THE PNEUMATIC HYBRIDIZATION CONCEPT FOR DOWNSIZING AND SUPERCHARGING GASOLINE ENGINES

Extensive fundamental research at ETH Zurich has yielded the world's first fully functional hybrid pneumatic engine. The pneumatic hybridization of gasoline engines primarily aims at maximal downsizing and increased driveability with minimal additional cost. When comparing engines with the same maximum power, the presented engine system proves to be up to 35 % more efficient on the NEDC.

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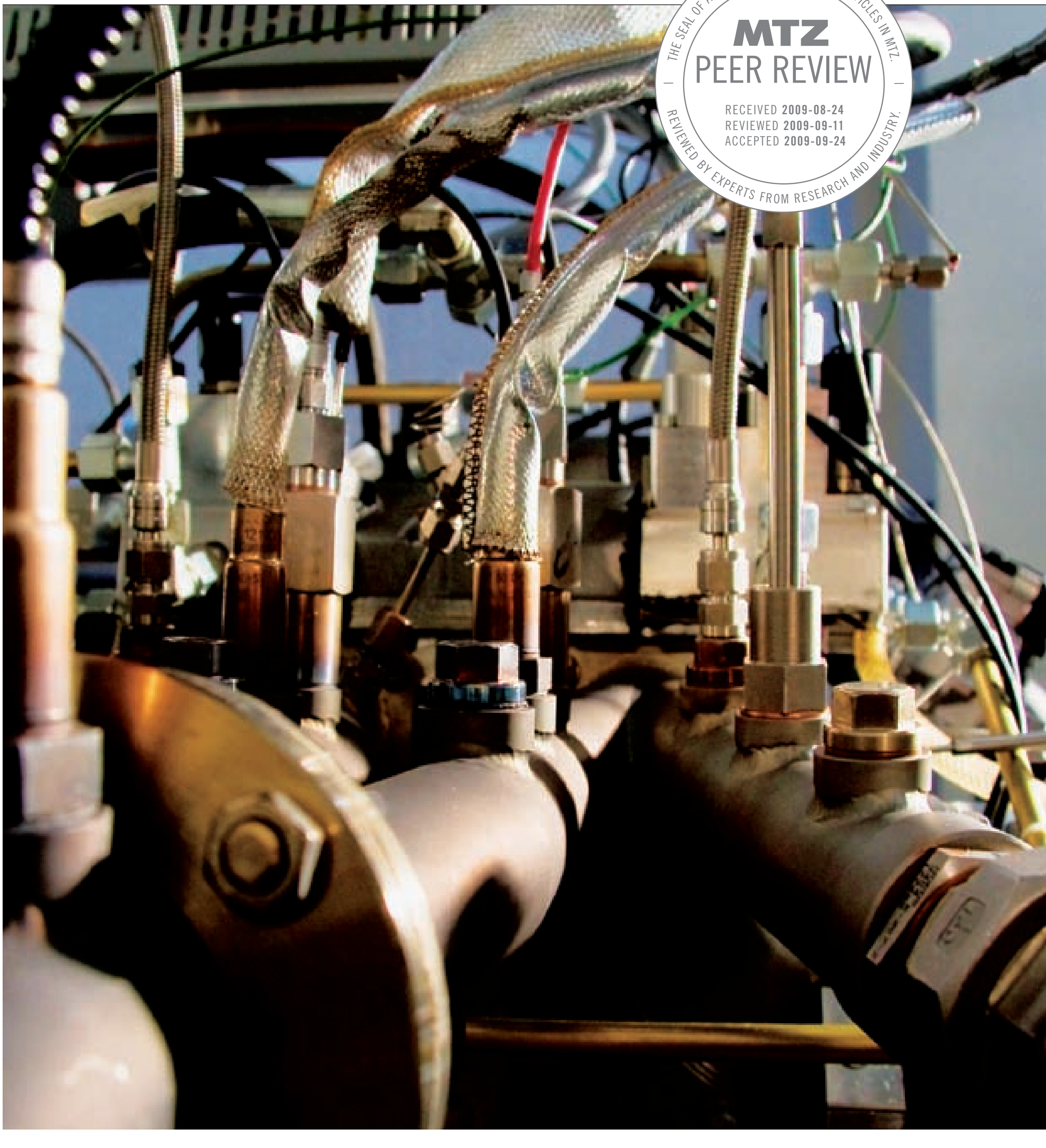

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1 INTRODUCTION

One always has to be careful with propulsion systems that are based on exotic energy carriers. Compared to conventional fuels, pressurized air exhibits an extremely low energy density. This would yield low driving ranges for propulsion systems primarily based on pressurized air. Therefore it must be emphasized that the concept presented here does not rely on pressurized air as the prime source of energy, but on conventional fuel.

2 DOWNSIZING

Large, naturally aspirated gasoline engines continue to enjoy great popularity among customers who value power and excellent driveability. Unfortunately, such engines have high fuel consumption particularly at part-load conditions. New propulsion systems are needed that satisfy consumer demands and environmental requirements. Electric hybridization is one possible option; however, its associated additional cost is very high.

