

Determining Soot Distribution in the Vehicle Exhaust Downstream of a Faulty Diesel Particulate Filter

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ABSTRACT

New emissions certification requirements for medium duty vehicles (MDV) meeting chassis dynamometer regulations in the 8,500 lb to 14,000 lb weight classes as well as heavy duty (HD) engine dynamometer certified applications in both the under 14,000 lb and over 14,000 lb weight classes employing large diameter exhaust pipes (up to 4") have created new exhaust stream sampling concerns. Current On-Board-Diagnostic (OBD) dyno certified particulate matter (PM) requirements were/are 7x the standard for 2010-2012 applications with a planned phase in down to 3x the standard by 2017. Chassis certified applications undergo a similar reduction down to 1.75x the standard for 2017 model year (MY) applications. Failure detection of a Diesel Particulate Filter (DPF) at these low detection limits facilitates the need for a particulate matter sensor. With the active sensing elements of the particulate matter (PM) sensors extending less than ½" into a 4" ID exhaust pipe, the question arises of where to locate the PM sensor to ensure it sees a properly mixed exhaust stream. Packaging and warranty requirements dictate the sensors be located near the outlet of the DPF cone, but generic fluid dynamics requirements dictate ten tube diameters after the outlet of the DPF cone. Experiments were conducted at the Ford Motor Company's Vehicle Emissions Research Laboratory on a medium duty vehicle (chassis certified application) with a diesel engine and an aftertreatment system containing a diesel oxidation catalyst (DOC), selective catalytic reduction (SCR) catalyst, and a diesel particulate filter (DPF) utilizing both artificial and induced actual DPF faults. Several downstream DPF axial locations were selected at distances between 5 times and 18 times the diameter of the exhaust pipe from the DPF outlet. Real time PM measurements were performed at multiple sample points of each axial location (soot plane) to map out the PM distribution in the exhaust pipe. As part of this series of experiments a few DPF failures initiated during drop-to-idle (DTI) DPF regeneration were monitored with PM instrumentation. Additionally, Computational Fluid Dynamics (CFD) analyses were performed to predict mixing efficiency of the PM at each of the axial locations of the exhaust system. Both experimental and computational data will be presented.

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INTRODUCTION

Stricter emissions regulations over the last several years (as well as future regulations) present unique challenges to the industry. For the MDV markets, diesel particulate filters were first added to vehicles for the 2007 model year (MY) and additional NOx aftertreatment controls were added starting in a similar time frame and phased in by various manufacturers over the next few years. Ever more stringent OBD requirements further complicate the challenges. One of the major changes in OBD regulations is the tighter detection limits on particulate matter (PM) emissions. For dyno certified applications the On-Board-Diagnostic (OBD) particulate matter (PM) requirements were/are 7x the standard for 2010-2012 applications. That detection limit is phased in to a reduced level of 3x the standard by 2017. [1]

Chassis certified applications undergo a similar phased in reduction to a final detection limit of 1.75x the 20 mg/mi standard for 2017 MY applications.[7] Most manufactures currently utilize a pressure based method to detect failures in a DPF. Typically a pressure based method can only detect gross failures and failures at these low detection limits facilitates the need for a particulate matter sensor.

Diesel particulate filters (DPF) are typically a substrate with porous walls and channels that are alternatively blocked, i.e. an inlet channel is open at inlet face of the substrate and blocked at the outlet face. An outlet channel is the opposite, blocked on the inlet face of the substrate and open at the exit face of the substrate. PM that enters through an inlet channel is initially deposited within the porous wall and as more PM enters the DPF a "soot cake" layer is built up within a given

inlet channel. The amount of PM that can be deposited within a DPF is limited. Regeneration is the process of removing PM from a DPF, it can be either passive (no active engine/vehicle control of the process) or active (typically DPF inlet temperature is raised significantly through varied engine / aftertreatment system actions). DPFs can be made from a variety of materials that may include silicon carbide (SiC), cordierite, aluminum titanate (AT) and other materials. DPFs may be manufactured as segmented sections connected with a cement layer or as a continuous extruded monolith. A schematic of a generic DPF is shown in [Figure 1](#).

