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LOW FUEL CONSUMPTION AND LOW EMISSIONS – ELECTROMECHANICAL VALVE TRAIN IN VEHICLE OPERATION

M. PISCHINGER, W. SALBER*, F. V. D. STAAY, H. BAUMGARTEN and H. KEMPER

FEV Motorentechnik GmbH, Neuenhofstrasse 181, 52078 Aachen, Germany

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ABSTRACT–The electromechanical valve train (EMV) technology allows for a reduction in fuel consumption while operating under a stoichiometric air-fuel-ratio and preserves the ability to use conventional exhaust gas aftertreatment technology with a 3-way-catalyst. Compared with an engine with a camshaft-driven valve train, the variable valve timing concept makes possible an additional optimization of cold start, warm-up and transient operation. In contrast with the conventionally throttled engine, optimized control of load and in-cylinder gas movement can be used for each individual cylinder and engine cycle. A load control strategy using a "Late Intake Valve Open" (LIO) provides a reduction in start-up HC emissions of approximately 60%. Due to reduced wall-wetting, the LIO control strategy improves the transition from start to idle. "Late Exhaust Valve Open" (LEO) timing during the exhaust stroke leads to exhaust gas afterburning and, thereby, results in high exhaust gas temperatures and low HC emissions. Vehicle investigations have demonstrated an improved accuracy of the air-fuel-ratio during transient operation. Results in the New European Driving Cycle have confirmed a reduction in fuel consumption of more than 15% while meeting EURO IV emission limits.

KEY WORDS : Electromechanical valve train

1. INTRODUCTION

The electromechanical valve train (EMV) technology allows controlled opening and closing events for all gas exchange valves and offers a big potential to minimize the fuel consumption and the emissions (Geringer and Lenz, 1988; Erickson et al., 1991; Fujiyoshi et al. 1993; Wichart, 1987; Dachs et al., 1989; Heuser et al., 1991; Enderle et al., 1992; Wolf, 1992; Adamis and Gnegel, 1994; Baier et al., 1999; Koch et al., 1999; Flierl and Grudno, 1999). One important aspect of this is that the pumping losses during gas exchange can be minimized. However, in addition, the boundary conditions for combustion, such as residual gas and gas motion can be controlled and optimized at each point in the engine map. Engine test cell based investigations have clearly shown that reductions in fuel consumption are attainable (Pischinger and Salber, 1999) without exceeding even the strictest emission limits. This paper describes results of investigations conducted with a passenger car that was equipped with an electromechanical valve train.

* *Corresponding Author.* e-mail:SALBER@FEV.DE

2. CONCEPT FOR ELECTRONIC CONTROL OF A VEHICLE POWERTRAIN

Since load-control on EMV engines is no longer achieved by throttling, but rather by an appropriate adaptation of valve timing, it is clear that electronic control of the vehicle powertrain must be significantly modified. The electronic engine control unit (ECU) provides central coordination of all engine functions. Based on the input information from the sensors, the outputs are determined and the actuators are subsequently set. Further communication with other control units is provided by dedicated channels, over a CAN bus.

Taking full advantage of the thermodynamic potential of an electromechanical valve train, requires the development of functions that are specific to the control of the EMV valve train. With FEV's EMV demonstrator vehicle, this functional development is made

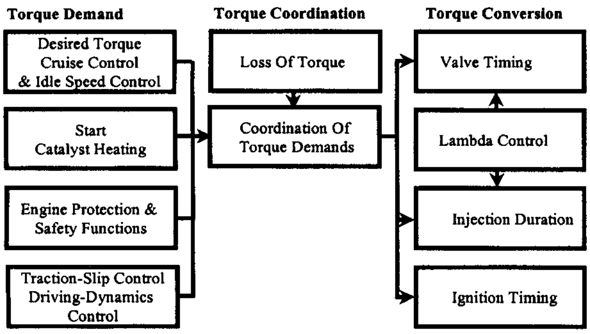

Figure 1. Torque oriented structure of the EMV engine.

possible by the use of a rapid prototyping system, ASCET-SD, produced by ETAS. With this tool the function development can be efficiently facilitated through the use of graphical tools such as transition-state-charts and block diagrams.

