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Pre-Turbo Aftertreatment Position for Large Bore Diesel Engines – Compact & Cost-Effective Aftertreatment with a Fuel Consumption Advantage

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ABSTRACT

Tier 4 emissions legislation is emerging as a clear pre-cursor for widespread adoption of exhaust aftertreatment in off-highway applications. Large bore engine manufacturers are faced with the significant challenge of packaging a multitude of catalyst technologies in essentially the same design envelope as their pre-Tier 4 manifestations, while contending with the fuel consumption consequences of the increased back pressure, as well as the incremental cost and weight associated with the aftertreatment equipment.

This paper discusses the use of robust metallic catalysts upstream of the exhaust gas turbine, as an effective means to reduce catalyst volume and hence the weight and cost of the entire aftertreatment package. The primarily steady-state operation of many large bore engine applications reduces the complication of overcoming pre-turbine catalyst thermal inertia under transient operation. Upstream placement of the catalyst packages also offers potential for reducing the overall fuel consumption penalty (associated with the use of aftertreatment) in comparison to the conventional post-turbine placement. This softening of the fuel consumption penalty can be attributed to better light-off and performance of catalyst substrates, as well as a reduction in the impact of aftertreatment pressure drop on engine pumping work.

The investigation involved numerical simulation of pre-turbo application of a diesel oxidation catalyst (DOC), partial-flow diesel particulate filter (DPF), and selective catalytic reduction (SCR) catalyst on a 30-35L class diesel engine. The effect of this placement over traditional downstream placement in terms of fuel consumption, package size, weight and cost was examined.

The investigation revealed that the inherently higher gas density in the pre-turbine location allows a dramatic reduction in catalyst volume of up to 70%. The fuel consumption penalty associated with the addition of aftertreatment can also be reduced by approximately 1% with upstream placement of the catalyst packages.

INTRODUCTION

The powertrain of today is cleaner and more fuel efficient than it has ever been. We are however ‘just getting started’, as progressively more stringent emissions and fleet average fuel consumption standards will continue to drive clean, fuel efficient technologies and the innovations required to make them possible. Aftertreatment is a well accepted enabler for reduction of pollutant emissions beyond the exhaust manifold. Unfortunately aftertreatment has an adverse effect on fuel consumption, making it difficult to accomplish emissions and fuel consumption reductions simultaneously. Engineers are therefore challenged to devise creative means to align these two seemingly opposed goals.

The reality of aftertreatment is that it aggravates exhaust system restriction, and often involves the use of additional reductants such as diesel exhaust fluid (aqueous urea), or fuel, to promote catalytic effects. A direct consequence of these facts is an inevitable increase in fuel consumption. A reasonable goal for the powertrain engineer is thus to “minimize” this increase in fuel consumption, as circumventing it is simply not possible. The size of aftertreatment components also affects fuel consumption due to the added weight. It is therefore beneficial to minimize the overall size of the aftertreatment system. Smaller, more compact systems also typically exhibit better thermal characteristics, a key determinant for catalyst efficiency. From a commercial standpoint, equally performing, but more modestly sized aftertreatment components offer a clear opportunity for cost reduction.

The notion of a pre-turbine catalyst (PTC) is by no means new. There have been numerous attempts to incorporate at least part of aftertreatment system in the pre-turbo position [1]. The motivation was to utilize a compact, ‘precursor’ catalyst in very close proximity to the exhaust port, enabling rapid light off, and efficient conversion of pollutant emissions. A second, more generously sized underfloor catalyst would then complete the conversion of any remaining pollutants prior to the exhaust stream exiting the tailpipe. Such a ‘split’ configuration was sufficient to reduce the overall size of the aftertreatment, due to the increased efficiency offered by the PTC. A PTC can be configured for application in the cylinder head, within the exhaust manifold, and even as part of the turbine housing. Figure 1 provides some examples of PTCs, as well as the implementation into a turbine housing.

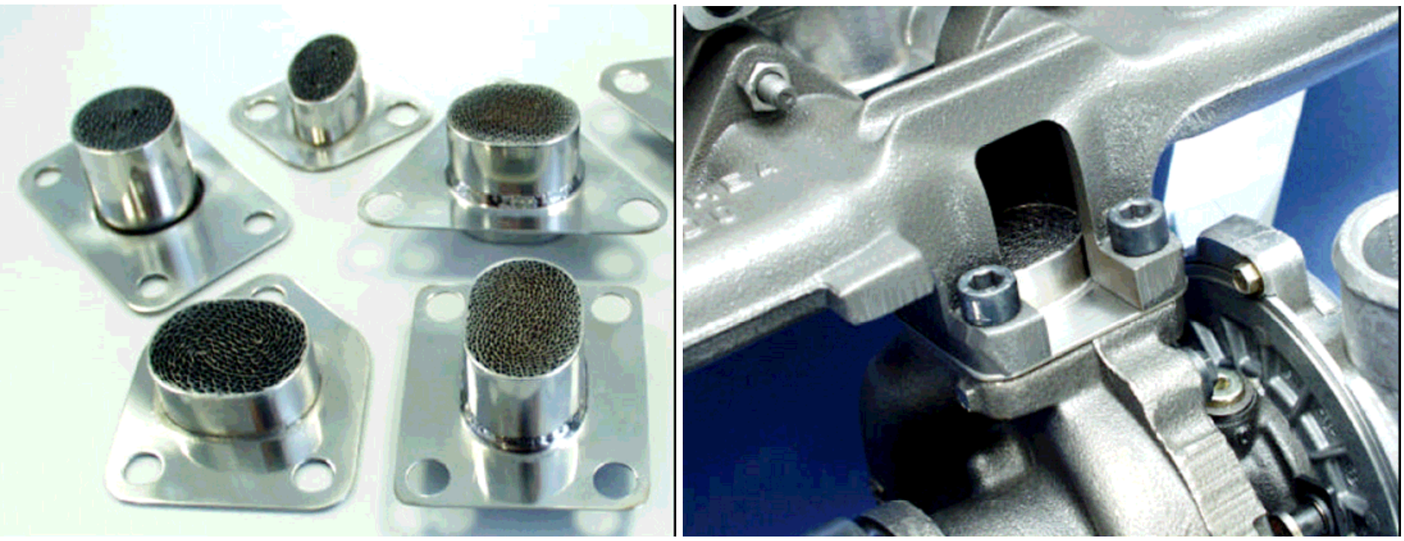

Figure 1: Pre-turbine Catalysts and Example of Turbine Housing Implementation [11]

