

Project Sabre: A Close-Spaced Direct Injection 3-Cylinder Engine with Synergistic Technologies to Achieve Low CO₂ Output

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ABSTRACT

The paper describes the design and development of 'Sabre', a 3-cylinder engine encompassing a combination of technologies to realise low CO₂ in a practical automotive application while retaining driving pleasure (vehicle acceleration performance). This project is a partnership with Continental Automotive, in which Lotus Engineering is responsible for the base engine and combustion system.

The decision process that led to a close-spaced direct injection combustion system that does not target high BMEP as the chief route to low fuel consumption is described. Instead of pursuing an approach in which specific power is maximized in order to reduce throttling losses at part load, mild downsizing coupled with throttling loss reduction and turbulence manipulation enabled by a switching valve train is employed. This approach, together with the use of an integrated exhaust manifold, enables cylinder head packaging benefits together with improved driveability and reduced high-load fuel consumption as a result of a lower boost requirement. The interaction of spray and air motion in the resulting homogeneous combustion system is briefly discussed.

The rationale behind the choice of a 3-cylinder layout is also discussed which, in addition to reducing friction and engine mass, also contributes towards knock control by removing blowdown pulse interaction between the cylinders. Friction reduction methods are discussed which centre around the use of laser-deposition bores and roller bearings on the balance shaft. The balance shaft helps to address the NVH issues expected from the layout, together with the very low CoV of IMEP afforded by the combustion process. The technology under-pinning the integrated exhaust manifold is also discussed. This simultaneously improves thermal management and reduces mass and bill-of-material (BOM) costs in this integrated engine concept.

INTRODUCTION

The Sabre project was formed to create an advanced engine to act as a baseline for future spark-ignition engine technologies. This is reflected in the acronym Sabre, short for 'Spark-ignition Advanced Baseline Research Engine'. The Project Sabre engine employs a novel and synergistic combination of engine downsizing, gasoline direct-injection and variable valve train technology to realize low CO₂ and improved driving pleasure in a cost effective, affordable manner.

The challenges facing the automotive industry include a requirement to reduce CO₂ emissions from the vehicle fleet whilst retaining driving pleasure (vehicle acceleration performance) in a cost effective manner. CO₂ emissions are directly related to fuel consumption and so many new technologies have been proposed, developed and productionised with the aim of improving fuel economy [1]. Of those related to engine efficiency, engine downsizing, direct injection and variable valve trains have all been introduced with varying degrees of success [2, 3, 4].

Extreme downsizing is one route to greater fuel economy that, in 2005, saw the series introduction of an engine combining turbocharger, supercharger and gasoline direct-injection system (GDI) in the Volkswagen TSI engine [5, 6]. This increased level of technology has been shown to significantly improve vehicle fuel consumption and so the trend is expected to continue, though the combination of roots blower and turbocharger has previously been employed by Lancia in their rally cars [7].

Despite this current developmental direction, there is still some desirability in not reducing swept volume excessively for a downsized engine. This is due to the fact that throttle response – so-called 'turbo lag' – becomes less of a challenge, and with it the engine

knock challenges of operating a spark-ignition combustion process at high brake mean effective pressure (BMEP). Indeed, the challenges faced by the engine designer are so great as the degree of downsizing of an engine increases that variable compression ratio (VCR) has been proposed [8], though there are significant challenges in productionising this concept in current engine architectures.

All of these approaches and problems stem from the fact that the automotive industry remains committed to the 4-stroke, or Otto, cycle and reducing the amount of throttling loss it suffers is the primary aim of most of these concepts.

That vehicle driveability starts to become a major issue is amply illustrated by the adoption of a supercharger in the Volkswagen TSI concept. This device is used to maximum effect because as well as providing 'tip-in' throttle response it has also allowed the turbocharger turbine to be enlarged to the benefit of full-load fuel consumption – the vehicle it has been introduced in is reported not to need fuel enrichment for component protection until a speed of 200 km/h (124 mph) is reached [6]. However, the supercharger, its drive system and extra air ducting (including bypass valve) all combine to add cost to a turbocharged GDI engine, as well as control challenges. Any approach which would permit the excellent fuel economy to be retained in a simpler, cheaper package while not requiring an overly small turbine to be used (to the benefit of high load fuel economy) should be of interest.

