

Investigation of PM Size Distributions in an Exhaust Plume Emitted By Heavy-Duty Diesel Trucks at Cruise and Idling Operations: Wind Tunnel Results.

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The present work is aimed at determining the diesel particulate matter (DPM) formation and evolution in the exhaust plume from Heavy-Duty Diesel Trucks (HDDT) operated in a wind tunnel. Diesel engines have been widely studied under controlled laboratory conditions with the use of constant volume sampling (CVS) systems and to a limited extent through on-road chase studies. Moreover, the understanding and knowledge has recently been further extended to new emission reduction technologies, such as the diesel particulate filter (DPF) which has dramatically changed the size distribution and chemical composition of PM and the selective catalytic reduction (SCR) technology, which has shown to further affect the formation of nucleation mode particles as well as alter their morphology. West Virginia University (WVU) is attempting to close the present knowledge gap between laboratory testing and real world emissions by conducting detailed experiments in a custom designed and constructed environmental wind tunnel.

The WVU wind tunnel is a subsonic, non-recirculating suction type tunnel, with a 16ft high and 16ft wide test section capable of housing a full-size cab of a heavy-duty tractor. This tunnel employs a 2,200hp suction fan to provide up to 80 mph wind speeds. The 115ft test cell length guarantees a 2 seconds residence time for the plume (at 35 mph) and complies with turbulence and quality flow standard identified for this study. In addition, an automated track-mounted cart, that houses the instruments, is connected to a probe system that affords three-dimensional measurement of spatially resolved plume characteristics. These targets and constraints lead to several aerodynamic and structural challenges. Data collected experimentally and computational fluid dynamics (CFD) simulations of the flow field within the wind tunnel show that the main mixing process between the exhaust and ambient air (dilution air) stream occur within a few feet downstream the exhaust stack (behind the truck's cabin), agreeing well with actual turbulent flow field measurements as reported by Gautam et al. (2003). Three vehicles with different aftertreatment configuration have been tested during the first set of experiments. Specifically, the selected vehicle/aftertreatment configurations include: pre-2007 heavy-duty diesel truck, post-2007 heavy-duty diesel truck and post-2010 heavy-duty diesel truck. Three different operating conditions have been simulated on the chassis-dynamometer for each of the three test vehicles as listed below: idle with 5 mph wind speed (steady state), cruise at 35 mph (steady state), cruise at 20 mph (steady state). Characterization of the plume has been carried on using several analyzers, an Engine Exhaust Particle Sizer (EEPS) for the DPM. At the same time CO₂ and NO_x identify the gas phase. In addition, a temperature sensor complete the suite of tools in use to characterize the plume. Indications from different physical measurements well agree with each other, providing a complete picture of core and peripheral zones of the plume. DPM formation and evolution is traced from raw exhaust to complete dilution, investigating dilution and mixing phenomena. PM emissions results will be discussed for the three test vehicles that are meant to represent three technological approaches to particulate matter control, as represented by a pre-2007, post-2007 and post-2010 vehicle. The results of the 20 mph tests will be discussed herein, while the remaining data will be discussed in future publications.

Analysis of the plume from the pre-2007 truck at second sampling plane (Plane2: 115mm after the exhaust stack) indicates that CO₂ and NO_x plots are quite similar in shape, dimensions, position and property gradient, and are very much symmetric with respect to the plume (exhaust outlet) centerline. Conversely, the TI, due to the aerodynamic interaction of the wake formed behind the truck and the exhaust, has a very asymmetric behavior. The sampling points for this plane are represented by the white circles in order to substantiate exhaust outlet and plume centerline. Figure 1 demonstrates the transformed measured TPC (EEPS reading) into a tailpipe corrected TPC through application of the local DR. It is noted that in this plot the contour scale (colored bar on the right) represents higher values due to the dilution correction. This figure clearly indicates a shift in the contour “center” toward the lower region of the plume, where higher TI is encountered. Figure 1 further illustrates that this shift and increase of the corrected TPC is driven by the nucleation mode, (nTPC). Note that the accumulation mode contour (aTPC) resembles the TPC, with the maximum value centered in the core of the plume. This result suggests that higher TI regions trigger more rapid cooling processes, and ultimately the growth of nucleation mode particles. Since the accumulation mode is composed mainly of solid particles, a similar transformation is not invoked by this rapid cooling process, as confirmed by Rönkkö et al. The CMDs are 12nm and 53nm, respectively, for nucleation and accumulation mode. These are very typical values for bimodal diesel PM PSDC. Further confirmation of the strong dependence of nucleation mode particle formation with increasing TI is provided by the PSDC in Figure 1. If one selects a point in the core of the plume (Point1 – red series) and a point where high TI is indicated (Point10 – blue series), the nucleation mode is shown to increase by as much as an order of magnitude (while the accumulation mode is nearly equal at both locations.. It is important to note that the formation of the nucleation mode occurs very close to the exhaust stack outlet, and from this point on only dilution (without any transformation of the PM PSDC) occurs. In Plane1 (15mm from the exhaust stack) a peak of 15% TI was measured. This would result in dilution processes that are far more violent than the ones that occur further downstream in the plume.

