Optical Measurement of the Valve Temperature

____ Modern engine development demands ever more flexible and dynamic processes. The core aspects are the speed and precision of the measuring methods. Porsche Engineering has developed a method for contactless transient online measurement of component temperatures that can be used directly on the engine test bench or in the vehicle. This new tool provides a substantial foundation for further increases both in specific engine power as well as future CO_2 and consumption optimizations.

By Johannes Wüst and Maximilian Fischer

Legal regulations and customer demands for lower-consumption vehicles have led to major changes in the engines of new vehicle generations in recent years. Three primary tendencies have shaped the technological development: first, the introduction of direct fuel injection, which is meanwhile practically universal in Europe. Now developers are faced with the question of implementing the future Euro 6 emissions limits with the lowest possible additional production costs. Second, naturally aspirated engines have been replaced by turbocharged engines with a smaller displacement, a shift referred to as downsizing. Third, further optimizations such as thermal management, start-stop functions, hybridization and friction reduction have come into play.

Direct fuel injection and downsizing in particular have resulted in rising specific engine power. Values between 90 and 100 kW/l are now the state of the art and, in view of continuous enhancements in the turbocharger field, injection technology and combustion process development, will continue to rise in the near future.

These performance optimizations lead directly to a significant increase in the specific heat energy, which in turn increases the thermal load for many engine components. It primarily affects the pistons, gas exchange valves, cylinder heads, the exhaust manifold and the turbocharger. The most common remedial measures are to modify the engine cooling, design means such as an integrated exhaust manifold, piston cooling or higher-quality materials. As a rule, however, this results in additional costs.

In any engine development process, one must continuously take account of the conflict between technical objectives such as reduced consumption and the marketability of a vehicle, i.e. cost thresholds. A typical example is the fuel selection and the design of exhaust valves: One option is to limit the exhaust-gas temperatures in the upper load range through mixture enrichment and thus also reduce the component temperatures of the exhaust valves. This makes it possible to use cheaper materials for the exhaust valves, albeit with higher fuel consumption in these load ranges. On the other hand one can use higher-quality materials, e.g. replacing a common steel alloy such as X50 with Nimonic, or using sodium-filled valves. Both options lead to a significant increase in part prices. In general, however, the focus is on completely exhausting the thermomechanical potential of the material and the design.

