

## **Der neue ECOTEC Turbo BioPower Motor von GM Powertrain – Nutzen der Energieressourcen der Natur**

### **The New ECOTEC Turbo BioPower Engine from GM Powertrain - Utilizing the Power of Nature's resources**

#### **Kurzfassung**

Nach mehreren erfolgreichen Einführungen von Varianten der ECOTEC Motor-Familie präsentiert General Motors (GM) mit dem Start des Modelljahres 2007,5 nun den 2.0L ECOTEC Turbo BioPower im Saab 9<sup>3</sup>. Die Umsetzung von E85 als Kraftstoff reduziert die Abhängigkeit von Rohöl basierten Kraftstoffen, was den weltweiten CO<sub>2</sub> Ausstoß reduziert.

Die firmeninterne Entwicklung der Motorsteuerung ermöglichte die schnelle Umsetzung des Programms. Gleiches gilt auch für die Entwicklung des Basis-Motors. Erfahrungen aus anderen von GM entwickelten E85 Applikationen, ebenso wie die enge Zusammenarbeit aller Teammitglieder, waren essenziell für die Ausführung des Projekts in dieser kurzen Zeit. Dabei ermöglichte die robuste Auslegung des Basis-Motors die schwerpunktmäßige Fokussierung auf die E85 spezifischen Bereiche.

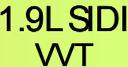
#### **Abstract**

After several successful introductions of engine variants from the ECOTEC engine family, General Motors now introduces the 2.0 L ECOTEC turbo BioPower in the model year 2007,5 Saab 9<sup>3</sup>. The utilization of E85 as a fuel reduces the dependency of petroleum based fuels, thus limiting the CO<sub>2</sub> pollution in the world.

In-house controls development facilitated the rapid execution of the program. The same is valid for the base engine development. Experience from other GM developed E85 applications as well as close teamwork between all team members was vital when executing this program on such short time. The robust design of the base engine made it possible to just focus on the E85 specific areas.

## Introduction

The ECOTEC engine family was first introduced into the world market as a 2.2 L natural aspirated engine in 2000 (Figure 1), and was presented at the 21st International Vienna Motor Symposium as well as at SAE [1,2]. The ECOTEC engine family was designed from the beginning with a modular structure, which means that new engine technologies can be added later as a single measure or combined with other technologies. In 2003 additional members of the engine family were launched, a 2.0 L MPFI turbocharged engine and a 2.2 L gasoline direct injection engine [3]. A 2.0 L MPFI engine with super-charger was launched one year later in order to meet the demands for high torque and excellent response of the US market. The next three ECOTEC engines, a 2.4 L MPFI engine for the US market [4] and 1.9 L and 2.2 L gasoline direct injection engines for Europe, were launched in calendar year 2005, both offering dual continuously variable cam phasers (D-CVCP). In 2006 GM presented the top-of-the-line ECOTEC engine, a 2.0 L spark-ignition direct-injection (SIDI) engine with D-CVCP and dual-scroll turbo charging. The engine is designed to meet worldwide market demands [5].

MY	2000	2003	2004	2005	2006	2007	2008
North America	2.2L MPFI 		2.0L MPFI Super-charged 		2.4L MPFI VVT 	2.0L SIDI VVT turbo 	
	2.2L MPFI 	2.2L SIDI 	2.0L MPFI turbo 		2.2L SIDI VVT 	1.9L SIDI VVT 	2.0L MPFI turbo BioPower 

**Bild 1:** Geschichte der großen 4-zylinder ECOTEC Motorenfamilie

**Figure 1:** History of the large 4-cylinder ECOTEC engine family

In 2007 GM is presenting a new exciting member of the ECOTEC family, the E85 compatible 2.0 L turbo BioPower engine. This engine meets customer demands for a flexible, environmentally friendly powertrain. It also offers not only CO<sub>2</sub> reduction, but increased power and torque as well, enabled by turbo charging technology combined with the superior properties of E85 fuel, the BioPower concept, thus providing even greater customer value.

## E85 as a Fuel for the Future

Historically, petroleum has fuelled internal combustion engines. However, the use of fossil petroleum returns the carbon as CO<sub>2</sub> to the atmosphere as a net addition. Awareness has grown that the continued addition of CO<sub>2</sub> to the atmosphere does not help the environment. Biofuels, fuels made from biological sources such as trees or crops, are a means of reducing the vehicle's impact on the environment. They exhibit a proven reduction in CO<sub>2</sub> emissions [6] due to the carbon they carry being from non-fossil origins. In many applications they can reduce levels of regulated emissions such as carbon monoxide. Governments around the world have recognized the beneficial effects of biofuels. They have encouraged their use by granting the fuels preferential tax regimes and production credits and even by mandating their inclusion in the fuel pool.

The European Union (EU) had set a target of 2% biofuels content by energy in transportation fuels by 2005 and a 5.75% target for 2010. The 2005 target was not reached so greater attention is being paid to meeting the 2010 target. Current gasoline specifications limit biofuels to 5 % by volume as ethanol and 2.7% by mass total oxygen (allowing 7.7% by volume ethanol as ethanol and ETBE). Diesel fuel specifications limit esters (biodiesel) to 5% by volume maximum. These limits make it hard to reach the 5.75% EU target or more aggressive targets such as 7% by 2010 proposed in France. Although the biofuel limits for gasoline and diesel fuel are under review a significant proportion of the current vehicle fleet was not designed to use fuel with biocomponent contents above the current regulations.

The greatest advantages from using biofuels result from using them in high concentrations. This is most easily done by using high ethanol blends. Many countries have encouraged the production of vehicles capable of running on high concentration ethanol. In the US and Sweden E85 (a blend of 85% denatured ethanol and 15% gasoline) is used. In Brazil, E100 (hydrated E95) is used.

In addition to the reduction in CO<sub>2</sub> emissions ethanol has several other advantages. The materials from which it is made are renewable in that they grow back and can be harvested again and again. The amount of petroleum used in the production and processing of ethanol and its feedstocks are small [6] and thus its use reduces dependence on petroleum. Ethanol has advantages during engine operation as well. It has a blend research octane number (RON) of ~110 to 120 making it a valuable octane enhancing blend agent (The blend octane is the apparent octane value when the ethanol is a small portion of the gasoline blend). The RON of E85 ethanol is 105 to 110 allowing the engine to have a higher compression ratio and more aggressive spark advance. It also has a heat of vaporization of 855 J/g, 280% more than gasoline. This higher heat of vaporization produces 245% more charge cooling when used as E85 and allows increased compression ratio and spark advance.

There are also disadvantages with E85. In Europe, it is not widely available; it is primarily available in Sweden with some additional stations across Northern Europe and the UK. In the USA it is primarily available in the upper Midwest, the main area of corn and ethanol production although the availability is spreading. The low vapor pressure of ethanol, or E85, inhibits startability in cold weather. There are winter blends of E85 which contain up to 30% gasoline for improved starting in cold weather. The low vapor pressure does

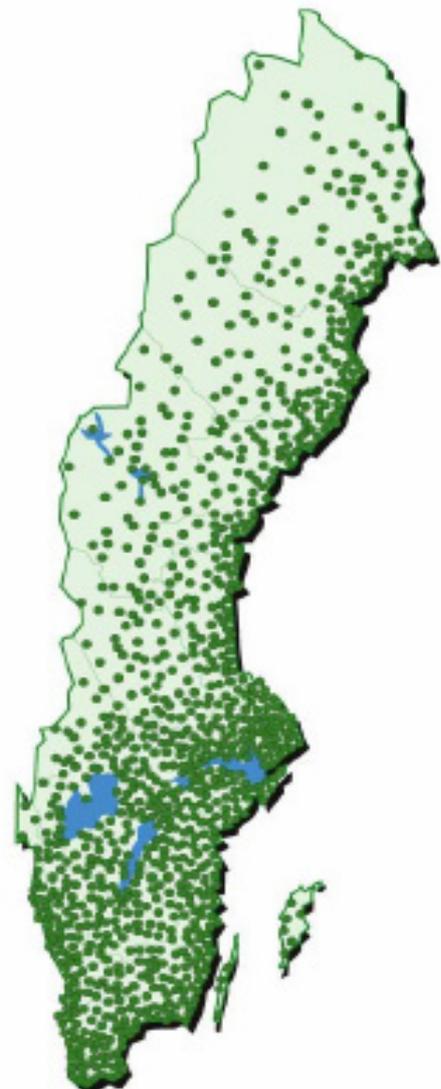
contribute to reduced evaporative emissions [7,8]. Finally, its use can promote wear, primarily of the engine valves and valve seats, necessitating premium material use for these critical parts. Ethanol has an energy density two thirds that of gasoline. This lower energy density is a result of the oxygen already present in the ethanol. In E85 usage the lower energy content would be observed as a theoretical increase in volumetric fuel consumption of 35-40%.

The Swedish government has set a goal of making Sweden independent of fossil fuels by 2020. Since the Swedish electricity and heating sectors already use little fossil fuel so the focus has been on transportation fuels.

Getting to fossil independence using the current fuels standards and biomass conversion technologies will be very difficult. Sweden has elected to move beyond conventional fuels and introduce E85 ethanol. Currently the majority of the ethanol used in Sweden is imported from Brazil. However, Sweden's extensive forest resources coupled with the rapidly evolving technology for producing ethanol from cellulosic sources should make this temporary.

A current problem with high concentration ethanol blends such as E85 is that neither the fuel nor the vehicles are widely available. Thus neither the automobile nor the fuel industry has any incentive to offer the product since the vehicles are not present to use the fuel and the fuel is not present to fuel the vehicles. In recognition of this dilemma Sweden has taken the lead in encouraging E85 use in Europe. E85 was introduced in 1995 together with a first vehicle fleet trial and numerous incentives to ensure its success.

The E85 fuel was tax advantaged to reduce its cost per unit energy below that of gasoline. The tax company car drivers pay was reduced by 20%, parking was free in major cities, and in Stockholm there was relief from the congestion charge. Finally, a requirement was instituted that progressively more fuel stations make E85 available, culminating in 50% of the Swedish network by 2009. The result has been a great success with rising sales of E85 capable cars and a spread of E85 across the Baltic and North Seas into the rest of Europe. In particular, after a brief fleet test last summer France has announced that it will install 500 fuel dispensers and make E85 available in 2007.