Downsizing internal combustion engines (ICEs) without complementary electric hybridization also has the potential to reduce fuel consumption significantly. The peak power of a larger naturally aspirated gasoline engine can be recovered using a turbocharger. Lower friction and, more importantly, operating the ICE more frequently in high efficiency regions results in lower fuel consumption [1, 2]. The first downsizing and supercharging concepts were developed more than ten years ago [3], and it has become a frequently used method. Most of the time, however, it is implemented at a moderate level in order to retain good driveability. The turbo-lag is reduced by using small turbines or turbines with costly variable geometry. In order to fully exploit the potential of downsizing and supercharging, a concept is needed that guarantees excellent driveability even at low engine speeds. Engine concepts using pressure wave superchargers [4] and dual-stage compression [5] were introduced; here an alternative solution is presented.

3 PNEUMATIC HYBRIDIZATION

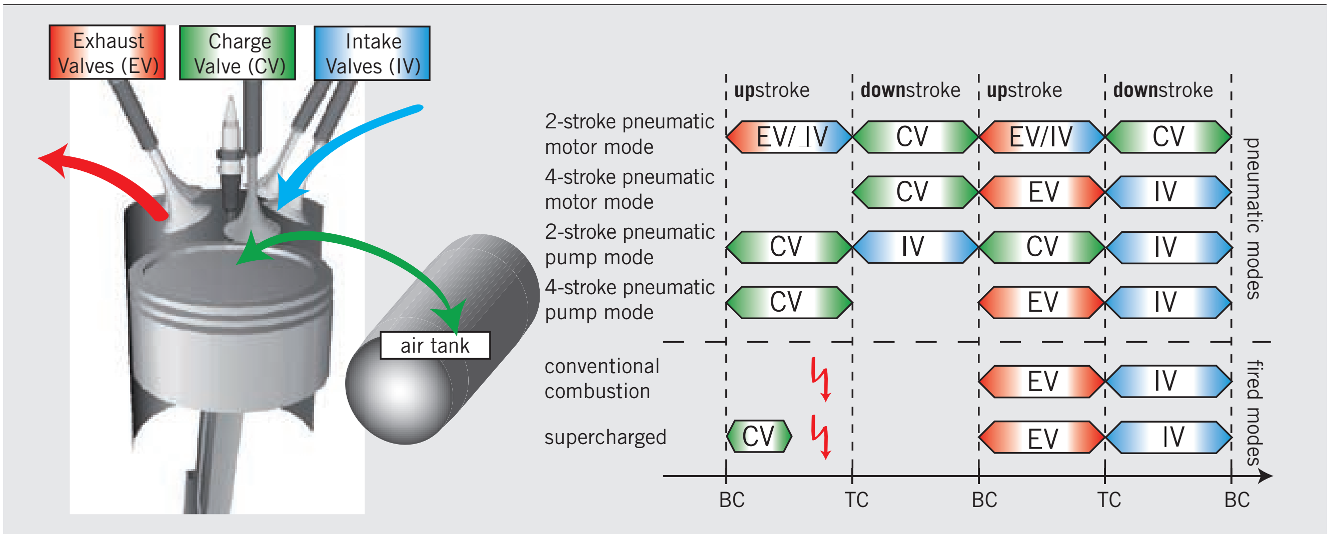
Since the late 1990s, pneumatic hybridization of ICEs has been discussed [6, 7]. The key idea is to use the ICE also as a pump to recuperate the vehicle's kinetic energy during braking phases, and as an expansion motor for propulsion. This can be realized by connecting an air pressure tank to all cylinders via electronically controlled charge valves as shown in ❶, left.

In addition to the recuperation capability, the idea offers the possibility of a rapid start/stop and permits to shift the engine's operating point to high efficiency zones. The latter can be achieved by operating half of the cylinders conventionally while the other half of the cylinders work in the pump mode ("recharge" mode). Previous concepts assumed two-stroke pump and pneumatic motor modes which is possible only if all valves of the cylinders can be variably actuated.

4 THE CONCEPT DEVELOPED AT ETH ZURICH

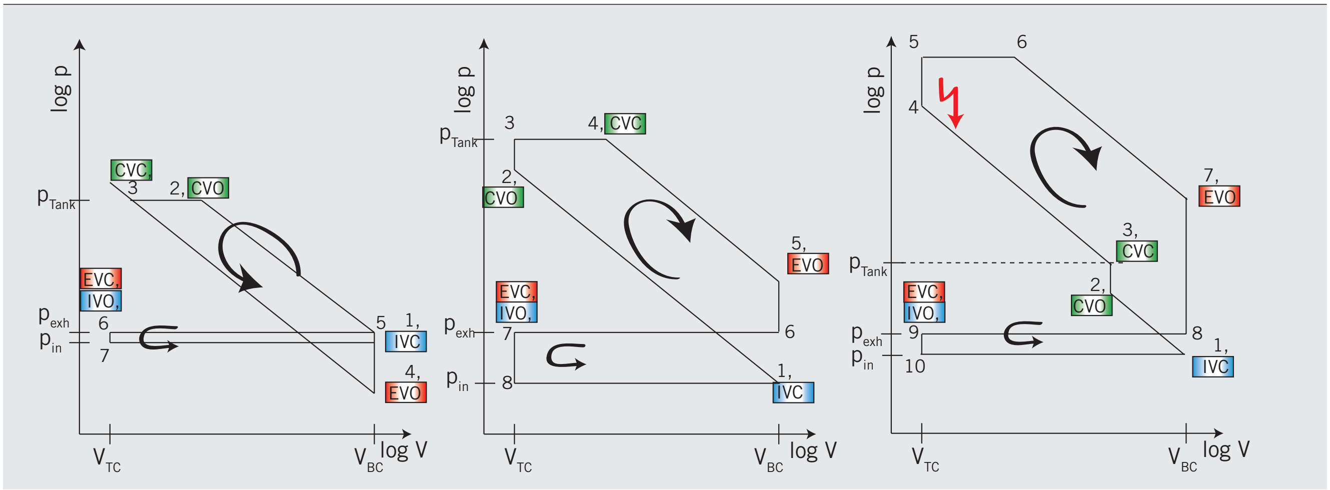
At the outset of the project, theoretical investigations were carried out to determine whether a less complex design for the pneumatic hybridization could provide the same benefits. In [8] it was shown that it is sufficient to keep all intake and exhaust valves actuated by non-variable camshafts while only the charge valve has to be actuated in a fully variable manner. Consequently, four-stroke operation is retained in all engine modes, ①, right, using a much less complex system with minimal additional cost.