PTC usage provides significantly higher catalyst inlet temperatures, which allows more rapid and efficient oxidation of exhaust pollutants. This effect can be demonstrated by Figure 2 which shows HC conversion efficiency as a function of time for both a PTC and a close coupled catalyst, during the European Emission Test Cycle [10].

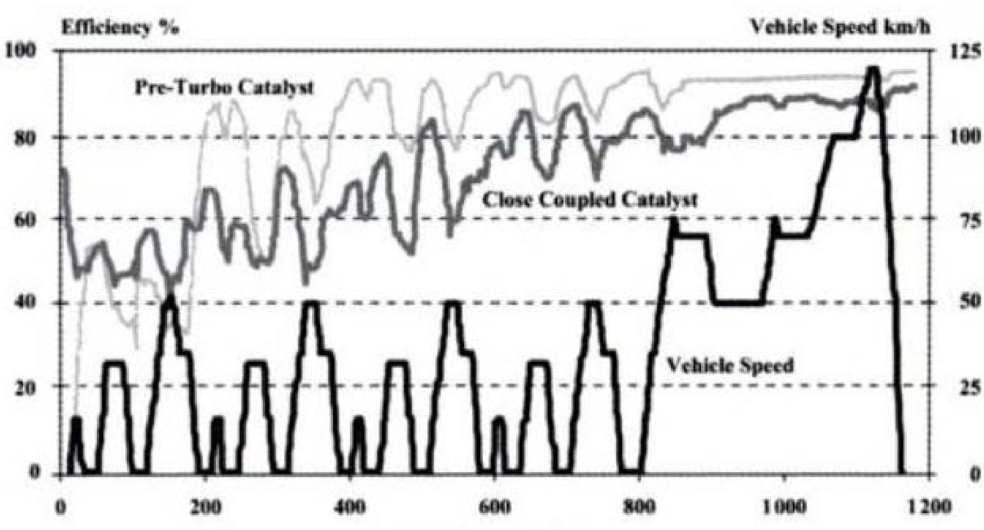

Figure 2: HC Conversion Efficiency Comparison between PTC and Close Coupled Catalyst [10]

Figure 3 shows the difference in catalyst inlet gas temperatures for a PTC configuration, compared to two downstream turbine configurations, in the close coupled, and underfloor positions respectively. The higher temperature regime of the PTC is clearly evident from this figure. This effect is particularly beneficial during cold stating and at lower engine loads, where exhaust gas enthalpy is lower due to leaner air fuel ratio operation. Extensive use of exhaust gas recirculation (EGR) in modern engines further increases the overall gas-to-fuel ratio during part load operation, making catalyst functionality even more challenging than before.

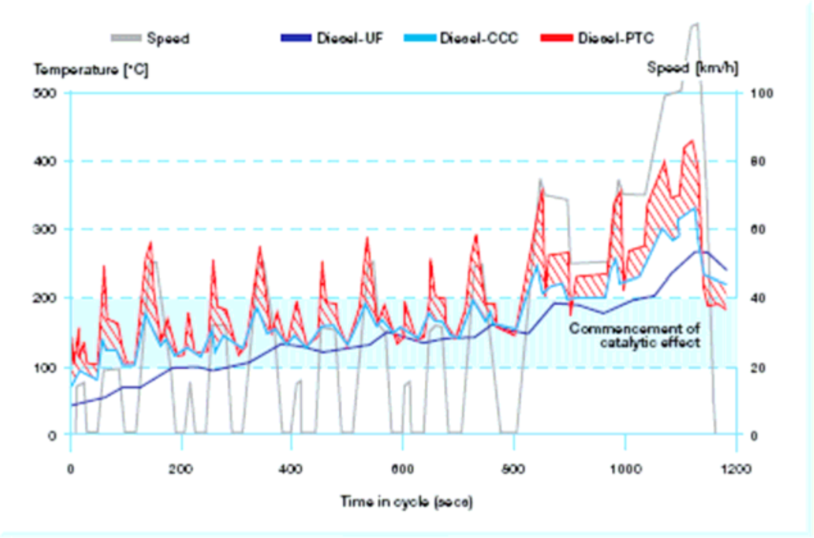

Figure 3: HC Conversion Efficiency Comparison between PTC and Close Coupled Catalyst [12]

PTC usage allows a significant reduction is catalyst volume over the post turbine configuration. This is due to higher gas density prior to expansion through the turbine, allowing the same substrate space velocity to be attained with a smaller cross sectional area. This brings about the previously mentioned opportunity for reduced catalyst volume, and hence cost and weight. The packaging benefits alone can be quite attractive, particularly if space is a commodity in the application of concern.

