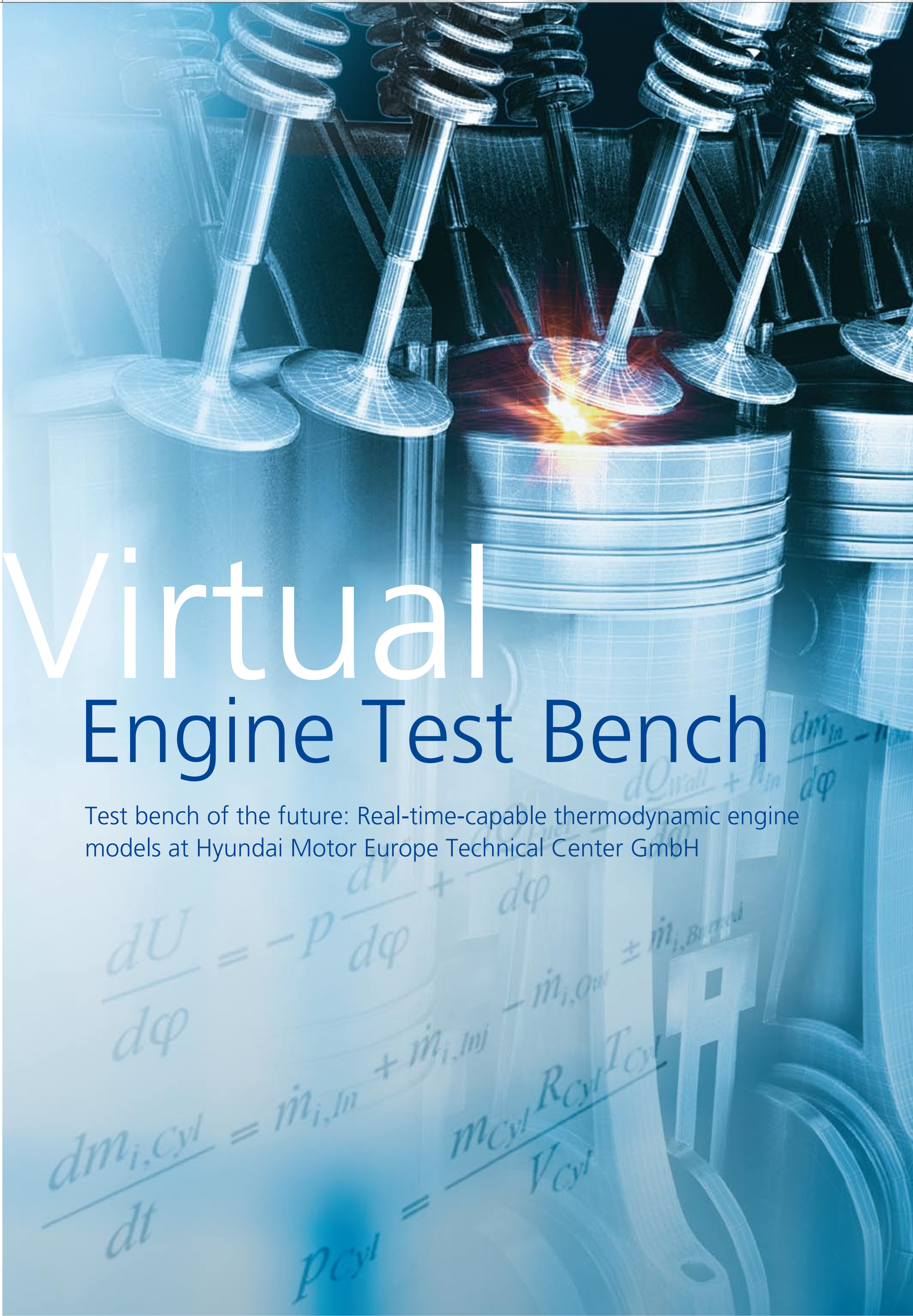
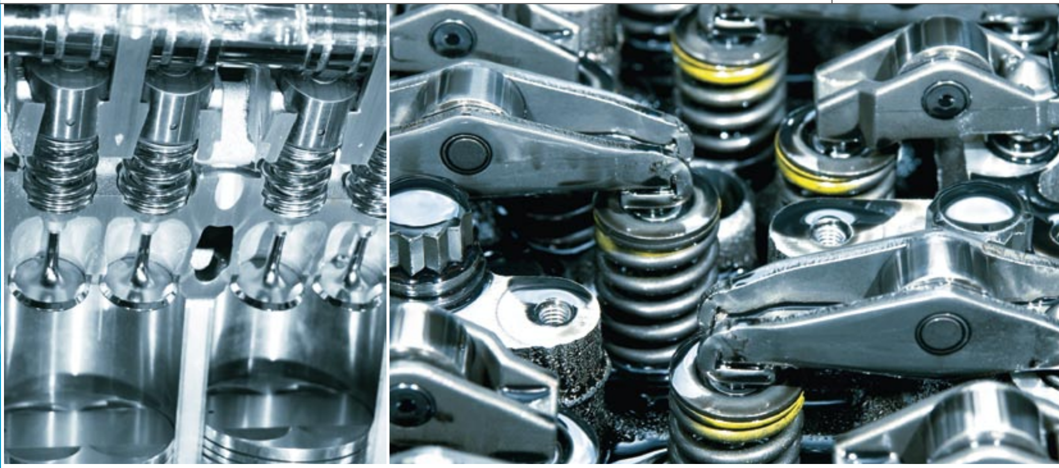


