

**LARGE ENGINE AFTERTREATMENT IN A PRE-TURBINE POSITION:  
A PATH TO COMPACT AND COST-EFFECTIVE EMISSIONS REDUCTION**

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**ABSTRACT**

With the impending implementation of the Tier 4 emissions standards in the non-road and locomotive sectors, exhaust gas aftertreatment systems will be needed on applications that previously did not require it. Based on the fact that the displacement of these engines is very large, the aftertreatment systems will also be relatively large, heavy and expensive. Additionally, even in these large engine applications, packaging space and systems cost is at a premium.

Placing a robust metal aftertreatment system up-stream of the turbo-charger offers an elegant solution to these issues. The higher temperatures and faster temperature rises before the turbine yield faster light-off and better emissions performance. The higher gas density allows the total size of the aftertreatment system in the pre-turbine position to be substantially smaller for a given conversion efficiency, leading to a remarkable packaging and cost benefit of up to 64%. Additionally, by placing the flow-restriction of an aftertreatment system upstream of the turbine, a fuel consumption benefit in the pre-turbine position can be realized as pumping losses of the engine are reduced. The largely steady-state operation of these large engines negates the heat sink effect of the pre-turbine catalytic converters in transient operating conditions.

This paper will investigate the benefits of placing an oxidation catalytic converter and partial-flow particulate filter up-stream of the turbo-charger on the fuel consumption of a stationary engine in the 30-35L class by simulation with GT-Power. Different locations for the aftertreatment package as well as optimized sizing for the different locations are investigated to identify the optimum solution for the engine. In addition to the fuel consumption benefits, the cost and weight advantage of the smaller pre-turbine system is emphasized. This view of both the technical and commercial side of the

applications, demonstrates a clear advantage for the pre-turbine arrangement of the metal emissions reduction components on large bore engines.

**CURRENT PRE-TURBINE CATALYSTS WORK**

The concept of placing catalytic converters up-stream of the turbo charger is not new. [1] Using a pre-turbine catalytic converter (PTC) has been demonstrated many times in engines ranging from light-duty to heavy-duty and non-road engines. These efforts have been motivated by two main ideas: First, using a small catalytic converter volume in the pre-turbine position can help to reduce the overall size of the aftertreatment system. A relatively small catalytic converter can yield high conversion efficiencies due to the high temperatures and specific mass flows (i.e. good mass transfer) in the pre-turbine position. However, a post-turbo catalytic converter is still needed to achieve the overall required conversion efficiency. A reduction of the overall size of the aftertreatment system can already be achieved with a split-volume (pre- & post-turbine). There have been limited publications on the concept of placing the entire oxidation catalytic converter volume up-stream of the turbo-charger. [2,3] The second motivation is the high temperatures and fast temperature rises in front of the turbo-charger. A catalytic converter needs to be heated to a certain temperature level (250 to 350°C) in order for the conversion of exhaust gas pollutants to take place. In the turbo-charger energy is extracted from the exhaust gas stream and used to compress the intake air to increase the power of the engine. During start up and at low temperature operation, the turbine acts as a heat sink and leads to delayed conversion of exhaust pollutants. Placing the catalytic converter in the pre-turbine position will allow for fast heat-up, i.e. earlier conversion of pollutants and functioning of the catalytic converter at lower load operation. This consideration is especially important when looking at future legislation levels (EPA 2010 & Tier 4) and test cycles (World Harmonized Test Cycle). The emission limits on

the future regulations are very stringent and the newer test cycles tend to run at very low exhaust temperatures. Both make the implementation of an effective aftertreatment system challenging. Figure 1 shows an example of the exhaust temperatures in the pre and post-turbo positions over the engine load in a large-bore engine. The temperature in the pre-turbine position reaches the catalytic converter light-off temperature of about 250°C at a 25% lower engine power level than the post-turbo position.