**Bild 2:** Versorgung von Schwedische tankstellen mit E85 Kraftstoff

**Figure 2:** Distribution of E85 stations in Sweden

GM has been a leader in building ethanol capable vehicles. GM warranted its vehicles to run on 10% ethanol in North America in 1979 and was the first to do so. GM was one of the leaders in the development of Flexpower E100/E22 flexfuel vehicles in the Brazilian market. GM also leads in building E85 flexfuel vehicles for the North American market. In Europe, Saab has taken the lead by building the advanced technology Saab BioPower. This vehicle combines the ecological benefits of high concentration biofuels with the advanced technology of a variable boost, turbocharged engine with fuel composition sensing technology. The turbocharger allows the engine to take advantage of the high octane of the ethanol and high ethanol blends.

### ECOTEC BioPower Development targets

After having introduced the Fam III BioPower engine, a true success story in the Saab 9<sup>5</sup>, it was evident that there was a need to offer a BioPower engine in the mid-size segment also. The BioPower concept, i.e. providing more performance on E85 than on gasoline, has been very well received by the customers as well as the authorities. It clearly promotes driving on the environmental friendly ethanol fuel rather than of the crude oil based gasoline.

Learning's from the Fam III engine and the experience from the ECOTEC family gave us the starting position that no overall redesign of the engine was required. The engine management system (EMS) needed new software (SW) functionality, and calibration. In addition a few base engine parts needed modifications. To save time, and not to proliferate parts in manufacturing, the fuel injectors were kept the same, thus being the limiting factor regarding maximum power.

After having run a pre-development project for 9 months, the following targets were defined.

Engine	Gasoline – Baseline	BioPower – Targets (On E85)
Displacement	2.0 L	2.0 L
Max Torque	265Nm @ 2500-4000rpm	300Nm @ 2500-4000 rpm
Max Power	129kW/175Hp @ 5500rpm	147kW/200Hp @ 5500rpm
Max cylinder pressure	80Bar	80Bar
Start ability	-29°C unassisted -40°C assisted (block heater)	-15°C unassisted -40°C assisted (block heater)
Ethanol sensing	-	Virtual, no sensor
Fuel consumption	<9,2 l/100km (CO <sub>2</sub> < 221g/km)	<140 g/km CO <sub>2</sub> Net

**Tabelle 1:** Zielwerte

**Table 1:** Targets

Another requirement was that the software should fit within the existing controller, thus avoiding a costly and time consuming EMS exchange. The BioPower functionality should be implemented as an add-on feature, thus avoiding recalibration of the gasoline parts of the software.

## **Impact of E85 on the base engine hardware**

### **Valves and Valve Seats**

The ECOTEC BioPower valvetrain basic architecture is a four valve DOHC type with roller finger followers and hydraulic lash adjusters. The valve train incorporates revised inlet- and exhaust cam profiles for model year 2007 and is capable of revolutions in excess of 7000 per minute.

Experience from the development of the Fam III, SAAB 9<sup>5</sup>, BioPower engine showed that valve seat recession was to be expected during endurance testing if standard valves and valve seats were used. Nevertheless, endurance end-of-test criteria and test durations were unchanged from those of the gasoline powered ECOTEC engine. The challenge was further magnified by the endurance tests being run on E85 only for the entire test duration.

The result was excessive valve seat recession leading to poor valve sealing and compression loss, which produced startability problems. As the lash adjuster operating range is consumed, the valve will no longer provide sealing, resulting in a burned valve, loss of compression and a walk home failure.

### **Valves**

Regarding the valves, the positive experience from the Fam III, SAAB 9<sup>5</sup>, BioPower engine was utilized. A holistic approach is vital in that the valve and the valve seat cannot be selected separately, valve parameters interact with valve seat insert material properties.

During model year 2006 the inlet valve supplied by TRW had previously been upgraded on the 2.0 ECOTEC turbo gasoline engine, incorporating a stiffer valve head. For the BioPower application, the valve was further modified in that the chrome plating of the valve stem was replaced by a full nitriding of the entire valve. The removal of the chrome plating of the valve stem to a large extent offset the extra cost of nitriding.

A concern with the nitriding was that the hardness of the induction hardened valve tip end would be reduced during the nitriding process. This in turn could lead to extensive tip end wear on the valve resulting from the high, localized, contact forces applied by the roller finger follower. In engine testing it was found that the nitrided layer was robust enough to protect for the lower hardness base material. The nitrided valve is currently being considered for introduction into the pure gasoline variant of the engine.

The exhaust valve selected was again a carry-over item, this time from the 2.0L SIDI turbo engine. The valve is sodium cooled with a Nimonic valve head without seat hard facing. It features an upgraded valve tip material with increased hardenability to better withstand valve tip end wear.

Given the existing valve seat insert material, it was known from previous engine programs that substituting a Nimonic valve without a hardened seat face for a hard faced valve would be beneficial in reducing wear. The Nimonic material has a high nickel content and

the wear reduction is achieved by increasing the dissimilarity between the valve material and the valve seat material.

## Valve Seat Inserts

The manufacturing strategy was to utilize existing machining equipment at the engine plant, thus it was not possible to change valve seat geometry. If possible, it was requested to carry over the current ECOTEC valve seat inserts as the machining line was not laid out to handle valve seat variants. The baseline valve seat insert materials were Brico 3220 on both inlet and exhaust side.

The majority of the valve recession was related to wear of the valve seat insert.

Parameters contributing to increased valve recession with E85 fuel are amongst others:

- Dry fuel
- Cleaner combustion giving less lubricating soot
- Higher contact forces due to increased combustion pressures
- Thermal effects, significant cooling of the inlet valve from the increased amount of fuel and the increased cooling effect of evaporation of the fuel.
- Chemical effects, reduced build up of protecting oxide films on the valve and valve seat wear surfaces.

The wear can be approximated by a material constant times surface load times sliding distance, divided by surface hardness.

$$\text{Wear} = C * \frac{\text{Load} * \text{Sliding distance}}{\text{Surface hardness}}$$

The wear is mainly abrasive in nature, the valve head flexes slightly when subjected to the combustion pressure and a sliding motion of the valve relative to the valve seat insert is developed. A stiffened valve head reduces the flexing, and hence the sliding distance, reducing wear despite the resulting increase in surface pressure.

## DOE Valve and Seat Parameters

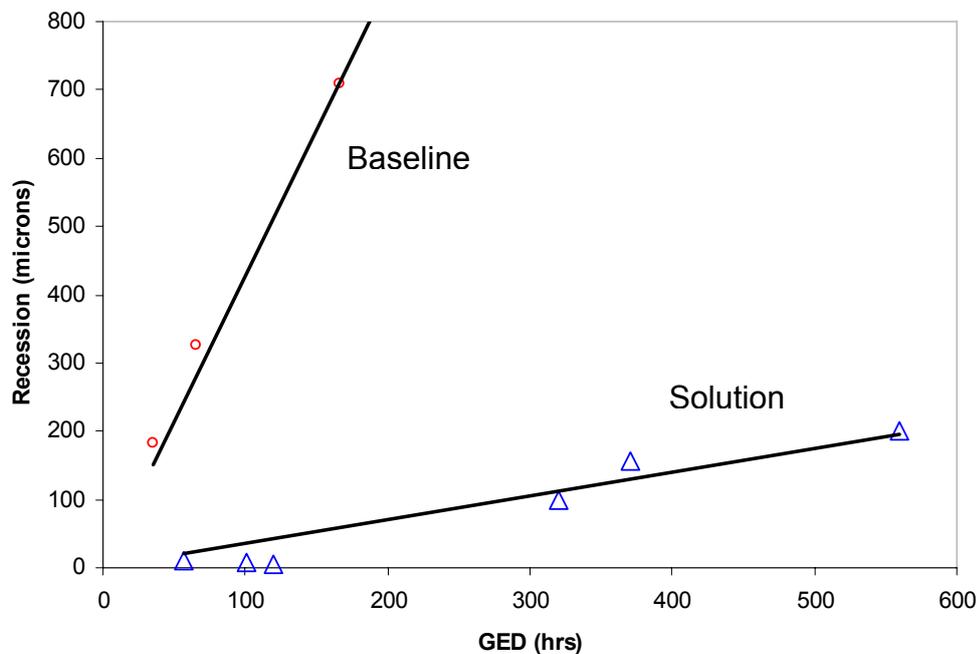
A 24 parameter self learning Neural Network (24 parameters: VSI composition, pressure load history, valve hardness, valve head stiffness, fuel, guide clearance etc.) was created, using empirical recession data from Fam III BioPower as well as ECOTEC.

By using predictions from the neural network it was possible to quickly rank performance of different combinations of valve designs and valve seat materials and narrow down the list of candidates, minimizing the number of engine tests as well as reducing the necessary number of prototypes.

On the inlet side it was found beneficial to minimize the amount of copper in the inlet valve seat insert, and hence the thermal conductivity, offsetting part of the cooling effect of the fuel. Increasing the surface hardness of the valve (via nitriding) and selecting a valve seat

insert material with higher amounts of tungsten, molybdenum and chrome was clearly shown to be beneficial for increasing robustness.

Using the Neural Network model to feed an L18 orthogonal array Design Of Experiments (DOE) gives the influence of exhaust valve parameters and some selected valve seat insert material parameters on robustness and recession resistance. Increasing the signal to noise (S/N) ratio increases the robustness of the system.