In contrast to the throttle-based method of load control, with charging and discharging processes of intake pipe volumes and their time-constants, the fully-variable electromechanical valve train allows a direct control of the mixture mass without of delay time. This, combined with the reduction of fuel film effects due to decreased manifold air pressure fluctuations, achieves a better separation of the respective engine duty-cycle. This potential during transient vehicle operation can only be fully used with a cycle-consistent control. This implies a consistent represen- tation of the fundamental physical and thermodynamic effects in a torque-control based structure. Fur- ther- more this allows a structured, uniform and transparent control-strategy definition with methods of the object-oriented software-development methodology.

The torque-control-structure consists of torque demand, torque coordination and the actual generation of the torque. These classical functions have been adapted to meet the needs of the EMV concept (Figure 1). Thus, the torque oriented concept allows for an idle speed controller, optimized for efficiency by defining a torque demand, which is subordinate to the drivers desired torque. An important difference is found in torque-generation, where the function of air metering through throttling is replaced by a function of fully variable valve control times. This complete independence in load control offers very interesting potential for further dynamic load composition strategies, i.e. cylinder deactivation and multiple stroke.

3. PROCESS CONTROL FOR AN SI-ENGINE WITH A VARIABLE VALVE TRAIN

The load-exchange determines the air mass, the load composition and the in-cylinder gas movement condition of the cylinder load and exercises an essential influence on the targets for:

- Efficiency
- Exhaust gas emissions
- Torque, performance
- Cold start and warm-up behavior and
- Transient behavior

of the engine process. In contrast with a conventional, camshaft controlled engine, process control with variable valve timing of the intake and exhaust valves increases the number of parameters which influence load exchange. A fundamental overview of the strategies to control the SI-engine process with variable valve timing and the possibilities they present for load-control and to influence load composition and the in-cylinder gas movement are provided below.

4. LOAD CONTROL STRATEGIES

The fuel consumption potential of an engine with a variable valve train, due to reduced pumping losses is adequately known(Geringer and Lenz, 1988; Erickson et al., 1991; Fujiyoshi et al. 1993; Wichart, 1987; Dachs et al., 1989; Heuser et al., 1991; Enderle et al., 1992; Wolf, 1992; Adamis and Gnegel, 1994; Baier et al., 1999; Koch et al., 1999; Flierl and Grudno, 1999). Numerous, more or less complex systems have been implemented to build up variable valve trains. These systems can be subdivided according to their function/ principles. In Wellmann (1989) an analysis of an existing system with hydraulic main-power transmis-sion is described. Moreover, in Böttcher (1990) variable valve timing systems with mechanical and electric power transmission are assessed.

The basis of the electromechanical valve train used in these investigations is described in (Schmitz, 1988; Scheidt, 1991). The valves can be opened and closed freely and individually by means of electrical actuators. The control of engine torque takes place by adjusting the closing time of the intake valves. An analysis of the mixture preparation process with unthrottled load-control, the influence on the high pressure process, as well as measures to transfer the complete potential of unthrottled load-control, are described in (Krenter and Wellmann, 1989; Esch and Göbel, 1993; Esch et al., 1995; Oehling and Vo, 1991; Kreuter, 1983).

Two main load control strategies "Early Intake Close (EIC)" and "Late Intake Close (LIC)" are possible. These are shown in Figure 2.

With unthrottled load control, the "Early intake close" strategy is preferred. For low engine loads at high

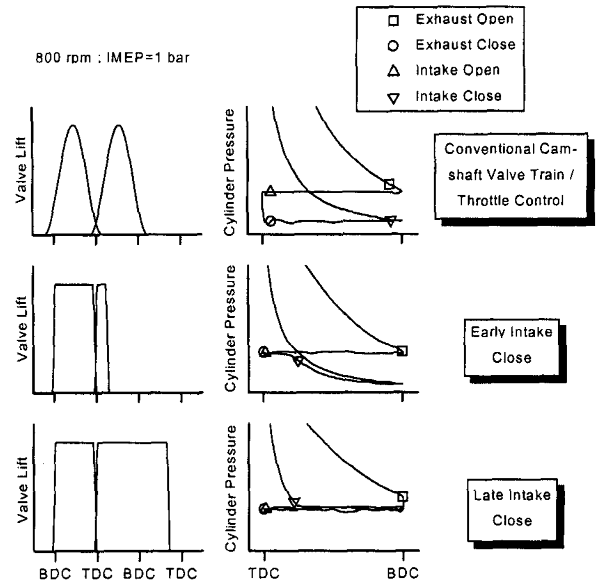

Figure 2. Valve lift and cylinder pressure for different load control strategies.

engine speeds the "Late intake close" strategy in combination with cylinder deactivation leads to good results.