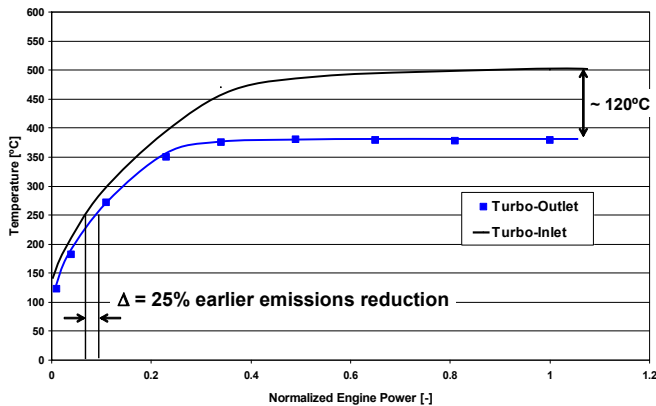


Figure 1: Catalytic converter Light-Off Advantage for Aftertreatment System in Pre-turbine Position

The main challenge with using pre-turbine catalytic converters has been its negative impact on transient response of the engine due to the heat sink effect. Light-duty applications (i.e. passenger cars) rely on the transient response of the engine to yield good drivability. On large stationary or locomotive engines the issues of fast transient response is not as critical. Either the engines are running at steady-state for most of their operating life (stationary engines) or the load changes from one operating point to the other are slow (locomotives). When transient response is not a key issue, the concept of pre-turbine aftertreatment offers many tangible benefits.

The position of the aftertreatment system up-stream of the turbo-charger makes the mechanical durability of the catalytic converter system a key consideration. The robust nature of the metal substrate, which is made of stainless-steel foil that is brazed into a tube or mantel, makes them suitable for placement in the pre-turbine position. The tube that the metal substrate is brazed into can be welded right into the exhaust system, no additional canning steps or materials are required.

## THEORETICAL REASONING [4,5]

Aftertreatment location has a direct impact on engine and turbocharger performance. This is affected by two primary factors, which are local gas density and impact on turbine expansion ratio.

The post-turbine aftertreatment system sees significantly lower gas densities than the pre-turbine aftertreatment system. This is because the exhaust gas has already expanded through the turbine in the post-turbo configuration and is at a significantly lower pressure. The gas temperature also decreases but the reduction in pressure is more drastic than the reduction in temperature. From the ideal gas equation of state, falling pressure results in a density reduction. The temperature fall dampens this reduction somewhat but pressure changes are more significant. Lower density results in higher volume flow rates and, for the same diameter geometry and substrate density, a consequent increase in pressure drop.

The second influencing factor is the turbine expansion ratio. For simplicity assume that the configurations are sized to have equivalent pressure drops for both the pre-turbine and post-turbine configurations. If this were done, it might look like comparable performance will be achieved by both engine setups. The pre-turbine setup would see a direct restriction of exhaust ports which would raise the pumping work necessary during exhaust strokes. The post-turbo setup would experience a reduction in expansion ratio, which would then require waste gate adjustment to compensate, which would then also raise the exhaust port pressures and aggravate pumping work. If this were true, approximately the same BMEP for both configurations is expected because the same pressure drop was experienced in the exhaust system, only at different locations. This, in reality, is not true. A more detailed analysis shows that a post turbine restriction is far more detrimental than a pre-turbine restriction. Figure 2 illustrates a simple example. Assume an initial  $P_3$  of 4 bar, and a nominal  $P_4$  of 1 bar for a system with no aftertreatment. The expansion ratio across the turbine is given by  $P_3/P_4$  which equals 4 in this case. Assume that the pressure drop through the aftertreatment system is fixed regardless of where it is placed (i.e. no sensitivity to gas properties). This pressure drop is assumed to be equal to 1 bar. In a pre-turbine configuration, this would have the effect of raising the pumping back pressure from 4 bar to 5 bar. The turbine expansion ratio stays the same. For a post-turbo setup,  $P_4$  will be raised to 2 bar. The expansion ratio is now reduced from 4 to 2. This lost expansion ratio can be gained back by increasing  $P_3$  by 1 bar. With  $P_3$  of 5 bar, and  $P_4$  of 2 bar, an expansion ratio of only 5/2 or 2.5 can be achieved. In order to get back to the expansion ratio of 4,  $P_3$  would have to be increased to 8 bar. That would result in a pumping back pressure of 8 bar. So the same pressure drop of 1 bar results in a 1 bar exhaust back pressure penalty when the aftertreatment system is upstream of the turbine, and an extremely significant

4 bar penalty when it is located downstream of the turbine (for the same expansion ratio).

