Gasoline Direct Injection for European Vehicle Applications

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Gasoline direct injection represents one of the most promising concepts for reducing CO_2 emissions produced by road traffic. A substantial part of the development activities is aimed at meeting current and future emission standards.

Stratified Charge

In contrast to conventional gasoline engines with manifold injection, stratified charge needs direct fuel injection into the combustion chamber during the compression stroke. A suitable quantity of fuel must be injected into the compression chamber in a short period and, furthermore, an optimally combustible air-fuel mixture must be produced and transported to the spark plug at the right time for ignition over a sufficiently wide operating range. This results in reduced throttling losses and at the same time utilizes the higher combustion efficiency caused by the lean mixture combustion.

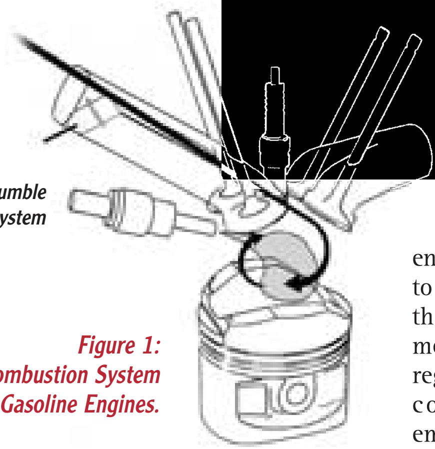

Figure 1: FEV Tumble Combustion System for DI Gasoline Engines.

Many „first generation" combustion systems and their application do not yet satisfactorily meet this requirement and can therefore only partly achieve the expected potential. This is why many manufacturers are already developing a second generation of DI gasoline engines in order to achieve further improvements with regard to fuel consumption, emissions and combustion stability. In this respect, the tumble combustion system developed by FEV (Figure 1) represents a promising approach, and has advantages especially with regard to low fuel consumption as well as to HC and soot emissions and, moreover, to excellent full-load operating characteristics.

Since in-cylinder flow characteristics are a decisive parameter, a special test bench has been designed with a basic engine equipped with an optical access cylinder to allow both an optical analysis of the charge motion and its development and a quick application of different cylinder head and piston geometries. The flow field can be analysed in different light sheets by means of the PIV measurement technique (Figure 2). In addition, the interaction between the injection spray and the charge motion can be visualized by means of laser induced fluorescence (LIF) or Mie scattering.

An example of the remarkable gain in combustion stability that may be achieved by an optimisation of details with the support of this development tool is shown in the injection/ignition timing diagram in Figure 3. Here, a modified piston bowl with improved flow guidance in the area of the fuel injection spray and the spark plug accompanied by an adaptation of the positioning of the horizontal inlet duct partition have been the essential optimisation steps for extending the stability window within which the engine runs without any misfire. The optimised piston bowl showed a significantly improved combustion stability, which is linked to a low sensitivity to manufacturing tolerances. Moreover, the optimised configuration showed a reduced tumble requirement in comparison to the basic design, offering the benefit of further reduced throttling losses.

Another consideration with regard to DI combustion systems concerns the occasionally experienced tendency towards increased soot emissions. If the combustion system has not been optimised, mixture formation under stratified charge conditions at high part load may be insufficient to avoid over-rich zones. Further negative consequences will result if the propagation of the fuel injection spray is hindered and an extensive fuel film is created on the wall. This wall film is only acceptable if a well-determined charge motion allows it to be removed from the wall within a sufficient time. The variable charge motion of the FEV combustion system offers an additional degree of freedom, which helps to minimize the consequences of this problems. In the lean burn operating range of the engine map, average black smoke emissions of 0.2 Bosch units are measured, and these do not increase beyond 0.5 Bosch units at individual points. This corresponds to the level known from conventional port injection engines.

