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performance, emissions and fuel economy**

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Influence of pre turbo catalyst design on Diesel engine performance, emissions and fuel economy

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ABSTRACT

This paper gives a thorough review of the HC/CO emissions challenge and discusses the effects of different diesel oxidation catalyst designs in a pre turbine and post turbine position on steady state and transient turbo charger performance as well as on HC and CO tailpipe emissions, fuel economy and performance of modern Diesel engines. Results from engine dynamometer testing are presented. Both classical diffusive and advanced premixed Diesel combustion modes are investigated to understand the various effects of possible future engine calibration strategies.

INTRODUCTION / LITERATURE REVIEW

Utilizing modern, premixed Diesel combustion concepts to achieve low NO_x and soot while maintaining excellent fuel economy, leads to increased engine out HC/CO emissions as well as lower exhaust temperatures.

One option to improve the performance of the Diesel oxidation catalyst system is to position considerable catalyst volume upstream of the turbo charger turbine. This allows taking advantage of faster catalyst light-off after a cold start and of increased average catalyst bed temperature during steady state and transient engine operation. However, apart from packaging constraints, the installation of catalytic converters upstream of the turbine is challenging for engine performance due to thermal inertia before the turbine and other effects on the turbo charger.

To explain the need for pre turbine catalysts, various future challenges will be reviewed in detail the following paragraphs.

THE EMISSIONS CHALLENGE

Over the last years the focus of the Diesel engine development community has clearly been to reduce NO_x and Particulate matter emissions into the environment.

The discussion, whether to reduce NO_x through engine internal measures, for example using high rates of cooled EGR or variable valve timing or through NO_x exhaust after treatment (such as NO_x-Absorber or SCR systems), is undecided.

Up to EURO4 the available DOC ("Diesel Oxidation Catalyst") technology in conjunction with significant improvements in engine technology, especially advances in common rail fuel injection technology [9], was able to control tailpipe HC and CO emissions to meet the regulations. "Critical" vehicles, such as highly powered sedans with low average engine loads in the test cycle were equipped with heavily Pt-loaded multiple-catalyst systems to minimize end of useful life HC/CO emissions increases due to catalyst aging and poisoning. For EURO5, new and more stable catalyst coatings [11, 12] are being introduced allowing lowering the (precious metal) costs of the DOC. Coated wall flow Diesel Particulate Filters with good HC/CO conversion capability have been introduced in almost all vehicle categories. This either allows reducing catalyst displacements and loadings further or to eliminate any additional DOC's required.

Up to EURO5, Diesel engines have been calibrated to run mostly in classical "diffusive" Diesel combustion mode. HC and CO emissions are traditionally low to moderate, because only little unburned Diesel fuel is dispersed in the piston bowl and therefore is not combusted. Most fuel is oxidized in or near the flame front at extremely high local temperatures. Ignition delays are typically very short, misfiring, which leads to high HC emissions, only occurs at very high exhaust gas recirculation rates and is usually due to EGR control imperfections or a very late center of combustion. In some limited operating areas of current EURO4 and EURO5 applications, extreme EGR rates in combination with high EGR cooling are calibrated to purposely lead to long ignition delays and therefore to partial premixing before combustion, which drives up HC and CO emissions. Furthermore, to achieve NO_x targets, compression ratios are being reduced to as low as 16:1,

which also increases the HC engine out emissions [9], especially during cold start at low ambient temperatures.

For EURO6 / Tier 2 Bin 5 engine calibrations, the areas of the engine operating map where premixed combustion modes (“PCCI” or “LTC”) are used to further lower engine out NOx emissions, will increase greatly. Future combustion concepts, shown for example in [7,6] will utilize partially to fully premixed combustion modes in a wide area of the engine map, while relying on classical Diesel combustion in the high load / speed areas. These combustion concepts rely heavily on advanced fuel injection and EGR/boosting systems as described in [1]. Engine out HC and CO emissions at loads < 2 BMEP (which typically correspond to cruising at speeds < 50 kph) are up to 5 times higher than for typical EURO4 calibrations as shown in FIG.1.

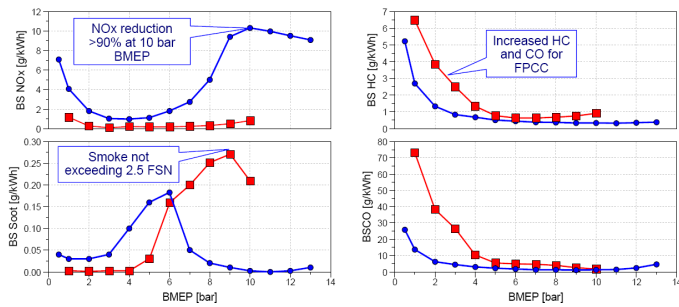


FIG.1: Ricardo’s Tier 2 Bin 5 Emissions concept [7]

Going one step further to fully premixed combustion (“HCCI”) in a wide engine operating area could mean increasing the equivalence ratio to near the stoichiometric value. FIG.2, taken from [4], shows that at equivalence ratios near one, considerable fuel energy content in form of HC & CO is not combusted but leaves the engine through the exhaust. This energy could not be recovered with current catalyst / turbo charger layouts. DOC’s downstream of the turbo charger oxidize these emissions – any “valuable” exhaust enthalpy increase is lost. At stoichiometric conditions however the lack of oxygen in the exhaust system would prevent any oxidation of HC/CO. Some form of secondary air introduction into the exhaust system before catalyst could be required.

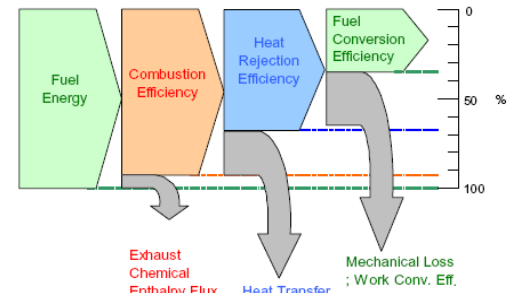
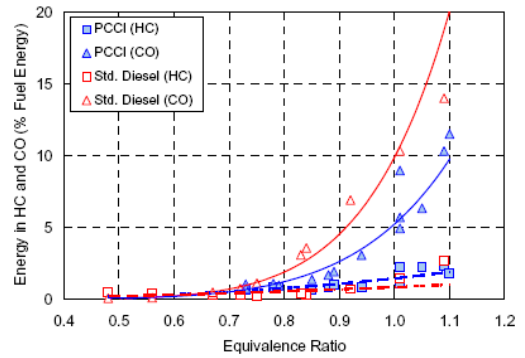


FIG.2: HC/CO energy and Energy flux in the “PCCI” Diesel engine

Engine out temperatures with premixed combustion are expected to be similar or even slightly lower than with classical “low NOx” Diesel combustion. The reason for this is the faster heat release rate, maintained around TDC for good fuel economy, with highly premixed combustion compared to diffusive combustion, using high EGR rates, with longer burn duration combined with later injection timing. Also, advanced high power EGR coolers reduce the intake manifold temperature, which also manifests in lower engine out exhaust temperature. Tailpipe exhaust mass flow will decrease due to higher exhaust gas recirculation rates [1, 13]. Depending on the catalyst position and the type of EGR system used (high pressure or low pressure EGR) the DOC could see significantly lower enthalpy flow. This will result in a longer catalyst bed warm up time and consequentially in higher test cycle HC/CO emissions.

FIG.3 shows that depending on the vehicle class (sedan, Minivan etc), the transmission (manual, step automatic, dual clutch type etc.) and the drive train (2WD or 4WD), the exhaust gas temperatures in the ECE part of the NEDC are below or near the light off temperature (50% conversion efficiency) of most modern catalyst formulations (aged).