Additionally, the higher the degree of supercharge applied to an engine the worse the knock problem may be expected to become, particularly at low engine speed. Knock, resulting from uncontrolled autoignition of the end gas of a spark ignition engine, has been one of the chief barriers to increased efficiency throughout the history of the spark ignition engine [9]. New technologies such as turboexpansion [10] and cooled EGR [11] are being developed to decrease the octane appetite of engines, but the adoption of GDI in high specific output engines has already allowed their compression ratio to be increased due to the beneficial effect of the evaporation of the fuel in the cylinder lowering the temperature of the charge (and with it end gas temperature). The advanced ignition angle also made possible by this effect together with the higher expansion ratio have both permitted lower exhaust gas temperatures, so helping to reduce pre-turbine temperature and with it the need for economy-reducing component protection fuelling at high road speeds. The introduction of fuel into the charge air only after the exhaust valve has shut permits greater amounts of valve overlap to be used. This results in an attendant shift of operating point on the compressor map, increasing the surge margin, and greater enthalpy in the exhaust due to secondary oxidation of CO in the manifold, both to the benefit of driveability. Because of all these advantages

and others, the turbo-GDI synergy is one of the strongest technologies for general fuel consumption reduction.

The combination of variable valvetrain and gasoline direct-injection unlocks the potential for true downsizing through reduction in throttling losses during low-load operation [1] while pressure charging maintains engine power. Thus the Sabre engine makes an excellent alternative powertrain for a modern, clean C-class vehicle – retaining the torque delivery of a 2.0 / 2.2 litre engine and thus retaining driving pleasure.

DESIGN RATIONALE

The Project Sabre engine set out to achieve three key objectives:

- Demonstrate low CO₂ emissions;
- Improved driving pleasure;
- Use of cost effective, affordable technology.

The decision process that led to the engine design concept that meets these objectives is set out below. Although appearing as discrete decisions in the text below, they are in fact all interlinked and the overall decision process was an iterative one.

Low CO₂ emissions can be achieved by downsizing, this being a clear industry direction with increasing degrees of downsizing being implemented. However, extreme downsizing requires operation at relatively high BMEP to be realised, and this brings about issues with driveability, combustion variability and fuel enrichment for component protection. Additionally, if the cylinder count is not to be reduced, the architecture potentially forms a type of barrier to the engine (since the bore size and thus the valve and injector packaging may become constraints).

Some of these issues can be addressed by advanced charging strategies, e.g. sequential turbocharging, variable geometry turbochargers [12] or electrically driven compressors [13] but these all add to the cost and complexity of the overall powertrain system. Against this, a fixed geometry turbocharger offers significant advantages in terms of BOM and control issues.

There are also related mechanical advantages from limiting the BMEP levels used. The maximum cylinder pressure is lower and thus the structure of the engine can be sized appropriately, which in turn has cost and weight benefits as well as potentially reducing the engineering required to ensure durability and reliability.

Decision 1 – Mild downsizing: Downsize from 2.2 litre 4-cylinder with natural aspiration to a 1.6 litre turbocharged

engine, thus maintaining performance. Maximum BMEP required: 20 bar.

The synergies between direct injection and turbocharging are well known and result in cold start emissions improvements and high load fuel consumption reductions. Further reductions in CO₂ emissions, along with performance and exhaust emissions benefits brought about by in-cylinder air and trapped exhaust gas management, can be obtained by using direct fuel injection and twin continuously variable cam phasing (CVCP) devices on turbocharged engines [14].

Centrally-mounted “vertical” or close-spaced fuel injectors exhibit less potential for cylinder bore washing with fuel and allow for alternative combustion strategies, e.g. homogeneous or stratified, compared to an under-port injector location. Such a close-spaced configuration does not compromise the intake port in the same way that an under-port injector location does.

