Aftertreatment in a Pre-Turbo Position: Size and Fuel Consumption Advantage for Tier 4 Large-Bore Diesel Engines

Dipl. Ing. Claus **Brüstle**, M. Sc. Markus **Downey**
Emitec Inc., Rochester Hills, MI, USA

M. Sc. Mark **Subramaniam**, B. Eng. Aaron **Birckett**, Dr. Dean **Tomazic**,
FEV Inc., Auburn Hills, MI, USA

Summary

As the implementation of the EPA Tier 4 legislation in 2014 fast approaches, the manufacturers of large bore diesel engines are faced with a dilemma: The stringent emissions limits mandated by the Tier 4 legislation require large, heavy and expensive emissions control systems. This stands in stark contrast to limited packaging space, weight and cost constraints for these systems. Elegant ways of saving space, weight and cost are therefore needed.

One approach to save space, weight and cost is to place an exhaust gas aftertreatment system upstream of the turbo-charger. Based on robust metal catalyst substrates, several advantages can be realized: the higher temperatures upstream of the turbo-charger yield a faster light-off of the catalysts, leading to a reduction of pollutants at lower engine power levels. The higher pressures along with the higher temperatures make the catalyst system more efficient and allow for significant down-sizing potential of the aftertreatment system. Placing the flow restriction associated with the aftertreatment system up-stream of the turbo-charger reduces the impact of the flow restriction on the engine and yields an advantage in fuel consumption. The negative impact that a pre-turbo aftertreatment system has on the transient response is largely mitigated, since large-bore diesel engines run primarily under steady state conditions or in vehicles with very slow transients compared to typical on-highway engine applications.

The paper will highlight the differences in placing an aftertreatment system in the pre- and post-turbo positions on a 35 liter diesel engine using a GT Power simulation approach. The aftertreatment system consists of an oxidation catalyst, a partial flow particulate filter and an SCR catalyst for nitrous oxide reduction. Exhaust gas recirculation (EGR), which is a commonly used technology on EPA Tier 4-compliant engines, is considered as part of this study as well. The effects of the placement of the aftertreatment system on the cost, size and fuel consumption are investigated.

1 Introduction

Legislation curbing the emission of exhaust gas pollutants on gasoline and heavy-duty on-road diesel engines are yielding some of the cleanest engines ever produced. Regulators are now focusing their attention on applications where greater reductions in exhaust pollutants are possible.

Large-bore engines are mainly in the non-road and locomotive sectors where previous legislation levels were met using engine management. Upcoming Tier 4 legislation that will take effect for non-road engines in 2014 and for locomotives in 2015 will require the implementation of exhaust aftertreatment systems similar to those used on on-road engines for US EPA 2010 legislation to reduce emissions of hydrocarbons (HC), carbon monoxide (CO), nitrous oxides (NO & NO_2) and particulate matter (PM). Figure 1 shows the development of the PM and NO_x standards for non-road engines > 560 kW:

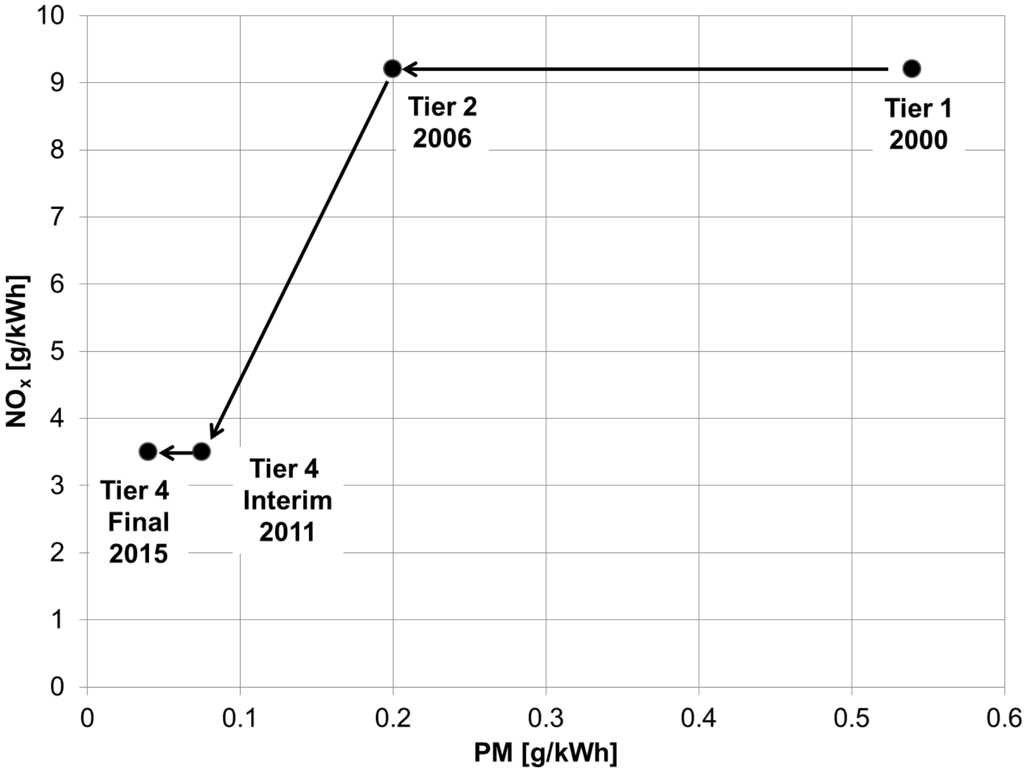

Figure 1: Development of PM and NO_x limits in EPA standards for non-road, large-bore diesel engines >560 kW [1]

Based on the displacement of the engines in question, these aftertreatment systems will be large, heavy and expensive. As an example, Electromotive Diesel Corporation (EMD) has recently shown a concept that combines a diesel oxidation catalyst (DOC), diesel particulate filter (DPF), selective catalytic reduction (SCR) and ammonia slip catalyst (ASC) for a locomotive Tier 4 system [2]. This system that includes HC injection for active regeneration of the DPF and urea injection for SCR is shown to be 4.2 meters in length. Any technology that could reduce the size of the aftertreatment system would be of great interest and value. Figure 2 shows a modern line-haul freight locomotive that will be affected by the upcoming legislation.

Figure 2: Modern line-haul locomotive that will require an aftertreatment system under the upcoming EPA Tier 4 legislation

One such technology is to place the aftertreatment system upstream of the turbo-charger. The concept of placing at least a portion of the aftertreatment system upstream of the turbo-charger has been suggested in previous publications [3,4] and has been implemented on large-bore diesel engines [5] in an experimental setup. There are a number of benefits to placing the aftertreatment system in the pre-turbo position:

First, the temperatures in the pre-turbo position are higher than in the post-turbo position. Temperature plays an important role since the aftertreatment system will not function below what is called light-off temperature. The light-off temperature is reached at lower engine power in the pre-turbo position [6]. Figure 3 shows an exemplary temperature comparison of the pre and post-turbo positions:

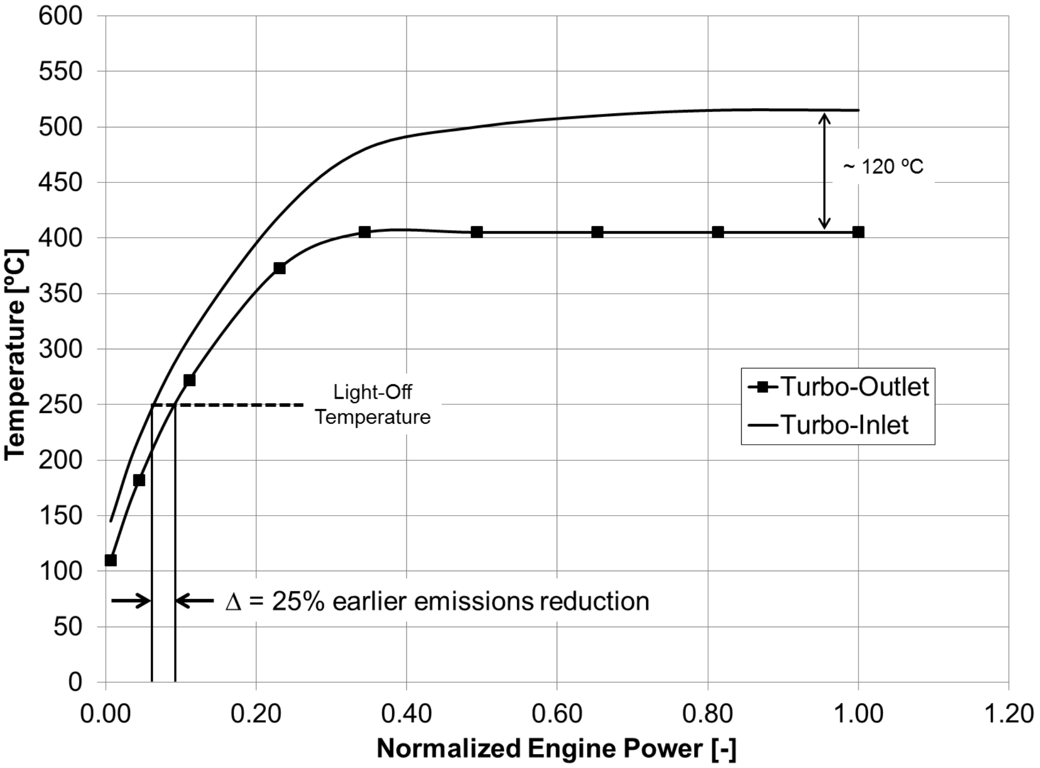

Figure 3: Comparison of generic pre- and post-turbo temperatures of a large-bore diesel engine

The light-off temperature of the aftertreatment system is reached at about 25% lower engine power in the pre-turbo position as well as having a higher temperature level at higher engine power settings.