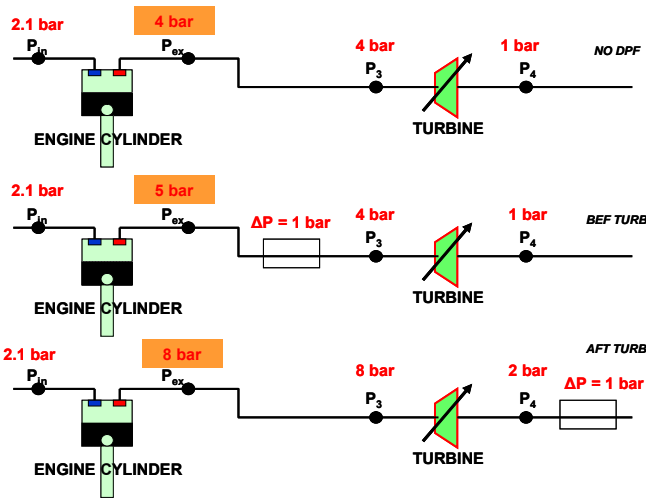


Figure 2: Theoretical aftertreatment effect on back pressure

Given the pressure drop in both locations, these phenomena show distinct theoretical benefits to a pre-turbine aftertreatment system as compared to its post-turbine counterpart. Many other factors need to be taken into account, such as functional requirements of the aftertreatment and actual turbine behavior. This is where simulation allows us to take a more detailed look.

### AFTERTREATMENT SYSTEM COMPONENTS

The major emissions of concern from diesel engines are unburned hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO & NO<sub>2</sub>) and particulate emissions (PM). A diesel oxidation catalyst (DOC) is used to oxidize the HC and CO emissions of the engine to carbon dioxide and water. The DOC will also enrich the amount of NO<sub>2</sub> in the exhaust gas. The NO<sub>2</sub> is important for the operation of the PM-Metalit, partial-flow particulate reduction device, explained in the following paragraphs, for passive regeneration.

In the DOC application, the longitudinal (LS) structure can be used to reduce the size of the DOC substrate. The blades that are rolled into the corrugated layer enhance the mass transfer within the catalytic converter channel, increasing the efficiency of the entire catalytic converter. [6] Based on this increased efficiency, the catalytic converter in a DOC application can be reduced in volume by up to 30% for a given emissions reduction performance. Figure 3 shows the internal design of the LS structure.

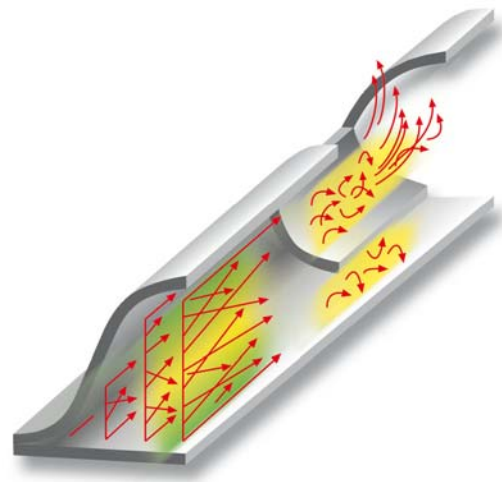


Figure 3: Internal Design of Longitudinal Structure

In addition to the use of an oxidation catalytic converter, a PM-Metalit is used to reduce the particulate emissions from the engine. The PM-Metalit is a partial-flow particulate filtration device that is continuously and passively regenerated, that has been in use in many OEM and retro-fit applications since 2004. [7]

Like all Emitec substrates, the PM-Metalit is constructed of alternating layers of flat and corrugated layers as seen in Figure 4.

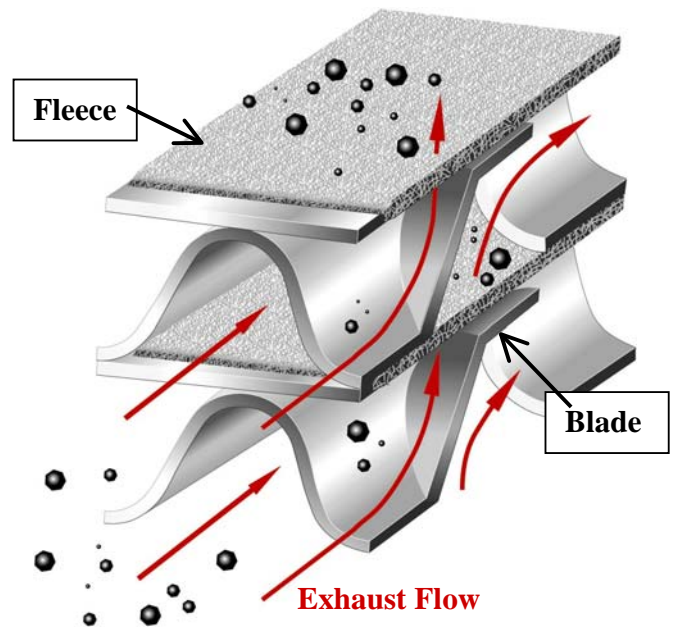


Figure 4: Internal Design of PM-Metalit [4]

