% Aero Drag Reduction		Strong Hybrid	

THE VALUE OF POWERTRAIN AND PASSENGER COMFORT THERMAL TECHNOLOGIES

Research performed by The ITB Group in 2015 and 2016 outlines the rapidly changing technical and market dynamics affecting commercialization of thermal technologies.[6]

Figure 3 graphically represents the value of over 60 thermal management technologies[7] that The ITB Group has identified as potentially beneficial within automotive applications and that should be considered within the midterm evaluation and upcoming ruling. These estimates are for conventional powertrain vehicles. There are two broad classes of technologies included: passenger comfort (blue) and powertrain (red) related. The thermal technologies fall into one of the four value categories: very high, high, moderate, and low. Those that are in the very high value categories are likely to be deployed sooner by OEMs in their vehicles. This is due to their lower technology cost versus higher CO_2 and fuel consumption impact. Those technologies in the low value category have a higher upfront technology cost and will not necessarily have as great of an impact to reduce a vehicle's CO_2 and fuel consumption numbers. Electrified vehicles have lower fuel consumption and are more likely to utilize new passenger comfort thermal technologies. Simultaneously, there are efforts being made to reduce the cost of the lower value technologies.

Powertrain-related (red) thermal technologies generally fall in the high and very high value categories. Some of the technologies are low cost, like software algorithm improvements. Technologies like Rankine Cycle and thermal electric exhaust heat recovery systems are not likely to be available by 2025, but continued development will reduce their cost to achieve higher value and make them more commercially viable.

Figure 3 Economic Comparison of Over 60 Thermal Management Technologies: Value vs. Cost of CO_2 Reduction

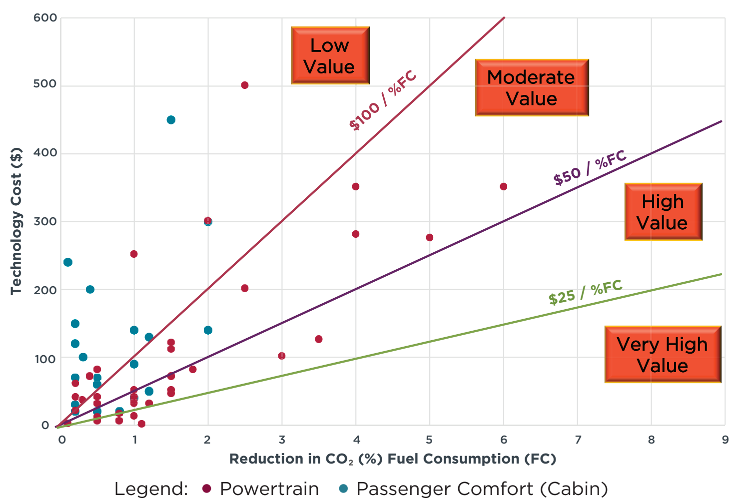


Table 6 lists the technologies mapped in figure 3. Definitions and acronyms can be found in the appendix.

6 The ITB Group, "Changing Paradigms in Automotive Thermal Management" (2015) and "Evolution versus Revolution in Powertrain Fluid Control" (2016).

7 It should be noted that the benefits from the majority of these thermal management technologies will vary based upon the application, including base engine and transmission design, vehicle integration, etc.

Table 6 Economic Comparison of Over 60 Thermal Management Technologies: Value vs. Cost of CO_2 Reduction

