

The innovative exhaust gas aftertreatment system for the new Volvo 4 Cylinder Engines; a unit catalyst system for gasoline and diesel cars

Mats Laurell, Johan Sjörs, Staffan Ovesson, Mats Lundgren
Volvo Car Cooperation, Gothenburgh (Sweden)

Rolf Brück, Manuel Presti
Emitec Gmbh, Lohmar (Germany)

Summary

The new Volvo I4 engine has a unique compact and modular exhaust after treatment architecture which is a world-first commonization between diesel and gasoline engines. The modular system means identical geometries on the complete range of applications and is applied in all Volvo vehicles ranging from V40 to XC90. The unique after treatment packaging provides high grade of substrate volume compared to installation space requirements. There are two key elements that have realized this success. First one is the outlet chamber that surrounds the first substrate and the second element is the connection between the first and the second substrate.

1 Introduction

Volvo Car Corporation will introduce a completely new engine family and architecture called Volvo Engine Architecture – VEA – in autumn 2013. The powertrain family at the first introduction consists of turbo charged engines in both gasoline and diesel versions with 2.0 liter displacement. Available at the introduction are one diesel engine with performance level 190 hp and two direct injected gasoline variants at 245 hp and 306 hp. There is a high degree of scalability between diesel and gasoline engines [1].

For the aftertreatment design this is immensely challenging: the emissions technologies required range from the relatively straightforward single-brick solutions for gasoline Euro6 to the sophisticated systems needed for gasoline SULEV30 and diesel Euro6, and packaging prerequisites vary considerably between vehicle platforms.

For diesel Euro6, the selected technology is a lean NOx trap (LNT) in front of a coated diesel particulate filter (DPF). The DPF should be close to the engine to facilitate regeneration and thereby save fuel and system cost. On the other hand, the LNT volume has to be large enough to provide the needed residence time for NOx storage and conversion. For gasoline, the architecture should provide space for a single-brick solution for Euro6 applications, which needs to be in a close-coupled

position to rapidly light-off for SULEV30 applications without additional hardware such as secondary air.

In summary, the design task involved the challenge of meeting simultaneously the following three demands on the aftertreatment system:

1. It should be possible to use the same installation on different platforms and with different components and, ideally, also on both diesel and gasoline engines.
2. A large catalyst volume should be installed in a close-coupled (CC) position without conflict with gear-box or all-wheel drive prop shaft units.
3. The inlet to the catalyst from the turbo should be straight in order to minimize heat losses and thereby utilize catalyst volume optimally.

Reviewing the competitors' aftertreatment architectures of East-West (E/W) engine installations, it can be noted that others have managed to meet one but not both of the last two demands, and none to our knowledge meets the first. The compact catalyst architecture, however, meets these challenges in a unique way.

2 Compact cat and its development

On the current Euro5 Volvo 5-cylinder diesel applications a close coupled DPF system is used on the 2-wheel drive (2WD) variants. Due to packaging restrictions an underfloor DPF system is used on the 4-wheel drive (4WD) variants **Figure 1**.

When developing the Euro6 LNT system for the new Volvo 4-cylinder diesel these two systems have certain benefits and limitations:

- The benefit for the close coupled DPF system is low thermal loss to the DPF substrate, but the system suffers from insufficient LNT volume for required NO_x conversion.
- The benefit for the underfloor system is sufficient LNT volume, but the drawback is temperature loss to the DPF substrate .

The new compact cat combines the benefits for these two systems and has both sufficient LNT volume and reduced temperature loss to the DPF substrate. This design can also be packaged in both 2WD and 4WD variants **Figure 1**.

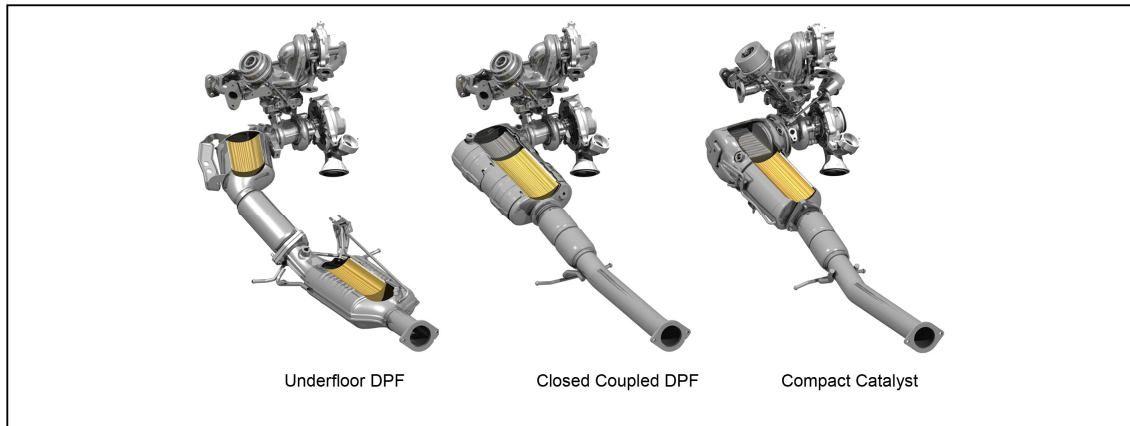


Fig. 1: Volvo diesel aftertreatment systems: Underfloor DPF(intro. 2005); closed coupled DPF(intro. 2010) and compact catalyst incl. NOx trap (intro. 2013)

The advanced engineering work with the outlet chamber began on the all-wheel drive version of the Volvo in-line 5 cylinder turbo gasoline engine. This engine is installed in the smallest vehicle platform (previously S40,V50,C30 and now V40). In this application it was unrealistic to manage a single brick installation without the support from the new outlet chamber ideas **Figure 2**. All other choices would create a clash with the prop shaft in this all wheel drive case. The same would apply to all recent Volvo turbo engine installations as they are characterized as EW and the hot side towards the passenger compartment.

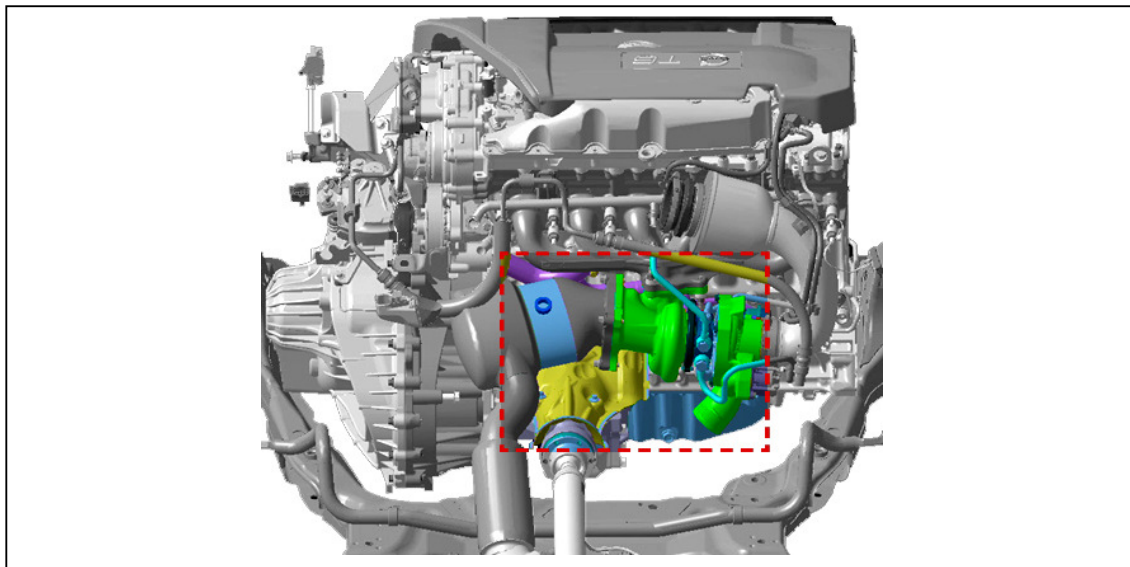


Fig. 2: Packaging investigation for Compact Cat installation in Advanced Engineering Phase

Based on that work, the idea was introduced to create a common catalyst design for gasoline and diesel engines. For sure the catalytic active coating has to be different

but the design should use the same catalyst size, the same inlet and outlet flange and the same insulation and also the possibility to add a second brick or DPF to it.