The flat layer is made of a metal fleece. The corrugated layer has blades rolled into the channels that redirect the gas flow into the fleece layer. As the gas flow passes through and along the fleece layer, soot is deposited into the fleece. This stored soot is then catalytically oxidized with  $\text{NO}_2$  (passive regeneration) from the upstream DOC. The storage and oxidation of the soot will reach equilibrium for a given operating point. Since there are multiple blades along the channel of the substrate, the exhaust gas will have multiple contacts with the fleece layer. This allows for a much better utilization of  $\text{NO}_2$  for passive regeneration in the PM-Metalit than in a traditional wall flow filter. [8] The burn-off of soot by means of a fuel burner or injection of additional diesel fuel into the exhaust system is not required. This means that there is a stable back pressure for a given engine operating point in addition to fuel saving.

An important aspect in the layout of the PM-Metalit is to have the correct aerodynamic forces in the channels of the substrate. When the flow velocity in the channels is sufficient, the flow will be redirected into the fleece layer and the soot stored there. If the duty cycle of the application is transient, a compromise needs to be found. A channel velocity of 15 m/s at rated condition is usually targeted as the layout criteria. This will give good filtration through out the operating range. The channel velocity is set by specifying the diameter of the PM-Metalit under the flow conditions at rated condition.

The reduction of oxides of nitrogen ( $\text{NO}_x = \text{NO} + \text{NO}_2$ ) emissions from the engine requires some additional technology. The main technology that is being investigated for heavy-duty and large-bore engines is urea SCR. In addition to the coated substrates, which facilitate the  $\text{NO}_x$  reduction, aqueous urea has to be injected into the exhaust stream. The urea is converted to ammonia, which reduces the  $\text{NO}_x$ . The temperature at which this  $\text{NO}_x$  reduction reaction takes place is critical. Here again the higher temperature level and faster heat-up of the aftertreatment system in the pre-turbine position is an advantage as well as the potential for down-sizing due to the better mass transfer within the catalytic converter. The issue of flow distribution and mixing length will have to be addressed separately.

Urea can be injected upstream of a PM-Metalit with a hydrolysis coating. In this configuration, called SCR<sub>i</sub>, the PM-Metalit takes on three functions: continuous particulate reduction, hydrolysis of urea to ammonia and enhanced evaporation of urea. [9] The SCR<sub>i</sub> yields an efficient and cost-effective aftertreatment system.

This paper will focus on the DOC and PM-Metalit parts of the aftertreatment system.

## SIMULATION SETUP

The 1D simulation software GT Suite version 6.2 was used to conduct the aftertreatment placement analyses. Figure 5 and Figure 6 show the layouts and pressure measurement locations of the pre-turbine and post-turbine exhaust aftertreatment systems studied in the analyses. The models are based on a large bore, 30-35L, V8 diesel engine (~ 1100 kW) 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 shown.

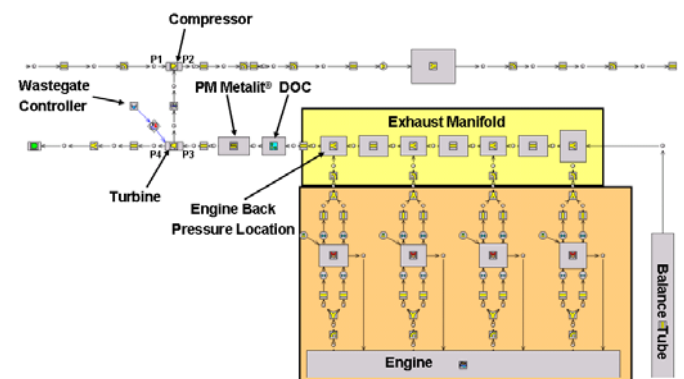


Figure 5: Pre-turbine system layout

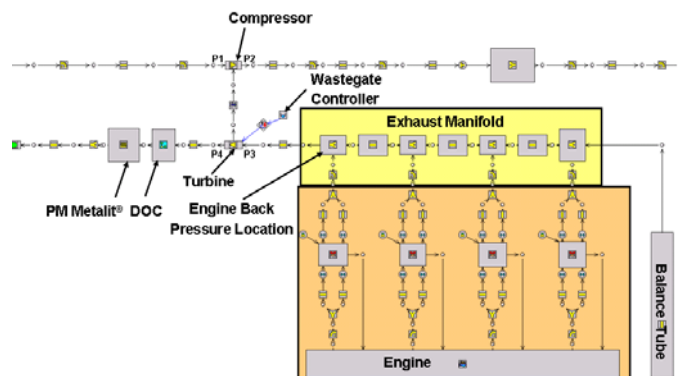


Figure 6: Post-turbine system layout

The original engine model piped the exhaust into a wide-open stack. This is not realistic for a locomotive or stationary engine with an aftertreatment system. To find the correct exhaust piping diameter several large bore engines were surveyed for their pre- and post turbo-charger piping diameters. Figure 7 shows the survey results and the chosen piping diameter for the model.