Close-spaced spray-guided systems are relatively expensive, with current stratified production systems adopting high-pressure piezo-injector technology [15]. Lean stratified operation also requires the use of an expensive de-NO_x catalyst giving cost and fuel consumption penalties. Since a cost-effective combination of technologies was an objective for the project, a homogeneous system was chosen due to the reduced demands for exhaust gas aftertreatment. However, while outward-opening piezo injectors offer charge preparation advantages over traditional swirl-injector-based solenoid systems, new developments have resulted in ‘multi-stream’ injectors offering better spray shape and fuel atomization than pressure-swirl-type components.

Decision 2 – Adopt direct injection in a centrally-mounted close-spaced configuration: Use new multi-stream solenoid injectors rather than a pressure-swirl type. Adopt twin cam phasers for improved control of gas exchange.

Choosing a close-spaced combustion system gives advantages in freedom of intake port design but clearly represents a challenge in terms of packaging in the combustion chamber. While 10 mm spark plugs are being productionized and were adopted for the project, it was considered that at 1.5 litres, a 4-cylinder engine (i.e. 375 cc per cylinder) would have had too restrictive a bore to package a central injector, spark plug and four adequately sized valves, given the targets and objectives for this particular project. A brief early study showed that an 83 mm bore would to all intents and purposes be too small to package all of the necessary components in this case.

Compared to a 4-cylinder layout, for any given swept volume a 3-cylinder configuration clearly allows a bigger bore size. While 83 mm was considered too small

regardless of cylinder number, the same study showed that with a bore of 86 mm uncompromised packaging space is available for a centrally-mounted direct injection system. With the 500 cc cylinder made possible by the 3-cylinder layout, a bore diameter of 86-88 mm is typical for a light-duty engine. The choice of a larger bore size clearly made packaging easier; packaging for a smaller bore size is possible with a different set of design targets and objectives.

Another advantage of adopting a 3-cylinder configuration is that in such even-firing cylinder groupings there is the eradication of inter-cylinder exhaust pulse interaction in the valve overlap period which may occur when the firing interval is less than 240°. This is of significant benefit in turbocharged engines. (Note that adoption of such a strategy on a 4-cylinder engine without a pulse-divided exhaust manifold [14] results in a very short exhaust valve event [16], though strategies such as Divided Exhaust Period can help offset the need for a 180° valve event. [17]). Removing pressure wave interference in the valve overlap period improves the scavenging process, improves enthalpy transport to the turbine and extends the knock limit further through reducing the mass of trapped residuals in the combustion chamber. While removing a cylinder reduces friction, a disadvantage of the 3-cylinder configuration is the creation of a primary couple, but this is of conical nature and can be addressed by using a counter-rotating balance shaft. Fitment of roller bearings to this shaft will minimize its friction.

Decision 3 – Adopt a 3-cylinder configuration for adequate packaging, lower BOM and knock limit extension: Adopt a roller-bearing balance shaft for NVH purposes.

Further reductions in CO₂ emissions can be obtained by reducing throttling losses. Stratified charge, spray-guided combustion systems enable direct reduction of throttling losses during part load operation because for any road load they permit a wider-open throttle [15]. There are also thermodynamic benefits through lean operation. However, they require relatively expensive piezo-injector technology and expensive exhaust aftertreatment systems capable of removing NO_x from the exhaust stream in an oxygen-rich environment. Such de-NO_x systems also require periodic regeneration with a rich/stoichiometric pulse which, while it can in many cases be synchronized with driving style, contributes to a reduction in the potential overall fuel consumption improvement.

Instead of stratified operation, other means of reducing throttling loss exist. Among other researchers, Tuttle [18, 19] showed that both early and late intake valve closing (EIVC or LIVC) could improve part load efficiency. This improvement resulted in the introduction of Valvetronic, a variable EIVC system, by BMW [4].

The advantages in this system stem from direct dethrottling of the intake phase, because gas exchange is performed at lower manifold depressions. Also, while the effective compression ratio reduces with advanced intake valve closing (EIVC), the expansion ratio does not change, giving a thermodynamic benefit.

Tuttle [18, 19] reported that, particularly in the case of EIVC, the combustion duration starts to increase, an effect believed to be due to the reduction in charge motion in the cylinder. To counter this, deactivating one intake valve at part load has the effect of increasing turbulence at reduced air flow. Such a technique has been employed in production engines with conventional valve events by GM. Honda have also used this approach with asymmetric valve profiles in their VTEC-E engines, and similar valve strategies were investigated by Wilson and co-workers [20] in a fully variable valve train research engine.