In order to make this real it was necessary to commonize the outlet flange design and the position of both gasoline and diesel turbocharger. **Figure 3** shows the “old” versions of the turbochargers as well as the new design. With this change in the turbocharger designs the first step for a common aftertreatment system was done.

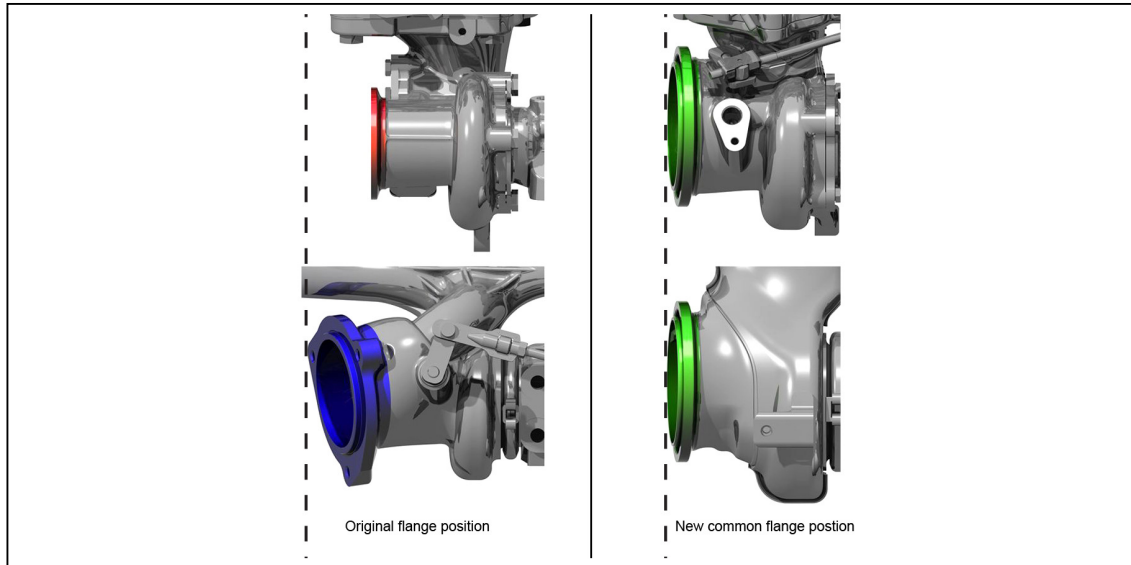


Fig. 3: Evolution of common Turbo Charger flange Design and Position for both Gasoline and Diesel Engines

The Compact Catalyst design is introduced on both diesel and gasoline variants and across all platforms. The commonality in design translates into a tremendous reduction in piece cost and tooling **Figure 4** left. The unique way in which the outlet chamber connects the second substrate to the first has been patented [2] **Figure 4** right.

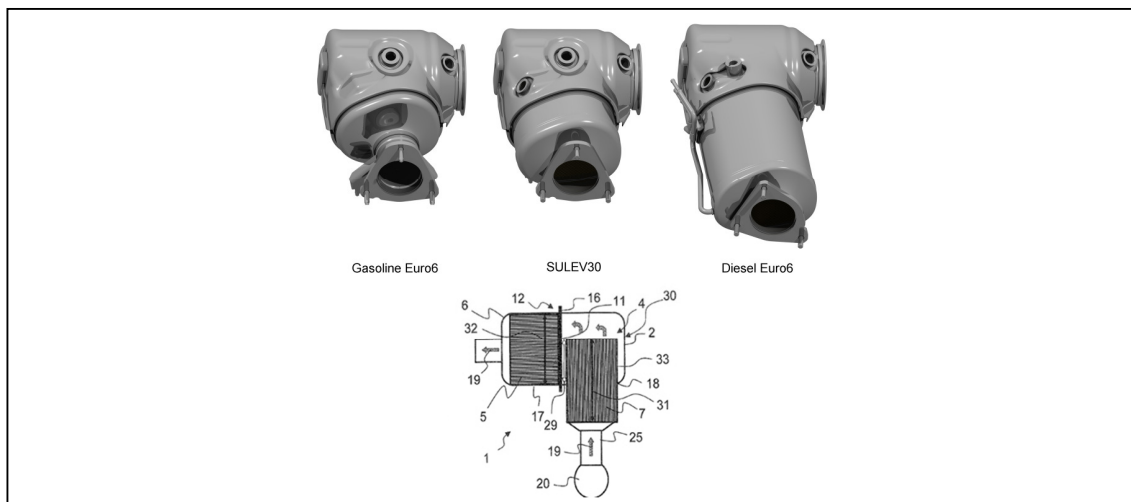


Fig. 4: Left: Compact Catalyst Designs in VEA: Gasoline Euro6, SULEV30, Diesel Euro6. Right: Original patent description: Chamber with 2nd brick connection

The significant basic step with the compact catalyst is that instead of an outlet cone mounted to the substrate, the complete substrate outlet is surrounded by an outlet chamber. The first converter itself is only connected to the casing on the inlet side. This means that the outlet part of the converter is hanging free in an outlet chamber and is surrounded by exhaust gas flow to the outlet pipe.

The outlet chamber brings with it two unique properties for installation freedom.

Firstly, the length of the substrate including outlet is minimized. Comparing with a normal outlet cone connected to an outlet pipe, the axial length of the cone has to be at least as long as the outlet pipe diameter. In the Compact Cat case the outlet pipe is not directly connected to the cone. Instead it is connected to the outlet chamber. Hereby the axial length of the cone is minimized. Secondly, the position of the outlet pipe from the chamber can be positioned anywhere which brings an enormous freedom both axially and radially for minimizing pipe length and pipe bends for the further downstream piping **Figure 5**.

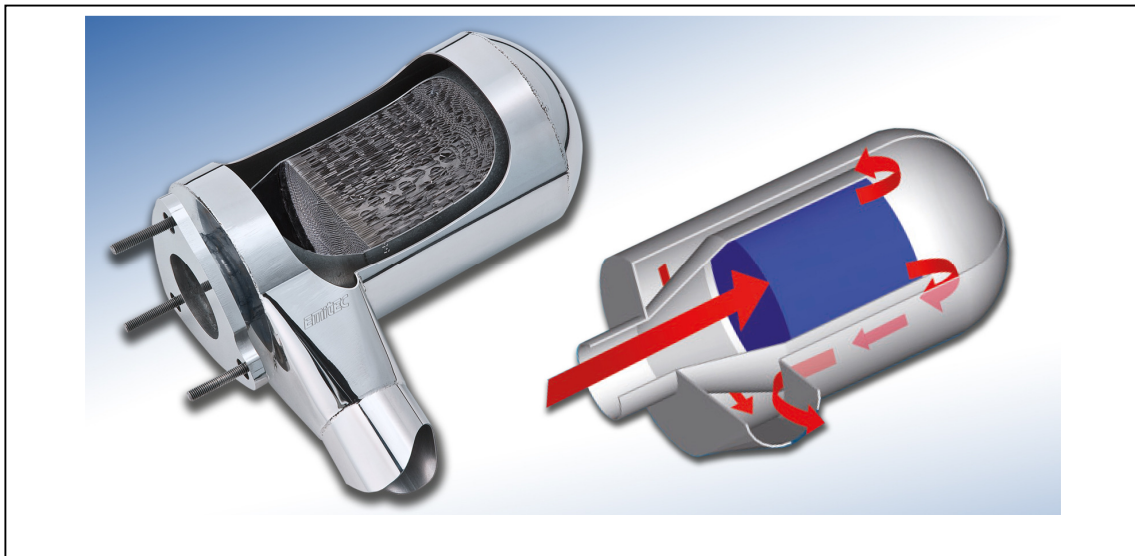


Fig. 5: Original Compact Cat development prototype and schematic illustration of operational principle

The original first brick solution illustrated in Figure 5 has been developed by Emitec and it is kind of tailor-made approach to fit with a metallic substrate. With metallic it is less complex to have a connection in only one end of the substrate and a substrate surrounded by hot gases.

