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Title: *Measurement of Emissions from both Active and Parked Regenerations of a Diesel Particulate Filter from Heavy Duty Trucks*

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ES. EXECUTIVE SUMMARY

ES-I Background and Introduction

This investigation is concerned with emissions associated with Diesel Particulate Filters, DPFs, on heavy duty diesel engines that are certified for compliance with 2007 and 2010 emission standards. A recent Phase I investigation, which was concerned with active parked regenerations of both 2007 and 2010 DPFs, has shown that there are significant differences between the quality and quantity of PM mass and particle number for the two technologies. For example, the 2007 DPF emitted a large amount of mass and large particles at the beginning of DPF regeneration, and this was followed by a relatively long period of a very large number of ultrafine particles. This result was unexpected, and it was one of the primary objectives of the present investigation to determine some of the chemical properties of these large PM particles. As was expected the 2010 DPF emitted less PM than the 2007 DPF during the active parked regeneration. The results showed that there had been significant improvement in the 2010 technology relative to the 2007 technology. However, the particle number results for the 2010 DPF were surprisingly similar to the 2007 results during the parked regenerations. Although the mass emissions were less for the 2010 DPF, the total time for the active parked regeneration was essentially the same for the 2007 and 2010 DPFs, and the level of ultrafine particle number concentration and size distributions of the particles were very similar.

A parked active regeneration is a special operating case for a diesel engine, since no power is being generated by the diesel engine to power the tractor and trailer on the road. With significant power generated by the engine for road travel the exhaust gases into the DPF are in a significantly different state. Therefore, it is expected that an active regeneration on the road will have different characteristics than a parked regeneration for both the 2007 and 2010 DPF technologies. Also, active road regenerations of DPFs occur much more frequently than parked active regenerations. Therefore, a primary part of the present study is to investigate active road regenerations of the 2007 and 2010 DPFs.

Recent advances in DPF technology have significantly increased passive regeneration in DPFs, as has been observed during extensive testing of 2010 DPFs. The present Phase II investigation was designed to have an extended period of stop and go traffic in order to build up a larger PM load in the 2010 DPF. For example, five to ten hours of stop and go traffic followed by high engine temperature road driving, and it was expected that this type of driving pattern would lead to a large release of passive regeneration PM and particle numbers from the 2010 DPF.

Another very important difference between this Phase II investigation and the previous Phase I study was the method used to load the DPF with stop and go traffic. In Phase I the cab and trailer were driven in stop and go traffic in the Sacramento area, while in the Phase II study the cab was driven on the MLD Depot Park chassis dynamometer with a driving pattern which was designed to simulate stop and go intercity conditions. At the start of this Phase II study it was not known to what extent the two different DPF loading conditions would influence the results, and it will be shown in this report that the differences are important.

ES-II Methods

There were two important changes that were added to the testing during Phase II compared to

Phase I, and they were the following: (1) The PM loading on the DPFs of the two trucks was accomplished with the use of the Depot Park chassis dynamometer; and (2) A filter system to collect PM for chemical analysis was built and added to the ambient wind tunnel. A brief description of the chassis dynamometer is given in Appendix I, but the most important task needed to employ the chassis dynamometer was to develop a method of loading of PM into the DPF. Shown in Figure ES-1 is the velocity speed and Selective Catalytic Reactive, SLR, temperature during dynamometer loading of the 2010 DPF. The vehicle speed varied between 12 and 22 mpg in an accelerating and deaccelerating pattern, which kept the exhaust system below 200 deg C, and this driving method allowed for an active DPF regeneration to occur after 30 to 35 hours of driving. The later time portion of Figure ES-1 shows the vehicle being accelerated to 55 mpg under heavy load, and this driving pattern was used for the passive regeneration part of the testing.

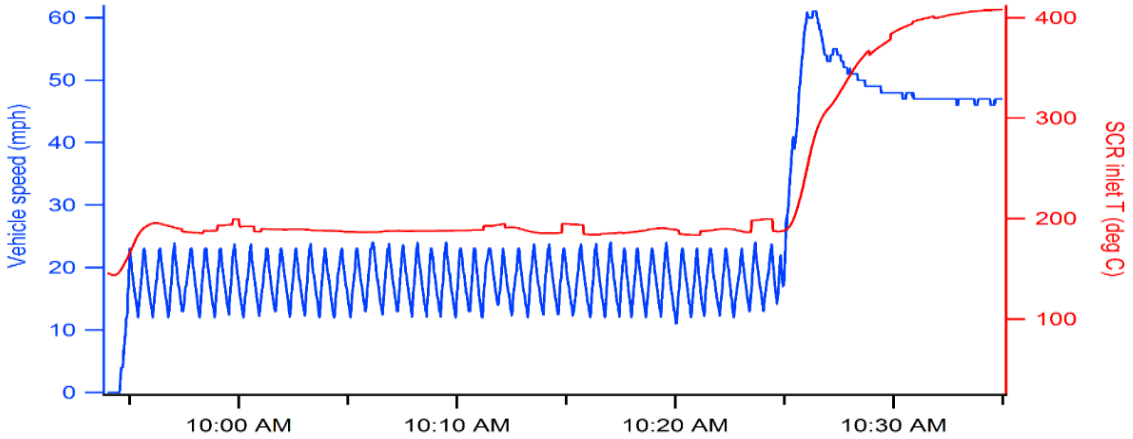

Figure ES-1 Typical velocity and exhaust temperature during dynamometer loading of a DPF

The second part of the changes to the ambient wind tunnel was the addition of a filter system to determine some of the chemical properties of the emitted PM, Figure ES-2. The filter system had four channels, but each channel had two separate filters. The purpose of the two separate filters was to separate the PM collected during the initial soot burning and later fuel burning phases of an active DPF regeneration. During Phase I of the testing there were a very significant differences in the PM size emitted from the DPFs during the first 25% of the regeneration and the remaining 75% of the active regeneration. The filter system collected and measured PM mass, PM sulfate, PM elemental and organic carbon (EC/OC), and elemental composition were analyzed by ECARS. The new filter holder system was built and designed by Professor Dwyer, RD staff, and Depot Park staff and the pumps and filter holders were supplied by RD and MLD.

Figure ES-2 Photograph of two stage filter system for soot and fuel burning phases.

ES-III Results

A total of eleven regeneration tests were carried out in Phase II, and they are summarize with the use of Table I. A total of five active regenerations of the 2007 DPF were performed, and three of the regenerations were parked and two were road regenerations. For the 2010 DPF six regenerations were performed, and these consisted of one parked active regeneration, two road active regenerations, and three passive regenerations.

Summary Table for Mass Estimates from Particle Instruments and Filters

Vehicle and test type	Test # and date	DMM-g	SMPS-g	Gravimetric Mass-g
2007/flashing light/park	test1-2/23/15	2.49	0.809	0.717
2007/flashing light/park	test2-3/18/15	1.78	1.71	0.981
2007/flashing light/park	test3-4/23/15	5.6	0.91	5.4
2007/light on/road	test4-5/12/15	3.25	0.59	1.87
2007/flashing light/road	test5-5/29/15	7.33	1.33	4.07
2010/light on/park	test6-7/15/15	6.47	1.14	2.64
2010/light on/road	test7-8/5/15	35.1	2.61	16.3
2010/light on/road	test8-8/26/15	23.3	3.32	9.44
2010/light on/passive	test9-9/15/15	0.025	0.012	0.159
2010/light on/passive	test10-9/17/15	XXX	0.036	0.102
2010/light on/passive	Test11-9/22/15	0.120	0.062	0.220

Parked Active Regenerations

The first two parked regenerations were carried out with a different stop and go driving pattern, while the third regeneration, test3, utilized the pattern shown in figure ES-1. Although all three tests had a flashing DPF light, the amount of PM emitted from the DPF was much larger for test3. Test3 had more than five times the amount of emitted PM than test1 and test2, and this a good example of the driving pattern having a strong influence on the emissions from the DPF.

An important part of the Phase II testing was to determine some chemical properties of the large amount of PM particles larger than 2.8 micron that were emitted by the 2007 DPF in the Phase I study. However, tests 1 thru 3 did not emit significant numbers of these large particles, and this is a good example of how the emitted PM is a function of the driving pattern. In general, the fuel burning part of the DPF regeneration was very similar for both Phase I and Phase II studies, and the amount and characteristics of the PM was very similar.

The active parked regeneration of the 2010 DPF, test7, resulted in more PM for Phase II compared to Phase I testing. Test7 also had insignificant emissions of particles larger than 2.8 microns, but the characteristics of the fuel burning phase were similar. However, Phase II emissions were larger by a factor of two, due to larger diameter particles being generated.

Road Active Regenerations

Road active regenerations were not performed in Phase I since a chassis dynamometer was not available, and four active road regenerations were carried out in Phase II. The road regenerations of 2010 DPF, test7 and test8, generated substantially more PM on the filter than the 2007 DPF, test4 and test5, and this was opposite to the active parked regeneration results in Phase I. The large amount of emitted PM from the 2010 DPF occurred with the DPF console light on, since it was not possible to generate a flashing light state for the 2010 DPF. Also, all active regenerations of both the 2007 and 2010 DPFs did not emit substantial amounts of PM particles larger than 2.8 microns.

For the 2007 DPF the amount of PM emitted for the parked and road regeneration had similar particle size characteristics and similar characteristics during the soot and fuel burning phases of the regeneration. However, the particle size emitted for the road regeneration of the 2010 DPF was much larger than the 2007 DPF, and the mean particle size emitted from active road regeneration of the 2010 approached 100 nanometers during the fuel burning phase of the regeneration. The particle number emissions for the road regeneration of the 2010 DPF were similar to other tests, but the large size of the PM particles were different than all previous testing for particles less than one micron.

Passive Road Regenerations

Three passive road regenerations were performed on the 2010 DPF. The DPF was loaded with five to ten hours of stop and go traffic, and this was followed by high speed and load driving as shown in figure ES-1. Since the exhaust temperature in the SCR after treatment reached values greater than 400 deg C, it was assumed that passive regeneration would begin quickly. For the first two tests, test9 and test10, the testing was stopped after twenty minutes, since only large numbers of particles less than twenty nanometers were emitted, and these particles have very small mass.