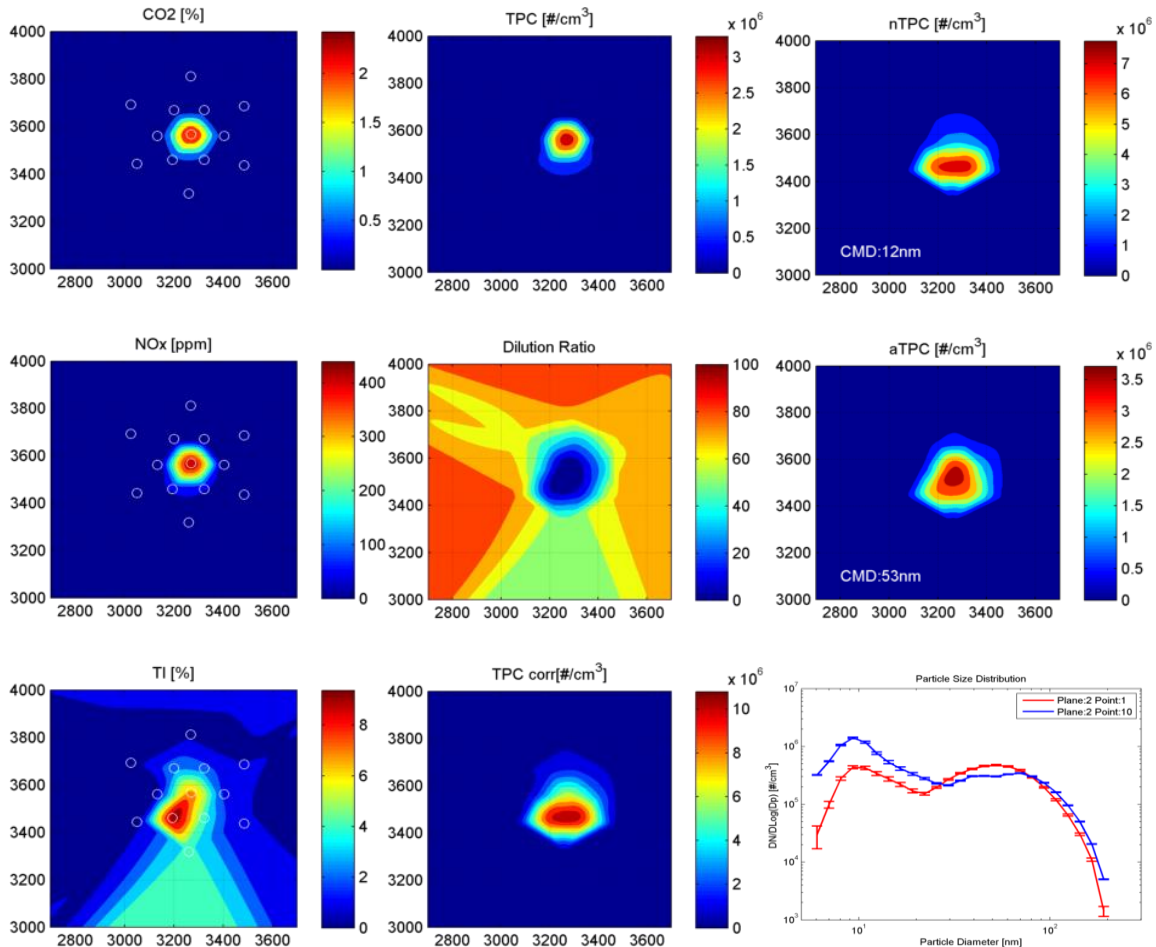


Figure 1: CO₂, NO_x, and Turbulence Intensity, Total Particle Count, Dilution Ratio, Corrected Total Particle Count, Nucleation and Accumulation mode Particle Count, Particle size distribution and concentration for the sampling point with higher turbulence intensity (Point1) and core of the plume (point10) for a pre-2007 truck measured 115mm from the stack at 20 mph wind speed. Measurement points are shown in white circles.

The post-2007 truck plume measurements were quite similar to those made from the Pre-2007, mainly because the cracked DPF allowed a portion of solid particles to pass through the DPF. However, overall PM and HC emissions were lower. As mentioned earlier, the crack in the DPF was not significant enough to prevent loading of the DPF and subsequent regeneration cycles. The active regeneration system on this HDDT operates injecting fuel directly into the engine-out exhaust via a 7th injector. During the regeneration event (observed between point8 and Point13 of Plane6), there was an increase of CO₂ emission concentrations from 8.37% to 11.45%, while NO_x and HC emissions were largely unaffected. During the regeneration event, measurements indicated that PM emissions increased by one order of magnitude in both nucleation and accumulation mode. Although, the regeneration event strongly influence the PM emissions the TI effect was still evidentiate. The chemical composition of the PM samples were not characterized, but from literature (Rönkkö et al) it is known that increased temperatures in the exhaust encountered during regeneration most likely changed the chemical composition of the nucleation mode as well.

The post-2010 truck, equipped with a state-of-the-art aftertreatment system, produced very low PM emissions that were difficult to differentiate from those naturally occurring PM found in the background air and the TI effect was not clearly visible.

In light of this results, deeper knowledge of the correlation of TI and nucleation mode formation is necessary, leading to evaluate methods and technologies capable to reduce such interaction. A reduction in exposure of hot exhaust to colder high-TI regions may inhibit or sensibly reduce the PM nanoparticle emissions, with greatest advantages at large.



West Virginia University

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Center for
Alternative Fuels,
Engines and
Emissions

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INTRODUCTION

- In 2009, a Team comprising of researchers from West Virginia University (WVU), Cornell University and NASA pro-posed to characterize the physical and chemical evolution of the exhaust plume from 2010 compliant Heavy-duty Diesel Engines (HDDE). With funding from the California Air Resources Board (CARB).
- The focus of the study is to measure and compare the changes in PM size distribution and optical properties of trucks compliant with different US EPA emission standards and at different vehicle speeds.
- The WVU tunnel is well equipped to characterize the initial plume dilution process, which is the key difference between the on road and laboratory measurements.