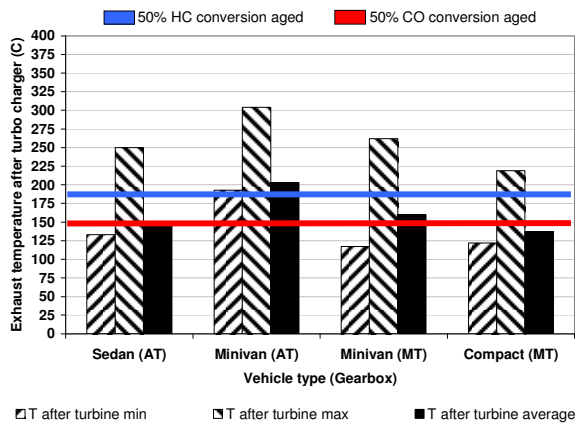


FIG. 3: Exhaust gas temperatures in the ECE part of the NEDC for various passenger vehicle categories

EMISSIONS LEGISLATION

The development of test cycle emissions in Europe in the last years was very focused on lowering NOx and PM - HC and CO numbers were left "virtually untouched". While the absolute HC limits have not significantly changed, the factor HC/NOx has therefore been steadily increasing for the European Emission legislation. This fact has encouraged engine calibrations with higher HC/CO engine out emissions. But the fact that HC + NOx are limited as well as NOx alone, generally limits the tolerable increase in HC when lowering NOx tailpipe emissions. In general, HC & CO do not present a significant problem for most EURO5 applications. But EURO6 will require a much closer look on HC & CO engine out emissions.

US Tier 2 legislation, currently very focused on NOx and Particulate emissions, has rather loose limits on CO, which in general can be easily met by modern Diesel engines. To comply with Tier 2 Bin 2 regulations however, HC tailpipe emissions must be drastically reduced. This will present a great challenge to any catalytic system.

The Japanese emissions legislation introduced in 2005 also imposes strict limits on NMHC, while CO limits are similar to the EURO5 regulation.

FIG.4 and FIG.5 show the progression of HC/CO and NOx test cycle limits in Europe and the US over the next years.

It can generally be said that reducing HC/CO tailpipe emissions will become more important in the future.

European Union: NEDC cycle

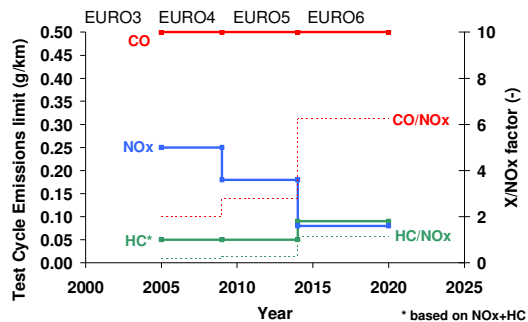


FIG. 4: Progression of HC and CO test cycle limits in Europe

US EPA: FTP75 cycle***

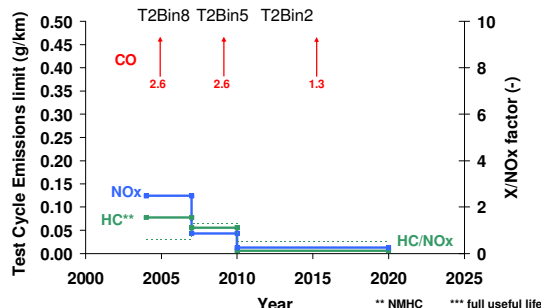


FIG. 5: Progression of HC and CO test cycle limits in the US

THE TRANSIENT CHALLENGE

One inherent problem of exhaust gas turbo charged engines is, that the speed of boost pressure buildup during a load transient is always limited by the exhaust gas energy available to the turbine. This problem was well described in [10] for a typical sedan with an automatic transmission and a state of the art variable geometry turbo charging system. FIG.6 shows the transient speed / load trace of an acceleration compared to the engine's steady state performance capability. Clearly, during rapid transients the engine's full torque capability at low speed cannot be utilized. This ultimately results in slower vehicle acceleration.

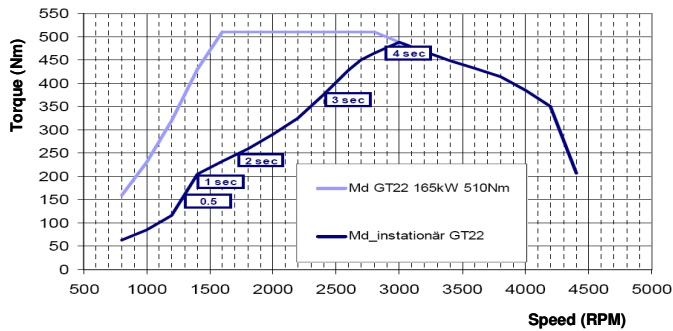


FIG. 6: Acceleration behavior of a Diesel engine with automatic transmission [10]

[1] describes that when large amounts of high pressure EGR are utilized to reduce tailpipe NOx emissions, the so called “turbo lag” increases in general as shown in FIG. 7. This is due to the fact that when using high pressure EGR, exhaust gas is drawn from before the turbine and rerouted to the intake side, leaving the turbine with less exhaust energy to accelerate the compressor wheel. Apart from lower NOx emissions using high pressure EGR, lower fuel consumption through reduced turbine pumping work is typically observed up to medium high pressure EGR rates. This effect is actually desired but encourages engine calibrations with lower transient performance capability. Using low pressure EGR on the other hand does not cause a decrease in turbo charger mass flow and therefore -performance, but the increased pumping work is also detrimental to fuel consumption at low speed. So low pressure EGR systems will also not be calibrated to lead to improved transient performance.

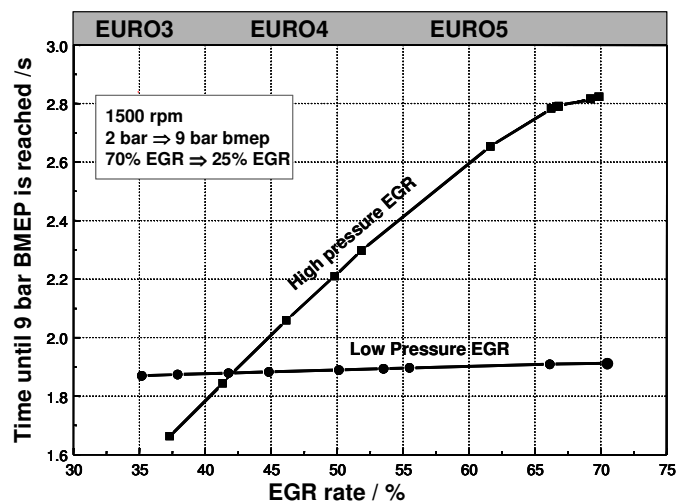


FIG. 7: Load response time as a function of EGR rate & EGR system layout

To reduce turbo lag of modern Diesel engines, apart from using further improved turbo charging hardware (lower inertia) or additional boost assist devices, the air intake side is optimized with respect to intake volume, for

example by using indirect (water/air) charge air cooling with reduced air ducting volume. The exhaust side is optimized for minimal heat rejection by using sheet metal exhaust manifolds that are sometimes even air gap insulated for reduced thermal inertia and radiation losses. All the above listed measures typically increase the costs of a Diesel engine. Adding exhaust side insulation methods can lead to reduced precious metal catalyst loading (catalyst cost reduction). So the cost increase can partially be recovered.

Overall, transient engine response has always been and is still being perceived as critical for turbo charged Diesel engines and all measures taken to reduce NOx/Soot emissions will not help to improve the responsiveness in the future. Therefore all measures investigated to reduce HC/CO emissions should not negatively affect transient performance in a significant way to be considered production viable.