For test11 the passive regeneration was extended to thirty minutes, and again it was stopped since the real time particle instruments were being dominated by large number of particles less than twenty nanometers. However, post-test analysis of the particle instrument data showed that

significant numbers of large particles were increasing for ten minutes, and these particles were as large as one hundred nanometers. Also, the filter data for test11 had more than twice as much mass emitted compared to tests 9 and 10. Further tests were not able to be performed, since the 2010 truck and DPF were need for other CARB testing, and the Phase II contract ended.

Particle Instrument Prediction of PM Mass Emissions

Shown in Table I are estimates of PM emissions from the particle instruments employed in the testing, which were the SMPS and the DMM. In general the filter weights were bracketed by the SMPS and the DMM estimates, with the DMM giving larger values and the SMPS giving smaller values. The mass predictions require the use of particle concentration versus size as well as particle density versus size, and there is uncertainty especially concerning particle density. Also, the DMM and SMPS record over different size ranges, different time sampling ranges, and assume different particle density distributions. Since the DMM records over a larger particle diameter range and assumes a larger density for larger particles, results in Table I appear to be quite reasonable. It can also be stated that both the DMM and SMPS gave valuable insight into all the regeneration events in this study.

Chemical analyses on PM filter samples

PM filter samples from the dilution tunnel were subject to four analyses including gravimetric mass, thermo-optical carbon, ion chromatography (IC), and X-ray fluorescence (XRF). Thermo-optical carbon is comprised of Organic Carbon (OC) and Elemental Carbon (EC); ion chromatography detects Na^+, K^+, NH_4^+, Ca^{2+}, Mg^{2+}, Cl^-, NO_3^-, SO_4^{2-}, and PO_4^{3-}; and XRF detects 44 total elements.

Due to relatively high ambient concentrations of several species including Na^+, Cl^-, and NO_3^-, only four species contributed to the speciated emitted mass: OC, EC, NH_4^+, and SO_4^{2-}. A total of 14 filters from 8 test were analyzed, and the percentage of gravimetric mass that was speciated was 79 ± 10% (quoted uncertainty is the standard error). Several factors could be contributing to the "missing mass." Thermo-optical carbon does not include any other elements (besides C) incorporated into the organic matter, and so any O, N, S, H, etc. that comprises this matter is not detected. IC only detects water-soluble ions, and so insoluble material is not included in this analysis. Also, XRF analysis occurs under a vacuum, and so any volatile PM may evaporate before it is detected. Finally, if any ambient PM entering the tunnel evaporates as it is warmed ~10-20 degrees above ambient temperature, the background subtraction will cause emitted PM to be biased low.

The molar ratio of $NH_4{:}SO_4$ was quite low, only 0.37 ± 0.07 for all tests, and was slightly lower for the 2010 truck (0.28 ± 0.11) than for the 2007 truck (0.39 ± 0.08). Since fully-neutralized sulfate has an $NH_4{:}SO_4$ ratio of 2, this indicates that the PM emitted during DPF regenerations is highly acidic. It is possible that some basic material besides ammonium is present in this PM analyses (such as organic amines).

The quantified mass was dominated by sulfate, which comprised 81 ± 2% of speciated PM mass (i.e. 64% of total gravimetric mass). This was true for both the 2007 (80 ± 3% sulfate) and 2010 (82 ± 5% sulfate) HDDV. This is consistent with previous studies of high-speed driving of 2010-compliant HDDVs. Carbon only comprised 9 ± 1% of the speciated PM by mass, suggesting that engine-out PM stored on the DPF was converted to CO_2 very efficiently. Sulfur was also detected by XRF, and a comparison between IC SO_4^{2-} and XRF S was performed. The amount of sulfate

detected by IC was consistently less than that predicted if all XRF sulfur was assumed to be in the form of sulfate. This suggests that about half of the sulfur is in a different form, perhaps incorporated into the organic material and/or in an insoluble organic form. Other than sulfur, the only XRF elements detected above ambient levels were phosphorus (4 tests), nickel (2 tests), and chromium and manganese (one test each). None except for sulfur contributed significantly (>1%) to quantified mass.

DPF Efficiency

RD and MLD staff were able to measure the DPF PM loading, and this measurement took considerable time and effort. The measurement required the DPF to be taken off the truck and carefully weighed. The DPF was then put back on the truck, and the truck was then placed on the dynamometer to collect the engine PM. After the DPF accumulated enough mass for a regeneration to be carried out, the DPF was again taken off the truck and weighed. If no PM was collected on the tunnel filter, the efficiency of the DPF would be 100%, since all the PM was converted in gaseous products. Therefore, the mass collected on the tunnel filter represents PM that was not converted to gaseous products plus gaseous products that were converted to PM, e.g. sulfate. With both the amount of mass collected by the DPF and the tunnels filters, a DPF efficiency can be defined as the DPF mass converted to gaseous products divided by DPF mass collected, which is given below.

$$DPF\,(efficiency) = \frac{DPF\ Mass\ Collected - Tunnel\ Filter\ Mass}{DPF\ Mass\ Collected} x100$$

The results of these measurements are shown in the table given below, and it can be seen that the DPF efficiency is high except for the road active regenerations of the 2010 DPF. Since these results are for two tests, general conclusions cannot be made. A possible recommendation for future research is to continue DPF loading studies with stop and go traffic. There is a possibility that stop and go traffic could lead to a different type of PM in the DPF.

Summary Table for Gravity Mass and DPF Efficiency Measurements

Vehicle and test type	Test # and date	Filter Mass-g	DPF Mass-g	Ratio PM/DPF	DPF Efficiency
2007/flashing light/park	test1-2/23/15	0.717	168.7	.00426	99.57
2007/flashing light/park	test2-3/18/15	0.981	137.1	.00715	99.28
2007/flashing light/park	test3-4/23/15	5.4	136.5	.03956	96.04
2007/light on/road	test4-5/12/15	1.87	100.9	.01856	98.14
2007/flashing light/road	test5-5/29/15	4.07	141.9	.02871	97.13
2010/light on/park	test6-7/15/15	2.64	120.3	.02172	97.83
2010/light on/road	test7-8/5/15	16.3	93.60	.17436	82.56
2010/light on/road	test8-8/26/15	9.44	89.15	.10846	89.15

I. BACKGROUND AND INTRODUCTION

This investigation is concerned with emissions associated with Diesel Particulate Filters, DPFs, on heavy duty diesel engines that are certified for compliance with 2007 and 2010 emission standards. A recent Phase I investigation, Ref. [1-13], which was concerned with active parked regenerations of both 2007 and 2010 DPFs, has shown that there are significant differences between the quality and quantity of PM mass and particle number for the two technologies. For example the 2007 DPF emitted a large amount of mass at the beginning of DPF regeneration, and this was followed by a relatively long period of a very large number of ultrafine particles. The PM mass emissions from the high mass initial phase of the parked regeneration for the 2007 DPF was measured with a DustTrak, and there were very large particles emitted in the PM 2.5 to 10.0 micron range. This result was unexpected, and it was one of the primary objectives of the present investigation to determine some of the chemical properties of these large PM particles. The ultrafine particle emissions from the 2007 DPF were measure with the EEPS and SMPS particle instruments, and the majority of these ultrafine particles were between 10 and 50 nm. Also, there were only trace amount of particles in the range between 1.0 microns and 2.5 microns.

As was expected the 2010 DPF emitted less PM than the 2007 DPF during the active parked regeneration, and the levels of the DustTrak emissions for the 2010 DPF at all times were lower than the early time emissions of the 2007 DPF. The results showed that there had been significant improvement in the 2010 technology relative to the 2007 technology. However, the particle number results for the 2010 DPF were surprisingly similar to the 2007 results during the parked regenerations. Although the mass emissions were less for the 2010 DPF, the total time for the active parked regeneration was essentially the same for the 2007 and 2010 DPFs, and the level of ultrafine particle number concentration and size distributions of the particles were very similar.

A parked active regeneration is a special operating case for a diesel engine, since no power is being generated by the diesel engine to power the tractor and trailer on the road. With significant power generated by the engine for road travel the exhaust gases into the DPF are in a significantly different state. Therefore, it is expected that an active regeneration on the road will have different characteristics than a parked regeneration for both the 2007 and 2010 DPF technologies. Also, active road regenerations of DPFs occur much more frequently than parked active regenerations. Therefore, a primary part of the present study is to investigate active road regenerations of the 2007 and 2010 DPFs.

Recent advances in DPF technology have significantly increased passive regeneration in DPFs, as was observed in the ACES 2 testing, Ref. [2], during extensive testing of 2010 DPFs. In fact, during a sixteen hour testing cycle no active regenerations were observed during the testing. However, there were periods when the passive regeneration resulted in the release of a large number of particles. The sixteen hour cycle used in Ref. [2] consisted of some stop and go traffic sub cycles, but the periods of high temperature road sub cycles were more numerous. The present Phase II investigation was designed to have an extended period of stop and go traffic in order to build up a larger PM load in the 2010 DPF. For example, five to ten hours of stop and go traffic followed by high temperature road driving. It was expected that this type of driving pattern would lead to a large release of passive regeneration PM and particle numbers from the 2010 DPF. Also, with the use of the small wind tunnel there should be more semi-volatile particles due to the higher dilution ratios and the lower temperatures in the mixed ambient air and exhaust gases.

Another very important difference between this Phase II investigation and the previous Phase I

study was the method used to load the DPF with stop and go traffic. In Phase I the cab and trailer were driven in stop and go traffic in the Sacramento area, while in the Phase II study the cab was driven on the MLD Depot Park chassis dynamometer with a driving pattern which was designed to simulate stop and go intercity conditions. At the start of this Phase II study it was not known to what extent the two different DPF loading conditions would influence the results, and it will be shown in this report that the differences are important. Some of the technical properties of the MLD heavy duty chassis dynamometer at Depot Park are given in Appendix I.