5. CONTROL OF LOAD COMPOSITION

The cylinder charge consists of the inducted air, the supplied fuel and the residual gas fraction in the cylinder. While the air-fuel ratio is determined by the supplied fuel, the residual gas fraction is influenced by the duration and the position of the valve-overlap. The variable valve train allows the adaptation of the residual gas amount, which is essentially controlled by the "Intake Open" and "Exhaust Close" valve timing, for the respective map point and for the operating condition of the engine.

For an engine with variable intake and exhaust valve-control, three different procedures are possible to realize internal exhaust gas recirculation (EGR) (see Figure 3):

- Exhaust gas recirculation through the intake port
- Exhaust gas recirculation through the exhaust port
- Exhaust gas recirculation within the combustion chamber

6. CONTROL OF IN-CYLINDER GAS MOTION

To increase the in-cylinder gas motion, it is necessary to open the intake valves after TDC. With negative valve overlap and late opening of the intake valves

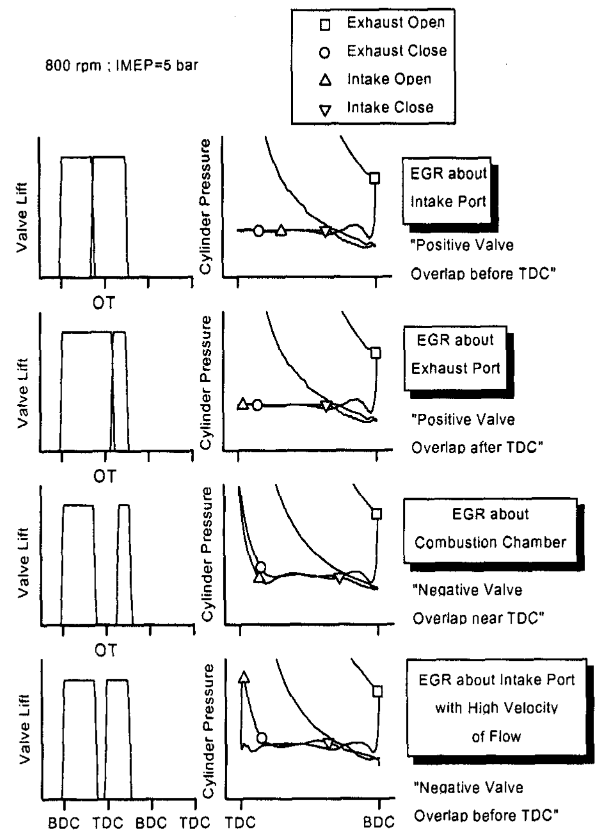

Figure 3. Residual gas control with variable valve timing.

after the TDC, a low pressure level originates with the downward movement of piston in the cylinder. The magnitude of the flow velocity is determined by the pressure-difference between intake port and cylinder when the intake valves open. The critical pressure ratio, which causes the mixture to flow into the cylinder at sonic speed, is indicated by the formula:

$$\frac{p}{p_0} < \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{(\kappa-1)}} \tag{1}$$

This formula determines the negative valve overlap period that is necessary to obtain a maximum flow rate in the valve gap. The mixture flows into the cylinder at sonic speed when the pressure in the intake port is 1 bar and the cylinder pressure is less than approxi- mately 0.56 bar.

