ABSTRACT

In order to achieve SULEV emission legislation the overall efficiency of the exhaust gas aftertreatment system has to be increased. Beside engine-out emissions and air/fuel ratio control especially during cold start and during transient driving conditions the catalyst has to be optimized regarding cold start and efficiency under warmed-up conditions. The paper will show emission test results of different catalyst designs (various cell-densities and foil thicknesses, cone-shape catalysts and electrically heated catalysts) measured on a dynamic engine test bench. With an optimized SULEV catalyst system emission tests in a close-coupled position of a mid-size passenger car will be presented.

1 INTRODUCTION

In recent years, motor vehicle emission limits have continued to be tightened world-wide. The strictest limits have been imposed in California under the SULEV (Super Ultra Low Emission Vehicle) legislation.

<table>
<thead>
<tr>
<th></th>
<th>HC</th>
<th>CO</th>
<th>NOx</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULEV*</td>
<td>0.04 g/m</td>
<td>1.7 g/m</td>
<td>0.2 g/m</td>
</tr>
<tr>
<td>ULEV (2003)*</td>
<td>0.01 g/m</td>
<td>1.0 g/m</td>
<td>0.02 g/m</td>
</tr>
<tr>
<td>EG III (2000)**</td>
<td>0.2 g/km</td>
<td>2.3 g/km</td>
<td>0.15 g/km</td>
</tr>
<tr>
<td>EG IV (2005)**</td>
<td>0.1 g/km</td>
<td>1.0 g/km</td>
<td>0.08 g/km</td>
</tr>
</tbody>
</table>

* FTP-Test; ** EG III Testcycle

Table 1: Emission limits

Originally, the Californian environmental authority CARB planned the compulsory introduction of electric vehicles for the model-year 2003, with the aim of reducing environmental damage, especially in the Los Angeles basin. International studies and fleet trials with electric vehicles showed that, while electric vehicles may indeed be considered “zero emission vehicles” at local level, globally emissions are nonetheless caused in the manufacturing and electricity generating processes [1]. Moreover, published exhaust gas results on modern vehicles fitted with state-of-the-art emission treatment systems increasingly show negative exhaust gas emission at normal running temperature, even when local emission levels are comparatively low. This indicates that, when fitted with active catalytic systems, these vehicles can make a positive contribution in dealing with the emissions issue, especially in urban areas. Catalytic coating of vehicle cooling systems also produces a reduction in ozone levels near the ground [2]. Given the presumption that over the coming 10 - 20 years the entire fleet of vehicles will be equipped with engines and catalytic systems that comply with SULEV or similar limits, the emissions problem can be considered solved as far as hydrocarbons, carbon monoxide and nitrogen oxide are concerned.

Besides the consumption of resources in fuel production, the emission of CO₂ remains in question as a possible cause of the “Greenhouse Effect”. If one looks at world-wide CO₂ emission levels occurring naturally and generated by man, it is clear that the contribution of private motoring is a mere 0.2% [3]. Whether the demonstrably rising CO₂ levels in the earth’s atmosphere cause global warming, or whether the warming is caused, for example, by lengthening of sunspot cycles, which in turn causes rising CO₂ emissions from the oceans, has not been explained unequivocally.

The reduction in fleet fuel consumption required by legislators will be achievable in the future by using new engine and transmission technologies, together with lightweight construction with no loss of comfort. In this context, the question of optimal drive methods takes on increased importance. When comparing new drive technologies, however, all environmentally relevant viewpoints must be taken into account.

2 DRIVE TECHNOLOGIES

Besides the familiar gasoline and diesel engines, lean-burn direct-injection gasoline engines, hybrid vehicles, fuel-cells and, as always, electric motors are under discussion as drive methods.
All these drive methods have to be measured up against the ULEV vehicle already introduced in the USA and the ZLEV vehicle presented in 1999 SAE. Diesel engines show a clear advantage over the gasoline engine with respect to fuel consumption. Emissions of particulates and further reductions in nitrogen oxide must however be seen as challenging for the diesel engine. Lean-burn direct-injection gasoline engines have the potential to reduce fuel consumption compared to MPFI engine due to reduced throttling losses in stratified engine operation and lean combustion. In the present state of catalyst and engine technology, lean-burn operation at all states of load, including cold-start, cannot yet be exhibited. Limitations of the potential to save fuel consumption in costumer use are mainly based on the need to reduce the NOx-emissions in lean exhaust gas and therefore the limitations of the NOx adsorber technology available today. These limitations are mainly coming from the need to do sulfur regenerations of the NOx adsorber because of the sulfur content of the fuel, the limited temperature window of the NOx-adsorber which forces the EMS to operate stochiometric and the need for temperature protection of the NOx-adsorber catalyst due to limited high temperature stability of the catalyst coating.

