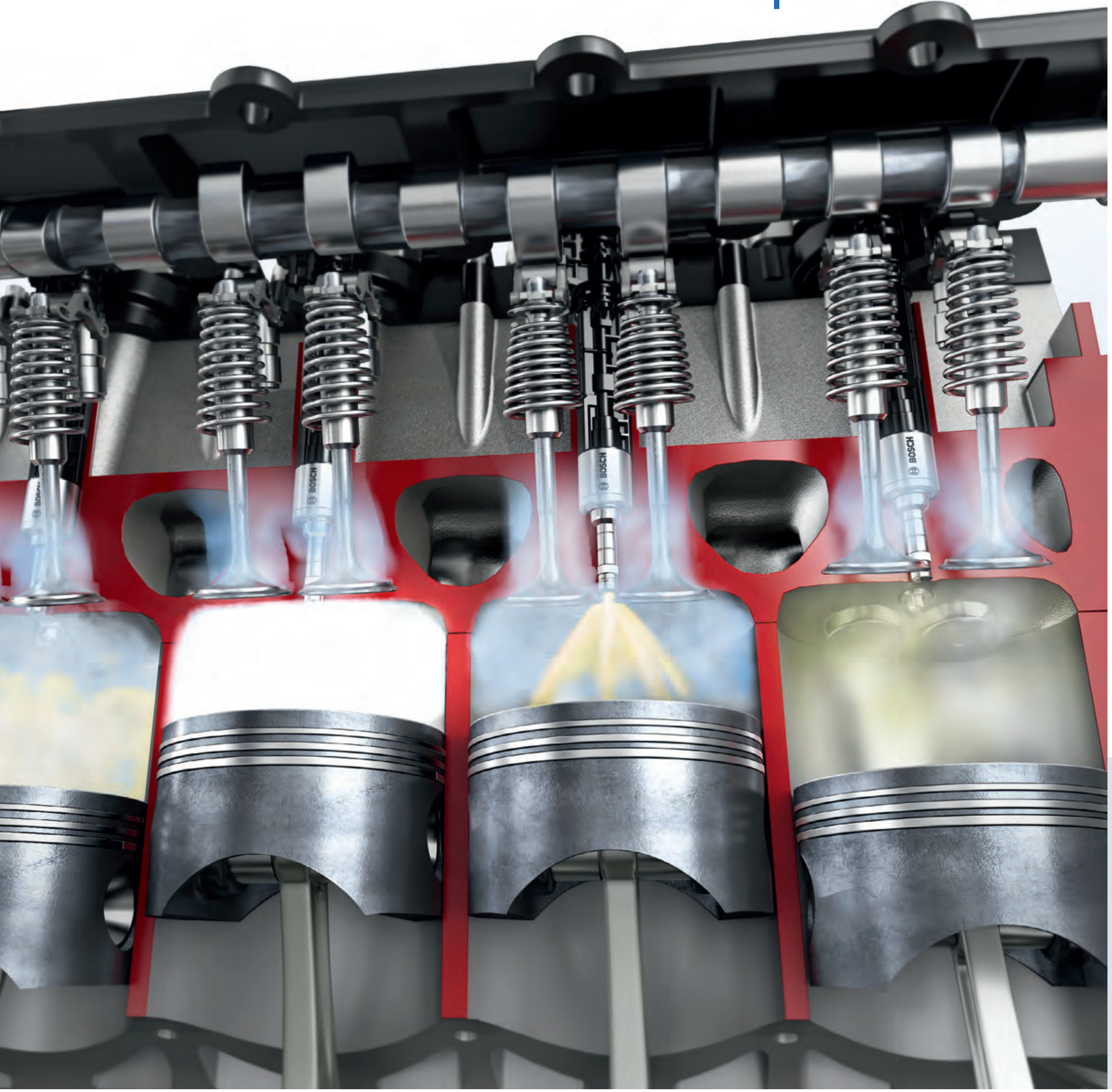
Precision-in-the-Loop



New development tools for clean engines

In modern injection systems, preset injection intervals are being replaced by mechatronic realtime control systems, whereby the engine control unit (ECU) determines the opening and closing of each injector needle and immediately corrects any deviations from the target values. With new high-precision development tools paving the way to series production, ETAS has brought its own Hardware-in-the-Loop solution onto the market. It can simulate the charging and discharging curves of the injectors' solenoid valve with unprecedented accuracy.