With metallic the durability complexity is decreased where the substrate position not is secured by friction forces (e.g. between the insulation mat and the mantle). Since with hot gases that surrounds the mantle the homogeneity of temperature and thereby material expansion would vary axially over the piece. Hereby even friction forces could then be critical. Another aspect is the substrate diameter. Even though the outlet chamber saves space axially it naturally occupies space in the radial direction. Here a metal substrate has the advantage that radial dimension is more efficient since the installation mat is avoided.

The catalyst inlet could now be performed with a straight inlet cone having the benefit of minimized heat loss before catalyst entrance (saving precious metal loading).

The first substrate on gasoline applications is equipped with an integrated sensor. This technology is also supporting compact solutions. Volvo developed this in early 21st century for an early start of the rear sensor. Volvo had it first time in production 2006 [3, 4]. Today this is a widely spread technology bringing both the benefit of sensor protection and flexibility of sensor mounting for efficient OBD functionality.

3 Second Substrate Design

Diesel applications cannot properly manage emission targets with only one catalyst brick. The most demanding aspect for the second brick is typically size and position of a diesel particulate filter (DPF). This application requires a certain volume to accommodate soot and ash from the engine. Also future gasoline engines are expected to have applications involving gasoline particulate filter (GPF). A close-coupled filter takes advantage of higher exhaust temperature to support efficient soot regeneration and also in the case of a coated filter for emission performance and cost efficiency of the PGM loading. Also the exhaust layout for the super low emissions gasoline applications such as SULEV30 was designed to protect for more than one substrate.

To find an efficient second substrate close-coupled position the innovative work between Volvo and Emitec brought the patented connection between the outlet chamber and second substrate. In the 90 degree turn of the chamber we could position the second substrate vertically underneath the horizontal first substrate with only a 15 mm distance. Here no pipes, bends or cones that would increase back pressure are needed and the packaging unit is kept extremely compact. The exhaust gas flow is kept expanded even though the flow direction is turned 90 degrees between the two substrates supporting the low back pressure effect. Some temperature losses between 1st and 2nd substrate occurs of course due to the surfaces in the outlet chamber. However, those are much less than what would have been the case if the second substrate were in the under body position.

Even though the Compact Catalyst layout provided a very beneficial space for the second brick, diesel applications have tough demands regarding DPF volume. A crucial optimization effort was made to utilize every possible square millimeter of cross sectional area. This iterative packaging process ended with a so called “potato” shaped cross sectional area **Figure 6**.

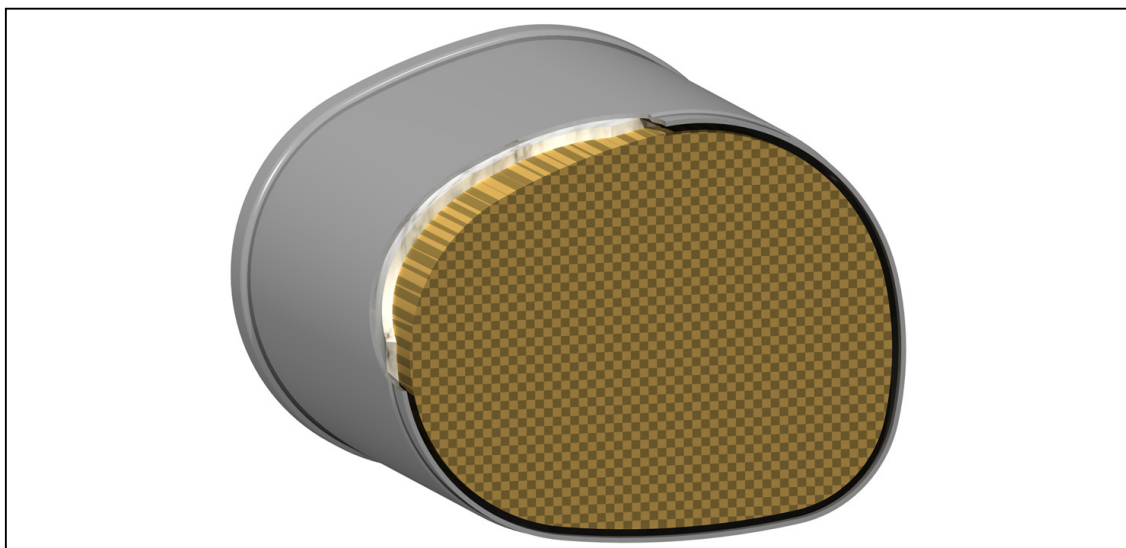


Fig. 6: Second Brick crosssection shape for maximized surface area

The area is 15084 mm² corresponding to a diameter of 138.6 mm if it was round. It is a success to fit this large dimension in this position! Not only does it provide the 3 liter DPF filter volume in an close coupled position, it also brings all in all a very competitive installation when it comes to back pressure. The potato shaped design of course also provides benefits for the other applications. In the petrol version it was requested that the second brick should have a 1 liter substrate. This substrate is then only 66.3 mm long and with its large cross sectional area the added back pressure is small. Actually comparing a 2 brick system and a single brick system the 2nd almost does not add anything to the overall system back pressure.

The efficient second substrate installation with a successfully achieved large cross sectional area brings further possibilities. The Compact Catalyst design is able to manage a challenging first substrate installation when it comes to length versus diameter relationship. Often it is difficult, for flow distribution reasons, to manage a short substrate with large diameter in a close coupled position, especially in the case where a second substrate cannot be mounted adjacent and in line with the first one. This is due to support of the second substrate to build up back pressure. A 2-brick installation that has to be in line is usually difficult for packaging reasons in the engine compartment. Here, with the Compact Catalyst design, we can have the corresponding 2 substrate interaction to support good flow distribution on a short first substrate with an easier to package unit. In the study the front brick was shortened from 122 mm to the length of 60 mm. The diameter of 124 mm was kept.

The size reduction was performed with reduced length on the inlet side (to shorten the outlet part did not bring beneficial flow distribution). It was found that a 2 brick solution =0.7 liter + 1.0 liter volume had a 25% back pressure decrease versus a single brick 1.45 liter solution. The CFD results showed only a negligible draw back on gas flow uniformity. When it comes to PGM optimization further advantages can be made with this configuration. The second substrate is protected from temperature aging in relation to the first substrate and the precious metals more easily resist aging in this case. The total PGM level in grams per vehicle can hereby be reduced compared with a single brick case. This is a very cost efficient way to solve applications where it is desired to be between a single brick solution and a full size two brick solution. All in all the Compact Catalyst design supports individual system tuning of applications still with the outer design untouched.

4 Design Challenges

The bracket concept for the Compact Cat was a real challenge due to the significant weight of the system and the long distance from the engine crankshaft. The variants have different weights and different centers of gravity and they are used on several engines with different vibration behavior, turbocharger layouts and exhaust gas temperatures. The design also needs to meet crash requirements for three different vehicle platforms. Despite all these variations it was decided that the target was to

use the same bracket system independent of variant and vehicle platform **Figure7**. The main challenge with this approach was to find the durability window where the bracket concept met all requirements. On the one hand the design needed to be weak enough to be able to collapse in a crash event and to handle the high thermal expansion. On the other hand the design needed to be stiff enough to handle the engine vibrations and avoid any Eigen frequency related NVH problems.