OBJECTIVES

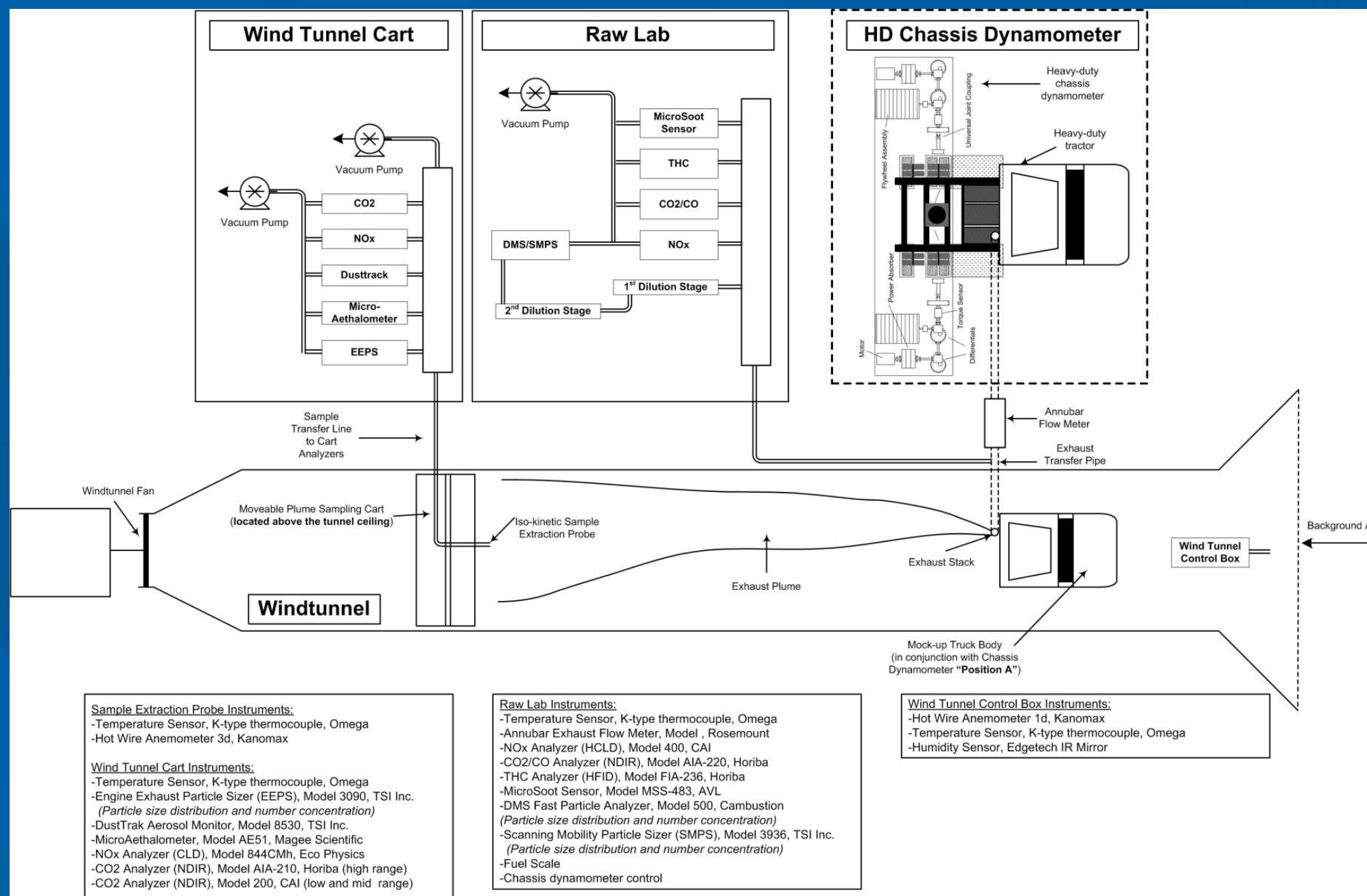
- Generate a benchmark database to bridge on-road and laboratory emission measurements;
- Quantify ultrafine particle formation/growth potentials;
- Compare particle formation and evolution among vehicles compliant with several US EPA standards
- Develop turbulent reacting flow model to quantify the aging process of diesel plumes and its effects on chemical and physical properties of diesel particulate matter.

WVU WIND TUNNEL SPECIFICATIONS

- The WVU design is a classic “pulling” tunnel, where the truck is located up-stream near the inlet.
- The air is pulled inward into the test section and then pulled out through a suction fan at the far end of the tunnel. The propeller is driven by a 220hp diesel engine.
- Common wind tunnel practice guarantees <1% Turbulence Intensity (TI).

	Value	Unit
Test Cell Width	16	Ft
Test Cell Height	16	Ft
Test Cell Length	115	Ft
Turbulence Intensity	<1	%
Max Wind Speed	60	mph

EXPERIMENTAL SETUP



Schematic of the Experimental Setup during the Wind Tunnel Testing

EXPERIMENTAL METHODOLOGY

- The plume investigation comprises of 130 sampling points divided into 10 planes. Each plane presents the same sampling pattern, with different vertical dimension and position, allowing to better focus on the plume shape evolution. The pattern is composed of 2 nested hexagons, rotated by 90°, and an additional center point.
- Three different vehicle/wind speed are tested: 20mph, 35mph and idling (5mph wind).