Hybrid vehicles such as the Toyota Prius represent a compromise between electric vehicles and diesel or gasoline engines. Apart from the complexity of this system, one of its main disadvantages is the additional weight compared to gasoline or diesel engines. Fuel consumption advantages can be achieved only in districts where vehicles predominantly operate in tailbacks or stop-start conditions. However due to the increased vehicle weight because of batteries fuel consumption can be increased in transient vehicle operation and at higher vehicle speed. The disadvantage of electric vehicles is, as always, the on-board energy supply. Even the latest battery technology fails to provide sufficient energy storage capacity to yield performance comparable with an internal combustion engine.

The fuel cell would be one solution allowing on-board generation of electric power. It is necessary to distinguish here between fuel cells with a direct supply of hydrogen (a hydrogen tank in the vehicle) and fuel cells with a connected-up reformer. A reformer will generate hydrogen from methanol and/or petrol. Using this system, the present-day petrol infrastructure could be employed. Current reformers and fuel-cell banks are however quite heavy, require a great deal of space and do have disadvantages in start up behaviour in cold conditions. Since the consumer is not prepared to accept inconveniences such as long waiting times before starting up, any large-scale introduction of this system within the next 10 years is doubtful.

The table below gives a summary evaluation of drive methods with regard to emissions, consumption (CO\textsubscript{2}) and weight/costs.

<table>
<thead>
<tr>
<th></th>
<th>Gasoline engine</th>
<th>Diesel engine</th>
<th>Gasoline engine (direct-injection lean-burn)</th>
<th>Hybrid car</th>
<th>Fuel cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>HC</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>NOx</td>
<td>+ (-)</td>
<td>- (-)</td>
<td>+</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>Particle</td>
<td>++</td>
<td>--</td>
<td>--</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>+ (+)</td>
<td>-</td>
<td>-</td>
<td>0 / --</td>
<td></td>
</tr>
<tr>
<td>Weight/ Costs</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>--</td>
<td>-</td>
</tr>
<tr>
<td>Sum</td>
<td>++</td>
<td>+</td>
<td>+</td>
<td>+ (+)</td>
<td>+</td>
</tr>
</tbody>
</table>

Table 2: Evaluation of various drive methods with regard to emissions and weight/costs.

3 EVALUATION OF CATALYSTS AND EMISSIONS

The above shown evaluation of each drive method shows clearly that the gasoline engine will remain the preferred drive method with lowest risks for at least the next 10 - 15 years. Even now, the gasoline engine on its own or in combination with new drive variants still shows great potential for improvements in performance, emissions and fuel consumption, with the consequence that the demands made of new drive methods will rise continually.

The goal now has to be to equip the vehicle with emission technology such that it will no longer make any sense, even in politics, to portray the motor vehicle as "Environmental Enemy No. 1", and to object to arbitrary political decisions such as the current debate over diesel taxation in Germany. The Californian SULEV limits are defined as the initial target.

The main course of cumulative HC emissions of a production car and the levels required by SULEV in the American FTP test are represented in fig 1.

![Fig. 1: Cumulative HC emissions in the FTP test](image-url)
Besides an almost 100% conversion rate at normal operating temperature, a very short start-up period in the catalyst is essential after starting the engine. The maximum duration of start-up period to achieve SULEV is directly dependent on raw engine emissions during cold start, and is varying between 3 and 15 seconds depending on the engine [6]. To achieve this short start up periode, the gas temperature in front of the catalyst must exceed the Light-off temperature of 200-300°C some seconds earlier. In order to avoid unnecessary heat losses in the down pipes to the catalyst, the catalyst should be positioned as close as possible to the engine, immediately behind the manifold.

The performance of the catalyst during cold start is determined, apart from the gas temperature and the catalytic coating, also by the physical and thermodynamic qualities of the substrates. During cold start, the catalyst works initially as a pure heat-exchanger, with catalytic activity from the time the light-off temperature is reached.

For this reason the aim should be to have the largest possible catalytic surface (GO) with lowest possible heat capacity (cp) available. In order to evaluate different systems, the so-called cold-start factor GO/cp is used [7]. Fig. 2 shows the cold-start factor of various metal substrates.

![Cold-start factor of various metal substrates (400 - 1200 cps).](image)

It should be noted that the cold-start factor increases with cell density together with a reduction in foil thickness. However, if the cell density is increased with no reduction in foil thickness, a deterioration will be observed.

A further important factor is the use of a heat cascade. By reducing the upstream cross-section of the first substrate, cold-start behaviour and flow distribution are both beneficially affected [8]. Fig. 3 shows the example of an close coupled converter cascade on a BMW 6-cylinder engine [9].