The one bracket system for all approach resulted in numerous fatigue calculations and crash simulations over a long period of time. In the end despite all variations we were finally able to find a stay design that met all requirements, lowered cost and reduced complexity in both the vehicle plants and for aftermarket.

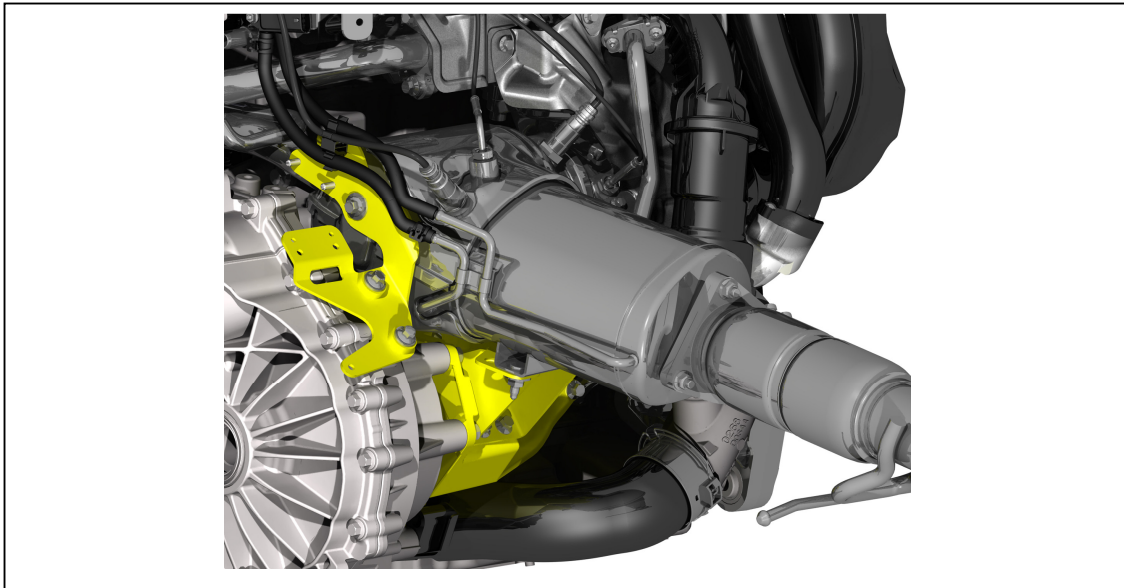


Fig. 7: Common bracket system (yellow) for diesel and gasoline versions

5 Modularity, Scalability and Commonization

The Compact Cat design consists of building blocks that could be combined to a large variety of catalyst variants to meet both current and future emission legislations. There are 6 main building blocks in the design; inlet, first substrate, chamber, second substrate, brackets and outlet. Flange, cone and sensor boss is the inlet block and all variants of the Compact Cat are using the same inlet. The first substrate always has the same diameter but the length can be adapted for different legislations and there is also the possibility to have an integrated sensor in the substrate when needed

Figure 8.

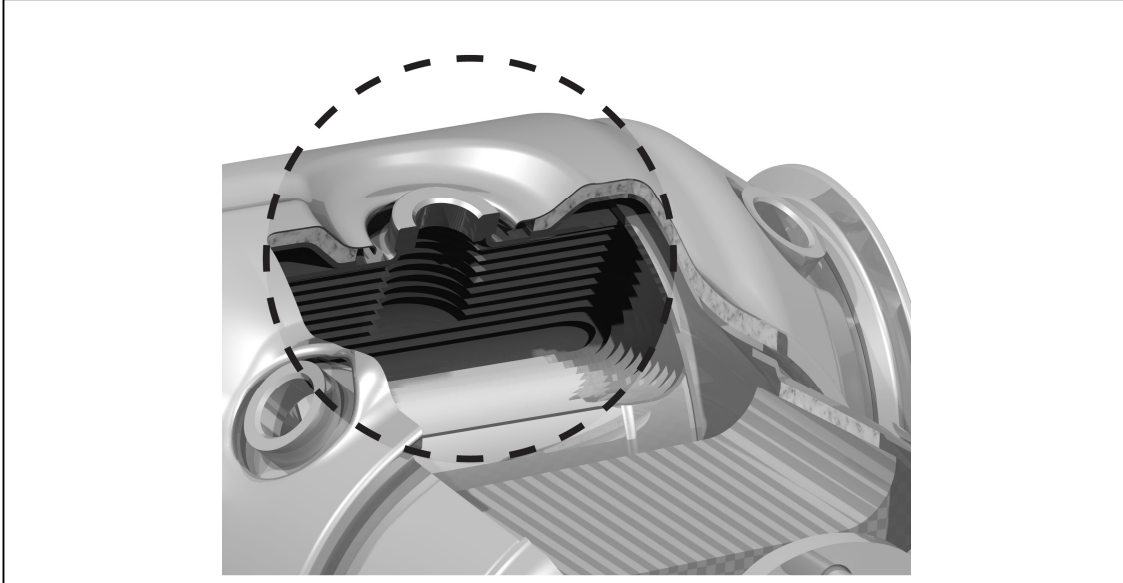


Fig. 8: Lambda Sensor catalyst with detail of sensor hole

The chamber is created by two half shells and main tooling for these shells are always the same independent of variant. Inserts in the tooling are used to create different positions for lambda bosses, temperature bosses and pressure pipes. The second substrate is a ceramic substrate. A pipe replaces the second substrate on markets which manage the emissions with only one substrate. The main bracket system is the same for all variants and it consists of a rear support and a front transmission bracket. The rear one has dual hole patterns to handle length variations. Flange and cone create the final block and the outlet can be fitted on all variants and there is also a possibility to add a pressure pipe if needed. Outlet flanges as well as outlet cones are highlighted in different colors for each variant **Figure 9**.

The building blocks enable high volume and low cost for the single parts but still enable high flexibility of the catalyst assemblies.

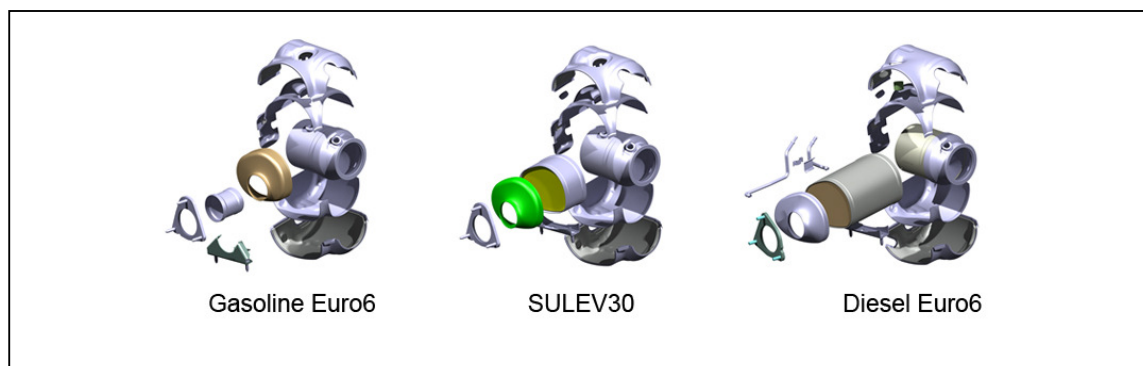


Fig. 9: Exploded view of assembly subcomponents

The building blocks can be easily combined in new ways and the design has a lot of potential also for future emission upgrades. For gasoline versions, the design can be adjusted to fit either an uncoated or coated GPF. For diesel engines the design can be adjusted to fit SCR and it is possible to add both gaseous and liquid injection.