Very High	High	Moderate	Low
Engine thermal mass reduction	Ejector Cycle	Cold storage accumulator	Low-E / IRR / PVB glazing
Model vs. map based algorithms	Passive cabin ventilation	Cabin exhaust heat exchanger (active)	Lower heat transfer glazing (PC)
Navigation based prediction	Active cabin ventilation (high recirculation)	Electric engine oil pump	Adaptive cabin temp control (IR Sensor)
Predictive powertrain control	Insulated coolant	EGR Cooling HP	Focused IR heating
Insulated oil pan	Encapsulated engine compartment	EGR Cooling (HP+LP)	Heat storage accumulator
Insulated auto/CVT/DCT transmission	Variable water pump (switchable)	Engine oil heating at start-up	Liquid cooled condenser
Insulated differential	Variable water pump (clutched)	Exhaust heat recirculation	HV PTC Heating
Variable engine oil pump	Electric water pump (EWP)	Exhaust heat to engine oil	Heat pump (XEV)
Reduced oil sump mass by 20%	Smart multi-way water valve	Map controlled thermostat	Integrated localized HVAC
Integrated liquid cooled exhaust / EGR	Smart valve with integrated EWP	Pre-heated coolant	Ventilated seats (heating + cooling)
Higher conductivity coolant	Transmission rapid warm-up	Rankine cycle (turbo steamer)	Insulated roof
Polymer material heat exchangers	Transmission dynamic thermal control	Powertrain Pre-conditioning	Insulated passenger cabin
Active Grille Shutters	Split engine cooling		Windshield electric defrost
	Dynamic engine thermal control		Solar panels
			Dual level (HT/LT) CAC
			Liquid cooled CAC
			Liquid cooled CAC + condenser
			Differential heating at start-up
			Thermoelectric capture and generation (TEG)
			Exhaust heat turbo generator
			Turbo cooling + trans thermal
			Thermal storage (PCM)
			Coolant heat storage tank

PASSENGER COMFORT RELATED TECHNOLOGIES ARE DIFFERENT

In general, passenger comfort technologies show lower value ($ per CO_2 reduction) than powertrain-related thermal technologies, since they primarily affect HVAC energy losses, which are relatively smaller than powertrain losses. Many HVAC solutions are an end consumer benefit and may not be focused on fuel efficiency as much as on consumer experience, but offer fuel efficiency benefits as a side effect. However, as vehicles become more efficient, the importance of passenger thermal comfort increases. In some cases conventional vehicles, particularly with start-stop systems, may require supplementary electric heating. Reducing energy needed for passenger comfort provides higher benefits (on a percentage basis) for more efficient electrified powertrains.

Electrified vehicles may require advanced passenger comfort for reasons other than CO_2 reduction. For example, when the engine is stopped advanced cabin heating and cooling, like electric heaters or cold storage evaporators, may be necessary to keep the passenger comfortable. Otherwise the conventional engine may need to be restarted. Therefore the costs of passenger comfort provide additional value beyond reductions in energy consumption and CO_2 emissions.

A primary method for heating electric vehicles is electric air or water heaters. Since these devices can consume significant electrical energy, other technologies are being developed to reduce passenger cabin thermal losses. Such loss reduction technologies being deployed for highly electrified vehicles include solar glazing and high fractional recirculation HVAC systems. Technologies like heated steering wheels and heated/cooled seats may more directly improve passenger comfort and reduce HVAC energy consumption.

In addition to maximizing comfort, passenger cabin HVAC technologies provide additional value for highly electrified vehicles. One major impact of HVAC technologies is electrified vehicle all-electric range. Energy consumption for driving electrified vehicles may be equivalent to that needed to condition the passenger cabin for some situations. In other words, city driving power of about 3kW may be exceeded by thermal comfort and dehumidification requirements for certain trips in very hot or cold ambient conditions. This means that electric vehicle range may fall by 50% or more for extremely cold or hot trips. A study by the U.S. National Renewable Energy Laboratory found

