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The SAVE Engine Concept

By Lino Guzella and
Roger Martin

An engine and vehicle concept is presented that was developed over the course of the last ten years by the Swiss company WENKO AG in Burgdorf, Switzerland. Their experience in racing applications showed that it was possible to achieve both high power and fuel economy in highly charged SI engines. On the basis of that experience, further development was directed specifically towards reduced engine size and high boost ratio, with the goal of significantly improving the partial-load behaviour of the engine. Objectives were to noticeably reduce the emissions and to keep system costs roughly equal to those of traditional approaches. With the engine installed in the SmILE vehicle, with the New European Driving Cycle and under consideration of the EURO III emission standards, a fuel consumption of 3.5 l/100 km was achieved, which is equivalent to a mean engine efficiency of approximately 22%.

1 Introduction

Mobility is one of the basic human needs, whose fulfilment must be assured in agreement with environmental and social concerns. When evaluating the new possibilities proposed, the following four points must first be considered:

1. Total system costs
2. Performance and transport capacities
3. Pollutant emissions
4. Fuel consumption or, more to the point, "well-to-wheel" CO_2 emission.

A noticeable ecological benefit of any vehicle can result only if it offers convincing solutions to all of the four points mentioned above. In this respect, the SAVE system presented here shows great potential, in addition to being applicable to any types of vehicles. **Figure 1** qualitatively shows the position of the SAVE concept with respect to other alternatives presently being considered. Despite the existence of comparable alternatives with regard to certain criteria, in an overall view, the SAVE system represents one of the most promising approaches at the present time [1].

2 The SmILE Vehicle

A new propulsion system is best judged by driving a vehicle in which it is installed. In this project, therefore, the SmILE vehicle – which is based on a series production car – was developed in co-operation with the two Swiss companies BRM Design and ESORO.

Without any changes to the vehicle's safety features, the improvements listed in **Table 1** were installed on the basic vehicle. It is important to note that none of the changes in the construction or in the materials used were in any way "exotic". About half of the weight reduction, for example, was achieved with the installation of the lighter SAVE engine.

The fuel consumption level of any vehicle depends on the amount of mechanical energy required to achieve a desired driving profile. The so-called New European Driving Cycle (NEDC) has become a standard and is also being used here. Since it is rather sharp-edged, it permits the derivation of a good estimate of the energy required for given vehicle resistances as shown in Eq. (1).

With reference to the data shown in Table

1 and using Eq. (1), a 30 % reduction in mechanical energy needed to drive the NEDC with the SmILE is observed. However, it would be premature to conclude from this that, without any changes to the engine, the fuel consumption would also be reduced by 30%. This potential is realized only if the powertrain and the vehicle are optimally matched, especially in the partial-load behaviour.

3 The Basic Idea

Globally, automobiles powered by SI engines which are operated at stoichiometric conditions predominate by far. These engines can be mass produced economically and they adequately fulfil customer demands with regard to driving performance. Moreover, using three-way catalytic converters, the pollutant emissions of these engines have become very low.

One of the disadvantages of present-day SI engines is the reduced efficiency that results whenever they are operated significantly below full load. **Figure 2** shows a schematic engine map, where the iso-efficiency curves are shown as a function of rpm (μ) and torque (M $\bar{\eta}/2$ represent points with an efficiency equal to one half of maximum efficiency). Both in real life and in test cycles, today's engines are typically operated in the grey area, i.e., clearly below their most efficient operating points. The two main reasons for this drawback are:

- Each engine requires a certain power to compensate for the losses due to friction, the relationship between net and friction power being worse in low-load than in high-load operation.
- In stoichiometrically operated SI engines, the load is determined by throttling the air intake. Unfortunately, this approach causes substantial losses.

The first set of these problems may be dealt with by constructive means, such as low-friction valve-trains, improved cooling, etc. This approach is being taken in all engine development projects. Chapter 6 will show some details of the measures taken in the SAVE engine concept. Notice that internal friction losses are substantially reduced with lower engine size, especially with a reduction in the number of cylinders.

The so-called "throttling losses" P_D occurring in "quantity-controlled" four-stroke engines may be estimated as shown in Eq. (2). In driving at reasonable, constant speeds, these losses may be on the same order of magnitude as the load necessary to propel the vehicle. Among the approaches that can be taken toward reducing these losses, we may list the following:

A) Lean-burn engines
B) Exhaust-gas recirculation
C) Variable valve timing
D) Reduction in engine size with an accompanying increase in engine speed
E) Reduction in engine size with an accompanying increase in boost pressure (the SAVE approach).

