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Automotive Thermal Management Technology

As automakers develop new technologies to improve vehicle and drivetrain efficiency, heat losses are a rising concern. Better thermal management can enhance the efficiency of conventional power trains and reduce energy losses for warming or cooling the passenger cabin. In electrified vehicles, these technologies play a magnified role in extending vehicle range while ensuring passenger comfort.

In conventional internal combustion power trains, thermal management technologies include advanced engine and transmission lubrication (to reduce heat generated by friction), reduced heat loss electrical systems, and hardware and software designed to regulate engine and transmission temperature. In passenger cabins, thermal management steps include improvements in heating, ventilation, and air-conditioning (HVAC), and glass designed to minimize heat transfer, among others.

In the past decade, there has been a proliferation of new devices to control heat and reduce energy losses. More than 60 thermal management technologies are currently in production or development. This heightened pace of development is expected to continue for the next 10 years under regulatory pressure to reduce fuel consumption and carbon dioxide emissions. Federal regulators did not specifically address most of these technologies in baseline and projected future vehicles when developing emissions and fuel-efficiency standards for 2017–2025.

Thermal management systems in conventional power trains are targeted primarily at improving efficiency, thus their primary evaluation metric is their effect on fuel consumption compared with cost. Thermal efficiency gains in the passenger compartments of conventional vehicles will mostly manifest as improved customer satisfaction and marketability. For electrified vehicles, the calculus is different. The primary value comes from extended battery range and reductions in size, mass, and cost of the battery pack, whether in the power train or in the passenger cabin.

As shown in figure 1, more than half of the 60-odd new thermal-management systems are projected to cost less than $50 for each 1% reduction in fuel consumption. Passenger cabin technologies tend to cost more, but

ABOUT THIS SERIES Under efficiency standards adopted in 2012, the U.S. passenger vehicle fleet must achieve an average fuel economy of 49.1 miles per gallon in 2025, or 54.5 mpg as measured in terms of carbon dioxide emissions with various credits for additional climate benefits factored in. While the fleet-average targets may change—the regulation provides for recalculating the fuel economy targets annually based on the mix of cars, pickups, and SUVs actually sold—they will still represent an average energy-efficiency improvement of 4.1% per year.

Automakers have responded by developing fuel-saving technologies even more rapidly and at lower cost than the U.S. EPA and NHTSA projected in 2011–2012, when the supporting analyses for the 2017–2025 rule were developed. In particular, innovations in conventional (as opposed to hybrid or electric) power trains and vehicle body design are significantly outpacing initial expectations. These technical briefs highlight the most important innovations and trends in those conventional automotive technologies.

For other papers in this series, as well as the more detailed technology surveys on which these briefs are based, go to www.theicct.org/series/us-passenger-vehicle-technology-trends.

This publication series is generously funded by the Heising-Simons Family.

their primary benefit is in customer comfort, which adds additional value beyond the fuel savings. Thermal management gains can yield declines in fuel consumption on the order of 2% to 7.5% over the next 10 years, depending on a power train's base thermal-management features.[1]

REGULATORY ENVIRONMENT

In preparation for the initial rulemaking on greenhouse-gas emissions for 2017–2025 vehicle models, the Environmental Protection Agency and the National Highway Traffic Safety Administration extensively investigated the cost and fuel-consumption impact of various technologies. Some of the technologies that didn't figure significantly in test-cycle results were found to deliver real-world improvements under conditions not covered by the test cycles.

As part of the rulemaking, regulators developed processes to grant off-cycle credits for technologies that provide benefits beyond those measured by federal test cycles. A large portion of these technologies are related to thermal management. Those rated by auto suppliers as delivering moderate to very high value (costing less than \$100 per 1% reduction in fuel usage) include waste heat recovery, solar reflective paint, passive or active cabin ventilation, active engine and transmission warm-up, and active aerodynamics.[2]