Table 7 Thermal Technology Market Penetration and Maturity Assessment

Technology	Market Penetration	Technical Maturity
Active Aerodynamics	4	7
Active Cabin Ventilation	7	6
Active Grille Shutters	8	8
Active Seat Ventilation	8	6
Active Transmission Warm-Up	10	8
Aero Drag (10%)	6	10
Coolant Heat Storage Tank	3	8
Differential Heating at Start-Up	3	8
EGR Cooling (HP)	8	8
EGR Cooling (HP+LP)	7	6
Engine Oil Heating at Start-Up	4	8
Engine Thermal Mass Reduction	7	8
Exhaust Heat Recirculation	6	4
Exhaust Heat to Engine Oil	2	4
Exhaust Heat Turbo Generator	2	3
Higher Conductivity Coolant	2	8
Insulated Coolant	5	4
Insulated Differential	3	6
Integrated Liquid Cooled Exhaust/EGR	8	8
Intelligent Cooling System	8	7
Low-E/IRR/PVB Glazing	10	8
Lower Heat Transfer Glazing (PC)	3	8
Passive Cabin Ventilation	9	8
Power Preconditioning	6	4
Pre-Heated Coolant	6	6
Rankine Cycle (Turbosteamer)	3	6
Reduced HVAC System Loading	8	7
Reduced Oil Sump Mass by 20%	5	8
Solar Panels	1	8
Solar Panels: Active Cabin Ventilation & Battery Charging	2	8
Thermoelectric Capture & Generation (TEG)	2	4
Turbo-Cooling + Transthermal	8	8
Variable Engine Oil Pump	10	8

that conventional HVAC heating and cooling technologies typically reduce plug-in vehicle range by 20%–30%.[8]

Certain technologies, like heat pumps, are being deployed on plug-in vehicles because they significantly improve vehicle range by reducing HVAC losses in low temperature ambient conditions. BMW claims that heating losses may be reduced by 50% when using a heat pump.[9] Mitsubishi found that a heat pump may reduce electric heating power by 20%–60% at ambient temperatures of 0º–10º Celsius.[10]

MARKET PENETRATION AND TECHNOLOGY MATURITY TRENDS

For thermal technology to be considered as a commercial alternative, it must be mature and have a sufficient market penetration rate. The ITB Group assessed 33 of the selected technologies that were used in the ruling by the agencies using proprietary data from The ITB Group's thermal management and powertrain fluid control reports. Note that technical maturity ratings do not imply high market penetration rates. Penetration rates are highly dependent on perceived value and component and application development costs.

The 2020–2025 market penetration[11] and technical maturity[12] trends were assessed by The ITB Group, using a ten-point scale[13] with higher values representing higher maturity or market penetration. Estimates of market penetration and maturity of 33 thermal technologies are shown in table 7.

HIGH VALUE THERMAL MANAGEMENT IMPROVEMENTS BEING COMMERCIALIZED

The development status of thermal technologies is an important factor when considering technologies which will be deployed before 2025. In order to generate an accurate representation of a particular technology, each of the 33 technologies was independently rated based on five characteristics: effectiveness, availability, market penetration, long-term cost viability, and technical maturity.

These five factors were evaluated on a ten-point scale for each of the 33 technologies, where 10 is the highest or strongest feature value. In order to rank the thermal technologies against each other, an overall non-weighted average rating was developed. Those that had an overall rating higher than a 7 are included in table 8. These technologies are anticipated to achieve high penetrations or become standard on certain vehicle models by 2025.

Table 8 Overall Commercial and Technical Rating of Thermal Technologies

Thermal Management Technology	Overall Rating	Cost-Value Rating*
Active Grille Shutters	8.8	Very High
Variable Engine Oil Pump	8.4	Very High
Active Transmission Warm-Up	8.0	High
Intelligent Cooling System	8.0	High
Integrated Liquid Cooled Exhaust/EGR	8.0	Very High
Aero Drag (10%)	8.0	High
Passive Cabin Ventilation	7.8	High
Active Seat Ventilation	7.6	Low
EGR Cooling (HP)	7.6	Moderate
Low-E/IRR/PVB Glazing	7.6	Low
Turbo-Cooling + Transthermal	7.6	Low
Engine Thermal Mass Reduction	7.4	Very High
Coolant Heat Storage Tank	7.2	Low
Reduced HVAC System Loading	7.2	High
Active Aerodynamics	7.0	Low
EGR Cooling (HP+LP)	7.0	Moderate

* From Table 6

8 Barnitt, Robb A., Aaron D. Brooker, Laurie Ramroth, John Rugh, and Kandler A. Smith, Proceedings of the 25th World Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition, China, Shenzhen (Nov. 2010).

