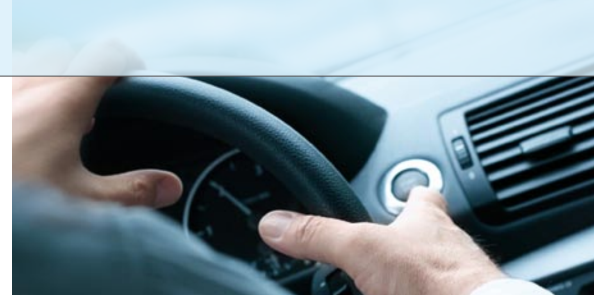
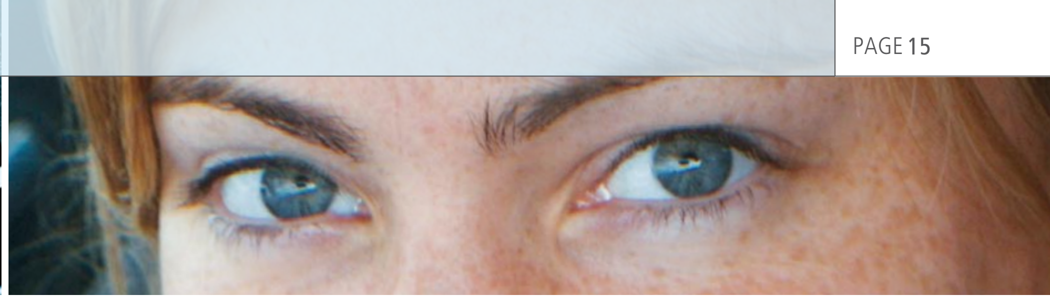


Looking forward

Predictive thermal management optimizes efficiency and dynamics



Mobility in Transition

Mobility as we know it today will not stay this way for ever. Under threat from the world's increasing energy requirements, limited fossil fuel resources, political crises and uncertain energy prices, mobility will undergo changes in the medium term. Legislators all over the world have responded with measures to limit fuel consumption and reduce CO_2 emissions. More than 90% of the world market is already subject to regulations on fuel consumption and CO_2. The legislation was not formulated and passed down to the last detail yet, but the general direction is clear: Over the next 10 years, car makers will have to reduce fuel consumption and CO_2 emissions by a further 25 - 30%. Anyone failing to meet this objective will face paying severe fines or will be unable to obtain approval for their products.

New Approaches to Combustion Engines

These tough reduction targets cannot be reached by classic development of the engine alone. The BMW Group therefore began to systematically analyze every single physical actuator and assess their effects on the energy balance.
The combustion engine will continue to play the dominant role as the main power convertor in a vehicle and is therefore undergoing intensive further development.
One decisive factor will be to cut vehicles' fuel consumption in typical customer driving without losing the dynamics of a premium brand vehicle. One promising approach, and part of the BMW EfficientDynamics strategy, is to integrate predictive information on the road ahead, with speed and curve profiles, and also hills or gradients, etc., into the thermal management of a conventional combustion engine. A prototype produced by the BMW Group demonstrates the benefits of predictive thermal management.

Modern Vehicle Thermal Management

Modern cooling system controls have requirements-driven thermal management that unites efficiency, dynamics and comfort while at the same time ensuring thermal operating reliability. Electrifying the actuators in the cooling circuit (figure 1), combined with whole-vehicle control strategies (implementing the increased degrees of freedom in the controlled systems), is already enabling functionalities that go far beyond the original purpose of cooling:
The core function of BMW's thermal management is to select operating modes within the engine control functions. For example, after a cold start a warm-up mode is activated to bring the engine up to an efficient operating range quickly. Because the electric coolant pump is decoupled from the engine speed, this mode produces a static coolant to reduce heat transfer from the combustion chamber walls to the coolant and hence the engine warms up faster.