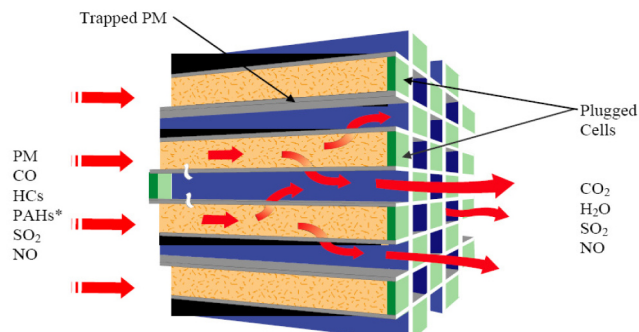


Figure 1. Generic DPF

A reduction in DPF filtration efficiency can be caused by a multitude of different failure mechanisms. The failure mechanisms may be influenced by the type of substrate material used, the substrate design, engine operating conditions, PM load within the filter, environmental conditions and a host of other items. The types of failures that can occur are just as widely varied. A DPF could suffer from a ring-off-crack (ROC), a localized crack, a localized melt with the substrate, a large melt, etc. The various types of failure modes can occur in diverse locations within the DPF resulting in an uneven distribution of PM leakage out of the DPF (PM could leak from a point source or uniformly across the whole cross-section or anywhere in-between). The obvious goal of the manufacturer is to design a system that minimizes failures and the diagnostic requirements dictate the need to be able to detect a failure if one should occur. So the question is, at what point downstream of the DPF should the sensor be located to ensure the sensor sees a uniform distribution of PM should a failure occur?

Currently available prototype soot sensors employ detection elements that are approximately $\frac{1}{2}$ "- $1\frac{1}{2}$ " in length, while MDVs use exhaust pipes >3 " in diameter. See [Figure 2](#) for a picture of an example PM sensor in a 3.5" diameter pipe. If the soot sensor is placed in the traditional gaseous sensor location of 6" after the outlet cone of the last component of aftertreatment it may not detect a DPF failure due to insufficient time for thorough mixing of the PM in the exhaust stream. An optimal location for the soot sensor based on fluid dynamic principles must be identified while adhering to internal Company exhaust system protocol constraints.

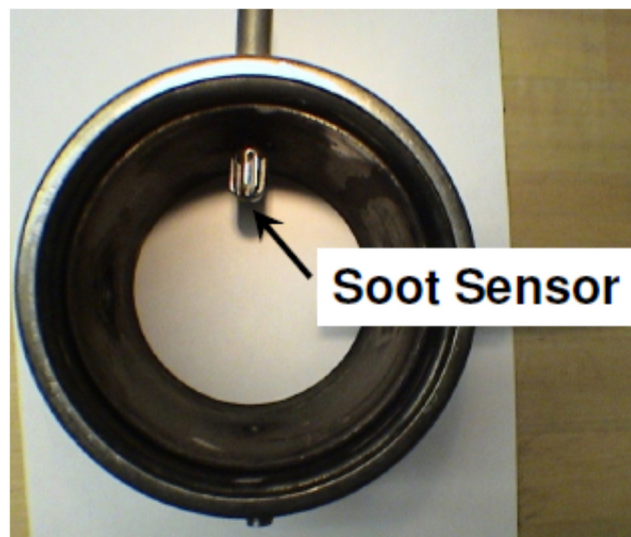


Figure 2. Soot sensor in 3.5" diameter pipe

To ensure the sensor is capable of meeting the OBD detection limits, the PM concentration must be mapped out radially and axially downstream of a failed DPF to identify proper sensor placement. Several artificial DPF failure methods were evaluated before selecting a rear-face-machined-out-section for the bulk of the testing. Real time particulate mass monitors sampled pre-DPF, soot plane, and tailpipe locations to quantify induced leak rate and soot plane concentration relative to the tailpipe measurement. Particle size distribution and particle number count (PN) were also identified at the soot plane. Furthermore a DPF failure was initiated during a DTI regeneration in an attempt to produce a "real" 1.5 times the standard DPF leak rate. Pre and post PM mass were recorded during the regeneration and during a subsequent EPA 75 to quantify the PM emission relative to the regulated mass standard [8].