9 BMW "BMW Group Innovation Day 2012: Efficient Dynamics," 2012.

10 Kondo, Toshihisa, Akira K ma, Hideki Suetake, and Masatoshi Morishita. "Development of Automotive Air-Conditioning Systems by Heat Pump Technology," *Mitsubishi Heavy Industries Technical Review* 48.2 (2011): 27–32.

11 Market penetration scaling definition: 1- Demonstrated by 2025; 3- Niche applications; 5- Available, but not widespread (≥ 5% of market); 7- Mass market availability (≥ 10% of market); 10- Widespread (≥ 25% of market).

12 Technical maturity scaling definition: 1- University Research Laboratory; 3- Technology available, but not in all vehicles; 4- First prototype in vehicles; 6- In fleet trials; 7- First entry into market; 10- Predominant technology

13 Ricardo and Systems Research and Applications Corporation (SRA), "Project Report: Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe," RD.10/157405.8 (2011).

THERMAL TECHNOLOGIES BEYOND THE 2025 RULING

Not all thermal management technologies are anticipated to achieve high penetration by 2025. These technologies are still being developed for their potential cost benefits. Some technologies are not implemented or researched as thoroughly by OEMs because the OEMs have limited resources and shorter term priorities to reduce their CO_2 percentage and fuel consumption by choosing more mature and cost effective alternatives.

Some of these technologies, such as using Rankine Cycle devices to generate electricity from exhaust heat, were not considered in the original ruling by the agencies due to a high cost ratio and an immature product development status. Others have a high implementation cost and therefore low value. Further research is needed on these technologies to decrease their cost and increase their technical maturity rating. Should this happen, then they may have higher market penetration rates in later years.

BARRIERS TO COMMERCIALIZATION

The cost side of the value equation is arguably more important than the performance of a given technology. OEMs and suppliers must deliver value to customers, and, for a given technology, cost must be minimized in order to maximize technology value. A major impact on cost and commercialization success is the ability of the OEMs to engineer new and modified powertrains faster and with performance that meets the expectations of consumers. With the wide range of thermal technology options available, companies must select specific sets of technologies to develop first. In this regard, the industry has been taking tremendous strides in developing suitable methodologies for systems development.

The move to new technologies like thermal management advancements puts further emphasis on engineering to meet the durability requirements of new technologies, as well as cost requirements. A central organizational and technical challenge for thermal management development is software and algorithm development. Honeywell Controls claims that for the transportation industry, lines of control software are increasing by a factor of 10 every eight years.[14] This means that by 2020, software development costs are expected to exceed hardware development costs.

This shift toward software and electronic controls is a tremendous opportunity but also a significant organizational barrier. Currently, OEMs and suppliers have resource constraints for certain technologies, including software, which may limit development scope and time. Model based software developments are being implemented to reduce development time and cost.

CONSUMER IMPACTS

Consumers directly benefit from advances in thermal management. By redefining the hardware and software in vehicles, automakers will be able to make vehicles more efficient and therefore meet consumers' increasing fuel economy expectations. A vehicle's fuel efficiency is one of the distinguishing characteristics that the average consumer uses in their vehicle purchase decision making process. Fuel efficiency is not the singular driver during the purchase process. Lower fuel prices have a reduced financial benefit for consumers. As a result in the United States, hybrid vehicle sales have fallen 20% from their 2013 peak.[15] If fuel prices increase in the future, then thermal management will have a greater consumer benefit.

With the introduction of new and more efficient powertrains, waste heat is reduced. This reduction places more emphasis on maintaining passenger thermal comfort. As waste heat is reduced, heat must be used more efficiently or supplemented by electric heating devices to meet passenger comfort requirements, particularly in cold ambient conditions. Note that some powertrain technologies like rapid powertrain warm-up also provide passenger comfort benefits. Thus, a mature technology like solar glazing, for example, may be deployed on more conventional vehicles beyond highly electrified vehicles where solar glazing is becoming a standard. Actual deployment will depend on cost vs. value relationships for various thermal technologies.

A focus on passenger comfort concerns is particularly important for hybrid, plug-in hybrid, or battery electric vehicles. This focus includes direct measures addressing time to comfort, heat, or cool a vehicle at start-up. Some conventional and electrified vehicles have limited heating or cooling power which may be noticed by the customer.