THE PERFORMANCE CHALLENGE

Due to the fact that exhaust back pressure increases the pumping work during the exhaust stroke and the trapped exhaust mass in the cylinder (=“internal EGR”), the engine’s performance is typically reduced. Elevated exhaust temperatures and smoke are also observed with higher exhaust restrictions. Modern Diesel engines using Diesel particulate filters and NOx after treatment technology typically have to work against considerably higher exhaust back pressures compared to EURO3 calibrated engines. Therefore costly efforts have been and are being undertaken to de-throttle the vehicle exhaust system to be able to keep increasing the engine’s specific power output.

The turbo charger turbine plays an even more significant role as a means to lower engine pumping work. At typical boost pressures for EURO5 engines the pressure drop through the turbine can vary between 30 and 300kPa. If desired boost pressures keep rising, pumping work will continue to increase. Therefore the turbo charger industry has focused on turbine design that allows achieving the same boost levels at lower back pressure levels. This goal is mainly reached through increased turbine efficiency coupled as well as higher turbine flow capability.

The Back pressures created by DOC and DPF have been managed to a certain extent by optimizing the substrate cross section with customized shapes, substrate cell density, wall thickness and coatings structure and amount.

Generally, the increase in back pressure through new after treatment system layouts (Diesel particulate filters, SCR systems etc.) would influence other engine components, such as the valve train system and the engine’s performance and would also not be accepted for production.

TURBO CHARGER / CATALYST / DPF LAYOUTS

To address the future air system requirements (rising airflow / boost pressure) that are necessary to achieve

- Lower NOx emissions
- Improved transient performance
- The continuing increase in engine power/torque

all engine manufacturers are introducing more and more complex boosting systems.

Variable Turbine Geometry turbo chargers as shown in FIG.8 have been on the market for many years with constantly increasing efficiencies while the first 2-stage boosting systems designed specifically for the passenger car market, as shown in FIG.9, were just introduced in 2004. It is believed that boost system complexity will increase even further, especially with the introduction of high EGR combustion systems such as "PCCI" or "HCCI".

Due to the higher amount of cast iron in a 2-stage turbo charger system, the thermal inertia of such a boosting system is significantly higher than that of a single turbo charger. During an emissions test cycle, nearly all the exhaust gas must pass through both the high pressure stage turbine and the low pressure stage turbine. The regulating valve is diverting some flow through an additional passage around the high pressure stage turbine. Therefore exhaust temperatures downstream of the turbo charger system will be generally lower during steady state and transient engine operation compared to a single turbo charger. This has a negative effect on the conversion capability of the DOC.

So these new, more complex boosting concepts could require sophisticated & expensive catalysts.

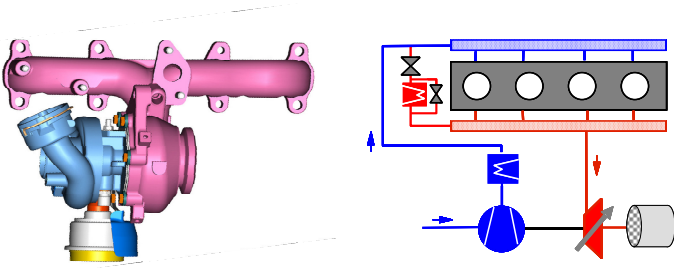


FIG.8: 1-Stage turbo charger layout for passenger cars

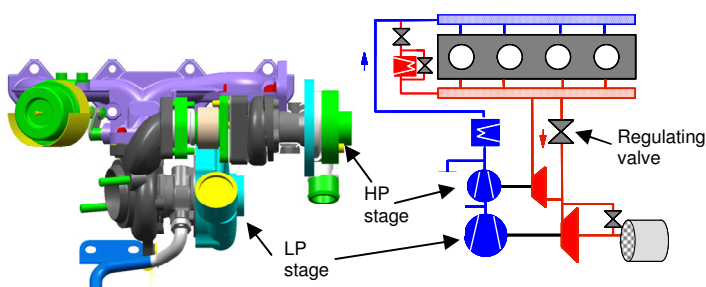


FIG.9: 2-stage turbo charger layouts for passenger cars

THE PRE TURBO CATALYST

Pre turbine catalysts have been investigated for some time as a possible solution to achieve better HC/CO performance while reducing the cost of the catalyst system.

FIG.10 and FIG.11 show different catalyst volumes that have been the focus of the previous publications and that are investigated in this paper. Most PTC's were considerably smaller than typical DOC's used downstream of the turbo charger turbine in today's applications. This had more practical reasons, because current engine designs have very limited space available before the turbine. Typically vehicle tests were performed with PTC hardware, so all prototype hardware had to fulfill stringent packaging requirements. Good conversion efficiencies were achieved mainly through increased turbulence in the small PTC's.



FIG.10: Previously engineered substrate samples for pre turbo installation (volumes less than 0.02 L)

Several publications were found on the application of pre turbine catalysts. [14], [15] give a good overview of the opportunities for pre turbo catalyst installation. Three papers [2], [3] & [16] on pre turbo catalysts will briefly be discussed, because of the high relevance to the work described in this paper.

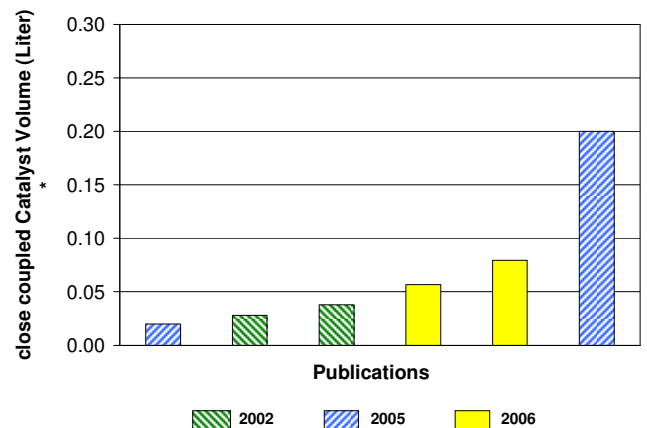


FIG.11: History of investigated PTC sizes (not complete)

One paper [2] only focuses on small PTC's (0.028L / 0.038L) being introduced into a production CC/UF catalyst system of a typical European sedan. The PTC's were built as "drop in" parts between the exhaust manifold and the turbine inlet, replacing the UF catalyst. No other geometrical changes were made to the air breathing system. In a further step the CC catalyst was also optimized.

The proposed, refined new system (PTC + optimized catalyst) showed a big improvement in HC/CO conversion at greatly reduced overall catalyst volume. The surprisingly high conversion efficiency of the PTC was explained with the extremely high space velocities in the small displacement substrate. The investigated pre turbo catalyst showed efficiencies above 50%. The channel flow within the substrate was highly turbulent which drastically improved mass transfer, but at the cost of increased pressure drop. The addition of the (relatively small) PTC therefore led to a power loss of 2.6%. The increased exhaust back pressure also resulted in higher internal EGR. Therefore test cycle PM-mass also increased by 27%. This could also be attributed to the limited capability of the PTC/CC system to reduce SOF's compared to the baseline catalyst system.

The second paper [3] investigated steady state HC/CO conversion through a 0.02L and a 0.2L size PTC. It was also demonstrated that with a PTC, the downstream DOC light off behavior improves significantly. This was explained with the lower absolute HC/CO emissions flowing into the downstream catalyst when placed after a PTC. Transient vehicle results verified the synergetic effects between PTC/DOC. The PTC lights off much faster due to its position before turbine while DOC light off is also improved as explained above.

Reduced performance of the aged PTC Catalyst system is also discussed in [3]. Due to the higher average temperature level (the margin to the catalyst's light off temperature greater), the test cycle HC/CO conversion efficiency of PTC's was shown to be less affected by aging. However, overall reaction was very well controlled by the availability of active sites/ PGM amount.

The third paper [16] focuses more on the interaction between PTC and the VTG turbo charger – investigating steady state as well as transient performance.