![Close coupled converter cascade on a BMW 6-cylinder engine.](image)

With the continuous reduction of the thermal masses of the catalyst substrate, the part played by the washcoat on the overall thermal mass becomes more and more important. Washcoat mass of 200 - 250 g/l are usually used for modern 3-way catalysts. A reduction of washcoat mass down to 150 or 100g, in a catalyst of 400 cpsi with a foil thickness of 0.05 mm will cause a reduction of washcoat share from 63% to 25%. With a substrate of 1000 cpsi and a foil thickness of 0.025 mm, there is an improvement of 53% achievable. The chart below shows clearly that the total thermal mass is dependent on the washcoat mass.

![Influence of washcoat mass on the total thermal mass of the catalyst](image)

To achieve best utilisation of the substrate and the noble metals contained in the coating, a uniform distribution of the washcoat along the cell periphery and the axis of the catalyst is absolutely essential. Fig. 5 shows examples of a thick and a thin washcoat within the cross-section of the cell.
High washcoat loading          Low washcoat loading

Fig. 5: Washcoat distribution, dependent on washcoat mass in the cross-section of the cell.

Given optimal lambda control, the catalytic efficiency at normal operating temperature is limited only by the mass transport. Mass transport within the laminar flow to the channel walls is influenced primarily by the hydraulic diameter of the channel. The value of GO/dh is used as a measure of efficiency [10]. Fig. 6 shows the efficiency factor GO/dh for various cell densities.

Higher cell densities mean improved efficiency for all pollutants [6.11] In this way it even becomes possible to reduce the volume of the catalyst and one can therefore dispense with additional under-floor catalyst. In this context, NOx reacts most critically to a reduction in catalyst volume when the engine is not tuned correctly.

If we analyse cumulative NOx emissions in an exhaust gas test, we will find that total emissions can mostly be traced back to just a few incidents during the test. These short bursts of NOx, represented in fig. 7, are not dependent on the volumetric load on the catalyst, but are triggered by non-optimal lambda control at the non-steady state regime. E-gas and faster engine management systems that allow targeted regulation of individual cylinders will allow a distinct improvement.

4 SULEV Catalyst Concept

In designing a SULEV vehicle, an engine with very low raw emissions and optimal lambda control is absolutely essential. For this reason, all further observations are based on a ULEV vehicle with SULEV potential currently on the market.

The raw emissions of this vehicle in an FTP test were around 1.6 g/mile.

The exhaust gas temperature and cumulative HC emissions during the first 100 seconds of the FTP test are shown in fig. 8.
capacity. The catalyst simulation program „KatProg“ was used for the process.

A basic idea was to develop a catalyst that could be modified up to SULEV standards to meet new legislation using a modular approach. Because of the OBD requirements, the system was to be a „two-brick“ solution, in which it was possible to monitor the first substrate separately. In view of the requirements for good flow distribution and improved cold-start efficiency, the catalyst system was designed as a cascade. In cases of very poor flow distribution because of space constraints, replacing the first substrate by a conically shaped converter is beneficial.

Cell density and foil thickness can be varied to suit the level of efficiency required. For applications with higher raw emissions or low gas temperatures, it is possible to replace the first brick, irrespective of space constraints, by an electrically heated catalyst, consisting of a heating disc and a supporting catalyst. Fig. 9 shows the principles of the system in various versions.

5 CATALYST CALCULATIONS

A catalyst system put together using the modular approach offers the possibility of meeting different emission standards without any changes of the catalyst canning. This is of course possible together with further engine development and improvements of the engine management. Catalysts with extra thin foils and high cell densities can be used only in conjunction with a well tuned engine management, without emission peaks occurring in transient driving conditions. However, these very active catalysts of low heat capacity, HC peaks in the raw emission lead to extreme rises of the local catalyst temperature compared to substrates with thicker foils, and thus to premature ageing of the catalyst. Table 3 represents needed variations of the cascade system to fulfill different emission legislation requirements. The complete catalyst volume is 1.4 l, and is thus 70% of the engine displacement of the test vehicle. Figures 10 and 11 show simulations of HC conversion rates and calculation of cumulative HC emissions during the first 100 seconds of the FTP test carried out with KatProg.

### Table 3: Variations to a catalyst system using the modular approach.

<table>
<thead>
<tr>
<th>1. Substrate</th>
<th>2. Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ø 80 x 74.5 mm</td>
<td>Ø 110 x 110 mm</td>
</tr>
<tr>
<td>Cell density / Foil thickness</td>
<td>Cold-start factor</td>
</tr>
<tr>
<td>LEV / EG III</td>
<td>300 cpsi / 0.05 mm</td>
</tr>
<tr>
<td>ULEV / EG IV</td>
<td>600 cpsi / 0.04 mm</td>
</tr>
<tr>
<td>SULEV</td>
<td>800 cpsi / 0.03 mm</td>
</tr>
<tr>
<td>EZEV</td>
<td>Heated disc</td>
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<td></td>
<td></td>
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</tbody>
</table>

![Fig. 9: Various versions of a catalyst system using modular approach](image)

![Fig. 10: HC conversion rates of various catalyst during the first 100 seconds of the FTP test](image)

![Fig. 11: Cumulative HC emissions of various catalyst during the first 100 seconds of the FTP test](image)
To ensure the validity of the program and catalyst efficiency, comparative calculations of the exhaust emissions of the original catalyst system were carried out showing a deviation of < 5%.