❷ shows a simplified illustration of the additional engine modes in double-logarithmic p-V diagrams. The four-stroke pneumatic motor mode reveals a peculiarity: more torque can be produced in this



❶ Principle of pneumatic hybridization (left); valve actuation requirements (right), EV = exhaust valves, CV = charge valve, IV = intake valves

❷ Additional engine modes – pump mode (left), pneumatic motor mode (center), “supercharged” mode (right)



mode by closing the throttle valve. Owing to the lowered intake pressure, the work to be done during compression is reduced. Further, this enables more air to flow from the tank to the cylinder.

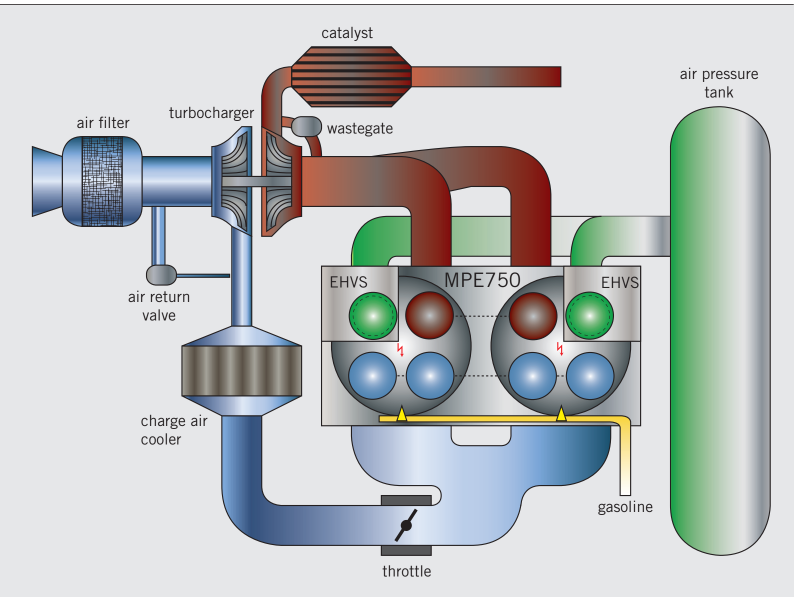
However, it should be emphasized that the main benefit of this concept is seen in the so-called supercharged mode. This is a modification of the conventional combustion cycle, ②, right. During compression, pressurized air is admitted via the charge valve into the cylinder allowing more fuel to be injected for the same engine cycle.

The “supercharged” mode enables the fastest torque step response possible. The main advantages of this mode lie in its use in combination with a turbocharger. The missing air in the system during transients is now made available using the air tank. The high fuel energy produces a high exhaust enthalpy that accelerates the turbocharger, making the additional air necessary for only a few seconds. This leads to the core of the concept: taking advantage of the synergy effects of downsizing with supercharging and the pneumatic hybridization. An illustration of the combined system investigated is shown in ❸.

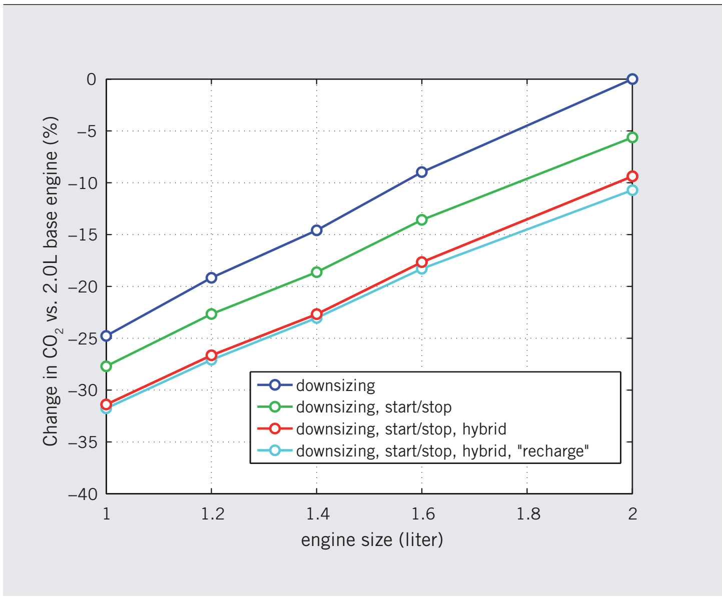
Another consequence of the described synergy effect is the elimination of the necessity to design the turbocharger for an optimal dynamic response. By contrast, it is now possible to maximally supercharge the engine system by configuring the turbocharger for highest efficiency. Thus, higher mean effective pressures and maximal downsizing are enabled.