14 Tariq Samad and Greg Stewart, "Systems Engineering and Innovation in Control- An Industry Perspective and an Application to Automotive Powertrains," University of Maryland Model-Based Systems Engineering Colloquia Series (28 October 2013).

15 Alternative Fuels Data Center, "US HEV Sales by Model," digital image, accessed Jan. 2016, http://www.afdc.energy.gov/data/10301.

Another big consumer challenge for electric vehicles is range variability due to high energy consumption of HVAC systems in cold ambient temperatures. Range can be reduced by up to 50% in very cold or very hot temperatures. Therefore, the passenger comfort thermal technologies that may have a lower overall CO_2 impact can provide high customer value. Examples of these technologies include high levels of cabin air recirculation and heat pumps.

Not only will consumers be able to see an impact on thermal technologies in the hybrid, plug-in hybrid, and battery electric vehicles, but they will also be able to see an impact in the traditional powertrain vehicles as well. Through technologies such as thermal glass and solar reflective paint, occupants will be able to enter a vehicle without experiencing as significant of a temperature differential. Additionally, with the active cabin ventilation features, the vehicle's internal temperatures will become more regulated allowing for more comfortable and agreeable driving conditions. Furthermore, improved passenger comfort technologies also improve fuel economy by lowering HVAC energy usage.

POTENTIAL OVERALL CONTRIBUTIONS

A study using a prototype Jaguar Land Rover (JLR) vehicle[16] highlights the potential contribution of thermal management technologies. The vehicle was constructed and tested by Ricardo in partnership with JLR, Valeo, SKF and others. The goal of this project was to demonstrate a 30 percent reduction in CO_2 for a large diesel vehicle. Some constraints for the project included achieving the results using proven technologies and without powertrain hybridization. Specific technologies were selected to give high performance at the lowest cost. When tested on the European NEDC cycle, the vehicle showed a 32.5 percent reduction in CO_2 emissions. The powertrain techniques used included turbo- and super-charging, low pressure EGR, and a start-stop system.

The thermal management coolant related technologies, including an advanced thermostat and coolant heat recovery system, contributed a 7.5 percent reduction in CO_2 emissions on this vehicle, which accounted for 23 percent of the total CO_2 reduction. Interestingly, simulation models predicted a 4.7 percent reduction in CO_2 due to thermal management, while actual vehicle tests showed 60 percent higher CO_2 reduction than expected. Additionally, engine oil related thermal effects due to low friction lubricants and a variable engine oil pump contributed to further thermal related improvements.

According to Ricardo in 2011, waste heat recovery encompasses a number of technologies such as turbo-charging and thermoelectric devices. For the 2017–2025 rule, the agencies defined waste heat recovery as "a system that captures heat that would otherwise be lost through the engine, exhaust system, or the radiator or other sources and converting that heat to electrical energy that is used to meet the electrical requirements of the vehicle or used to augment the warming of other load reduction technologies." The agencies further mentioned that this did include cabin warming, active engine or transmission warm-up technologies. Ricardo 2011 evaluated the system as having a lower market penetration and maturity, but it fell in the midrange for availability and long-term cost viability.

QUALITATIVE ASSESSMENT OF OEM STRATEGIES

As shown in The ITB Group's 2015 thermal report, there are significant differences in thermal management between OEMs worldwide. Japanese OEMs were the initial leaders in electrified vehicles and certain supporting thermal management technologies, whereas certain European and North American OEMs have produced market leading electrified vehicles and powertrain related thermal management techniques (e.g. BMW, Tesla, GM) with many more OEMs growing in this field (e.g. VW, Daimler, etc.).

