

## COMMONISED DIESEL AND GASOLINE CATALYST ARCHITECTURE

Volvo Cars has developed a standardised catalytic converter architecture for diesel and gasoline engines – the scalable so-called Compact Cat. The system covers both Euro 6 and SULEV applications for gasoline engines as well as Euro 6 applications for diesel engines. The standardised design using shared parts results in a considerable reduction in unit costs and tooling requirements.

## AUTHORS



### DIPL.-ING. MATS LAURELL

is Technical Specialist for Exhaust Gas Aftertreatment Gasoline Engines at the Volvo Car Corporation in Gothenburg (Sweden).



### DIPL.-ING. JOHAN SJÖRS

is Senior Engineer Exhaust Systems at the Volvo Car Corporation in Gothenburg (Sweden).



### BJÖRN WERNLUND

is Design Engineer Exhaust Systems at the Volvo Car Corporation in Gothenburg (Sweden).



### DIPL.-ING. ROLF BRÜCK

is Managing Director Research, Development & Application at the Emitec GmbH in Lohmar (Germany).

## HIGH DEGREE OF SCALABILITY BETWEEN DIESEL AND GASOLINE ENGINES

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 turbocharged engines in both gasoline and diesel versions with 2.0-l displacement. Available at the introduction are one diesel engine with a performance level of 133 kW and two direct injected gasoline variants at 180 and 225 kW. 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 Euro 6 to the sophisticated systems needed for gasoline SULEV30 and diesel Euro 6, and packaging prerequisites vary considerably between vehicle platforms.

For diesel Euro 6, the selected technology is a lean NO<sub>x</sub> 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 NO<sub>x</sub> storage and conversion. For gasoline, the architecture should provide space for a single-brick solution for Euro 6 applications but also 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:

- : 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.
- : A large catalyst volume should be installed in a close-coupled (CC) position without conflict with gearbox or all-wheel drive prop shaft units.
- : The inlet to the catalyst from the turbo should be straight in order to minimise heat losses and thereby utilise catalyst volume optimally.

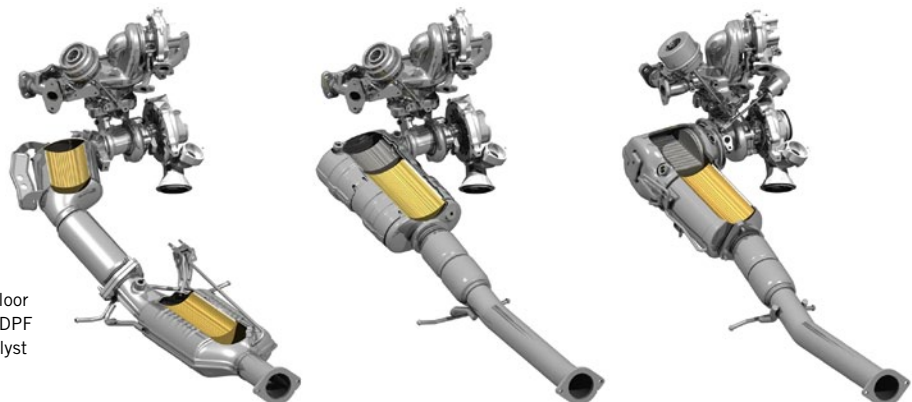
Reviewing the competitors' aftertreatment architectures of east/west (E/W) engine installations, it can be noted that others have managed to meet one but not both of the last two demands, and none to Volvo's knowledge meets the first. The so-called Compact Catalyst architecture, however, meets these challenges in a unique way.

## COMPACT CAT AND ITS DEVELOPMENT

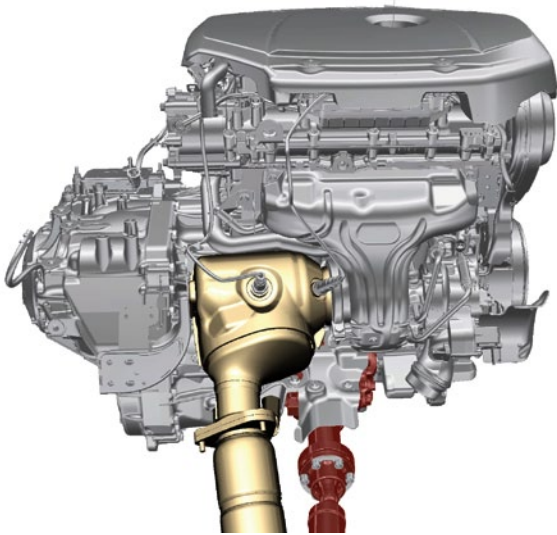
On the current Euro 5 Volvo five-cylinder diesel applications a close-coupled DPF system is used on the two-wheel drive (2WD) variants. Due to packaging restrictions an underfloor DPF system is used on the four-wheel drive (4WD) variants, ❶.