II. TEST METHODS USED AND DEVELOPED FOR EXPERIMENTS

A. Design and Construction

The small ambient wind tunnel of this project is a high dilution flow channel that mixes ambient air with the exhaust gases from the truck diesel engine, and it is the same system used for Phase I of this study, Ref. [1]. The small wind tunnel is shown in Fig. II-1, and it consists of six sections of length 5 feet and a square area of 4 feet by 4 feet. The material used for construction was 18 gauge galvanized steel ductwork. Attached to the rear or exit section of the tunnel is a fan that produced a volume flow rate of 9000 cfm, cubic feet per minute. The front or entrance section of the wind tunnel is shown in Figure II-2, and at the entrance there is a six inch long aluminum honeycomb section with channels of diameter of ½ inch to provide a more uniform entrance flow. At the center of the entrance section a five inch circular steel pipe was inserted and supported, and this pipe was connected to the diesel engine exhaust pipe with a twelve foot long flexible extension pipe. It should also be mentioned that PEMS instrumentation for regulated emissions was employed outside the tunnel on the circular steel entrance pipe.

A mixing plate was attached to the exhaust of the entrance pipe, and the mixing plate consisted of an eight inch circular plate with some holes drilled in it. The purpose of the mixing plate was to encourage mixing of the ambient air with the truck exhaust gases, and thus encourage formation of semi-volatile condensation particles in the gases. The mixing plate can be easily detached if a more natural mixing of the diesel exhaust gases with the ambient air was desired for another possible experiment.

Figure II-1 – Small wind tunnel with attached whole house fan. Tunnel length is 30' and the cross-sectional area is 4' by 4'.

Figure II-2 – Honeycomb inlet section of small wind tunnel with connection pipe for the truck exhaust pipe.

B. Design and Construction of Emission Sampling System

Close to the exit of the tunnel two sampling tubes were supported at the center of the tunnel, and the entrance of the sampling tubes were located at 27.75 feet from the wind tunnel entrance. One of the 2 inch sampling probes was approximately two and one and half feet long, and the sampling tube gases entered a 5 inch diameter settling chamber outside the tunnel that was approximately one foot long. The exit of the settling chamber was attached to part of a filter system followed by vacuum pump, as shown in Figure II-3, and the vacuum pump created a steady flow of approximately 170 liters per minute. Under these conditions it is estimated that more than 99% of all particles greater than 5 nm will pass thru the sampling tube without diffusional loses to the

wall. The only measurements taken inside the tunnel were temperature at various locations and CO_2/CO/relative humidity with the use of a Q-Trak Plus near the sampling probe entrance. The second sampling 2 inch tube was 8 feet long and was attached to the second part of the filter system, and another vacuum pump created a flow of approximately 170 liters per minute. An external view of the settling chamber with sampling tube connections for instrumentation is shown in Figure II-4, and the entire experimental testing setup is shown in Figure II-5.

Figure II-3 Photograph of two stage filter system for soot and fuel burning phases.

Figure II-4 Sampling tube with individual ports for emission instrumentation.

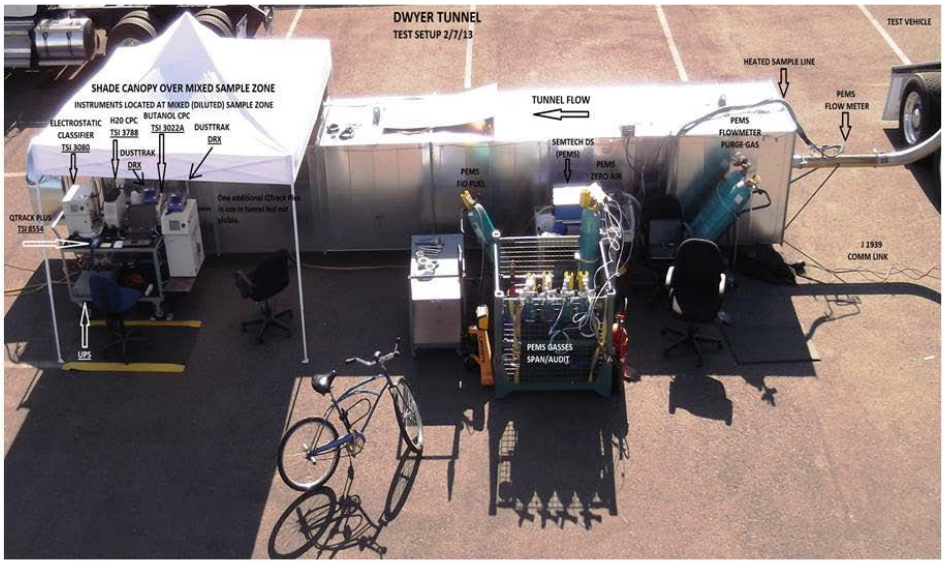

Figure II-5 Photograph of small wind tunnel and emission instrumentation

A detailed description of the instrumentation, filter system, and test plan are given in Appendix II, and a brief description will now be presented. A list of the instrumentation used in the testing and their location is given below:

Entrance Tube: (1) Portable Emission Measurement System, PEMS, (SEMTECH-DS, Sensors Inc.) for regulated emissions and diesel exhaust gas flow rate; (2) Thermocouples for measuring the temperature of exhaust gases entering the small wind tunnel; (3) SMPS for sampling the ambient; and (4) An entrance filter system for recording ambient air properties.

Inside the wind tunnel near the sampling probe: (1) Temperature of gases entering the sampling tube, CO2, CO, and relative humidity with the use of a Q-Trak Plus (TSI).

Instruments connected to settling chamber: (1) EEPS, FMPS, and SMPS (TSI); (2) DustTrak DRX–model 8533; (3) Temperature (Thermocouples); and (4) DMM-230, and (5) Aethalometer. Note: Only the SMPS and DMM were able to be used in the tunnel due to the very large concentration of particles. The EEPS and FMPS needed a particle diluter which was available during the testing.

On Board Diagnostics, OBD, from Truck Engines: Some information was made available and recorded from the OBD system of the engine manufacturer. Of particular importance was the outlet temperature from the DPF.

C. Filter System

The primary objectives for ambient wind tunnel filter sampling system are the following:

- A robust sampling system that collected emission samples on filters for the following four emission categories: (1.) PM mass and Ions; (2.) EC/OC; (3.) Elemental Composition; and (4.) An additional sampling line with MOUDI instrumentation.

- A panel showing the flow rates (rotometers and pressure gauges) into the filters, which was centrally located and visible for staff to adjust and control a proper filter face velocity into each filter.
- The filter system for the active regeneration study was capable of obtaining separate filters for the initial soot burning phase and the final fuel burning phase of the regeneration process.

D. Performance of the small wind tunnel

The small wind tunnel is designed to provide a homogeneous mixture of ambient air and exhaust gases to the sampling tube, and it is important to measure the quality of the flow being sampled. The flow in the small wind tunnel was been measured in the Phase I investigation by performing temperature and velocity measurements at various sections. At the location of the sampling tube, 24.75 feet from the tunnel entrance, both the vertical and horizontal velocity and temperature profiles are quite uniform, and it can be concluded that the exhaust gases and the ambient air are well mixed.

E. Description of test vehicles

The two HDD vehicles used in the testing were supplied by Depot Park, and both vehicles had Cummings engines and after treatment. The older vehicle was 2007 compliant with an engine displacement of 14.9 liters and the newer vehicle was 2010 compliant with an engine displacement of 14.9 liters. The major difference between the vehicles was that the 2010 compliant vehicle had a Selective Catalytic Reduction, SCR, system to reduce NO_x emissions. Also, it should be mentioned that the DPF for the 2010 vehicle had substantially enhancements over the 2007 DPF. The primary enhancements for the 2010 DPF were improvements of the catalyst materials to increase passive regeneration and the increased use of NO_2 to burn out PM in the DPF.

F. DPF regeneration events

The number of DPF regenerations that were carried out was eleven, and there were some variations in similar tests, which will be explained as the individual tests are described. The labeling of the regenerations is given in Table I, and this labeling will be used in the discussion of the results. The reasons and rational for the testing sequences will be discussed with the results for each particular test.

Table I – Labels for the Regeneration Tests

Regeneration Test	Test Description of Active Parked, Active Road Regeneration, and Passive Road Regenerations
Test1	2007 DPF, Light flashing, Active Parked Regeneration
Test2	2007 DPF, Light flashing, Active Parked Regeneration
Test3	2007 DPF, Light flashing, Active Parked Regeneration
Test4	2007 DPF, Light on, not flashing, Active Road Regeneration
Test5	2007 DPF, Light on flashing, Active Road Regeneration

Test6	2010 DPF, Light on, not flashing, Active Parked Regeneration
Test7	2010 DPF, Light on, not flashing, Active Road Regeneration
Test8	2010 DPF, Light on, not flashing, Active Road Regeneration
Test9	2010 DPF, Light not on, Passive Road Regeneration
Test10	2010 DPF, Light not on, Passive Road Regeneration
Test11	2010 DPF, Light not on, Passive Road Regeneration

III-RESULTS

This study has investigated the three primary regeneration methods employed on DPFs, and the goals were different for each type of regeneration. For the parked active regeneration studies the emphasis was on the 2007 DPF, since a large amount mass and large particles were emitted in Phase I of this study. For active road regenerations the emphasis was on the 2010 DPF, since these DPFs are most closely related to the latest technology associated with DPFs. For the passive road regenerations the emphasis was on the 2010 DPF, since these DPFs are designed to optimize passive regeneration in the DPF. Also, it should be mentioned that the loading of PM on a DPF takes considerable staff and dynamometer time, and the completion of eleven tests took a considerable amount of time and effort, as well as analysis.

Shown in Figure III-1 is the vehicle speed loading pattern that was used to load the DPFs in this Phase II investigation. The vehicle speed varied between 12 and 22 mph, and the engine was adjusted to keep the exhaust temperatures below 200 deg C. This particular figure was for a passive regeneration of the 2010 DPF, and the later time part of the figure shows a transition to high speed driving under heavy load. During the high speed driving the temperature in the SCR system increased rapidly to values above 400 deg C, and this temperature condition maximizes passive regeneration in the DPF and SCR systems. The details of the passive regeneration will be given in lather section of this report.

