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Development of an Engine Management Strategy and a Cost Effective Catalyst System to meet SULEV Emission Requirements demonstrated on a V-6 Engine

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ABSTRACT

The study presented in this paper focuses on measures to minimize exhaust gas emissions to meet SULEV targets on a V6 engine by using a cost efficient system configuration.

The study consists of three parts.

A) In the first stage, the influence of engine management both on raw emissions and catalyst light off performance was optimized.

B) Afterwards, the predefined high cell density catalyst system was tested on an engine test bench. In this stage, thermal data and engine out emissions were used for modeling and prediction of light-off performance for further optimized catalyst concepts.

C) In the final stage of the program, the emission performance of the test matrix, including high cell density as well as multifunctional single substrate systems, are studied during the FTP cycle.

The presented results show the approach to achieve SULEV emission compliance with innovative engine control strategies in combination with a cost effective metallic catalyst design.

INTRODUCTION

With the increased emission requirements of the future, it will be a challenge to design a cost efficient and robust propulsion system, which will meet stringent emission limits like SULEV, especially for engines with bigger displacements. This paper demonstrates, that the combination of innovative engine control strategies and an optimized catalytic converter layout can provide a cost efficient way to achieve future emission requirements.

The engine used for the study is a 3,6L PFI V6 engine with dual variable cam, cast iron exhaust manifolds, no secondary air injection, no external EGR and two closed coupled converters. The baseline engine complies with LEV2 emission requirements. The engine was tested on an engine test bench to further minimize exhaust emissions and increase exhaust gas and catalyst temperature to the expected SULEV requirement (500 deg. C catalyst bed temperature) after the first 20s of idling. Therefore exhaust gas temperature and engine out emissions were studied to help optimize the engine management calibration for the cold start strategy. The following development steps were taken to achieve the emission level as well as the desired catalyst temperatures after start:

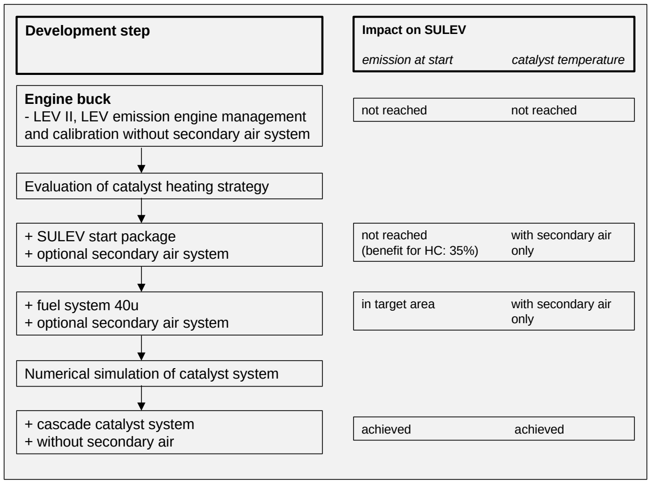

Figure 1: development steps

Each development step will be discussed in detail later. The main focus was to achieve emission reduction and catalyst light off without secondary air injection.

For the calibration and optimization of the engine controls, a baseline 1.1ltr catalyst with 600cpsi was used, which was not originally designed for a SULEV application. In parallel a numerical tool to study catalyst light-off performance and design was utilized to develop a cost effective converter.

After optimizing the engine cold start strategy and defining the catalyst layout, the engine management is further optimized to minimize tail pipe emissions during hot transient conditions. For this investigation, FTP tests are carried out with stepwise upgraded fuel system, catalyst system and corresponding software and calibration on a chassis dynamometer.

A) ENGINE MANAGEMENT

The measures related to the EMS, shown in Figure 1 are:

Catalyst Heating Evaluation
1. Exothermic reaction before converter
2. Influence of secondary air injection

Engine Start Optimization
3. Control of engine start flare
4. Optimization of start and after-start fueling

Optimized Fuel and Ignition System
5. Increase fuel pressure to establish small SMD
6. Increase ignition energy

CATALYST HEATING EVALUATION

1. Exothermic Reaction before converter:

The engine was installed on an engine dynamometer to simulate the idling phase of the FTP cold start. Thermocouples have been installed to record exhaust gas inlet temperature and substrate bed temperature for evaluation of the catalyst heat up and pre catalyst temperature. Figure 2 shows the temperature traces for the configuration with and without secondary air injection. The engine speed was similar for both configuration.