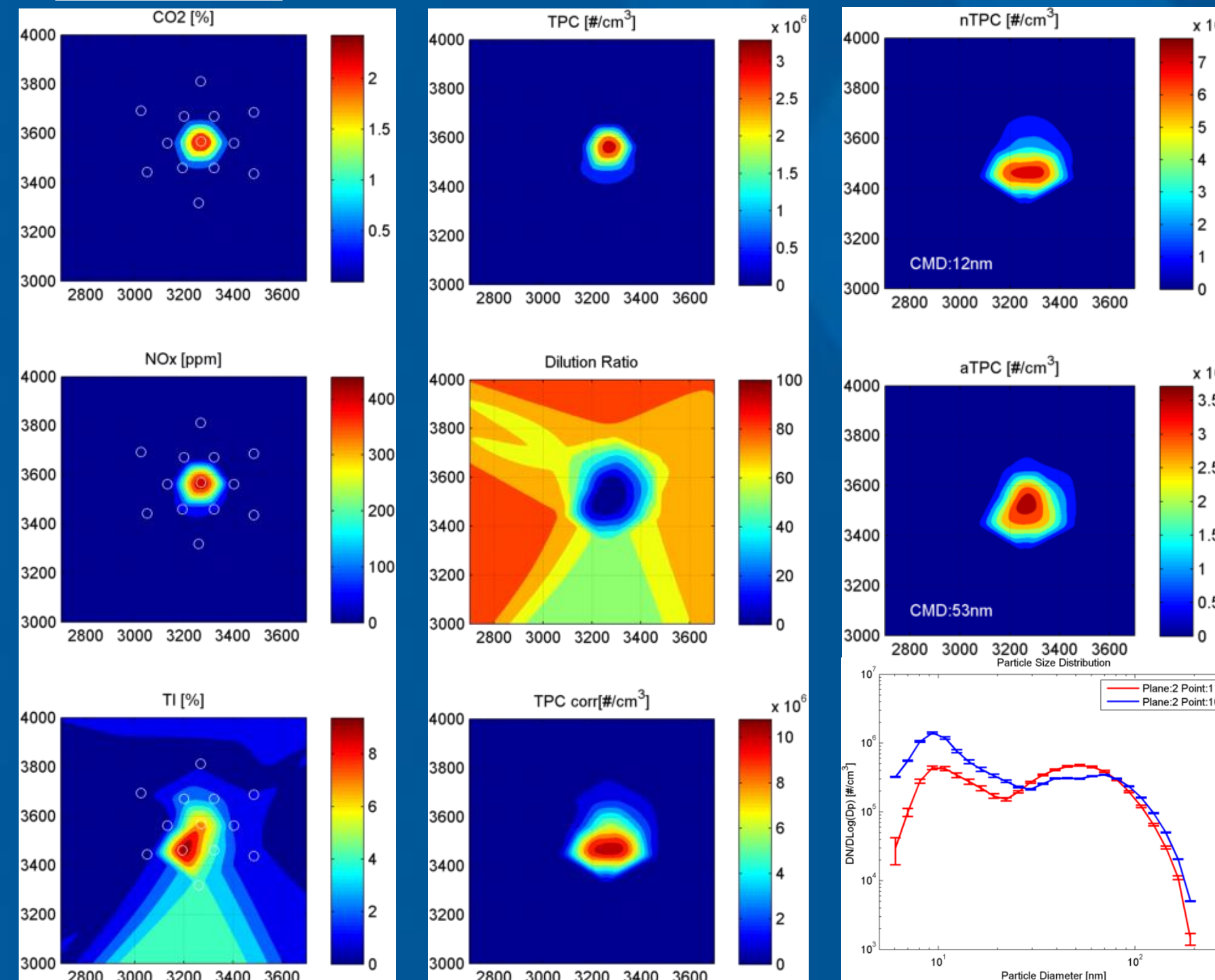
The class8 heavy-duty diesel trucks identified for this test campaign and investigation are:

- MY95 Mack CH613 equipped with 11.93l E7-400 engine. The vehicle is not equipped with any after-treatment devices and it is part of the CAFEE fleet.
- MY08 Freightliner C1120 equipped with 14.0l Detroit Diesel Series60 engine. The vehicle is equipped with DOC/DPF to meet the 2007 US EPA regulations.
- MY11 Mack CXU613 equipped with 12.8l MP8-445C engine. The vehicle is equipped with urea-based SCR and DOC/DPF assembly to meet the 2010 US EPA regulations.