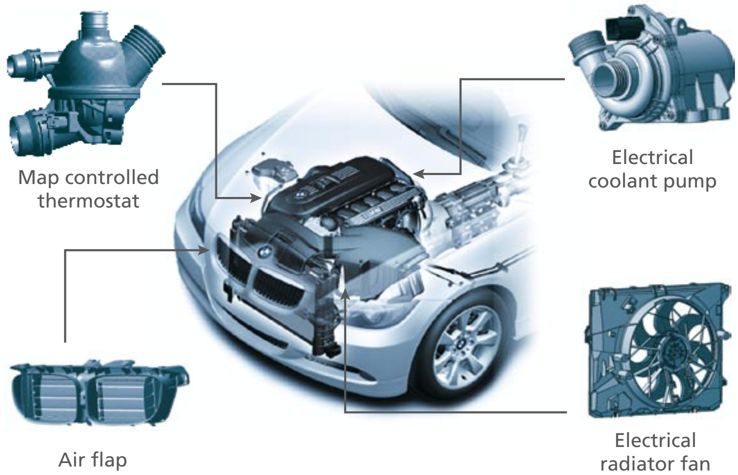


Figure 1: Electrified actuators in the cooling system (source: BMW, International Technical Training).

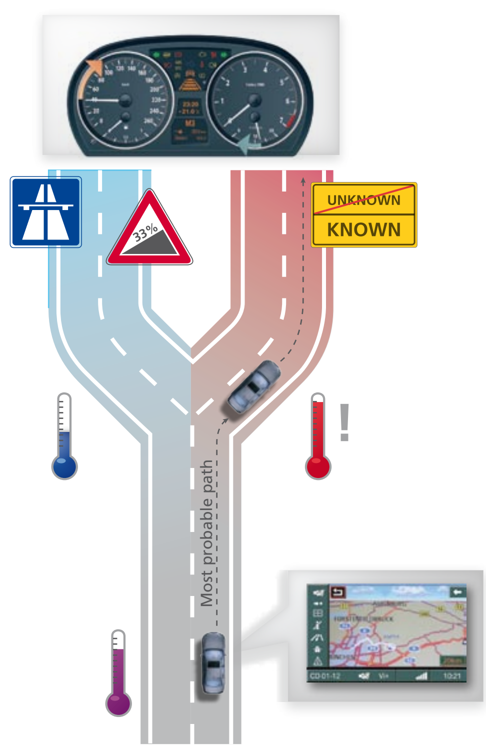
Situation-Dependent Control Strategies

When the warm-up phase has been completed, the engine control computes the coolant requirement in accordance with the driving situation. The conventional control strategy attempts to reconcile two conflicting objectives: It has to reduce the internal friction by increasing the engine and coolant temperatures, but at the same time it must not compromise the thermal reliability standards. The entire engine performance range is determined by the operational maps in combination with fixed thresholds. These influence the fluid temperature and cooling temperature, which in turn determine the cooling system operation modes for the conventional thermal management control. The associated cooling levels range from consumption-oriented operation (ECO operation) with considerably reduced cooling and higher coolant temperatures, to highly dynamic operation. This highly dynamic operation mode provides maximum cooling at significantly reduced coolant temperatures under high engine loads. Depending on the situation, the operating strategy currently used in production vehicles can result in unnecessary adjustment of the requested cooling power. This is especially evident, for example, at intersections in an urban environment, where the conventional thermal management system takes preventive measures to compensate for the additional heat gain caused by sudden acceleration. The energy required to reduce the coolant temperature is wasted in this case. Thermal reliability always has top priority in the control strategy because the current driving situation is primarily fed into the control system.

The Limits of a Situation-Driven Approach

The BMW Group evaluated test drives with respect to cooling system behavior and identified application cases for predictive control. Typical application cases are acceleration from a standstill at intersections, brief accelerations on country roads, or when the engine is turned off. Even with only a slightly dynamic driving style, these influences can cause conventional thermal management to leave ECO operation due to the conventional reactive control directly responding to the current driving situation. When the driver briefly hits the accelerator pedal, the cooling power rises so that the cooling temperature drops, even though this is not always necessary, for example, in an urban area.

Figure 2: Idea and approach of predictive thermal management: The engine and the cooling system are systematically preconditioned according to the most probable path. This example shows an uphill stretch of freeway with a low temperature and an urban driving situation with a high temperature.