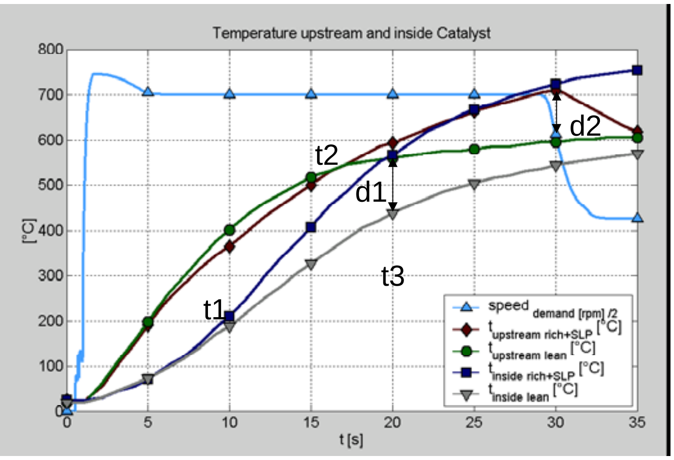

Figure 2 Evaluation of catalyst heating strategy

There is no rise in pre catalyst temperature up to t2, but thereafter to d2 a pre catalyst exothermic reaction starts. The exothermic reaction could be improved by double walled steel tubing optimization of exhaust manifold design and secondary air injection system. With the current configuration, there is no pre catalyst exothermic reaction useable for FTP.

After t1 the catalyst bed temperature transient is higher for the SAI configuration due to exothermic reaction achieved through enrichment (engine lambda 0.77). The catalyst bed temperature is about 130 Kelvin (d1) higher for the SAI configuration at 20s (t3). The HC brought in by rich engine lambda reacts only at the catalyst. If the enrichment of engine lambda starts too early or too strong, the HC may not react at the catalyst completely.

While there was no thermal reaction upstream of the catalyst, secondary air was still necessary to heat the baseline catalysts to the expected SULEV range.

2. Influence of secondary air injection

The engine starts with lean AFR to minimize engine out emissions. After catalyst light-off, fueling was switched to rich to achieve exothermic reaction by adding secondary air and accelerate total light-off. It was necessary to delay the enrichment until the point where the lean fueling strategy had started the first catalyst conversion reaction in order to optimize the engine-out raw emissions. A rich fueling strategy with secondary air right from the beginning would increase engine-out raw emissions and reduce overall catalyst bed temperature.

During the rich converter heating phase for the V6 engine, a very high secondary air mass flow was necessary to counter with the engine mass flow. By using a reduced secondary air mass flow the possible engine enrichment was limited in order to avoid rich exhaust lambda. The recorded exhaust lambda for two SAI mass flows are shown in Figure 3.

In this study, two secondary air pumps have been used to establish sufficient mass flow. Figure 4 compares the SAI-mass flow recorded for one and two stage secondary air pump application. Engine speed was similar therefore engine mass flow comparable.

Figure 3 and 4 show the boundary of secondary air usage. One secondary air pump has can’t come up with an higher engine mass flow, so the torque reserve and the possible enrichment is limited. To find a packaging for a bigger or for two secondary air pumps in a row is hardly possible.

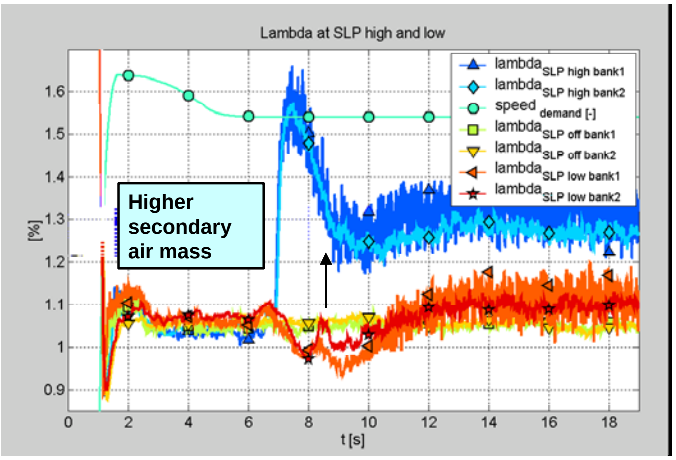

Figure 3: Exhaust lambda without SAI and at high and low SAI , engine enrichment to 0.75

An optimization of the secondary air system is essential to achieve a sufficient secondary air mass flow to the exhaust system.

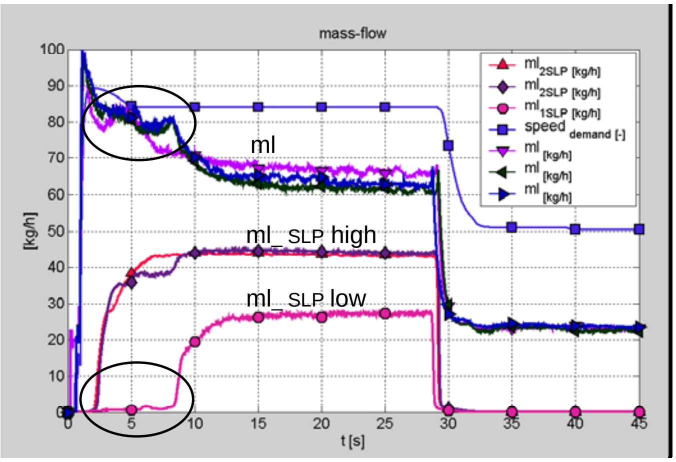

Figure 4: Engine and SAI mass flow at high and low SAI, high engine mass suppresses SAI

Catalyst bed temperature for the SAI configuration was above 550°C and 350°C with the lean baseline calibration 20s after start. (Figure 5)

Properly heated catalysts are essential for passing the first hill of the FTP without emission penalty. However, there was no difference in the integrated 20s tail pipe emissions between lean start and secondary air usage.