6 Vehicle benefits

The exhaust after treatment systems in modern vehicles is becoming more and more complex driven by emission legislations and the manufactures strive for making green cars for image and public requests. The Compact Catalyst system will support Volvo in these trends with minimum negative effects on other customer related properties. It has already been mentioned the back pressure benefits with the new layout. More complex systems often bring additional vehicle weight and also this negative impact can be kept on the lower side. With the compactness, space is made available for other sub systems or interior compartment.

One subsystem that already could take advantage of liberated space is the silencer system. With more space available it was possible to design this system with lower back pressure than previous versions.

The concept has liberated space as illustrated in **Figure 10**. One sub system that is expected to take advantage of this is the battery system of future electrified vehicles.

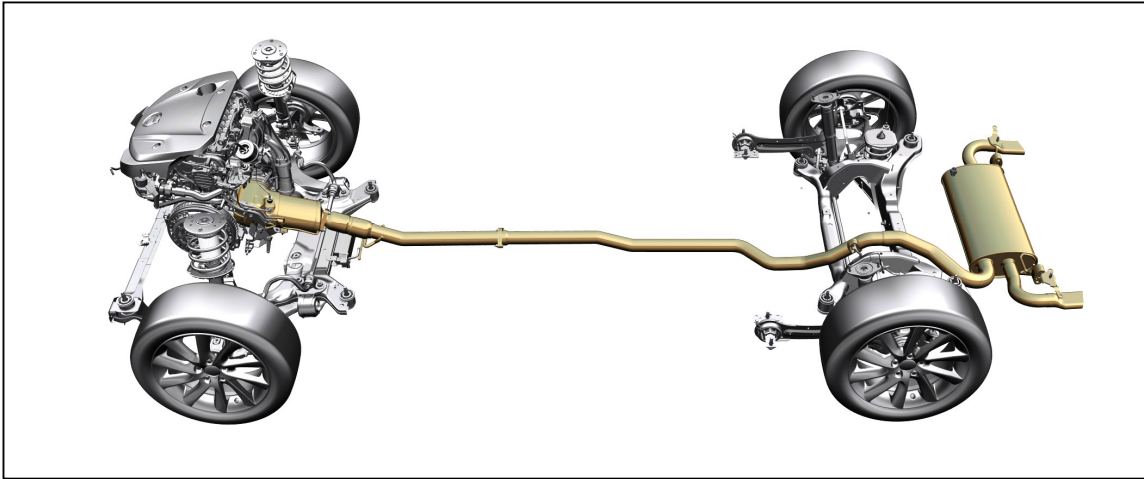


Fig. 10: The new installation liberates space in under floor position

Fuel consumption is of course a highlight for all new engine introductions. VEA architecture brings a system that reduces the negative impact on back pressure that an aftertreatment system normally provides. The system has less heat losses supporting the engine to run efficiently without creating unnecessary additional heat to the aftertreatment system. It is also characterized by less weight impact and the smaller size provides benefits for other subsystem to contribute to fuel consumption. Together all of this, in addition to efficient exhaust gas after-treatment, brings low fuel consumption. The environmental efforts in this application are supported by the exhaust gas aftertreatment architecture.

7 Results: Flow distribution, back pressure and emissions

The uniformity of exhaust gas flow into a catalyst is expressed in the uniformity index, γ . In order to protect the catalyst from aging Volvo requires $\gamma > 0.9$ at high flow. Fulfilling this requirement turned out to be a demanding task, in particular for gasoline. The reason is that with the straight inlet, which is beneficial for light-off, at full load the jet stream from the turbo hits the catalyst front face directly, creating a hot spot where thermal deactivation is accelerated **Figure 11a**. Several countermeasures have been employed to mitigate this effect. First of all the position and angle of the waste-gate plate is of vital importance.

It was necessary to direct the flow from the waste gate inwards, thus mixing it with the main flow, but also deflect it so as to follow the wall of the turbo outlet down to the catalyst substrate **Figure 11b-c**.