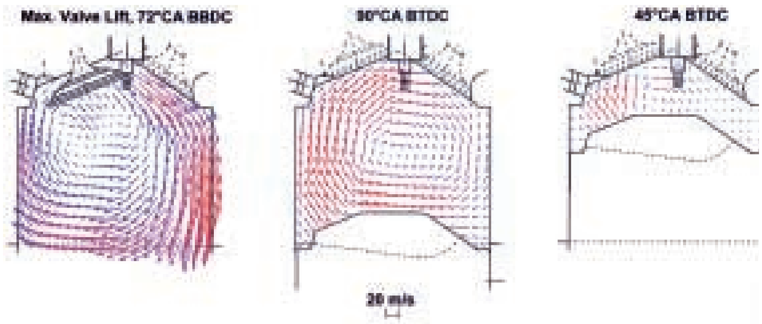

Figure 2: In-Cylinder Flow Field Visualization with Laser Sheet Analysis (PIV) at 2000 rpm, unthrottled, VCM flap closed.

Homogeneous Operation

The advantages of lean burn combustion in terms of fuel economy may also be obtained outside the stratified operating range. This is achieved within the FEV combustion system by the application of an additional operating mode with a homogeneous lean mixture in the mid-load range. It allows the advantages of the lean burn operation to be extended to a BMEP level of 6 bar.

Operation with a homogeneous mixture is achieved by fuel injection during the intake stroke. At higher loads, the tumble flap is opened and the full flow capacity of the inlet duct is available. In order to avoid knocking, the tumble created under these conditions is adapted to the full-load operating behaviour of the engine. Wide experience at FEV obtained from extensive benchmark investigations on DI gasoline engines with different charge motion concepts prove the superiority of tumble combustion systems with regard to full-load operating behaviour (Figure 4). When the gas exchange process has been optimised with regard to valve timing and intake manifold geometry, significant full-load benefits can be achieved. This results in a new definition of the upper limit of the scatter band based on FEV measurement values. This excellent full-load behaviour allows the definition of a relatively long axle ratio, which makes load collectives in a more fuel efficient range of the engine map available for the test cycle.

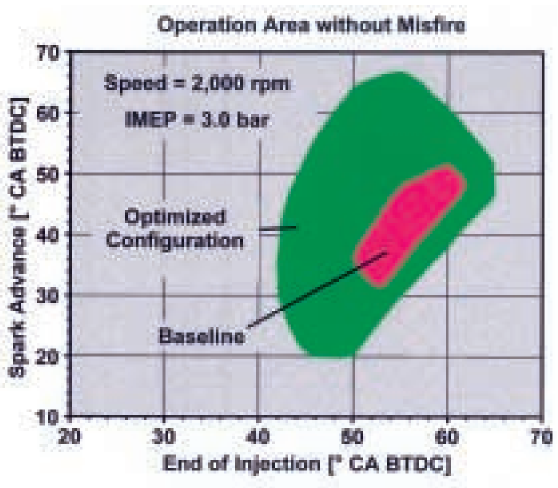

Figure 3: Optimisation of Combustion System Stability

Vehicle Calibration

Engine management calibration of a DI gasoline engine is more complex than for a conventional gasoline engine due to the extra parameters required for optimising and utilising the different combustion modes: homogeneous stoichiometric, homogeneous lean and stratified lean. Furthermore, the trade-off between optimum fuel consumption and NOx emissions is a complex issue. The target for the application engineer is to find the best compromise with regard to emissions, drivability and fuel consumption. The extra parameters and the different combustion modes lead to a large amount of calibration measurements.

Without using statistical analysis and simulation models, it is hard to perform calibration projects in an acceptable time schedule and quality.

Basic calibration for the different combustion modes is performed on automated engine test benches and supported by statistical tools such as Design of Experiments (DOE) tools. Besides optimum fuel consumption and