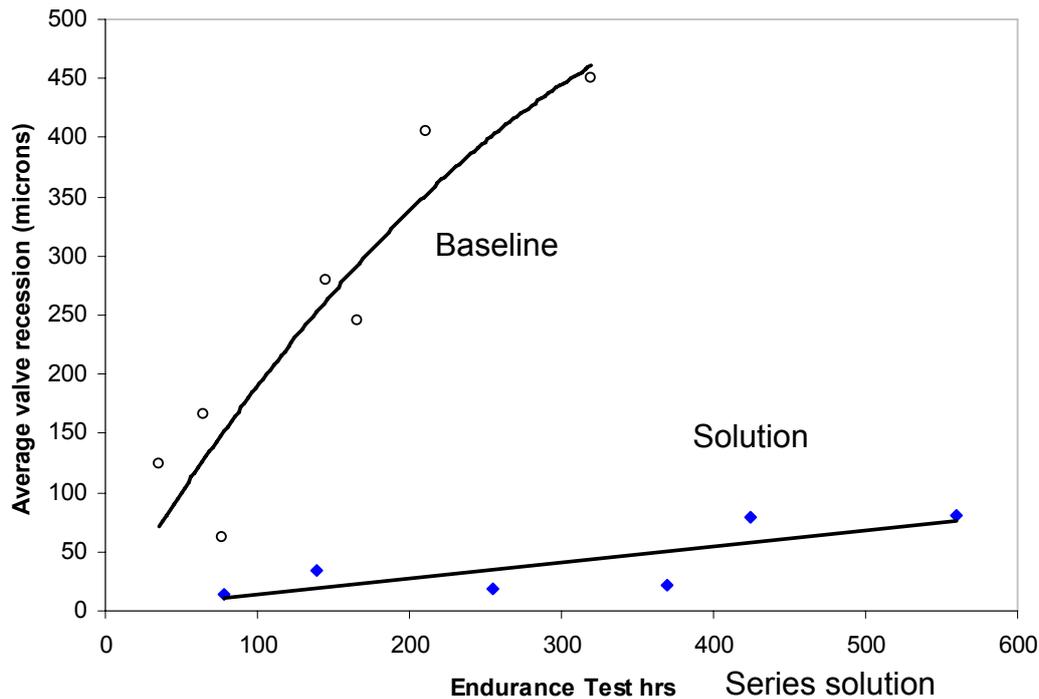
**Bild 3:** Einlassventil-Einsinktiefe in der Dauerhaltbarkeitprüfung, Ausgangssituation im Vergleich zur Serienlösung. Einsinkrate reduziert von 4,25  $\mu\text{m}/\text{h}$  auf 0,34  $\mu\text{m}/\text{h}$

**Figure 3:** Inlet recession in endurance testing, baseline versus series solution. Recession rate reduced from 4,25 microns/hr to 0,34 microns/hr

The three most effective parameters are nitriding of the valve and an increased amount of the alloys tungsten and chromium in the valve seat insert. Actually, nitriding the exhaust valve was found to be a more effective solution than using Nimonic, but this would have meant introduction of yet another part number in the assembly line and was not a viable option.

Hardness of the valve seat insert did not have a significant influence in the range surveyed for the BioPower application. As on the inlet valve seat insert material, selection of a material with increased amounts of tungsten and chromium was beneficial for both robustness and wear reduction.

Effects of valve seating velocity and hence seating impact load on valve recession was previously investigated on the Fam III BioPower engine, a threefold increase in seating velocity was completely masked by the forces of the combustion pressure.



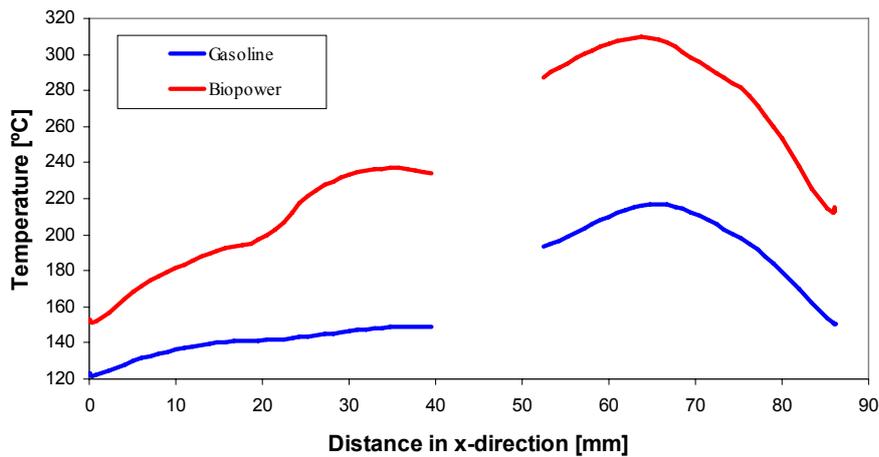
**Bild 4:** Auslassventil-Einsinkrate im Dauerlauf wurde reduziert von 1,75  $\mu\text{m}/\text{h}$  auf 0,13  $\mu\text{m}/\text{h}$  reduziert. Testdauer 560h

**Figure 4:** Exhaust recession in endurance testing was reduced from 1,75 micron/hr to 0,13microns/hr. 560hrs test duration

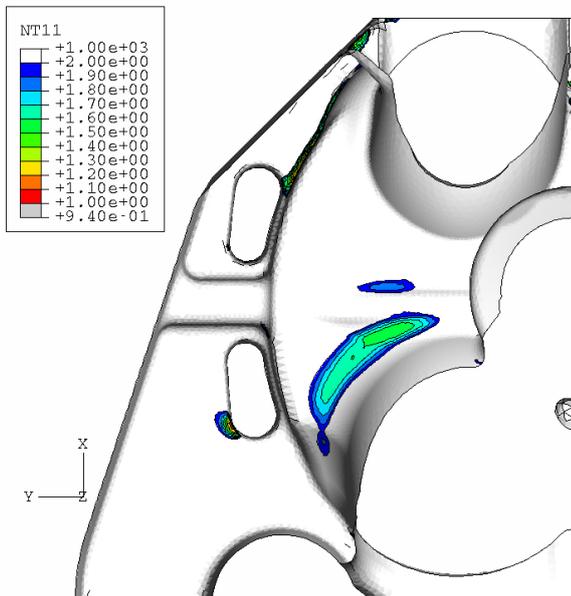
### Cylinder Head

The ECOTEC cylinder head is a A356-T6 semi permanent mould casting. They are supplied by Hydro, Hungary, and machined in the Kaiserslautern plant in Germany, on the same machining line as the other European ECOTEC derivatives.

The increased fuel vaporization enthalpy and increased amount of fuel in the inlet port has a strong cooling effect and thereby increases the thermal gradient across the cylinder head as shown in figure 5. The stress induced by the thermal gradient is superimposed on other stresses from mechanical load, increased combustion pressure and residual stresses from the heat treatment.



**Bild 5:** Oberflächentemperatur, im Brennraum  
**Figure 5:** Surface temperature, across combustion chamber



Cracks formed in the highly stressed zones, initiating at surface irregularities in the cast water jacket surface, breaking into the inlet port and causing internal engine coolant leakages. See figure 6.

In endurance testing the time to failure greatly decreased with the baseline cylinder head. In cooperation with the supplier Hydro, an alloy with an increased amount of copper was implemented, thereby enabling a revised heat treatment process utilizing an air quench of the casting instead of water quench. This quench significantly lowered residual stresses in the casting resulting in an improved fatigue life.

**Bild 6:** Zonen der höchsten Belastungen im Zylinderkopf, Wassermantel-seite  
**Figure 6:** High stress zones in cylinder head, water jacket side

	ECOTEC Gasoline	BioPower
Alloy	A356	AlSi7MgCu0.5
Heat treatment	T6-Water quench	T6-Air quench
B5% life in endurance testing	208h (gasoline) 89h (E85)	401h (E85)

**Tabelle 2:** Zylinderkopfvergleich der Basis (Benzin) im Vergleich zu BioPower  
**Table 2:** Cylinder head comparison baseline (gasoline) vs. BioPower



durability test with repeated starts at the lowest unassisted starting temperature was performed to evaluate risk for scuffing and wear with high fuel dilution.

Extensive validation has shown that no components in the cranktrain needed to be changed due to E85 operation. The linear wear increases, but are still maintained within acceptable levels.

### **Polymer materials / sealing resistance**

In adapting the ECOTEC engine for E85 fuel special focus was addressed to the seals in the engine.

As very little knowledge and experience with E85 existed with seal suppliers there was a need to empirically test the different sealing concepts and materials with E85 fuel. The approach in testing was as follows:

Three main types of testing were used.

1. Evaluation of general material properties for different rubber and plastic materials when exposed to E85.
2. Full testing according to our normal engine program validation process with all E85, all gasoline and mixes of the two fuel types has been performed. This includes endurance and high speed testing in test bed and in vehicle, thermal cycle testing etc.
3. Testing of functionality and properties of the seals at sealing and sub system suppliers has been conducted.

Obviously the fuel system needs to be capable of running on pure gasoline, on pure E85 and any mix of the two. The test criteria for this system are quite straightforward, all included parts need to be able to withstand continuous exposure to the two fuels in any mixture over a defined temperature range. This has been checked for both the complete engine in the engine program validation process and by testing properties (swelling, dimension, hardness, ageing etc.) of the materials when submerged in E85 fuel.

The more difficult part is to understand the effects of E85 fuel on components in the lubrication and ventilation system of the engine. As is the case with gasoline, but to an even higher extent, E85 fuel will dilute the engine oil at cold starts. This means that depending on the frequency of cold starts and engine running temperatures there will be very different levels of ethanol in the engine oil. Up to 30% higher fuel dilution was observed during the testing. On top of this the ethanol that reaches the crankcase is affected by the combustion and the used oil. It is very difficult to calibrate the test methods to correspond to what a sealing and its sub system are actually exposed to in a worst case scenario.

As an example the sealing components of the vacuum pump has been tested submerged in a mix of 85% new engine oil and 15% new ethanol at 60 °C. The test result shows totally unacceptable values for swelling. However, in the engine program validation testing

there were no concerns whatsoever with these seals. To be on the safe side the sealing materials were upgraded anyway.

As is understood from the above real confidence in the design initially comes from back-to-back engine program validation testing with gasoline and E85 fuel versions. A continuous refinement of seal designs for E85 fuel is in progress.

### **The PCV system and oil dilution**

The PCV systems did not need any modifications for the BioPower variant. Since model year 2005 all MPFI ECOTEC turbo engines use the same PCV hardware, such as the low and high load orifices. Possible aspects that could affect crankcase pressures are the increased power and torque when running on E85, but since the system already was calibrated to cope with up to 210hp and 300Nm this was not an issue.

An investigation of blow-by, crankcase pressures, NO<sub>x</sub> in the crankcase and engine oil dilution with gasoline and ethanol has been performed. Blow-by and crankcase pressures were similar to those of the equivalent gasoline engine.