Virtual Engine Test Bench

Test bench of the future: Real-time-capable thermodynamic engine models at Hyundai Motor Europe Technical Center GmbH



Variable valve systems improve the efficiency of modern gasoline engines. Testing the engine control units designed for them requires novel, detailed simulation models with high physical resolution. Rapid prototyping systems can be used in such precise simulation environments to test engine control functions in very early stages when no control units are available: another step towards a virtual test bench.

Direct injection reduced fuel consumption in diesel engines, and new control concepts now promise to do the same for gasoline engines. Among them are homogeneous charged compression ignition (HCCI), variable valve control timing (VVT), and continuous variable valve lift (CVVL). These replace the classic throttle-based cylinder charge control and reduce gas exchange losses, which greatly improves fuel consumption (see Technology Background on page 11). However, this new freedom to control valve opening and closing events and also valve lift (CVVL) involves extra work in developing and calibrating engine control functions. It also creates new demands on hardware-in-the-loop simulation (HIL) on a virtual engine test bench. Up to now, mean value models were used, but these need now to be extended to represent the effects of the new control organs on engine processes. On the positive side, the new detailed engine models will also allow some classic calibration tasks to be moved from a real engine test bench to a HIL test bench. Thus, the new physical, real-time-capable engine models streamline the model-based development process and make development as a whole lot more efficient.