Improved low speed steady state engine performance at full load is described to be caused by better flow distribution before the turbine. On the other hand, lower rated power is observed. This again is explained with the pressure drop before the turbo charger turbine that effectively reduces available turbine power. The longer catalyst (0.08L) performs worse than the smaller catalyst (0.057L). This is clearly due to the difference in substrate length, which results in a higher substrate pressure drop.

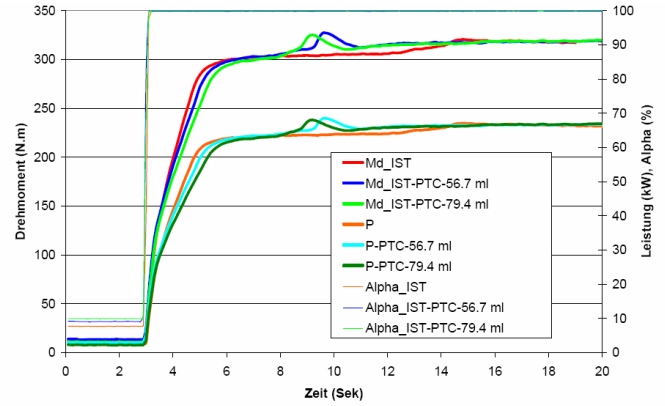


FIG.12: load step performance comparison at 2000 rpm with different PTC's

It is also described in [16] that the difference in transient response can be attributed to the boost pressure controller. In the initial phase of torque buildup (Second 3 to 8), shown in FIG.12, the VTG vanes are fully closed for all cases. The VTG is already calibrated for delivering maximum turbine power resulting in best possible boost pressure buildup. An enhancement of turbine performance in this phase to compensate for the loss in response is not possible without changes to the turbo charger hardware. In FIG.13 it is shown that from Second 8 to 15 the VTG's boost controller affects the boost pressure in a way that leads to significant torque fluctuations with a PTC upstream of the turbine. It should be possible to minimize these fluctuations by recalibrating the boost controller. The delay in initial response with PTC's is believed to be inherent to the system and therefore inevitable without substantial changes to the turbo charging hardware.

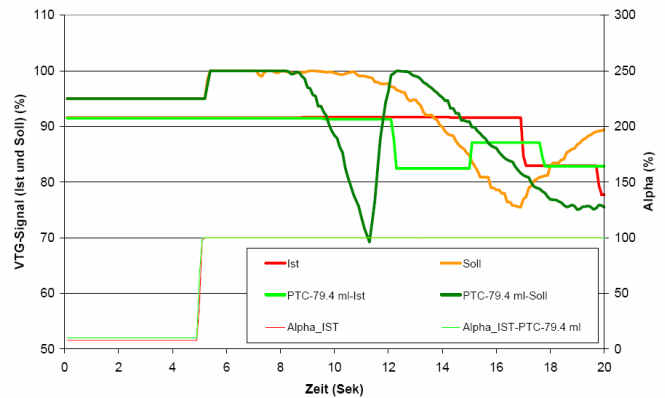


FIG. 13: boost controller performance comparison at 2000 rpm with different PTC's

Although the severe exhaust manifold environment (high exhaust pressure and temperature fluctuations) results in increased stress for the PTC element, [16] states that durability has been proven.

The literature search can be summarized such that an emissions improvement at reduced package is reported with pre turbine catalysts, but not without a measurable impact on full load and transient engine performance.

REQUIREMENTS FOR PRE TURBO CATALYSTS

Based on all of the described challenges, the requirements for catalysts have to be adapted as described in FIG.14, when positioned before turbine.

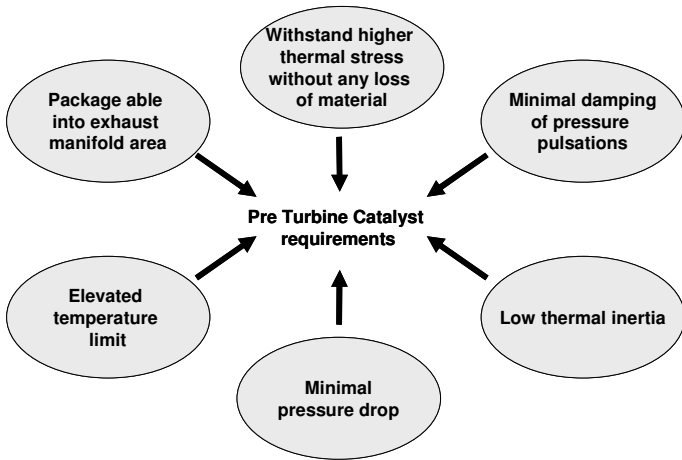


FIG.14: Enhanced requirements for pre turbine catalysts

Due to the limited package space before the turbo charger, the catalyst needs to be optimally integrated without creating a high pressure drop. That would severely affect turbine and subsequently engine performance. For this reason a close development between the engine manufacturer, the turbo system manufacturer and the catalyst manufacturer is required for a successful application of the PTC.

The higher overall temperature level and temperature gradients require the substrate and catalyst coating to withstand higher thermal stress. The turbine wheel, operating under high stress at high speeds and temperatures downstream of the catalyst, is extremely sensitive to the impact of parts onto the turbine blades. No loss of catalyst material - substrate or coating - is tolerable.

Thermal inertia of the catalyst substrate will influence the available exhaust enthalpy at the turbine inlet during a transient, while posing no problem to steady state performance. Steady state performance will be more affected by heat rejection through radiation or poor thermal insulation of the catalyst canning.

The damping of exhaust pulsations, typically expected from a catalyst substrate will have an influence on the turbine's performance.

This significance of effect remains to be investigated.

OBJECTIVE

The objective of this paper is to understand, how bigger pre turbine catalysts, than evaluated in the past, influence HC/CO emissions and steady state as well as transient engine performance and how advanced combustion systems, emitting high amounts of HC/CO, affect the interaction between pre turbine catalysts of different sizes and the turbo charger.

TEST SETUP

To address these questions, a 2.0L inline 4 cylinder Diesel engine was set up. The engine's breathing system, similar to that shown in FIG.8, was adapted to include catalysts in the pre- or post turbine position. The turbo charger was moved away from the engine block and dropped slightly to make room for the various pre turbo substrates. The turbo charger oil lines had to be adapted to achieve good oil draining to avoid oil leaking through the turbo charger shaft seals into the turbine and compressor housing. FIG.15 shows the schematic of the engine setup. The tests were performed on a fully transient capable AC dynamometer. A state of the art emissions bench (Horiba MEXA 7100) was used to measure the gaseous emissions, sampled at three different points shown in FIG.16, in the exhaust system. Pressures were measured using ring type probes that provide an average pressure independent of the exhaust duct geometry around the probe. In addition to average gas temperatures and pressures a fast pressure transducer was implemented to evaluate pressure pulsations before turbine. For all steady state measurements the positions 30, 40 and 50 were measured consecutively using a solenoid controlled, switch able sample manifold. During the transient tests only position 50 was measured.