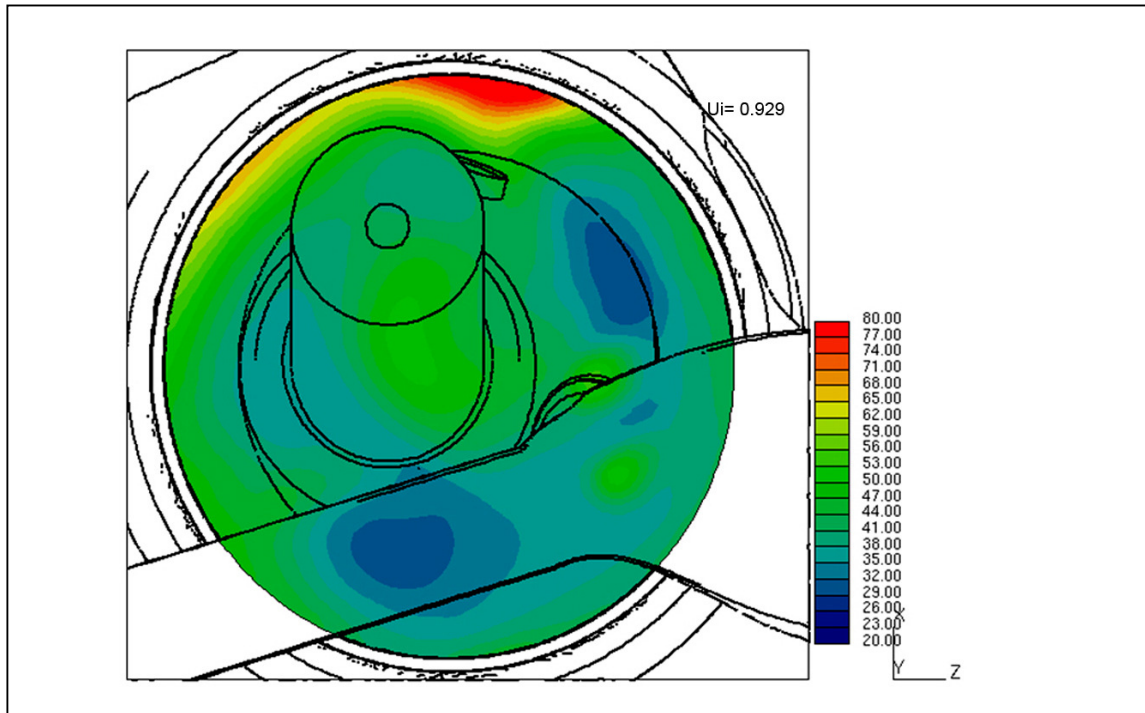


Fig. 11a: Top view of substrate

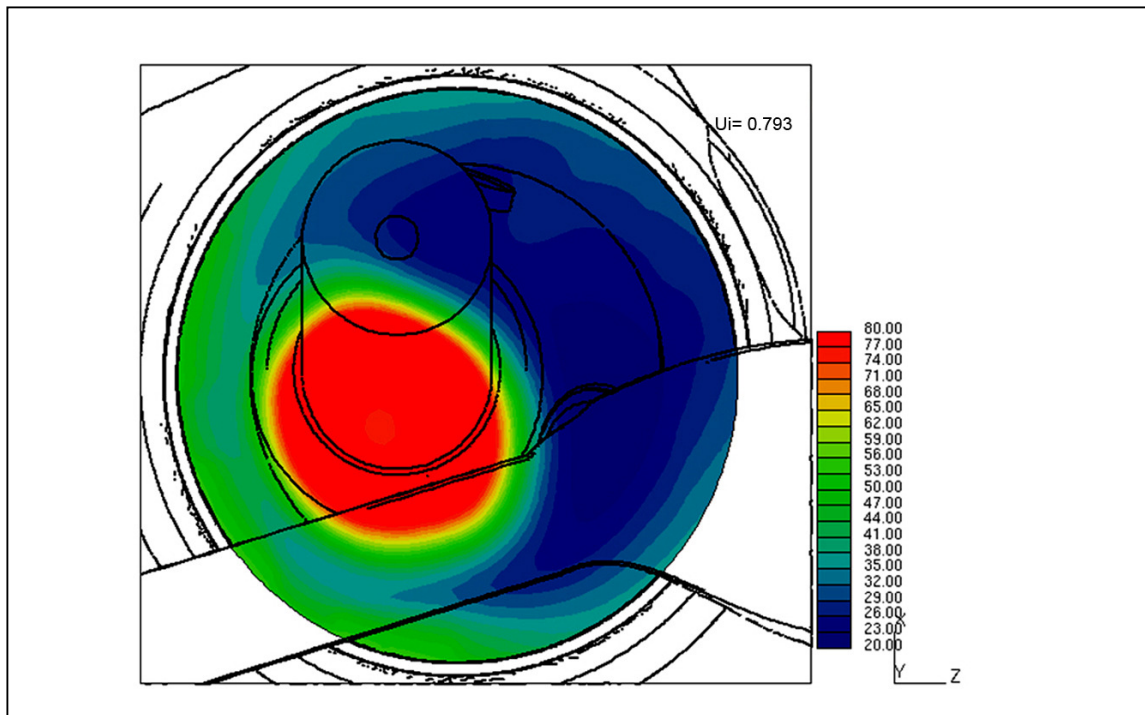


Fig. 11b: Top view of substrate

However, that measure alone instead created high flow speeds at the catalyst periphery in load points with high waste-gate flow. The solution was to introduce a breaking wall that prevents the waste-gate flow from taking the shortest path to the catalyst along the wall **Figure 11d**.

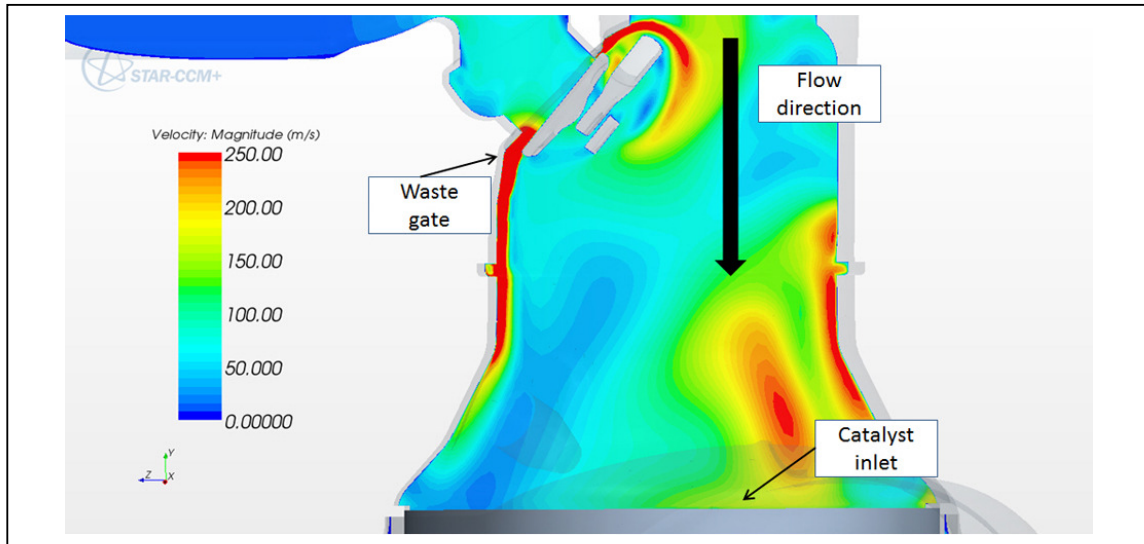


Fig. 11c: Open waste-gate, no breaking wall

A major concern with this design was that pressure drop would be unacceptably high considering the shape of the outlet chamber. Early computational fluid dynamics (CFD) simulations had indicated that the overall backpressure would actually be very competitive in this sense. However, the compact cat differs so much from everything that had been tested before that there was reasonable doubt as to the validity of CFD assessments.

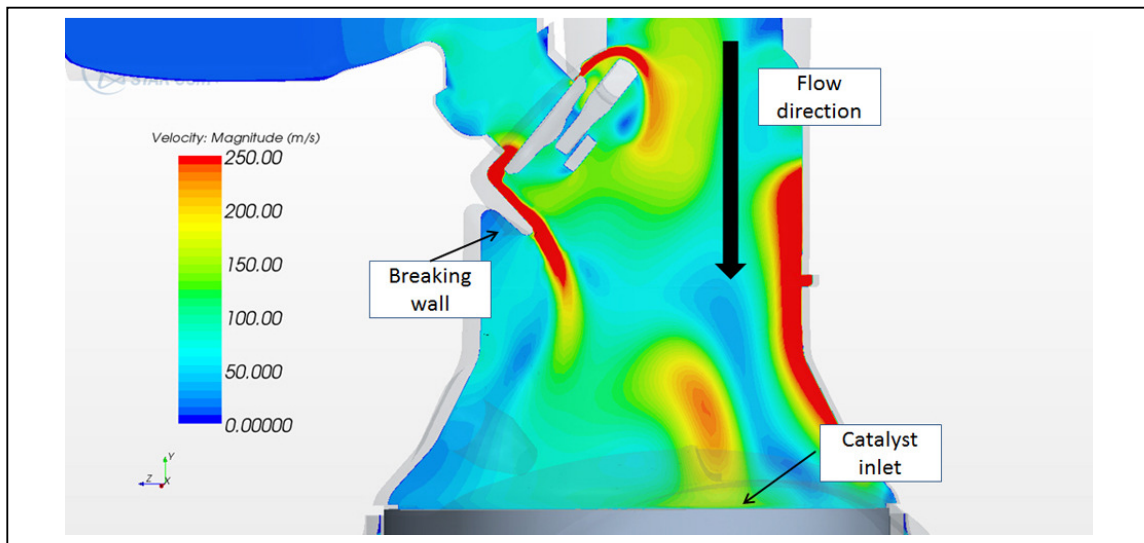


Fig. 11d: Open waste-gate, with breaking wall

For this reason, full-load backpressure tests were performed on a 2.5L Turbo slave engine comparing the Compact Cat with the more conventional catalyst for the MY11 3.0L Turbo engine **Figure 12**. The results confirmed the conclusions from CFD and

provided strong evidence that the design was the best candidate for further optimization.

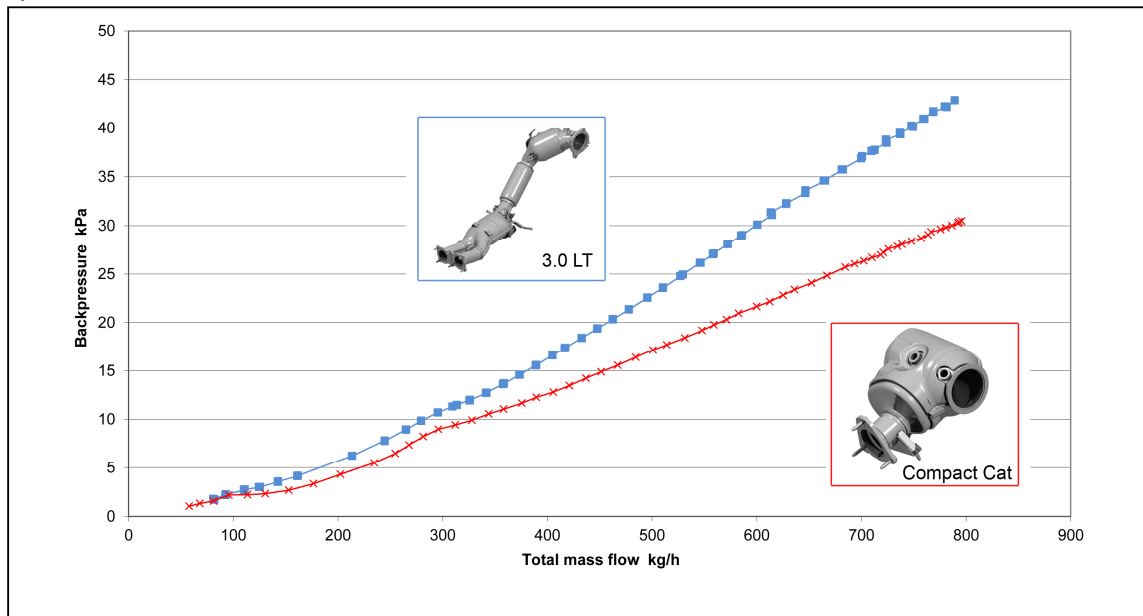


Fig. 12: Full-load backpressure assessment of the Euro6 Compact cat system, tested against the 3.0 L turbo system