Despite the clear benefits associated with PTC usage, the concept is not without its challenges. The pre-turbine location is a much harsher thermodynamic environment, compared to the post-turbine location. A PTC needs to be robust and durable against higher temperature and pressure gradients, as well as pulsation effects associated with engine firing order. Secondly, it should be noted that any substantial application of aftertreatment in the pre-turbine positions (i.e. anything beyond a very modest pre-catalyst), will result in a degradation in engine transient performance. This is due to the 'heat sink' effect of the aftertreatment system components, particularly the particulate filter. Pre-turbine aftertreatment is therefore best suited for engines that operate in a largely steady state manner, or that feature very gradual load changes. Non-road, large-bore applications are therefore optimal candidates for pre-turbine aftertreatment.

BODY

THEORETICAL UNDERPINNINGS

Aftertreatment location has a direct impact on engine and turbocharger performance. This manifests via two distinct pathways, which are local gas density and impact on turbine expansion ratio.

A post-turbine aftertreatment system sees significantly lower gas densities than a 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, however the reduction in pressure is more drastic than the reduction in temperature, resulting in a net gas density that is lower. Lower density results in higher volume flow rates and, for the same diameter geometry and substrate density, a consequent increase in pressure loss across the aftertreatment.

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 as though 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 ~~Figure~~ ~~Figure~~ 4 is a simple illustration of this phenomenon. Assume an initial turbine inlet pressure (P_3) of 4 bar, and a nominal turbine outlet pressure (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 for the moment 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 only be re-gained back by increasing P_3 to 8 bar. That would raise the pumping back pressure to 8 bar as well. 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 a much more significant 4 bar penalty when it is located downstream of the turbine (for the same expansion ratio).

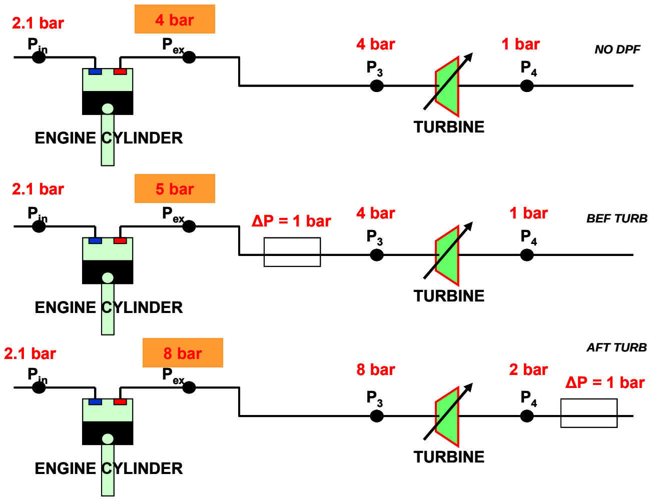

Figure 4: Theoretical Impact of Aftertreatment on Engine Back Pressure

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. Numerous other factors need to be taken into account, such as functional requirements of the aftertreatment and actual turbine behavior to define the practical aspects of such an approach. Engine performance modeling can prove useful in this regard.

AFTERTREATMENT SYSTEM MAKEUP

The major emissions of concern from diesel engines are unburned hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO & NO_2) 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_2 in the exhaust gas. The NO_2 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 ~~Figure~~ ~~Figure~~ 5 shows the internal design of the LS structure.

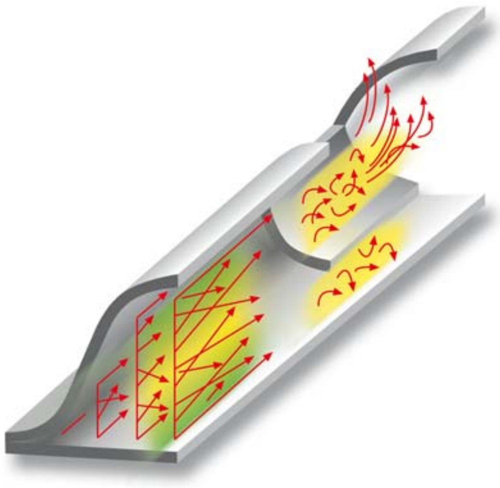

Figure 5: Internal Design of Longitudinal Structure

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 ~~Figure~~ ~~Figure ~~.

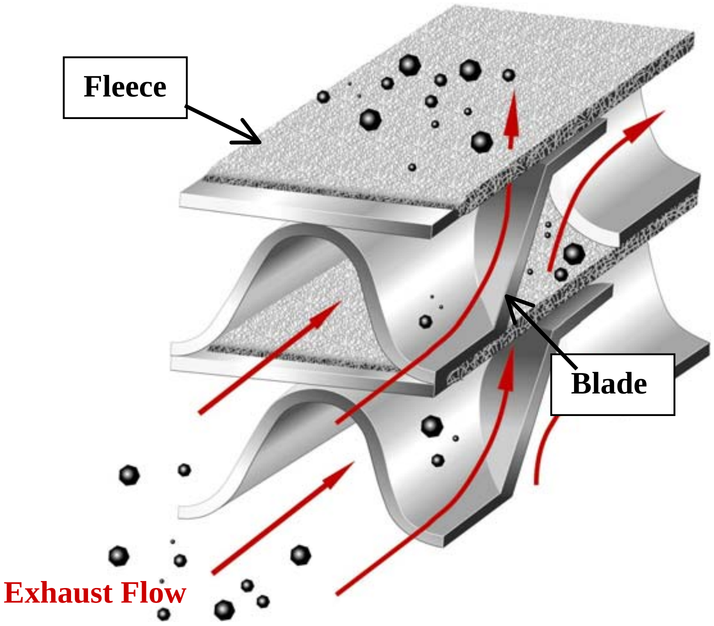

Figure 6: Internal Design of PM-Metalit [4]

The flat layer is made of a sinter 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 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 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 ($NO_x = NO + NO_2$) emissions from the engine requires some additional technology. The main technology that is the being investigated for heavy-duty and large-bore engines is urea SCR. The same robust metal substrate technology used in the DOC catalyst can also be implemented for the SCR catalyst. The coating in this case would be a vanadium or Fe- or Cu-Zeolite coating, instead of the Pt or Pt/Rh coating on the DOC. As flow and ammonia distribution is a critical factor in the successful implementation of an SCR system, the longitudinal-perforated (LSPE) structure can be used for the SCR catalyst. As shown in Figure 7, the same corrugated layer as the LS structure is used and a perforated flat layer is added to the LSPE catalyst. In addition to the enhanced mass transfer of the bladed corrugated layer, the perforations in the flat layer allow for communication between neighboring channel and mixing within the substrate.