Similar research work undertaken by the HOTFIRE consortium (funded by the Engineering and Physical Sciences Research Council in the UK) using the same electrohydraulic Active Valve Train (AVT™) system was targeted at realizing the benefits of homogeneous DI with variable valve actuation. This research project provided results that substantiated the adoption of this approach [21, 22] and helped to develop the strategy of using the valve profiles necessary for Miller-cycle operation to also manipulate the air motion in the cylinder which promotes swirl and improves mixture preparation. Extensive experience of the development and productionization of switching valve train systems (especially the so-called cam profile switching or CPS tappet) ensured that the technology could be implemented in Sabre in a cost effective manner.

Hence, by combining valve deactivation with cam profile switching, a solution could be realised that reduces throttling losses whilst simultaneously enhancing in-cylinder air motion (swirl) - this was a significant factor in developing a close-spaced DI combustion system. The adoption of so-called 'swirl-DI' allowed the extension of the combustion period noted by Tuttle [18, 19] to be minimized. Note that similar synergies between asymmetric valve events and DI combustion systems have been noted by other workers. Audi have just productionized an engine with a combination of an under-port direct injection system and switching valve train to reduce throttling loss [23].

In concert with the adoption of this strategy, less extreme downsizing to mitigate throttling loss is permitted because a proportion of this parasitic load is removed by the valve train. As a consequence, the need for ever-higher BMEPs is avoided, and with it the attendant challenge of controlling knock and irregular combustion. It is also suggested that since good thermal efficiency can be arranged in what is effectively

a larger displacement engine, the Sabre engine may be more attractive to the marketplace.

Decision 4 – Adopt switchable valvetrain system to afford Miller cycle operation: Deactivate one intake valve, switch the other to a low lift / short duration profile to generate increased turbulence.

As a consequence of employing direct throttling loss reduction through the functionality of the valve train the use of a larger swept volume engine is supported. Improving driving pleasure through mild downsizing and turbocharging avoids the issues of driveability associated with extreme downsizing but the concept can still be vulnerable to "turbo-lag". To help address this, mild hybrid systems have been studied in conjunction with turbocharged engines through their ability to enhance transient torque while the turbocharger is spooling up [12]. They have also been shown to contribute to a reduction in CO₂ emissions through stop-start operation and idle stop functionality. As a contribution from the engine side, the reduction in turbo-lag by the requirement for only modest downsizing means that the requirements placed on the hybridization system are less severe and hence its costs can be better supported. In the Sabre engine, the use of mild hybridization also indirectly supports the use of an exhaust manifold integrated into the cylinder head (IEM) because the transient torque increase of the hybrid system offsets any effect that the reduction in enthalpy has as a result of cooling the pre-turbine exhaust gas in the aluminium of the manifold. This will be returned to later.

Decision 5 – Use a mild hybrid system: Crankshaft mounted starter / alternator for start / stop, regeneration and torque assist functions.

The considerations discussed above led to the decision to design a relatively large displacement 3-cylinder engine in which the use of direct injection and dual cam phasers, in concert with the removal of pulse interaction through the 240° period of the firing impulses, would all contribute to a minimization of the requirement for overfuelling for knock suppression. However, even if overfuelling to extend the knock limit was avoided, it is often necessary to over-fuel at high load for component protection of either the piston crown, exhaust valves, turbine wheel or catalyst. This results in a reduction in combustion efficiency and fuel economy which is not required to suppress knock. Methods to remove this requirement altogether were thus considered desirable.

Correct valve and seat material specification can mitigate the problem of exhaust valve temperature, but turbine and catalyst limitations are more difficult to mitigate. For this reason, an integrated exhaust manifold (IEM) was specified, a technology area in which Lotus had built up considerable expertise [24].