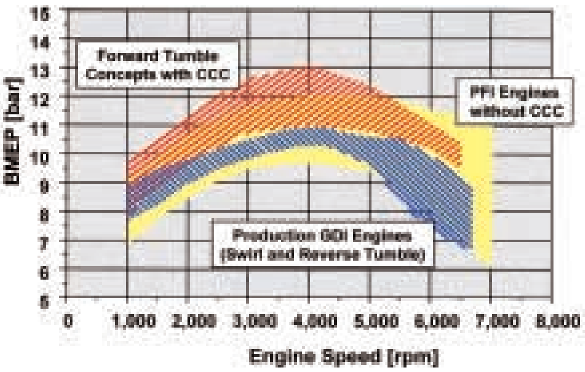

Figure 4 : Full-Load Performance of Different GDI Concepts

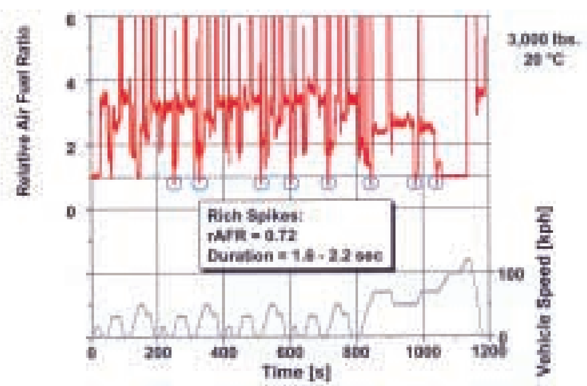

Figure 5 : Relative Air/Fuel Ratio during the NEDC

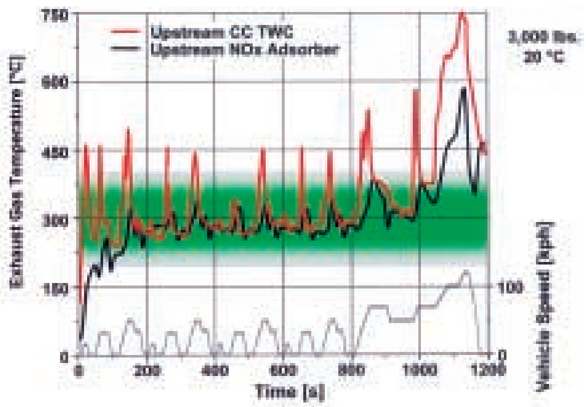

Figure 6 : Exhaust Gas Temperatures Upstream of a Close-Coupled Three-Way Catalyst and an NOx Trap Catalyst during the NEDC.

emissions, combustion stability, soot levels and exhaust gas temperatures upstream of the catalyst are important boundary conditions when defining the operation strategy and mappings.

Once these mappings have been calibrated at steady-state conditions, the calibration is on a level to start with the vehicle calibration. At the same time, a detailed calibration optimisation for emissions and fuel consumption can begin, preferably supported by transient engine test benches. Fixed boundary conditions, excellent repeatability and fast pre-conditioning of the engine for cold starts are advantageous in finding the best compromise in calibration for optimum fuel consumption, exhaust gas emissions and transient performance within a short time.

Operational Strategy

Figure 5 shows the operational strategy of an FEV tumble concept engine during the NEDC for a mid-size passenger car. In order to generate the maximum benefit with respect to fuel consumption, the engine is operated most of the time at lean stratified mode. Lean operation starts shortly after engine start and is only limited by the exhaust gas temperatures (EGT) and the NOx load.

Figure 6 shows the EGT´s of the vehicle. After a cold start, the engine is operated in the homogeneous mode for fast catalyst light off. As soon as the NOx trap catalyst is sufficiently active, stratified lean operation is applied. In spite of a longer warm-up phase, an advantage in fuel consumption has been measured compared to warming up in the homogeneous stoichiometric mode. The EGT level has to be between 200°C and 400°C for the best NOx conversion of the NOx trap catalyst. During the Extra Urban Driving Cycle (EUDC), the EGT upstream of the catalytic converter exceeds this level. Consequently, the engine either has to be operated stoichiometrically or additional measures to improve the high-temperature NOx storage behaviour of the catalyst or to reduce the EGT at higher vehicle speed have to be implemented.

A comparison between the fuel consumption of the baseline PFI engine and the FEV DI version of this engine is shown in Figure 7. At the end of the city part of the test cycle, a fuel consumption benefit of 22% is achieved. Due to higher engine loads and the stoichiometric operation of the engine at high vehicle speeds, the fuel consumption benefit during the EUDC cycle is lower compared to the ECE cycle. Therefore, a final result of a 13% benefit in fuel consumption is achieved by the engine with the FEV forward tumble combustion system compared to its equivalent PFI lambda 1 engine.