Potential gas exchange control strategies with a "Late Intake Open" strategy are shown in Figure 4 under idle conditions. The LIO gas exchange strategy is combined in the upper part of the figure with the EIC load control strategy. Due to the low pressure level in the cylinder when the intake valve opens late,

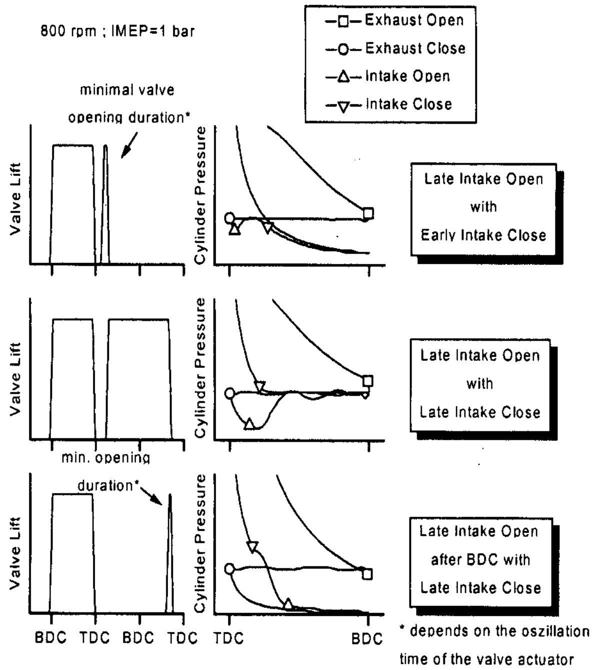

Figure 4. Gas exchange strategy "Late Intake Open" for an engine with variable valve timing.

a large intake mass flow occurs during the valve open event.

Therefore, the intake valve must be closed very quickly when low engine loads are desired. The earliest time that Intake valve closure can occur is limited by the minimum opening duration allowed by the chosen electromechanical valve actuators. Because of this characteristic boundary condition for any given EMV actuator, use of the EIC control strategy results in a practical limit at the indicated idle point for the position of the late intake open event.

The "Late Intake Close" strategy represents another possibility to realize a maximum flow rate at idle. This potential is also shown in Figure 4. The indicated p-V-diagram clarifies that the pumping-losses increase further when the intake-valve is opened late. The pumping losses only decrease when the intake valve is opened very late after BDC in the compression stroke because of the near congruence of the expansion and compression line. The later intake of the mixture increases the in-cylinder gas motion at ignition and during combustion. Opening the intake valve during the compression stroke with minimal valve open duration will generate the maximum in-cylinder gas motion during combustion. Since the cylinder-pressure is higher than the ambient-pressure level while the intake valve is closed, a back flow of the mixture takes place during the minimal valve-open duration.

7. VALVE TIMING "EXHAUS T OPEN"

The Exhaust Open valve timing influences the process efficiency, the exhaust gas temperature level and the secondary reactions of the hydrocarbon emissions in the cylinder and in the exhaust system. In contrast to the intake valve timing and the exhaust valve close timing, the exhaust open timing cannot be assigned explicitly to one combustion cycle. The criteria for optimizing the exhaust open valve timing are the losses from the previous cycle in the expansion and exhaust phase as well as the influence of the exhaust valve opening on the gas exchange of the following cycle due to the dynamics in the exhaust system.

The exhaust valve open timing can influence the exhaust gas temperature and, consequently, the secondary reactions in the cylinder and in the exhaust port. A temperature increase with surplus oxygen promotes secondary reactions and leads, because of the heat transfer as a result of the exothermic reaction, to a higher exhaust gas temperature. Late opening of the exhaust valve promotes further secondary reactions in the cylinder and opening the exhaust valves earlier leads to a downstream movement of the secondary reactions into the exhaust system. Careful adaptation of the exhaust valve open timing can be used in the part load area, at idle, to influence the minimal residual gas fraction and during warm-up, leading to faster catalyst light-off.

8. COLD START AND WARM-UP BEHAVIOR OF AN ENGINE WITH A VARIABLE VALVE TRAIN

The engine management system allows cycle-synchronous control of the parameters for ignition, injection and the valve train. Therefore, at engine start, cycle-synchronous and reproducible engine management can be achieved from the very first fired cycle at cranking speed. Stable idle and transient load changes are characteristic of the resulting engine operation.

In contrast to a throttled engine, the engine load during engine start with a variable valve train is controlled with the intake valve close timing. Initially at start-up, full load torque is requested in order to guarantee the fastest possible start (Pischinger and Salber, 1999).