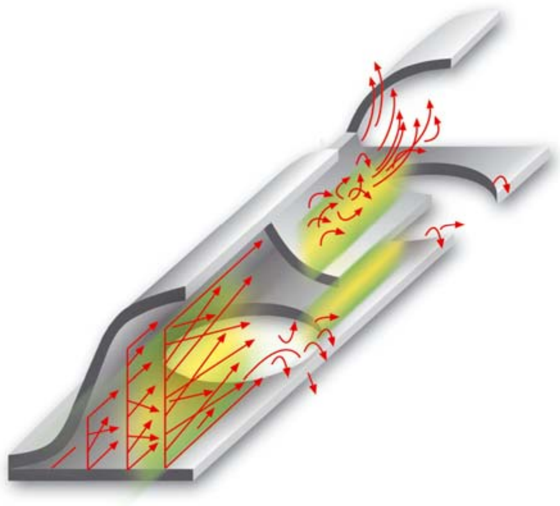

Figure 7: Internal Design Longitudinal-Perforated Structure

In addition to the coated substrates, which facilitate the NO_x reduction, aqueous urea has to be injected into the exhaust stream. The urea is converted to ammonia, which reduces the NO_x. The temperature at which this 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 SCRi, the PM-Metalit takes on three functions: continuous particulate reduction, hydrolysis of urea to ammonia and enhanced evaporation of urea. [9] The SCRi yields an efficient and cost-effective aftertreatment system.

This paper will focus on a configuration comprised of DOC, PM-Metalit and SCR catalysts respectively.

SIMULATION METHODOLOGY

The 1D engine performance software GT Suite version 6.2 was used to conduct the aftertreatment placement analyses.

Figure

~~Figure~~

~~Figure~~ Figures 8 and 9 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 (~ 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.