This paper quantifies post DPF and tailpipe PM levels for artificial and real DPF failures of differing leak rates using real time particle mass, particle size distribution, and particle number count to identify proper placement for the OBD soot sensor. Data presented here is from an MDV diesel truck operating in the 8.5K-10K weight class.

METHODOLOGY

Test Cell Configuration

The vehicle was operated on a 48-inch (1.22 m), single-roll, AC electric dynamometer. Vehicle exhaust was diluted after exiting the tailpipe using a Remote Mix Tee (RMT). The connection from the tailpipe to the RMT consisted of a 4 foot long 4" ID flexible stainless steel coupling. After dilution, exhaust was transferred to a Constant Volume Sampling (CVS) unit. Exhaust volume was determined by the Smooth Approach Orifice (SAO) method. See [figure 3](#) for

picture of the test cell layout with the vehicle installed on the chassis rolls.

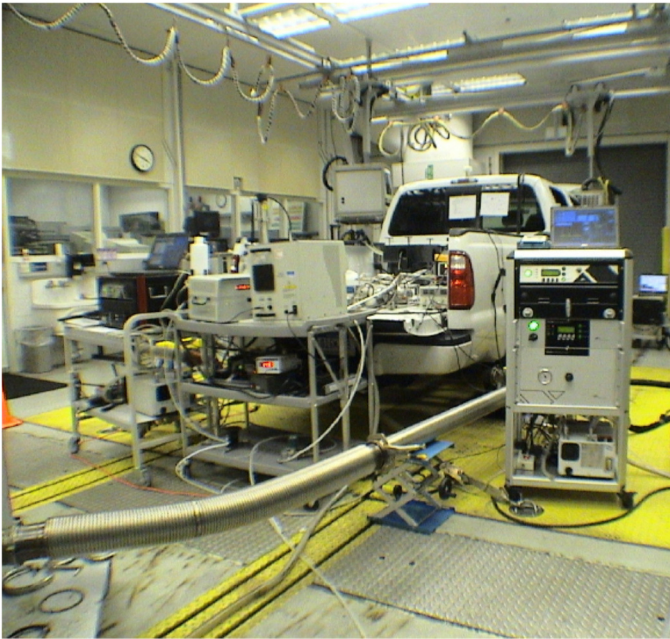


Figure 3. Test Cell Layout with Vehicle on Chassis Rolls

PM Measurement Instrumentation

Two Dekati Mass Monitors (DMM) were used at post DPF (soot plane) and tailpipe exit locations when mapping the soot planes. The soot planes are defined as multiple sample points across the diameter of the exhaust pipe. The sample points occur at the center, 8 points clocked 45° apart on the radius of 7/8" from center, and 8 points clocked 45° apart on the radius 3/8" from the pipe wall. See Figure 4 for a schematic of the instrumentation. Any drift or fluctuations in the diesel engine emissions over the course of the tests is taken into account by simultaneously monitoring the PM at both locations. Sample lines were heated to 190C to reduce both thermophoretic losses and water condensation. Dilution was done by either a 2-stage Dekati ejector diluter system (DI-100) as seen in Figure 5 or a Dekati Fine Particle Sampler (FPS-4000) as pictured in Figure 6. In both cases, heated dilution, at 190C, was used at the first dilution stage. Total dilution for post DPF and tailpipe sampling was in the range of 35 - 70, and for any pre DPF sampling the dilution was increased to be around 400 - 450.

Operation of the DMM is based on particle charging followed by size separation and electrical detection as the diluted exhaust sample flows through a series of impactor stages as depicted in Figure 7. Particle density is determined by both mobility and aerodynamic size properties. All of this information is used to calculate PM mass concentration [2]. Detection sensitivity is specified at approximately 1ug/m3 for particles < 1.5 microns in size. Since the DMM has a time response of 1 Hz, it is useful for both transient drive cycles and steady state engine conditions. Correlation measurements with both DMMs were performed at the start and end of each test.