When developing the Euro 6 LNT system for the new Volvo four-cylinder diesel these two systems have certain benefits and limitations:

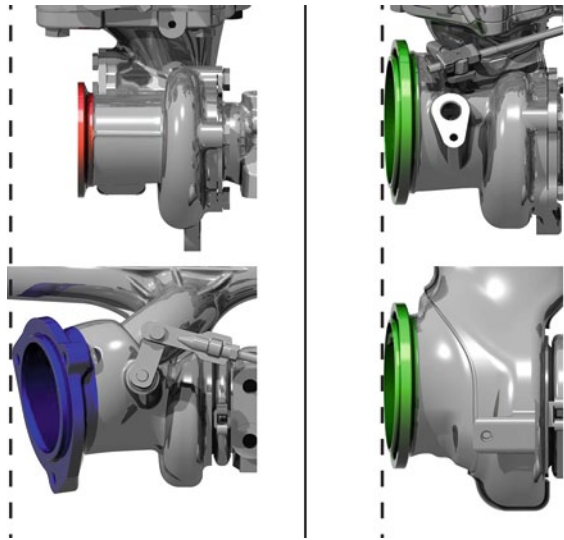
- : The benefit for the close-coupled DPF system is low thermal loss to the DPF substrate, but the system suffers from insufficient LNT volume for required NO<sub>x</sub> conversion.
- : The benefit for the underfloor system is sufficient LNT volume, but the drawback is temperature loss to the DPF substrate.



❶ Volvo diesel aftertreatment systems: underfloor DPF (introduction 2005, left); closed-coupled DPF (introduction 2010, middle) and Compact Catalyst including NO<sub>x</sub> trap (introduction 2013, right)



② Packaging accomplished for Compact Cat installation with new outlet chamber on all-wheel drive application



③ Evolution of common turbo charger flange design and position; current five-cylinder diesel and gasoline (left), VEA diesel and gasoline (right)

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.

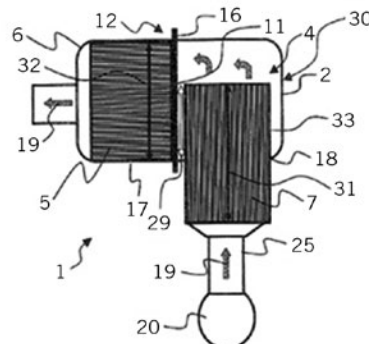
The advanced engineering work with the outlet chamber began on the all-wheel drive version of the Volvo in-line five-cylinder turbo gasoline engine. This engine is installed in the smallest vehicle platform (previously S40, V50, C30 and now V40). In this application it was unrealistic to manage a single brick installation without the support from the new outlet chamber ideas. 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 characterised as E/W and the hot side towards the passenger compartment.

Based on the work with a chamber solving all-wheel drive, ②, 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 size, 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 commonise the outlet flange design and the position of both gasoline and diesel turbocharger. ③ shows the old well as the new design of the turbochargers. With this change

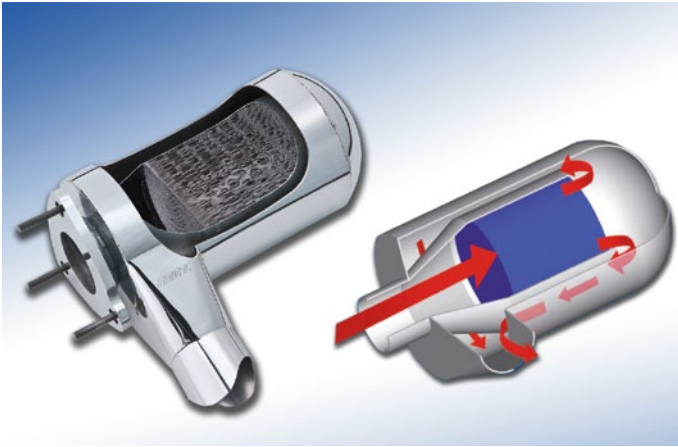
in the designs the first step for a common aftertreatment system was taken.