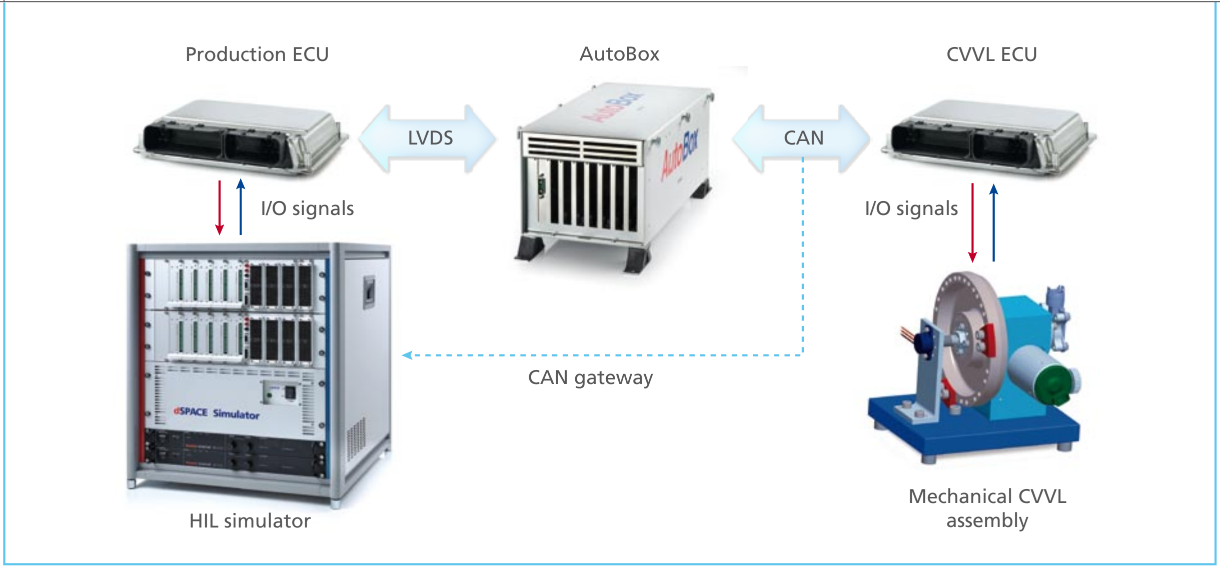


Figure 1: Design of the HIL system with a production ECU, a rapid prototyping system for the new CVVL functions, and a real load for determining the actual valve train value.

Development of Continuously Variable Valve Lift

In an advanced engineering project at the Hyundai Motor Europe Technical Center (HMETC) in Rüsselsheim, Germany, engine control functions are being analyzed for a gasoline engine with continuously variable valve lift. An existing gasoline engine electronic control unit (ECU) has been extended by an ECU function for variable valve lift by using a dSPACE AutoBox as a prototyping system in bypass mode (see Technology Background). The new ASM Gasoline Engine InCylinder models are based on in-cylinder pressure, and are used to test and calibrate the new functions on the HIL test bench at an early stage of development. ASM Gasoline InCylinder models are part of the Automotive Simulation Models (ASM) from dSPACE.

Structure of the Controller Prototype

To develop the new engine controls, the existing production ECU for a throttle-controlled gasoline engine is being used alongside a dSPACE AutoBox that executes the new functions. The throttle-based cylinder charge control on the production ECU was deactivated. The new variable valve lift functions on the prototyping system replace the old cylinder charge control and are executed by the ECU in bypass mode (see Technology Background). Most of the existing structure of the production ECU can therefore be left as it was.

Functions of the HIL Simulator

The task of the HIL system is to simulate, in real time, the interaction between the charge request on the production ECU, the charge control on the prototyping system, and the engine charge calculated by the model. The new in-cylinder-based engine models in ASM Gasoline InCylinder are used to calculate the effect of variable valve lift on the engine process. This new generation of engine models calculates the cylinder charge as a function of the gas mix flowing through the inlet and outlet valves, making it easy to include the effect of variable valve trains in the simulation. In this project, the modular structure of the open model made the integration of the valve lift variability on the inlet side easy.

Technical Implementation

The production engine ECU was extended by a DCI-GSI bypass and calibration module to make a development ECU, which was connected to the prototyping system dSPACE AutoBox via a fast low-voltage differential signaling (LVDS) connection (figure 1). The required cylinder charge is calculated on the production ECU and is transferred to the functions under development on the AutoBox via the LVDS connection. The functions calculate the required valve lift and send it via CAN bus to another satellite ECU, the CVVL driver, which contains the valve lift position controller. To implement realistic feedback for the CVVL driver's position sensors, the mechatronic part of the valve train was constructed as a real load so that the CVVL driver ECU can operate in a closed control loop. In addition, a substitute model of the CVVL system was installed on the HIL system. The HIL simulation of the variable valve lift can therefore use either the measured lift from the real load, or the modeled lift.

Patrizio Agostinelli

Patrizio Agostinelli is responsible for developing new control concepts for advanced gasoline engines at Hyundai Motor Europe Technical Center in Rüsselsheim, Germany.

> "By using the HIL simulator and the new in-cylinder pressure-based engine models, we were able to develop and validate new algorithms for the charge control of a gasoline engine with continuously variable valve lift very quickly and very efficiently, and then to use them successfully in a prototype vehicle."