The second benefit is a reduced impact on the fuel consumption of the engine. The turbo-changer has a turbine expansion ratio that will amplify any flow restriction that is placed down-stream. To better illustrate this point, figure 4 shows an example of a flow restriction that is placed in the pre- and post-turbo positions:

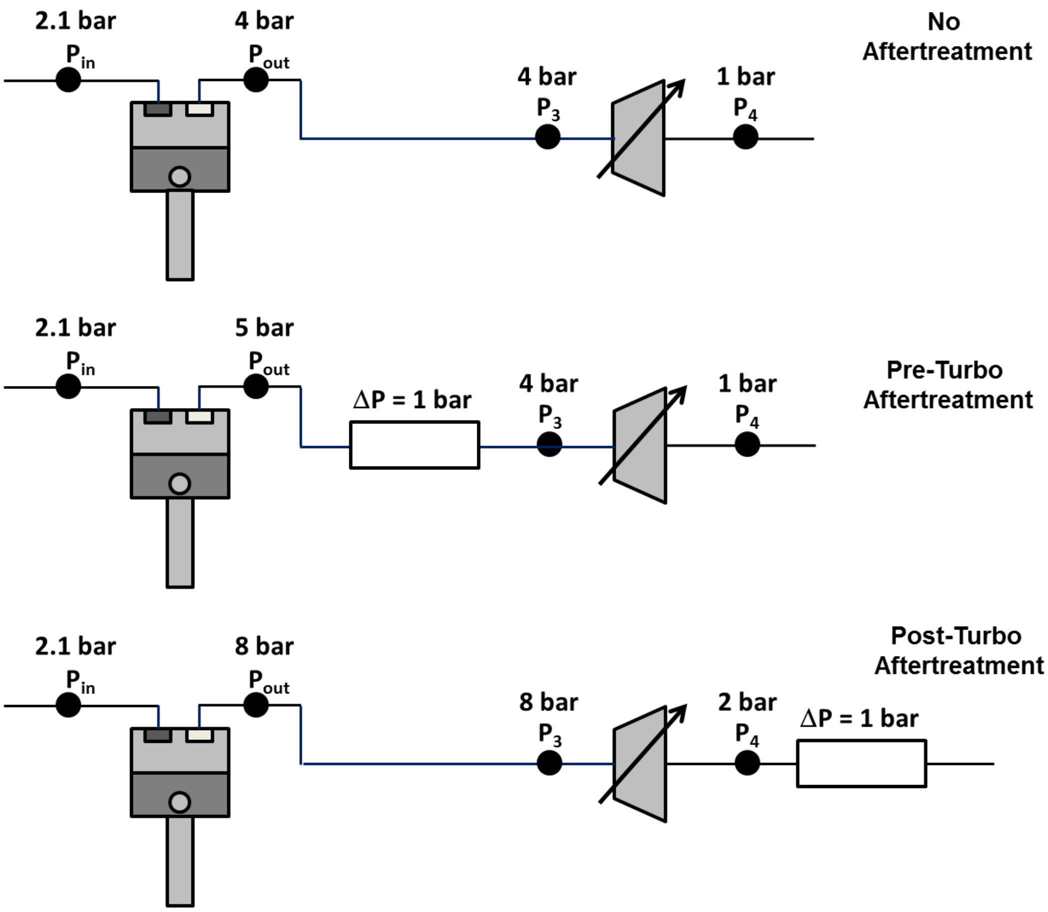

Figure 4: Impact of the flow restriction of the aftertreatment system on the total engine back pressure

In the top case of figure 4 there is no aftertreatment system on the engine. The turbo outlet pressure (p4) is approximately atmospheric pressure (1 bar). With a turbine expansion ratio of 4, the turbine inlet pressure (p3) will be 4 bar, which is the pressure that the engine has to pump against to exhaust the cylinders. The middle case in figure 4 is an aftertreatment system with a flow restriction of 1 bar that is placed in the pre-turbo position. P4 is still 1 bar and p3 is still 4 bar. When the 1 bar pressure drop of the aftertreatment system is added, the outlet of the cylinders will be at 5 bar. The bottom case of figure 4 is the traditional post-turbo position. Here the 1 bar flow restriction is added to the 1 bar of atmospheric pressure to yield 2 bar behind the turbo-charger (p4). In order to maintain the required compressor power, the turbine expansion ratio is maintained at 4. P3 is now 8 bar, requiring more power to exhaust the cylinders. This additional energy manifests itself in higher fuel consumption, due to higher pumping losses and lower engine power.

Potential challenges in implementing a pre-turbo aftertreatment system are for one the harsher environment (higher temperatures, temperature transients, gas pulsations) that the components are exposed to. The most robust components available must be implemented as any loss of substrate material will have dire consequences for the longevity of the turbo-charger blades. Also, the additional thermal mass of the aftertreatment system has an impact on the transient response of the engine. The aftertreatment system has to be heated up, which reduces enthalpy for the turbine in this condition. This fact has been discussed in the literature [7] and makes the pre-turbo aftertreatment concept especially applicable to engines that run at steady-state or where transient response is of secondary concern.

2 Components of the Aftertreatment System

The major pollutants from diesel engines are unburned hydrocarbons (HC), carbon monoxide (CO), nitrous oxides (NO & NO_2) and particulate matter (PM). Different components of the aftertreatment system address each of these pollutants.

Metal substrate technology is the ideal choice for pre-turbo applications. The metal foils used for the matrix offer thin walls while still maintaining a robust substrate. 65µm or 80µm foil thicknesses are used for pre-turbo applications, while thinner foils (50µm and thinner) can be applied in post-turbo applications. The substrate is delivered “pre-canned” in an outer tube or mantel. The mantel can be used to integrate the substrate into the aftertreatment system. No additional matting is required for retention. Figure 5 shows an example of an Emitec substrate:

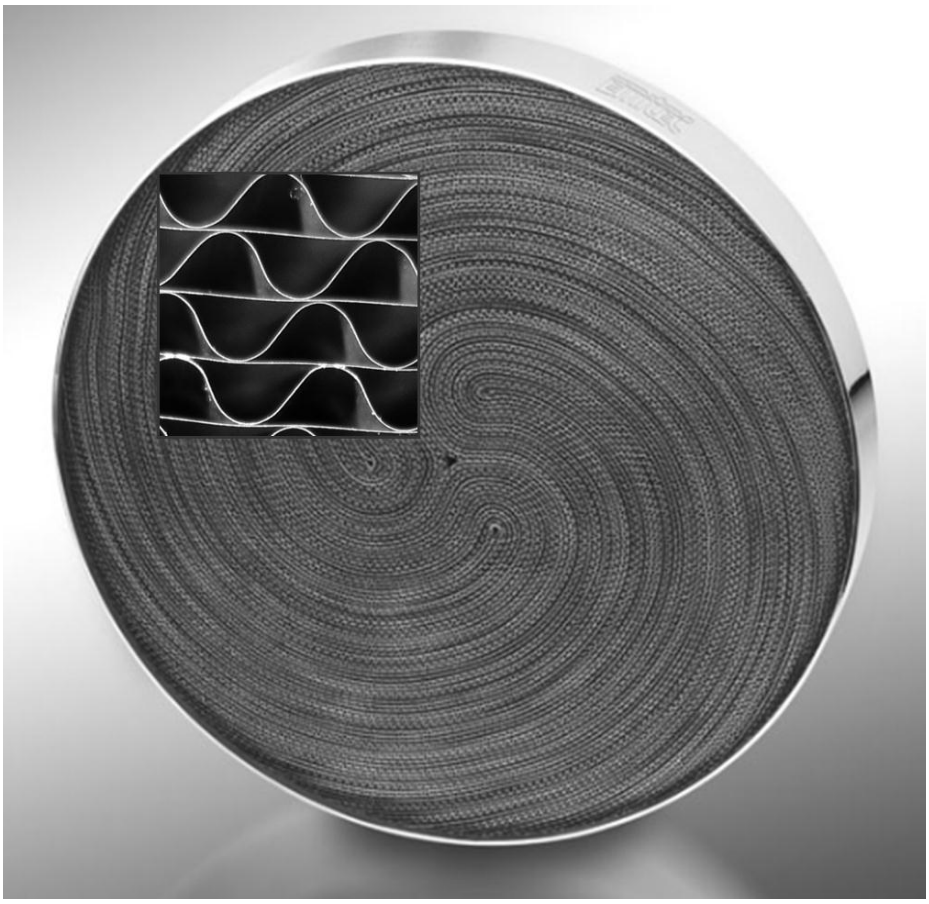

Figure 5: Emitec’s metal substrate and thin foil technology for use in pre-turbo applications

To provide the required robustness for a transient, mobile application, the substrate is brazed in two areas: First, the foil material is high temperature brazed within the front and rear face of the substrate as shown in figure 6. This bonds all the foil layers together to provide stability; secondly, the matrix is brazed to the mantel to retain the matrix within the mantel.