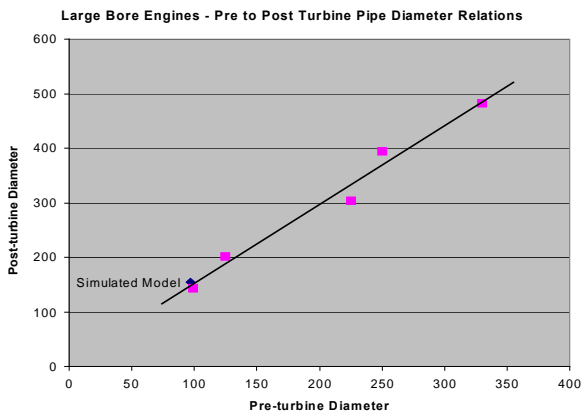


Figure 7: Optimization of Exhaust Piping Diameter of GT Power Engine Model, based on Survey of Existing Large Bore Engines

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 the wastegate to divert exhaust gas around or through the turbine. Closing the wastegate forces more exhaust gas through the turbine, increasing the amount of air pumped into the engine, and thereby the fuel and power. Opening the wastegate bypasses the turbine, reducing the engine power.

Increased restriction of the aftertreatment on the exhaust system requires the turbine to compensate by producing more power. The turbine of the base engine does not have the reserve required to maintain the AFR once the aftertreatment is added, so a turbine is needed to provide higher pressure ratios with a given mass flow rate. The same turbo with waste-gate was used for the after-treatment in the pre- and post-turbine position. For this study, the mass flow of the base engine turbine map is scaled down to provide higher pressure ratios at a given mass flow rate. This emulates a smaller turbine, which would have a lower efficiency. The efficiency was also scaled down in the turbine map by a factor based on benchmarking of similar turbines. Figure 8 shows the adjusted turbine map with the original.

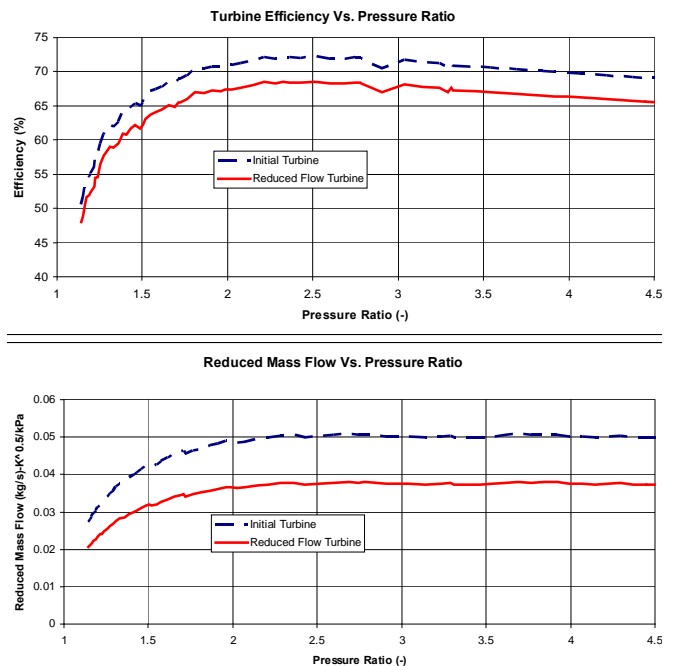


Figure 8: Turbine map adjustments

## SYSTEM COMPARISONS

The first set of aftertreatment systems investigated compares a pre-turbine system of diameter 173mm to a post-turbine system of diameter 298mm. These have equal velocities through the aftertreatment at 1200 rpm (Figure 9). In this configuration, the pre-turbine system has approximately 58% the diameter and 64% the volume/cost of the post-turbine system. With these diameters, the post turbine system has 0.5-1 g/kW\*hr lower fuel consumption (Figure 10).