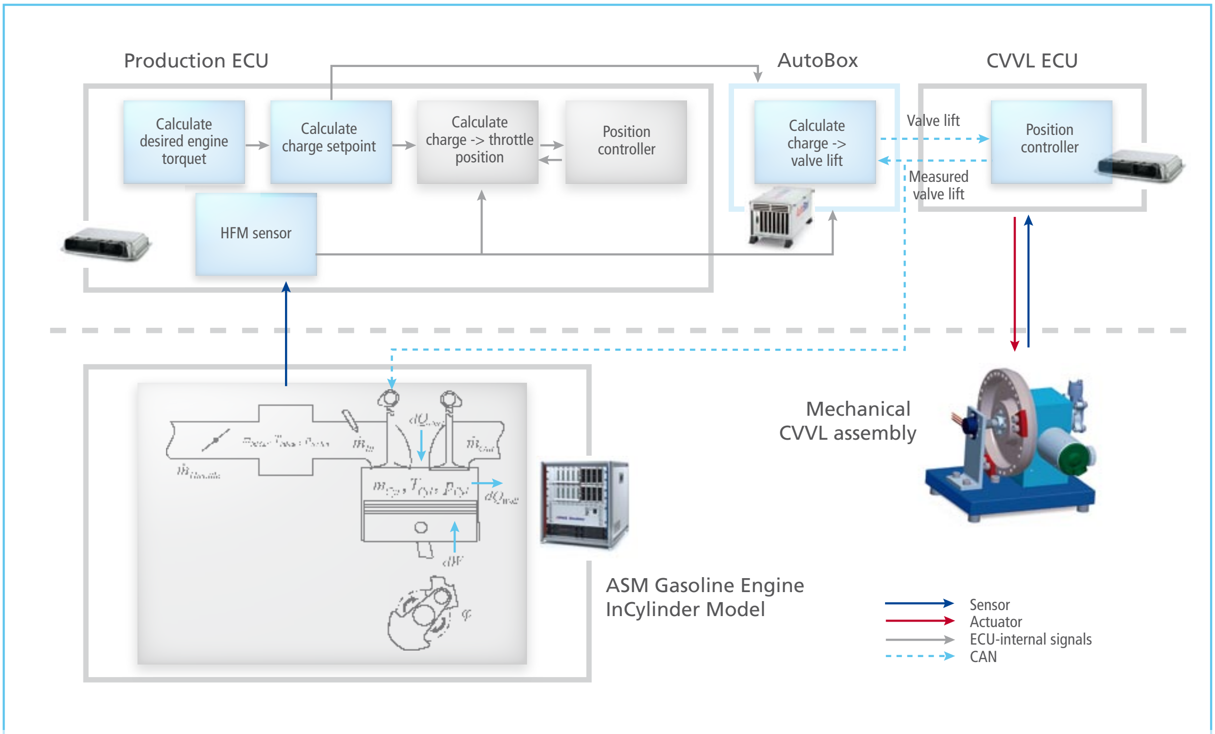
Patrizio Agostinelli, Hyundai Motor Europe Technical Center

The necessary signals between the AutoBox and the CVVL driver are passed to the HIL simulation via a CAN gateway. This means that the HIL system can also be put into operation without a real load plus CVVL driver, which increases maintainability and flexibility, and helps pinpoint possible sources of error.

Function Structure of Controller and Controlled System

The production ECU calculates the driver torque demand from the current engine speed and accelerator position, after which the required reference variable, the cylinder charge, is determined (figure 2). The task of the charge control consists in calculating the appropriate charge influencing control variables for any given required cylinder charge. Leaving aside the effect of valve timing for the sake of simplicity, it can be said that in conventional systems, the main control variable is the throttle. In CVVL operation, the control variable is the lift of the inlet valve. The conversion from one variable to the other is executed on the AutoBox, usually via a model-based feedforward control overlaid by an adaptation algorithm that compensates for any model error. The calculated reference valve lift is sent to the CVVL driver, which is in charge of the valve lift control and returns the actual lift. The actual lift is used together with other variables, such as intake pressure/temperature, engine speed, and valve timing, to calculate the actual cylinder charge. For adaptation, the measured cylinder charge is also required. To obtain it, the ECU evaluates the mass flow in the air intake system via a hot film air mass meter (HFM).
In this set-up of a production ECU

Figure 2: The development ECU, consisting of a production ECU and the AutoBox, is connected to an HIL simulator.



with rapid prototyping and HIL systems, all the necessary measurement variables can be obtained from the plant model executed on an HIL simulator. For example, the engine model provides the simulated mass flow in the air intake system. Physically based simulation makes it possible to simulate the mass flow as a function of the controlled inlet valve lift (figure 3).