Today's downsizing engines combine remarkably low fuel consumption with surprising agility. The key lies in their modern injection systems, which feature injectors that provide a highly sophisticated millisecond-staccato of pre-, main, and post-injection to deliver milligram-precise dosages of fuel into the combustion chambers. The volumes of fuel are so accurately controlled that, under ideal conditions, they burn leaving almost no residue. However, the effects of aging and manufacturing tolerances on the injectors can nullify this precision. Preset injection intervals perform less effectively when the opening and closing times of the injectors vary. That's why developers are now designing ECUs that can interpret the characteristic current and voltage signals produced when the electromagnetically controlled injectors open and close. Knowing exactly when the injector needle opens and closes enables the system to calculate the amount of fuel that is injected as well as the precise moment of injection for each individual injector. Should the results deviate from the target values, the control system can immediately make adjustments, meaning the system can compensate for changes in the injectors' behavior. In view of future on-board emissions monitoring, this will also help to permanently stabilize fuel consumption and exhaust emission levels.

Precision development tools are a must for precise injection requirements

Fuel injectors rely on electromagnetic mechanisms. To raise the needle, a current flows through a coil in the injector and generates a magnetic field that lifts the needle against the pressure of a closing spring (Figure 1). This allows pressurized fuel in the rail to then flow into the combustion chamber. Fuel injection ceases as soon as the electrical current is interrupted and the closing spring presses the needle back down.

Yet what exactly is the time difference between applying the voltage to the coil and the valve opening? And how quickly does it close again after the current has stopped? The necessary answers can be found in the characteristics of the voltage and current curves. These depend on the inductance and ohmic resistance in the injector, which are expressed in charging and discharging curves. The ECU can use this information to redefine the preset intervals in response to each injector's

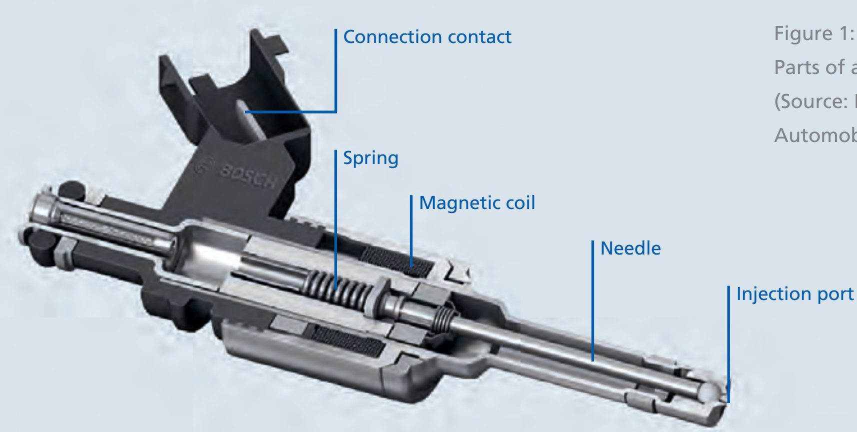


Figure 1:
Parts of an injector
(Source: Bosch Fachinformation Automobil).