As a direct result of the evolution of hybrid vehicle designs, supporting technologies like power electronics and battery thermal management have evolved considerably. Further, these electrified vehicle designs have also driven significant improvements in passenger comfort technologies since passenger cabin losses have become relatively more important for highly efficient electrified vehicles. The sheer magnitude, in terms of component volume and research and development investments over the past 20 years have resulted in Toyota's technical, volume, and cost leadership in many thermal management areas such as electric pumps and exhaust heat recirculation.[17]

In general it has been found that Europe is leading by several years in implementing many thermal and vehicular fuel

16 John Challen, "Emissions Statement," *Ricardo Quarterly Review* Q4 2013: 16–20.

17 Ricardo and Systems Research and Applications Corporation, "Computer Simulation of Light-Duty Vehicle Technologies" (n. 13 above).

consumption reduction technologies. This is presumably because of higher fuel costs and the challenging regulatory regime in Europe. Particularly for diesel powertrains and start-stop conventional vehicles, European companies have a significant experiential advantage. These technologies include EGR cooling, variable mechanical devices, and electrified mechatronic accessories. Electric water pumps have been in use at BMW for many years and smart thermal management valve systems are also notable areas of leadership by European companies. It is important to note that BMW has been shifting away from main electric water pumps toward higher value variable mechanical water pumps in combination with advanced coolant control thermostatic valves and auxiliary electric pumps.

North American OEMs have been followers in the application of advanced thermal management technologies. This may be due in part to the relatively low price of fuel in the United States, however sensitivity to fuel price is considerably higher today than before the Great Recession. North American manufacturers are also quite sensitive to component costs. As a result, advancements in the North American market are often introduced after designs are refined and costs are reduced. Automakers in North America are currently deploying the highest value thermal technologies and will develop lower value technologies over time. In all cases, engineering efforts are being made to reduce technology costs through systems development and integration, which improves value.

Fuel cell vehicles are also a development platform for OEMs and suppliers. Leaders include Toyota, Honda and Hyundai. Thermal management is also an important consideration for fuel cell vehicles due to their high efficiency and limited waste heat. The Toyota Mirai design incorporates five heat exchangers for thermal management at the front of the vehicle. Passenger cabin thermal management is an important consideration to maximize vehicle range and minimize range variability in fuel cell and plug-in vehicles.

In order to meet the many future challenges of developing powertrains for the automotive market it will be important for both OEMs and suppliers to have effective global development capabilities. This global capability will need to encompass regionally integrated centers and the ability to launch models simultaneously around the world. It will be paramount to have standardized global processes enhanced by a global purchasing base. Not only will the OEMs need to manage higher levels of regional complexity, they will need to bring in improved levels of system and software engineering.

For many OEMs this is not proving to be an easy task where different groups within the OEM's engineering groups, even at the same site, need to work together. Finding suitable platforms to introduce new integrated systems is often a complex task. Passenger compartment and powertrain thermal management integration is one such example where inter-departmental engineering is required but proves difficult to implement at the OEM level. Furthermore, organizational challenges become even greater when the OEM must work closely with engineers at Tier One suppliers to commercialize complex thermal management system innovations.

This assessment supports the notion that there is a wide range of thermal management and other vehicle technologies being developed to help vehicles meet future regulatory requirements. The key open question is cost of the technologies. Extensive effort is being expended throughout the value chain to reduce cost of thermal as well as other conventional and electrified vehicle CO_2 reduction technologies.

SUMMARY

Thermal management techniques are critical for the robust and efficient performance of conventional and electrified vehicles. In the past decade there has been a proliferation of thermal management technological solutions. As a result, automotive suppliers have been developing new products like electric pumps and coolant control valves. At the same time, lower cost variable mechanical solutions are being developed, which can offer benefits over electrified devices depending upon the application.

This paper expanded the thermal management methods beyond those included in the 2017–2025 rulemaking. These technologies include, but are not limited to, active engine warm-up, active seat ventilation, cooled exhaust-gas recirculation (EGR), and friction reduction.[18] Analyses for this report considered qualitative and quantitative factors, which are driving the application of thermal management advances.

Thermal management systems not only support reduction of emissions in absolute terms, but also contribute to reducing emissions variability for different driving conditions. Thermal management can contribute on the order of 2% to 7.5% reductions in fuel consumption over the

18 2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards; Final Rule, 77 Federal Register 199 (15 October 2012), pp. 62623–63200.

next ten years depending on a vehicle powertrain's base thermal management features.