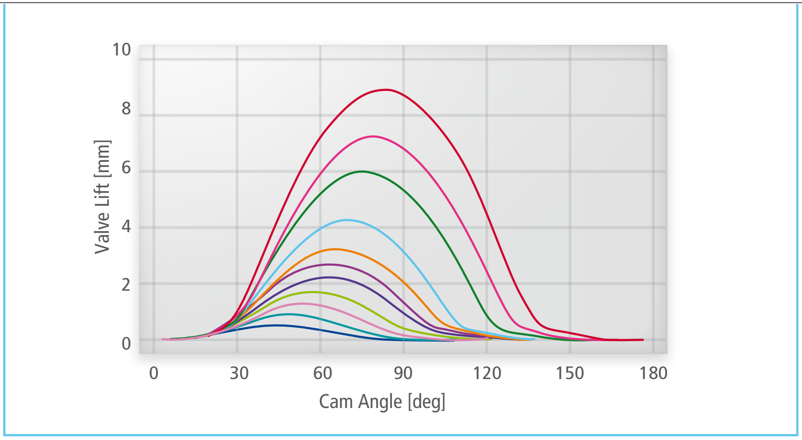


Figure 3: Variable valve lifts for CVVL integrated into ASM Gasoline Engine InCylinder Models.

Evaluation of the Development System

This combination of an HIL simulator, a prototyping bypass system and physical engine models enables plausible real-time simulation of new engine ECU functions in a very early development phase. The engine model was parameterized relatively quickly by means of test bench measurement data, so that the modeled and the measured values were a good match. The in-cylinder pressure model calculates the pressure and mass flow values with sufficient precision, and the ECU can be operated without errors. Even engine operating conditions with valve timing and lift combinations that were not measured on the engine test bench can also be simulated plausibly.
The open models make it easy to extend the simulation model. The required parameters and measurement variables can easily be found and visualized in real-time calibration.

Benefit: Precalibration by Simulator

Not only pure function tests can be performed. The parameters of the controller can also be precalibrated at an early stage on the HIL system, so the rapid control prototyping system goes into operation on the engine test bench with a suitably parameterized controller. This means that some of the necessary experimenting activities can be moved from the expensive engine test bench to the comparatively inexpensive HIL simulator. By combining HIL and rapid control prototyping in controller development, users have more flexibility in calibrating and structuring the controller. Moreover, it also enables them to modify the parameters and submodels in the plant itself, making it easy to study different variants. This task would require time-consuming and cost-intensive adaptation work on the test bench.

Benefit: Frontloading by Linking RCP and HIL

Another advantage is that the models, layouts and automated tests from the HIL test bench can be reused after the extended functionality has been transferred from the rapid prototyping ECU to the production ECU. This new ECU also has to be tested thoroughly. Developers can use the existing model and the experiment environment from the earlier development phase for this. In other words, the new physical models improve integration between the development process on the HIL system and the development process on the real test bench, both during the controller development phase and during subsequent function testing. ■

Patrizio Agostinelli
Hyundai Motor Europe Technical Center GmbH, Germany

Conclusion

The new valve adjustment techniques also necessitate new methods and models for HIL testing. The physical engine models made it possible to test the ECU project on the HIL system at a very early stage of development, without the new functionalities being implemented in the production ECU. Instead, a bypass system was used in conjunction with a production ECU. The in-cylinder pressure-based engine models made it possible to perform not only pure function tests but also precalibration tasks for the new controller concept on the HIL test bench, which reduced the number of real test bench trials that were necessary. In downstream development steps, being able to reuse test scenarios is a great advantage. Since they were already implemented for the production ECU with the rapid control prototyping system, they can now be used for the subsequent prototype phase.


The Hyundai Motor Europe Technical Center (HMETC) in Rüsselsheim, Germany.