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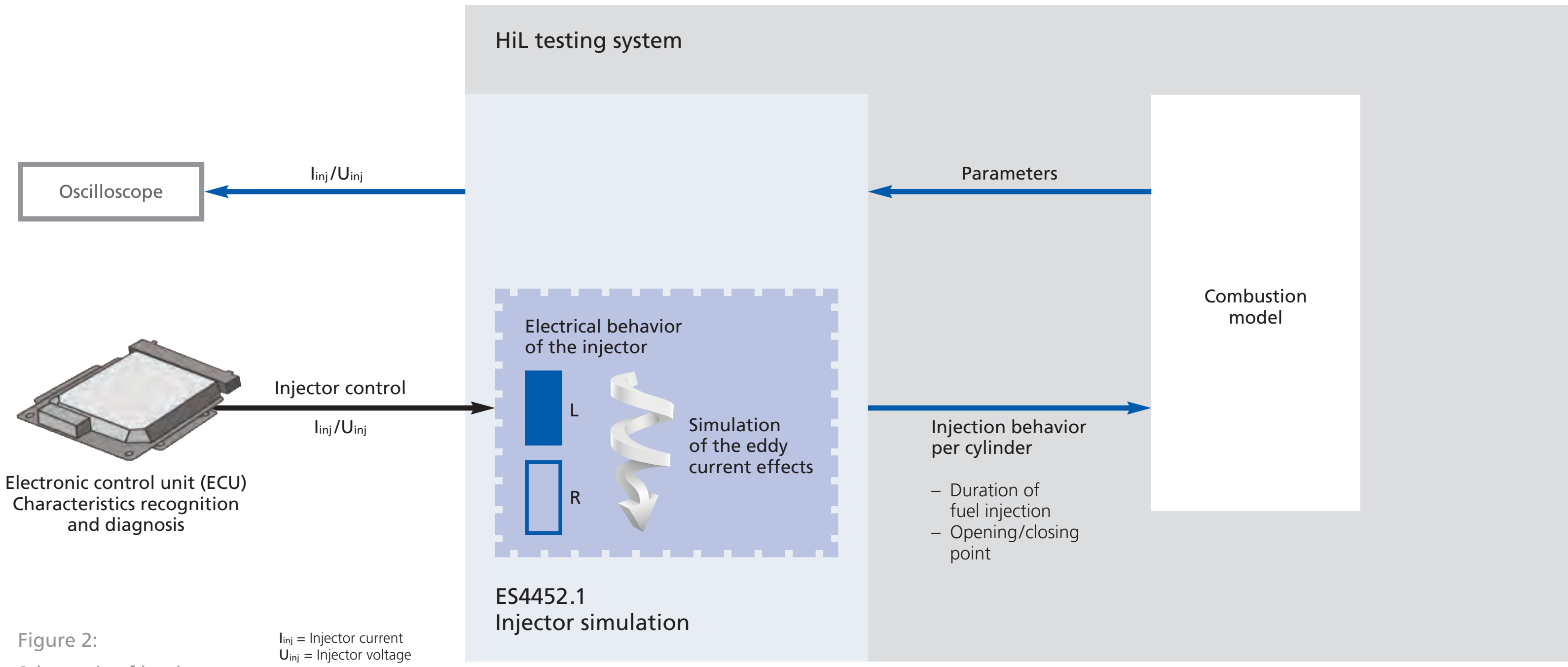

Figure 2: Schematic of load simulation in the HiL system.

I_{inj} = Injector current
U_{inj} = Injector voltage

changing reaction times. This process follows established software routines.

To be successfully deployed in series production, this part of the control unit software has to be tested and tried out in all possible operating states. Conducting tests using simulated or emulated components is ideal for a number of reasons, such as the fact that software testing usually starts long before the engine and its control unit and injectors are physically available. What's more, testing the most significant factor, the aging of the injectors, on an engine test bench would require a major investment of time and money. It's just as unrealistic to use test bench trials to investigate how software behaves when the injection system malfunctions. Last but not least, testing the injectors would require them to be operated around the clock in a fluid medium and at realistic pressure levels, as otherwise they would stall and their opening and closing behavior change.

Software tests in a virtual environment avoid these problems. Hardware-in-the-Loop (HiL) setups allow developers to test the operating strategy of a control unit while taking into account all conceivable parameter permutations, be it the aging of the simulated injectors or artificially created malfunctions. However, until now, no HiL solution on the market was able to reproduce the injectors' behavior precisely enough for the new control strategy to be tested in the closed loop of control unit and injection system. The most important aspect for any such HiL testing environment is that it must be able to precisely reproduce the charging and discharging curves of the injectors.

New HiL solution accurately reproduces injector behavior

For developers to test the control strategy on an in-the-loop test bench, the system has to supply the control unit with realistic voltage, electricity, inductance, and resistance values while the unit is in various states of operation. The unit needs to use these values to infer the opening and closing times of each virtual injector and in the end the amount of fuel that is injected. This requires that the charging and discharging curves be simulated so consistently that the control unit can recognize the simulated spikes.

The major challenge for simulation lies in hardware, more precisely in managing the discontinuities in the supply of voltage and electricity that are normally triggered every time active electronics intervene. Developers of the test system have to limit these breaks in supply enough to ensure the control unit doesn't misinterpret them as a movement of the needle or as an injector malfunction. Another challenge is simulating the eddy current effects in the injector coil accurately and at the right time, since they too can affect the discharging curve.