The special design of the outlet chamber allowed for a connection onto the second substrate without the contraction and expansion at inlet and outlet cones that would have been necessary with a traditional design. It is an astonishing fact that starting from the single-brick design a second brick of 1 liter could be added with almost no penalty on backpressure: the difference between the gasoline single-brick Euro6 and the two-brick SULEV30 is only a couple of kPa (CFD results in **Figure 13**). For applications with particulate filters, which always add substantial pressure drop, this feature offers a competitive advantage for engine performance.

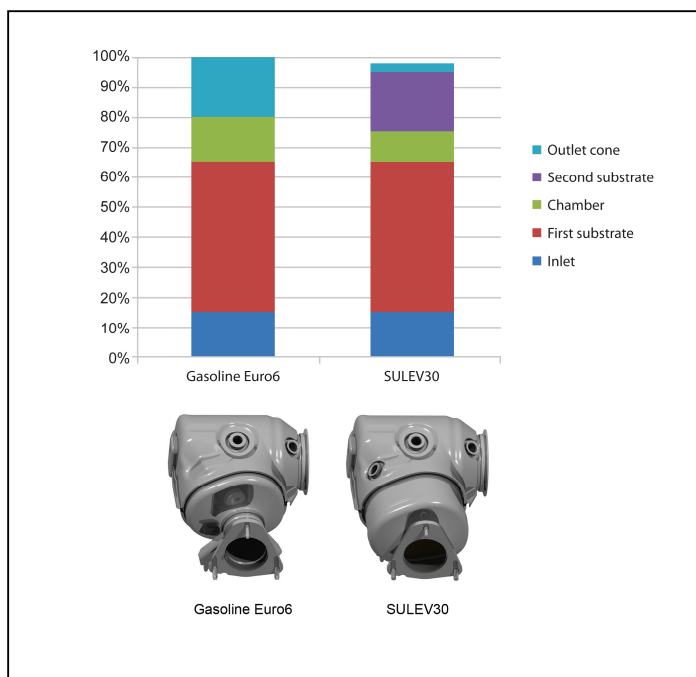


Fig. 13: Pressure drop over Euro6 and SULEV30 systems, split into subsections, as calculated with CFD

The Compact Catalyst design also shows significant back pressure benefits on diesel applications. Looking back to previous concepts as the under floor DPF layout. During evolution the desire was to improve the temperature conditions for the DPF for improved catalytic utilization and improved soot regeneration. The close coupled DPF (current 5 cylinder diesel variants) was developed and a drawback with increased back pressure had to be accepted. With the now introduced unique design the temperature benefit could be kept while still achieving the lowest possible back pressure among all concepts Figure 14. In addition the Compact Catalyst volume benefit brought that the desired NOx trap could fit.

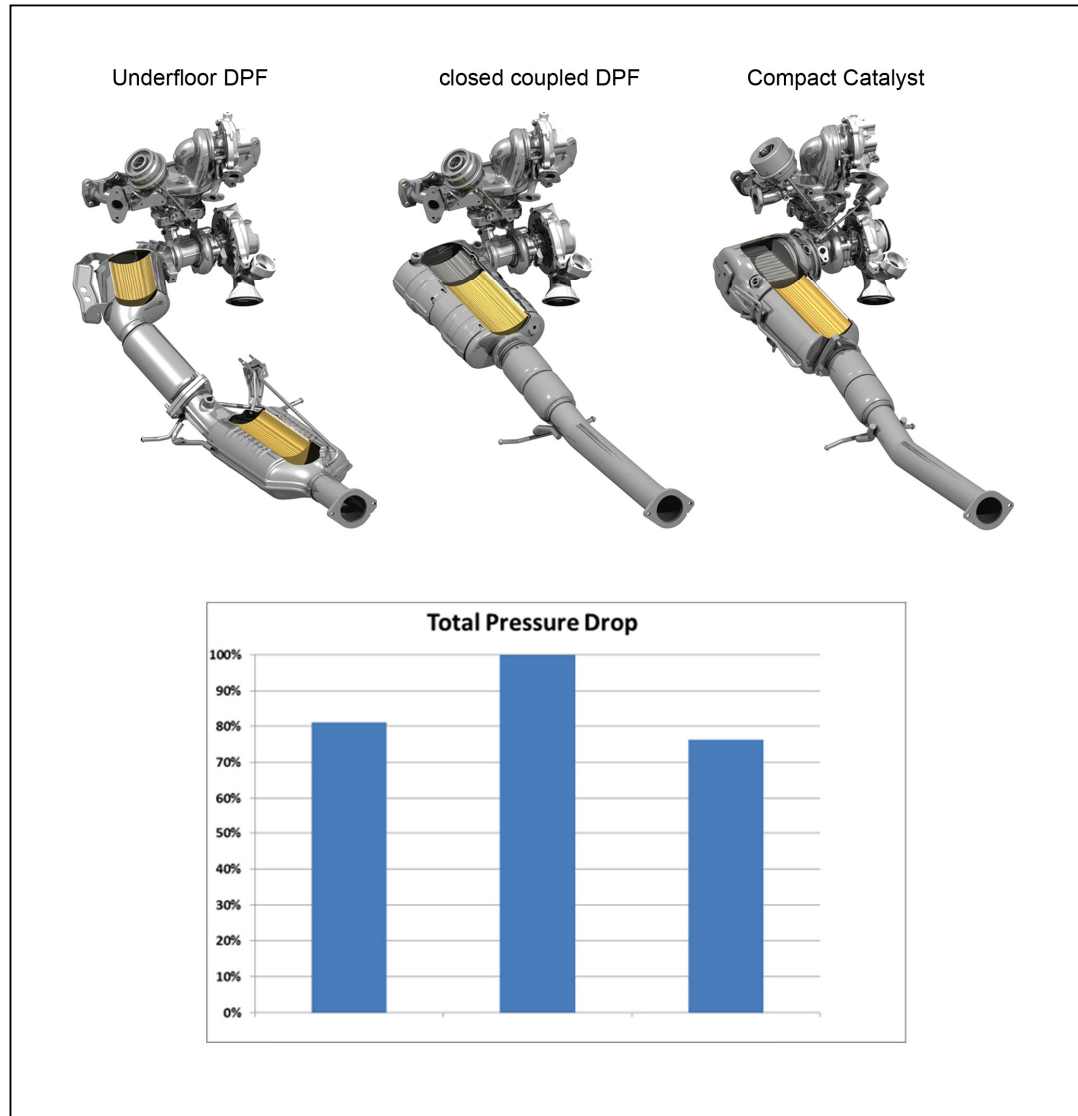


Fig. 14: Pressure drop calculated in CFD for different Volvo diesel aftertreatment systems

The Compact cat can be used to design high-end emissions systems for SULEV30 requirements as well as cost-efficient systems at the Euro6 level.