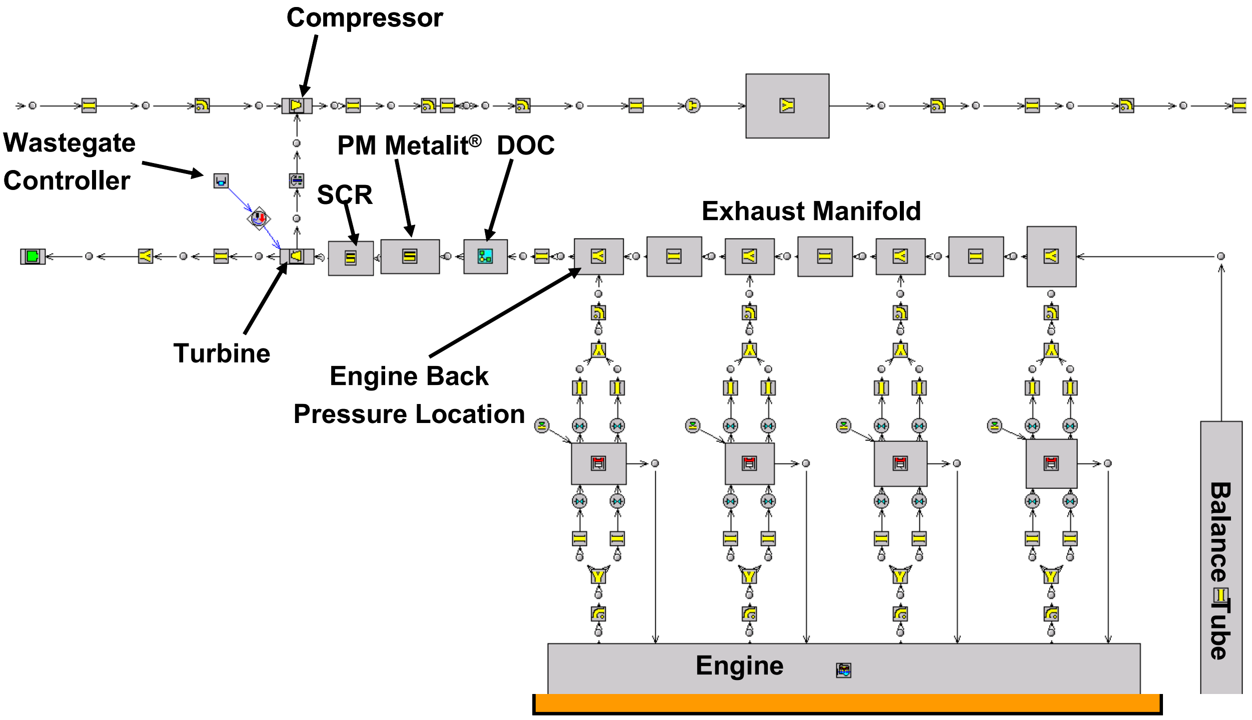

Figure 8: Pre-turbine system layout

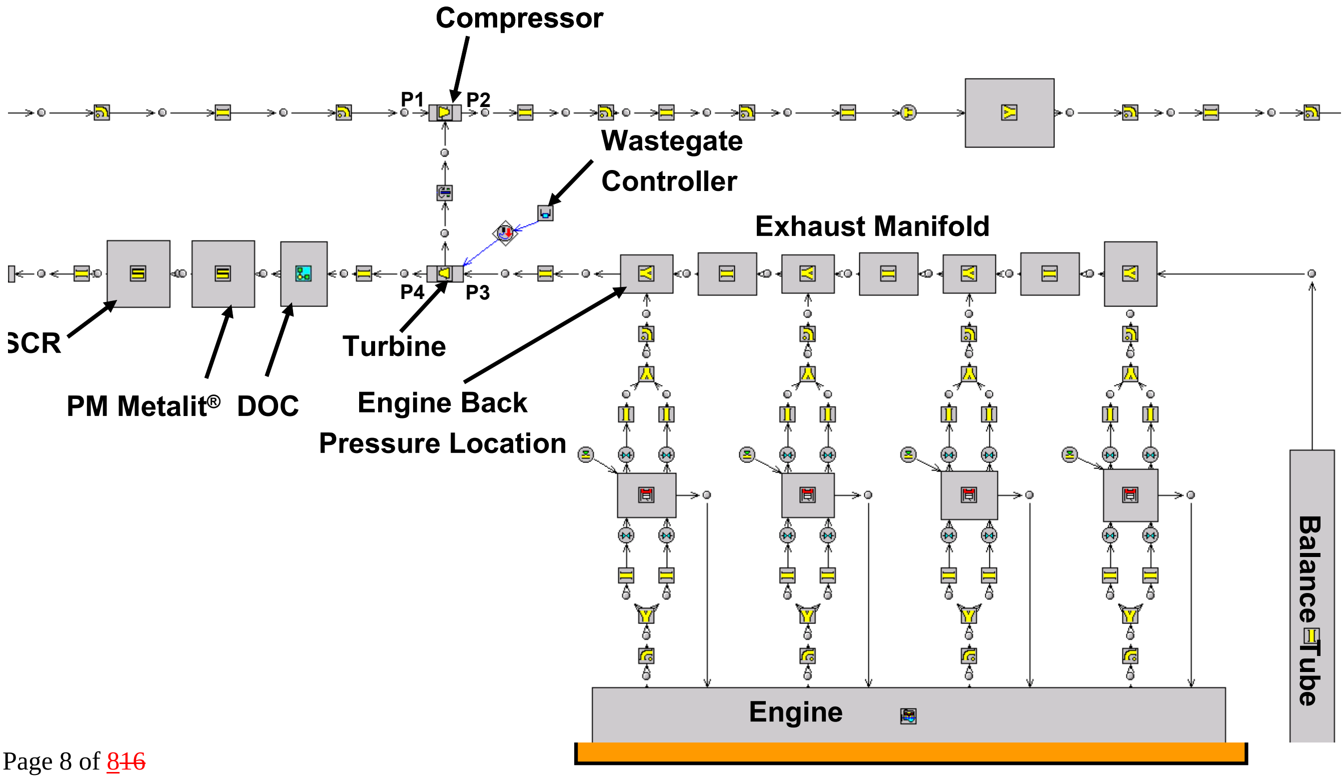

Figure 9: Post-turbine system layout

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 ~~Figure~~ ~~Figure~~ 10 shows the survey results and the selected piping diameter for the model.

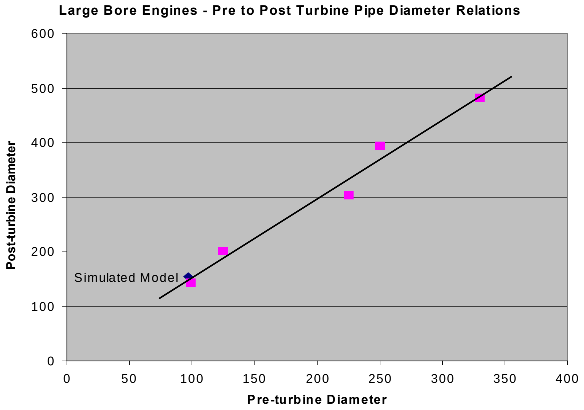

Figure 10: Optimization of Exhaust Piping Diameter of GT Power Engine Model, based on Survey of Existing Large Bore Engines

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 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 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).

RESULTS AND DISCUSSION

By virtue of its placement, pre-turbine catalysts would need to be smaller in cross-section to not sustain a significant reduction in space velocity, which would be detrimental to the effectiveness of the catalyst. Figure 11 shows the familiar increase in velocity seen with traditional post-turbine placement of aftertreatment as engine horsepower increases.

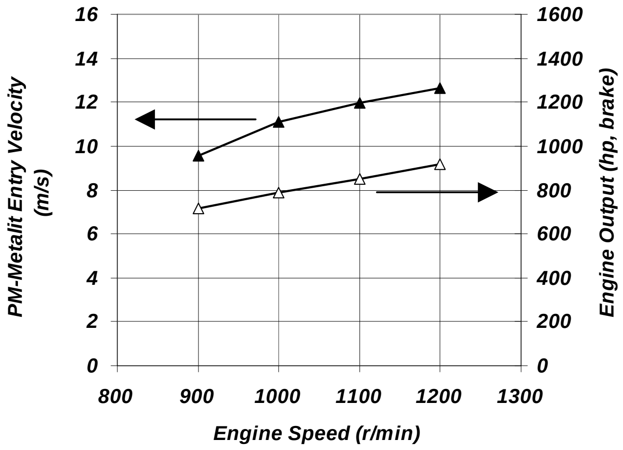

Figure 11: Catalyst Inlet Velocity Increasing with Engine Output

This effect is dominated by the increasing mass flow rate associated with the increasing power. The thermodynamic state of the gas in the downstream position is not changed significantly enough to alter this direct relationship between mass flow rate and velocity over the engine speed range. This could be somewhat different depending on the combustion system and air-fuel calibration; however the general increasing trend can be expected for most applications. Catalyst designs must therefore be capable of effective operation over a range of flow rates and hence velocities. This requires some degree of compromise so that acceptable performance is attained across the operating range, with no-adverse consequences at either end of this range.