In a cylinder-head IEM, the water jacket cools the manifold directly as part of the engine cooling system. The system adopted for Sabre was of this nature and not of the more complicated water-cooled separate exhaust manifold type. As a consequence, the number of parts is reduced (and with it the assembly process made simpler) and the volume and surface area of the exhaust manifold before the turbine minimized. From this comes the potential advantages that engine warm-up is accelerated (since less heat is wasted to atmosphere, being instead absorbed by the coolant) and that the catalyst light-off time is reduced because the sum of the products of surface area and heat transfer coefficient for all components in the gas path before the catalyst is lower. The engine mass is lower too, and the package size is reduced.

The reduction in pre-turbine volume also contributes to better throttle response, though at low speeds there is a reduction in exhaust gas thermal energy to drive the turbine. This is addressed by the mild hybrid system already discussed (but can also be addressed by exhaust manifold dimensioning). At full load, however, the cooling system removes heat before the turbine and therefore helps towards achievement of stoichiometric operation throughout the engine map. Again, the avoidance of severe downsizing helps in this situation, since a lower turbine expansion ratio results in less heat rejection to the structure of the engine.

A 3-cylinder configuration also helps the adoption of an integrated exhaust manifold. Fitting such an integrated manifold to a 4-cylinder engine effectively removes the possibility to easily specify a pulse-divided manifold arrangement. The benefit or otherwise of such manifolds on turbocharged DI engines has been extensively discussed [14, 25], but as already mentioned, a 3-cylinder arrangement with its 240° firing interval effectively gives the best of both worlds: no reduction in available energy together with no pulse interaction. As a consequence, this advantage is used in a production turbocharged DI engine by BMW [26].

The use of an electric water pump can also aid warm up (as well as reducing power consumption) and, together with a split cooling system which preferentially warms the cylinder block through restricting water flow at part load, can optimize the warm-up process to the benefit of fuel consumption. The IEM is synergistic with both strategies, permitting increased rates of heat transfer to the coolant during the warm-up phase. The use of a water-oil heat exchanger in the coolant circuit ensures that some of the heat ordinarily lost during the heating of a conventional cast-iron manifold is instead used to heat the oil to the benefit of friction reduction.

Decision 6 – Adopt a water-cooled exhaust manifold integrated into the cylinder head (IEM): Use an advanced cooling system to tailor the characteristics of

the heat rejection from the engine to vehicle operation. Specify a water-oil heat exchanger to assist in friction reduction.

All of the preceding reasoning meant that the design process converged on the configuration discussed in detail in the later sections of this paper. All of the principal technologies discussed above are synergistic and led to a basic engine design which would be capable of low fuel consumption while leaving potential for future technology upgrades to improve efficiency further. It is hoped that future versions will include such technologies as spray-guided direct injection (because the degree of downsizing means that dethrottling is still attractive) or two-stage charging systems (because of the benefits of 3-cylinder banks in turbocharged engines).

DETAIL ENGINE DESIGN

From the above, the basic specification of the Sabre engine was decided as a 3-cylinder, 1.5 litre turbocharged engine with four valves per cylinder and twin overhead camshafts with dual CVCP. Since a bore size greater than 86 mm was required for cylinder head packaging reasons (see above), the base engine dimensions were taken from an existing engine design to save time during the initial layout phase. This base engine design was the same as the engines used in the HOTFIRE research project [21, 22], and was itself based on an automotive V6 engine. The bore and stroke of the Sabre engine are therefore 88 mm and 82.1 mm respectively. Adoption of this geometry also permitted direct carryover of knowledge gained within the HOTFIRE project to the Sabre engine.

Adoption of existing geometry allowed the design team to focus their efforts on including the novel combination of engine technologies. These included:

- Variable valve actuation based on switching tappets and twin cam phasers.
- Homogeneous air / fuel mixture with direct injection using multi-stream solenoid injectors.
- Single-stage, single-entry fixed geometry turbocharger.
- Cylinder head with integrated exhaust manifold (IEM).
- Mild hybridization.
- Friction reduction concepts.

In this first phase of engine evolution, all of these technologies were chosen to be consistent with an “affordable technology” concept. Switching tappets, cam phasers, solenoid injectors and the fixed geometry

turbocharger are all known, current production technologies that are available at reasonable cost.

Once the basic packaging of these engine technologies was complete, and the engine loads better understood through detailed simulation, the design was re-optimized to reduce friction through the use of smaller bearings throughout the rotating assembly.