Technology Background

The technologies and development methods used in the CVVL engine test bench

Future Gasoline Engine Concepts

Combustion engines run on a mixture of fuel and air. Engine designers use two characteristics to describe the mixture. The first is the air/fuel ratio that is required to burn off precisely the injected quantity of fuel, called the stoichiometric ratio. In a gasoline engine, it is 14.6, though it also depends on the fuel. In other words, 14.6 kg of air is required to burn 1 kg of fuel. The second important characteristic is the lambda value. This indicates the extent to which the mixture already taken in deviates from the stoichiometric ratio. In gasoline engines, the engine performance is controlled via the quantity of gas mixture that is taken in. The appropriate amount of fuel for the fresh air quantity is injected before the cylinders, where it mixes with the air. This fuel/air mixture is mostly stoichiometric, i.e., there is always precisely the right amount of air to burn the fuel. Thus, in gasoline engines with their gas mixture intake, there is no direct way of controlling engine performance via the injected fuel quantity, as the control always maintains a lambda value of one. To allow a specific quantity of fuel to be injected, the quantity of fresh air has to be controlled.

The classic method of implementing this type of charge control is to use a throttle. This reduces the cross-section area in the engine's intake system, thereby controlling the air pressure before the inlet valves. The appropriate fuel for the given air pressure is injected before the inlet valves to form the fuel/air mixture. When the inlet valves open, this mixture is sucked into the cylinder at the currently set air pressure. The lower the air pressure that the throttle sets, the lower the mass of the mixture in the cylinder after the inlet valve closes. The volume of the mixture remains approximately constant. This means that the mass of fuel that is taken in is also lower, as it is in a constant ratio to the mass of the air. The setting of the intake manifold pressure can therefore be used to implement a charge control. The disadvantage of this method is that the lower the air pressure before the valves, the more work is needed to draw in the mixture. This so-called gas exchange work has to be performed by the cylinders in which combustion takes place, so it reduces the power available at the crankshaft.
With variable valve trains, i.e. with variable valve timing and/or variable valve lift, the quantity of mixture in the gasoline engine can be set for the entire load/engine speed map without using a throttle. The gas exchange work, and therefore also fuel consumption, can be reduced because the mixture can be taken in under ambient conditions across the entire load/engine speed range (figure 4).

In addition, the internal exhaust gas recirculation and the proportion of residual gas in the cylinder can be controlled by varying the spread of the inlet and outlet valves. Removing the throttle and improving the air/fuel mix increases the gasoline engine's efficiency and reduces fuel consumption.

HIL Tests

Hardware-in-the-loop (HIL) simulators allow reproducible and automatable function testing of elec-