In the case of the pre-turbine application, the pressure of the gas increases in proportion to the mass flow. This in turn causes a densification of gas which is also proportional to the mass flow. The net effect is a constant gas velocity, because the mass flow and density rise in conjunction with each other. Figure 12 shows the density and resulting gas velocity for both pre and post-turbine configurations, illustrating this distinct difference.

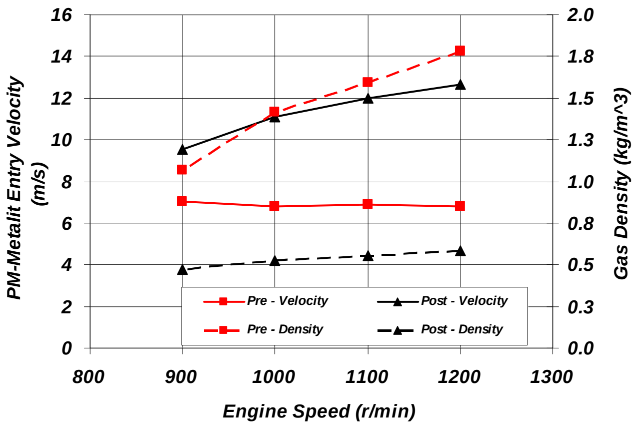

Figure 12: Density and Velocity Dynamic for Pre and Post-turbine Systems

This constant velocity behavior represents a prime opportunity for optimization of the catalyst design. There is essentially a single design point, due to the insensitivity of velocity to mass flow. It can be seen that this target velocity for the pre-turbine PM-Metalit was in the 6-8 m/sec range. This velocity resulted from a catalyst diameter of 230 mm for pre-turbine system. The post-turbine system featured a diameter of 298mm, with a target velocity range of 9-14 m/sec. It can be seen that the pre-turbine system enjoys the added benefit of being designed for lower space velocities, due to it's more or less constant velocity operation, which allows careful customization of the substrate for lower velocity (and hence pressure drop) operation. The wider operating bandwidth of the post-turbine system requires overall higher velocities for adequate performance across this wider range.

It should be noted that the results shown above were obtained from running the pre and post-turbine models elaborate with DOC, PM-Metalit and SCR catalysts respectively. The entrance velocities that are shown in Figures 11 and 12 are for the PM-Metalit only, entrance velocities to the other catalysts behavior in a similar fashion and will be shown later. All three aftertreatment components in the pre-turbine configuration featured diameters of 230 mm, and similarly in the post turbine configurations, the aftertreatment components were at diameters of 298 mm. Table 1 provides catalyst specifications for both the pre and post-turbine configurations:

Table 1 – Specifications for Pre and Post-Turbine Aftertreatment Configurations

Aftertreatment Component	Pre-turbine	Post-turbine
DOC	230 x 115 mm, 200 CPSI, 4.8 L	298 x 115 mm, 200 CPSI, 7.7 L
PM-Metalit	230 x 174 mm, 7.2 L	298 x 174 mm, 12.1 L
SCR	230 x (155+155+155) mm, 200 CPSI, 19.3 L	298 x (155+155+155) mm, 200 CPSI, 31.4 L

As illustrated in the theory section of the paper, post-turbine placement results in a 'choking' of the turbine expansion ratio. The turbine inlet pressure to maintain engine power is therefore higher than in the pre-turbine configuration. Figure 13 illustrates this effect of higher turbine inlet pressure for the post turbine case while both pre and post-turbine configurations produce the same brake power.

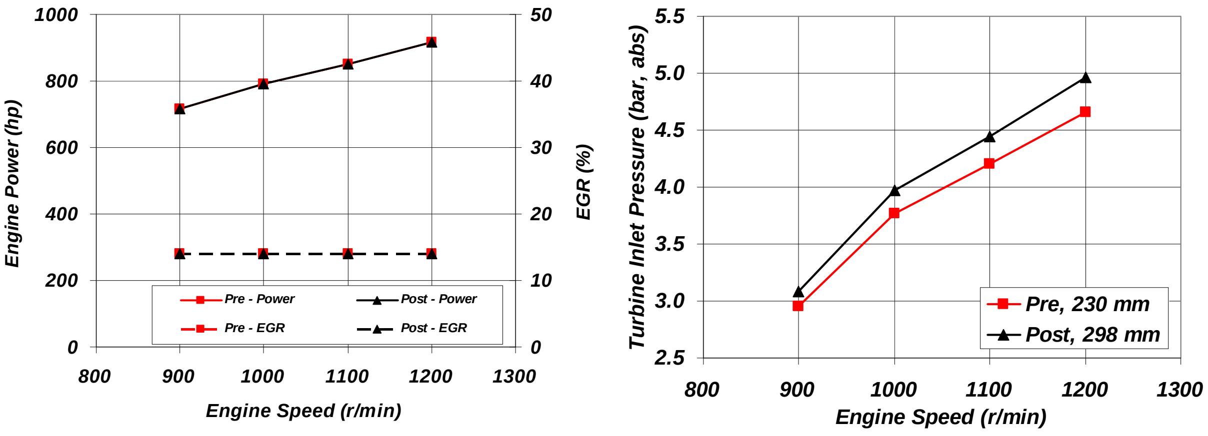

Figure 13: Turbine Inlet Pressure Differences under Identical Power and EGR Conditions

This then manifests as higher pumping losses, and hence BSFC as shown in Figure 14.