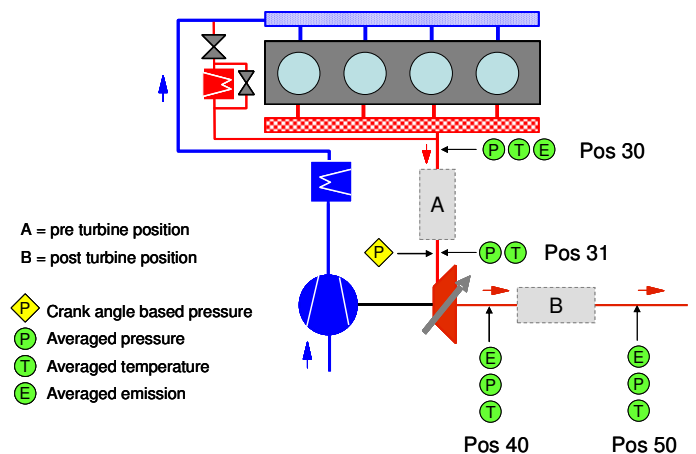


FIG.15: Engine dynamometer test setup

POSITION	DESCRIPTION
30	At the outlet of the 4 in 1 exhaust manifold Downstream of the HP-EGR junction Upstream of the PRE TURBINE catalyst
31	Downstream of the PRE TURBINE catalyst Upstream of the turbo charger turbine inlet
40	Downstream of turbo charger turbine outlet Upstream of POST TURBINE catalyst
50	Downstream of the POST TURBINE catalyst

FIG.16: Engine dynamometer measurement positions

Dimension mm	Cell Density cpsi	Wall thickness mm	Volume Liter	Coating g/cft Pt:Pd
∅50 x L50.8	200	0.08	0.1	140 2:1
∅90 x L90	300TS	0.05	0.57	140 2:1
∅118 x L127	200/400 LS/PE	0.04	1.39	80 1:0

FIG.17: Evaluated Pre Turbo Catalysts substrates

Three different metallic catalyst substrates described in FIG.17 were investigated, compared to dummy pipes – straight pipes with constant diameter - in the respective positions. All catalysts were designed to study the fundamental characteristic of extreme pre turbo DOC application.

FIG.18 shows that the medium and large pre turbine catalysts were considerably bigger in size than what had been previously tested. Nonetheless the smallest substrate was exposed to space velocities > 10 million 1/h. The largest catalyst saw space velocities a factor of 10 lower. The loading for the smaller substrate was chosen to be higher to increase active sites in case of turbulent flow.

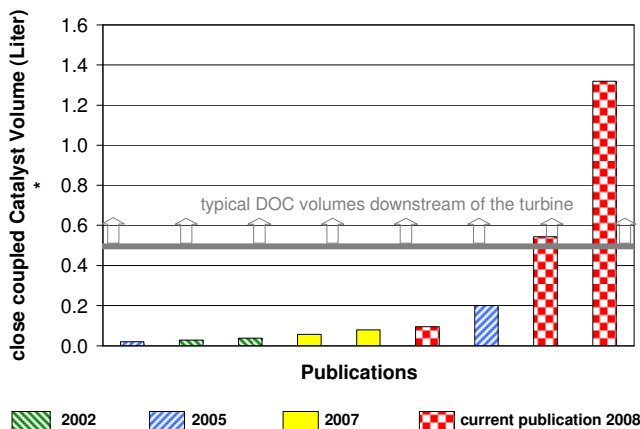


FIG.18: Investigated pre turbine catalyst sizes compared to previous publications

Substrate technology and the catalyst coating were optimized for each substrate. The small substrates were designed to rely on turbulence due to high space velocity only. Since channel velocity was expected to be reduced

for the largest substrate, LS technology with perforated foil layer was applied to enhance turbulence within the system. Details about LS and LS PE substrate technology can be found in [17, 18].

Special emphasis was put on the ability to rapidly switch catalyst and dummy pipe configurations without having to reposition the turbo charger. So all catalysts, including the piping and flanges, were of equal length and had identical mating flange geometry. All investigated substrates had a D/L ratio of approximately 1, which theoretically (See FIG.19) would result in good pressure drop performance. Inlet and outlet pipe diameters were sized to match the turbine inlet diameter. This resulted in very steep cones for the large, 1.39L catalyst.

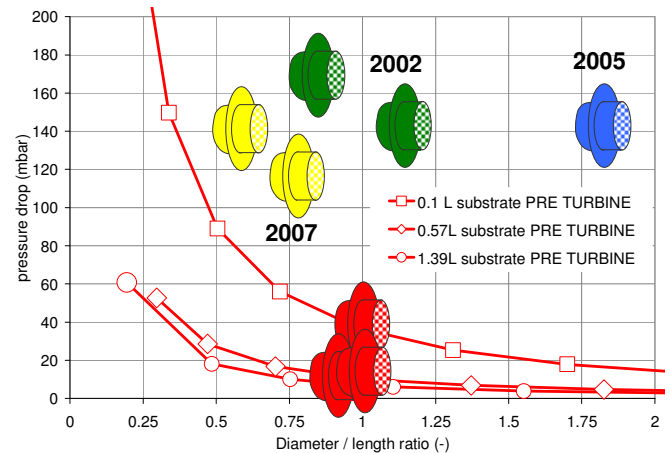


FIG.19: D/L ratio and ΔP of investigated pre turbine substrates compared to previous publications at a constant operating point and for a constant substrate

RESULTS

To describe the system performance with each catalyst variant, different effects were evaluated and will be described in the following section.

EFFECT ON HC/CO EMISSIONS

To analyze the HC/CO performance, steady state points typical for a certification test cycle as well as the substrate's light-off performance were evaluated. After thermal stabilization of the exhaust system, both pre and post turbine positions were evaluated. Catalyst exhaust inlet concentrations were similar for the pre turbo and post turbo installation for each steady state point. However, engine out concentration changed when the engine load point was increased to achieve higher exhaust temperature and exhaust flow rates.

FIG.20 shows the HC/CO conversion performance of the large 1.39 L catalyst in the pre and post turbine position. Variations in flow velocity (high pressure pulsations at the catalyst inlet) and longer exposure time through flow reversal lead to an improved CO conversion in the pre turbine position, with a reduction in CO light off temperature by nearly 30 °C. In both positions the large catalyst is able to achieve >90% CO conversion at >220 °C inlet temperature. It should however be emphasized that a post turbine catalyst inlet temperature of 200 °C corresponds to a pre turbine temperature of approximately 300 °C. If compared at constant load, the catalyst in pre turbine position has a huge safety margin (100 °C) in terms of CO light off temperature. It should also be noted that the engine's HC and CO emissions were not constant at all loads, which also influences the conversion behavior.

The HC light-off performance shows a somewhat different behavior. The maximum conversion efficiency is much lower than for CO and the post turbine position shows the better performance, based on catalyst inlet temperature. Reasons for this may again be variations in HC emissions. Nonetheless the pre turbine position outperforms the post turbine position when compared at equal turbine inlet temperature (= same engine operating point).

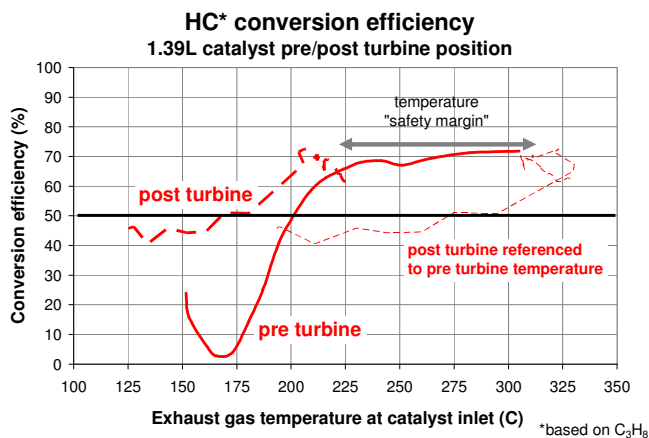
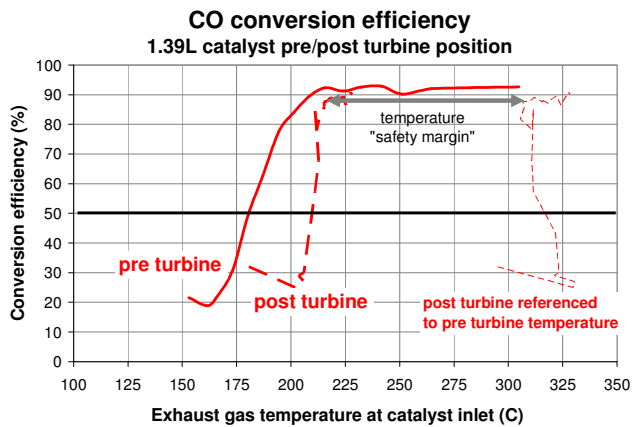