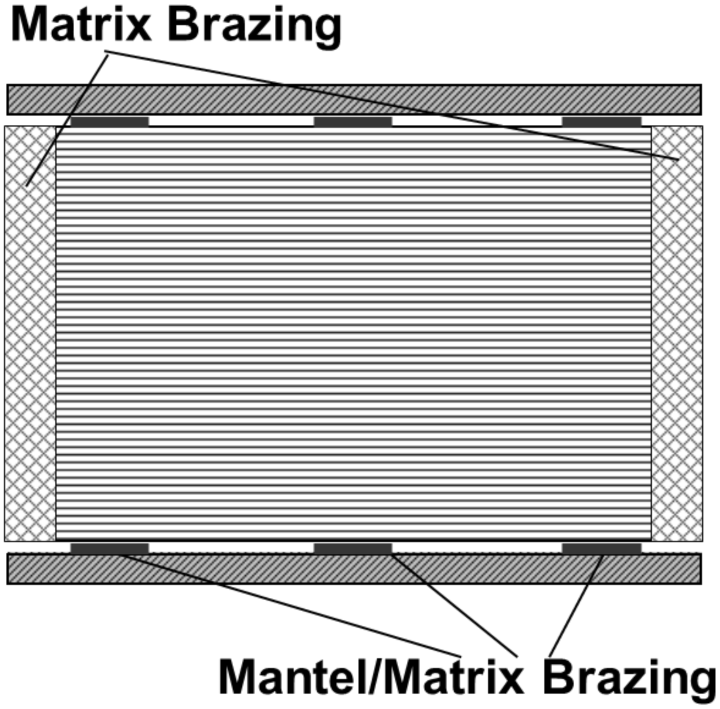

Figure 6: Areas of brazing within an Emitec substrate [8]

These substrates are used for different functions, depending on what kind of active coating is applied for the application.

Diesel Oxidation Catalyst (DOC)

The diesel oxidation catalyst (DOC) oxidizes HC to CO_2 as well as oxidizing CO to CO_2. Additionally, the amount of NO_2 can be increased, which is important for the passive regeneration of the particulate filter and to facilitate the Fast-SCR reaction in the SCR catalyst. Given the high flow velocities and therefore favourable mass-transfer conditions seen in the pre-turbo position, the standard channel structure gives the best balance between low flow restriction and conversion efficiency. However, in the post-turbo position DOC size optimization can be accomplished by application of Emitec’s turbulent foil structures like the longitudinal structure (LS), as was successfully demonstrated for a US EPA2010 compliant heavy-duty diesel on road engine family [9]. Figure 7 shows the flow characteristics of standard and LS® foil technology.

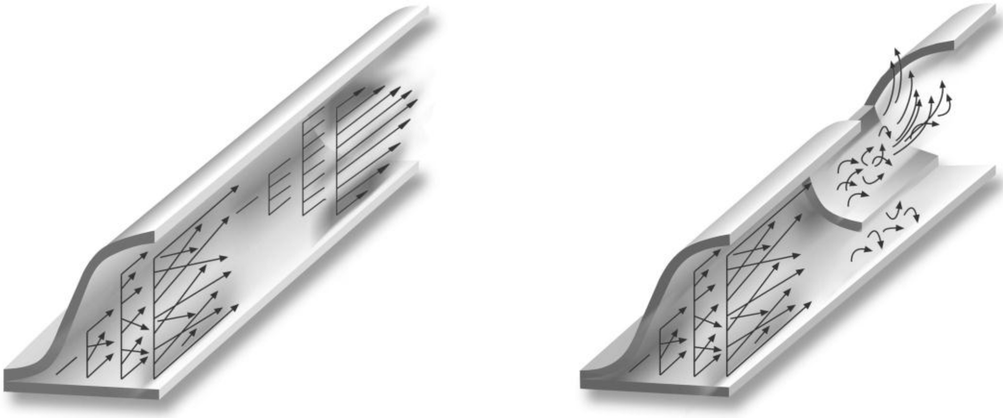

Figure 7: Structure of standard (on left) and longitudinal (LS®) foil technology

Particulate Reduction

The reduction of particulate matter is another important function in the aftertreatment system. With the oxidation of HC by the DOC some simultaneous reduction of particulate matter will take place. To facilitate the required reduction of PM a particulate filter device is usually required. The PM-Metalit partial-flow filter has been in serial production for OEM and retrofit applications since 2004 and is an attractive device for pre-turbo aftertreatment systems. Using the same robust construction as other Emitec substrates the PM-Metalit uses a sinter metal fleece to filter and store soot. Blades in the channels deflect the exhaust flow into and through the fleece layers. As there are multiple blades per channel, depending on the length of the substrate, the exhaust gas will have multiple contacts with the filter medium. Figure 8 shows the internal structure of the PM-Metalit:

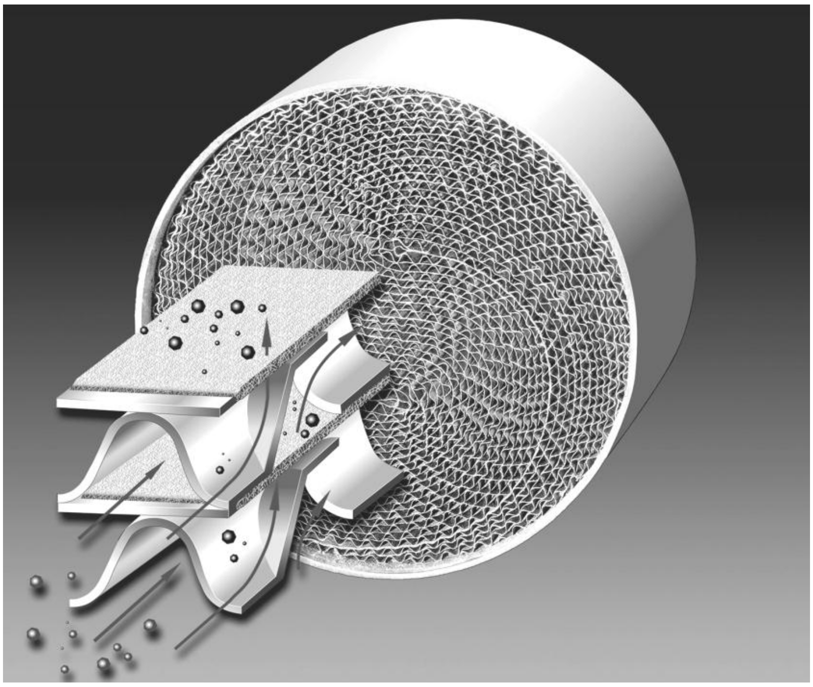

Figure 8: Internal structure of PM-Metalit substrate

The sizing of the PM-Metalit is also different than that of a DPF, which is usually sized for ash storage capacity. To get sufficient aerodynamic forces to redirect the flow into the fleece, there needs to be sufficient flow velocity in the channels. A velocity of 15 m/s at rated condition has been shown to be a good compromise for the functionality over the operating range. This flow velocity will dictate the frontal area of the PM-Metalit device. The length of the PM-Metalit will dictate the filtration efficiency. The longer the substrate, the higher the filtration efficiency. Unlike wall-flow DPF systems that need to be actively regenerated periodically by means of a burner system or hydrocarbon injection, the PM-Metalit is continuously, passively regenerated with NO_2 from the upstream DOC. Passive regeneration works well on these devices since the exhaust gas has multiple contacts with the soot. The continuous regeneration not only reduces the amount of equipment needed on the exhaust system but also reduces the back pressure variations associated with a soot accumulating and then actively regenerated DPF.

Selective Catalytic Reduction (SCR)

The reduction of oxides of nitrogen (NO & NO_2) requires the use of ammonia as a reactant. Since there can be health and safety issues with the storage of ammonia in mobile applications, urea is used as a precursor. The urea is injected into the exhaust stream and evaporates. The vaporized urea is then converted to ammonia in either in the SCR catalyst or in a dedicated hydrolysis catalyst. The ammonia reacts with the NO_X in the SCR catalyst creating nitrogen gas and water.

One configuration that is advantageous when a PM-Metalit is used in conjunction with an SCR system is known as the SCR Integrated system or SCRi system. Here the PM-Metalit is coated with a hydrolysis coating and takes on three functions: 1) continuous particle reduction, 2) droplet evaporation and 3) hydrolysis of urea to ammonia [10]. Figure 9 shows the layout of an SCRi system.