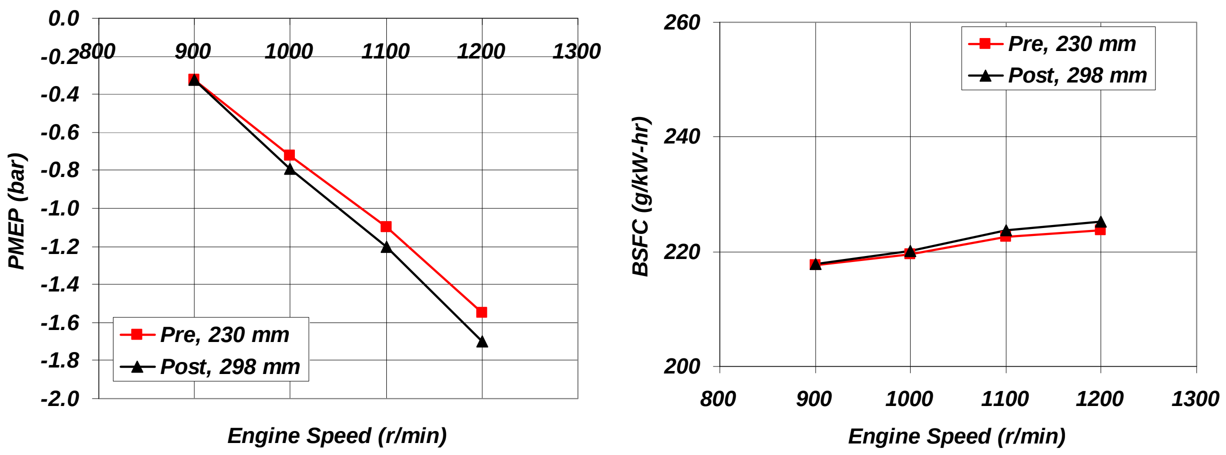

Figure 14: Lower Pumping Losses and BSFC for the Pre-Turbine Configuration

Pumping losses are a strongly influenced by turbocharger efficiency. Figure 15 shows the turbine and compressor efficiencies for both configurations, as well as the resulting overall efficiency.

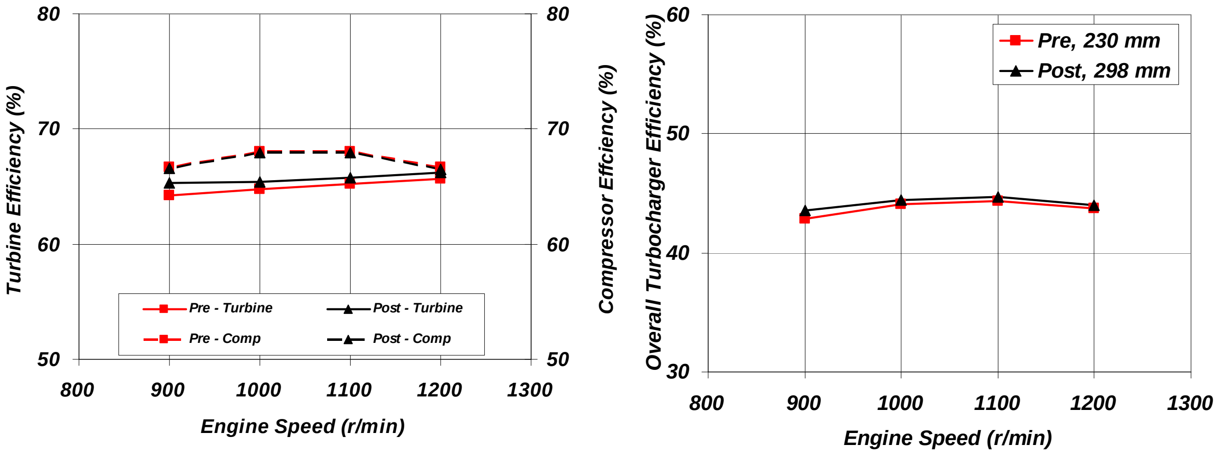

Figure 15: Turbine, Compressor, and Overall Efficiencies

It can be seen that the efficiencies are quite comparable between configurations, and the overall efficiency is very slightly in favor of the post-turbine system. Should the overall efficiencies have been exactly identical, one would expect a corresponding further reduction in BSFC for the pre-turbine configuration. Figure 16 shows the overall aftertreatment pressure drop for both the pre and post-turbine configurations. It can be seen that at 900 r/min, the post turbine system has a slightly higher pressure drop than its pre-turbine counterpart. This is due to the higher space velocity in the post-turbine system resulting from the sizing of the catalyst. As speed increases however, the pre-turbine configuration experiences a more or less constant pressure drop due to its constant velocity tendency regardless of mass flow. The post turbine pressure drop continues to climb because its velocity is directly proportional to mass flow.

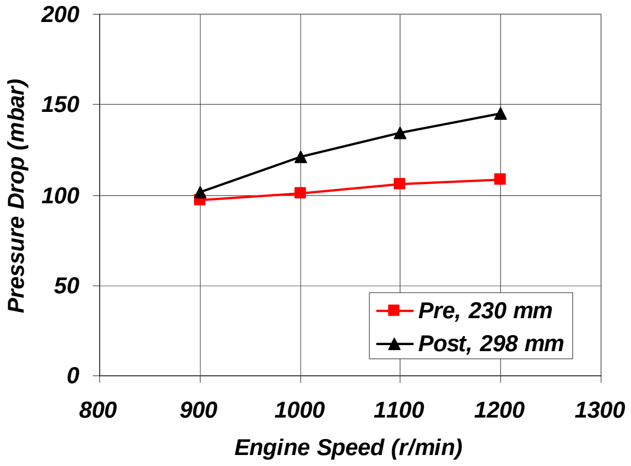

Figure 16: Pre versus Post-Turbine Aftertreatment Pressure Drop

All the results seen thus far correspond to an unloaded PM-Metalit. Due to physics of the expansion ratio ‘choking’ present with post-turbine systems, a loaded particulate filter will aggravate the difference seen between a pre and post-turbine system. This is because the pressure drop of the aftertreatment affects engine back pressure additively for a pre-turbine system, but multiplicatively for a post-turbine system. Figure 17 shows the relative improvement in BSFC of the pre-turbine system over the post-turbine system, for both a clean as well as a loaded particulate filter.

