

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 NOx 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 NOx and Particulate matter emissions into the environment.

The discussion, whether to reduce NOx through engine internal measures, for example using high rates of cooled EGR or variable valve timing or through NOx exhaust after treatment (such as NOx-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 NOx 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.

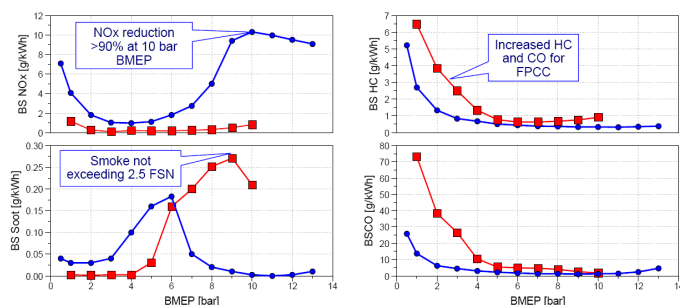


FIG.1: Ricardo's Tier 2 Bin 5 Emissions concept [7]

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.

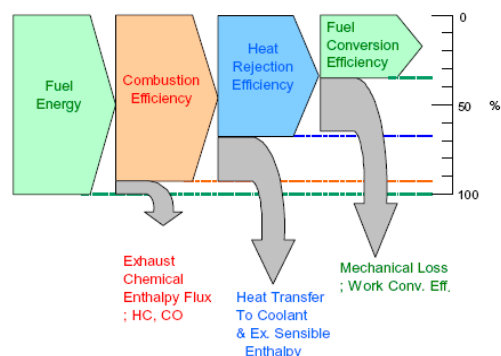
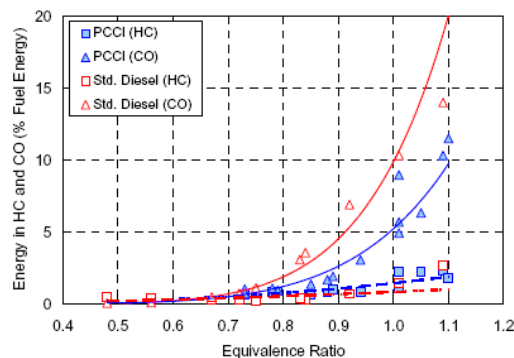


FIG.2: HC/CO energy and Energy flux in the “PCCI” Diesel engine

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).

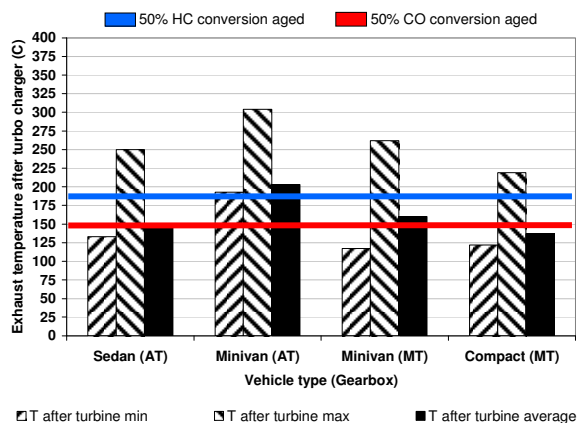


FIG. 3: Exhaust gas temperatures in the ECE part of the NEDC for various passenger vehicle categories

EMISSIONS LEGISLATION

The development of test cycle emissions in Europe in the last years was very focused on lowering NO_x and PM - HC and CO numbers were left "virtually untouched". While the absolute HC limits have not significantly changed, the factor HC/NO_x 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 + NO_x are limited as well as NO_x alone, generally limits the tolerable increase in HC when lowering NO_x 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 NO_x 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 NO_x 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

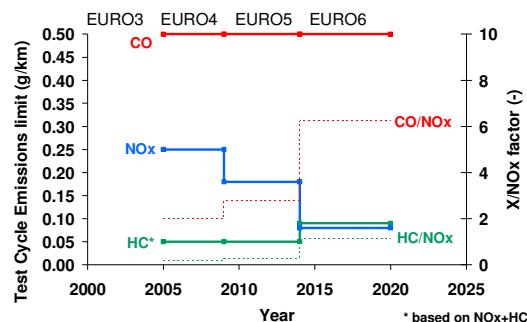


FIG. 4: Progression of HC and CO test cycle limits in Europe

US EPA: FTP75 cycle***

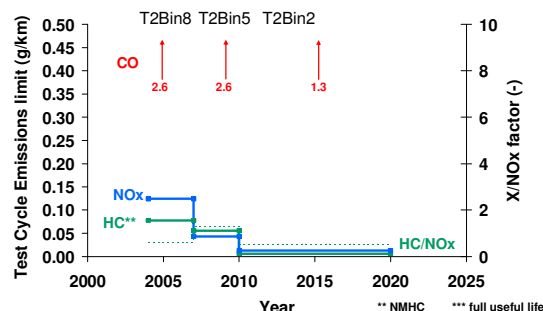


FIG. 5: Progression of HC and CO test cycle limits in the US

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.