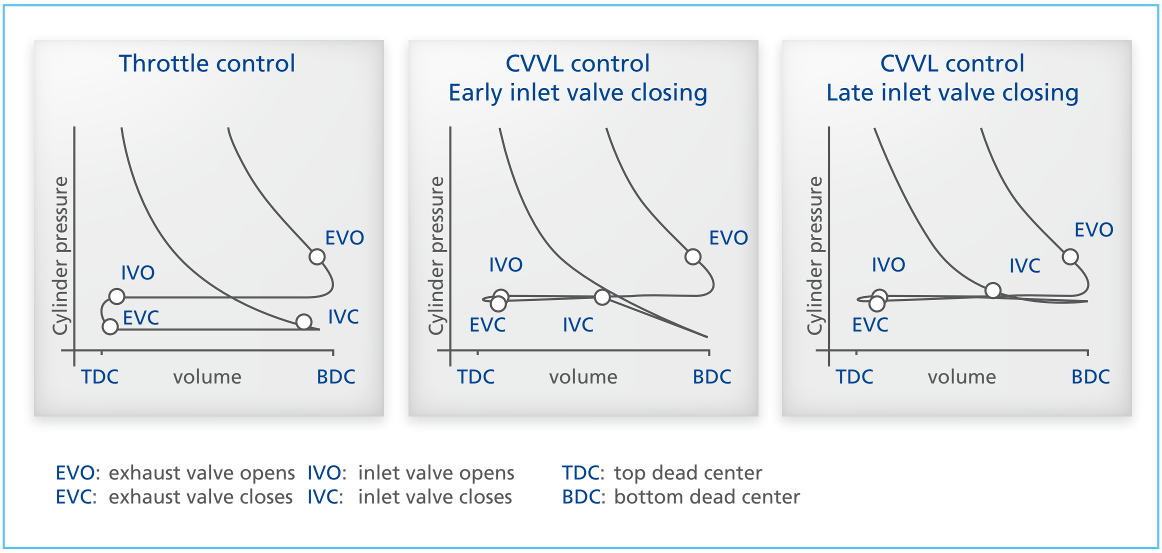


Figure 4: Gas exchange work for gasoline engines with throttle (left) and with variable valve lift (center and right).

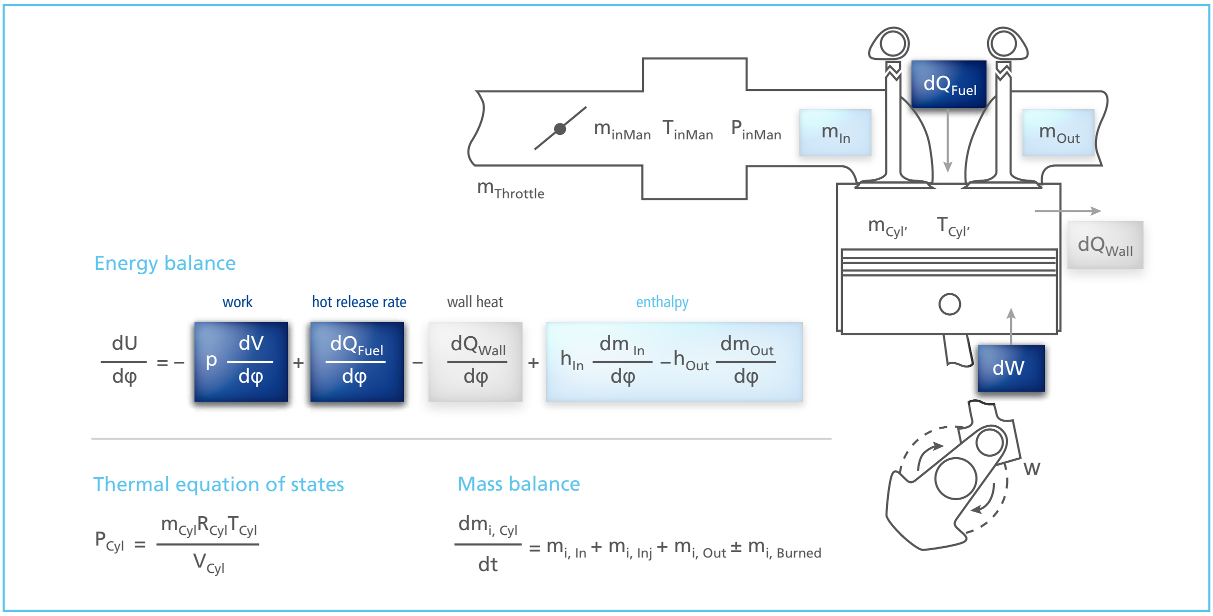
tronic control units with a virtual engine. The ECU actuator signals are read by I/O boards and provided to a real-time engine model, which calculates the engine behavior from the available information and generates plausible sensor values that are returned to the ECU as electric signals. This makes it possible to run tests in a closed control loop with a simulated engine.

Engine Simulation Models

Real-time engine simulation currently uses what are called mean value models. With these, all the simulated engine operating data is averaged across one working cycle, i.e. for two crankshaft rotations of the engine, and simulated. This type of model provides sufficient quality for the majority of HIL test benches. It is a sensible compromise between simulation precision, computing time requirement and parameterization effort. However, future engine concepts will make tougher demands on real-time-capable simulation models. Diesel engines with in-cylinder pressure measurement and gasoline engines with variable valve control times and valve lift require new, real-time-capable models that describe the engine process far more precisely than the current mean value models. These in-cylinder pressure models make it possible to calculate the cylinder charge, for example, by simulating the flows through the inlet and outlet valves. No look-up tables for cylinder charging are used. Instead, the mass flow between the air system and the cylinder is calculated as a function of the valve opening and closing timing and the current valve lift, so that the quantity of the mixture in the cylinder is provided automatically by the simulation. This means that the simulation can also take into account changes in valve lift and valve timing. Figure 5 shows the basic simulation approach, which is based on the first law of thermodynamics, mass balances for fresh air, fuel and exhaust gas, and the ideal gas law. The states inside the cylinder are calculated as functions of the combustion, piston work, wall heat losses and enthalpy flows through the inlet and outlet valves. This enables values such as pressure, temperature and masses to be represented as time-dependent behaviors with a step size of 100 µs for now.