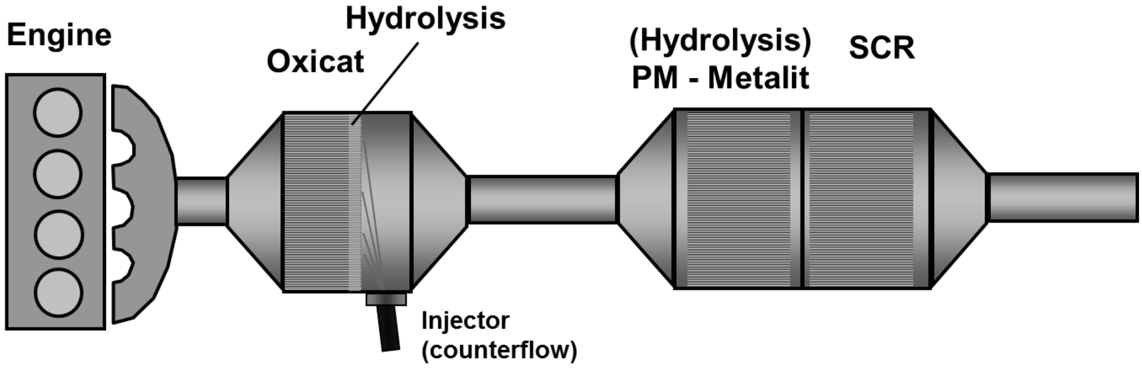

Figure 9: Layout of an SCRi system [10]

3 Simulation

The analysis of the placement of the aftertreatment system was performed by FEV Inc. using 1D engine performance software GT Suite Version 6.2. The models are based on a large bore, 35L, V8 diesel engine (~ 1000 hp) with one turbo-charger per cylinder bank and have been correlated to test data. Aftertreatment systems were then added to the correlated model in the locations identified. Figures 10 and 11 show the model layouts of the pre- and post-turbo aftertreatment systems respectively.

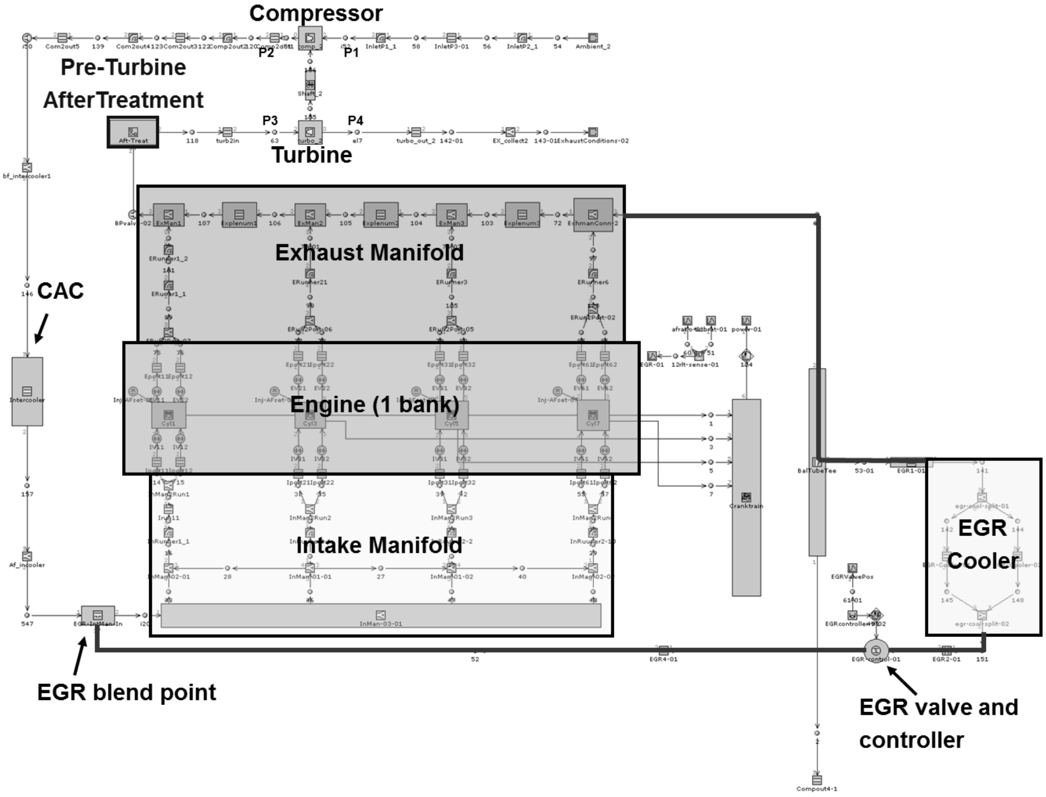

Figure 10: Layout of pre-turbo aftertreatment configuration model in GT Power [11]

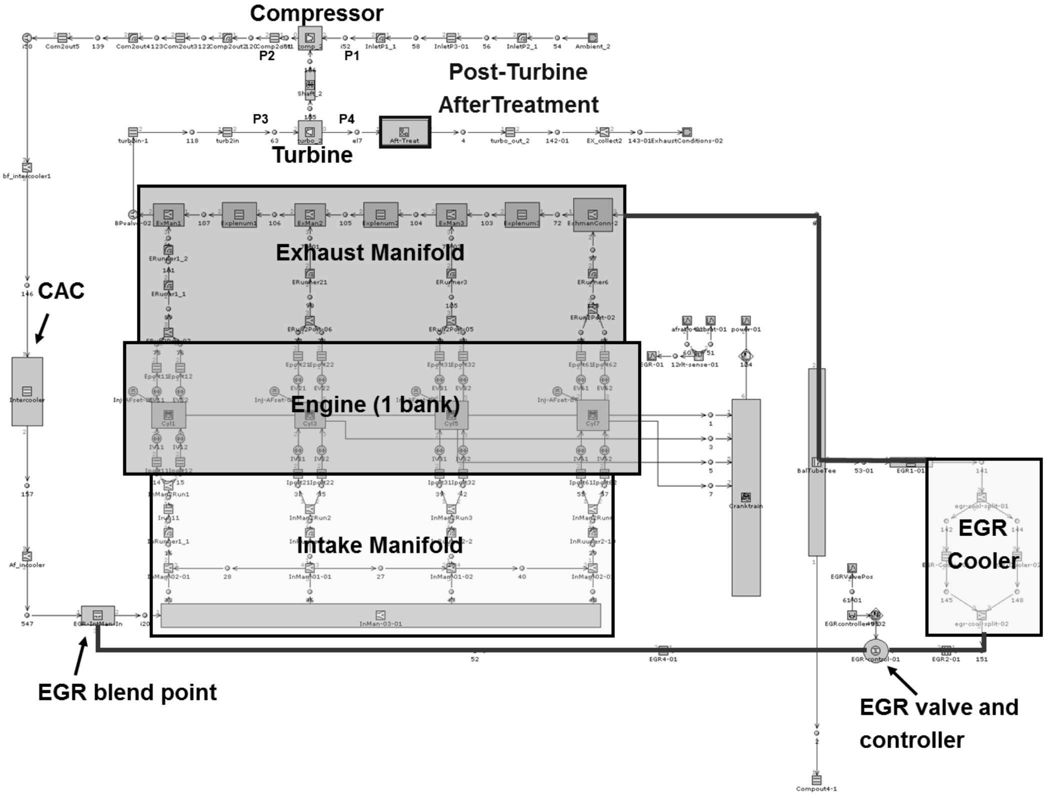

Figure 11: Layout of post-turbo aftertreatment configuration model in GT Power [11]

The models are run at a specific minimum air fuel ratio (AFR) at each engine speed, injecting fuel until the ratio is reached. This AFR limit is dictated by the desire to maintain efficient combustion system performance, and to remain below visible smoke limits. Power of the engine is controlled by opening or closing of the turbocharger wastegate to direct exhaust gas through or around the turbine. This boost-based control is later used to compensate for losses or gains associated with different aftertreatment placement options, so that engine power can be maintained. This then allows a fair comparison of fuel efficiency from concept to concept, as power and air fuel ratio are constant between concepts.

The model also featured high pressure, cooled EGR. EGR levels at full load did not exceed 15%. The philosophy embraced for the combustion and aftertreatment systems was modest in-cylinder NO_x relief with use of EGR and injection timing measures to maintain a stable burn and reasonable combustion efficiency. The remainder of the emissions reduction was executed via aftertreatment measures. The target emissions compliance for this engine was Tier 4 final status (2015) [10]. Figure 12 shows the EGR rate and air-fuel ratio at the simulated engine operating points.