RESULTS

- PM emissions results will be compared from the three test vehicles that are meant to represent three technological approaches to particulate matter control, as represented by a pre-2007, post-2007 and post-2010 vehicle. The results of the 20 mph tests will be discussed herein, while the remaining data will be discussed in future publications.

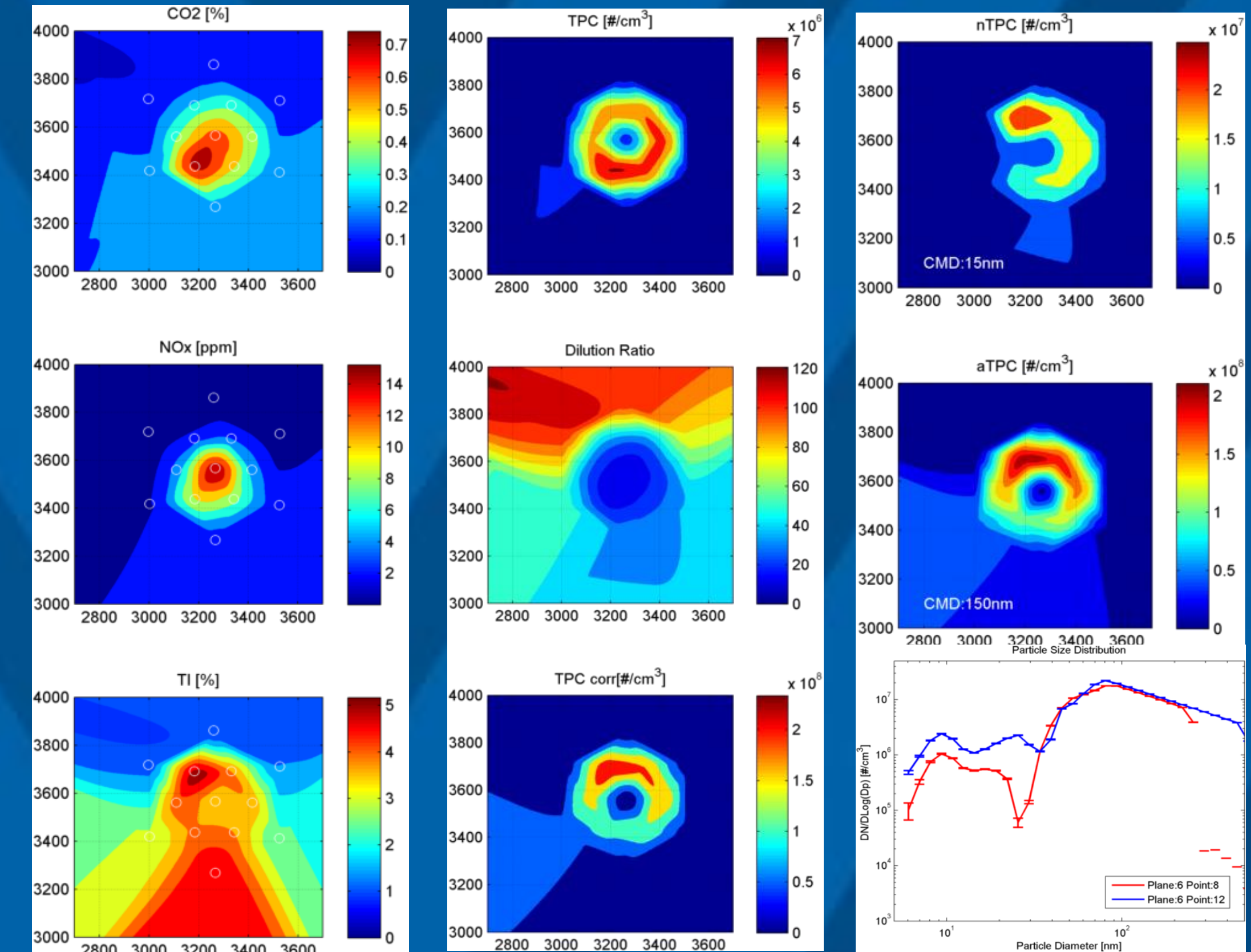
Pre-2007 Truck



Cut-Plot for Pre2007 Truck at Sampling Plane 2 (315mm behind the exhaust stack)