There are also targets for preventing the turbocharger bearing system from leaking oil, such as always keeping the crankcase pressure lower than the exhaust back pressure as well as avoiding occurrences of crankcase pressure above atmospheric pressure. This is to spare the crankshaft seals and keep NO<sub>x</sub> levels low. There is also a target for oil carryover that limits the flow in the oil separator or the separator design.

Oil dilution with ethanol can be large if the engine is repeatedly started in cold climate and run for a short distance. At temperatures below -10°C without assisted start (block heater) there can be as much as two deciliters of ethanol per engine start that dilutes the engine oil. This is not harmful as long as the engine is given time to reach normal operating conditions, preferably within ten cold starts. The evaporation of ethanol from the oil will not cause any damage when running the engine in normal operation. However, it is a major concern for EMS fuel control as described later in this paper.

## **Fuel Injection System**

The BioPower fuel injection system is a carry over design from the ECOTEC 2.0 L turbo model year 2007.

The MPFI 300kPa in-house assembled return system consists of:

- Fuel rail
- Fuel pressure regulator
- Fuel injectors

To get the same power output for an E85 fuel as with regular gasoline the fuel flow requirements are approximately 30-35% higher due to the lower energy content in ethanol. For the current performance level of the ECOTEC BioPower engine fuel demand calculations determined that fuel pressure was sufficient and that the injectors had enough flow capacity to cover the additional demand. For increased power output there will be a need to extend the injector fuel flow capability.

The fuel rail is a brazed stainless steel assembly located on top of the intake manifold and is bolted to the cylinder head. The fuel rail assembly contains four injectors and a fuel pressure regulator. Also installed on the rail is an electrical harness delivering control signals to the injectors. Rail pressure is variable depending on operating condition and is controlled by a reference air pressure hose connected to the pressure regulator and the intake manifold. The pressure regulator will control the fuel pressure to a fixed differential value between the inlet and fuel.

## SW algorithms

### SW development background

The EMS used on the BioPower is an in-house developed system called Trionic 8. Using E85 instead of gasoline sets a huge demand on the control algorithms, the algorithms developed for gasoline have been in use for quite a long time and have been tested and verified successfully. These algorithms are not capable of handling a new type of fuel with a quite different specification. Therefore some of these algorithms had to be modified and some new ones had to be created.

Due to the short development time of the whole project it was necessary to predict the areas which would be affected by E85. It was confirmed that the fuel related algorithms were most affected and therefore the major focus was put on them.

The first problem to solve was the longer injection time which is needed when running on E85. Injection time gets much longer when starting at cold temperatures. This is because at these temperatures only the gasoline part of the fuel contributes in the combustion for the first combustion cycles.

Some of the unburned ethanol ends up in the oil pan and will evaporate when the engine temperature rises to about +70°C. This boiled off ethanol will participate in the combustion by entering the cylinders via the crankcase ventilation system and can cause severe driveability problems.

Another problem that had to be solved was to detect that a refuel has occurred and then to determine the ethanol content of the fuel and finally adjust fuel, ignition and torque parameters. Every refuel event must be detected (even small amounts) otherwise it could result in serious engine damage. When a refuel event is detected the amount of fuel and upper and lower limits of possible ethanol content are calculated.

The next step was to determine the actual ethanol content of the fuel after a refuel event. This central value is determined using air/fuel ratio (AFR), this had to be done as precisely as possible to be able to use the advantages of E85 most effectively. It is important to mention that this precision is highly dependent on the precision of the EMS components used in the system. The mass air flow sensor used in Trionic 8 can be mentioned as an example. This component has a tolerance of +/- 3%. With a system that is calibrated on an engine with nominal components this can give a worst case AFR error of +/- 7% from nominal value on an engine with non-nominal components.

The front O<sub>2</sub> sensor is the main sensor to detect fuel ethanol content changes. Therefore some algorithms had to be developed to compensate in case this important component should fail (System Action).

Since the customer should not experience any drivability reduction in comparison to gasoline fueled cars a number of algorithms had to be modified or created to ensure this.

A list and brief description of these algorithms changes can be seen in the following pages.

A large number of fuel, ignition, air, torque and system action (failure recovery) functions has been modified and/or extended to cope with gasoline, E85 and any blend in between. Also a number of brand new functions have been developed.

### **New algorithms BioPower application only**

- Re-Fuel Detection

AFR, ignition and torque must be adjusted if the ethanol content is changed. The accuracy depends mostly on fuel level sensor precision and calibration. This is extra problematic when a small amount of fuel is added and not detected, especially at low fuel levels.

- Blend adaptation

Gasoline and E85 have different AFRs (~14.65 for gasoline and ~9.85 for E85). This will result in more fuel needed to keep the engine at stoichiometric ratio when E85 or blends of it are present in the fuel tank. When a refuel event is detected then the correct AFR must be determined due to the possibility that the new fuel could be gasoline or E85. To determine the new AFR the front O<sub>2</sub> sensor is used. The accuracy depends on engine calibration. There is also a conflict between fuel trim and ethanol content adaptation.

- Hi-Load Ethanol Adaptation

Blend adaptation is crucial if a refuel is detected but the closed loop fuel mode is not activated as in the case of full load operation. Since the standard ethanol adaptation needs closed loop fuel for feedback a new algorithm was required for open loop fuel mode. A typical situation could be refueling close to a highway and there after a rapid acceleration or a car carrying a trailer.

- Ethanol Boil off

During cold starts a large amount of ethanol ends up in the oil pan. When the oil is warmed up the ethanol will evaporate and enter the combustion chamber. This fuel is not known to the system and must be compensated for with an estimation algorithm. Absolute lambda controller value is the main input therefore it is dependent of precision in basic calibration. The phenomena can delay or disturb the ethanol adaptation when or if it is active. If compensation is not performed it will lead to drivability issues and false MIL setting due to rich operation.

- Cold engine torque limit

Max Engine Torque had to be limited as a function of engine coolant temperature to assure stable combustion.

- Efficiency compensation of requested air mass

The efficiency of the engine increases when running on E85, or blends of it, due to advanced spark timing. Therefore the air mass must be reduced to keep the requested torque.

The automatic transmission uses the accelerator pedal and predicted engine torque as inputs for AT internal purposes (calculation of gear shifting etc). The correlation between these two values must remain unchanged when running on different blends of ethanol.

- System action front O<sub>2</sub> sensor for ethanol adaptation.

If the front O<sub>2</sub> sensor fails and refuel is detected then it must be possible to proceed with ethanol estimation to secure drivability, startability and prevent engine damage. This is achieved by using the rear O<sub>2</sub> sensor instead of the front sensor.

- System action Fuel Level Gauge

If the fuel level sensor fails then it is impossible to detect a refuel. To prevent any damage to the engine an algorithm is activated and an ethanol estimation is triggered if a car stops longer than a configurable value due to the possibility of a refuel event.

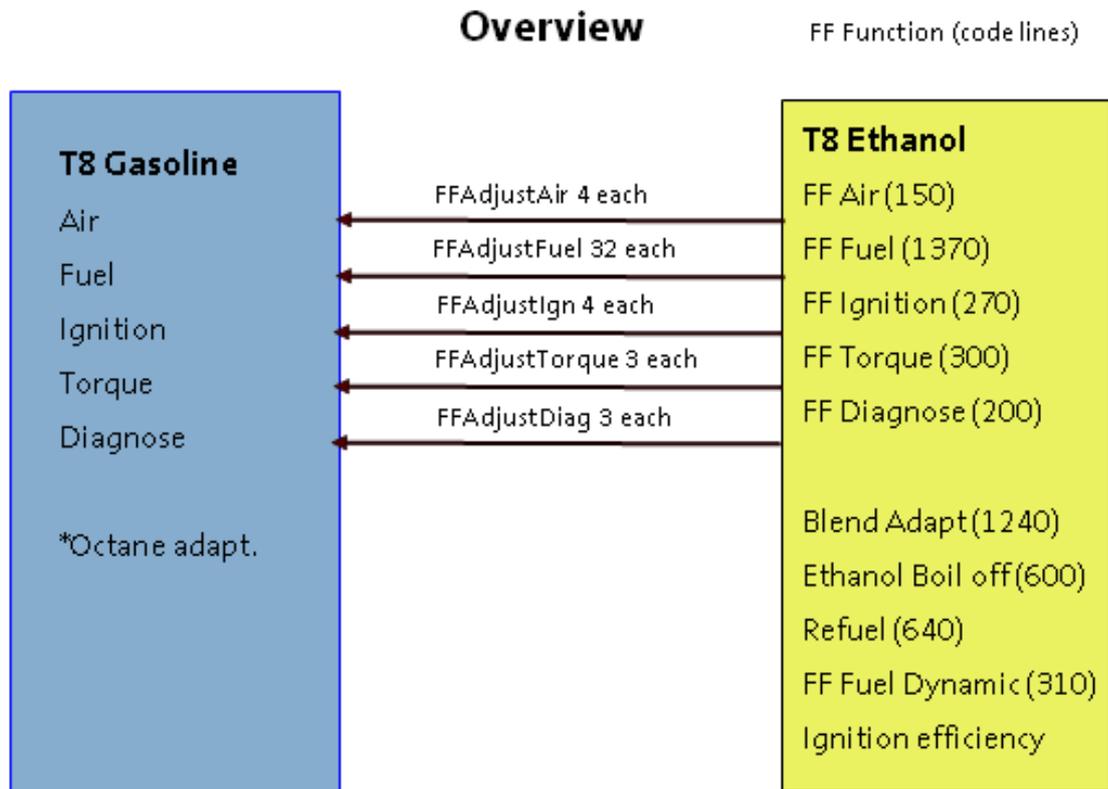
- System action speedometer

If the speedometer signal fails then the refuel logic will be disturbed because there will be no speed reference value to determine when the car comes to a stop.

To prevent any harm to the engine in that case a second speedometer sensor, from a different wheel, will be used.

## SW changes for E85 in Trionic 8

# SW changes for E85 in Trionic 8



**Bild 8:** SW-Änderungen, inklusive der Anzahl der geänderten/erneuerten Codes  
**Figure 8:** SW changes, including number of lines of code modified/new

Total SW development time to production equals 1 year. This is the time from when the first Change Request was written until the production software was released. About 90 Change Requests have been initiated, investigated, tested, granted and finally implemented. Every single change in the code has been reviewed by a group of SW engineers to secure a safe implementation. BioPower algorithms generated about 5000 lines of new code.