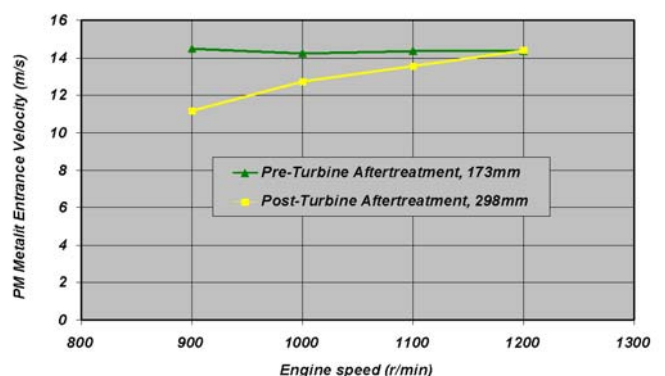


Figure 9: Aftertreatment entrance velocities

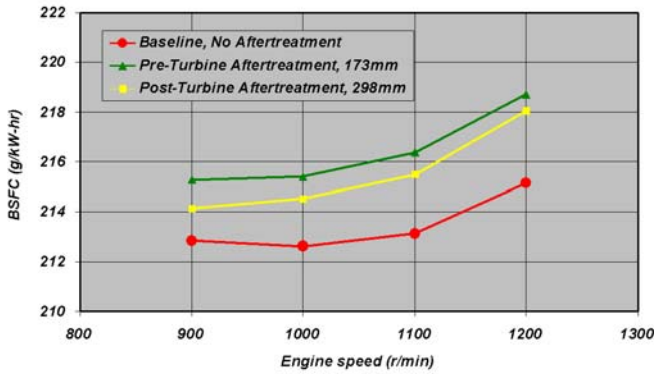


Figure 10: Clean filter fuel consumption comparison, equal max velocities

Figure 11 shows how the BSFC and aftertreatment velocities at 1200 rpm change as the diameter of the pre-turbine aftertreatment is increased. Increasing the pre-turbine system diameter to approximately Ø180mm gives equivalent fuel consumption as the Ø298mm post-turbine system, while the aftertreatment velocities drop to 13.5 m/s.

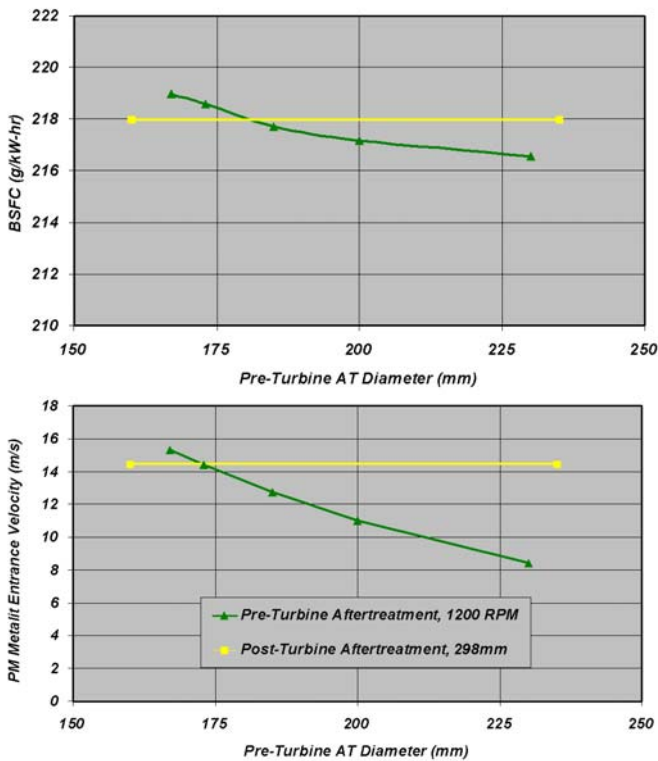


Figure 11: Pre-turbine velocity tradeoff for fuel consumption

In Figure 9 above, the velocity of the pre-turbine case is essentially constant, while the post-turbine velocity increases

with engine speed. This is due to the pressure increasing with mass flow before the turbine, which increases the density of the exhaust gas. Figure 12 plots the density of both cases with the velocity. The increasing density of the pre-turbine case holds the velocities constant as the mass flow increases. This constant velocity allows the pre-turbine aftertreatment diameter to be optimized for a lower velocity instead of compromising to allow for varying velocities.