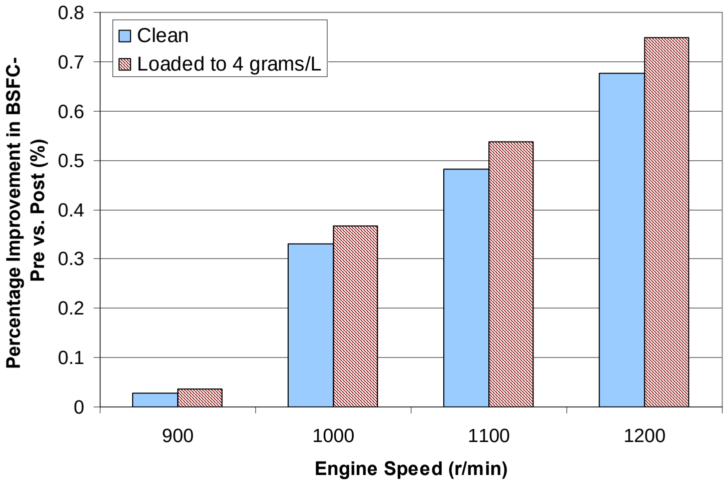

Figure 17: Enhanced Pre-Turbine BSFC Benefit for Loaded PM-Metalit

The analysis has shown that with a pre-turbine catalyst, reduction in catalyst volume and an improvement in BSFC are possible. In some cases, reducing catalyst volume may be a higher priority. In such a situation, it is possible to further reduce pre-turbine catalyst volume at the expense of fuel consumption. Figure 18 illustrates this effect. It is clear that a significant further reduction in catalyst size is possible. An interesting point in the trade-off is the break-even point where both pre and post-turbine systems experience the same BSFC. At that point, the pre-turbine catalyst has a diameter of approximately 170mm. This corresponds to a reduction in catalyst volume of almost 70%, representing a substantial opportunity for reduced package size, and cost. Figure 19 provides an alternate view this trade-off, where for a given BSFC, the corresponding aftertreatment system diameter can be determined for both the pre and post turbine configurations.

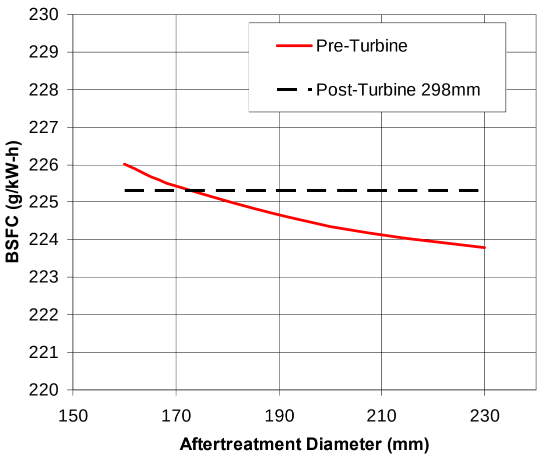

Figure 18: BSFC and Catalyst Size Trade-Off (1200 RPM, Pre-Turbine Only Varied)

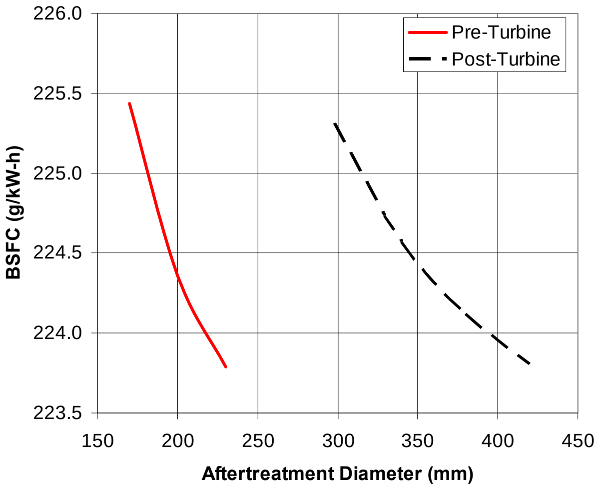

Figure 19: BSFC and Catalyst Size Trade-Off (1200 RPM, Both Configurations Varied)

SUMMARY/CONCLUSIONS

It has been shown that a pre-turbine aftertreatment system offers clear and distinct benefits in terms of compact, cost-effective emissions reduction, with the additional advantage of reduced fuel consumption. The analysis conducted here reveals potential for a 40% reduction in catalyst volume with a simultaneous reduction in fuel consumption of between 0.5 and 1% with a pre-turbine system as compared to a comparably-functioning post-turbine system. The pre-turbine aftertreatment system can also be configured to minimize package size and cost with equivalent fuel consumption to a comparably-functioning post turbine system. In this scenario, a reduction of catalyst volume of up to 70% is possible.

Key aspects of a pre-turbine aftertreatment system that are crucial to its success are durability and robustness given the harsher thermodynamic environment upstream of the turbine, and the lack of any significant transient operation. It is therefore recommended that a robust metallic catalyst be selected for pre-turbine application, and that pre-turbine aftertreatment should only be considered for applications that are characterized by largely steady state operation.

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