Due to the new variables, tables, maps and different algorithms the memory usage was increased in Trionic 8 as below.

RAM	+648 bytes	(2.8%)
FLASH (total)	+34 216 bytes	(5.4%)
Calibration data	+4 840 bytes	(11.5%)
Adaptation Data	+64 bytes	(2.5%)

About 392 new symbols were added in Trionic 8 for BioPower functionalities, this is a 5.6 percent increase in the total number of variables.

About 220 of the new variables are calibration variables.

The whole BioPower implementation increased the CPU load by 2-3%.

## **Program execution**

### **Overall timing**

During the first 9 months of 2005 a pre-development project was executed with the purpose of understanding the impact of utilizing E85 as fuel, including finding the engine and EMS boundaries. Also a demonstrator vehicle was built to demonstrate the excellent performance and drivability that E85 offers. Algorithms and SW were analyzed and partly developed but originally a pure E85 calibration was used. The engine was well received and the order to start production development came even before the pre-development project was finalized.

The first durability engine was run on E85 only during the winter of 2005/6. Failures with pre-ignition forced a recalibration of cylinder pressure as well as a change of sparkplugs. With this issue solved the next concern was cylinder head durability. Even if the cylinder pressure was limited to the same maximum level as on gasoline the time to failure was very short. After having carried out a thorough thermal survey of the cylinder head it was evident that the cause was the steep thermal gradient from the intake duct to the centre of the combustion chamber. This was more than the cylinder head could withstand. After having upgraded the cylinder head alloy it was finally possible to complete durability tests. In parallel to this all algorithms, software and calibration were developed.

Late failures due to intake valve seat wear caused additional development effort during the late part of 2006. Earlier tests had indicated that the chosen valve seat and intake valve combination would be sufficient; however when it finally was possible to run complete durability tests, inspection showed that the valve seats were not durable enough. Earlier experience quickly led to the proper selection regarding valve seat material, and final tests at the end of 2006 was successful.

In order to make this development feasible in an extremely short period of time a number of things have been vital:

In-house controls development. Having the algorithm development, software development, calibration and base engine development under the same roof has been mandatory since all these areas have to be developed in parallel, sharing the knowledge between the people involved. The same is true for the base engine development. Close teamwork between all team members is vital when executing a program in this short time frame. The robust design of the base engine made it possible to focus on the flexfuel specific areas. Last, but not least, the enormous dedication of the people participating in the development, with the clear target of creating a success, even at times when not everything was going as expected.

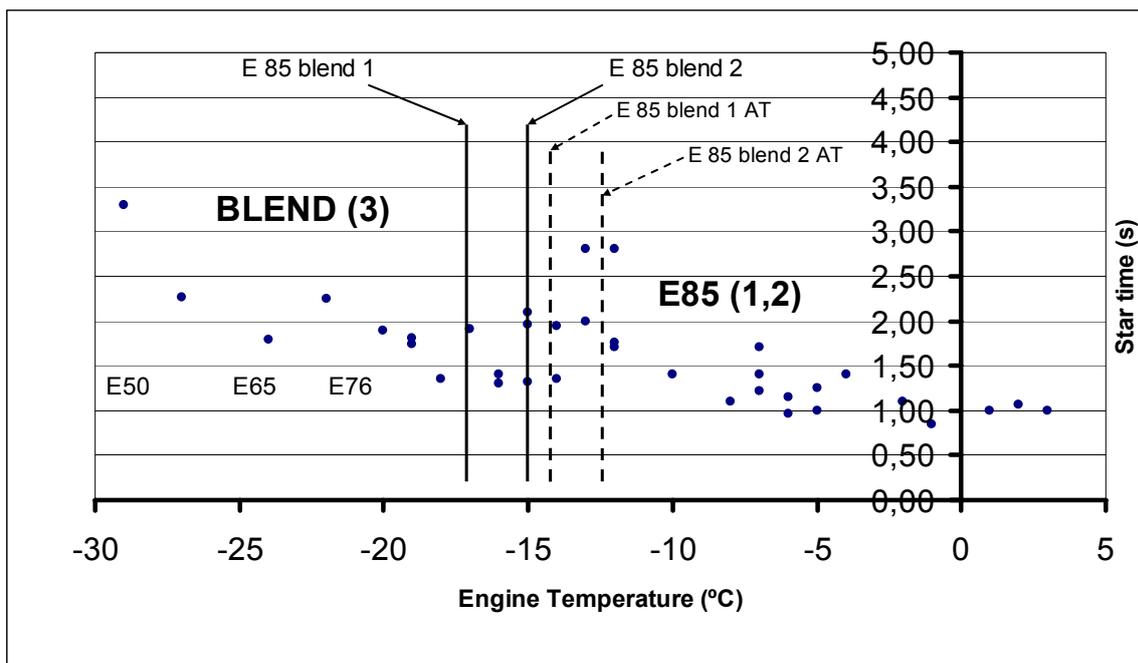
## Results

### Engine startability and warm up phase

The engine starting time diagram in figure 9 shows startability borderline engine temperatures and engine start times for the ECOTEC BioPower engine.

#### Blends tested:

1. Tests using E85 blend made with Swedish winter quality gasoline (gasoline RVP 85-95 kPa) show that the minimum start temperature is approx -17 °C for manual transmission cars and -15 °C for automatic (AT) cars.
2. E85 made with summer quality gasoline (gasoline RVP 60 kPa) shows borderline temperatures for startability approx 2 °C higher vs. E85 blend with winter quality gasoline part.
3. Lower blends E76 to E50 allow starting temperatures almost comparable to gasoline.



**Bild 9:** Startzeiten

**Figure 9:** Starting times

Start times below -5 °C are significantly longer (up to 40%) using E85 blended using summer quality gasoline, compared to E85 made with winter quality gasoline. The new Swedish winter standard for bio ethanol, E75 with RVP 50 allows approx 10 °C lower starting temperatures (down to -25 °C).

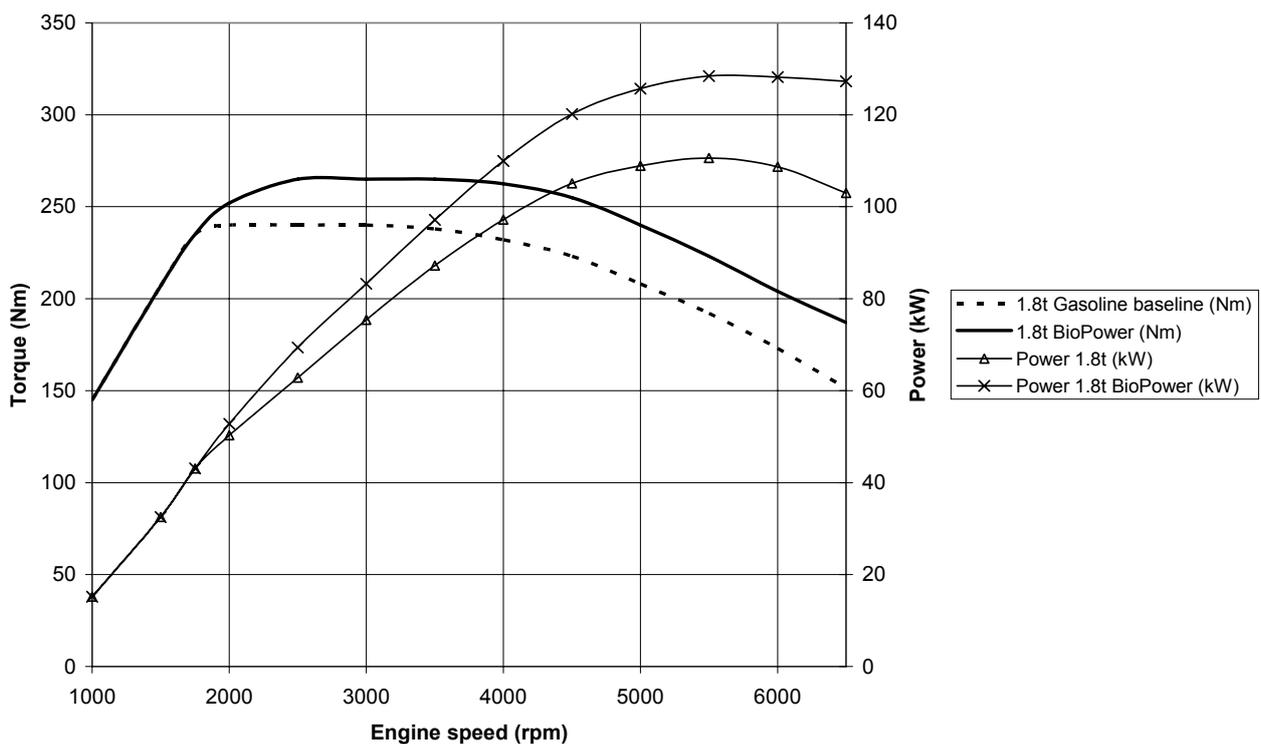
## Performance, including pressure capabilities

The SAAB BioPower concept gives the driver a change in performance level with ethanol content. This is not mandatory to have, but gives the driver a more fun-to-drive vehicle besides the environmental advantages with a low fossil fuel. A modern controller can keep the performance equal regardless of ethanol content.

The ECOTEC BioPower is offered in two engine versions, the 1.8t BioPower and 2.0t BioPower. These are based on the gasoline 1.8t and 2.0t engines which were in the powertrain line-up before the BioPower concept. Both engines have a 2.0 liter displacement (1998 cm<sup>3</sup>) even though the low output version says otherwise. No base engine hardware differs between the two versions, so the engine performance span of 150-200 hp is the result of a very flexible hardware matching.