FIG.20: CO & HC conversion for 1.39L catalyst in the pre and post turbine position

FIG.21 shows the comparison between the small substrate (0.1L), the medium substrate (0.57L) and the large substrate (1.39L), all in the pre turbine position. It reveals that the smallest substrate shows substantially lower HC and CO conversion capability. This can be attributed to the 14 times higher space velocity of the small catalyst at fit well to previous publications. On the other hand the substrate used in the 0.1 L catalyst was designed specifically for low pressure drop and needs higher turbulence for good conversion efficiency, whereas the large substrates were designed for good material transport. The HC light-off performance of the small catalyst is less favorable than the CO performance. It can be stated that the 0.1L catalyst is undersized for this engine application but would not be used without an additional - but size reduced - DOC downstream of the turbine. The medium catalyst shows better HC/CO performance than the 0.1L catalyst, but does not achieve >90% conversion efficiency even at higher temperatures.

Overall the 1.39L catalyst in the pre turbine position shows the best light off and conversion performance. That >95% HC and CO performance are not achieved could be due to the poor flow distribution (steep inlet cone) in the large substrate. This fact would currently limit its use as a stand alone pre turbo catalyst to certain applications and would therefore require a design optimization.

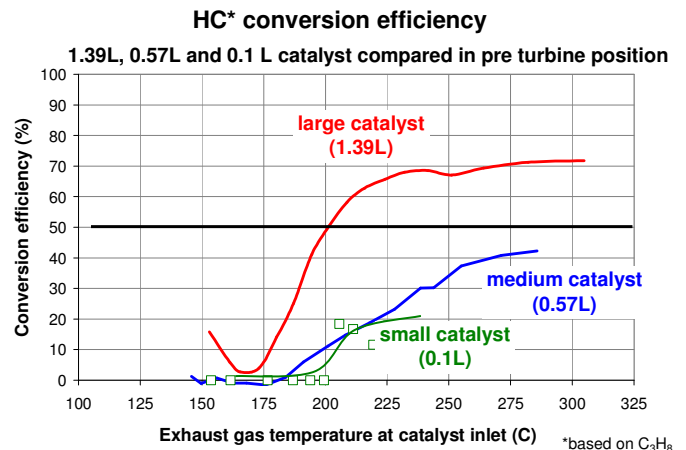
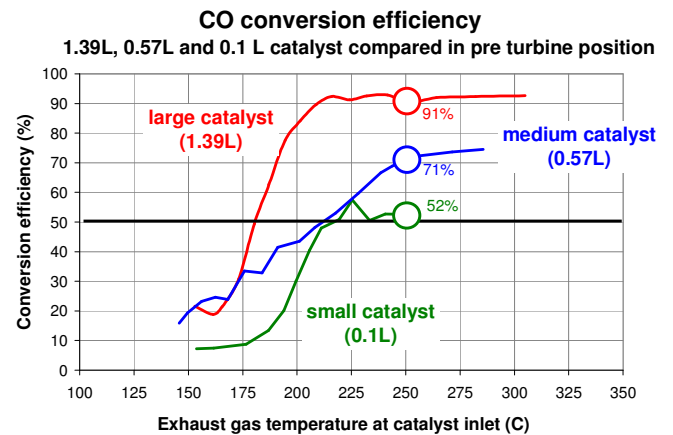


FIG.21: CO/HC conversion comparing the 0.1L, the 0.57L and the 1.39L catalyst in the pre turbine position

EFFECT ON STEADY STATE ENGINE PERFORMANCE

When analyzing the effects of the pre turbine catalyst on the engine's steady state performance, two phenomena must be considered:

Flow Restriction

The turbine pressure ratio and power output of the turbo charger is negatively affected by adding a pressure drop element upstream of the turbo charger. FIG.22 describes this in an exaggerated fashion.

Assuming the same boost pressure requirement and very similar exhaust temperatures for the pre turbine and post turbine case, the turbine pressure ratio must remain constant. Adding a pressure drop element of a certain magnitude downstream of the turbine, the pressure before turbine must be adjusted, for example by means of a VTG. This will lead to significantly higher engine pumping work, resulting in a BSFC penalty. When adding the same pressure drop element upstream of the turbine, the pressure ratio of the turbine is affected in a much less severe way. Therefore after adjustment of the VTG the overall engine pumping work will increase less severely. Assuming a much higher exhaust gas density upstream of the turbine - especially true for operating points with high boost demand - the pressure drop through a pre turbine substrate will be lower than that of an equally sized post turbine substrate. Therefore even an upsizing of the pre turbine catalyst, which could lead to a lower substrate pressure drop, would seem to make sense. Of course packaging constraints in the pre turbine position generally limit this possibility.

The catalyst substrates tested showed somewhat unexpected pressure drop behavior. While FIG.19 predicts the ΔP of the 1.39L catalyst to be far lower than that of the 0.1 L substrate, the test results shown in FIG.23 indicate exactly the opposite behavior. This can be explained on the one hand by the canning of the large substrate, which results in high inlet and outlet cone pressure loss [17] and very non-uniform flow distribution, resulting in higher flow velocities and Reynolds numbers. Also the fact that the substrates were chosen to be structurally different has measurable influence on the pressure drop. The channel flow velocities are believed to be too high for the large substrate's turbulence enhancing LS structure. The magnitude of this effect compared to the poor flow distribution is not clear. The results indicate that a low ΔP substrate technology – a standard substrate for example - with appropriate sizing would result in the best trade off for flow restriction and emission performance. Further investigations are needed to understand influences like flow pulsation and flow uniformity on system back pressure.

The 0.57L catalyst shows good pressure drop behavior. The less steep cones allow better flow distribution.

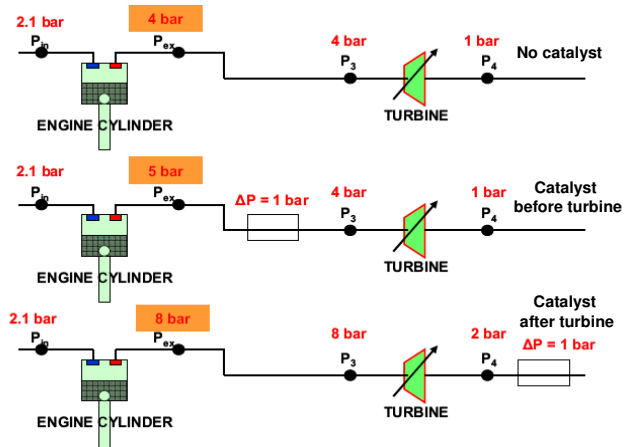


FIG.22: Schematic view of back pressure effects on the turbine pressure ratio (exaggerated)

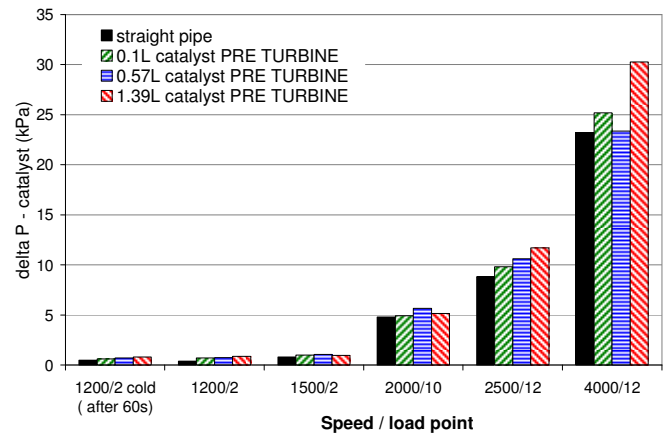


FIG.23: Steady state pressure drop for different pre turbine substrates

Exothermal Energy conversion at full load

In engine operating points with extremely high HC/CO emissions, for example at low engine speed and WOT (maximum torque) where the performance is oxygen limited and the engine is operating at low air to fuel ratios (2-3% exhaust O_2), another effect becomes noticeable: At this operating point the catalyst is able to effectively utilize the remaining oxygen in the exhaust gas to oxidize large amounts of HC/CO.