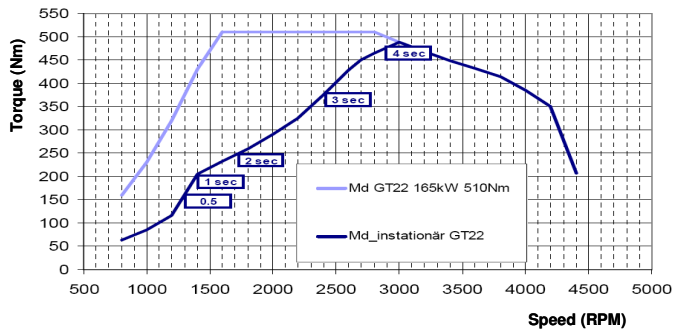


FIG. 6: Acceleration behavior of a Diesel engine with automatic transmission [10]

[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.

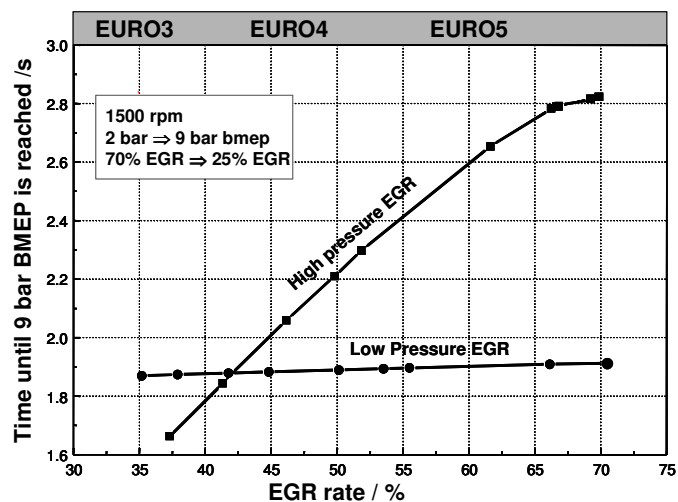


FIG. 7: Load response time as a function of EGR rate & EGR system layout

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 NO_x 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.

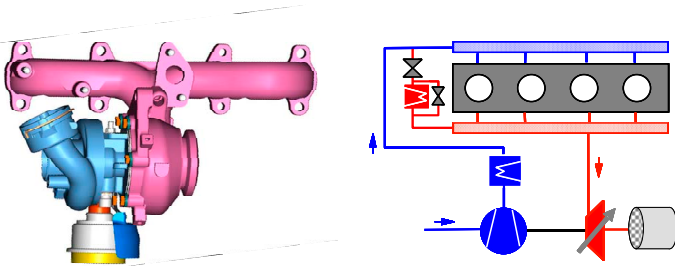


FIG.8: 1-Stage turbo charger layout for passenger cars

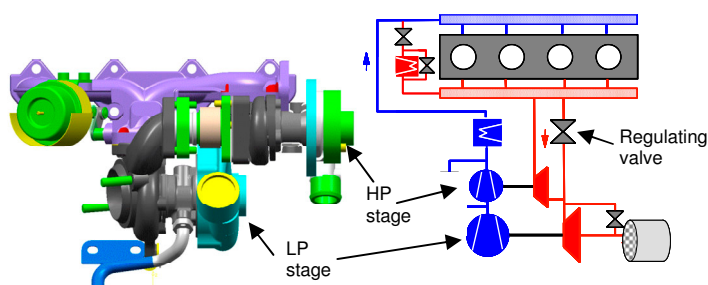


FIG.9: 2-stage turbo charger layouts for passenger cars

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.

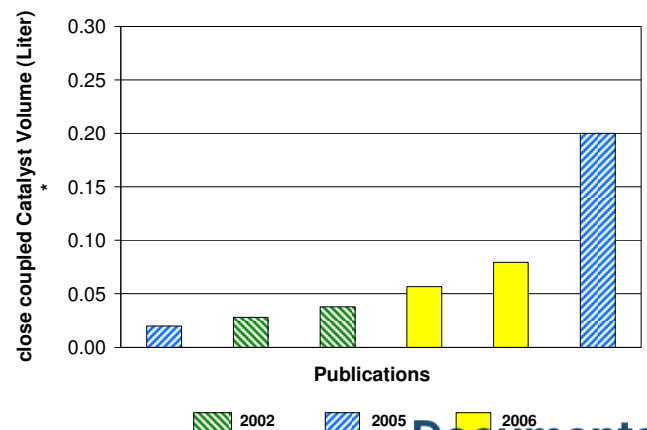


FIG.11: History of investigated PTC sizes (not complete)