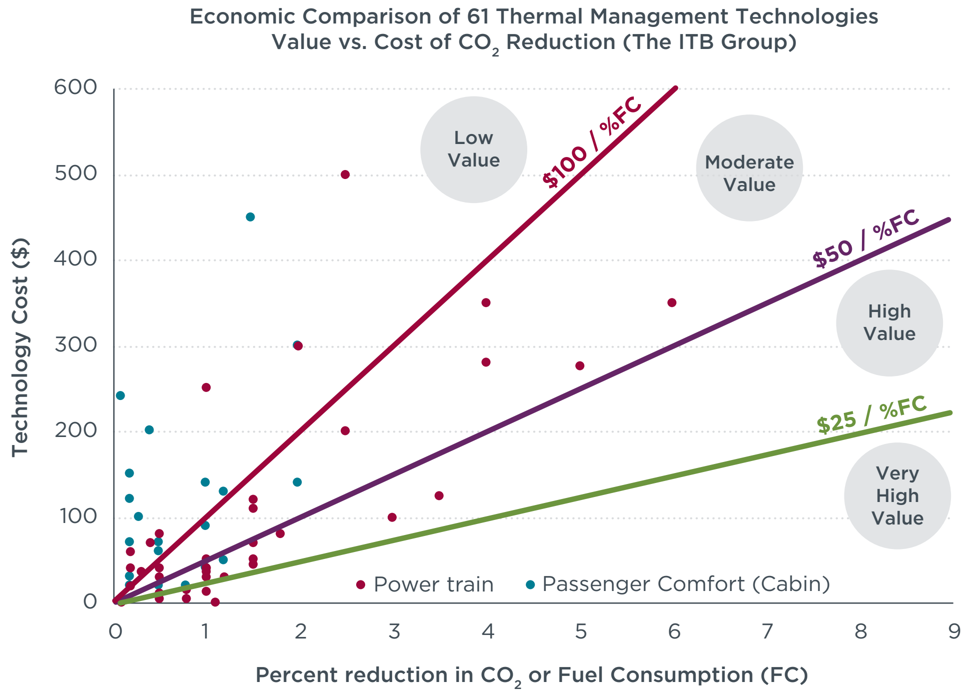

Figure 1 Economic comparison of thermal management technologies.

Some thermal-management technologies have both on-cycle and off-cycle benefits. These include intelligent coolant pumps, electric coolant control valves, transmission oil bypass valves, exhaust heat recovery systems, and thermoelectric generators.

POWER TRAIN TECHNOLOGIES

Figure 2 presents the value of 13 vehicle and power train technologies that were incorporated into the 2017–2025 rulemaking. The cost for each 1% reduction in CO_2 varies widely, with the cost of vehicle architectures such as strong hybrids, advanced diesel, and 48V hybrid vehicles close to \$100 for each 1% reduction in CO_2. Other conventional power train technologies provide higher value, with costs below \$50 or even \$25 for each 1% CO_2 reduction, although the amounts of reduction they provide are smaller. Automakers combine technology sets into packages to achieve targeted improvement goals, and the automotive value chain is focused on finding the lowest overall cost.

Power train-related thermal technologies as a group generally fall in the high and very-high value categories, as shown in figure 1 (the red dots). The figure represents the value in conventional power train vehicles of more than 60 thermal management technologies identified as potentially beneficial. The benefits include both on-cycle and off-cycle improvements. Some of these technologies are low-cost, such as software algorithm improvements. Others, such as Rankine-cycle devices and thermoelectric exhaust-heat recovery systems, are not likely to be available by 2025 because of high costs, but continued development will lower prices and make them commercially more viable.

In general, European automakers are ahead by several years in implementing thermal and fuel-consumption reduction technologies, perhaps because of higher fuel costs in Europe than in the United

1 Sean Osborne, Dr. Joel Kopinsky, Sarah Norton, Andy Sutherland, David Lancaster, Erika Nielsen, Aaron Isenstadt, John German, *Automotive Thermal Management Technology* (ICCT: Washington DC, 2016). http://www.theicct.org/automotive-thermal-management-technology

2 One example of active aerodynamics is grille shutters that open and close to manage air flow based on power train thermal conditions, thus reducing vehicle drag at higher vehicle speeds.

States. These technologies include exhaust-gas recirculation (EGR) cooling, variable mechanical devices, and replacement of mechanical with electric pumps and accessories. For example, electric water pumps have been in use at BMW for many years, and European companies lead in the use of smart thermal management valve systems.