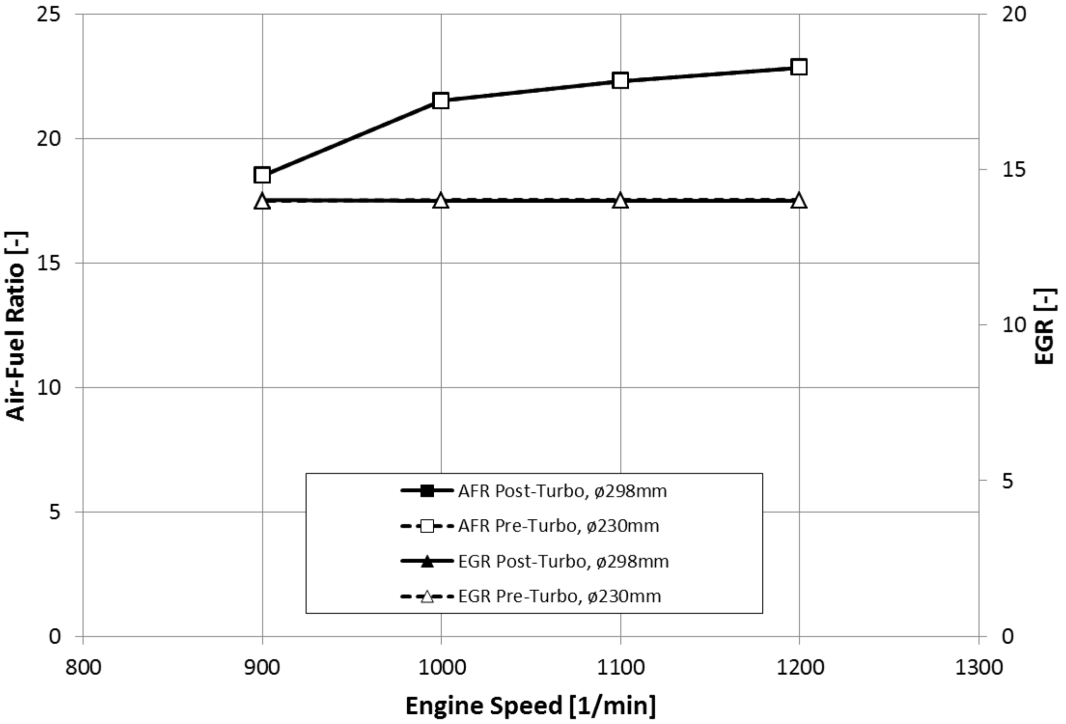

Figure 12: Comparison of air-fuel-ratio and EGR rate for the pre- and post-turbo aftertreatment systems

4 Results and Discussion

As shown in part 2, the functionality of the PM-Metalit depends on the channel velocity. Based on the widely varying flow conditions across the operating range of a typical application, the sizing of the PM-Metalit is usually a compromize. A larger diameter is needed to keep the flow restriction as low as possible at high loads while still guaranteeing sufficient channel velocities at part loads. One result from the simulation was that the channel velocity in the PM-Metalit in the pre-turbo position is approximatly constant throughout the operating range. This is because the gas density increases with increasing load, offsetting the increased mass flow. In the post-turbo position the gas density is about constant, resulting in an increasing channel velocity with increasing load. Figure 13 shows the gas densities and channel velocities for the pre- and post-turbo configurations, while figure 14 shows the pressure drops of the pre- and post-turbo aftertreatment systems throughout the engine operating range.

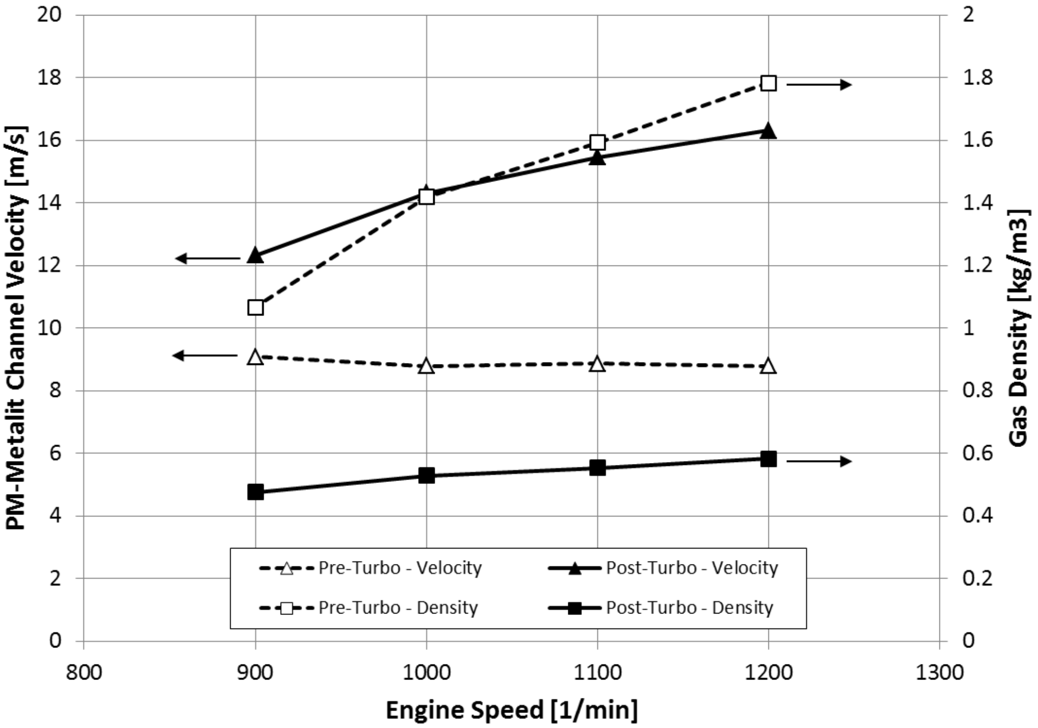

Figure 13: Gas density and PM-Metalit entrance velocity for pre- and post-turbo aftertreatment system configurations

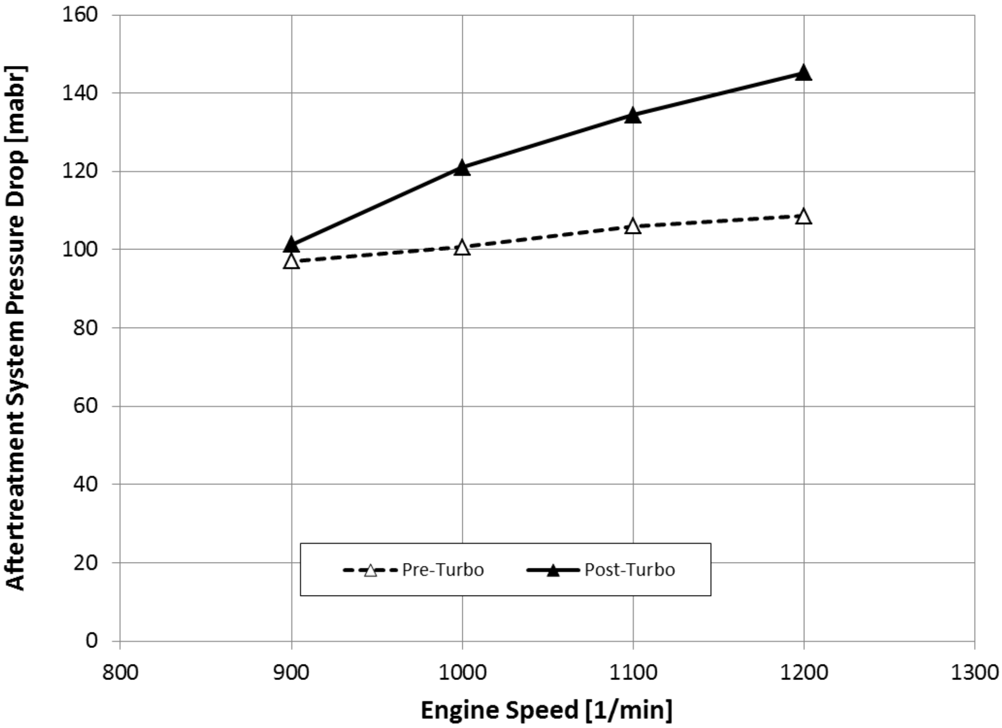

Figure 14: Pressure drop of aftertreatment systems in pre- and post-turbo position

As a result of the constant channel velocity in the pre-turbo position, the pre-turbo aftertreatment system can be optimized for a single channel velocity. A channel velocity of 8 m/s has been shown to still yield good filtration efficiency. This dictates a PM-Metalit substrate diameter of 230mm for the pre-turbo position. Based on the variable channel velocity, the PM-Metalit of the post-turbo aftertreatment system still needs to be laid out in the usual manner and yields a substrate diameter of 298mm. The same PM-Metalit substrate length is kept for both pre- and post-turbo systems to have comparable filtration efficiencies.

The DOC and SCR substrates were laid out to yield the same mass transfer performance as described in the literature [12]. Substrate diameters were kept the same as the PM-Metalit substrates in the respective positions. The substrate lengths were kept the same for both the pre- and post-turbo systems. The pre-turbo aftertreatment system is shown in figure 15 to be about 40% smaller than the post-turbo system. Figure 16 shows a comparison of the pre- and post-turbo system weights on a per cylinder bank basis. Included in both are cones and a mixing tube in front of the SCR catalyst. The pre-turbo aftertreatment system yields a 28% weight advantage over the post-turbo system. The weight advantage of the pre-turbo system is less than the volume advantage due to the increased foil thickness which is applied due to the higher mechanical and thermal loads on the pre-turbo substrates.