An essential parameter during the start and warm-up phases is the flow rate of the mixture into the cylinder. With this single parameter the mixture preparation, the fuel transport into the cylinder and the in-cylinder gas motion are all supported (Salber and Spiegel, 1997; Esch and Salber, 1997; Salber, 1998; Andrian and Salber, 1998a, 1998b). With a variable valve train concept, this flow rate is controlled by adaptation of the late intake valve open timing.

Due to the reduced wall wetting, the injected fuel mass is much lower with the "Late Intake Open" control strategy in comparison with the conventional intake open timing. In the first cycle, for a cranking speed of 250 rpm, the injected fuel mass is reduced by approximately 30%.

The investigations with lower start temperatures and lower engine loads (Pischinger and Salber, 1999) indicate advantages for the "Late Intake Open" control strategy. The flow in the intake port is much higher for a start temperature of 0°C and for a start procedure with lower engine torque during the start cycles. The low flow rate in the intake port with conventional intake valve open timing leads to poor mixture preparation and to inhomogeneity of the cylinder charge at 250 rpm. The mixture preparation is clearly improved by an increased flow rate. With the Late Intake Open control strategy, the combustion is accelerated and the required spark advance can be reduced.

Baseline vehicle concept:	Ford Mondeo 1.6L – 16 V, MY 1993
Inertia weight class:	3000 lbs
Rated power:	66 KW @ 5250 rpm
Max. torque:	137 Nm @ 3500 rpm
Compression ratio:	10.3 : 1
Modifications:	
Integration of the electromechanical valve train	
Integration of a turbocharger to realize the power target of 100 KW	
Reduction of the compression ratio from 10.3:1 to 9.0:1	
Gear box and axle ratios not modified	

Figure 5. Vehicle specification.

9. WARM-UP BEHAVIOR

The idle phase directly after the start cycles has a particular importance with respect to the emissions behavior during warm-up. During this phase, high exhaust gas temperature to heat up the catalyst and low raw emissions, especially before catalyst light-off, are very important. Smooth and quiet engine operation must be achieved as quickly as possible with only slightly elevated idle speed, for driver/passenger acceptance reasons.

A possibility to reduce hydrocarbon emissions during idle, involves a late opening of the exhaust valveafter the BDC. Because of the low temperature and pressure level during idle, the in-cylinder pressure at BDC gets lower than the pressure in the exhaust port. Therefore, with a conventional "Exhaust Open" timing there is a reverse flow of exhaust gas from the previous cycle back into the cylinder and a cooling of the burned cylinder charge. If the exhaust valve is opened after BDC, this leads to an improved secondary reaction in the cylinder and to a noticeable reduction in the hydrocarbon emissions.

10. VEHICLE TEST RESULTS

The primary vehicle specifications are as follows:
In parallel with the integration of the EMV specific components into the vehicle, the calibration for steady-state operation was established on an engine test bench. After an initial calibration of the drive ability, the vehicle was tested to the New European Driving Cycle (NEDC) on a chassis dynamometer. All vehicle investigations were done without the usage of a throttle flap.

In the urban driving cycle (ECE), the fuel consumption of the vehicle with an electromechanical valve train (EMV) was improved by 23% in comparison to the baseline vehicle concept. The benefit of the EMV technology in the complete NEDC test was approximately 16%.

The operating strategy of the vehicle with EMV technology is demonstrated in Figure 6. In the speed range below 1400 rpm and up to about 5 bar IMEP engine load, all cylinders were operated in a 2-valve mode. With increasing load and engine speed, this strategy changes to 3-valve operation on all 4 cylinders with alternating activation of the exhaust valves from one engine cycle to the next (called exhaust toggle).

For engine speeds exceeding 1400 rpm and low engine loads, a cylinder deactivation strategy was chosen. This improves, on the one hand, the efficiency of the combustion due to the increased load in the fired cylinders. On the other hand, it allows the full benefits of unthrottled operation to be realized in combination with the Early Intake Valve Closing strategy.