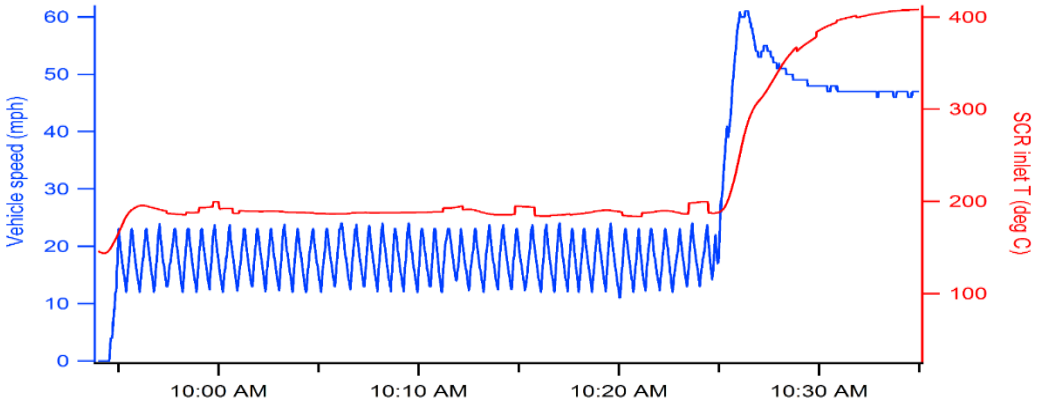

Figure III-1 Typical velocity and exhaust temperature during dynamometer loading of a DPF

A. Active Parked Regenerations of the 2007 and 2010 DPFs

Four active parked regenerations were performed in this Phase II investigation, and three regenerations were performed on the 2007 DPF and one on the 2010 DPF. The most important goal of this part of the study was to gain some insight into the large amount of mass emissions in the initial soot burning phase of the DPF active regeneration that was observed during Phase I, as well as the chemical composition of the particles larger than 2.5 microns associated with these emissions. The 2007 DPF had the largest mass emissions of large particles, while the 2010 DPF had only a minor contribution of large particles in the Phase I study.

First Parked Regeneration of the 2007 DPF

All DPF loading in Phase II was accomplished with the use of a newly installed chassis dynamometer at Depot Park, and the dynamometer was able to load the DPF in a very efficient manner. However, as will be seen from the results it appears that the Phase II DPF regenerations had a significantly different nature than previous tests that were performed with the DPF loading accomplished by stop and go traffic in the Sacramento region. The results are compared to one of the previous tests that were performed in 2013, Phase I, with the same 2007 DPF. The condition of the DPF loading was the light flashing, and the conditions of the ambient wind tunnel and instrumentation were essentially the same.

In order to show the important differences between the Phase I and Phase II results, similar tests in the two studies will be compared. Shown in figures IIIA-1a, 2015 test, and IIIA-1b, 2013 test, are the SMPS total particle concentrations from the testing. For the 2015 testing the particle concentration were significantly higher, but there was no obvious soot burning of large particles during early time in the regeneration. The total time for the regenerations were similar, and the total number of particles emitted during the test was larger for the 2015 test.

Shown in Figures IIIA-2a, 2015 test, and IIIA-2b, 2013 test, are the SMPS predicted total emission rates in the tunnel in units of g PM/hr, as well as the accumulated mass during the tests. For the 2015 test there is a lack of a well-defined soot burning regime at early times, and the total SMPS mass emissions for the tests are larger for the 2013 test compared to the 2015 test, 1.49 gr to .809 gr. However, during most of the time during the tests the emission rate for the 2015 testing was larger. It should also be mentioned that the particle diameter sampling range of the SMPS was larger for the 2015 testing, 512 nm, than the 2013 testing, 191 nm, and despite the smaller range the SMPS predicted more mass for the 2013 testing.

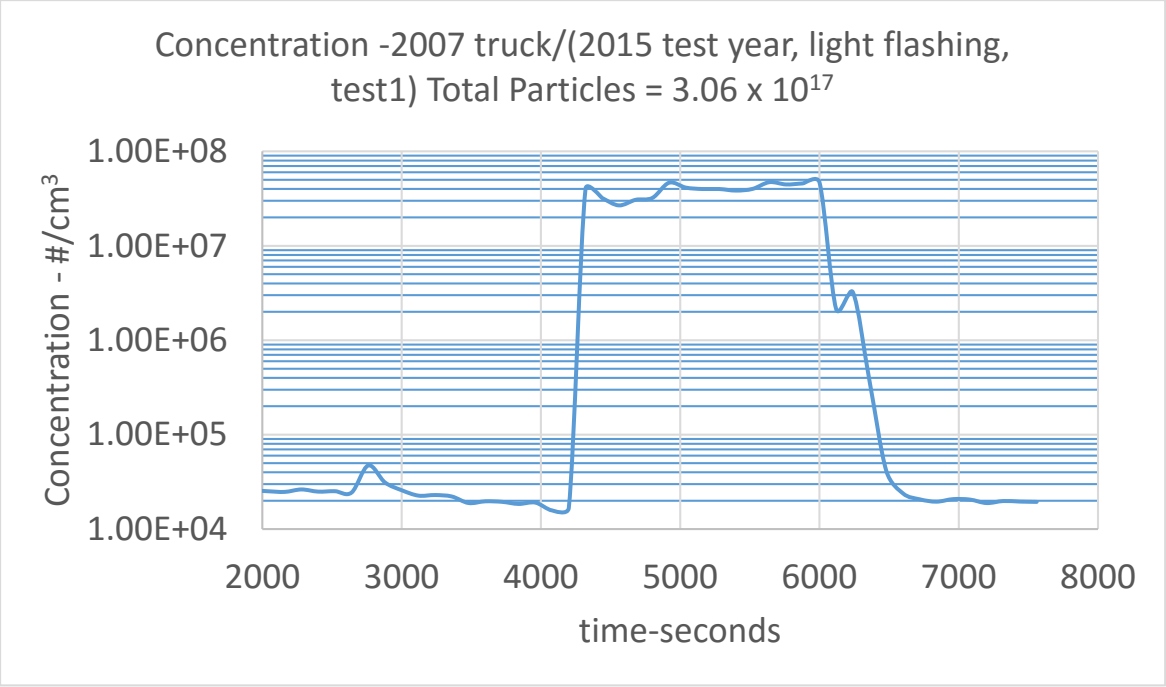

Figure IIIA-1a – Tunnel particle concentrations -2007 truck - (2015 test year, light flashing, test1)

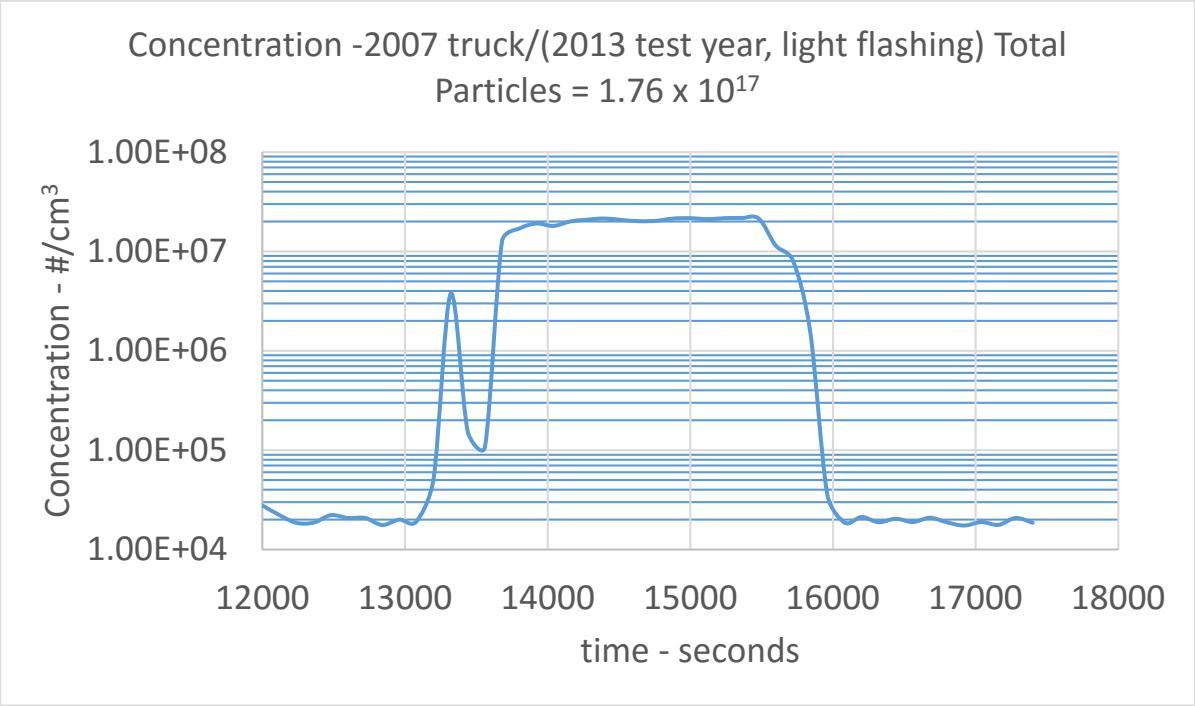

Figure IIIA-1b – Tunnel particle concentrations -2007 truck - (2013 test year, light flashing)