State of the art for measuring the valve temperatures

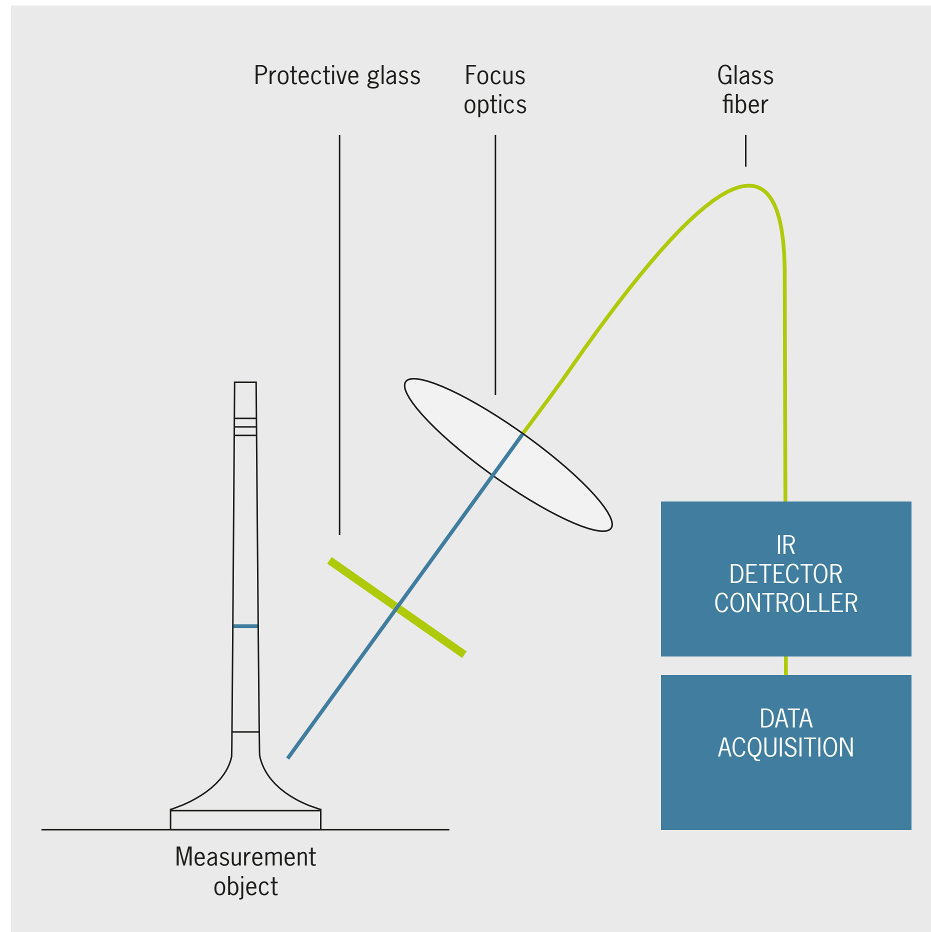
To determine the valve temperatures, thermometric valves have been used for many years from which the valve temperature can be deduced from changes in the material hardness. This procedure is well established, but the measurement values are only available much later: The engine must first be dismantled and the valves analyzed in the lab, which from a time perspective is difficult to incorporate into today's dynamic development processes. It is still only possible to use certain materials, which means that the measurement valves may not reflect the actual state. Furthermore, the results only indicate the maximum temperature reached with the applied application state in a measured operating point. Information regarding the valve temperature in other load points or with other applications cannot be attained in a single measurement.

In special cases, thermocouples are also integrated in the valves and monitored through telemetric signal transmission. This procedure is expensive and critical in terms of reliability and has therefore not established itself as a standard.

Requirements and motivation

The focus of the development by Porsche Engineering was the generation of a measurement signal that could be made available to the test engineers in real time at the test bench or in the vehicle. This would make it possible to significantly increase the efficiency of the development process both in terms of the mechanics and the application. The specifications defined:

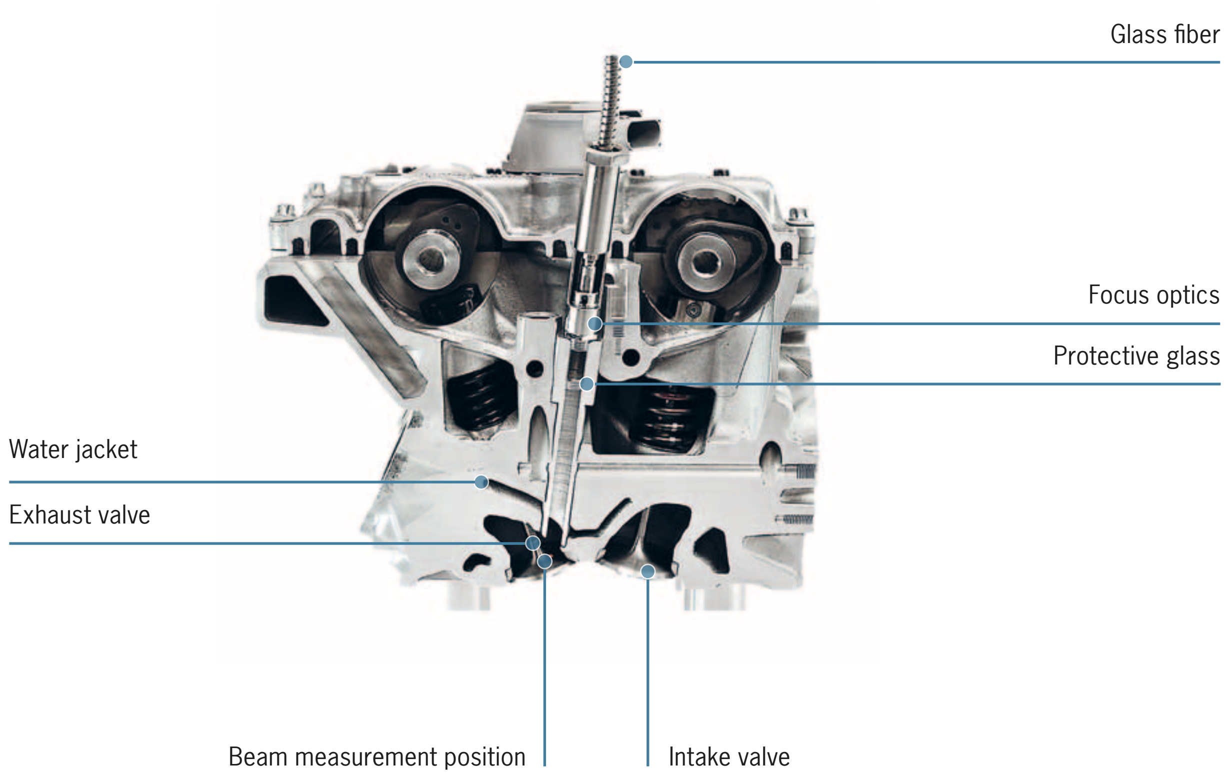
> Measurement range of up to approx. 500 degrees Celsius for intake valves and approx. 900 degrees for exhaust valves, with a sensor ambient temperature of max. 125 degrees Celsius.
> Measurement accuracy comparable to or better than thermometric valves (<10 kelvins)
> High dynamic range of the signal and availability of the measurement signal in real time
> Resistant to reflections and slight soiling
> Small size



Technical setup

From initial deliberations to market launch in 2013, the project went through multiple development cycles. Since that time, the measuring method has been successfully used in some customer projects. It was used, for example, to examine the causes of valve damage and excessive wear on valve-seat rings. Other uses included a comparison of different valve designs with and without sodium filling as well as different engine applications in order to select the most cost-effective valve material for every application variant.

The development tool is currently in use at Porsche Engineering in its 4th stage of evolution. ›



Sensor integration in cylinder head of a Porsche 911 engine

The measuring system

The central component in valve temperature measurement is a pyrometric infrared sensor. In pre-trials, appropriate sensor types were selected on the basis of their suitability for the application.

The measurement chain consists of the infrared sensor, a controller and a measurement PC. The sensor is protected against the high exhaust-gas temperatures and exhaust backpressure with sapphire glass. The measurement signal can easily be integrated into the conventional systems in engine test benches. If the measurement is to be conducted in the vehicle, the signal can alternatively be recorded in the application computer to detect direct reactions to the application status.

The construction design must be tested individually for each engine type. The purpose and reason for the measurement can impact the placement of the sensor.

One challenge of this design—assuming that it cannot be included in the cast part in prototype cylinder heads—is creating the sensor access through the oil chamber, the cooling water jacket and into the outlet port. One problematic issue was that the sealing of the sleeve against the cooling water causes significant difficulties here, which was resolved using an elaborate welding procedure. This enables the procedure to be used on already developed cylinder heads.

In the current stage of evolution, another sensor type is in use that can be mounted completely separately from the engine via a fiber-optic cable. In addition to even greater dynamics, this design is even more resistant to thermal loads, soiling and mechanical sensor loads. Possible optical reflections are avoided by means of black matte coatings and an optimal incidence angle of the "measurement beam."