Exhaust Gas Emissions

Another method of achieving emissions optimisation when using a catalyst system with an NOx adsorber is the regeneration strategy for the NOx trap. Figure 8 shows the influence of optimised NOx regeneration on HC and NOx emissions during the NEDC. Most of the HC emissions are emitted before catalyst light off, but there is still a noticeable part that results from the NOx regeneration cycles when the mixture is enriched briefly in order to purge the adsorbed NOx charge. Nevertheless, the HC emissions during the NEDC remain within the range of 50% of the EU 4 emission limits, which are due to come into force from 2005.

Half of the NOx emissions are emitted before the NOx trap catalyst has achieved its light off. The remaining part is emitted during the EUDC cycle, because both the NOx load and the EGT increase. In total, the NOx emission result is below 50% of the EU 4 legislation limit.

Optimisation of the NOx regeneration has to be carried out in such a way that the NOx adsorber regenerates to a sufficient extent. Acceleration events, during which the combustion mode is changed from stratified to homogeneous, are utilized to apply rich spikes for the NOx trap regeneration. This results in a relatively small additional fuel consumption. On the other hand, the HC level should not be increased too much by the rich mixture. Therefore, a sophisticated NOx model is essential for applying the NOx regeneration in time to avoid a saturated NOx adsorber without significant fuel economy and HC drawbacks.

The development of gasoline engines with direct fuel injection for vehicle applications requires an interdisciplinary and simultaneous approach to the development of

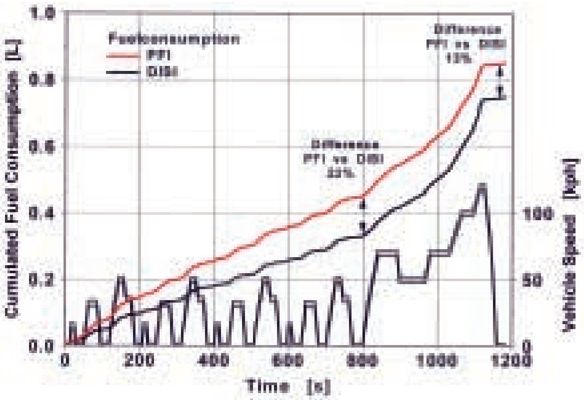

Figure 7 : Cumulative Fuel Consumption during the NEDC.

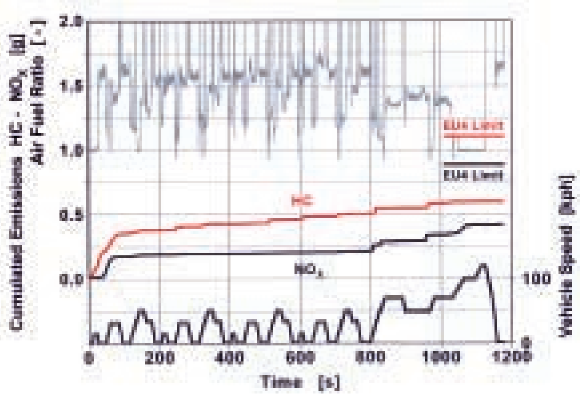

Figure 8 : Influence of NOx regeneration on HC and NOx emissions during the NEDC.

combustion, catalyst and engine control algorithms. Different solutions compete in the area of further advancement of combustion methods. An essential criterion for the necessary improvements will be the realization of the lowest possible raw emissions together with high operating stability. In the course of this, equal importance has to be attached to HC and NOx emissions. Combustion systems operating with minimum wall film have a fundamental advantage in this respect.

By utilizing this advantage, the FEV tumble combustion system furthermore has substantial benefits with regard to emissions behaviour at part load and as well under full-load operation. HC and soot emissions in particular are at a level which is promising even with regard to future legislative requirements. Whilst meeting the EU 4 emission targets, actual vehicle test results show a benefit of 13% fuel consumption compared to the PFI version.

The operational strategy of the engine is mainly influenced by the exhaust gas aftertreatment technology. Stratified operation is limited by either too low or too high exhaust gas temperatures, which result in an insufficient activity of the NOx trap catalyst. However, the combustion system provides stable operation immediately after engine start. Future catalyst developments that achieve an extended NOx storage window up to higher temperatures and an improved sulphur regeneration capability together with the present introduction of low sulphur fuel will lead to considerable further advancements.