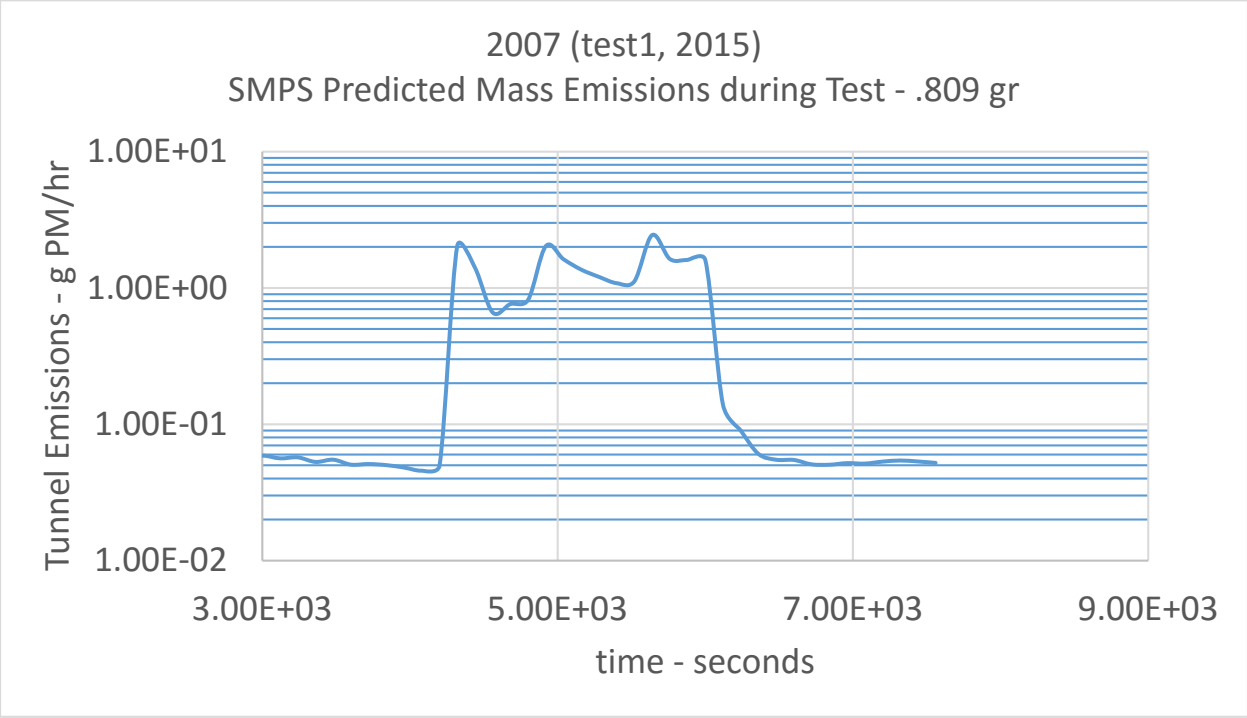

Figure IIIA-2a SMPS Predicted Mass Emissions during Test - .809 gr, 2007 (test1, 2015)

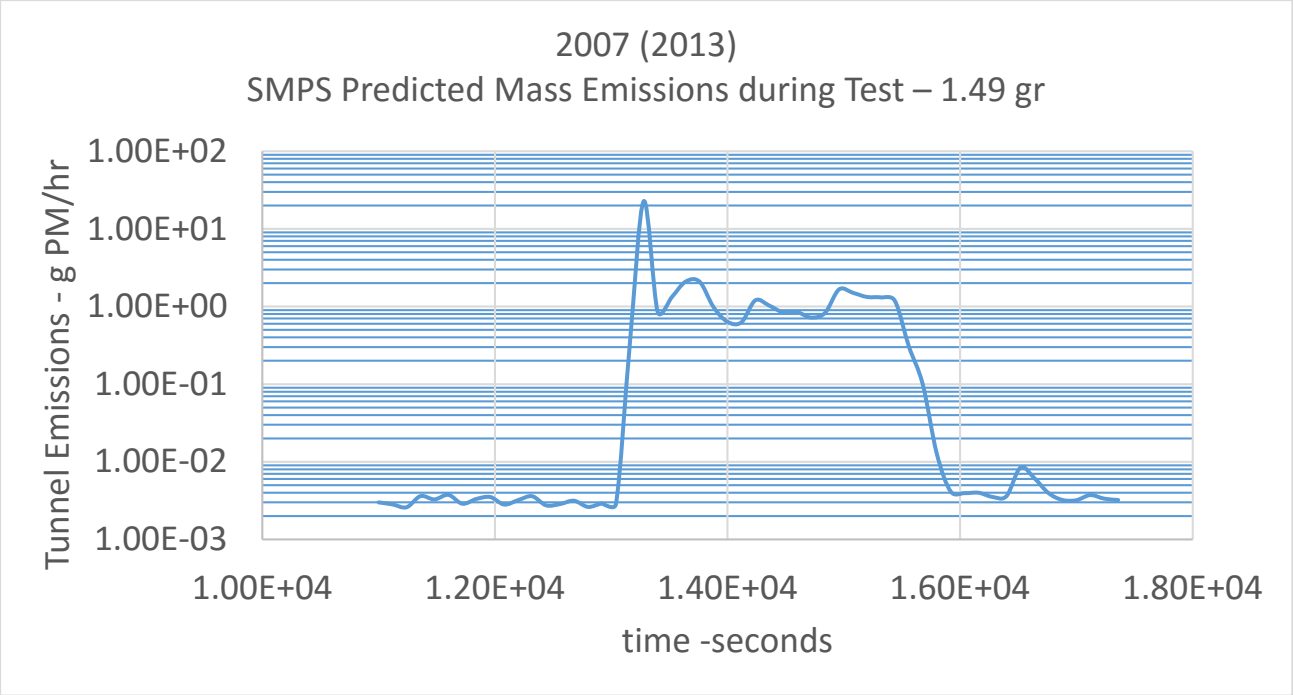

Figure IIIA-2b SMPS Predicted Mass Emissions during Test – 1.49 gr, 2007 (2013)

Shown in Figure IIIA-3a, 2015 test, and IIIA-3b, 2013 test, are SMPS relative spectral particle concentration measurements during the testing, and these results exhibit the spectral content of the emissions as a function of particle diameter and time. Again the primary difference between the 2015 and 2013 results is a lack of a large particle soot burning regime at early times. After the large particle soot burning regime the 2015 and 2013 regenerations are quite similar during the fuel burning regime.

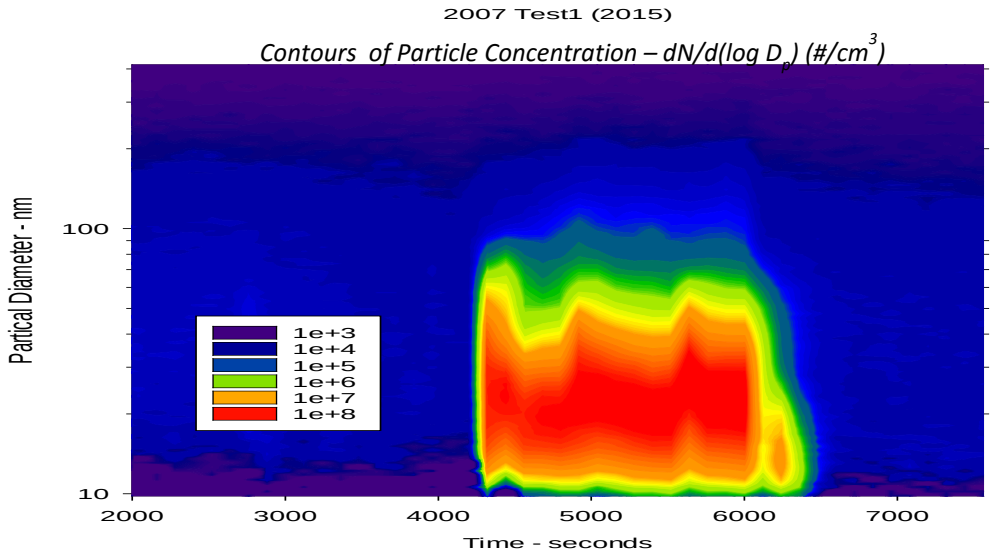

Figure IIIA-3a SMPS spectral emissions, test1 2015

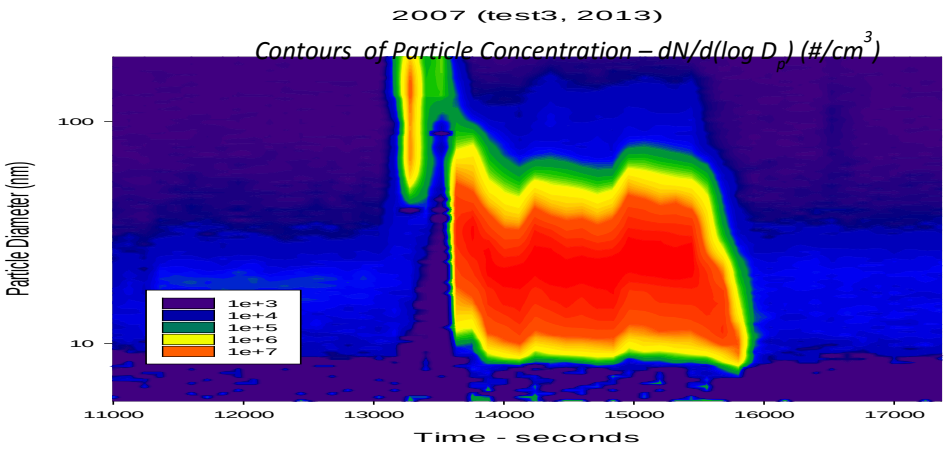

Figure IIIA-3b SMPS spectral emissions, 2013

In order to observe particles larger than 1.0 microns use was made of the DustTrak particle instrument. Shown in Figures IIIA-4a, 2015 test, and IIIA-4b, 2013 test, are the DustTrak measurements for both tests, and these are the most important and only measurements made for the large particles greater than one micron. It is clear from a comparison of the 2015 and 2013 tests that the DustTrak did not record any large particles during testing of the 2015 event. The total concentration measurements of the DustTrak had a range of particle diameters from .1 micron to 10.0 microns.