SWITCHABLE VALVETRAIN SYSTEM

A variable valve train system employing switching tappets was used at low load to deactivate one of the intake valves in a conventional 4-valve combustion chamber while switching the other to a low-lift, short duration profile. This arrangement is shown in Figure 1.

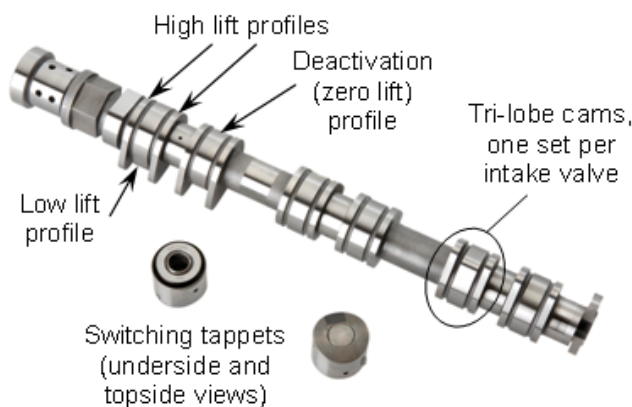


Fig. 1: Intake camshaft and switching tappets

This strategy has been shown, from extensive work using single-cylinder optical and thermodynamic engines in conjunction with advanced measuring techniques on the HOTFIRE research project, to simultaneously reduce throttling losses while increasing charge motion through swirl to the benefit of combustion efficiency [21, 22]. Figure 2 shows an example, taken from work on the HOTFIRE project [21, 22], of the in-cylinder airflow structures quantified by particle image velocimetry for various valvetrain strategies.

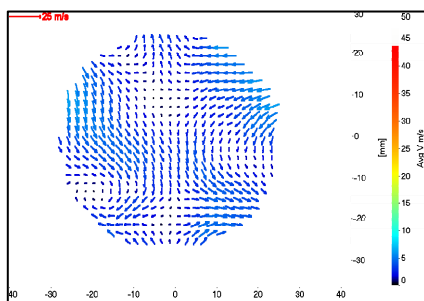


Fig. 2a: Throttled case – full lift on both intake valves, valves near maximum lift

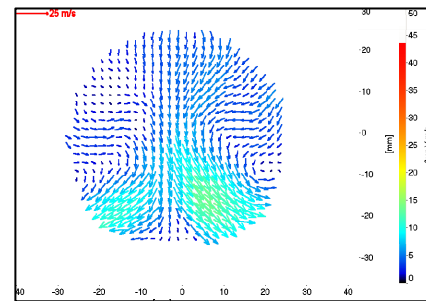


Fig. 2b: Unthrottled case – low lift on both intake valves, valves near minimum lift (closing)

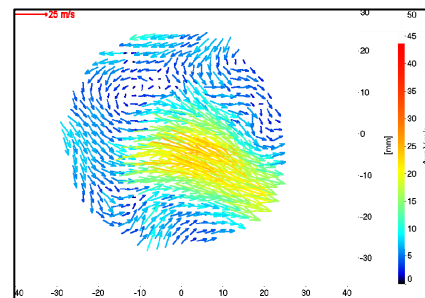


Fig. 2c: Unthrottled case – low lift on one intake valve (valve near minimum lift (closing)), other intake valve closed

Fig.2: In-cylinder airflow structures (swirl plane, 454.8° crank angle ATDC compression)

In conjunction with homogeneous gasoline direct injection and the positioning of the injector in relation to the one open intake valve, the airflow structure combines to give good air-fuel mixing.

GASOLINE DI COMBUSTION SYSTEM

The high cost within the after-treatment and fuel systems for a spray-guided stratified combustion system lead to the decision to realize within this engine a more affordable homogeneous combustion system using solenoid driven fuel injectors and a classical three-way catalyst.

A basic decision for the design of the cylinder head was the positioning of the injector within the DI combustion chamber. In general the current 'conventional' position for an injector is to mount it under the intake ports. An under-port solution has the advantages of more easy integration of the injector into an existing head design, better accessibility of the injector, easier integration of the fuel rail and lower injector tip temperatures. Disadvantages include the design impact on the intake port.