As a direct result of the evolution of hybrid vehicles, supporting technologies like power electronics and battery thermal management have also evolved considerably. The sheer magnitude of component production and research and development investments over the past 20 years has resulted in Toyota's technical, volume, and cost leadership in many thermal management areas such as electric pumps and exhaust heat recirculation.

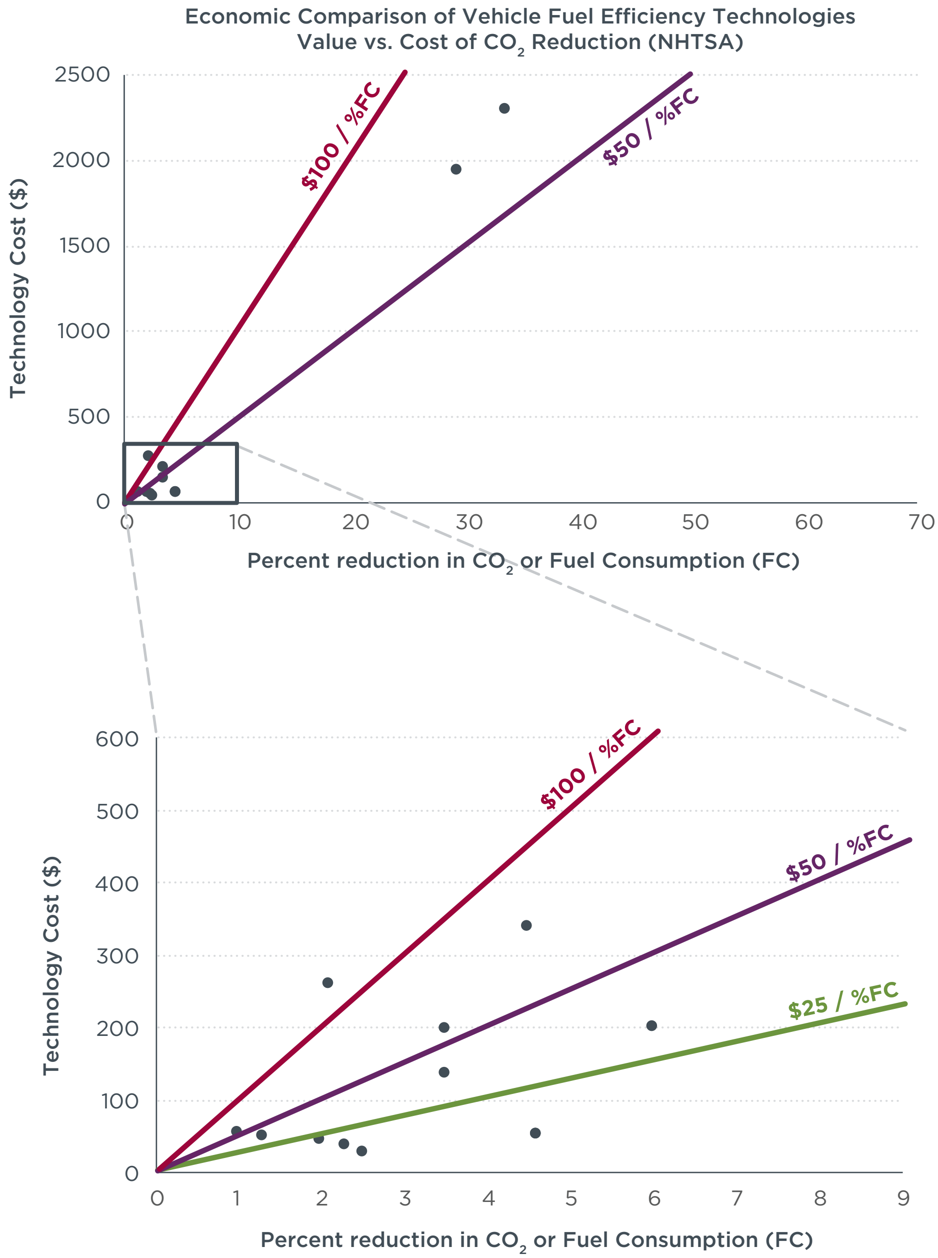

Figure 2 Economic comparison of vehicle and power train fuel efficiency technology value vs. cost of CO_2 reduction (NHTSA)