To minimize emissions, the system must be tuned to ensure a stoichiometric air-to-fuel ratio. This is another advantage of the concept: using the established and cost-efficient three-way catalyst technology results in very low emissions.

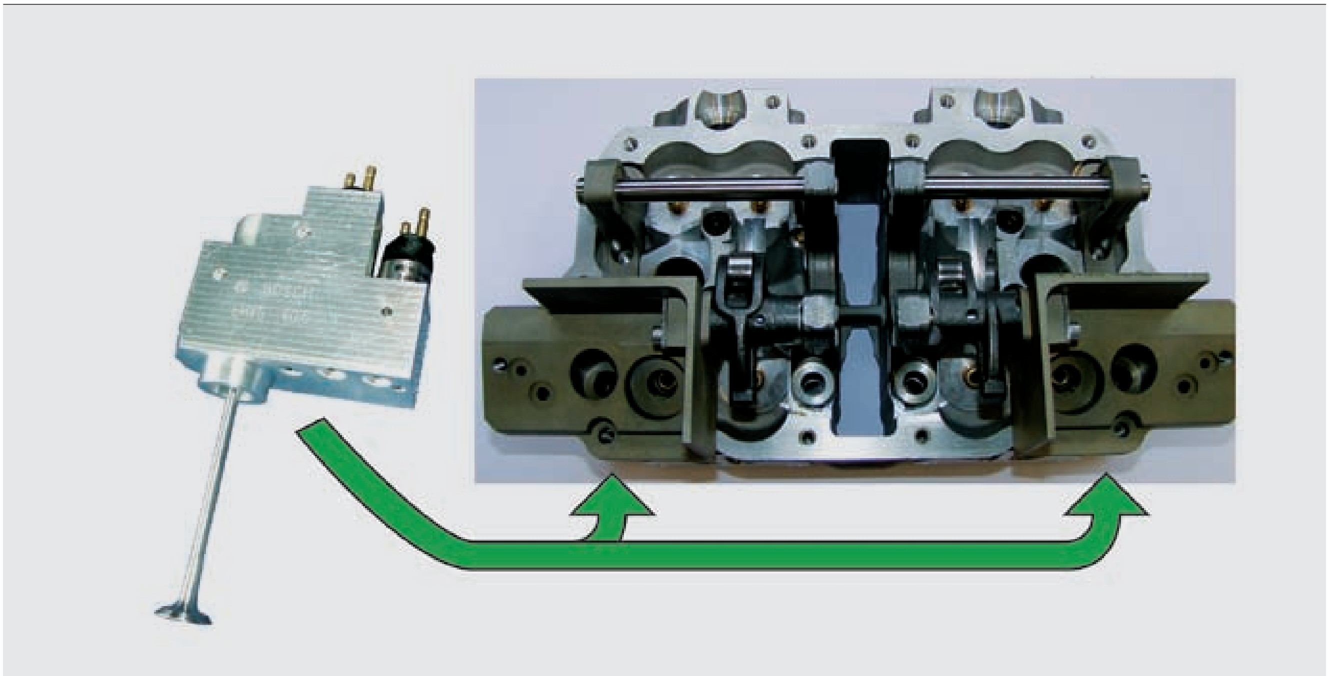
The main objective of the concept presented is to reduce fuel consumption without compromising driveability. Quasi-static simulations conducted in [9] revealed the amount of fuel savings that can be expected from the indiviual concept features. The results are summarized in ❹. The base engine for this investigation is a naturally aspirated gasoline engine with a displaced volume of 2.0 l and a rated power of 100 kW. The downsized engines investigated reach the same rated power



❸ Schematic of the downsizing boost concept



❹ Fuel saving potential study (NEDC)



❺ Modified gasoline engine MPE750 with electro-hydraulic valve system

using turbochargers. The most significant share of fuel consumption reduction results from strongly downsizing the engine. The start/stop and recuperation functionalities as well as the optional "recharge" mode only play minor roles for reducing fuel consumption.

5 HARDWARE AND TESTBENCH

All experiments were conducted by modifying a conventional gasoline engine (MPE750 produced by Weber Automotive). The MPE750 is a turbocharged two-cylinder engine with a displaced volume of 0.75 l (compression ratio 9.0), port fuel injection and a rated power of 61 kW. The pneumatic hybridization was realized by replacing one of the two exhaust valves per cylinder by a charge valve. A series production engine would of course require a cylinder head redesign to ensure an optimal compromise between exhaust back pressure at high engine speeds, volumetric efficiency and boost capacity. Adding direct injection devices to the engine would further increase the requirements for the cylinder head design.