To study this phenomenon in greater detail, the operating point 1000 RPM / WOT was investigated. The results are shown in FIG.24. In this particular case especially the large catalyst is able to reduce CO and HC in a very effective way, independent of its position before or after the turbo charger. The catalyst's space velocity is <100.000 1/h. When positioned before the turbine however, the increased exhaust enthalpy (through fuel energy converted into heat) enhances the performance of the turbo charger turbine. A higher turbine speed (+6k

RPM with the 0.1L pre turbine catalyst and with the 1.39L pre turbine catalyst compared to no catalyst in the pre turbine position) is observed. At low speeds, where engine performance is closely coupled to the turbo charger's ability to create boost pressure, this results in a significant increase in brake torque shown in FIG.25. This phenomenon has been previously well described [16]. The results obtained are quite comparable to [16] and are in the magnitude of 4-8%.

The large pre turbine catalyst shows a greater exothermal behavior leading to lower tail pipe HC/CO emissions. This indicates better conversion efficiency compared to the small catalyst, as expected. Overall the same power enhancement can be achieved as seen with the small catalyst. FIG.23, FIG.24 and FIG.25 indicate that the loss in power due to the higher pressure drop is obviously compensated in this operating point by the increase in turbine performance due to the higher turbine inlet temperature.

When comparing only the 1.39L catalyst in the pre and post turbine position, the flow velocity at the evaluated operating point is slightly higher in the downstream position than in the position upstream of the turbine. The slightly lower catalyst inlet temperature ($\rho \uparrow$, $FV \downarrow$) is compensated by the significantly lower exhaust pressure level ($\rho \downarrow \downarrow$, $FV \uparrow \uparrow$). The conversion efficiency at the observed temperatures ($>400^\circ\text{C}$) is therefore observed to be similar when comparing the two positions.

The fact that at high speed and full torque the exothermal behavior of the pre turbine catalyst is only minimal (high FV and typically low HC/CO engine out emissions) and the substrate pressure drop behavior becomes dominant, both pre turbine catalysts in the tested configuration show decreased power capability. For high speed and load operating points a low substrate ΔP is key! This has also been described in [2, 16]

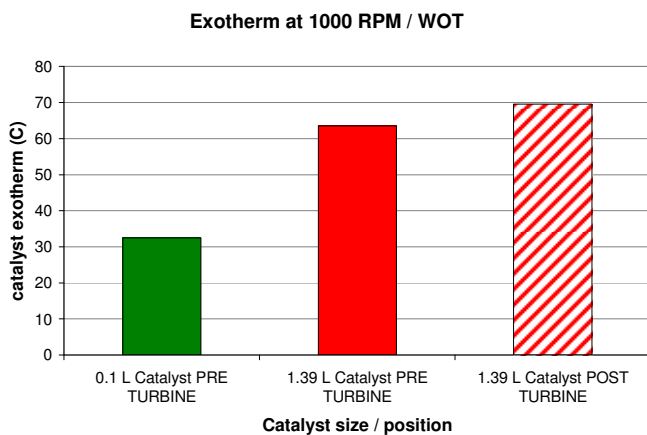


FIG.24: Exhaust temperature increase due to catalyst exotherm for different catalyst sizes & positions

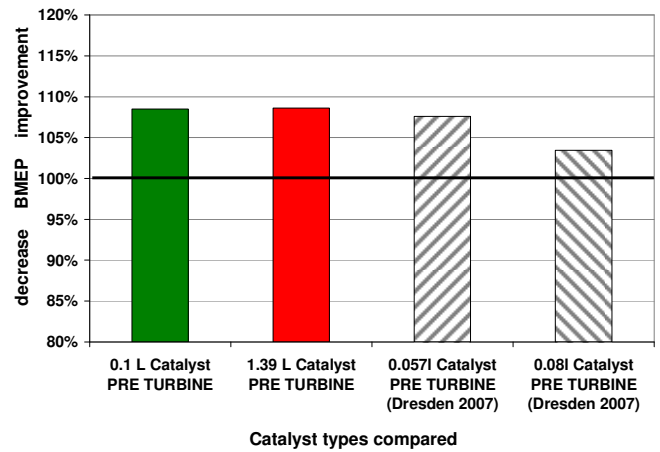


FIG.25: Increase in performance at 1000 RPM / WOT for different pre turbine catalysts

Exothermal energy conversion at part load

Significant exothermal behavior can also be expected at part load when the engine is running in a "PCCI" or "LTC" low NOx combustion mode and producing HC/CO rich exhaust. The small (0.1L), medium (0.57L) and large (1.39L) catalysts were compared in the pre turbine and post turbine position. 1500 RPM / 2 BMEP were investigated. The engine was calibrated at various EGR rates to achieve different amount of engine out HC/CO. To ensure realistic exotherm magnitudes, maximum emissions numbers were set to be similar to what was described in FIG.1 by [7].

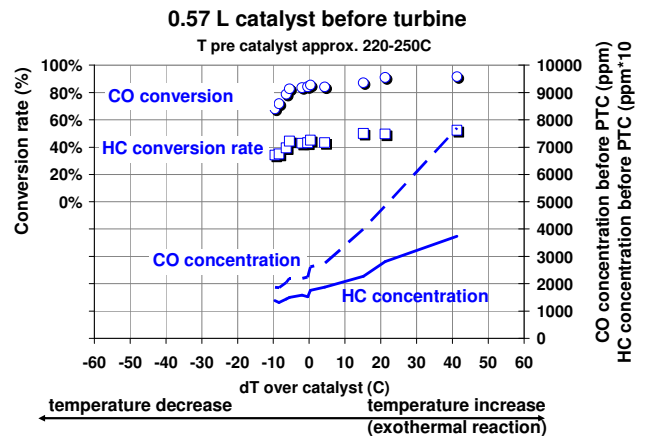


FIG.26: Conversion efficiency and exotherm for increasing engine out emissions at 1500 RPM / 2 BMEP (PCCI combustion mode)

FIG.26 shows that the medium catalyst in the pre turbine position shows consistently high conversion rates for CO (up to 8000 PPM) and HC (up to 400 PPM) at exhaust temperatures in the range of 220°C-280°C. The conversion of HC & CO increases the turbine inlet temperature, which ultimately leads to a turbine speed benefit of approx 3000 rpm (15%) compared to the post

turbine position. However a significant benefit in turbo charger performance was not measurable. This can be attributed to the poor compressor efficiency in this operating point so that enhanced turbine power cannot be effectively utilized. The large catalyst shows very similar behavior while the small catalyst's conversion rates drop off when flooded with the highest amounts of HC/CO. This is mainly due to the limited amount of active sites in the small substrate.

EFFECT ON TRANSIENT ENGINE PERFORMANCE

The different pre turbine catalysts were evaluated in terms of their influence on exhaust temperatures and performance during engine warm up and during a rapid load change.

To compare cold start behavior (initial coolant temperature=40°C, exhaust system temperature=30°C) a simple test was defined. After cold start, the engine speed was set to 1200 RPM / 2 BMEP and held constant for 10 Minutes. HC/CO Emissions and exhaust temperatures were evaluated.