## Torque characteristic

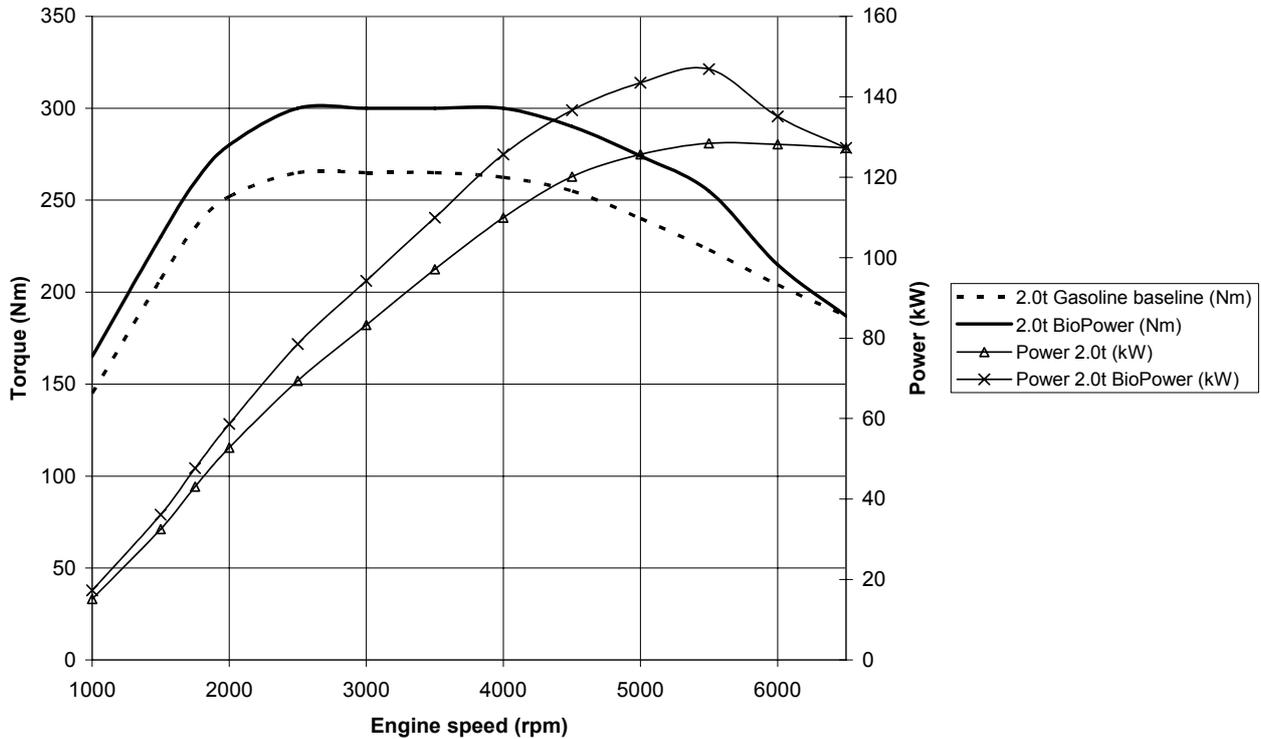
The 1.8t BioPower has a gasoline baseline of 240 Nm of torque in the speed range 2000-3500 rpm and 110 kW (150Hp) @ 5500rpm. With E85 this is increased to 265 Nm between 2500-4000 rpm and 129 kW (175Hp) @ 5500rpm.



**Bild 10:** Leistung & Drehmoment für 1.8t BioPower

**Figure 10:** Power & Torque for 1.8t BioPower

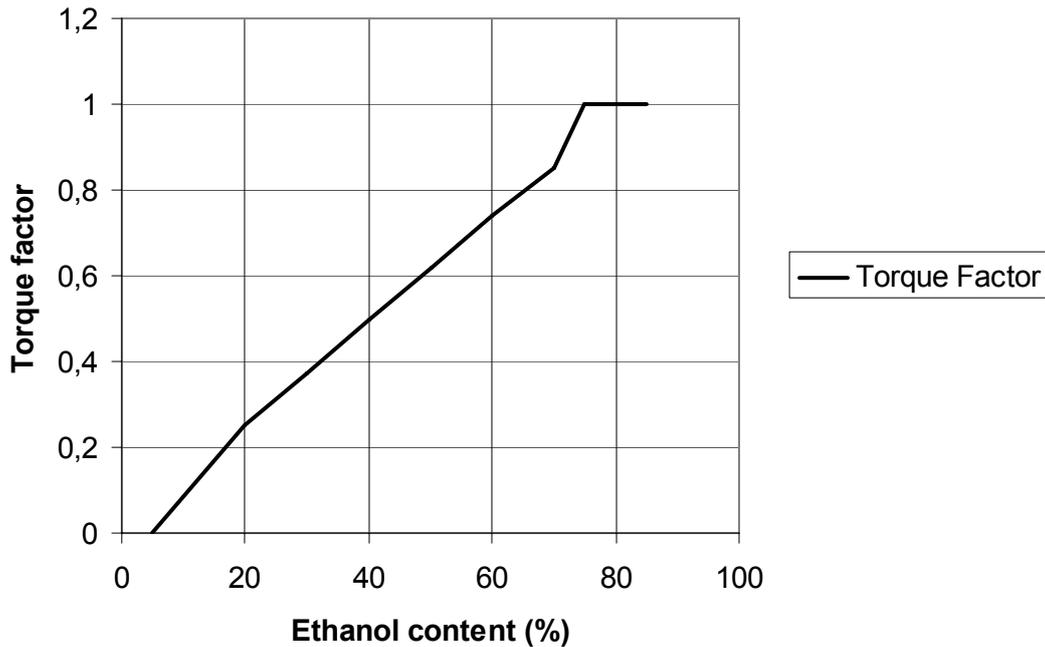
The 2.0t BioPower has a gasoline baseline of 265 Nm of torque in the speed range 2500-4000 rpm and 129 kW (175Hp) @ 5500rpm. With E85 the torque is increased throughout the engine speed range and peak torque and power is 300 Nm between 2500-4000 rpm and 147 kW (200Hp) @ 5500rpm. Having 90 % of maximum torque between 1900-5000 rpm and fast response at low engine speeds makes it a very dynamic and easy to drive engine.



**Bild 11:** Leistung & Drehmoment für 2.0t BioPower

**Figure 11:** Power & Torque for 2.0t BioPower

Engine performance relative to ethanol content follows a pre-calibrated table as can be seen in figure 12. At 5% ethanol in the fuel (EN228) the engine performance follows the lower torque characteristic and above 75% full performance is reached. The high torque is kept down to 75% to allow for small errors in ethanol content adaption and winter fuel quality.



**Bild 12:** Leistung, abhängig vom Ethanol-Anteil  
**Figure 12:** Performance depending on ethanol content

### Combustion analysis

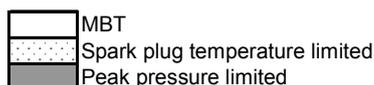
The E85 fuel has a higher RON number (105-110 octane) and a higher vaporization enthalpy and therefore gives a less knock sensitive engine. This enables an advanced spark in knock limited areas and is especially useful on turbocharged engines. The chart in figure 13 shows the difference between E85 and RON95 spark maps. In the MBT (Mean Best Torque) region spark had to be retarded in some points relative to the RON95 map, but they are still at MBT. This is due to a faster combustion with ethanol.

RPM	Load relative maximum torque (%)																	
	9	11	13	20	27	40	47	53	60	67	73	80	87	93	100	107	113	120
500	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1000	0	0	-11	-8	-5	-2	0	4	9	11	10	13	13	12	0	0	0	0
1250	0	-5	-11	-6	-3	0	1	5	12	11	10	13	13	12	0	0	0	0
1500	0	-8	-8	-3	-5	0	-1	4	11	11	12	11	10	11	11	10	9	8
1750	0	-5	-9	-7	-6	-2	-2	2	9	11	11	11	11	9	8	6	9	9
2000	0	-7	-8	-7	-5	-4	-2	3	8	8	10	10	9	8	8	7	5	5
2500	0	-6	-9	-7	-5	-4	0	1	6	7	7	7	6	7	5	5	4	3
3000	0	-3	-5	-6	-5	-1	0	2	3	3	3	5	5	4	5	4	3	2
3500	0	2	-2	-4	-7	-1	0	1	2	3	2	1	2	2	1	2	1	1
4000	0	0	-2	-9	-9	-4	-3	-2	-4	1	-1	1	1	1	1	1	0	-1
4500	0	0	-2	-6	-9	-3	-2	0	0	-1	2	1	0	2	2	2	0	1
5000	0	0	0	0	0	0	0	0	0	-1	0	0	1	2	1	1	1	1
5500	0	0	0	0	0	0	0	1	1	0	-2	-3	-1	0	1	1	1	1
6000	0	0	0	0	0	0	0	0	0	0	-1	-2	1	-1	1	1	1	1
6500	0	0	0	0	0	0	0	-1	-1	-1	-1	-2	0	-1	0	1	1	3

**Bild 13:** Vorzündungsdifferenz zwischen E85 & Benzin (deg. C.A.)  
**Figure 13:** Spark advance difference between E85 & gasoline (deg. C.A.)

At higher loads spark can be advanced for E85 and the limiter will be maximum allowed peak pressure and not knock. At high engine speed and load there is an additional limiting factor, spark plug temperature. Both center and ground electrodes have to be kept under a certain temperature limit (<700 °C for the center electrode) to avoid pre-ignition of the air-fuel mixture. The chart in figure 14 shows the absolute E85 spark map and a schematic view of the limiting factor for the allowed spark advance.