The load and speed range, in which the engine is operated during the NEDC, as well as the WOT limit, are shown in Figure 6. The engine is most frequently operated with 2 valves or 3 valves and firing on all cylinders. During some parts of the test (approximately 30% of the time), the vehicle is operated in the 2-

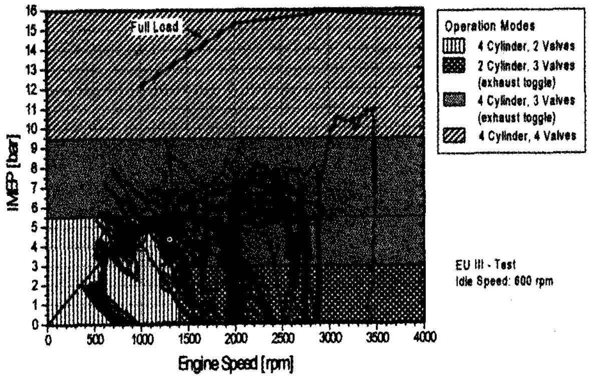

Figure 6. Operation strategy and load / speed-range of the vehicle with EMV technology in the NEDC.

cylinder and 3-valve mode with exhaust toggle. Operation of the engine in the 4-cylinder, 4-valve mode is only conducted in the extra-urban driving cycle (EUDC).

A detailed breakdown of the EMV specific fuel consumption benefits is discussed below (Figure 7). Despite the reduction in compression ratio from 10.3:1 to 9.0:1 (see Figure 5) the advantage of the electromechanical valve train, alone, in the NEDC is approxi-mately 8.5% when compared with the baseline vehicle concept. The improved combustion stability of the engine with EMV technology, especially at low engine loads, can be used to reduce the idle speed, resulting in another increase in fuel economy of approximately 1.5%. By using the full benefits of the operational strategies as discussed above, the fuel consumption of the EMV equipped vehicle is reduced by 16%.

Further potential for the reduction of fuel consumption can be realized due to the fact that, currently, the compression ratio has not yet been fully optimized. Precise control of the residual gas fraction, as well as the effective compression ratio at high engine loads (Miller-cycle) with the aid of the electromechanical valve train allows the possibility to increase the compression ratio to the level of the baseline vehicle.

This provides an additional reduction in fuel consumption of about 4%. Optimization of the energy conversion efficiency from mechanical energy to the valve train is of special interest for the EMV engine. The use of an improved generator with an increased efficiency from about 50% to 80% would translate to an additional improvement by 2% in fuel economy. Furthermore, an additional reduction in fuel consumption of approximately 4% could be realized if the gear ratios were modified with respect to the improved full load performance of the engine with EMV technology (Esch et al., 1988).

Figure 8 presents the emission results of the EMV vehicle in the NEDC without the 40 second preconditioning (EUIII). Although still early in the project, the advantages of the EMV technology alone, without any additional catalyst heating and warm-up functions, resulted in emissions levels of about 35% (CO) and 50% (NO_x) below the EUIV standards. These result were possible despite the disadvantages presented by the exhaust gas turbine which causes additional heat losses during catalyst warm-up. Therefore, when optimizing emissions, it was possible to concentrate on reducing hydrocarbon emissions with the smallest possible fuel consumption penalty.

The required reduction of the hydrocarbon emissions was accomplished by using the potential of the EMV technology to reduce raw emissions during cold start and warm-up as well as to increase the exhaust gas temperature for faster catalyst light off. By using the additional degrees of freedom, made available by the EMV technology with regard to control of the combustion process, the normally required measures

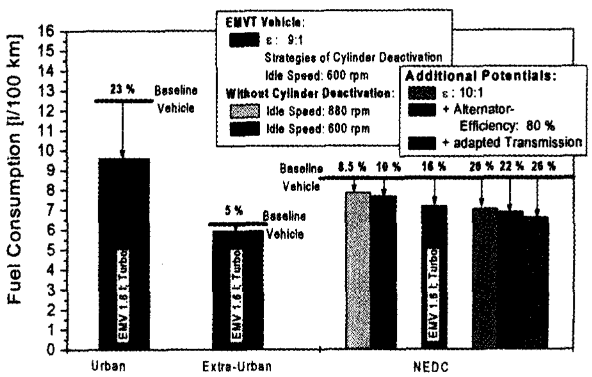

Figure 7: Analysis of the fuel consumption benefits of the vehicle with EMV technology in the NEDC.