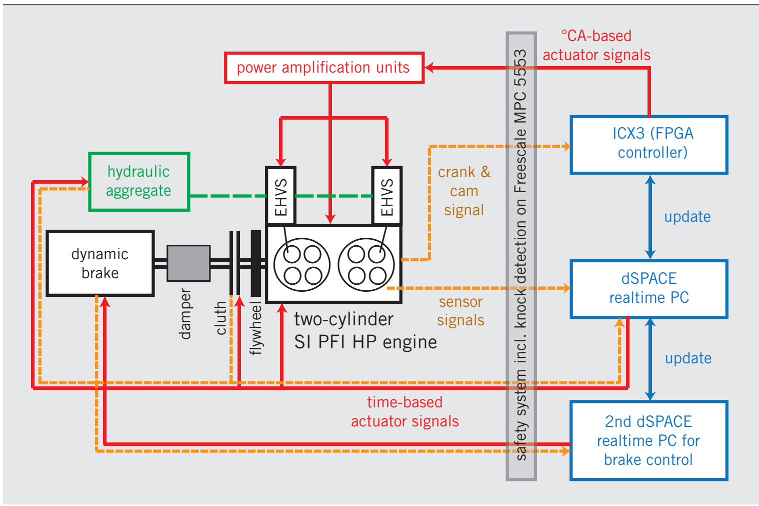
The charge valves are actuated by the electro-hydraulic valve system (EHVS, ❺), a research tool by Robert Bosch GmbH. The EHVS enables almost any variation of the opening angle, the closing angle, the opening speed and the lift from one cycle to the next [10]. Collisions of the charge valves with the piston are ruled out by limiting the maximum valve lift to 5 mm. This fully variable valve actuation system allows all additional engine modes illustrated in ②. In order to fully exploit the downsizing potential of the engine, the turbine of the GT12 turbocharger was replaced by the turbine of the GT14 turbocharger.

A 30-l steel air tank was used. It is mainly operated in the range of 4 to 16 bar. The calculations presented in [11] have shown that the volume of the air tank could also be decreased to about 10 to 15 l without having to compromise on the fuel saving potential of the engine concept. The air tank is not insulated, so that the air in the tank remains near ambient temperatures. This cold-tank strategy reduces the likelihood of knock when utilizing the "supercharged" mode.

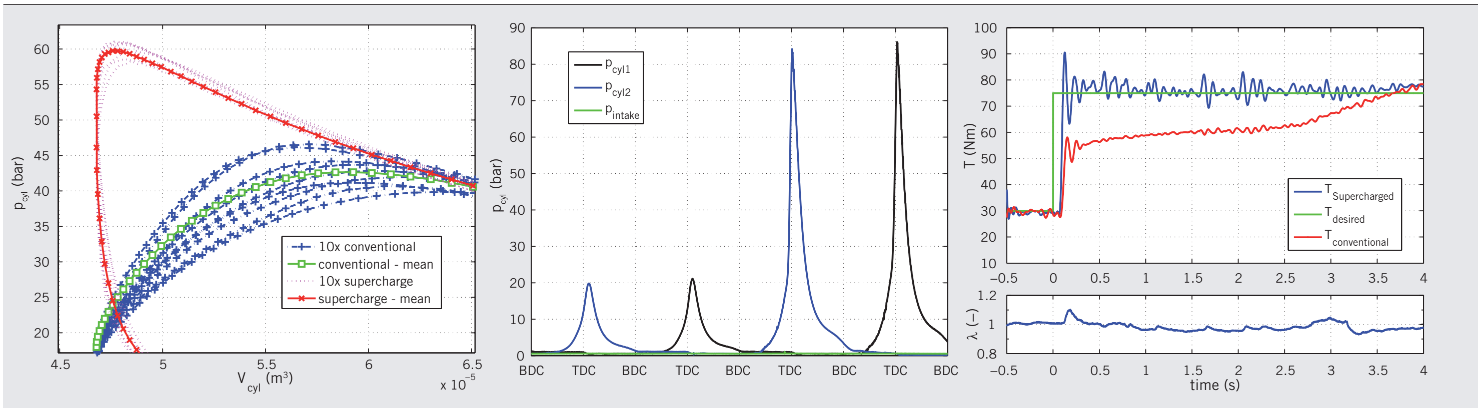
The testbench architecture, ❻, was designed to accommodate crank angle and time based sensors and actuators. This requirement calls for a flexibly programmable controller (FPGA). The IDSC has a long history of developing suitable research tools [12]. Hence, the very powerful tool ICX-3 was used to quickly advance the planned research activities.

6 MEASUREMENTS AND CONTROLS

The "supercharged" mode with inducted pressurized air proves to be advantageous for the combustion process, ❼, left. The generated turbulence results in a fast and stable combustion.



❻ Testbench architecture



❼ "Supercharged" mode measurements – combustion properties (left), torque step (center), overcoming the turbo lag (right)

However, the "supercharged" mode is only needed for a very short time in this concept: until the turbocharger approaches its steady state speed. The main contribution of the "supercharged" mode is therefore most directly described as overcoming the turbo lag. The "supercharged" mode allows instantaneous torque steps to be realized, ⑦, center. Here a torque step from 10 to 90 % load was performed and the cylinder pressure sensor signals are evaluated. Using this kind of torque step, the turbo lag can be eliminated, ⑦, right. The red curve represents the dynamic response of the system without the "supercharged" mode. This comparison shows clearly that the pneumatic hybridization inherently enables a strong downsizing without the loss of driveability.

