

# Secondary Fuel Injection Layout Influences on DOC-DPF Active Regeneration Performance

Adam Kotrba, Alan Brockman, Scott Martin, Alan Mikovits, and Gary L. Butzke  
Tenneco Inc.

Zack Richey and Matthew Leudeke  
Caterpillar Emissions Solutions

## ABSTRACT

Catalysts and filters continue to be applied widely to meet particulate matter regulations across new and retrofit diesel engines. Soot management of the filter continues to be enhanced, including regeneration methodologies. Concerns regarding in-cylinder post-injection of fuel for active regeneration increases interests in directly injecting this fuel into the exhaust. Performance of secondary fuel injection layouts is discussed, and sensitivities on thermal uniformity are measured and analyzed, providing insight to packaging challenges and methods to characterize and improve application designs. Influences of end cone geometries, mixers, and injector mounting positions are quantified via thermal distribution at each substrate's outlet. A flow laboratory is applied for steady state characterization, repeated on an engine dynamometer, which also provides transient results across the NRTC. An example of an installed system on a hydraulic excavator is provided, as well as recommendations for further studies.

**CITATION:** Kotrba, A., Brockman, A., Martin, S., Mikovits, A. et al., "Secondary Fuel Injection Layout Influences on DOC-DPF Active Regeneration Performance," *SAE Int. J. Commer. Veh.* 6(2):2013, doi:10.4271/2013-01-2465.

## INTRODUCTION

Over the past decade much development attention has been given towards integrating diesel particulate filters (DPFs) into the exhaust of diesel engines, providing a robust solution for particulate matter (PM) control as regulated across many regions and markets, including retrofits to resolve localized non-compliance with National Ambient Air Quality Standards (NAAQS). As soot is filtered by the DPF, it accumulates over time and the resulting soot load, influenced by PM and NO<sub>2</sub> concentrations, mass flow rate, and temperature, must be managed. PM control is typically referred to as "regeneration", and it is often categorized as "passive" or "active", indicating its control methodology. Passive regeneration occurs catalytically, elevating NO<sub>2</sub> content with precious-metal coatings upstream on a diesel oxidation catalyst (DOC), enabling reactivity with the soot to consume the carbon, yielding CO<sub>2</sub> [1]. But, like many catalytic responses, its reactivity and rate is temperature sensitive, and within many applications the exhaust conditions are not conducive, requiring periodic active

regeneration for robust soot load management [2]. Active regeneration elevates exhaust temperatures to enable natural oxidation of the soot, occurring typically above 600°C and requiring some external energy input, which is why it is less preferred since it increases fuel consumption. Fuel burners are one solution for active regeneration, enabling autonomous thermal control, decoupled from duty cycle effects, providing temperatures at any time as needed [3, 4, 5]. Alternatively, the DOCs already integrated for passive regeneration may also be applied to support periodic active regeneration, producing an exothermic response as fuel is introduced into the exhaust and catalytically oxidized [6, 7, 8, 9]. The fuel has traditionally been introduced into the exhaust system using in-cylinder post-injection, which essentially injects fuel into the combustion chamber during the exhaust stroke, possible with enhanced common rail and piezoelectric injector technologies. Such integration is preferred since the added fuel is well mixed and evaporated prior to the catalyst, and it reduces hardware costs and complexities. However, over time this could lead to significant cylinder wall wetting and eventual oil dilution, reducing the effectiveness of the applied fuel and increasing risks of engine wear [10].

Therefore, secondary fuel injection (SFI) is of interest, separating the additional fuel from the combustion chamber and injecting it directly into the exhaust, which is also a more appropriate solution for retrofits which cannot apply post-injection.

SFI must be appropriately integrated with the engine and exhaust to obtain robust performance of the DOC and DPF during the regeneration event. Thermal uniformity is essential and must be within established limits across the catalyst and filter cross-section, particularly since the fuel distribution could vary significantly from the exhaust flow distribution, and more so with larger droplets, resulting in uneven fuel distribution and damaging hot and cold spots. Such effects result in catalyst damage, excessive HC slip, uneven soot oxidation distribution, or even extreme thermal stress and likely damage to the substrates (DOC and DPF), ultimately resulting in emissions failures. And, like Urea SCR systems, the injected fluid and its mixing path have many influences that affect performance, including injector spray quality (droplet size and distribution) and mount, mixers and mixing lengths, up and downstream geometries, as well as of course input conditions such as exhaust and fuel mass flow rates, and exhaust temperature before and after the DOC [11, 12, 13, 14]. Additionally, catalyst and filter positioning and sizing, as well as their materials, cell structures, and coatings, also have significant influence on performance robustness. And all noted instances apply in other aftertreatment systems employing fuel or ethanol, such as with lean NO<sub>x</sub> catalysts (LNC) [15-16].