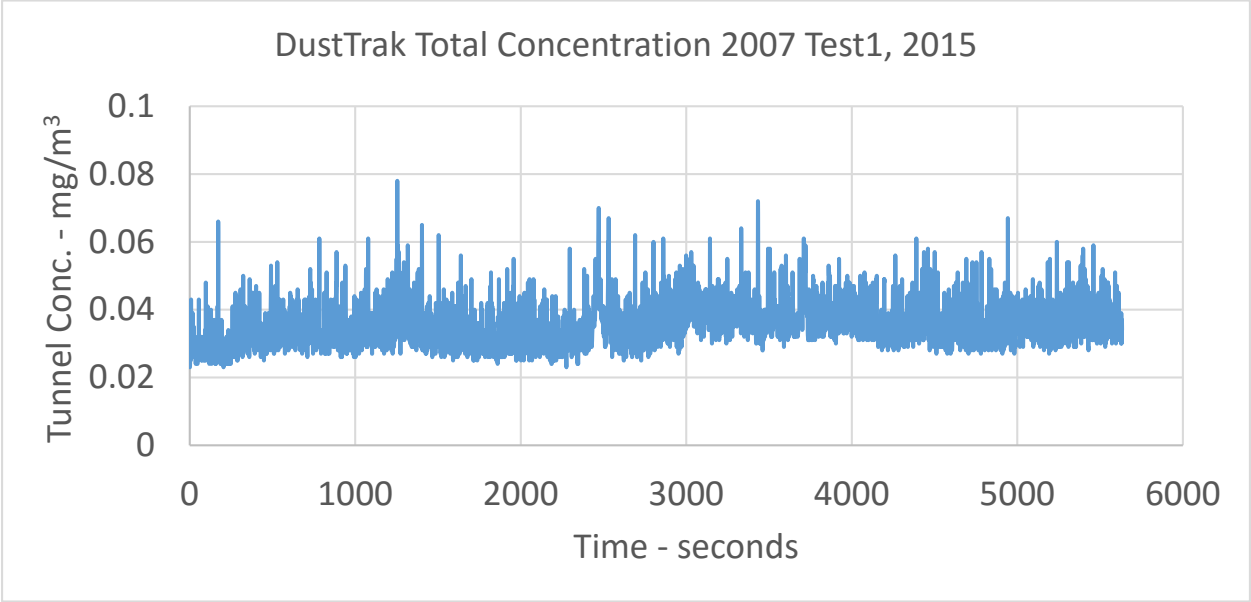

Figure IIIA-4a DustTrak total concentration 2007 test1, 2015

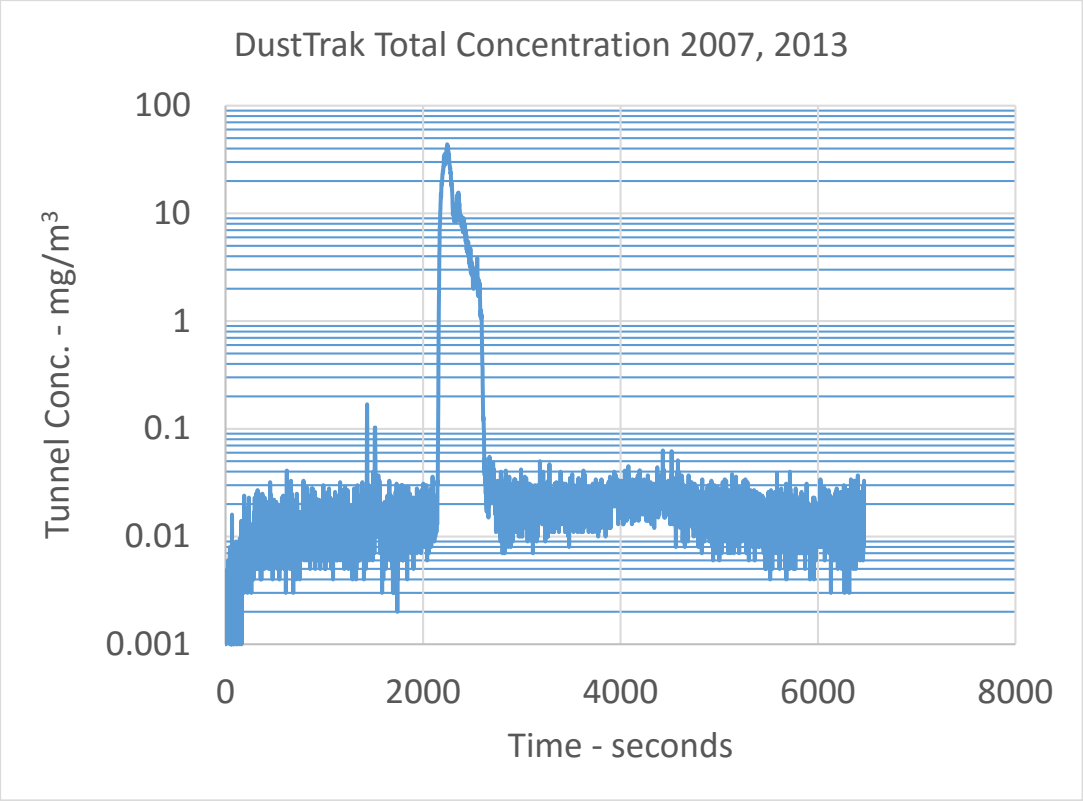

Figure IIIA-4b DustTrak total concentration 2007, 2013

During the Phase II testing both the DMM and the Aethalometer instruments were recording properly, and their results are shown in Figures IIIA-5 and IIIA-6. In Figure IIIA-5 are the predicted tunnel mass emissions by the DMM, and these emissions are larger than SMPS, Fig. IIIA-2a, and DustTrak, Fig.IIIA-4b. It appears that the DustTrak completely missed the regeneration event in the 2015 testing. The mass emissions predicted by the DMM for the 2015 testing was 2.49 grams, and this is larger than the SMPS predicted mass emissions of 0.809 grams for the 2015 testing. It is also larger than the SMPS mass emission predictions from test3 of the 2013 testing, 1.49 grams. The filter measurements for the 2015 and 2013 testing for the 2007 DPF were 0.72 grams and 8.34 grams, respectively, and these filter measurements and particle instrument results clearly show that the active parked regenerations were much different. At the present time it appears that the method of loading the DPF has played a very significant role in the emissions from the same DPF, and this result will be further confirmed in tests 2 thru 8.

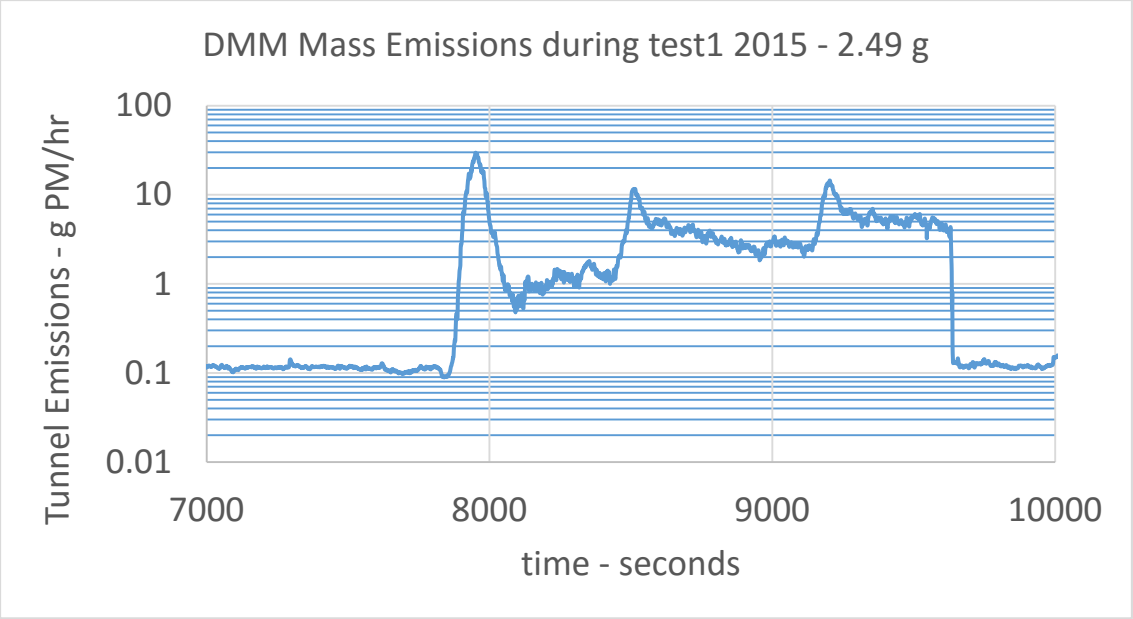

Figure IIIA-5 DMM mass emission during test1 of the 2007 DPF

The final results to be shown for test1 are the aethalometer indications of black carbon, BC, concentrations for test1 of the 2015 testing, Figure IIIA-6. The aethalometer results show the same three peaks in the emissions that are shown in Figures IIIA-2a, IIIA-3a, and IIIA-5, but they also show a smaller amount of BC during the first peak at early times in the regeneration event. Figure IIIA-5 from the DMM measurements show higher mass emission during the initial first peak of the regeneration event, and the first peak is related to soot burning as opposed to fuel burning in the DPF. The results in Fig. IIIA-6 indicate that black carbon concentrations in the fuel burning phase of the DPF regeneration is larger than the soot burning part of the regeneration.

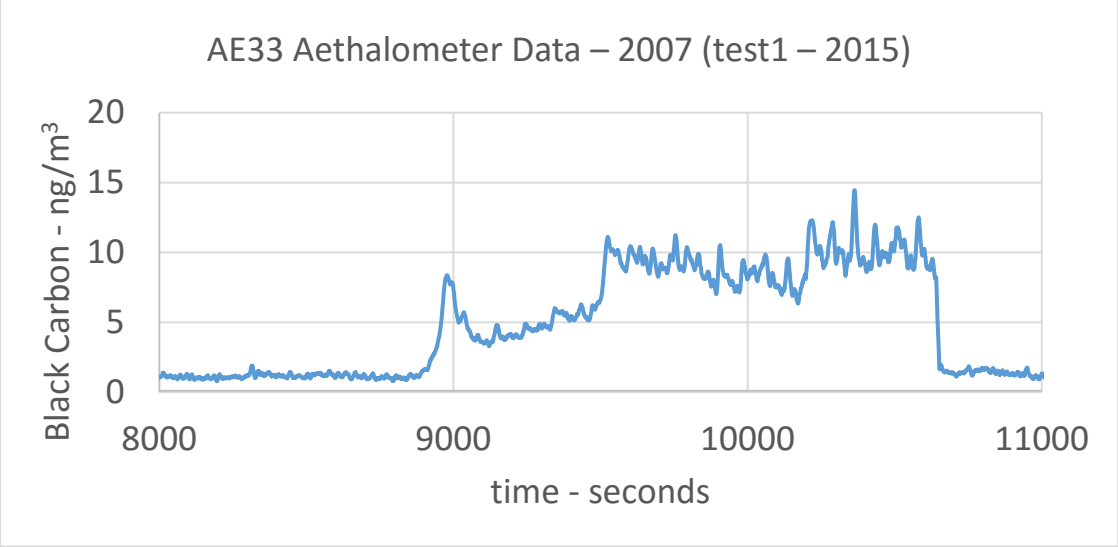

Figure IIIA-6 Aethalometer measurements of the black carbon measurements during test1, 2015.