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, ④ (top). The unique way in which the outlet chamber connects the second substrate to the first has been patented [2], ④ (bottom).

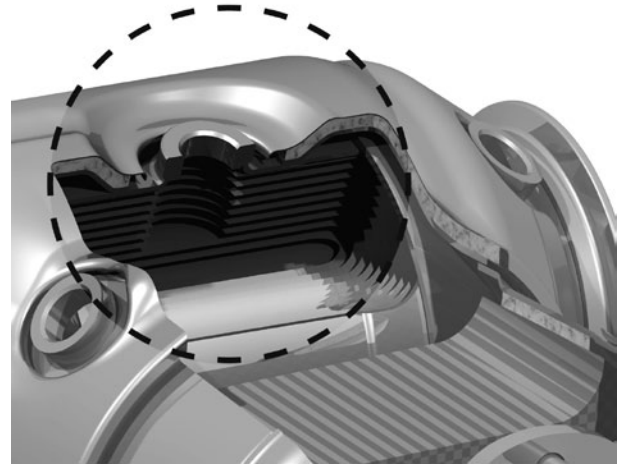
The significant basic step with the Compact Catalyst is that instead of an outlet cone mounted to the substrate, the complete substrate outlet is surrounded by an outlet chamber. The first converter itself is only connected to the canning on the inlet side. This means that the outlet part of the converter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



④ Compact Catalyst designs in VEA gasoline Euro 6, SULEV30 and diesel Euro 6 (above, from left to right); original patent description: chamber with 2<sup>nd</sup> brick connection (bottom)



5 Development prototype and schematic illustration of operational principle



6 Detail of sensor hole for lambda sensor

The outlet chamber brings with it two unique properties for installation freedom. Firstly, the length of the substrate including outlet is minimised. 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 minimised. Secondly, the outlet pipe from the chamber can be positioned anywhere which brings an enormous freedom both axially and radially for minimising pipe length and pipe bends for the further downstream piping, 5. The original first brick solution illustrated in 5 has been developed by Emitec and it is kind of tailor-made 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.

The first substrate on gasoline applications is equipped with an integrated sensor. This technology is also supporting compact solutions. Volvo developed this in early 21<sup>st</sup> 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 (On-Board Diagnosis) functionality.

To find an efficient second substrate close-coupled position the work between Volvo and Emitec brought the patented connection between the outlet chamber and second substrate. In the 90° turn of

the chamber the second substrate could be positioned 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° between the two substrates supporting the low back pressure effect. Some temperature losses between 1<sup>st</sup> and 2<sup>nd</sup> 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 optimisation effort was made to utilise every possible square millimeter of cross sectional area. This iterative packaging process ended with a so-called “potato” shaped cross sectional area. The area is 15,084 mm<sup>2</sup> 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 3-1 DPF filter volume in a 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 other applications such as gasoline particulate filter (GPF). In the gasoline SULEV30 version it was requested that the second brick should have a 1 l 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 two brick system and a single brick system the 2<sup>nd</sup> almost does not add anything to the overall system back pressure.

#### MODULARITY, SCALABILITY AND COMMONISATION

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 six 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 124 mm diameter but the length can be adapted for different legislations. There is also the possibility to have an integrated sensor in the substrate when needed, 6.

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 that 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 fit-

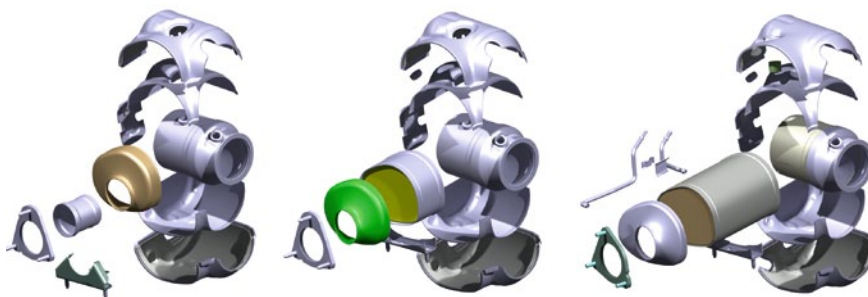
## DEVELOPMENT EXHAUST AFTERTREATMENT

ted 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, 7.