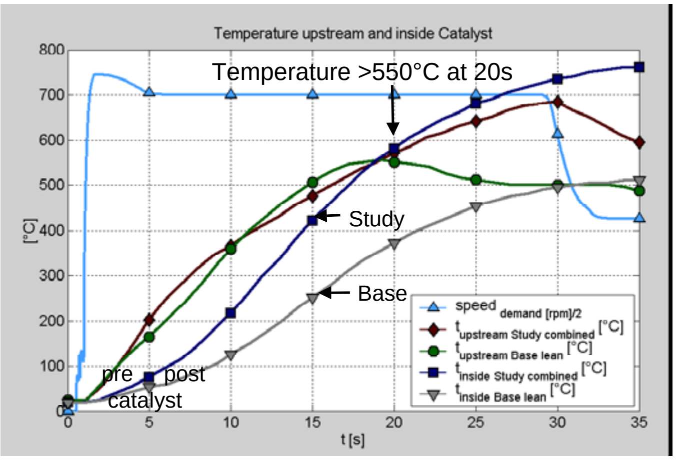

Figure 5: Temperature comparison SAI to lean base, upstream and inside catalyst

These results already showed the limits of the possible secondary air usage. In order to establish a cost effective system, the later focus was changed to a lean concept without secondary air, also with improved catalysts.

ENGINE START OPTIMIZATION

Any raw emissions at start will just pass through the cold catalysts, therefore reducing raw emissions at start is essential and directly visible in bag 1 of the FTP test procedure.

3. Control of engine start flare

A controlled after-start intake manifold pressure decrease by modeling the engine speed increase at start is one major method for the engine start optimization.

A carefully controlled engine run-up during start will prevent a possible evaporation of complete sections of wall- applied fuel film at pressure flares below 500 mbar manifold pressure. This fuel from the intake manifold will accumulate in small droplets and will pass through the still cold converter, resulting in a negative emission impact.

This can prevented by engine load prediction at start and proper throttle position. A constant throttle position at start and a smooth release to the torque structure provides the necessary start stability and prevents a decrease in MAP below 500 mbar during the start, which is shown in figure 6 & 7.

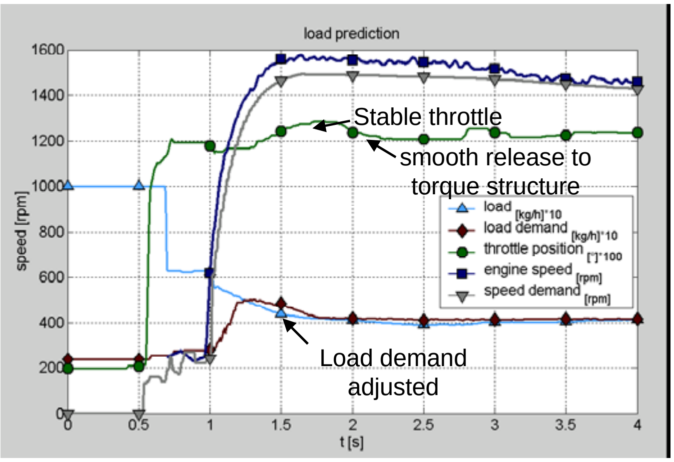

Figure 6: Engine load prediction at start

Figure 6 shows how the naturally unthrottled start with high engine load is considered in the load prediction to provide stabilized throttle position.

In order to have a balanced idle speed control with active capability for operation, ignition angle controller parameter and boundary use specific wider parameter sets directly at start.

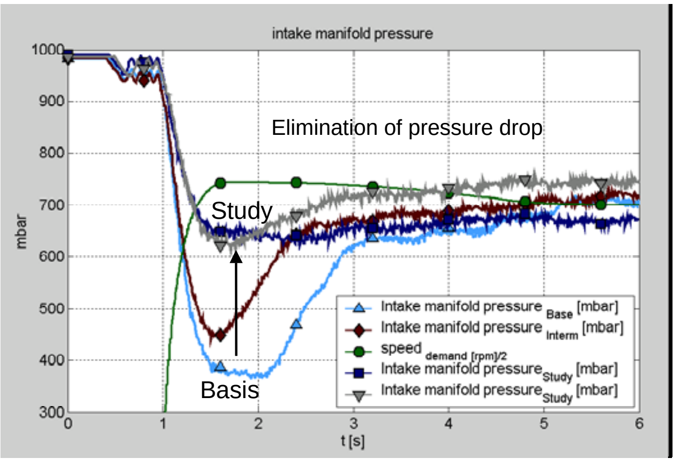

Figure 7: Elimination of pressure undershoot with described engine management measures

The timing for the torque reserve (spark retard) at start is essential also. Generally a fast, almost instant ramp in of all start parameters to their closed loop control levels was the most efficient way to establish a controlled engine run up, resulting in a moderate manifold pressure decrease to prevent excessive raw emissions during the start phase.