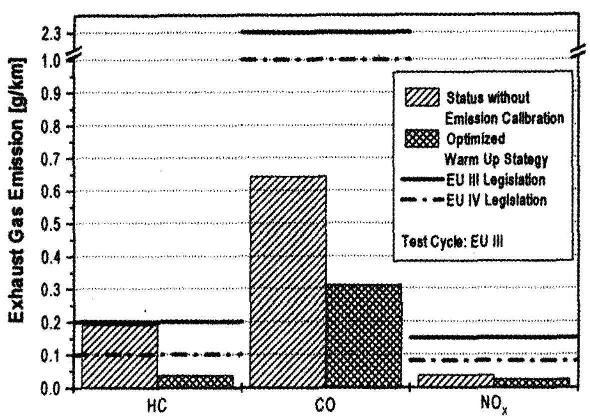

Figure 8. Emission results in the NEDC.

for a fast catalyst light off could be reduced. The EMV engine is capable of fulfilling even the challenging EU IV emissions limits, despite the exhaust turbine, without the use of secondary air injection in most cases. This provides an additional fuel consumption benefit in comparison to conventional exhaust gas aftertreatment concepts.

The increase in charge motion through late intake valve opening represents a distinct benefit of the electromechanical valve train. This effect results in improved combustion stability, especially with the lean mixtures after cold start. During a cold start with the EMV engine, even the first cycle burns with high cylinder pressures and there is no misfiring or cycles with a delayed combustion process. Another benefit is that the oxidation of the unburned mixture fraction inside the cylinder can be significantly improved by a late exhaust valve opening, which results in higher exhaust gas temperatures at a low feed gas emission level. These strategies can be used in order to reduce the HC-emissions during cold start and warm-up by about 50% compared to conventional valve timing, and cannot be realized by a conventional valve train. Due to the improved control of the air mass on each combustion cycle, the amount of fuel can be adjusted very precisely which additionally reduces the cold start emissions of the EMV engine in comparison to a conventional SI-engine.

Despite the potential of the electromechanical valve train to reduce the cold start emissions, there were still measures required in order to increase the exhaust gas temperature for a fast catalyst light off, especially due to the turbocharger. Consequently, EMV specific operational strategies were used in order to improve the engine out emissions and to increase the exhaust gas temperature simultaneously. With these strategies and in combination with conventional catalyst heating

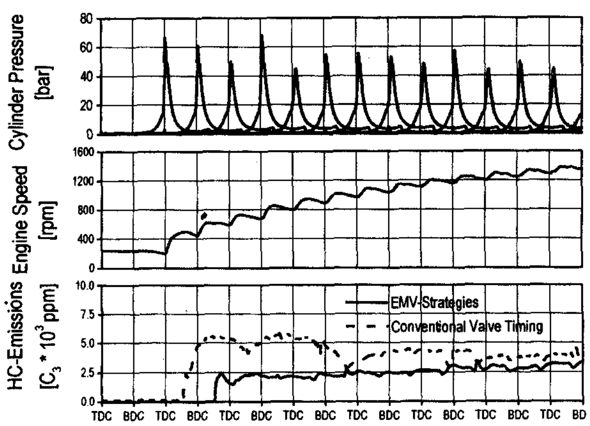

Figure 9. Reduction of HC-emission during cold start bt EMV operation stratiges.

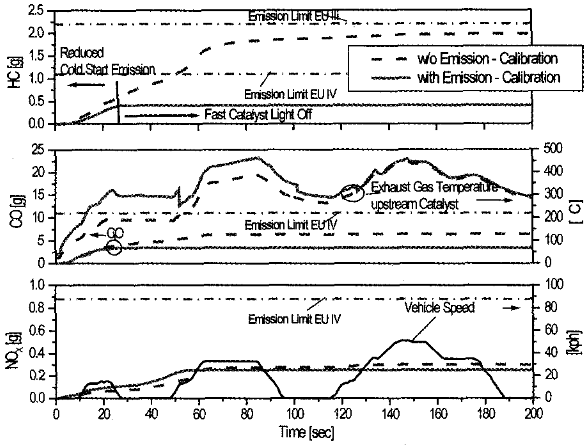

Figure 10. Cumulative exhaust gas emissions of the EMV vehicle in the NEDC (EU III test cycle).

measures (e.g. increased idle speed and retarded spark advance) the exhaust gas temperature upstream of the catalyst is increased by about 100°C compared to the initial calibration, see Figure 10. The cumulative HC and CO emissions prove that the catalyst light-off can be realized before the end of the first driving profile within the first 25 seconds of the driving cycle test.