Rapid Prototyping

Rapid prototyping is a proven technology for implementing and testing new control algorithms on the real plant. A control algorithm that was developed in Simulink can be downloaded directly to powerful prototyping hardware via autocoding. The algorithm can be connected to the plant via the I/O interfaces already defined in the Simulink model. In the ECU development process, a distinction is made between fullpassing and bypassing.



$$\frac{dU}{d\varphi} = -p\frac{dV}{d\varphi} + \frac{dQ_{Fuel}}{d\varphi} - \frac{dQ_{Wall}}{d\varphi} + h_{In}\frac{dm_{In}}{d\varphi} - h_{Out}\frac{dm_{Out}}{d\varphi}$$

$$P_{Cyl} = \frac{m_{Cyl}R_{Cyl}T_{Cyl}}{V_{Cyl}}$$

$$\frac{dm_{i,\,Cyl}}{dt} = m_{i,\,In} + m_{i,\,Inj} + m_{i,\,Out} \pm m_{i,\,Burned}$$

Figure 5: Equations in the in-cylinder pressure model.

In fullpassing, an entire ECU is represented on the prototyping hardware and controls an engine, etc. In bypassing, an existing engine ECU is extended by a functionality on the prototyping hardware (figure 6). For example, cylinder charging is not controlled by means of the throttle. Instead, the desired charge is forwarded to the new control algorithm on the prototyping ECU as a reference value. The algorithm then calculates the necessary valve lift. This set-up allows the previous ECU to remain in use.

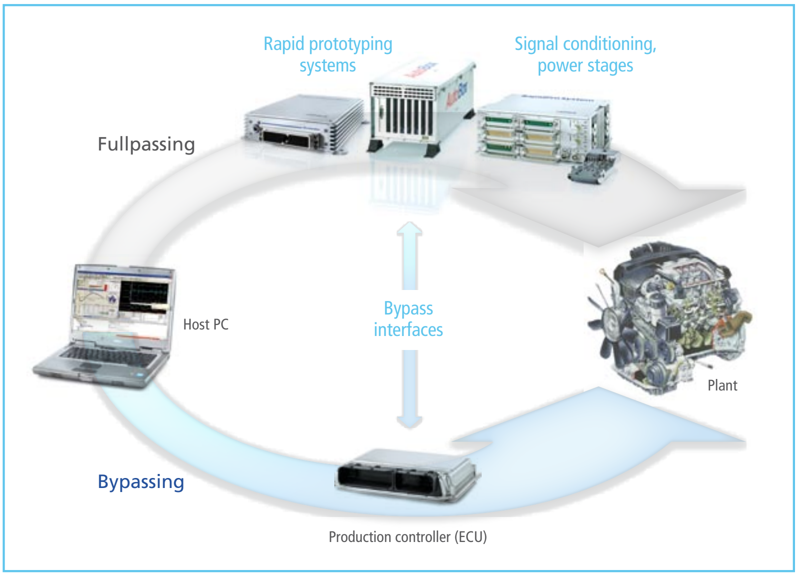


Figure 6: Rapid prototyping in fullpassing and bypassing.

Glossary

CVVL – Continuous variable valve lift allows the lift, duration or timing of intake and exhaust valves to be changed while the engine is in operation.

DCI GSI – Low-latency bypass interface for connecting dSPACE prototyping systems to a host PC

HCCI – Homogeneous charged compression ignition. A form of combustion in which well-mixed fuel and air are compressed to the point of self-ignition in the entire combustion chamber.

LVDS – Low-voltage differential signalling, an interface standard for high-speed data transmission.