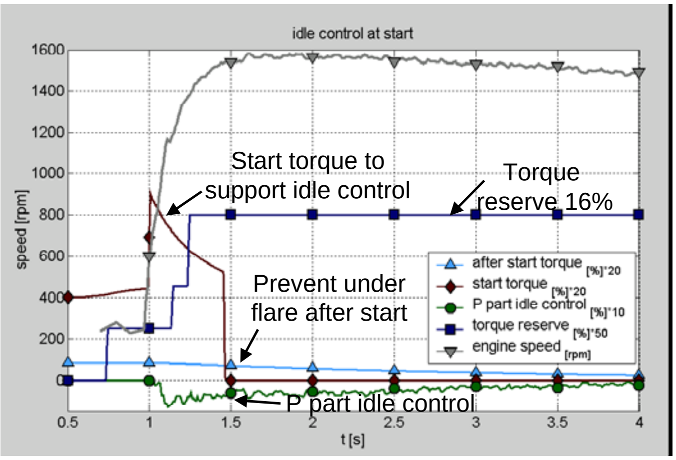

Figure 8: Torque reserve and idle control at start

4. Optimization of start and after-start fueling

The next focus for the engine management was a precise optimization of the start and after-start fueling amount. During the start and after-start phase the fueling demand of an engine can be highly non linear. The classical approach is an exponential decay of fueling, not accounting for additional or reduced fuel demands of the engine during this phase.

The optimization was achieved by first adjusting the cylinder individual fueling during the engine run up, using a Fast-FID. In the second phase the overall fueling was calibrated to a steady lambda trace.

Without changing any engine hardware, the described engine management efforts saved 35 % on integrated HC emission at the first 20 seconds after start.

FUEL AND IGNITION SYSTEM

5. Increase fuel pressure to establish small SMD

At this point the fuel system was changed to 7 bar with a 40µ droplet size injector. The reduced droplet size is an effective way to reduce raw emissions [1]. It helps stabilize the combustion and allows a more complete reaction in the cylinder which emits less HC.

Also, a stabilized combustion allows a faster enleanment after start, which again decreases HC emissions.

The engine management strategy for lean start was maintained, while the calibration of the changed fuel system took place. In addition to the general adjustments regarding different dynamic flow and opening delay due to higher fuel pressure, a new start and after-start calibration was established (see section 4).

Adding the engine management strategy to the 40µ SMD fuel system reduces the HC raw emissions significantly during the cold start as shown in Figure 9. This measure yields reduced emissions after start while maintaining the run-up conditions, described in section 3.

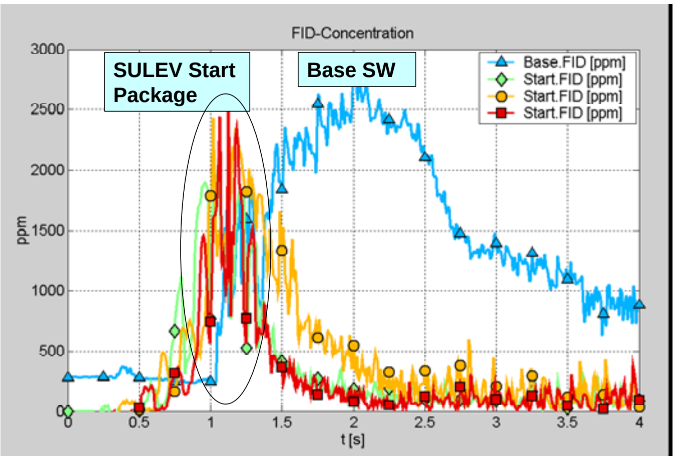

Figure 9: Reduced HC emissions during start, avoid evaporation of complete sections of wall applied fuel film

6. Increase ignition energy

The fast enleanment strategy discussed in section 5 was supported further by increasing the ignition energy.

This was accomplished by instrumenting the engine with an ignition system that delivered the energy of 65mJ, compared to 45mJ with the baseline system. All investigations under section 5 have been carried out by utilizing the more powerful ignition system.

The HC accumulations for the improved system are compared to the baseline in Figure 10. For emissions, the fuel system and the increased ignition power reduced about 40% of HC emissions at 20 s after start. This is independent from the effects of a secondary air system, because all the described measures are taking place before the secondary air pump is activated.