PASSENGER COMFORT TECHNOLOGIES

Passenger comfort technologies (figure 1, blue dots) tend to show lower values than those related to power train in conventional vehicles. For example, cabin thermal technologies primarily affect HVAC energy losses, which are relatively smaller than power train losses, resulting in smaller fuel consumption reductions. However, the primary value to the consumer is improved comfort, which is not included in the simple cost per 1% reduction in CO_2. Most of the HVAC solutions offer fuel efficiency gains as a side effect to these consumer benefits. However, as vehicles become more efficient, the thermal importance of passenger comfort systems increases. For example, conventional vehicles with start-stop systems (including hybrids) may soon benefit from supplementary cabin heating. Since passenger comfort technologies primarily provide other consumer benefits, they probably will not come into the fleet exclusively to improve fuel economy, at least on conventional vehicles.

ELECTRIFIED VEHICLES

Electric vehicles achieve their range in part because of the efficiency of their propulsion system. For a given amount of energy, an electric vehicle can travel three to four times farther than a vehicle with a conventional power train. But this advantage does not apply to heating or cooling the passenger compartment. HVAC efficiency is similar on electric and conventional vehicles, so the energy needed to power the air-conditioning system relative to powering the vehicle is about three times higher on an electric vehicle. Heating the passenger cabin is even worse, because for that conventional vehicles use virtually free energy—the waste heat from the engine cooling system. Heating with electricity is much less efficient than the electric propulsion motor.

This is a crucial consideration for battery-powered driving range. In some situations, the amount of energy required to propel a vehicle may be equivalent to what's needed to condition the passenger compartment. For example, thermal comfort and dehumidification requirements in very hot or cold conditions may exceed city driving power of about 3kW. As a result, vehicle range may fall by 50% or more for extremely cold trips. A study by the U.S. National Renewable Energy Laboratory found that conventional HVAC technologies typically reduce plug-in vehicle range by 20%–30%.

To address this problem, engineers are developing other technologies to reduce passenger-cabin thermal losses. These include solar glazing—glass designed to minimize heat transfer—and high fractional recirculation HVAC systems, in which a large portion of air is recirculated. Technologies such as heated steering wheels and heated or cooled seats may more directly improve passenger comfort and reduce energy consumption by heating or cooling only where it is directly needed.

Some automakers are deploying heat pumps on plug-in vehicles because they can significantly improve vehicle range by reducing HVAC losses in low-temperature conditions. BMW says a heat pump can reduce heating losses by 50%. Mitsubishi found that a heat pump could reduce electric heating power by 20%–60% at ambient temperatures of 0°–10° Celsius.

IMPLICATIONS FOR MIDTERM EVALUATION

Technologies for thermal management have multiplied far beyond those included in the government's 2017–2025 rulemaking. These technologies include active engine warm-up, active seat ventilation, cooled exhaust-gas recirculation, and friction reduction. Automakers are already incorporating thermal-management technologies in a significant share of new vehicles. For example, a high percentage of BMW autos have active cabin ventilation (85%) and active engine warm-up (79%). Fiat Chrysler Automotive focuses on passive cabin ventilation and glazing technologies as well as active engine warm-up. Active seat ventilation has become a common technology, with penetration as high as 63% for Jaguar Land Rover (JLR). Thermal managing glass is already on 51% of the U.S. new-vehicle fleet.

A study using a prototype JLR vehicle highlights the potential of thermal management technologies. The project set out to demonstrate a 30% reduction in CO_2 for a large diesel vehicle using proven technologies without power train hybridization. When tested on the European NEDC cycle, the vehicle showed a 32.5% reduction in CO_2 emissions. Thermal management-related technologies, including an advanced thermostat and coolant heat recovery system, contributed a 7.5% CO_2 reduction, amounting to almost a quarter of the total reduction. This substantially beat the projected thermal management savings of 4.7% based on simulations.

Thermal management systems not only support reduction of emissions in absolute terms, but they also contribute to reducing emissions variability for different driving conditions. Enhanced thermal management can contribute 2% to 7.5% reductions in fuel consumption over the next 10 years, depending on a vehicle power train's base thermal management features. As automakers push the limits of obtaining economies from other technologies, the potential incremental contributions of thermal management systems become more significant.