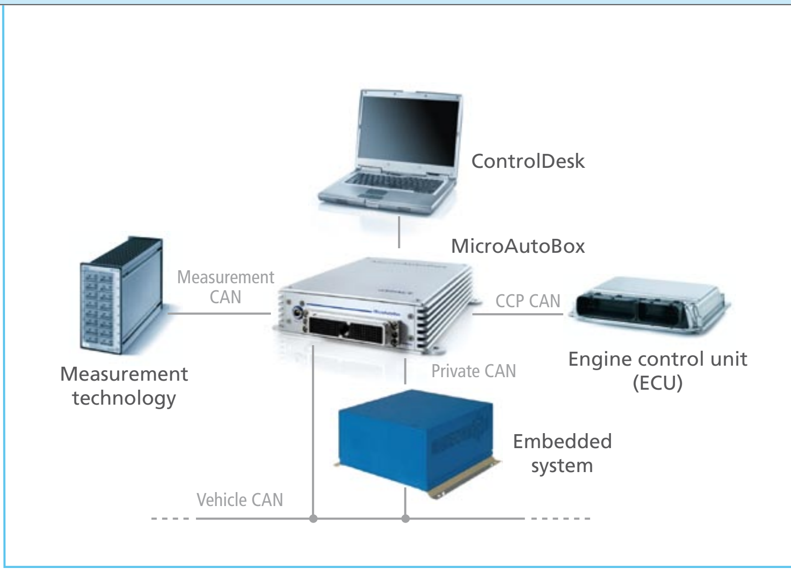


Figure 3: Hardware and communication structure in the experimental vehicle.

Predictive Operating Strategies

The analysis and evaluation of data on the road ahead is called the electronic horizon. Predictive thermal management uses the electronic horizon to intelligently prevent inherent inertia depending on the driving situation. The electronic horizon can also precondition the engine and the cooling system. The driving situation is further differentiated by using driver types ranging from steady to sporty (figure 2).
The required cooling power can be better estimated and regulated through predictive information, which is used to classify the acceleration with respect to duration and possible maximum end speed. In this case, maintaining ECO operation reduces fuel consumption. This helps to avoid a higher load on the actuators such as the electrical coolant pump. During the short acceleration action, the raised temperature level can be maintained without exceeding the limits of the cooling system.

Predictive Adjustments for Improved Dynamics

Predictive thermal management enables predictive adjustment of the cooling power and the engine temperature, so that the engine is preconditioned for upcoming higher performance requirements. These have a greater impact on cooling requirements in order to maintain optimum engine performance. The extent of predictive intervention can be selected according to the driver type and the type of transition between different driving situations. Predictive conditioning performed by thermal management has a positive effect on knock behavior, engine cylinder charging, etc. These can considerably enhance the dynamics of the vehicle, for example, when it is driven onto the freeway in a sporty manner.

Prototype Vehicle Setup

To verify the feasibility of the concept vehicle, the thermal management division within the BMW Group prepared a prototype based on a production BMW 335i for the application cases described above. The electronic horizon in the prototype vehicle was developed by BMW Forschung und Technik GmbH. The Intelligent Learning Navigation (iLeNa) project offers extended functionalities compared with current off-the-shelf navigation solutions. One of the extra functionalities is the learning application knowledge database, which can store the actually driven road profiles, for example, habitual speed patterns, and not only the official speed limits from a digital map. A destination and route estimator uses stored driving patterns to calculate the most probable path even if the driver has not activated the navigation system.
To determine the position and perform map matching, iLeNa accesses the vehicle's GPS antenna via the vehicle bus. An automotive-capable embedded system with an MS Windows operating system (figure 3)

Glossary

ADASIS – Advanced Driver Assistance Systems Interface Specification, ADASIS Forum on the Internet: www.ertico.com/en/activities/safemobility/adasis_forum.htm

ADAS RP – Advanced Driver Assistance Systems Research Platform. Development platform for map-based driver asistance systems from NAVTEQ.

BMW EfficientDynamics – A strategy used by the BMW Group to achieve what was previously thought to be unachievable: the reduction of fuel consumption and CO_2 emissions with a simultaneous increase in vehicle dynamics and engine power. Or to put it another way: Squeezing every last drop of fun out of every drop of fuel.