The three current, 2015, parked regeneration test of 2007 DPF, tests 1 thru 3, all had a similar character, and they will be compared. The only test that had a significant difference was test3, which had a temperature overshoot during the start of the parked active regeneration. A similar overshoot was observed in the Phase I testing, and these overshoots are related to the flashing light condition of the DPF. The flashing light condition indicates the DPF has been loaded to its maximum condition, and that any further loading could result in damage to the DPF and possibly to the engine.

Shown in Figure IIIA-7a and IIIA-7b are the DPF outlet temperatures at the start of test3, 2015, and a test in 2013, respectively. The design temperature for DPF regeneration is 1060 deg F, and for both tests this design temperature was exceeded by almost 100 deg F. The control system for the DPF decreased the Diesel Oxidation Catalyst, DOC, output, and the system returned to the design system over time period of hundreds of seconds. Overall the response of the DPF control system was very similar for both the 2015 and 2013 events.

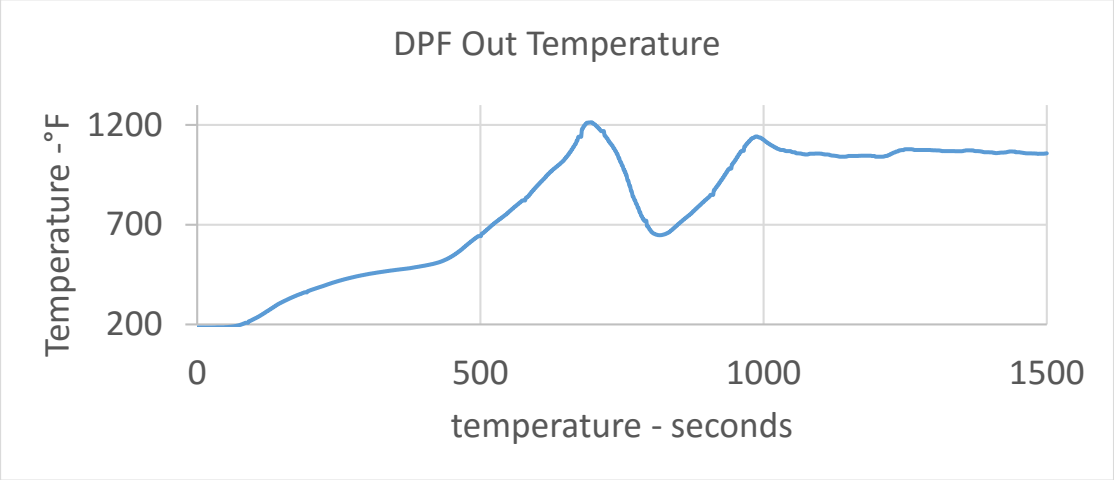

Figure IIIA-7a DPF outlet temperature during startup of DPF regeneration, 2015 test3.

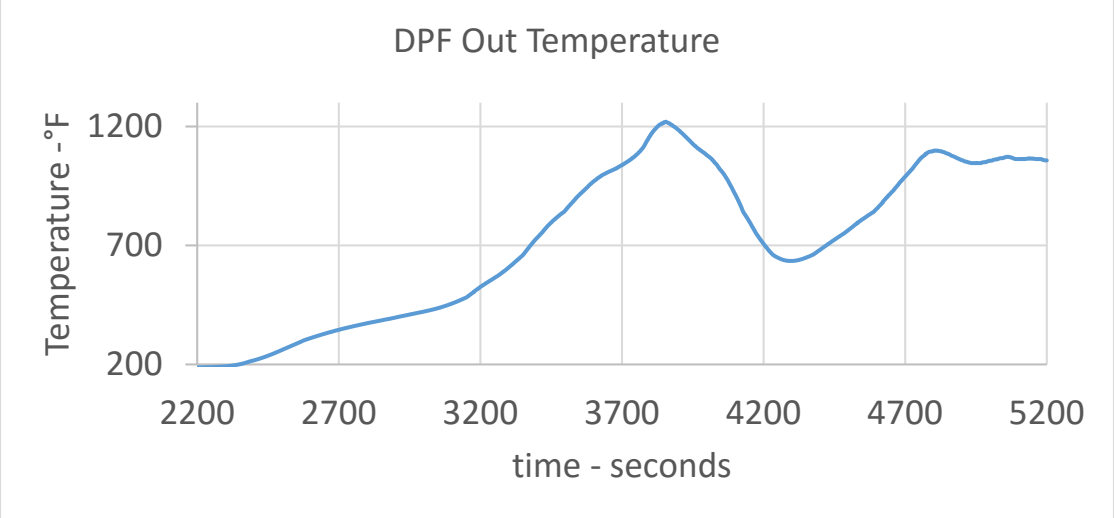

Figure IIIA-7b DPF outlet temperature during startup of DPF regeneration, 2013 test.

All three tests of the 2007 DPF in phase II have given significantly lower mass emissions than the previous tests with the flashing light two years ago. The amount of mass is similar to the test with the light just on in Phase I and not flashing. Also, all testing in Phase II did not generate significant particles greater than one micron, which was much different than previous testing two years ago.

Shown in Figures IIIA-8a, IIIA-8b, and IIIA-8c are the tunnel particle concentrations from the SMPS for all 2015 tests of 2007 DPF with the flashing light on for the DPF. Figure IIIA-8a is for test3 where the temperature overshoot occurred in the DPF outlet temperature. The dip in the particle concentration in Figure IIIA-8a is directly related to the decrease in fuel injection from the DOC, and there is no dip in Figures IIIA-8b and IIIA-8c where the overshoot did not occur. Also, the total number of particles for test3 was two and four times lower than tests 1 and 2, respectively.