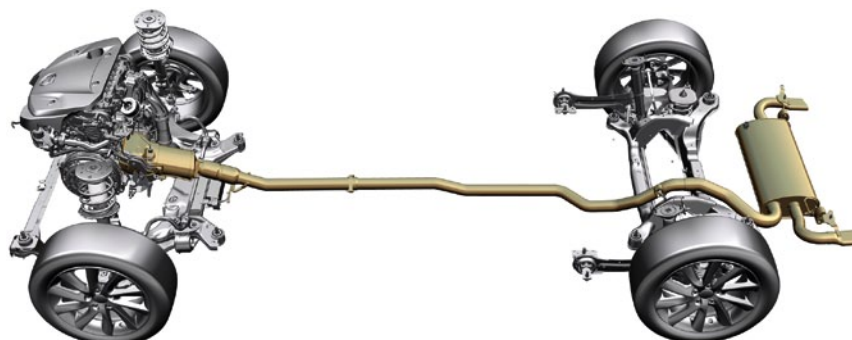
The building blocks enable high volume and low cost for the single parts but still enable high flexibility of the catalyst assemblies. The building blocks can be easily combined in new ways and the design has a lot of potential also for future emission upgrades. For gasoline versions, the design can 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.

### VEHICLE BENEFITS

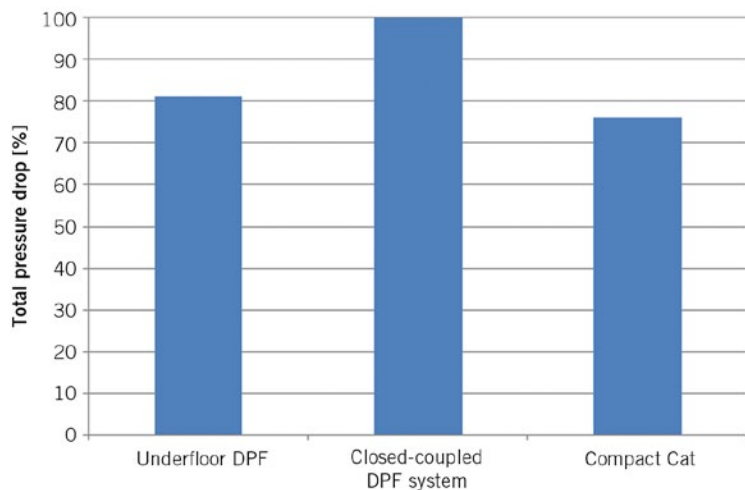
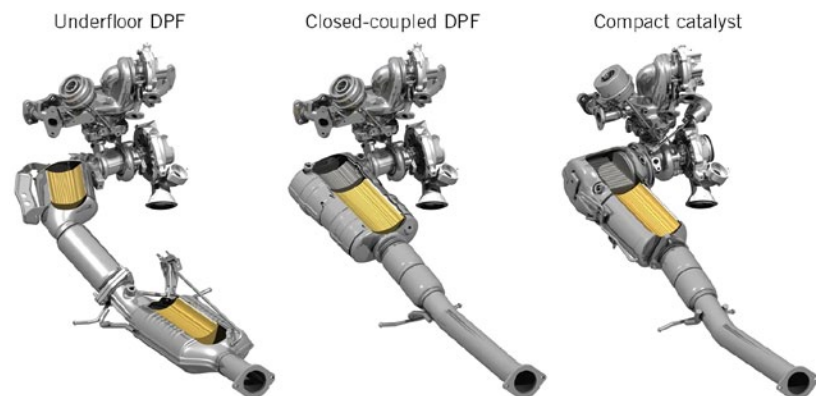
The exhaust aftertreatment systems in modern vehicles is becoming more and more complex driven by emission legislations and the manufactures strive for making green cars for image and public requests. The Compact Catalyst system