GPS – Global Positioning System is a global navigation satellite system for determining position and measuring time.

Map matching – Matching a found position to the geographical data on a digital map.

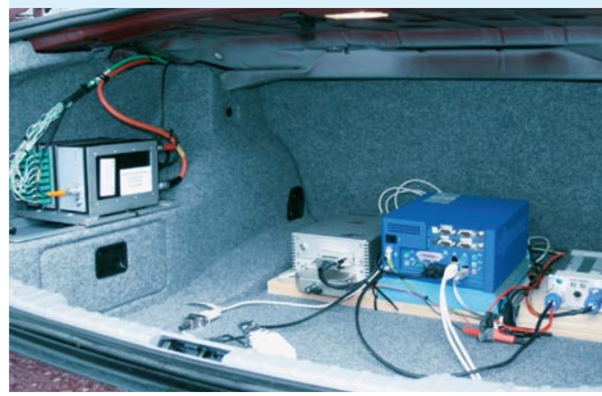


Figure 4: Hardware setup in the experimental vehicle: measurement devices, MicroAutoBox, embedded system, voltage supply (from left to right).

forms the hardware environment of the navigation platform. This is based on the NAVTEQ development environment for map-based driver assistance systems (ADAS RP).

Controller Structure and Function Logic

A CAN interface with the CAN Calibration Protocol (CCP) was installed between the BMW thermal management system partitioned on the engine control (DME) and the MicroAutoBox.

The controller structure and the function logic of the predictive thermal management system was designed with MATLAB®/Simulink®/Stateflow from The MathWorks® and implemented on a dSPACE MicroAutoBox in the vehicle (figure 4).

Existing measurement technology, such as for temperature and voltage capture, was easily integrated into the Simulink® model and coupled with the MicroAutoBox by reading in the appropriate DBC configuration file via the dSPACE RTI CAN Blockset.

Function Blocks of the Predictive Thermal Management

The predictive thermal management comprises several logical function blocks (figure 5). The Reconstructor is the interface to the iLeNa and processes the data packets sent via the CAN bus. The communication protocol used for this is an ADASIS protocol that has been adapted to BMW-specific requirements. Because the electronic horizon is transmitted cyclically to reduce the load on the vehicle bus, there is a memory block that functions as a buffer and an interface for thermal-management-specific situation evaluation. The profiles for the type (from the digital map) and the expected speed (from the iLeNa knowledge database) are filtered with respect to the situations described above and transferred to the actual predictive function logic together with distance data. The logic evaluates the situation horizon with respect to the current position and calculates the extent and timing of control interventions by the thermal management system. Finally, the validity of the preview and additional current vehicle parameters are used to prioritize the function interventions or to switch the system to the production ECU behavior.

The evaluated information on current and upcoming environment situations is displayed by dSPACE ControlDesk together with the conventional and predictive thermal management operating strategies and the consumption effects in the vehicle.

> "With predictive operating strategies, we can specifically precondition the engine and the cooling system to increase dynamics and efficiency."
>
> *Mathias Braun, BMW Group*

Results of Fuel Consumption Reduction

Networking the thermal management system with the vehicle navigation system allows the intelligent, simultaneous further development of a vehicle's efficiency and dynamics. A more homogeneous coolant temperature behavior at a raised temperature level can be implemented for typical customer in-town driving. The load on the vehicle's electrical system is reduced by avoiding unnecessary spikes in the requested cooling power, and fuel consumption is also reduced in a range of up to 1% simply by ad-