Soiling of the optics and solutions to this problem

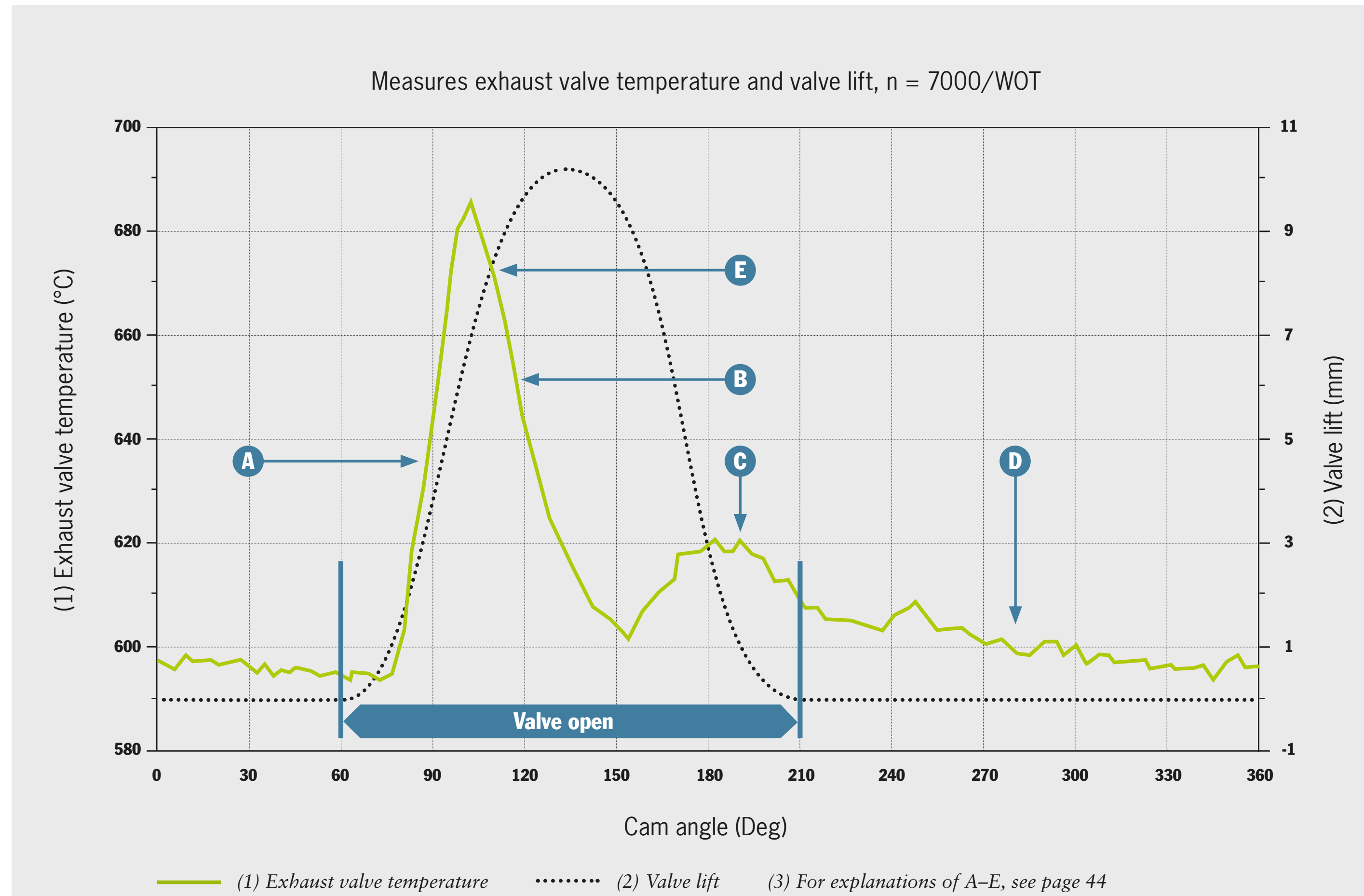
One neuralgic issue is the soiling of the protective glass by soot from the exhaust gas. In particular where valve temperature measurements are to be carried out over lengthy testing periods, the deposits of certain fuels in different countries can substantially shorten the potential measuring period. To resolve this issue, the engineers developed two different measures: a design that enables fast cleaning of the protective glass and a two-color pyrometer.