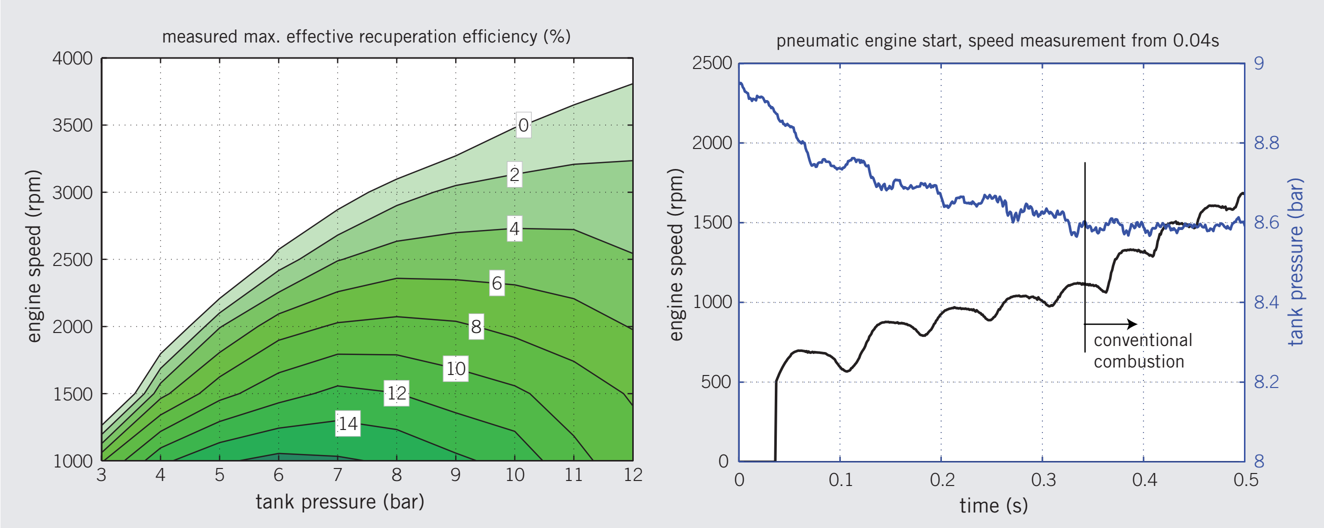
The realization of this kind of torque step poses difficult challenges to the control algorithms and the physical models that they are based on. The air mass inducted during the intake stroke as well as the fuel mass actually entering the combustion chamber has to be estimated very accurately to avoid misfire or increased emissions. Prior to injecting pressurized air into the cylinder, air-to-fuel ratios of down to $\lambda = 0.4$ are obtained. Hence, precise control of the EHVS has to ensure that exactly the missing air mass to reach $\lambda = 1$ is injected into the cylinder. Additionally, supervisory algorithms must guarantee that the charge valve is always closed once the cylinder pressure exceeds the tank pressure.

The purely pneumatic modes were realized for wide operating ranges. As expected, the use of the recuperated energy for pneumatic driving does not contribute much to the overall fuel savings. This can also be concluded from looking at the measured effective regenerative efficiencies, shown in ❽, left.

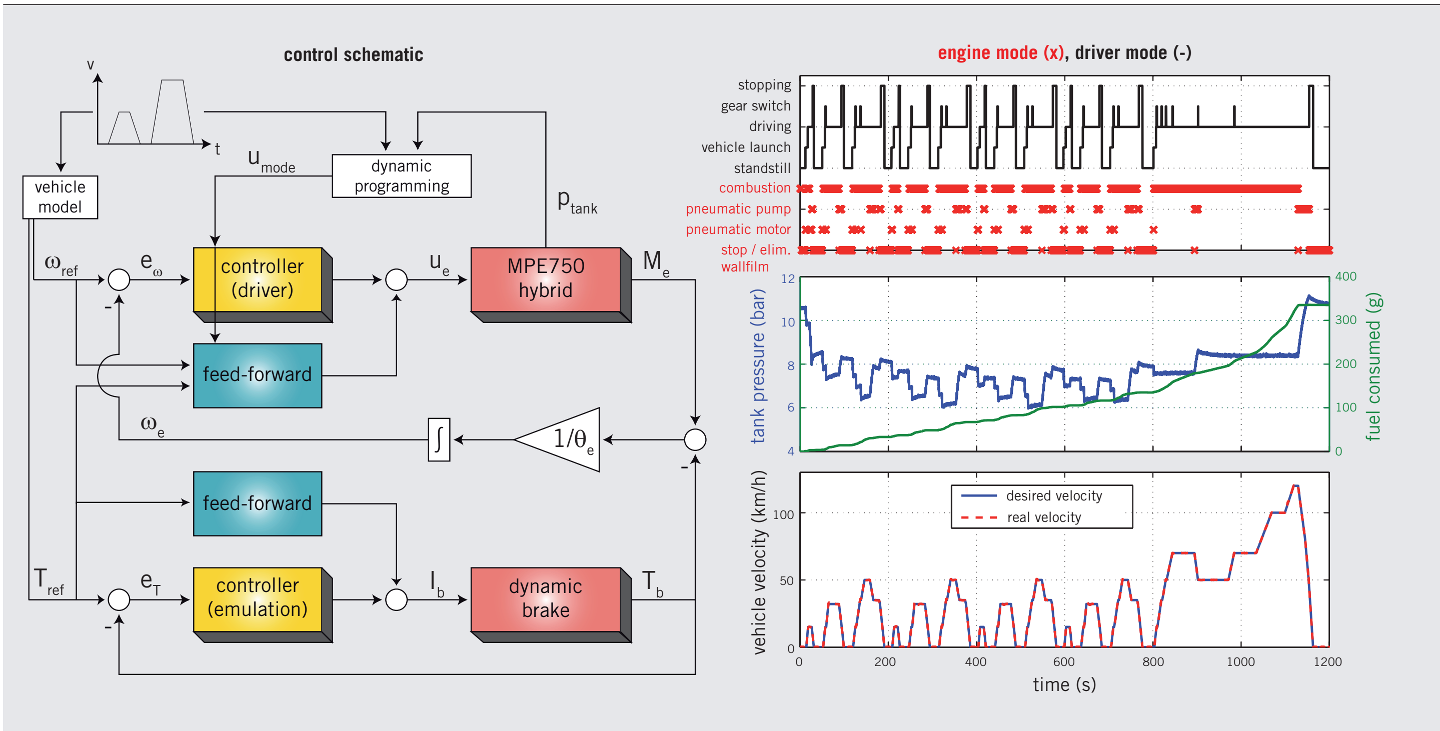
The pneumatic start could also be realized, ⑧, right. The incurred pressure drop amounts to about 300 mbar per start (for an air tank volume of 30 l). The pneumatic start is more than twice as fast as a conventional engine start and thus justifies the start/stop operation.