The NO_x emissions are slightly higher due to a leaner ixture during the first 50 seconds of the test, but the mission level is still non-critical. These results llustrate that a level of 50 % of the EUIV emission imits, which are valid in 2005, can be achieved, using the benefits of the EMV technology, for all regulated emission components, despite the disadvantage of an exhaust gas turbine.

11. OUTLOOK

A fuel consumption analysis of passenger cars with SI and Diesel engines in the NEDC shows clearly that the direct injection Diesel engine offers the lowest fuel consumption. (Figure 11). With the current status of the EMV vehicle a fuel consumption level was shown that is comparable with the level of Diesel engines with indirect injection. Projections shows that by using the potentials mentioned above the fuel consumption of the EMV engine can be reduced and nearly decreased to the level of the direct injection Diesel engine. A fuel consumption per distance of about 3.5 l/ 100 km appears for this engine concept to be possible, if additional measures at the vehicle as weight reduction and air resistance reduction as well as the use of a consumption optimized transmission control - nearly like demonstrated for the direct injection Diesel engine - are integrated.

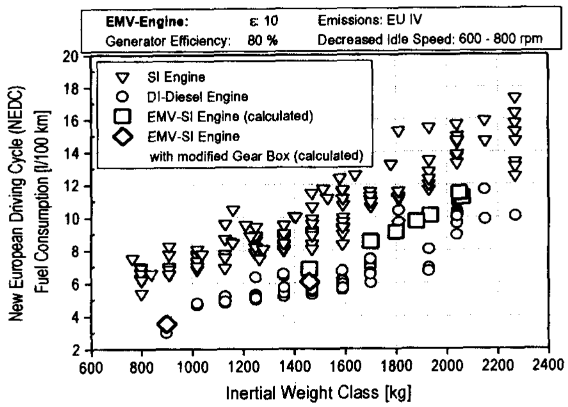

Figure 11. Fuel Consumption of passenger cars at NEDC versus inertial weight class.

Further potential for the decrease of fuel consumption can be realized by a combination of EMV and other technologies like lean spark ignition engines with direct injection also as downsizing with high pressure supercharging. In the case of combination of EMV with direct injection the following advantages are given :

(1) Decrease of the wall heat losses by stratified charge operation at the EMV engine
(2) Increase of the thermal efficiency by increasing the ratio of specific heats by lean combustion operation
(3) Minimization of the NO_X untreated emissions of the DI SI engine by residual exhaust gas control at the EMV engine
(4) Minimization of fuel consumption of the SI DI engine during homogeneous operation
(5) Increase of the charging efficiency and improving of the knocking behavior by internal cooling with direct injection

Using a combination of EMV, lean combustion operation and downsizing with high pressure supercharging and variable compression ratio a reduction of the fuel consumption of about 30 % in the NEDC can be achieved.

12. CONCLUSIONS

To achieve low emission levels during vehicle operation it is important to optimize the cold start and warm-up behavior of the EMV engine. The Late Intake Open valve control strategy (LIO) is used for cold start. By using LIO, the air-fuel mixture enters the combustion chamber with high velocity which leads to a reduced level of HC emissions at start-up. The reduction of the wall wetting with LIO improves the transition behavior into idle.

The Late Exhaust Open strategy (LEO) leads to reduced HC-emissions in the combustion chamber and to high exhaust gas temperatures. The investigations of engine start and transient behavior showed the high potential regarding emissions and load control, when a cycle consistent control of the gas composition and motion is used.

The results of the vehicle investigations in the New European Driving Cycle (NEDC) show a reduction of the fuel consumption of more than 15% compared to the camshaft driven baseline engine while, in parallel, the EU IV emission levels could be reached.

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