In FIG.27 one can see that the large (1.39L) catalyst in the pre turbine position shows the lowest HC tailpipe emissions, even though the temperature before catalyst is lowest. This can be attributed to the low space velocities and the increased HC storage potential of the large substrate. The performance of the medium size (0.57L) catalyst can be seen as acceptable. The smallest (0.1L) catalyst is clearly undersized for this and shows only little HC conversion below 250 °C. An explanation for this can be found in the limited HC storage capacity of the 0.1L substrate. Since the small PTC would require a second DOC downstream of the turbine anyway, this is not perceived as critical.

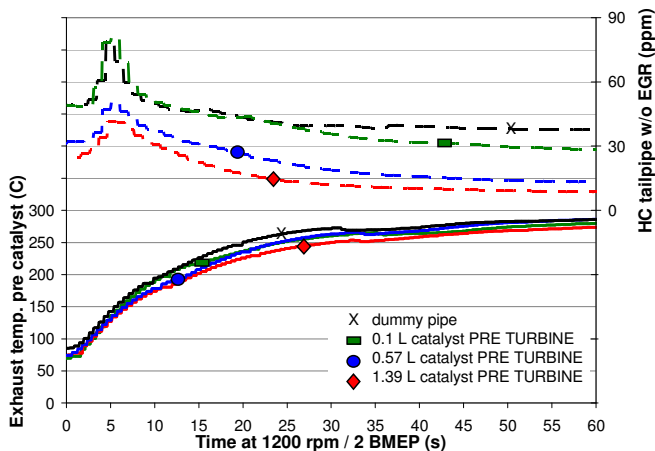


FIG.27: HC tailpipe emissions after a cold start for different pre turbine catalyst sizes

In addition to the cold start test, a step response test was performed. Keeping engine speed constant at 1500 RPM, the load was instantly changed from 2 to 10 BMEP. The engine was initially running approximately 40% high pressure EGR at 2 BMEP (typical for a EURO 4/5 calibration), EGR was switched off during the fast

transient (also quite typical for today's calibrations) and remained off at 10 BMEP. The VTG vanes were kept fully closed during the whole test, which allowed evaluating the load response of the system without any cross influence by the boost pressure controller.

FIG.28 and FIG.29 show the effect of the load step on boost pressure and turbine speed. The medium and large catalysts clearly act as a heat sink during the transient. The turbine speed increases considerably slower than with the small catalyst. The result is a slower increase in boost pressure up to the steady state value. The small catalyst performs similar to the dummy pipe. There is no immediate lag in boost pressure build up or turbine enthalpy increase.

While today slower turbo response primarily affects drivability of the vehicle ("turbo lag" is perceived), future emissions concepts will suffer from the lack of transient boosting capability. It will be difficult to maintain / control desired EGR rates during transients without sufficient turbo charger support. Overall the large and medium catalyst show less favorable transient behavior. It is doubtful that these catalysts can be implemented without additional changes to the turbo charger system.

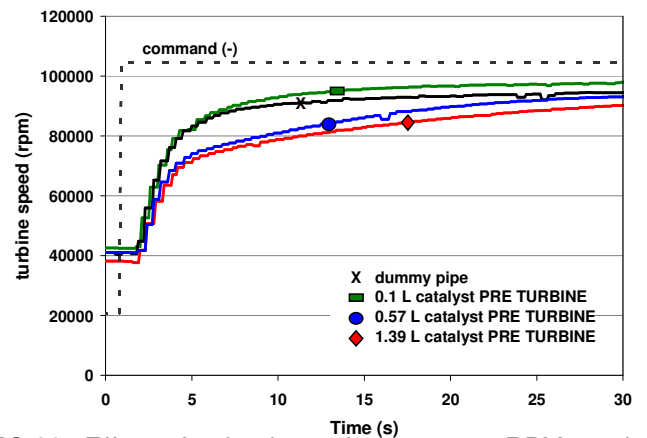


FIG.28: Effect of a load transient at 1500 RPM on the boost pressure

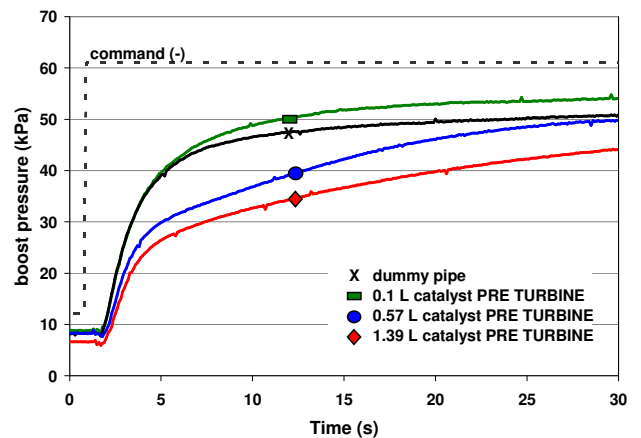


FIG.29: Effect of a load transient at 1500 RPM on the turbine speed

CONCLUSION

Pre turbine catalysts of different sizes were investigated in the pre and post turbine position to understand the effects on engine steady state and transient emissions and performance. The focus, compared to previous publications, was on the use of larger substrates and on the implication for the engine's turbo charger. The following conclusions were obtained:

PTC's are advantageous in terms of reducing cold start HC/CO tailpipe emissions, which will become more important in the future.

The small size PTC investigated can be used in conjunction with a post turbine DOC and only when slight power degradation is acceptable. When packaged optimally however, only little power loss can be predicted. This matches with what has previously been published. The transient response of a breathing system including a small pre turbine catalyst would be considered acceptable for series introduction with today's turbo charging technology. Such systems in LD vehicles will benefit from faster catalyst light-off during cold start and higher conversion efficiencies during transient operation.

The medium size catalyst showed reasonable conversion and transient performance and could be considered a viable option for applications with high HC/CO and low overall test cycle exhaust temperatures that are also less critical in terms of transient response, when coupled with an additional DOC. Here, standard turbo chargers with improved transient behavior should be used.

The largest catalyst in the pre turbine position showed the best emissions performance, which would be considered sufficient even when used without any post turbine DOC. On the other hand system response time was negatively impacted. Further studies are needed to understand effects of gas pulsations and mal distributions and substrate cell structure on the pressure drop behavior. Large Pre Turbo catalysts might be more feasible for applications where the turbo charger's transient response is less critical for dynamically maintaining challenging EGR rate targets. These systems would require large improvements on the turbo charger side.

The effect of an optimized large PTC on engine power and fuel consumption is expected to be positive, although it was not possible to prove the statement in this study. The back pressure performance for such systems needs to be optimized. For an optimization the packaging will be a big challenge.

When considering the higher overall exhaust temperature level and the higher peak temperatures, more robust catalyst technologies are needed to avoid thermal catalyst degradation to ensure life time conversion efficiencies.

During DPF regeneration a large pre turbine catalyst with high conversion efficiency will further increase the thermal load on the turbo charger, but will decrease the stress induced by large temperature gradients. Changes in the regeneration strategy will be necessary to control/limit the temperatures before turbo charger.

The next steps will be to investigate methods to increase the transient turbine performance even when coupled with an optimized, pre turbine oxidation catalyst with the goal of an overall superior and very cost effective engine breathing system.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

RPM: Engine speed in revolutions per minute

WOT: Wide open throttle (= maximum load)

BSFC: Brake specific fuel consumption

VTG: Variable turbine geometry

EGR: Exhaust gas recirculation

NMHC: Non methane hydrocarbons

PPM: Parts per million

HC: Hydrocarbon

CO: Carbon monoxide

PCCI: Premixed charge compression ignition

HCCI: Homogenous charge compression ignition

LTC: Low temperature combustion

DOC: Diesel oxidation catalyst

SCR: Selective catalytic reduction

CC: Close coupled

UF: Under floor

SV: Space velocity

FV: Flow velocity

ρ : Gas density

SOF: Soluble organic fraction

FTP75: US test procedure for light duty vehicles

NEDC: New European driving cycle