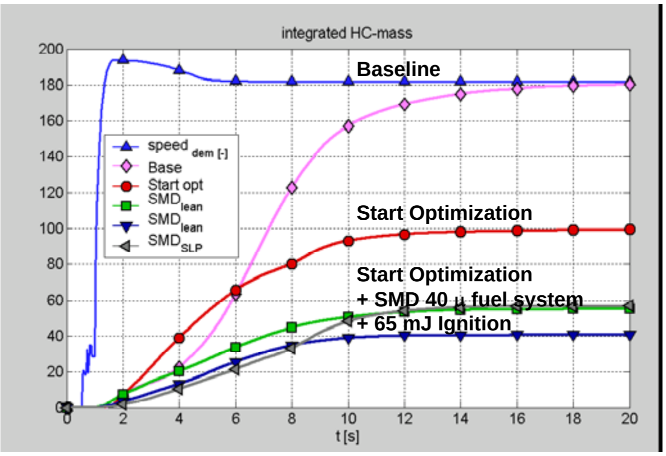

Figure 10: Intermediate emission benefits compared to baseline at 20s after start with described measures

At this stage of the program, a secondary air system was still necessary in order to reach the desired catalyst bed temperatures after 20s of idle.

The test results of the engine management system are summarized in the following table:

	SAI Application	w/o SAI lean start
Exhaust Gas Inlet Temperature transient	Comparable	
Exhaust Gas Mass Flow	110 kg/hr	65kg/ hr
Catalyst Bed Temperature	500ºC after 20sec	350ºC after 20sec
HC Tail Pipe Emissions	Comparable	

At this point of the program the results showed that a significant reduction in engine out and tail pipe emissions during the first 20s of idle could be established. A 75% decrease of HC raw emissions, compared to the baseline (LEVII) could be achieved.

This high reduction was independent of secondary air usage, because the engine operates at a low load condition (idle). However in order to pass a FTP test cycle it is mandatory to raise the catalyst bed temperature above 500 °C within the first 20 seconds (Figure 11).

Without using a secondary air system this goal can be met by using a predefined high cell density catalyst system. This leads to part B) of the study.

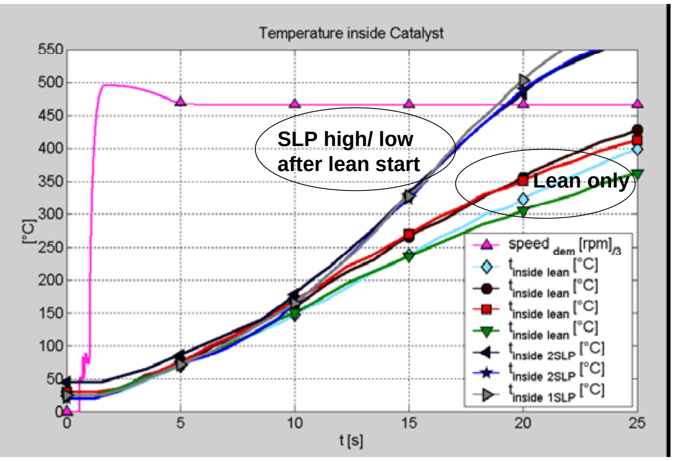

Figure 11: Comparison of Catalyst 1inch bed temperature with and without SLP at engine start

B) NUMERICAL STUDY

Previous publications demonstrated the light-off advantage of smaller diameter and higher cell density substrate technology [5,6,7,8]. The cascaded converter system or the conical converter system incorporates the advantage of fast heat up and therefore quick light-off though reduced cross section and minimized back pressure [2,3,4].

The exhaust gas temperature, mass flow and gas concentration recorded on the engine bench were used to simulate the catalyst light-off performance with respect to the converter design for a 25second idling phase. For this purposes a two dimensional numerical tool “KatProg” was used to study the influence of catalyst cross section and substrate cell density.

- Catalyst diameter: Ø85, Ø110, Ø118
- Substrate cell density: 600, 900, 1200cpsi

The substrate length is secondary for the heat up for this time period and was kept constant for all converters with 60mm.

The same front face positions of the substrate were assumed and therefore exhaust gas temperature conditions constant for all calculations. The exhaust gas temperature and mass flow during the idling phase is shown in Figure 12. It is obvious that additional benefits of a smaller converter system could be realized through packaging and therefore closer position of a cascaded converter system. The exhaust gas temperature is similar due to the symmetrical exhaust pipe design in each bank. Half of the exhaust gas mass flow is used for the prediction of catalyst light-off.