The results of the calculation clearly demonstrate the advantage of higher cell densities in conjunction with thinner foils. Cold-start emissions can be reduced by 23% with identical catalyst canning only by a change of cell density from 300 cpsi / 0.05 mm to 800 cpsi / 0.03 mm. The use of catalysts with electric heating will additionally give a potential improvement of emission reduction of 60% in a cold-start. At normal operating temperature, raising the cell density will similarly mean a clear improvement in catalyst efficiency through better mass transfer to the channel walls.

The possibility of realising converter systems using identical canning provides the most cost-effective solution for vehicles which over the course of their production life will have to achieve different exhaust emission standards.

6 EMISSION TEST RESULTS

In addition to the calculations shown above several emission tests were conducted on the same vehicle of which the boundary conditions for the catalyst calculations (chapter 5) had been taken from (mass flow, engine out emissions and gas inlet temperature). As described, this car is available as a series production ULEV-vehicle. For the emission tests the following converter configuration was chosen:

1st brick: EHC Ø 80 x 12 mm / 400 cpsi / 40 µm / 0.04 Ohms + Ø 80 x 74.5 mm / 600 cpsi / 30 µm

2nd brick: Main converter Ø 110 x 110 mm / 1000 cpsi / 25 µm.

The metal substrates were equipped with a 3-metal coating with 100 g/ft³ and a PM-ratio of 1:14:1. For the first tests this converter system was integrated into the series production vehicle. Then, in stabilized condition, FTP-cycles were conducted with the EHC in heated and unheated condition. For the heated test, the EHC was activated for 25 seconds from engine cranking on.

Fig. 12 shows the resulting THC cold start emissions for both the heated and the unheated test. It can be noticed that in the unheated case light-off is reached after about 30 seconds. Heating the EHC with an energy of 2.5 kW (at 10 Volts) shortens the light-off time down to 22 seconds. The THC overall test result for the unheated case was 0.036 g/mile which could be reduced by about 22% to 0.028 g/mile by heating (see also table 4).

<table>
<thead>
<tr>
<th></th>
<th>HC [g/mile]</th>
<th>CO [g/mile]</th>
<th>NOx [g/mile]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unheated</td>
<td>0.036</td>
<td>0.186</td>
<td>0.058</td>
</tr>
<tr>
<td>Heated</td>
<td>0.028</td>
<td>0.089</td>
<td>0.018</td>
</tr>
</tbody>
</table>

Table 4: FTP total test results of the 2-brick EHC-system (heated/unheated)

These results were received using the series setup of the test vehicle and show still some potential for further optimization. According to the measurement results, the air/fuel ratio during cold start and idling was slightly rich. Therefore, as a next step it is planned to equip the car with a secondary air blower in order to achieve a more lean gas mixture and to improve the light-off behavior further. In addition several preheating strategies to reduce the cold start emissions down to SULEV limits are planned.

7 SUMMARY

The emission levels already achieved in prototype vehicles exhibited in the USA make it clear that it will in the future be possible to build vehicles whose exhaust gases in urban areas will be cleaner than the air taken in, and will thus meet future restrictions on emissions. The car, then, will clean up the environment.

Comparison of the different drive methods currently under discussion supports the leading role of the gasoline engine over the next 10 - 15 years, apart from CO$_2$ emissions. The degree of importance attaching to CO$_2$ in this context plainly depends on the extent to which carbon dioxide given off by private motoring contributes to global warming, and to what extent it is just a means of exerting political pressure.

With a view to meeting future exhaust limits using the gasoline engine, it is urgently necessary to optimise the catalyst, the engine, and engine management system. The complete system of engine, engine management, catalyst substrates and catalytic coating must be addressed as one. Given this prerequisite, it will be possible to build modular catalyst systems that comply with future requirements.
Modular catalyst systems make possible cost-effective adaptation of catalyst efficiency by raising cell density while simultaneously reducing foil thickness (thermal capacity), or alternatively by installing conical or electrically heated catalysts. Use of these methods, together with simultaneous improvements in the overall system, renders additional catalyst volume unnecessary.

Confirmation of the emission calculations and an examination of mechanical and thermal durability are currently in progress.

7 REFERENCES