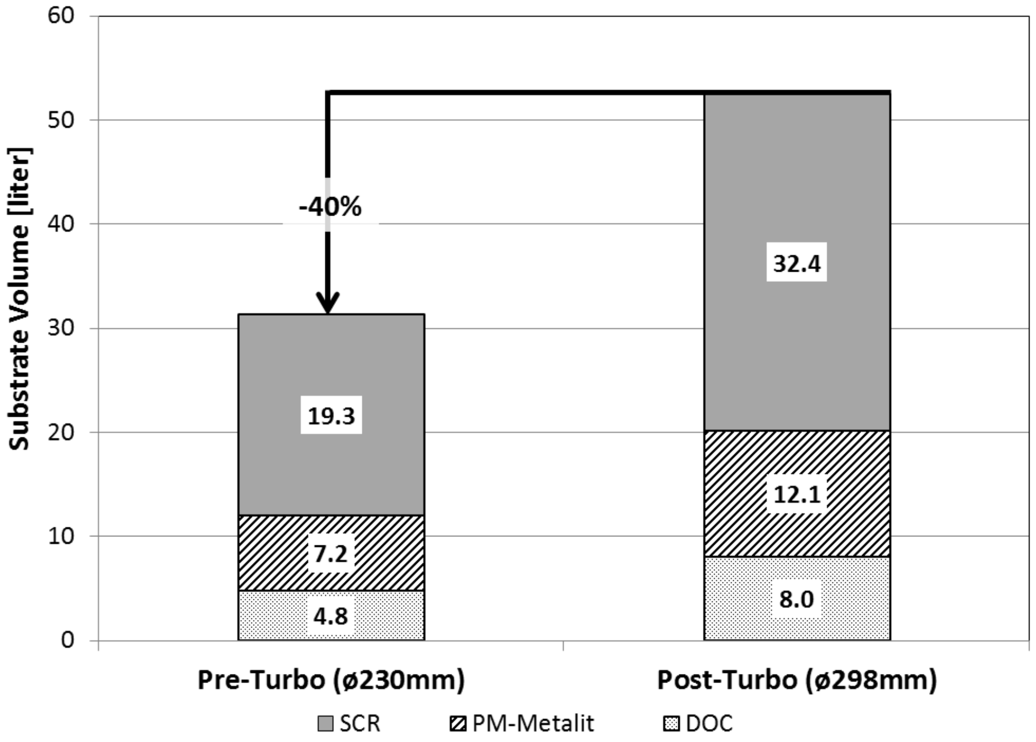

Figure 15: Comparison of pre- and post-turbo aftertreatment system sizes

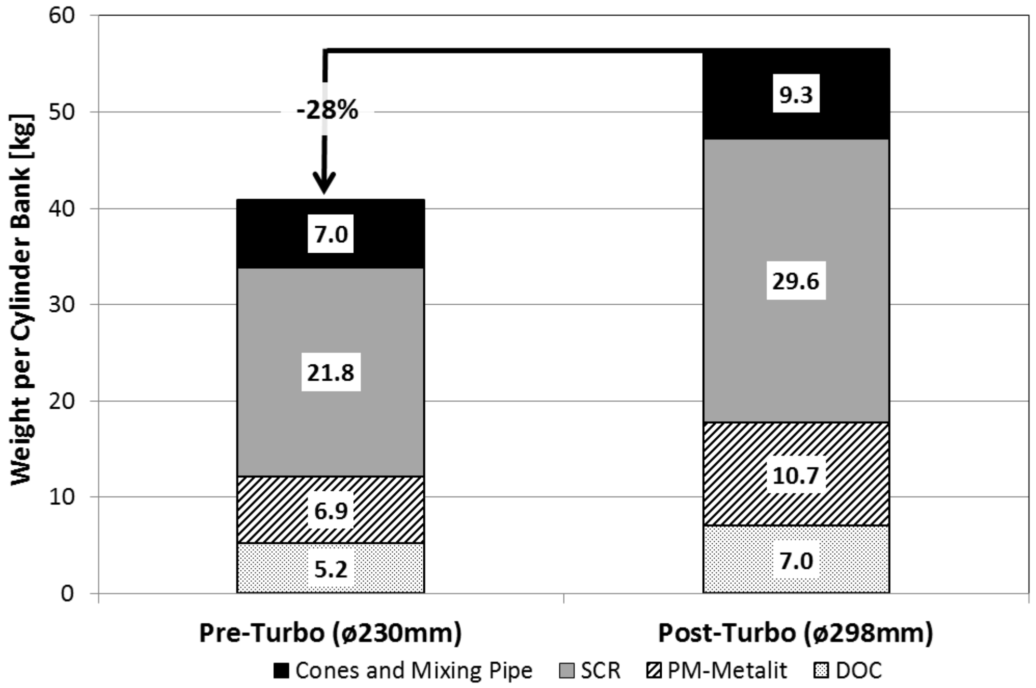

Figure 16: Weight comparison of pre- and post-turbo aftertreatment systems per cylinder bank.

For both the pre- and post-turbo aftertreatment system cases, the turbo-chargers had to be optimized for the new flow conditions. Figures 17 and 18 show the compressor and turbine maps for the optimized turbo-charger.