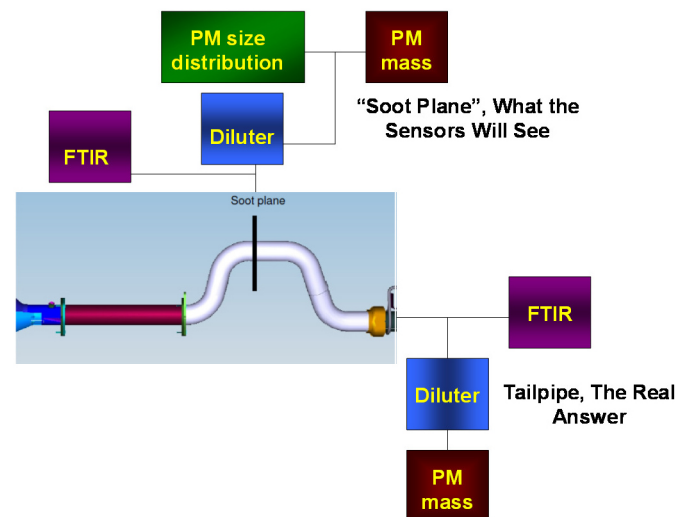


Figure 4. Schematic of Dual PM Sampling Points

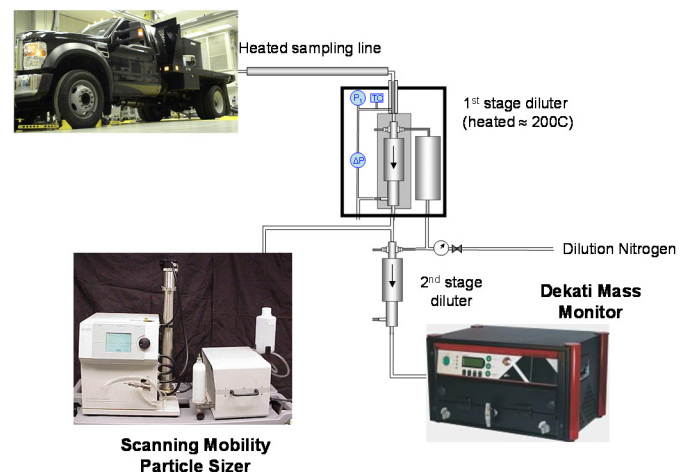


Figure 5. Dilution system schematic using Dekati Ejector Diluter System (DI-1000)