All these approaches have the goal of bringing less fuel into the cylinder (which reduces the torque), without reducing the manifold pressure. Approach A has successfully been used in Diesel engines for over a hundred years and is now being applied to GDI engines as well. If pollutant emissions do not have to be taken into account, such quality-controlled engines (ideally Diesel engines) are a good choice, as far as efficiency is concerned. Approach B has become wide-spread already, particularly for emissions reduction. However, its disadvantage is that it does not allow the load to be controlled in its full width. Approach C has been a research topic for a long time; the fact that the breakthrough has not occurred as yet is probably due to technical problems. Approach D requires automatic transmissions with a large gear ratio (ideally continuously variable) and with very fast responses to ratio changes. However, even at best, those engine dynamics are unlikely ever to reach those of modern SI engines.

Approach E, on the other hand (black curves in Figure 2), in accordance with Eq. (2), shows some real promise in that the first term of Eq. (2) does not suffer any worsening (in contrast to approach D). At the same time, E reduces both of the other two factors. Due to the smaller engine size, the engine is being operated frequently at WOT (cf. black full-load line AL (p=1) in Fig. 2). Obviously, without any additonal measures being taken, such an engine can never fulfill the drivers demands with respect to driveability. In the SAVE approach, these torque peaks are covered by an increase in the manifold pressure (again, cf. black full-load line AL (p=2) in Figure2).

The desired consumption reduction is achieved only through rather significant reductions in engine size, which result in the concurrently high boost-pressure ratios. The related open questions such as response time, control problems, engine knocking, etc., will be discussed below.

4 The SAVE System

As an example, **Figure 3** shows a three-cylinder engine system structured according to the SAVE approach. The following three controls are noteworthy (since the injection system is tied to the air mass, it is not shown in detail, nor is the burner/ventilator being considered since it is active during cold starts only):

1) Regular throttle valve DK1, which controls the load control for low torques (i.e., idle speed up to around half load, in Figure2 between 0 and π=1).
2) "Variable gas pocket intake" (VGTZ), which controls the high loads (in Figure3, between π=1 and π=2)
3) Additional throttle valve DK3, which controls the mass of scavenge air flowing through the supercharger.

The boost ratio of a pressure-wave supercharger (PWSC) is controlled in a way similar to that of a turbocharger (TC) with a waste gate, where part of the exhaust gas is led past the boost process. However, in a PWSC the scavenge process needs energy, too. Therefore a "variable gas pocket intake" (VGTZ) diverts a controllable variable part of the exhaust gas past the high pressure process, but not past the scavenge process. In the SAVE concept, exhaust gas cleaning is closely tied in with the PWSC system. Since a pressure wave loader adds fresh air to the exhaust in the scavenge process, it is possible to use that as a basis for further improvements and greater efficiency in the cleaning of exhaust emissions. The first catalyst acts as a three-way catalyst in the low-end to medium torque range up to about 20 bar pme, i.e., with a stoichiometric mixture. Due to its physical location close to the engine, it reaches its "light-off" temperature very fast. At high torque levels, the mixture is enriched for inner cooling. This causes the NO_x reduction step in the first catalyst to work very efficiently, although some HC and CO in the exhaust remain unoxidized. Due to the PWSC rinseover, however, these emissions are oxidized in the second catalyst. The controller, assisted by the throttle valve DK3, ensures an optimal temperature for this catalyst.

The catalytic converters utilized are two commercially available metal catalysts with a three-way lining of 100 g/ft^3 (Pt:Pd:Rh =0:14:1). The results shown in Section 7 indicate that, with optimized lining combinations and an improved engine electronics system, it is possible to fulfil the expected EURO IV or ULEV norms without any problems.

5 Boosting with PWSC

One of the unusual features of the SAVE system is the pressure wave supercharger (PWSC). Except in a race car variety, PWSCs so far have only been utilized in Diesel engines. Mazda once produced about 150,000 passenger cars equipped with Diesel engines and PWSCs [3]. The PWSCs used in the SAVE engine, however, are quite different from those, particularly with respect to their behaviour in the low engine speed region.