7 DRIVE CYCLE RESULTS

The verification of the fuel consumption reduction of the concept presented was conducted by means of a vehicle emulation using the test bench's fully programmable dynamometer. The dynamometer serves in this procedure as a virtual vehicle in a drive cycle. All relevant control algorithms for the engine and the brake systems were programmed in a Matlab/Simulink environment. This implementation has three principal modules. First, there are the



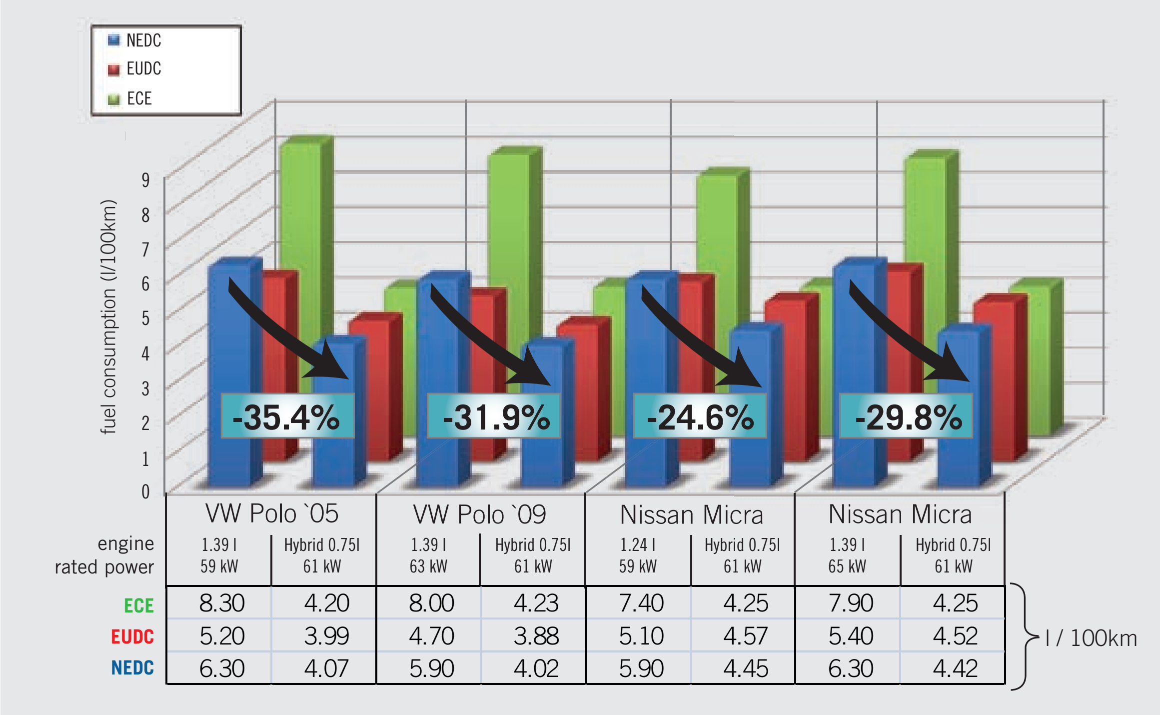
❽ Pneumatic modes measurements – measured regenerative efficiencies (left), measurement of a pneumatic engine start (right)



❾ Control schematic for vehicle emulation (left), fuel consumption, tank pressure and virtual speed measurements of a VW Polo with modified MPE750, including engine and driver modes (right)

control algorithms for the conventional operation and the additional modes, the mode change phases, and the optimal pneumatic start. Next there is a controller designed to emulate the torque demands of a typical driver. Finally, a controller for the brake is needed that emulates the vehicle according to the control structure illustrated in ❾, left.