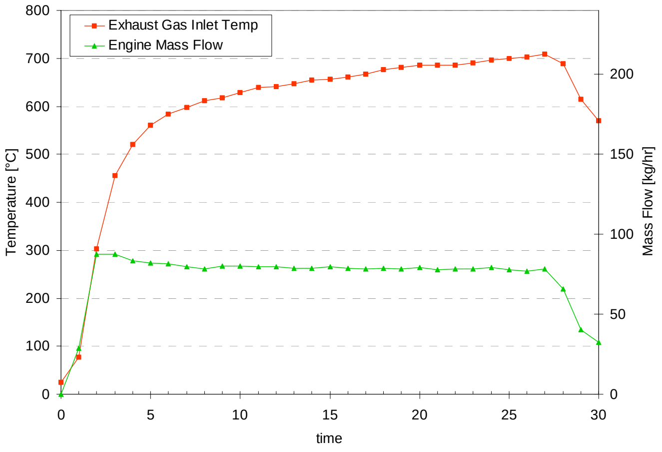

Figure 12: Exhaust gas temperature and mass flow during the lean start.

The predicted substrate bed temperatures at the center 25mm after the front face are plotted in Figure 14. The 85mm diameter design shows about 109Kelvin higher bed temperature at the same position compared to the 118mm design. The temperature profile in radial direction 25mm after front face is compared in Figure 16. The calculated temperature level of the 85mm converter design is significant higher.

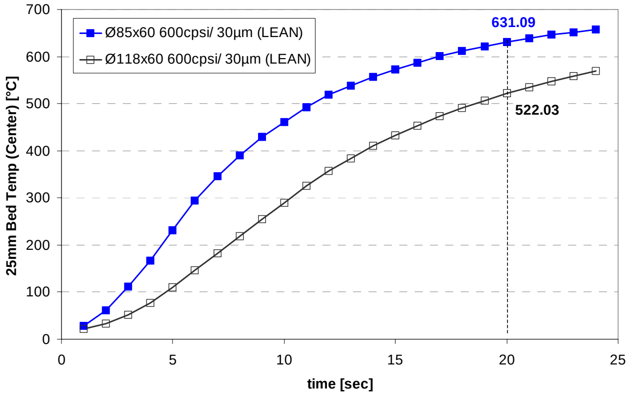

Figure 13: Predicted bed temperature 25mm after front face at the center depending on diameter

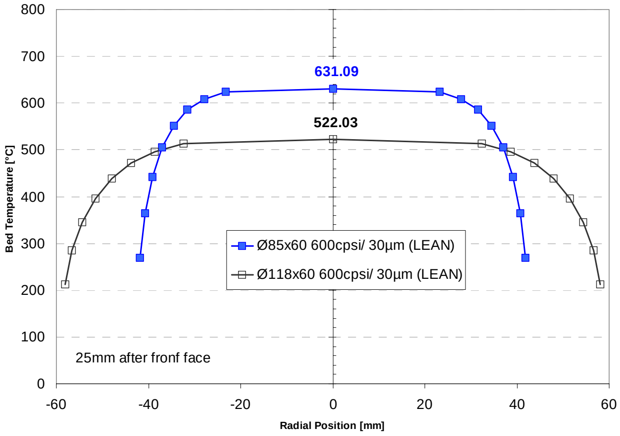

Figure 14: Predicted bed temperature 25mm after front face (t=20 seconds)

The conversion efficiency as a function of the diameter and cell density is shown in Figure 15. Higher catalyst efficiency for the Ø85mm designs is achieved after 16 seconds. Afterwards, the active GSA limits maximum conversion rate. The Ø85mm 1200cpsi substrate shows a superior light-off advantage over the first 20 seconds, which result in 16mg HC accumulation shown in Figure 16. Hence, the predicted HC for the 600cpsi substrate with Ø85mm are lower compared to the Ø118mm 1200cpsi design.

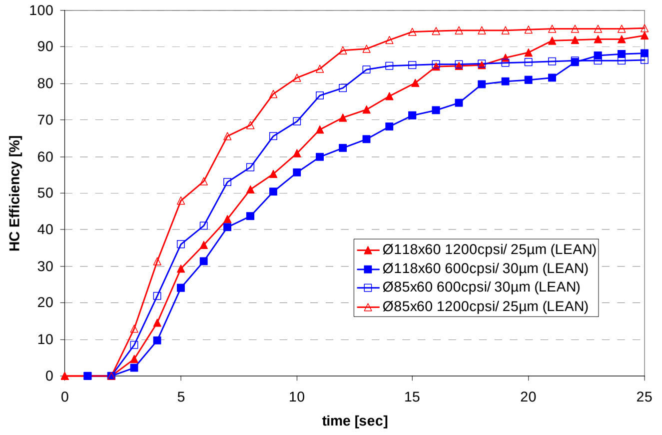

Figure 15: Calculated HC Light-Off depending on diameter and substrate cell density