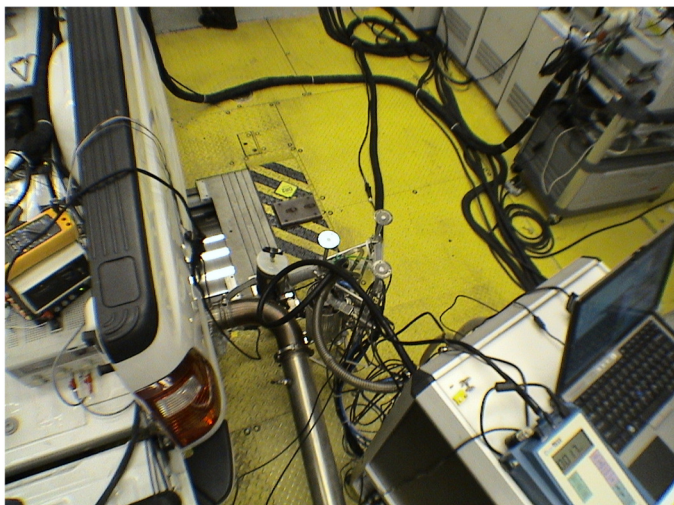


Figure 6. Dilution System Setup with FPS-4000

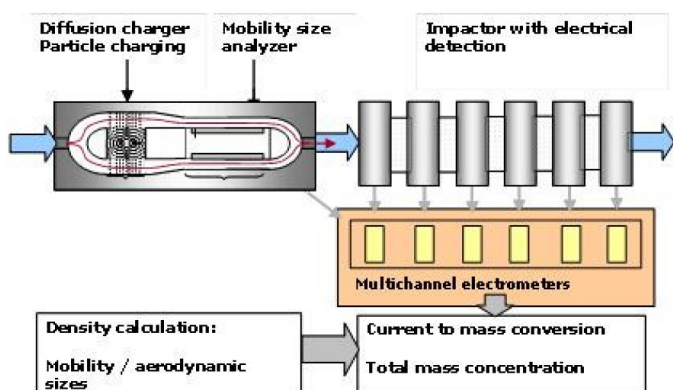


Figure 7. Schematic of DMM operating principle [2]

In addition, particle size distribution measurements were made using a TSI, Inc. Scanning Mobility Particle Sizer (SMPS). The instrument was typically sampling from the soot plane location to look for any changes in particle size across the selected plane relative to the tailpipe. Sampling and dilution used the same equipment as for the PM mass measurements; however, only one stage of dilution, with a dilution factor of 8, was required for the post DPF measurements. The SMPS generates high resolution size distribution spectra based on particle electrical mobility. See [figure 8](#) for a generic schematic of the SMPS [3]. It was configured to span a size range of 7 - 300 nm with a scanning time of 2 minutes. Along with particle number count, both mean particle diameter and geometric standard deviation were calculated by fitting the spectra to a lognormal distribution. For the tests with the diesel engine, particle diameter was typically around 60 - 100 nm, depending on engine operating conditions.

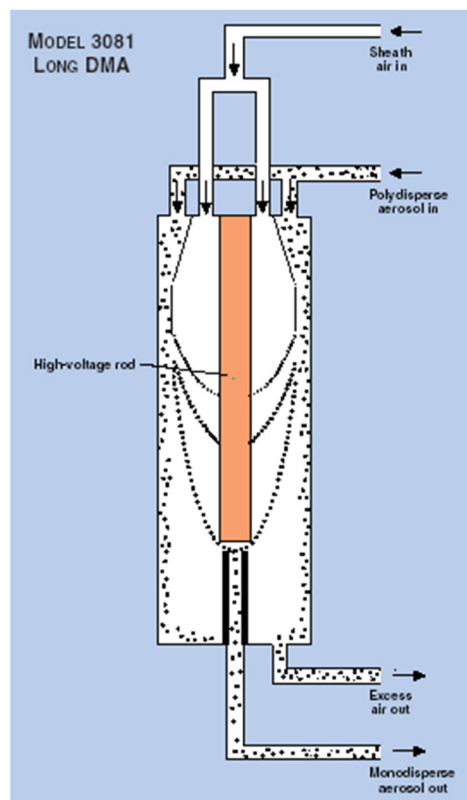


Figure 8. Schematic of SMPS operating principle [3]

Initial DPF Bypass Fault Simulations

Several DPF “bypass” rigs were studied before deciding on the final model. A first attempt was a simple one inch pipe bypass around the DPF with a ball valve and a 4” angle cut insertion tube (back into the pipe after the DPF), see [Figure 9](#). A sample probe that was cross drilled 1/2” along the axial length from the terminated tip was employed to simulate the exposed soot sensor sampling surface area ([Figure 10](#)). The probe was positioned radially across the inner diameter of the exhaust pipe to record PM mass with the DMM at the 3 different locations noted in [Figure 11](#) (an additional measurement was also taken downstream at the tailpipe). Using graphite ferrules the probe was moved to each position, then tightened down, a one minute sample was taken, then loosened and moved to the next position. Note the maldistribution of PM at the various sample positions shown in the chart in [Figure 12](#). Control of the PM leak rate with the ball valve by-pass was extremely limited as was the PM mixing downstream due to the angle cut by-pass return tube.