The principle of two-color pyrometry is based on the use of two infrared detectors that measure in different wavelength ranges. The fiber optics still receive the signal and direct it in the sensor housing to the two sensors through a prism. The specific signal intensity of each wavelength analogous to the temperature makes it possible to compare the signals in the controller by deriving coefficients. This increases the precision of the measurement and any signal attenuation is compensated for. This also makes it possible to determine the intensity loss and thus also the degree of soiling. Specifying a maximum permissible signal attenuation value causes the controller to switch off the sensor when the threshold value is reached; the optics must then be cleaned. This procedure ensures the uniform quality of the measurements.

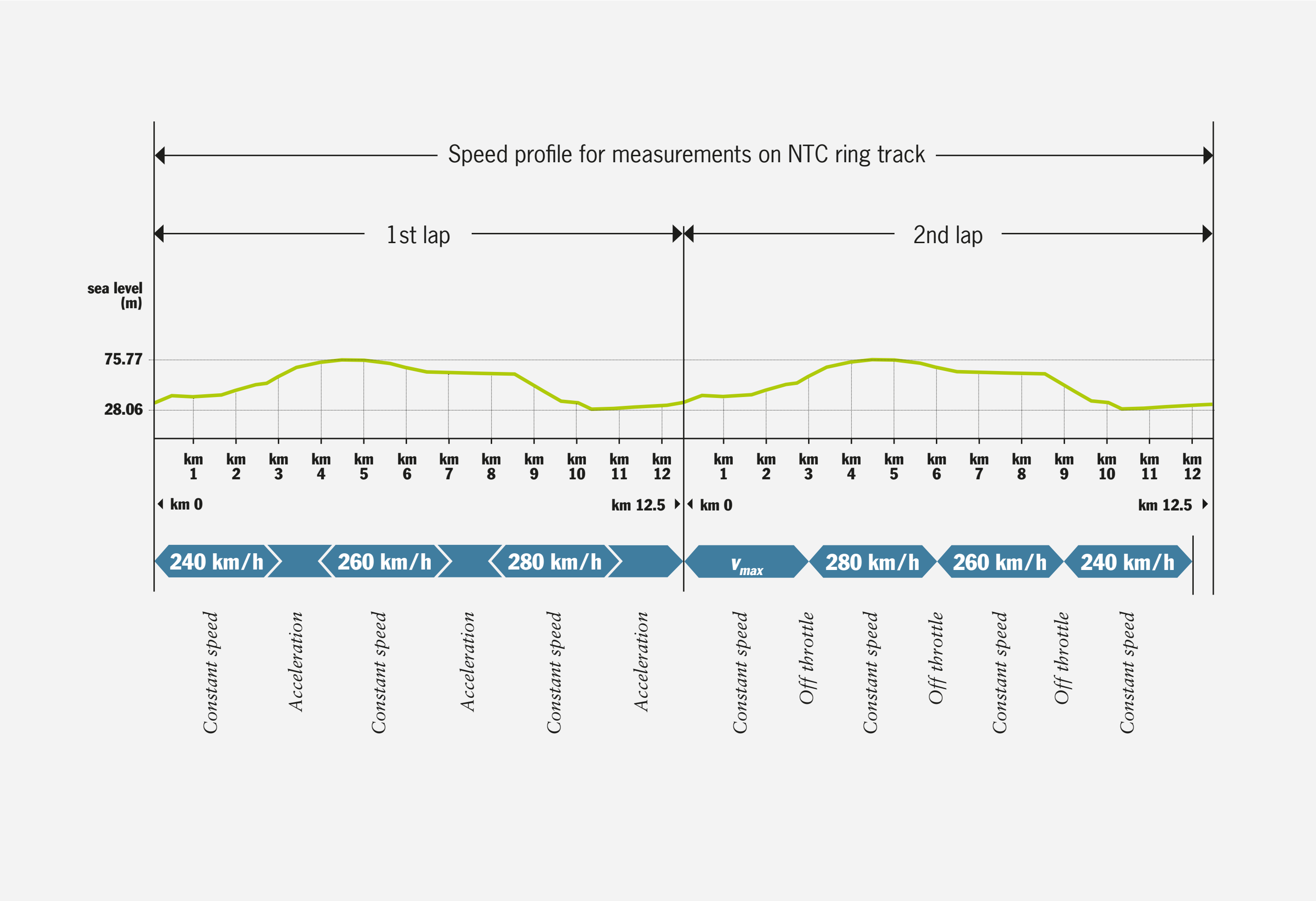
Concept validation

To demonstrate the capabilities of the system, in early 2014 an extensive internal series of tests was conducted with two test vehicles in Nardò, Italy. Both vehicles withstood the two-day, 1,600 km outbound trip as well as the return on their own steam to demonstrate the robustness of the measuring system through long-term data logging.

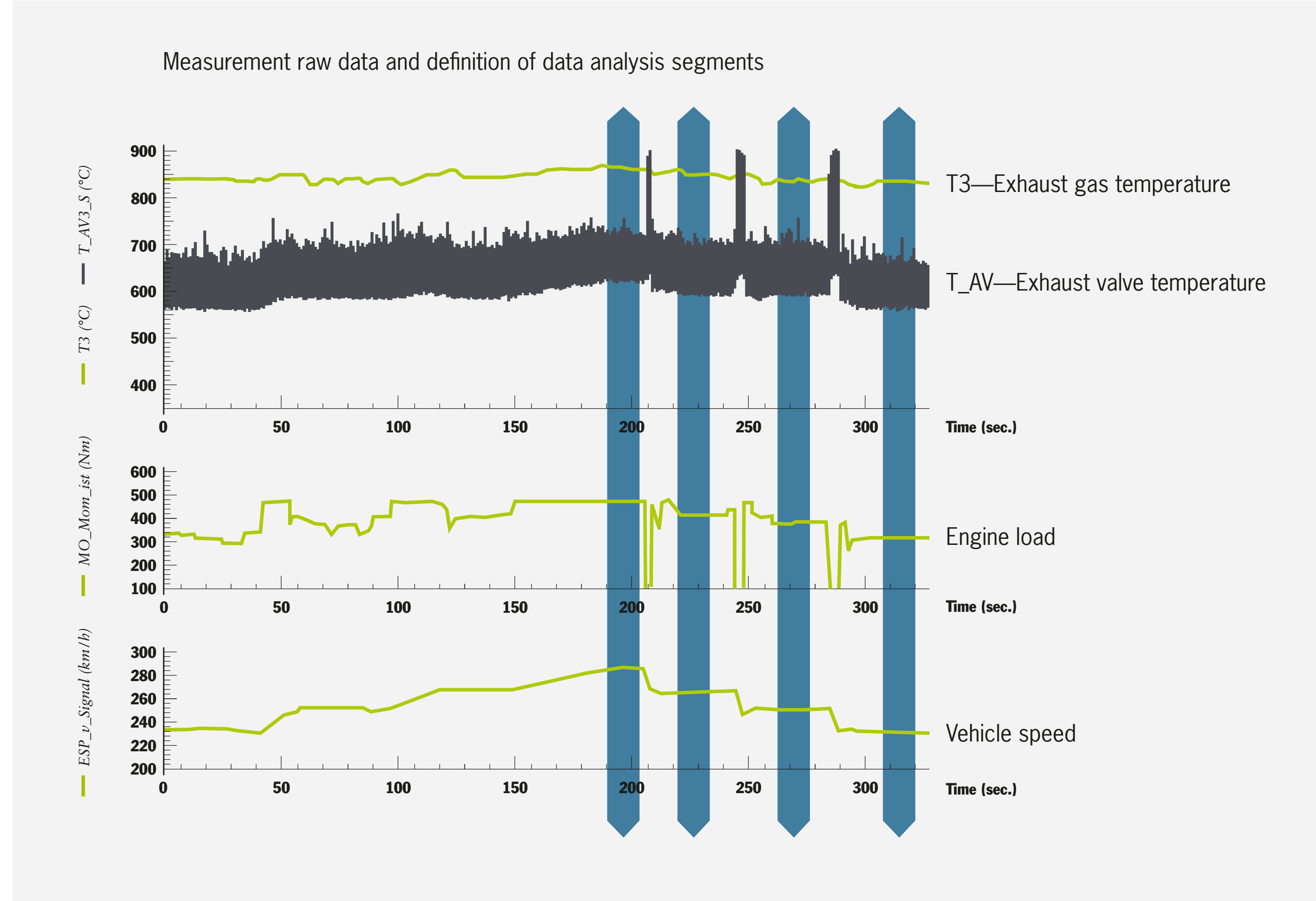
The measurements at Porsche Engineering's Nardò Technical Center were conducted as part of an extensive testing program. Both test vehicles were equipped with direct-fuel-injection, flat-six naturally aspirated engines in two different performance classes. ›