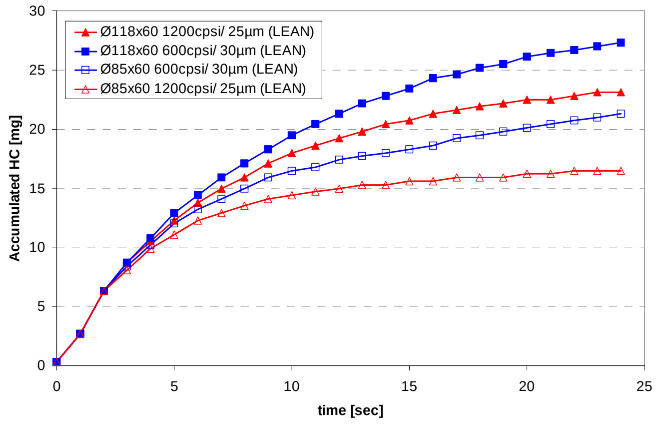

Figure 16: Accumulated HC after converter depending on the design - only one bank

The predicted HC results are plotted against the substrate diameter as a function of the cell density in Figure 17. HC emissions are between 15 to 20% lower by reducing the diameter from 118mm to 85mm. 1200cpsi substrates show a 10% HC reduction compared to the 600cpsi standard designs for all diameters.

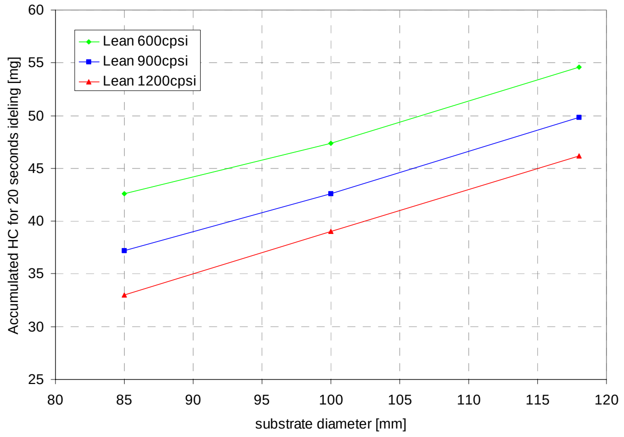

Figure 17: HC prediction depending on cell density and diameter (only 20 seconds idling)

The predicted results demonstrate the fast heat-up at smaller cross section through thermo physically advantages. This can be transferred in faster light-off combined with higher cell density technology. However, additional design tuning is needed to reach maximum conversion efficiency during higher exhaust gas flow condition.

For further calibration and emission optimization work at the engine bench a cascaded converter system was made with a diameter of 85mm and 1200cpsi followed by a Ø110mm 1000cpsi substrate.

CASCADE CONVERTER SYSTEM

The cascaded system was installed in the same location as the baseline converter to investigate the light-off performance. The cold start strategy was optimized for the cascade catalyst by using the identical measures discussed in sections 3, 4, 5 and 6.

The recorded front catalyst bed temperature exceeds 500 °C seven seconds after start, while the second brick still has a heat-up rate comparable to the base catalysts.

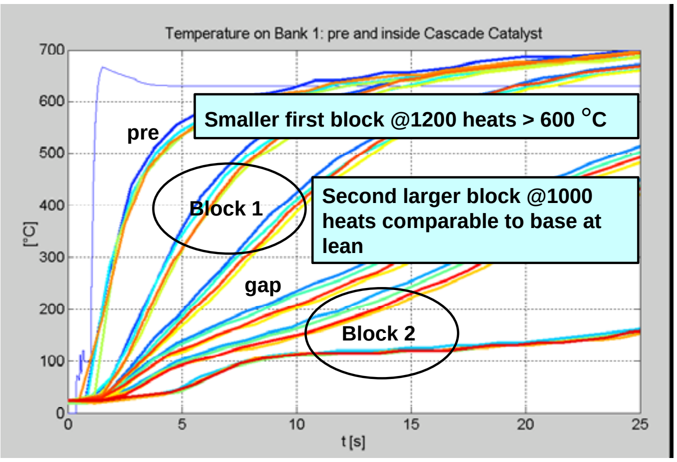

Figure 18: Cascade Catalyst temperatures

Using the cascade catalysts, the HC emissions during start could be reduced by 50% (see Figure 19).

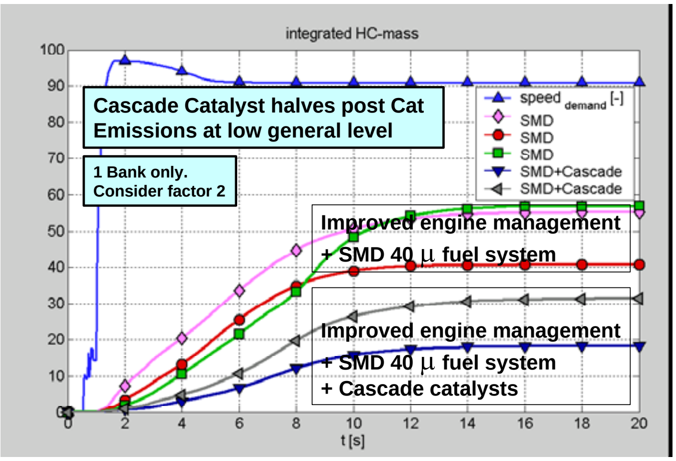

Figure 19: Emission benefit of cascade catalyst system

Now, catalyst temperatures and emission levels after start are in the expected SULEV range. After 20 seconds HC accumulation are in a range of 20 to 30mg on each bank and total HC emissions for both banks expected between 40 to 60mg respectively.