There has also been an improvement with regards to off-cycle emissions credits. In the 2017–2025 final ruling, the "EPA has been encouraged by automakers' interest in off-cycle credits since the program was finalized for the MYs 2012–2016 GHG program and concluded that extending the program to MY 2017 and beyond may continue to encourage automakers to invest in off-cycle technologies that could have the benefit of realized additional reduction in the light-duty fleet over the longer-term."

A central factor in the application of individual or sets of thermal technologies is the value in terms of fuel consumption (or CO_2) reduction versus the change in cost for a technological improvement. As illustrated in figure 3, this view is extremely important because automakers are striving to apply the highest value and most mature technologies first.

APPENDIX: GLOSSARY OF THERMAL TECHNOLOGIES

Thermal Technology	Definition
Active Cabin Ventilation (High Recirculation)	Active control of cabin ventilation and recirculation, particularly to minimize thermal increases during vehicle soaking.
Active Grille Shutters	Mechanically actuated flaps that control radiator airflow and reduce drag.
Adaptive Cabin Temp Control (IR Sensor)	Temperature control using an infrared sensor to better regulate occupant temperature.
Cabin Exhaust Heat Exchanger (Active)	Recapture of waste thermal energy from the passenger cabin.
Cold Storage Accumulator	Device which typically uses a phase change material in conjunction with the evaporator to store thermal energy to keep the cabin cool for a period of time.
Coolant Heat Storage Tank	Device which stores coolant thermal heat energy for rapid powertrain and passenger cabin warm-up.
Differential Heating at Start-Up	Techniques to more rapidly warm the differential.
Dual Level (HT/LT) CAC	Charge air cooling (CAC) device utilizing higher- and lower-temperature control circuits.
Dynamic Engine Thermal Control	Adjusting engine control temperature dynamically based on operating conditions like powertrain load.
EGR Cooling (HP+LP)	Combustion concept that involves utilizing cooled exhaust gas as a charge diluent for controlling combustion temperatures prior to its introduction to the combustion system. A dual-loop system incorporates high and low pressure EGR loops and dual EGR coolers.
EGR Cooling HP	A more advanced version of a cooled-EGR system that employs high combustion pressures.
Ejector Cycle	A device which uses energy otherwise wasted by an A/C expansion valve improving cycle efficiency.
Electric Engine Oil Pump	Engine oil pump driven by an electric motor.
Electric Water Pump	Vehicle coolant pump driven by an electric motor.
Encapsulated Engine Compartment	Reducing thermal flux for the powertrain through insulated panels to reduce heat losses and foster rapid warm-up.
Engine Oil Heating at Start-Up	Technology to rapidly warm engine oil through heat exchange and/or reduced oil flow.
Engine Thermal Mass Reduction	A variety of techniques ranging from improved design and better component integration to application of lighter and higher-strength materials.
Exhaust Heat Recirculation	Capturing exhaust heat in the coolant which would otherwise be lost in the engine exhaust.
Exhaust Heat to Engine Oil	Capturing heat in engine oil which would otherwise be lost in the engine exhaust.
Exhaust Heat Turbo Generator	Using exhaust gas to mechanically generate electricity.
Focused IR Heating	Using an infrared device to directly heat occupants through radiation rather than air conduction/convection.
Heat Pump (XEV)	A device capturing heat from the atmosphere or other sources to heat the passenger cabin.
Heat Storage Accumulator	A device typically using phase change material to capture waste heat for redeployment to the powertrain or passenger cabin when necessary.
Higher Conductivity Coolant	Techniques used to raise the coolant fluid conductivity for improved heat exchange efficiency.
HV PTC Heating	PTC (positive temperature coefficient) heating using high voltage ("HV",>12V) for improved electric energy conversion efficiency.