The choice of a PWSC was made after a six-year period of unsuccessful attempts at utilising turbochargers (TC) or mechanical chargers (MC). Neither of those are suitable for use in small engines (i.e., less than one litre displaced volume) and high boost levels (i.e., greater than 2 bar). The main reasons are as follows:
- MC: With rising boost pressure, noise levels rise disproportionately. The power needed to drive an MC is so high that it causes comfort problems when the loader is engaged, and the fuel consumption advantage gained due to the small engine size is largely lost again.
- TC: Aside from the dynamic behaviour, the best pressure ratios statically possible for small displacement engines are unsatisfactory. In addition, the efficiency of small TCs decreases substantially. Further problems arise due to high temperatures and the high shaft speeds.

Figure 4 shows the static behaviour of a very small TC specially developed for use in small engines and its corresponding PWSC. Clearly, with the TC, practically no boost pressure is generated below 3,000 rpm, whereas with the PWSC, full power is already available at just over 2,000 rpm. If transient behaviour was considered, or if the TC had somewhat larger dimensions (i.e., with reserves for altitude compensation and durability), the difference would be even more obvious.

The well-known advantages of the PWSC are
- Extremely fast response times (delays in the range of a few 10 ms)
- High boost pressures at low engine speeds (with a 360 cc engine, 2 bar at 1,700 rpm were attained)
- Positive pressure differences over the engine in most operating conditions
- Large altitude reserves, i.e., no problems with overspeeding
- No problems due to mechanical or thermal stresses at high pressure levels
- Good damping of engine noise due to the multi-cell rotor. In the SmILE vehicle, with only an absorption muffler, the Swiss regulations were easily met (69.5 dB A).

The recirculation of the "blow-by" or the purging of the active carbon canister have also been solved for SI engines. Noise has been reduced to a negligible level due to the asymmetrical arrangement of cells. And finally, the use of new controllers has helped to reduce the problems associated with cold starts and the undesirable recirculation of exhaust gases.

Inhouse developments of PWSC at WENKO over the past three years have yielded the following improvements (compared to the situation in 1995):
- Increased pressure ratios at low speeds by a factor of two (i.e., from p=1.2 to π =2.4 at 2,000 rpm)
- Further reduced noise level over the entire operating region by 8-15 dB (A)
- Improvement of the compression efficiency at medium or high engine speeds.

In contrast to these achievements, a two-year development project on an especially small TC in cooperation with a leading manufacturer did not yield any significant improvements. The top pressure ratio at around 2,000 rpm was merely raised from about 1.1 to 1.25.

6 Mechanical Design

In the SmILE project, a 2-cylinder SAVE engine in boxer configuration is used, **Figure 5.** As far as cost is concerned, as well as in its friction behaviour, it is comparable to other 2-cylinder engines, either in-line or V type with balancing shafts. With respect to vibrations, of course, the SAVE engine is far superior to other concepts. The crankshaft drives an intermediate shaft via a cogwheel which in turn drives the two overhead camshafts via sets of cogwheels and chains. The engine concept allows for simple adaptation of the cast cylinder blocks on either side. Further engine data are listed in **Table 2.**

One of the primary design goals of this engine was low friction. Therefore, only the crankshaft is supported by a journal bearing and is pressure lubricated. All other rotating parts are on roller or needle bearings and spray lubricated.

Only two openings in the crankshaft housing were necessary, one for the crankshaft and one for the water pump. Due to the high mean effective pressures, the pistons are similar to other high-performance types, both as far as their length and the number of rings are concerned.

Based on many years of experience with highly supercharged engines, the SAVE engine was designed to withstand high loads. Neither the piston speeds and accelerations to be dealt with, nor the loads on the crankshaft pose any particular problems concerning stresses, as they are no higher than those in mass produced supercharged engines currently in use. The high power density, however, causes unusually high thermal loads, which require a special cooling system design for the cylinder head. With this novel design, improvements in friction, full-load, and knock behaviour were observed, too. So far, no long-time full-load test runs have been performed due to limited project funds. However, 50,000 km driven on the road as well as several hundred hours on the test bench with no serious mechanical failures demonstrate the engine's mechanical and thermal qualities.

Regarding the overall costs, it is important to consider the entire system rather than single components only. Obviously, smaller and lighter engines require less demanding mountings, simpler and thus cheaper noise-abatement provisions (also due to the PWSC), and they have a number of positive secondary effects (e.g., requirement for smaller tanks, starters, and batteries). In comparison to engines of various other designs, such as TDI, GDI, or even hybrid or fuel-cell vehicles, the overall costs of the SAVE engine should be no higher than any of those.