C) FTP TESTING

The FTP testing is performed in the following sequence:

1. Vehicle baseline testing with the 600cpsi converter aged to simulated 120,000 miles road condition
2. Engine management measures for engine start with baseline 120k converter and 7 bar fuel system
3. Engine management measures for hot driving with advanced exhaust manifold, increased ignition energy and 120k baseline converters.
4. Engine management measures with all previous hardware and cascade converters installed

At the time of the paper release, step 1 and 2 have been covered. In step 2 the HC emissions in phase 1 of the FTP test cycle could be reduced by more than 50% (Figure 20) while maintaining the NOx level. Also, the modal analysis data from FTP corresponds to the integrated HC values from the first 20 seconds FID measurement.

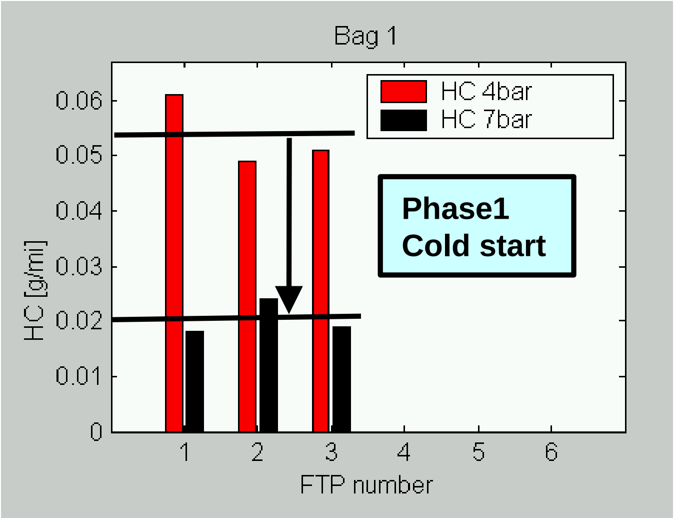

Figure 20: HC bag 1 of FTP

The total weighted FTP HC emissions were reduced by 37% through increasing of fuel pressure to 7 bar.

With steps 3 and 4 a further reduction of HC is expected, so that SULEV emission target levels can be met.

Conclusion

Engine management optimizations

The implementation of a secondary air injection system in conjunction with cold start enrichment did not yield a significant exhaust gas temperature increase in front of the catalyst. On the other hand, catalyst heat up was accelerated due to additional exothermic energy.

The engine cold start strategy such as engine start flare and optimization of start and after-start fueling led to 35% reduction of HC raw emissions.

By a further optimization of the fuel injection system (increased fuel pressure with subsequent decrease of droplet size) and an increase of ignition energy, a 40% HC raw emission reduction was achieved without usage of secondary air system.

Catalyst design optimization

Although engine out emissions have been significantly reduced by EMS development, SULEV target could not be achieved without secondary air, which means major system cost penalties.

Therefore advanced catalytic converter design (substrate thermo-physical properties and washcoat technology) is essential to maximize light-off performance.

The converter was designed by means of numerical analysis. In particular substrate diameter, cell density and converter volume allocation was optimized to achieve maximum light-off performance via a cascade system.

Experimental tests on an engine bench were in very good agreement with the expected results, confirming the advantages of high cell density cascade converters. The accumulated emissions during FTP cold start phase met the required SULEV levels. Nevertheless maximum catalyst efficiency is required during the entire FTP to achieve SULEV.

Outlook

The combination of innovative engine control strategies with an optimized catalytic converter layout will be improved, as it is the most efficient way to meet SULEV requirements for engines with bigger displacements in a cost effective manner.

On the engine control side of the investigation, the focus will be on the impact of cylinder individual lambda control and double feedback fuel trim.

A further catalyst design optimization has been planned for the next development stage. In particular, innovative substrate technologies such as perforated foil and integrated oxygen sensor will be tested. The former leads to high degree of mixing within the substrate, eliminating the necessity of dual brick approach. The latter significantly shortens the time to closed loop operation after cold start. Moreover the integration of oxygen sensor in the substrate protects from fast sensor aging and water hammer.

Such a multifunctional-single-brick approach leads to a cost effective solution for SULEV, while keeping high degree of system simplicity.

ACKNOWLEDGMENTS

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

EMS: Engine Management System
FTP: Federal test Procedure
FID: Flame Ionization Detector
GSA: Geometric Surface Area
HC: Hydro Carbon
MAP: Intake Manifold Pressure
NOx: Oxides of Nitrogen
SAI: Secondary Air Injection
SMD: Sauter Mean Diameter

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