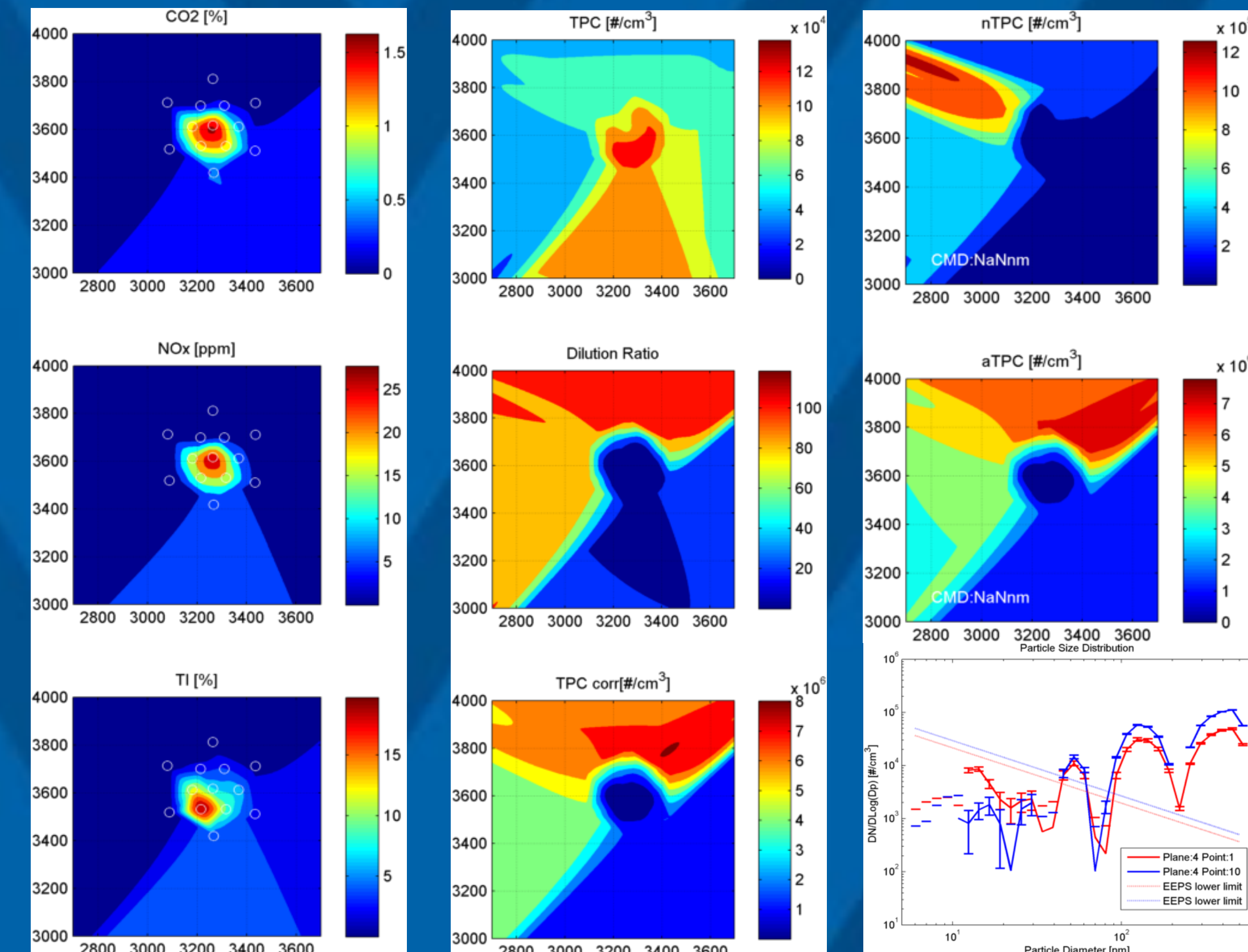
RESULTS (cont'd)

Post-2007 Truck



Cut-Plot for Post2007 Truck at Sampling Plane 6 (1815mm behind the exhaust stack) during regeneration event

Post-2010 Truck



Cut-Plot for Post2010 Truck at Sampling Plane 4 (815mm behind the exhaust stack)