Thermal Technology	Definition
Insulated Auto/CVT/DCT Transmission	Technique to retain otherwise lost heat from the transmission for better efficiency.
Insulated Coolant	Techniques to retain otherwise lost heat in the coolant system.
Insulated Differential	Technique to retain otherwise lost heat from the differential for better efficiency.
Insulated Oil pan	Technique to retain otherwise lost heat from an engine oil pan for better efficiency.
Insulated Passenger Cabin	Techniques to retain otherwise lost thermal energy from the passenger cabin.
Insulated Roof	Technique to retain otherwise lost thermal energy from the passenger cabin roof.
Integrated Liquid Cooled Exhaust/EGR	Cooling exhaust/EGR using coolant in a tightly coupled exhaust manifold design.
Integrated Localized HVAC	Techniques to provide localized passenger comfort including seats and other surfaces.
Liquid Cooled CAC	Charge air cooling device utilizing a liquid charge-air heat exchanger.
Liquid Cooled CAC + condenser	Cooling system employing a liquid charge-air heat exchanger and liquid cooled A/C condenser.
Liquid Cooled Condenser	A/C condenser cooling device utilizing a liquid to refrigerant heat exchanger.
Low-E/IRR/PVB Glazing	Automotive glass incorporating solar reflective or absorbing features to reduce passenger cabin thermal effects which require higher cooling energy usage.
Lower Heat Transfer Glazing (PC)	Automotive glass designed to reduce thermal conduction through the glass (polycar-bonate, PC).
Map Controlled Thermostat	Thermostat for controlling engine coolant temperature based on vehicle operating conditions and loading (engine map).
Model vs. Map Based Algorithms	Model based algorithms for thermal system control which can be more dynamic than map-based approaches.
Navigation Based Prediction	Predictive thermal management control based on GPS geographic positioning and traffic data.
Passive Cabin Ventilation	Passive mechanism allowing heat transfer to continue even after the engine and HVAC system have shut off in order to maintain an ambient temperature in the cabin.
Polymer Material Heat Exchangers	Heat exchange devices using high conductivity polymer rather than higher conductivity metals.
Powertrain Pre-conditioning	Actively pre-warming the powertrain in soaking conditions.
Predictive Powertrain Control	Predictive thermal management control based on vehicle operating conditions.
Pre-Heated Coolant	Coolant heating prior to powertrain start-up.
Rankine Cycle (Turbo Steamer)	Using waste exhaust heat to generate electricity.
Reduced Oil Sump Mass by 20%	Reduced engine oil capacity.
Smart Multi-Way Water Valve	Electronically controlled multi-way coolant valve for finer fluid control and faster powertrain and cabin warm-up.
Smart Valve with Integrated EWP	Electronically controlled multi-way coolant valve with integrated electric water pump (EWP).
Solar Panels	External installation of horizontally-oriented panels with direct and unimpeded solar exposure that is used to provide energy to an electric drive system.
Solar Reflective Paint	Vehicle paint or other surface coating which reflects at least 65% of the infrared solar energy. Must be applied at a minimum to all the approximately horizontal surfaces of the vehicle that border the passenger and luggage compartments of the vehicle.
Split Engine Cooling	Engine cooling system using separate head and block thermal control circuits.
Thermal Storage (PCM)	Device which stores thermal heat energy in a phase change material (PCM) for rapid powertrain and passenger cabin warm-up.

Thermal Technology	Definition
Thermoelectric Capture and Generation (TEG)	Utilization of exhaust heat to generate electricity using a thermoelectric device.
Transmission Dynamic Thermal Control	Dynamic control of transmission operating temperature based on vehicle operating conditions.
Transmission Rapid Warm-Up	Technique for rapidly warming a vehicle's transmission.
Turbo Cooling + Trans Thermal	Capture of heat from the turbocharger housing in conjunction with rapid transmission warm-up.
Variable Engine Oil Pump	Variable mechanical engine oil pump to better match pump flow with engine requirement.
Variable Water Pump (Clutched)	Variable mechanical coolant pump using a clutch device.
Variable Water Pump (Switchable)	Variable mechanical coolant pump using a switchable element.
Ventilated Seats (Heating + Cooling)	Passenger seats incorporating a fan for ventilating the surfaces.
Windshield Electric Defrost	Windshield incorporating an electric heating device for defrosting.