Valve lift and valve temperature at 7,000 rpm and full load



Vehicle speed profile on the circular track in Nardò



Individual measurement and definition of the static evaluation ranges, taking a 1 km journey as a reference

The exhaust valves to be tested were sodium-filled, hollow-shaft valves.

Testing included varying fuel types, driving profiles and sensors as well as alternating application values for ignition angle, oxygen value, exhaust backpressure and coolant temperature. The scope of the test matrix alone shows the data acquisition potential of this measuring technology.

Results

Even a small sampling of the results underscores the capabilities of the measuring system. One example is the high-resolution temperature signal. The figure on page 43 shows a load point at 7,000 rpm under a full load but not yet steady conditions. In addition to the temperature, it also shows the valve lift.

We see extremely high temperature gradients that are only visible with massless measuring methods. The interpretation of these temperature gradients is not easy, however. The curve of the locally measured valve temperature is interpreted as an interaction of at least four different effects:

- Heating by means of exhaust escaping at high pressure from the combustion chamber (in the figure on page 43, item A),
- Apparent cooling due to movement of the measurement position towards the colder valve shaft (B),
- Expansion effects and gas-pressure oscillation in the exhaust channel (C),
- Cooling due to heat transfer from the surface to the inside of the valve, the valve seat and the valve guide (D).

Another effect may be a rise and fall in temperature due to passing over the hottest point on the valve (E).

To evaluate the test matrix, the entire dataset was highly compressed through statistical analyses of average and maximum values. A uniform driving profile (top figure) ensured directly comparable results. For the statistical evaluations, in each case the engineers looked at a one-kilometer section of the second measurement lap (figure to right).

Under a load, the highest exhaust valve temperature (T_AV) measured in this test series was 805.6 °C. This was reached while using the poor-quality fuel in conjunction with a slight application modification. The highest recorded exhaust-gas temperature T3 of 893.8 °C was determined using a conventional thermocouple while using Super Plus 100 in conjunction with only a slight application modification—a lean adjustment in the composition of the mixture. The highest exhaust valve temperatures overall were recorded in the fired thrust. Here the new non-inertial measuring system was able to record temperatures of over 900 degrees Celsius, the upper temperature limit of the sensor calibration selected for this test series.

Conclusion

With this new measuring methodology, Porsche Engineering has created a valuable tool for the development of engines that are more efficient, lighter and yet more powerful and robust. The measurement results are directly available during the test and the effect of remedial measures can be represented in a direct comparison of "before and after" values. This significantly shortens development and testing times. Another advantage of the contactless measuring method is that it offers additional means of CO_2 and fuel savings by better exploiting the thermomechanical limits of the valves.

The robustness and reliability of the measuring system has already proven itself over a total deployment duration of over 25,000 defect-free kilometers. In early 2014, the procedure was successfully used for the first time for temperature measurement on the turbine wheel of a VTG turbocharger. As an enhancement, a water-cooled infrared sensor was used. ■