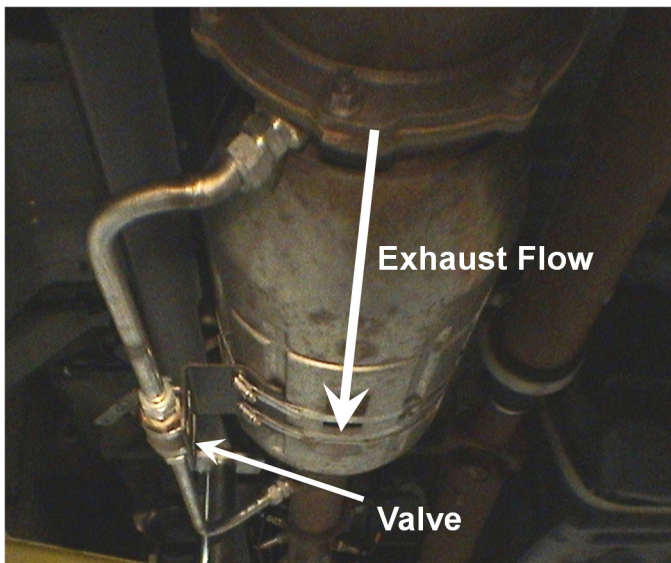


Figure 9. 1st generation DPF by-pass-picture of by-pass and schematic of re-entry pipe at bottom



Figure 10. Picture of cross-drilled sample probe and sample PM sensor

Bypass
(Soot In)

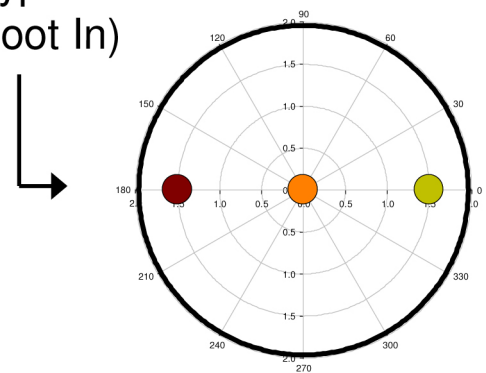


Figure 11. Schematic of probe location test points for 1st generation DPF by-pass testing

W208 F450 diesel - PM probe
evaluation (post DPF)

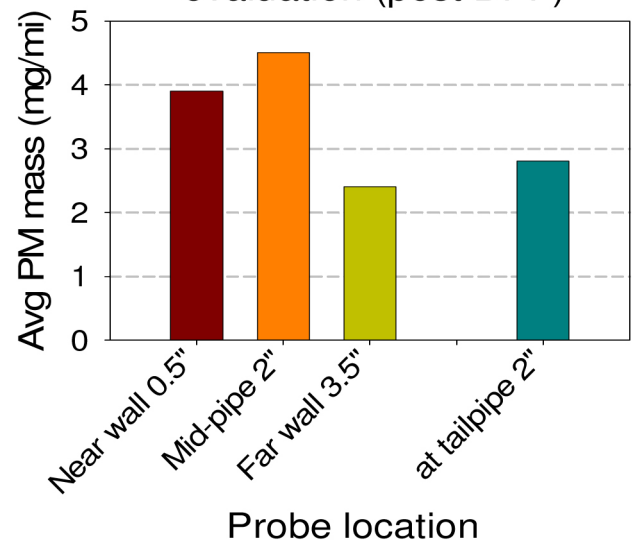


Figure 12. PM mass results from 1st generation DPF by-pass as a function of probe location

A second generation DPF “bypass” rig is shown in Figure 13. This unit was constructed to evaluate various prototype PM measurement instruments. The unit uses a full size 8”×10” DPF with a “full flow” 2 ½” bypass that was designed to be placed at the rear of a diesel vehicle with no DPF installed. The unit has DPF inlet and bypass butterfly control valves. This unit provided much better range of bypass control but was still not completely representative of a DPF brick failure. Limited results are shown in Figure 14. Based on the results so far it was determined that a more representative simulated DPF fault was required to better understand soot distribution in order to optimize PM sensor placement. An original equipment DPF would need to be modified to more closely replicate a real world DPF fault. A modified DPF would accurately represent the flow of PM