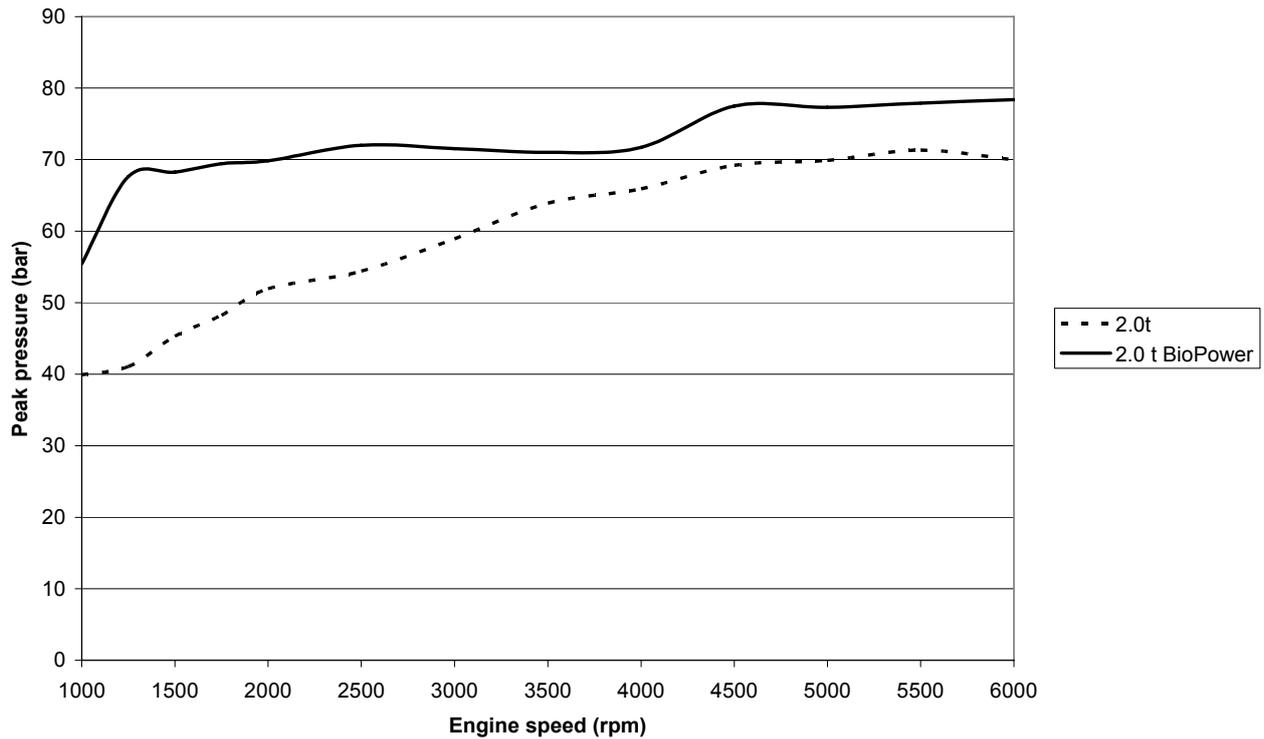
RPM	Load relative maximum torque (%)																	
	9	11	13	20	27	40	47	53	60	67	73	80	87	93	100	107	113	120
500	28	28	28	22	16	12	8	5	1	0	0	0	0	0	0	0	0	0
750	30	32	34	26	20	14	10	6	4	1	0	0	0	0	0	0	0	0
1000	35	38	27	20	20	17	16	15	15	3	2	0	0	0	0	0	0	0
1250	37	34	28	23	23	20	19	18	22	17	14	15	13	12	0	0	0	0
1500	40	32	31	27	22	24	22	21	24	20	20	17	13	13	11	10	9	8
1750	42	36	32	26	24	23	22	22	24	23	21	18	16	13	11	8	10	9
2000	44	35	32	27	26	23	23	25	25	22	21	18	16	14	12	10	8	6
2500	44	36	35	31	29	27	28	27	27	26	22	20	17	15	12	9	8	5
3000	42	40	39	34	31	31	30	29	29	27	24	22	18	15	13	11	9	6
3500	40	44	42	38	34	33	31	30	29	29	26	21	19	17	14	12	10	8
4000	40	40	42	35	34	32	31	30	27	28	24	22	19	17	15	13	11	9
4500	40	40	42	38	34	33	32	31	30	28	28	24	21	20	17	16	13	12
5000	40	40	42	44	40	36	34	32	30	29	28	25	23	21	19	18	16	14
5500	40	40	42	44	40	36	35	33	32	29	26	26	23	21	20	18	17	16
6000	40	40	41	44	42	37	35	32	31	29	27	26	24	22	21	19	18	17
6500	40	40	40	41	42	36	34	32	30	29	27	26	25	23	22	21	19	18



**Bild 14:** Absolute Vorzündung bei E85 (deg. C.A.)  
**Figure 14:** Absolute spark advance on E85 (deg. C.A.)

At blends between 5 and 85 % the spark is calculated according to a non linear characteristic line that links the two spark maps. Since the mapping is not performed to the knocking border, the high map can be kept down to 50 % ethanol content.

As stated earlier maximum spark advanced is limited by the maximum allowable peak combustion pressure (defined by the maximum allowable stress for piston, bearings and cylinder head). Since spark advance of the gasoline version is mainly limited by knocking, spark advance, peak pressure, and such engine efficiency could be increased when using E85. The target was to not increase the peak pressures beyond those of the 154 kW (210Hp) version of the ECOTEC engine.

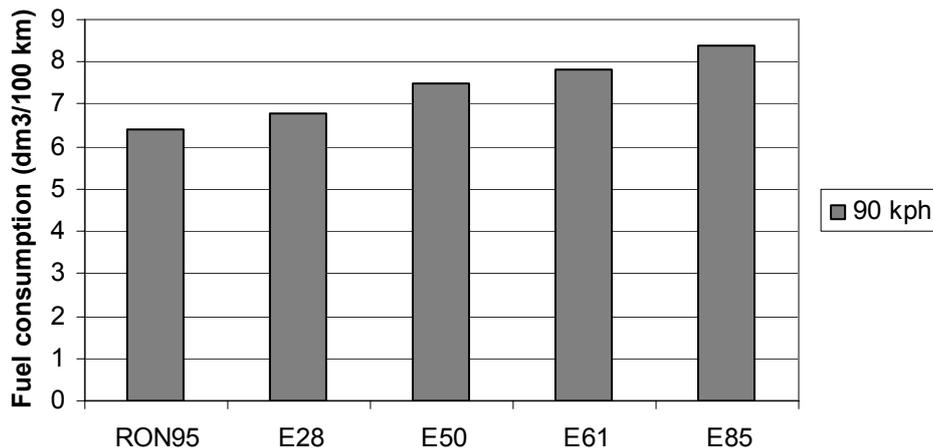


**Bild 15:** Zylinderspitzenndruck vom 2.0t und 2.0t BioPower im Drehmoment Zielwert  
**Figure 15:** Cylinder peak pressure for 2.0t and 2.0t BioPower at torque target

Also the fuelling such as basic fuel (component protection) and start fuel follows non linear characteristic lines that link gasoline and E85 operation. The basic fuel factor differs a lot from the start fuel factor in relation to ethanol content which is why two separate lines are necessary. The work put into creating these blend dependant fuel characteristic lines is massive.

## Fuel consumption

The volumetric fuel consumption increases with increasing amount of ethanol in the fuel. The enthalpy for RON95 is approximately 42 MJ/kg and for E85 29 MJ/kg. The density is 750 kg/m<sup>3</sup> for gasoline and 780 kg/m<sup>3</sup> for E85. This will give a theoretical fuel consumption increase of 39% by volume with E85 at stoichiometric conditions. In actual driving conditions with an E85 optimized engine the increase in fuel consumption ends up at around 30%.



**Bild 16:** Fahrzeugkraftstoffverbrauch bei konstanter Geschwindigkeit (90 km/h) und unterschiedlichen Ethanol konzentrationen

**Figure 16:** In vehicle fuel consumption at constant vehicle speed (90 kph) and at different ethanol blends

Fuel consumption on the European driving cycle is seen in table 5.

Body	Transmission	Gasoline (l/100km)	E85 (l/100km)
Saab 9 <sup>3</sup> Sedan	Manual – 5 speed	7,7	10,2
Saab 9 <sup>3</sup> Sedan	Automatic – 5 speed	8,5	11,3
Saab 9 <sup>3</sup> Wagon	Manual – 5 speed	7,9	10,5
Saab 9 <sup>3</sup> Wagon	Automatic – 5 speed	9,2	12,2

**Tabelle 3:** Kraftstoffverbrauch des 1.8t und 1.8t BioPower im Saab 9<sup>3</sup>

**Table 3:** Fuel consumption for the 1.8t and 1.8t BioPower in Saab 9<sup>3</sup>

The net CO<sub>2</sub> emission balance depends on how the ethanol is produced. For example, the Saab 9<sup>3</sup> Wagon, 5 speed manual, produces 42 g/km of net CO<sub>2</sub> if the ethanol is produced by Domsjö (Sweden) from paper pulp and up to 85 g/km if the ethanol is produced from wine in Italy (Production and distribution included).

## Emissions

Emission level driven by the same lambda parameters as for gasoline with just a blend factor affecting the lambda switch point:

	HC (g/km)	CO (g/km)	NO <sub>x</sub> (g/km)
E85	0,090*	0,86	0,020
Gasoline (E5 Pump quality)	0,077	0,43	0,041
Limit (Euro 4)	0,10	1,0	0,08

**Tabelle 4:** Durchschnittsfahrzeugwerte mit manuellem Getriebe und 50k km gealtertem Katalysator, MVEG-B +20°C

**Table 4:** Average results from a manual car with 50k aged catalyst, MVEG-B +20°C

\*The ethanol part of the organic gas (hydrocarbons + oxygenates) is 30 -40 %.

## Fuel system validation

All parts in the fuel system in contact with the fuel are made of stainless steel and have been thoroughly validated for the most aggressive E85. The experience from the Fam III BioPower application gave good guidance in the choice of materials and validation strategy for the fuel delivery system. The use of stainless steel parts and test fuel related to findings on the market and in different fuel standards was a requirement for E85 compatibility. To get a good understanding for the test fuel demands we compared the European work group agreement, CWA 15293, Swedish standard and market fuels with the GMPT-US test fuel specifications for different fuels and that gave us the possibility to refine the needed validation methods.

The Swedish E85 fuel standard was developed during 2006. GMPT-Europe participates in the steering group, responsible for the current Swedish standard for E85 fuel, SS 15 54 80.

## Engine oil degradation

Use of E85 fuel appears to result in more stable engine oil viscosity. The viscosity increase that is usually seen during City-Cycle, Characteristics Aging and in Captured Test Fleet (CTF) is much reduced when using E85 compared to gasoline. A reasonable explanation for these observations is that the amount of reactive combustion components produced during combustion of ethanol is less than during combustion of gasoline. This results in a less reactive blow-by gas composition giving a lower speed of engine oil thickening due to chemical aging.