7 Test Results

Figure 6 shows the engine map of the SAVE engine used in the SmILE vehicle. The fuel consumption data shown are those measured at ETH in 1997, where the full load was artificially limited. Those measurements were made on a standard test bench in accordance with the current standards. The fuel mixture was stoichiometric at lower loads and enriched ($\lambda \geq 0{,}88$) at higher loads. The ignition point was chosen to be at MBT or at the knock limit, respectively, as detected by means of cylinder pressure sensors. The fuel was lead-free gasoline (ROZ nominal 95; density at 20° C of 747.4 kg/m^3, mass fractions C = 85.62%, H = 13.77%, O_2 = 0.7%).

The full-load trace shown in Figure 6 represents the latest results (1998) achieved by the SAVE engine as measured at WENKO AG. Moreover, a number of measurements showed significant reductions in fuel consumption (5% – 7% at relevant operating points).

An analysis of the efficiency contours clearly shows the main difference between the SAVE engine and "typical" SI engines: Rather than aiming for minimal fuel consumption at high loads, the SAVE engine concept achieves a broad "minimum-consumption island" at those operating points most relevant in day-to-day operation and in the NEDC. At high loads, the fuel efficiency decreases slightly due to the rich mixture, later ignition (knocking prevention), etc. However, since those operating points do not occur frequently, fuel efficiency in overall use is clearly improved.

The latest version of the SAVE engine was tested according to the EURO III standards in April 1998 at the Swiss Federal Materials Testing Institute (EMPA) in Dübendorf, Switzerland. The results are listed in **Table 3**. The good results indicate a potential for achieving more stringent standards such as the German D3 or the EURO IV norms. Moreover, the CO_2 emission level clearly fulfils the conditions postulated for a "three-litre vehicle", with a fuel consumption of only 3 litres per 100 km.

Further details concerning the SAVE system are shown in **Figure 7 and 8**, although they relate to the older PWSC version. As important as fuel efficiency and low exhaust emissions are, the aspect of driveability is a decisive factor for customer acceptance. The dynamic response of the engine to a quickly increasing torque requirement is shown in **Figure 9**. Between the desired torque derived from the position of the driver's pedal and the actual boost pressure, a negligible time delay of about 0.1 s can be seen at sufficiently high engine speeds. Similarly good responses at all relevant operating points and engine temperatures are achieved with the latest version of the SAVE engine.

8 Conclusions and Outlook

The SAVE engine concept presented in this paper permits a significant reduction in fuel consumption for automobiles all the way up to the upper mid-size class, without any compromises in power, comfort, driveability, or pollutant emissions.

The replacement of current passenger car engines by smaller, highly supercharged types not only makes these cars run more economically, but a better weight distribution improves their driveability. The smaller size of the powertrain opens new possibilities for the design and the installation of safety features as well. The weight spiral evident over the past years can thus be reversed (reduced fuel consumption means smaller fuel tanks, and engines with reduced friction require smaller starter motors and smaller batteries, etc.).

This engine concept obviously still requires further development steps before it is suitable for series production. However, there is no doubt that the automobile industry is able and motivated to develop and market this or similar economical engines and vehicles. These efforts remain futile, however, as long as such cars do not appeal to the buyer. The market decides mostly on the basis of economics rather than ecology. Nevertheless, the reduction in fuel consumption over the entire spectrum of vehicle classes is of pre-eminent importance in the effort to reduce possible greenhouse effects. The proposed SAVE design for car engines is meant to be a contribution towards the solution of these problems.

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The ideas and prototypes described in the paper have been proposed by H. P. Götti, H. R. Jenny, B. Kohler, R. Martin and U. Wenger, WENKO AG, Burgdorf. The boost controllers and some calculations and measurements have been contributed by A. Amstutz, E. Cortona, L. Guzzella, R. Pfiffner, P. Soltic, and F. Weber, ETH Zürich.

$$E = 19'000 \cdot c_w \cdot A_f + 860 \cdot c_r \cdot m_f + 12.7 \cdot m_f \ kJ/100\ km \text{ NEFZ} \quad (1)$$

$c_w \cdot A_f$ = drag coefficient x frontal area, in m^2

$c_r \cdot m_f$ = rolling friction coefficient x vehicle mass, in kg

$$P_D \approx \frac{n}{2} \cdot V_h \cdot (p_0 - p_m) \quad (2)$$

n = engine speed in rps

V_h = swept volume in m^3

$p_0 - p_m$ = engine pressure difference in Pa