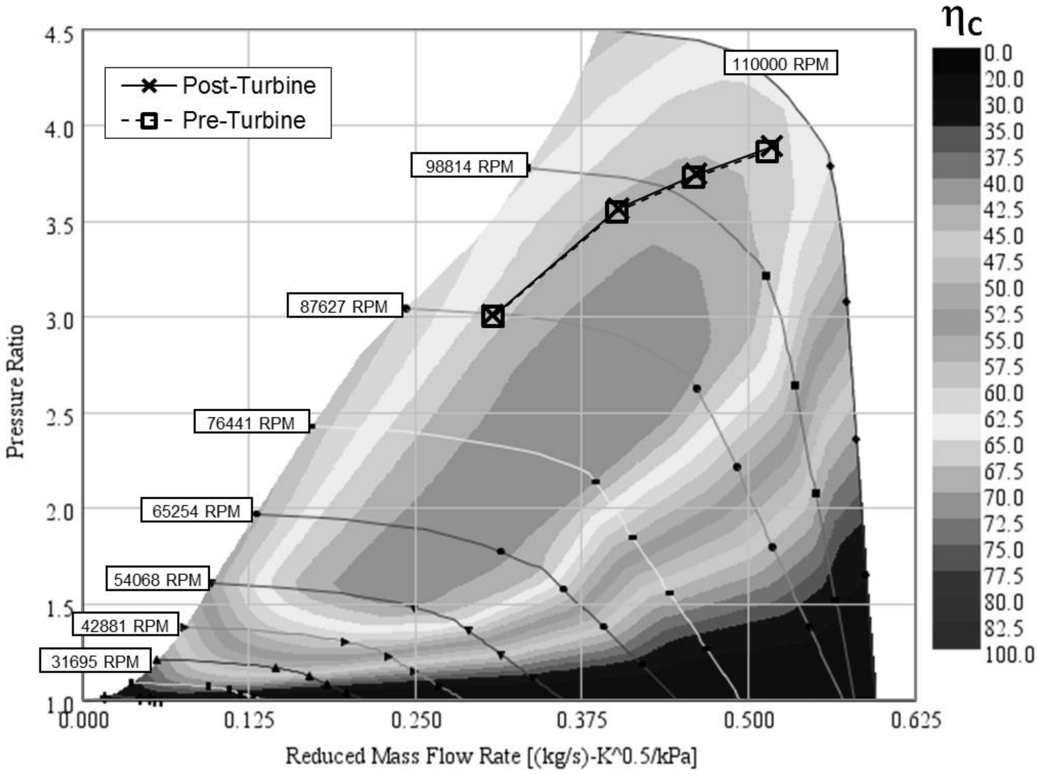

Figure 17: Compressor map for the optimized turbo-charger

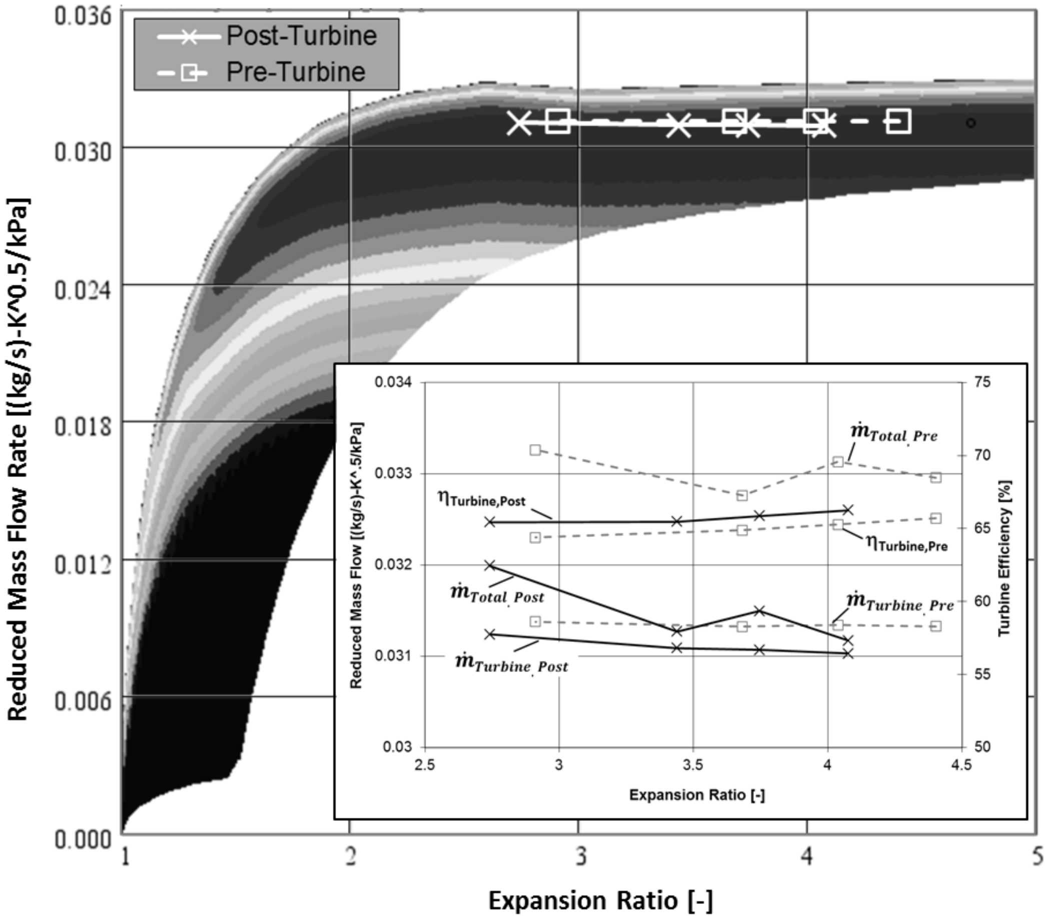

Figure 18: Turbine operating points, pre- vs. post-turbo

The much lower ratio of turbine mass flow to total mass flow seen with the pre-turbo configuration, shows that a larger turbine could potentially be selected for this configuration, increasing turbine throughput and efficiency. This implies that there is potential for further fuel consumption improvements with the pre-turbo system

Figure 19 shows the difference in turbine inlet pressure vs. crank angle. As shown the fluctuations of p3 for the pre-turbo case are much smaller than in the post-turbo case.

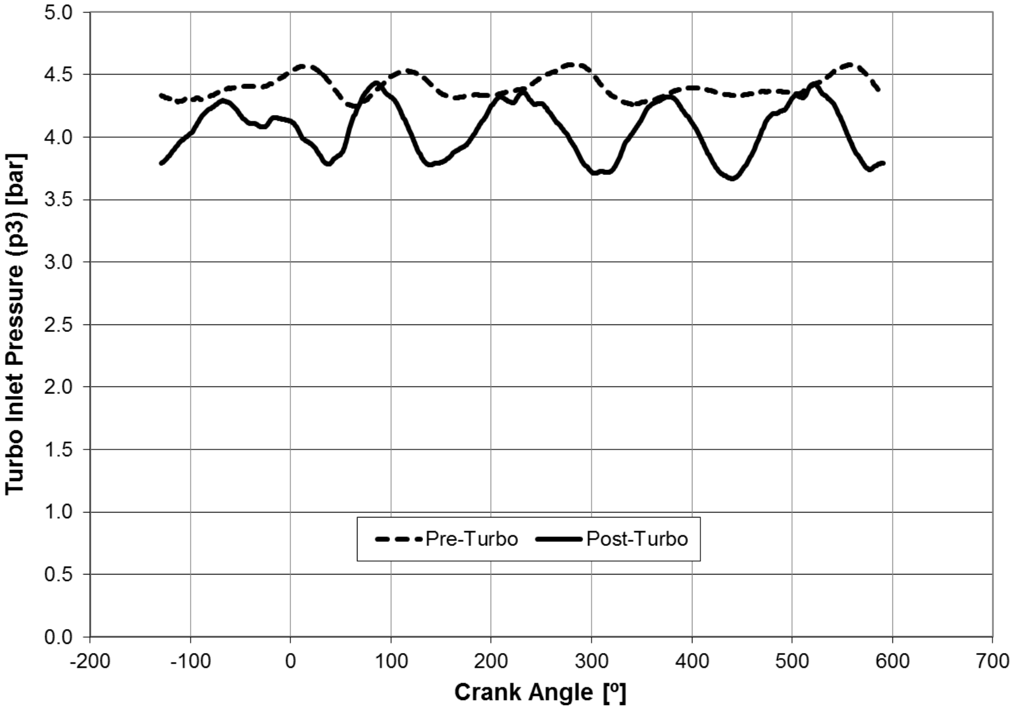

Figure 19: Turbine inlet pressure (p3) as a function of aftertreatment system placement

With the aftertreatment in the pre-turbo position the turbocharging system works rather as a “constant-pressure” system as compared to more of a “pulse-turbocharging” system with the aftertreatment in the post-turbo position. This again suggests that further optimization can be carried out in terms of turbine sizing for improved back pressure and subsequent BSFC improvement.

The theoretical pumping loss benefit of the placement of the flow restriction relative to the turbo-charger was shown in figure 4 above. This is in addition to the 40% size advantage for the pre-turbo aftertreatment system as shown in figure 15. The impact of the placement of the flow restriction was simulated in this project. Figure 20 shows the fuel consumption with the pre- and post-turbo aftertreatment systems with a clean (unloaded) PM-Metalit. What is clearly shown is that the pre-turbo aftertreatment system leads to a fuel consumption advantage over the post-turbo aftertreatment system. This advantage ranges from 0.03% at low load to 0.68% at high load. The fuel consumption advantage with the pre-turbo system increases as the PM-Metalit gets loaded with soot. A typical soot loading for the PM-Metalit during operation is 4 g/liter of substrate volume.

Figure 21 shows the relative fuel consumption improvement of the pre- over the post-turbo aftertreatment system when the PM-Metalit is loaded with 4 g/liter. The benefit for the pre-turbo system ranges from 0.4 to 0.76% for the loaded case.

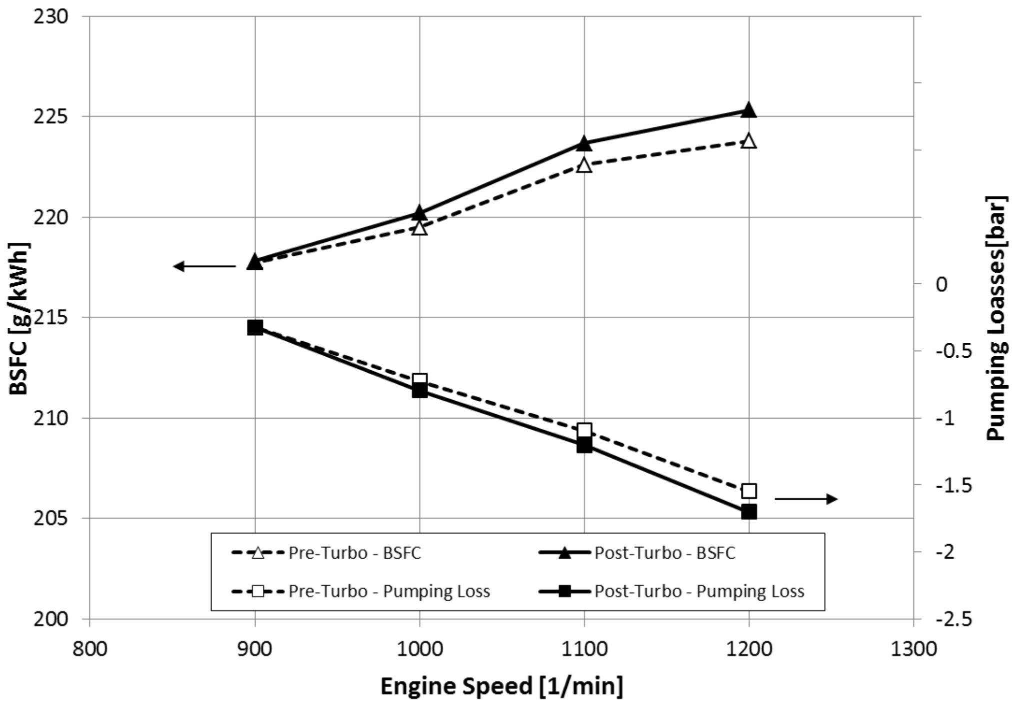

Figure 20: Fuel consumption and pumping losses of pre- and post-turbo aftertreatment systems in unloaded condition