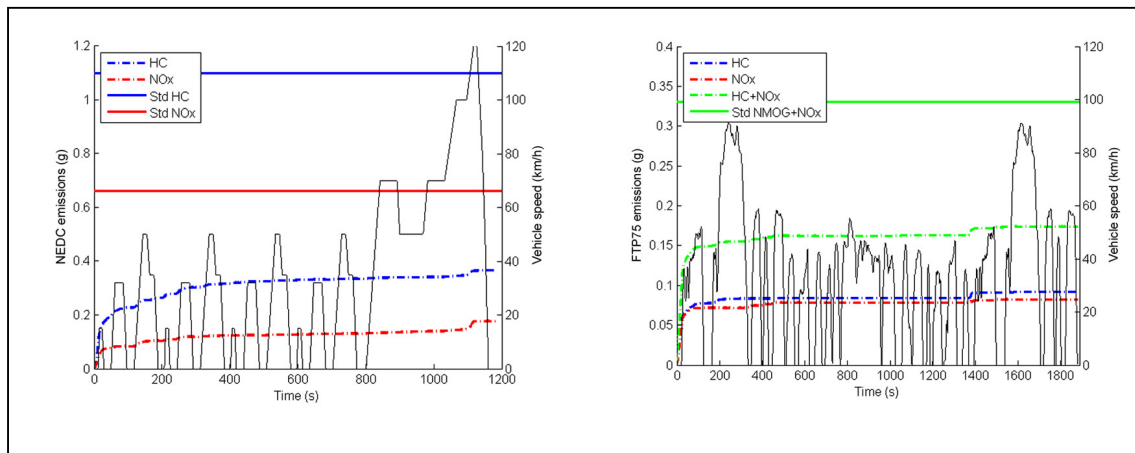


Fig. 15: Gasoline engine. Accumulated HC and NO_x emissions NEDC (Euro6) and FTP75 (SULEV30) together with the emissions standards. In the FTP75 chart the 10 min soak has been suppressed. The bar for the NMOG+NO_x standard depicts SULEV30 as 30 mg/mi × 11 mi

Accumulated emissions for gasoline application for two such systems are displayed in **Figure 15**. Requirements are met by wide margins in both cases. The straight inlet facilitates fast catalyst light-off as required for SULEV30, and the single-brick volume is large enough to cope with the high-speed parts of NEDC. Moreover, as the second substrate is so close to the engine reduces the cooling down during engine shut-off (e.g. 80K less than an under-floor installation during the FTP75 soak), which is beneficial for stop-start and hybrid applications.

For the diesel accumulated emission, shown in **Figure 16**, it was challenging meeting Euro6 level with the new engine having extremely low exhaust gas temperatures (as a result from optimized combustion). Also here the straight inlet and large first brick volume (in this case LNT) supported successfully high NO_x and CO conversion efficiency.

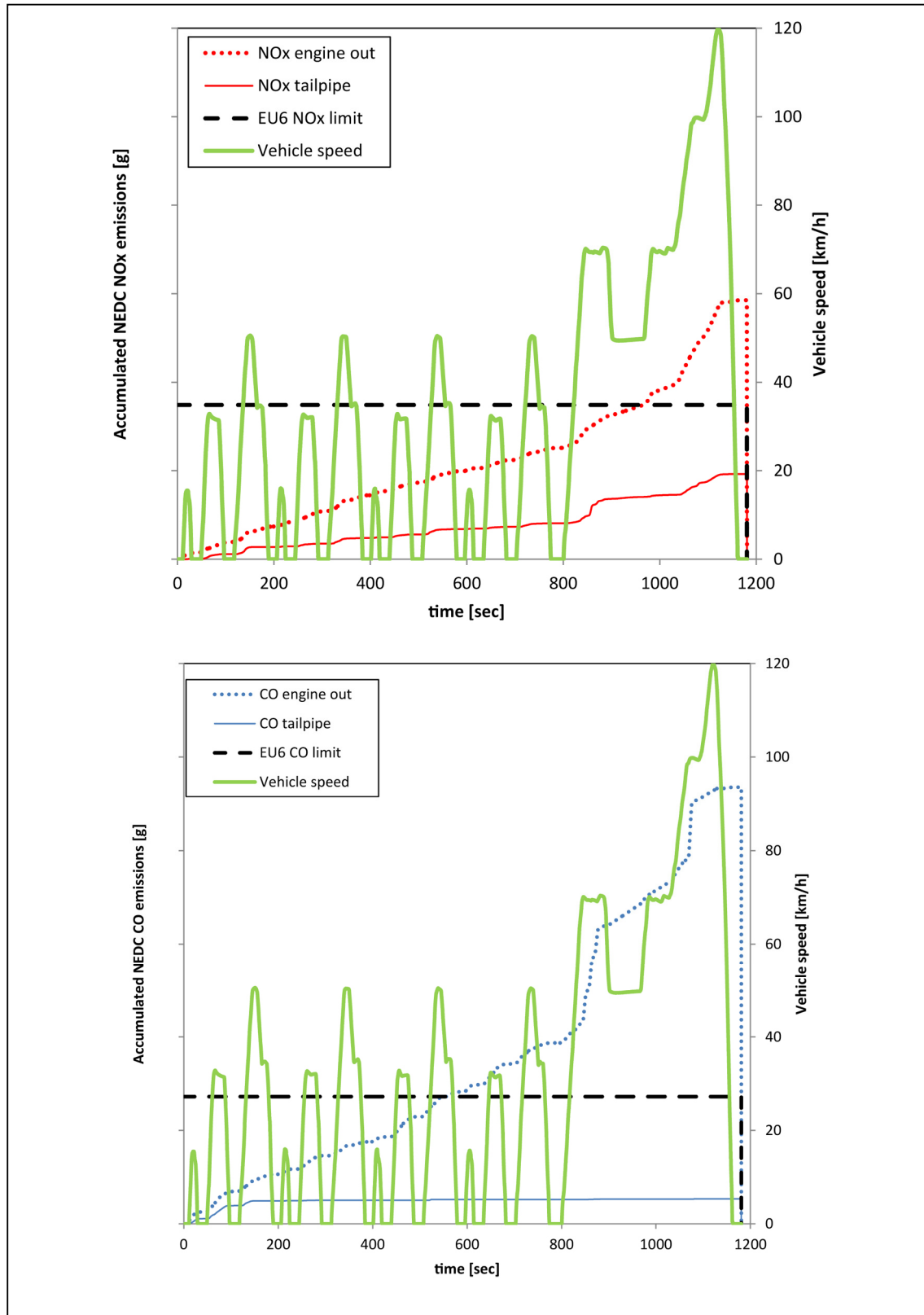


Fig. 16 : Diesel engine. Accumulated HC and NOx emissions NEDC (Euro6) together with the emissions standards

8 Conclusions

Bridging diesel and gasoline engines by a high degree of similarity and extreme compactness of both exhaust aftertreatment systems across different applications and platforms, represents, at the present stage, a technical breakthrough in the industry.

As a result, the same tooling is used for all variants. Also, flexible tools for different canning lengths (1.0, 2.5 or 3.0 liters) can be used. With the same inlet and outlet flange position also the same fixture can be used. Consequently a remarkable reduction in overall investments could be attained.

The emission results for gasoline and diesel gained from an improvement in warming-up emissions. The inlet cone is straight minimizing temperature losses. The first substrate volume is maximized supporting a high volume that is quickly warmed up. The second substrate is close-coupled, still with sufficient volume, avoiding temperature losses that a down pipe between CCC and UFC would bring. The achieved LNT volume on the diesel variants is essential for its emission performance.

Moreover also the vehicle attributes are improved, such as reduced fuel consumption by means of better heat management and efficient back pressure balance.

Additionally, the system compactness allowed for liberated space, which could be used, for instance, in case subsystems for electrification are needed.

9 References

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