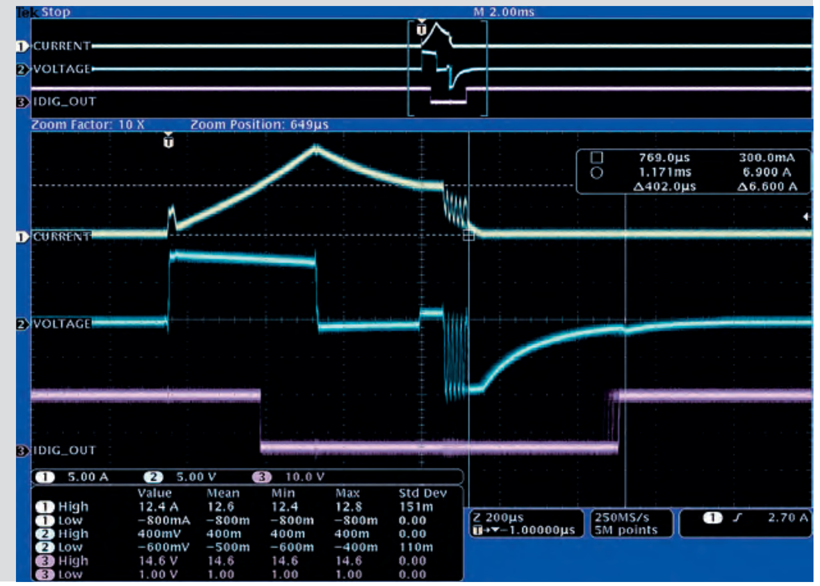

Figure 3: Signal trace of an injection.

ETAS has now developed a HiL solution that overcomes these challenges. It simulates the individual fuel injectors through resistance and inductance and also incorporates eddy current effects – without generating malfunctions and discontinuities in the charging and discharging curves. No HiL system has been able to do this before.

Tests carried out in cooperation with a Tier 1 supplier over several months indicated that the solution could realistically reproduce injector behavior in both hardware- and software-based modeling even with variable boundary conditions, meaning injector aging could also be simulated. The core component of the solution is the ES4452.1 plug-in board for the ETAS LABCAR platform with a Field-Programmable Gate Array (FPGA).

Fast reaction times

The new control strategies require the opening and closing of the injector needles to be determined down to the last microsecond. Hence ETAS has ensured that its new solution features delays of no more than two to three microseconds – some 50 times shorter than the shortest injection times. This is achieved by providing a digital output signal that simulates the points at which the virtual injector opens and closes. These signals are synchronized with each other in the crankshaft angle for up to four different injector simulations. The command set for the board is openly accessible. Standardized interfaces, 100 Mbit/s Ethernet; SCPI (Standard Commands for Programmable Instruments), ensure the HiL solution integrates smoothly into existing development environments. The solution also features precise, dynamic analog output that can depict the voltage and current for each simulated injector via an oscilloscope or another measuring instrument, thereby making changes in the configuration directly visible without the need for expensive, high-precision current clamps.

Configuration settings, such as those dependent on rail pressure, changes in opening times, fuel temperature, or the threshold values of voltage and electricity, can be set – and changed – prior to and during the simulation by means of the SCPI protocol. The first version of the ES4452.1, which has been commercially available since mid 2015, is tailored for gasoline direct injection. The solution for diesel systems, the ES4457.1, was recently published.

Outlook

As part of efforts to improve combustion efficiency and reduce emissions, modern injection systems can regulate the amount of fuel they dispense down to the milligram. Now, the ability to compare the active injectors' actual condition with the target values enables new control strategies to be developed that can compensate for aging-related changes in injector behavior by adjusting system parameters. For mechatronic injection control systems to be successfully deployed in series production, they too have to pass various functional tests. ETAS developed the highly precise LABCAR HiL system with the ES4452.1 and ES4457.1 plug-in boards to allow these components to be tested in virtual form in Hardware-in-the-Loop testing environments. It is the first HiL system able to simulate injector activity with sufficient accuracy to allow control unit software to be geared to the new control strategies. The software is able to learn the future behavior of the injectors without having to integrate actual injectors into the loop.