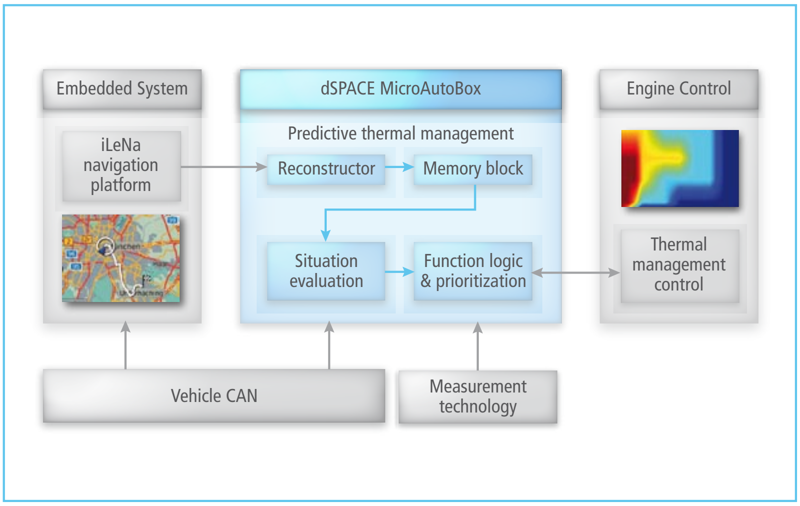


Figure 5: Software and control structure of the predictive management.

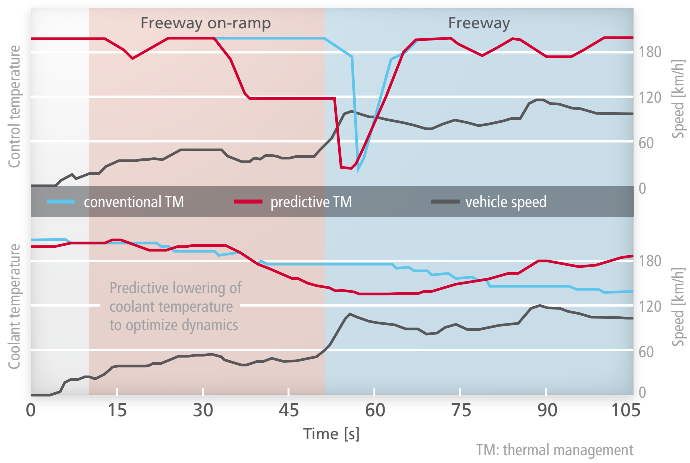


Figure 6: Comparison between controls for conventional and for predictive thermal management.

justing the operating strategy, i.e., without using additional components. This is another important future strategy alongside numerous others in the overall BMW Efficient-Dynamics package.

The Achieved Increase in Dynamics

In the second application case described here, predictive thermal management allows the engine temperature level to be raised at low loads without increasing the risk of exceeding temperature limits during the transition to higher load points. Moreover, it was found that preconditioning the engine by predictive reduction in the temperature level (figure 6) can also bring about increased dynamics. These effects are measurable in the acceleration phase, especially in naturally aspirated engines and their typical intermediate accelerations (e.g., elasticity at 60 - 120 km/h), and are in a range of 3 - 5 % in the uncharged BMW 6-cylinder in-line engine.
The positive effects of predictive thermal management are less obvious in turbo-charged engines. This is due to the in-cylinder charge being dependent on the operational process of the turbo-charger. However, at full engine load, the predictive temperature reduction can increase the efficiency of the turbo-charged engine by selecting a more favorable ignition angle, which in turn optimizes the in-cylinder combustion. ■

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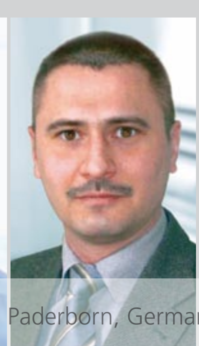

Summary and Outlook:

Thermal management in a conventional powertrain was intelligently further developed by adding a predictive component. With a Series 3 BMW as a basis, initial control strategies were implemented in a prototype, and their functionality and potential were verified. Networking different ECUs to use information that already exists in the vehicle results in increased efficiency and increased dynamics, as was seen from the example of predictive thermal management.
The networking of navigation domains has been a benefit to driver assistance systems such as Adaptive Cruise Control and speed limit displays. Progress in navigation systems with respect to the quantity and quality of information in the digital map (even if navigation is not activated) opens up the potential for predictive functions for optimum control of the energy and heat flows in vehicles.
In addition to predictive thermal management, there are other possibilities, such as computing the driving range of purely electric vehicles more precisely. These would be ideal additions to the BMW Group's successfully implemented BMW EfficientDynamics strategy.