On the other hand, use of E85 appears to result in a slightly increased rate of TBN depletion. The increased rate has been observed during test bed validation (GED) and vehicle validation (High-Speed, City-Cycle, and Characteristics Aging) tests, as well as in CTF-vehicles (Captured Test Fleet). This depletion corresponds to a faster degradation of the detergent and dispersant additives. However, the difference in TBN depletion rate in

the 1.8t BioPower and 2.0t BioPower engines is not, by itself, large enough to indicate a need to reduce the service interval by 50%.

Using the FTIR technique, no significant difference was seen in used oil oxidation tests between E85 and gasoline fueled engines. However, the data are not conclusive because a precise comparison is difficult when an ester containing engine oil is used. The reason is that the FTIR wave numbers used to determine oxidation (1800 and 1670  $\text{cm}^{-1}$ ) are partially overlapped by the characteristic wave numbers of the ester component in the oil. This overlap has resulted in negative oxidation values in some of the 1.8t and 2.0t engines that we are comparing (both BioPower and gasoline) calling the usefulness of the data into question.

Nitration by FTIR, on the other hand, is measured using a light wave length that is not greatly influenced by the composition of the engine oil. These data indicate a tendency towards lower FTIR nitration values when using E85 instead of gasoline.

Based on the above observations we conclude that, although contrary to our findings during the development of the Saab 9<sup>5</sup> Fam III BioPower, there are not clear tendencies toward faster chemical degradation of the engine oil when using E85 instead of gasoline.

### **Oil life algorithm**

The GM oil life algorithm (OLM) was already incorporated into the Trionic 8 software at the introduction of the 1.8t and 2.0t gasoline engine in 2003. To better model the expected oil degradation in the BioPower engines the oil life algorithm was recalibrated. Based on experience from Fam III BioPower development the target mileage was set to 15 000 km / 1 year. The number of allowed cold starts, allowed crank shaft revolutions and maximum allowed mileage was recalibrated accordingly. The one year service interval is covered by a platform calibration because the engine ECU does not have a calendar time function. As have been seen with the gasoline versions most customers will reach the targeted mileage before the clock function signals the need for a change.

### **Conclusion regarding engine oil**

Engine oil analysis data indicates that the chemical degradation of the engine oil in the 1.8t and 2.0t BioPower engines is equivalent to the chemical degradation in their gasoline counterparts. However, the concentrations of wear metals are somewhat increased with use of E85. This is supported by examination of engines upon completion of endurance tests. These examinations have revealed slight increase in cylinder liner wear with the use of E85 instead of gasoline. This observation would explain the increased iron (cylinder liner), chromium, tin (piston ring), and aluminum (piston) concentrations seen when E85 test fuels are used. The higher engine oil wear metals are largely limited to the higher power tests. They are linked to the higher specific power of the BioPower engines when fueled with E85. However, the wear metal levels in the 1,8t and 2,0t BioPower engines are still within limits and will not result in engine damage or increased engine oil consumption over the life of the engine. Nevertheless, the recommended service interval will be 15 000 km / 1 year. The reason for this is that the current engine-wear life assessments have been performed using data from engines running with only that particular service interval, and a longer service interval would have to be properly validated. Even more important, the inlet deposit formation issue, explained in the following chapter, suggests a need for a service interval of approximately 15 000 km.

## Deposit formation in intake system

During development of the BioPower engine it has been noted that there is a significant inlet system deposit build up. The build up is mainly on inlet valves, inlet channels and, most severely, on the fuel injector. It forms downstream of the injector and results in a thick, reddish, gluey deposit. The deposits were analyzed to be mainly PIB (Poly Iso Butylene). As the deposits can not be found upstream of the injectors the focus was turned to the E85 fuel. The fuel is a blend of denaturated fuel ethanol and normal Swedish UL95, according to SS 15 54 22. In the SS 15 54 22 fuel specification it is required that the gasoline fuel have a keep clean function. To meet that specification all gasoline in Sweden uses keep clean additives. By using a revised unwashed gum analysis method it was discovered that E85 in Sweden contained approximately 70 mg/kg of a PIB-based keep clean additive. That keep clean additive came from the gasoline part of the E85.

## Deposit formation speed

The deposits can be seen in all BioPower engines that have run on only E85. The amount of deposits differs dramatically between different engines and it could be clearly seen that the deposit formation speed was strongly dependent on the driving cycle. In high speed / high load testing the deposit formation was very slow and there were never any problems as a result of the deposits. In “normal” driving the deposit formation speed was clearly higher and in extreme city type driving the highest deposit formation speed was found. In an in-house test cycle designed to cover extreme city type driving, City-Cycle, the deposit formation speed is high enough to be one of the factors determining the right time for engine service, usually something that is determined solely on engine oil degradation.

Deposit after 15 000 km in City-Cycle-test



Deposit after 60 000 km in High Speed-test



**Bild 17:** Ablagerungsbildung abhängig vom Fahrzyklus

**Figure 17:** Deposit formation speed depending on driving cycle

## Cold engine start and drivability problems

Just by looking at the amount of deposits on inlet valves, injectors and in the inlet channel one can assume that there will be start and drivability problems. This was confirmed in the City-Cycle tests where the cold start and drivability problems started to appear at approximately 15 000 km. If the deposit formation is allowed to continue the customer will experience problems. For the customer this will be obvious when the “Check Engine” light will be engaged due to misfire.

## **Fuel Additive**

As it has been determined that the inlet system deposit consists mainly of PIB and that the source of the PIB is the keep clean additive inherited from the petrol part in the E85. The first idea was to produce a PIB-free E85. We consulted the main E85 supplier in Sweden and a batch of PIB-free E85 was produced. The fuel was used in an ongoing City-Cycle test and parallel to this the E85 was analyzed for traces of PIB. It was found that the PIB-free E85 still contained PIB additive at a reduced level. What used to be approximately 70 mg/kg of PIB ended up at between 10 and 30 mg/kg. The reason for this contamination was traced to the mandatory use of keep clean additive in gasoline. All fuel delivery and storage systems have traces of keep clean additives and therefore PIB-free E85 was impossible to produce if the normal distribution system was to be used. These findings, together with the result that the reduced PIB E85 caused the same, or even worse, deposit problems, caused abandonment of the PIB-free E85 idea. One other reason for abandoning the PIB-free track is that the BioPower engines are designed to be flexfuel engines. That will result in customers using gasoline, E85 and any mixtures between those fuels producing PIB in the tank regardless of whether pure E85 is PIB-free or not.

The function of keep clean additive is to soften the deposits in the inlet until they are soft enough for the fuel flow to flush the deposit/additive mixture away from the surfaces. This explains the findings that a low amount of keep clean additives results in an increased deposit build up. If there is too little keep clean additive in the fuel the deposits will never get soft enough to be flushed away and the keep clean additive that is incorporated into the deposit will stay there and contribute to the deposit formation.

Poly Iso Butylene based additives are the most common keep clean fuel additive carriers used in commercial gasoline. The other additive system is Poly Ether Amine (PEA). It is compatible with both hydrocarbons and alcohol while PIB is easily dissolved in hydrocarbons but not in alcohol. The amount of PIB that is carried into the E85 from the gasoline is kept dispersed in the fuel tank and through the fuel delivery system, but deposits in the inlet system as the ethanol evaporates.

As it is clear that the deposit build up in the inlet system will eventually cause cold start and drivability problems as well as emission concerns there is a strong need for clean up and keep clean methods. The task to solve the problem has been divided into a short term and a long term solution. Short term solution will be something that the customer or the service work shop can do at certain periods or when problems occur while the long term solution most likely will be some sort of additive package that copes with PIB deposits when running on pure E85 and is fully compatible with any mixtures of ethanol, gasoline and with normal fuel additives that can be found on the market.

## **Tests of after market fuel additives**

Additives to be used as "bottle solutions" have been tested from two different additive suppliers. Both suppliers recommended additives based on PEA technology as they would be easily soluble in gasoline, E85 and any mixtures between the both fuels. It was also believed that PEA based additives would have a good effect on PIB deposits. Recommended levels were approximately 2 000 mg/kg from both suppliers and levels between 1 600 to 3 200 mg/kg have been tested. Additives from both suppliers showed

clean up effect on inlet channels and valves, but no effect on injectors. At high dosage the effect on the injectors might even be an increased deposit build up speed.

Injector deposit at start of clean up



Injector deposit after one tank of clean up



**Bild 18:** Kein Einspritzventilreinigungseffekt mit getesteten PEA basierten Additiven

**Figure 18:** No injector clean up effect with tested PEA-based additives

### Short term solution

One method that has an immense clean up effect is to use gasoline. In tests it has been shown that after only 100 km most of the injector deposits have been cleaned away. The same is true for inlet channels and valves. This shows that the deposits originates from the fuel and will be flushed away when using the type of fuel the additive was originally intended for.

Injector deposit at start of gasoline clean up



Injector deposit after 100 km on gasoline



**Bild 19:** Einspritzventilreinigung bei Verwendung von Benzin

**Figure 19:** Injector clean up using gasoline

## **Long term solution**

There are ongoing investigations on suitable long term solutions. Both additive companies and GM-Brazil will be involved together with GMPT-E and GMPT-NAO. The goal will be to find a long term solution that most likely will be an additive package that copes with PIB deposits when running on pure E85 and is fully compatible with any mixtures of ethanol, gasoline and with normal fuel additives that can be found on the market. This additive package will be added to the bulk E85 fuel and by that solve the deposit problem. The additive level needs to be able to function in the pure E85 and also in the mixture of E85 and gasoline, resulting in lower levels of the E85 additive package while increasing the commercial gasoline additive level in the mixture. The timeframe for this development is somewhere between one and two years.

## **Conclusion**

The new ECOTEC turbo BioPower is the logical progression of the Saab BioPower line. It adapts the ECOTEC engine family to the Saab BioPower tradition. It enables the greater use of E85 ethanol fuel, reducing our dependence on fossil petroleum and reducing CO2 emissions. In addition, the use of the higher octane E85 ethanol fuel allows significant increases in power and torque, extending the BioPower concept.

Close cooperation among team members coupled with the robust structure of the base engine design and the lessons learned on the previous BioPower engines allowed rapid development of this engine. Several development obstacles were encountered and overcome including pre-ignition, cylinder head cracking, and valve seat recession. Extensive software and calibration development was also accomplished. The program goals of maximum reuse of existing parts and manufacturing processes while delivering a robust and exciting product were realized.

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