7 Exploded view of assembly subcomponents: gasoline Euro 6 (left), gasoline SULEV30 (middle), diesel Euro 6 (right)



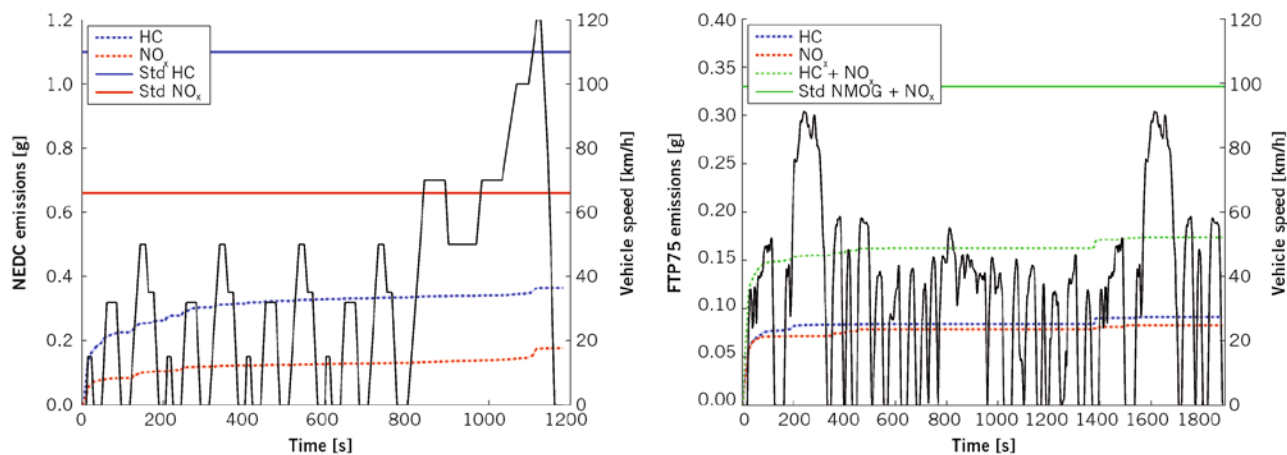
8 The new installation liberates space in under floor position



9 Pressure drop calculated in CFD for different Volvo diesel aftertreatment systems

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, 8. One sub system that is expected to take advantage of this is the battery of future electrified vehicles.

Fuel consumption is an important factor 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 characterised by less weight impact and the smaller size provides benefits for other subsystem to contribute to fuel economy. 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.



10 Accumulated HC and NO<sub>x</sub> emissions in NEDC (Euro 6) and FTP75 (SULEV30) for gasoline engines together with the emissions standards (in the FTP75 chart the 10 min soak has been suppressed, the bar for the NMOG+NO<sub>x</sub> standard depicts SULEV30 as 30 mg/mi × 11 mi)

## RESULTS: BACK PRESSURE AND EMISSIONS

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. This was confirmed in a full load engine test showing significant improvement compared with existing products (four-, five- and six-cylinder gasoline engines).

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 utilisation and improved soot regeneration. With the close-coupled DPF of the current five-cylinder diesel variants a draw-back 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, 9. In addition the Compact Catalyst volume benefit brought that the desired NO<sub>x</sub> trap could fit and successfully meet Euro 6.

The Compact cat can be used to design high-end emissions systems for SULEV30 requirements as well as cost-efficient systems at the Euro 6 level. Accumulated emissions for gasoline application for two such systems are displayed in 10.

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, the fact that the second substrate is so close to the engine reduces the cooling down during engine shut-off (e.g. 80 K less than an under-floor installation during the FTP75 soak), which is beneficial for start/stop and hybrid applications.

## 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 l) 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 gain from an improvement in warming-up emissions. The inlet cone is straight minimising temperature losses. The first substrate volume is maximised 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 close-coupled and under-

floor catalyst would bring. The achieved LNT volume on the diesel variants is essential for its emission performance.

Moreover, 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 allows for liberated space, which could be used, for instance, in case subsystems for electrification are needed.

## REFERENCES

- [1] Crabb, D. C.; Fleiss, M.; Larsson, J-E.; Somhorst, J.H.E.: New Modular Engine Platform from Volvo. In: MTZ 74 (2013), No. 9, pp. 632-640
- [2] Johansson, C.; Laurell, M.; Brück, R.: Exhaust gas treatment device for use near engine. Pat. DE 10 2009 024 718, Germany
- [3] Laurell, M.; Dahlgren, J.; Karlfo, M.; Althöfer, K.; Brück, R.: A Metal Substrate with Integrated Oxygen Sensor; Functionality and Influence on Air/Fuel Ratio Control. SAE 2003-01-0818
- [4] Laurell, M.; Dahlgren, J.; Väisänen, J.: The Volvo S40/V50 PZEV MY2007 with an Optimized 2.4-l Engine. SAE 2007-01-1260

## THANKS

To this article there have been large contributions from Staffan Ovesson, Mats Lundgren and Christoffer Håkansson (Volvo) as well as Katrin Konieczny and Manuel Presti (Emitec). The suppliers Faurecia, NGK, Corning and Johnson Matthey have contributed significantly to the realisation of the Compact Catalyst.