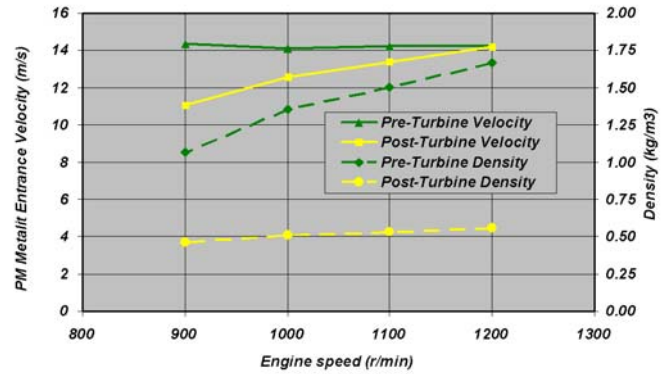


Figure 12: Constant velocity with increasing density

The constant velocity of the pre-turbine arrangement allows the aftertreatment diameter to be increased while maintaining emissions reduction performance. This reduces the velocity (Figure 13) and pressure drop through the aftertreatment. Figure 14 shows the resulting fuel consumption benefit. The pre-turbine system now has both lower fuel consumption and a smaller packaging space requirement than the post-turbine system. As the filter becomes loaded with soot (Figure 15), the pre-turbine fuel consumption benefit over the post-turbine increases.

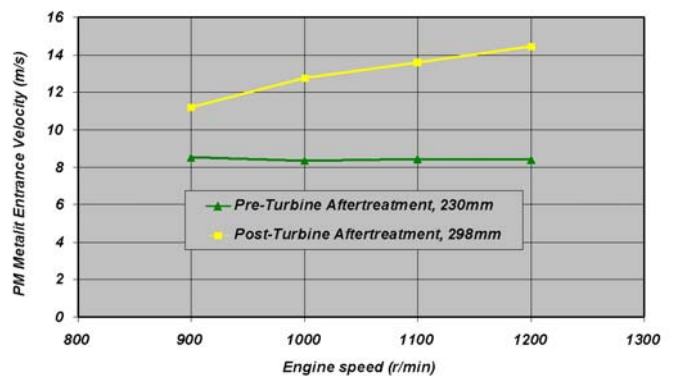


Figure 13: Aftertreatment entrance velocities

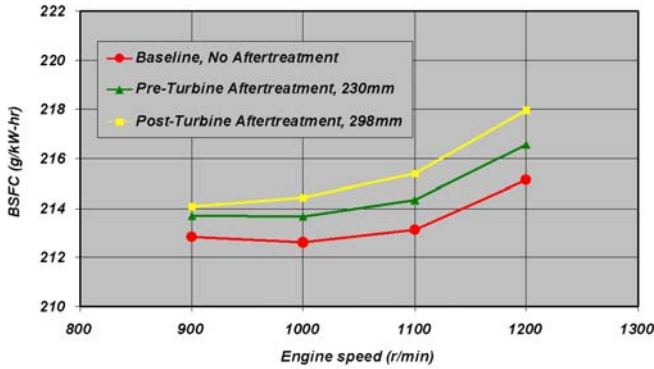


Figure 14: Clean fuel consumption comparison, optimized pre-turbine velocity

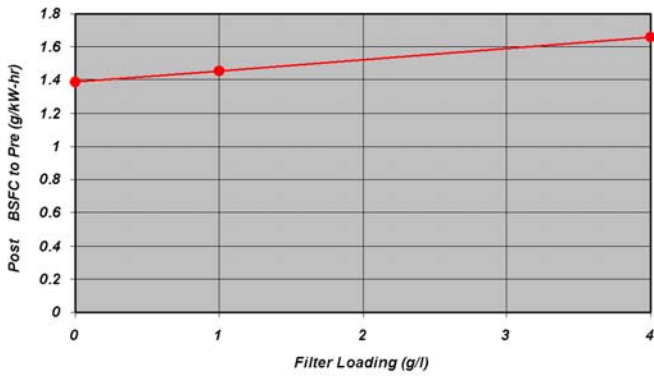


Figure 15: Pre-turbine fuel consumption benefit with filter loading; 230mm pre-turbine vs. 298mm post-turbine

## KEY RESULTS

Figure 16 shows the volume reduction advantage of the pre-turbine system. The cost of the system is also proportionate to the volume and the weight of the system.