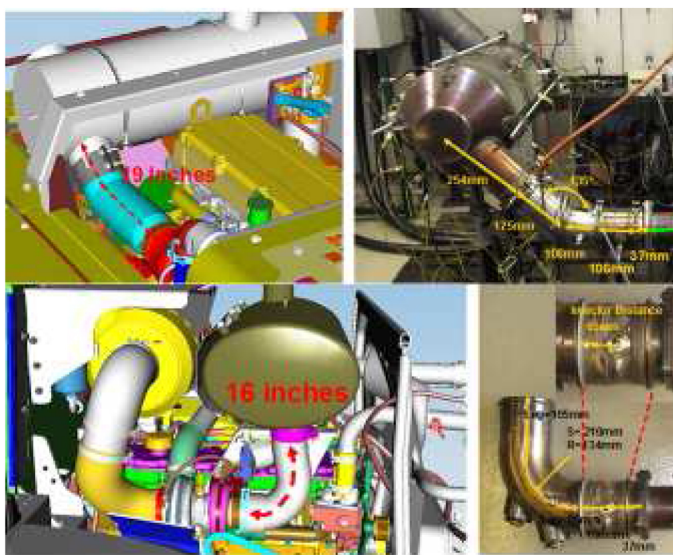


**Figure 1. Packaging examples and corresponding test hardware**

As evidenced in Figure 1, real-world packaging environments are very tight, requiring fuel injectors to be mounted close to turbochargers creating hot pipe and underhood temperatures and high-frequency vibrations. Mixing lengths are relatively short requiring attention to flow

and fuel distributions across the catalyst face. Certainly, active systems require control schemes with appropriate sensors and diagnostics to enable transient functionality, controlling injected fuel mass flow rates based on changing conditions of the engine speed and load, exhaust conditions such as soot loadings, and other environmental influences [17]. Figure 2 demonstrates two scenarios how thermal distribution with limited temperature sensor inputs creates risks not only with hot spots, but cold as well, resulting in localized soot overloading and eventual failure.

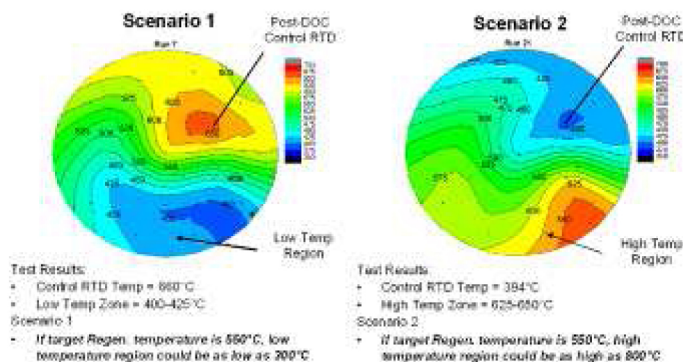


**Figure 2. Control concern scenarios with cold (left) or hot (right) spots**

## OBJECTIVES

The objectives of this study are to evaluate various design sensitivity factors that influence the performance of an actively regenerated DOC-DPF system using SFI and demonstrate appropriate characterization methodologies to drive system optimization. Design factors are chosen to help understand the influences of anticipated packaging constraints with the intent to have a modular design of a few standard components applied widely across many applications. Injector mount position and location relative to the mixer and catalyst is discussed, including vertical and side mounting on the pipe circumference, distance between injector and mixer (1" or 2"), and an 18" mixing length from the injector to the catalyst. Axial and radial end cone geometries are applied, quantifying differences between straight-in and out geometries versus side-in and out, and each layout is compared with and without a mixer.

Steady state input conditions are controlled to low, medium, and high exhaust mass flow rates (~ 500, 1000, 1500 kg/hr), relatively low exhaust DOC-inlet temperatures (300°C for low and medium flows and 400°C for high), and adequate fuel to provide the target average outlet temperature of 650°C. An XNO<sub>x</sub>™ injector applying pressure-swirl atomization at 80psi (manufactured by Tenneco and also applied with minor differences as a urea injector) is used to dose the fuel into the exhaust, controlling its mass flow rate with pulse-width modulation and enabling direct mounting on the hot exhaust with return-flow cooling (cooling block not necessary). Two substrate diameters are applied, each with