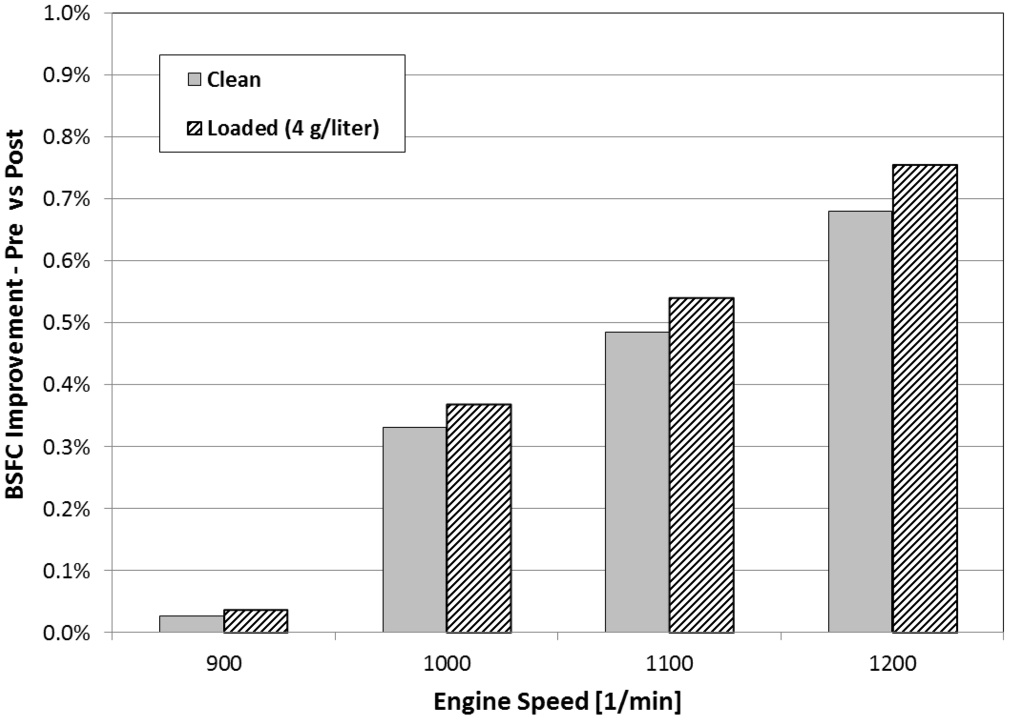

Figure 21: Improvement in fuel consumption of pre- vs post-turbo aftertreatment system placement in loaded and unloaded conditions

While these percentages seem small, over the operational life of a large-bore engine a few percent improvement yields a substantial fuel cost savings and CO_2-reduction for the environment. It has to be kept in mind that the improvement in fuel consumption is in addition to the system volume, material and substantial weight reduction of the pre-turbo system, which leads to further cost advantages.

This leads to the trade-off between aftertreatment size reduction (capital cost) and fuel consumption advantage (operating cost). The example shown above has an advantage of both fuel consumption and system size. Depending on what kind of cost is important for a given application, the sizing of the pre-turbo aftertreatment system could be different. Figure 22 shows different pre- and post-turbo aftertreatment system sizes (represented here by the diameter of the substrates in the system) and their associated fuel consumption (operating cost). Also shown are the system cost (capital cost) relative to the ø298mm post-turbo system. Depending on the specific targets, either maximum BSFC-improvement or maximum aftertreatment system size reduction can be accomplished in comparison to the traditional post-turbo aftertreatment strategy.

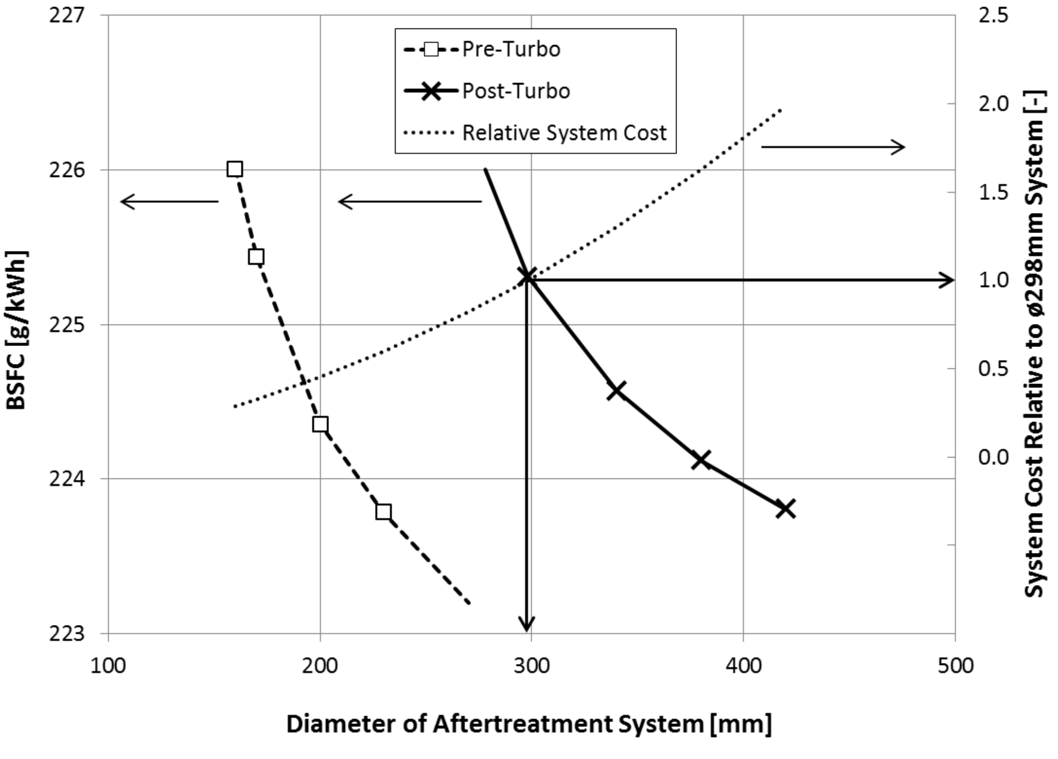

Figure 22: Fuel consumption, system size and system cost trade-off for pre- and post-turbo aftertreatment systems at equal emissions reduction performance

5 Conclusion

The benefits of placing an entire aftertreatment system (DOC+PM-Metalit+SCR) upstream of the turbo-charger of a large-bore diesel engine was simulated using GTPower. The use of robust metal substrate technology for DOC, SCR and particulate filtration in the pre-turbo position offers a reliable, cost, weight and size optimized solution. A pre-turbo aftertreatment system was shown to have a 40% smaller volume and resulting in up to a 0.75% fuel consumption advantage over a traditional post-turbo system. Further, the trade-off between system size (system cost) reduction and fuel consumption (operating cost) advantage can be used in order to optimize the system for the specific application to either lower BSFC or substantial aftertreatment system size reduction compared to the conventional arrangement with the aftertreatment system downstream of the turbo-charger. The pre-turbo system clearly outperforms as an overall more environmentally friendly systems approach.

6 References

Please list all your references using the following pattern:

[1] Dieselnet.com
Emissions Standards, United States, Non-Road Engines
http://www.dieselnet.com/standards/us/nonroad.php

[2] VANTUONO, W.
How motive power boosts productivity
Railway Age, May 2011, p 17-24
New York, 2011

[3] BRÜSTLE, C., et al
Katalysatortechnologie für zukünftige Abgasgrenzwerte
15. Wiener Motorensymposium
Wien, 1994

[4] SUBRAMANIAM, et al
Feasibility Assessment for a Pre-turbo After-Treatment System with a 1D Modeling Approach
SAE World Congress 2009
Detroit, 2009

[5] OSBORNE, M., et al
Exhaust Emissions From a 2,850 kW EMD SD60 Locomotive Equipped with a Diesel Oxidation Catalyst
Joint Rail Conference & Internal Combustion Engine Spring Technical Conference
Colorado, 2007

[6] ZELLBECK, H., et. al.
Ein Vollkatalysatorsystem vor Abgasturbolader; Auslegung, Berechnung und Untersuchungen am Motorprüfstand
14. Aufladetechnische Konferenz
Dresden, 2010

[7] CODAN, E., et al.
IMO III Emission Regulation: Impact on the Turbocharging System
CIMAC Congress 2010
Bergen, 2010

[8] ALTHOEFER, K., et al.
Metallkatalysatoren – Bauteil- und Schadensanalyse im Fokus innovativer Designentwicklung
VDI
Wuerzburg, 2007

[9] KRAMER, J., et al
Development And Practical Experience Of A 2010 Compliant HD Diesel Engine And Aftertreatment System
20th Aachen Colloquium ”Automobile and Engine Technology”
Aachen, 2011

[10] RICE, M., et al.
NOX Aftertreatment for Passenger Cars and Heavy Duty Truck Applications for EU 6 and EUVI/US2010 Legislation
SAE World Congress 2009
Detroit, 2009

[11] SUBRAMANIAM, M., et al.
Pre-Turbo Aftertreatment Position for Large Bore Diesel Engines – Compact & Cost-Effective Aftertreatment with a Fuel Consumption Advantage
SAE World Congress 2011
Detroit, 2011

[12] BLANCHET, S., et al.
Implementation of the Effectiveness-NTU Methodology for Catalytic Converter Design
SAE World Congress 1998
Detroit, 1998