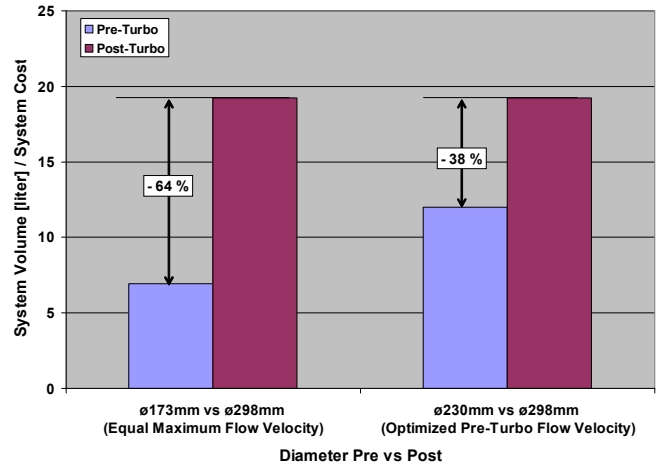


Figure 16: System Volume and Cost Reduction Advantage of Pre-turbine Aftertreatment System

Figure 17 shows how the fuel consumption changes with increasing aftertreatment system diameters. The cost, weight, and volume of the aftertreatment go up exponentially as the diameter increases. This is also shown on the chart as a relative increase or decrease from the 298mm post-turbine values.

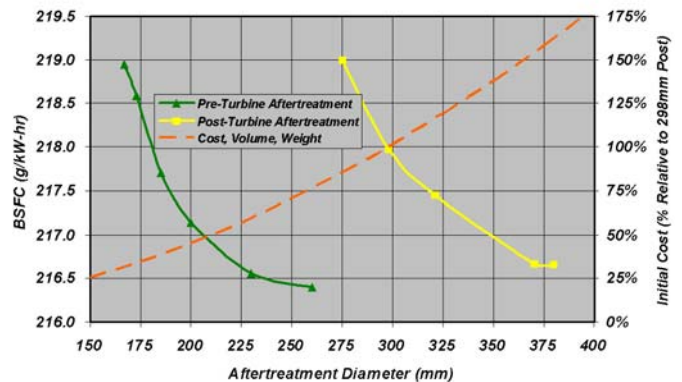


Figure 17: Aftertreatment diameter influence on BSFC and cost

To put the fuel cost savings into perspective, the case of the optimized pre-turbine PM-Metalit system (ø230mm vs ø298mm) is used. Influencing factors are the cost of diesel fuel and the duty cycle of the engine. A good assumption might be that the engine will be operated at 75% load for 8000 hours per year. This might be a GenSet application. From there the fuel savings for the pre-turbine system over the post-turbo system can be calculated. The cost of diesel fuel will play a significant roll in cost savings, the higher the fuel cost, the greater the savings will be. Figure 18 shows the total fuel cost savings per year with fuel prices ranging from 2 \$/gallon to 5 \$/gallon.

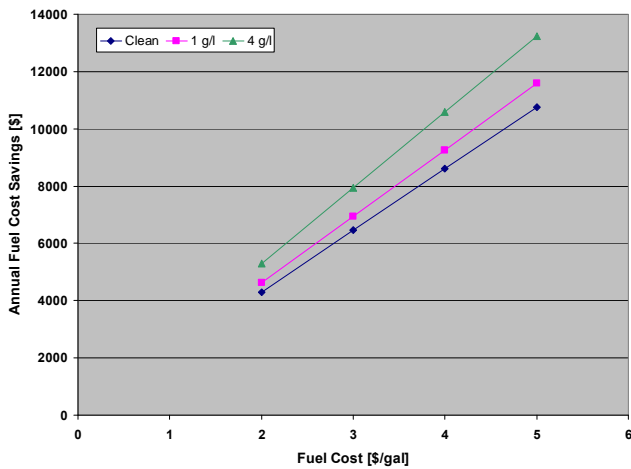


Figure 18: Annual Fuel Cost Savings of the Pre-turbine System over the Post-Turbo System at different Filter Loadings for 75% load for 8000h per year. Fuel Cost is Variable

Keeping in mind that these operational cost savings are in addition the lower initial system cost shows the remarkable potential for the placement of the aftertreatment system in the pre-turbine position.

## CONCLUSION

The placement of the aftertreatment system upstream of the turbo-charger has been shown to have many advantages for large-bore engine where transient behavior is of a secondary concern. Having the pressure drop of the aftertreatment system upstream of the turbo-charger can have a positive impact on the fuel consumption. The system can be laid out to either yield a maximum size and cost reduction or maximize the fuel consumption advantage of the aftertreatment in the pre-turbine position while still providing substantial smaller packaging requirements.

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