Since the pump mode is based on a four-stroke cycle, the torque that can be recuperated is limited. Hence, 500 kJ of the available braking energy cannot be recuperated when considering a VW Polo emulated in the New European Drive Cycle (NEDC). However, one still has the option of using an electric generator to provide this energy to electric auxiliaries.



	VW Polo `05		VW Polo `09		Nissan Micra		Nissan Micra	
engine rated power	1.39 l 59 kW	Hybrid 0.75l 61 kW	1.39 l 63 kW	Hybrid 0.75l 61 kW	1.24 l 59 kW	Hybrid 0.75l 61 kW	1.39 l 65 kW	Hybrid 0.75l 61 kW
ECE	8.30	4.20	8.00	4.23	7.40	4.25	7.90	4.25
EUDC	5.20	3.99	4.70	3.88	5.10	4.57	5.40	4.52
NEDC	6.30	4.07	5.90	4.02	5.90	4.45	6.30	4.42

l / 100km

❿ Measured consumption reductions for various emulated vehicles

The results for the modified engine in a virtual VW Polo are shown in ⑨, right. The algorithms specify and implement the optimal engine mode for every point of time, thereby guaranteeing charge sustenance for the air tank over the whole drive cycle. The virtual driver can follow the demanded velocity trajectory without problems within the given boundaries.

To establish a fair comparison, commercially available vehicles with engines of similar rated power were chosen as the basis of comparison. The measured amounts of fuel consumed are illustrated in ❿. The fuel savings of the concept presented are in the range of 25 to 35 %, depending on the vehicle and engine power investigated. It was assumed that no additional torque was required for the operation of electric auxiliaries since electric recuperation provides a sufficient amount of energy throughout the drive cycle.

8 SUMMARY

The downsizing and supercharging concept for gasoline engines based on pneumatic hybridization developed at ETH Zurich was realized using a modified two-cylinder engine (displaced volume of 0.75 l, rated power of 61 kW). The anticipated driveability and fuel economy benefits were observed. In particular, the ability of this concept to eliminate the effect of turbo lag on the driveability of downsized and supercharged engines was confirmed. This engine concept proved to be capable of providing the fastest torque step that is possible using an engine's air path. Fuel consumption reductions of up to 35 % proved to be realistic.

The results shown could also be achieved using an electric hybridization. However, the additional drive train costs for a pneumatic hybridization are a small fraction of those associated with an electric hybridization.

REFERENCES

[1] Guzzella, L.; Onder, C.: Introduction to Modeling and Control of Internal Combustion Engine Systems. Berlin: Springer, 2004

[2] Guzzella, L.; Sciarretta, A.: Vehicle Propulsion Systems. Berlin: Springer, 2nd Edition, 2007

[3] Pfiffner, R.; Weber, F.; Amstutz, A.; Guzzella, L.: Modeling and Model-based Control of Supercharged SI-Engines for Cars with Minimal Fuel Consumption. In: Proceedings 16th American Control Conference (1997), Vol. 1, pp. 304-308

[4] Guzzella, L.; Martin, R: Das Save-Motorkonzept. In: MTZ 59 (1998), Nr. 10, S. 644-650

[5] Krebs, R.; Szengel, R.; Middendorf, H.; Fleiß, M.; Laumann, A.; Voeltz, S.: Neuer Ottomotor mit Direkteinspritzung und Doppelaufladung von Volkswagen. Teil 1. In: MTZ 66 (2005), Nr. 11, S. 844-856

[6] Schechter, M.: New Cycles for Automobile Engines. SAE Technical Paper 1999-01-0623, USA, 1999

[7] Higelin, P.; Charlet, A.; Chamaillard, Y.: Thermodynamic Simulation of a Hybrid Pneumatic Combustion Engine Concept. In: Int. J. of Applied Thermodynamics, Vol. 5 (2002), No. 1, pp 1-11

[8] Dönitz, C.; Vasile, I.; Onder, C.; Guzzella, L.: Modelling and Optimizing Two and Four-Stroke Hybrid Pneumatic Engines. In: Proc. IMechE, Part D: J. Automobile Engineering, Vol. 223 (2009), No. 2, pp 255-280

[9] Dönitz, C.; Vasile, I.; Onder, C.; Guzzella, L.: Dynamic Programming for Hybrid Pneumatic Vehicles. In: Proceedings 28th American Control Conference (2009), USA, pp 3956-3963

[10] Mischker, K.; Denger, D.: Anforderungen an einen vollvariablen Ventiltrieb und Realisierung durch die elektrohydraulische Ventilsteuerung EHVS. In: 24. Internationales Wiener Motorensymposium, Österreich, 2003

[11] Dönitz, C.; Vasile, I.; Onder, C.; Guzzella, L.: Realizing a Concept for High Efficiency and Excellent Driveability: The Downsized and Supercharged Hybrid Pneumatic Engine. SAE Technical Paper 2009-01-1326, USA, 2009

[12] Guzzella, L.; Geering, H. P.; Hirzel, H.: Anwendungsspezifische Chips für die Regelung von Ottomotoren. Technische Rundschau, 1987, Nr. 1/2, S. 46-49

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