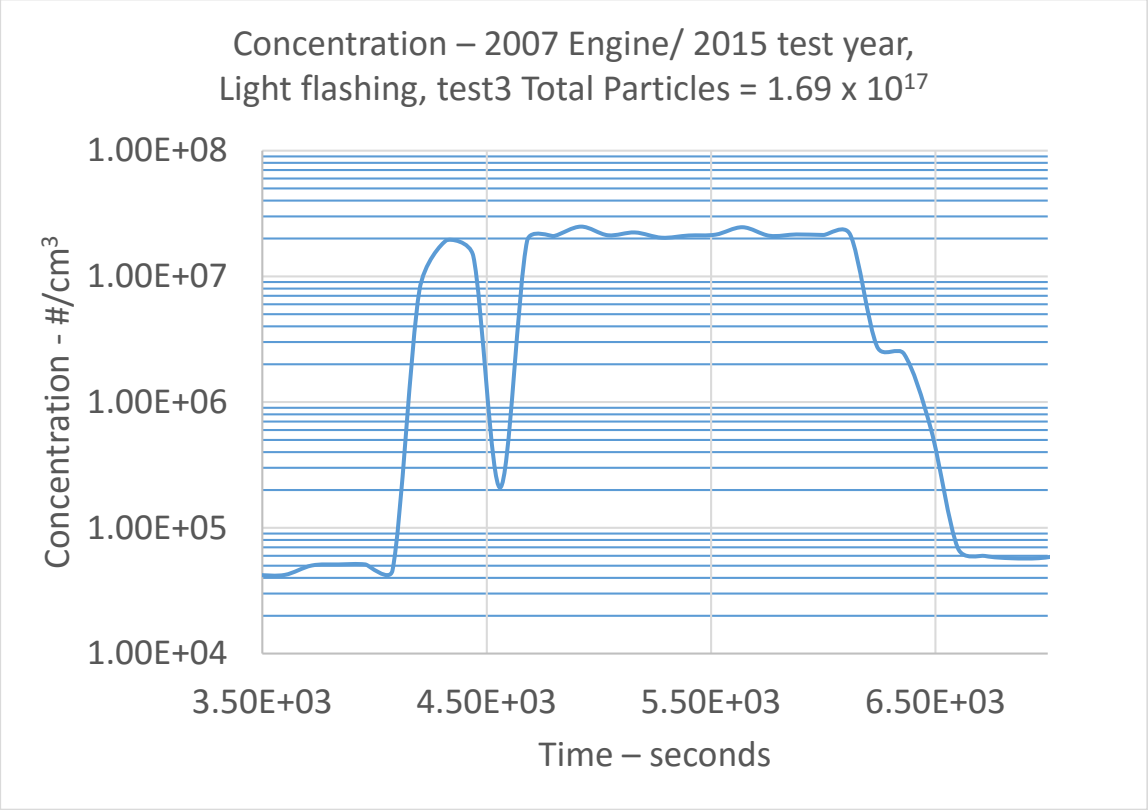

Figure IIIA-8a SMPS particle concentrations during test3 of the 2007 DPF

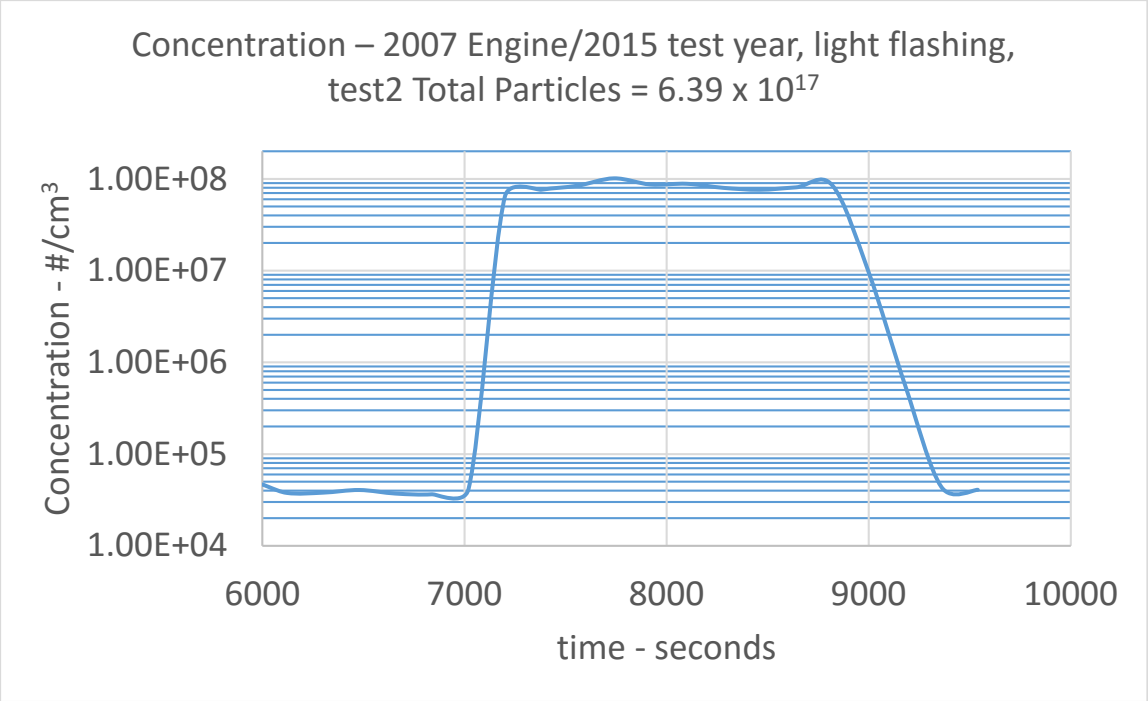

Figure IIIA-8b SMPS particle concentrations during test2 of the 2007 DPF

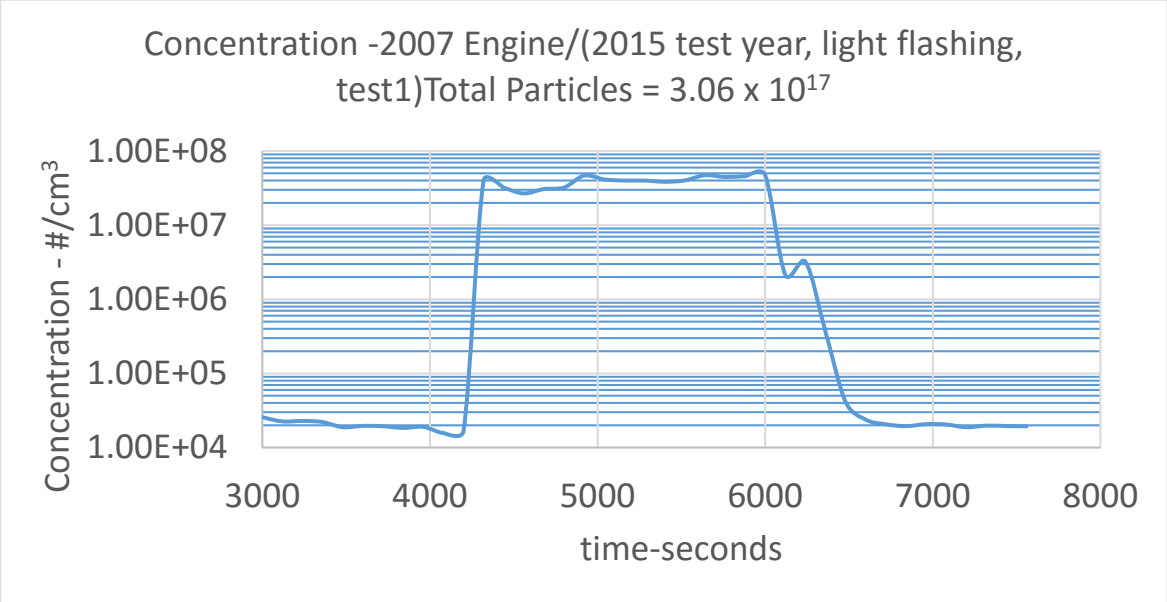

Figure IIIA-8c SMPS particle concentrations during test1 of the 2007 DPF

Shown in Figures IIIA-9a, IIIA-9b, and IIIA-9c are the predicted SMPS mass emissions for all 2015 tests with the flashing light on for the DPF. Figure IIIA-9a for test3 had the highest peak mass emissions by a small amount compared to test2, but less total accumulated mass than test2, Figure IIIA-9b. Test1 had the lowest total accumulated mass emissions, but test1 had double the total number of particles compared to test3. In general the three tests show many similar, except for the DPF temperature overshoot

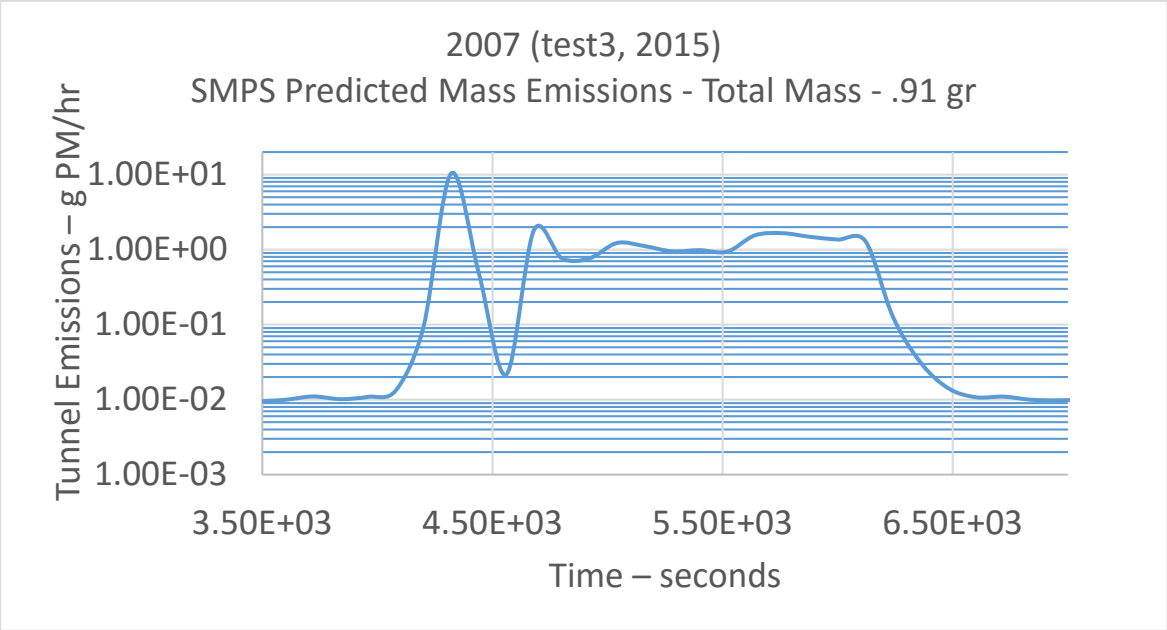

Figure IIIA-9a – Tunnel emissions during test3

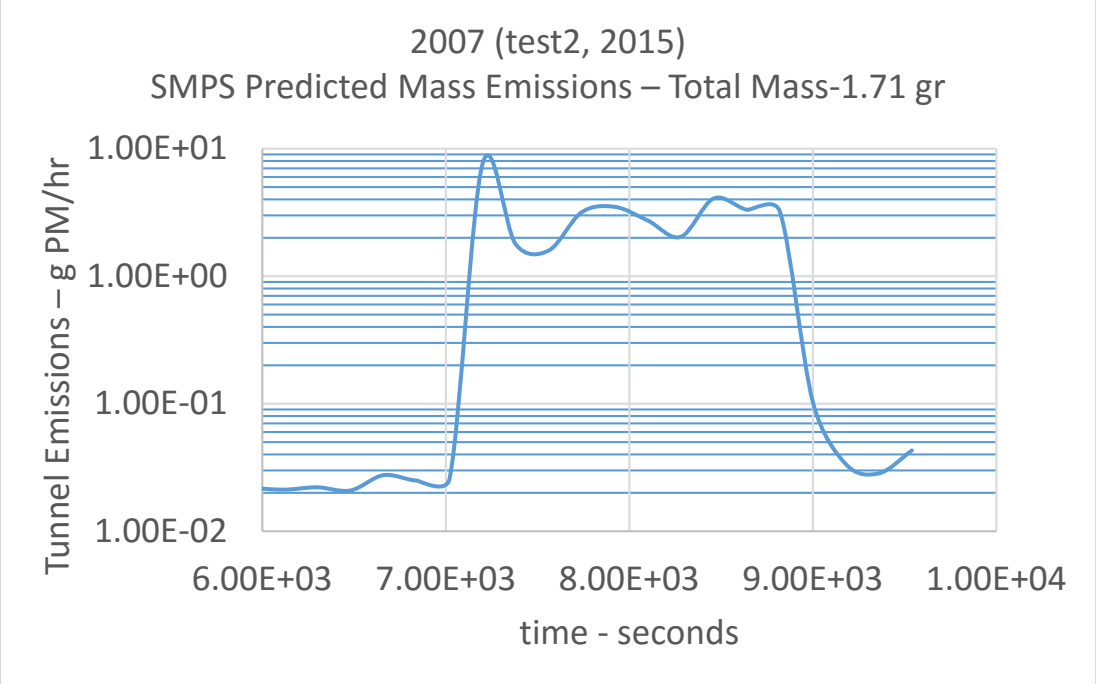

Figure IIIA-9b – Tunnel emissions during test2

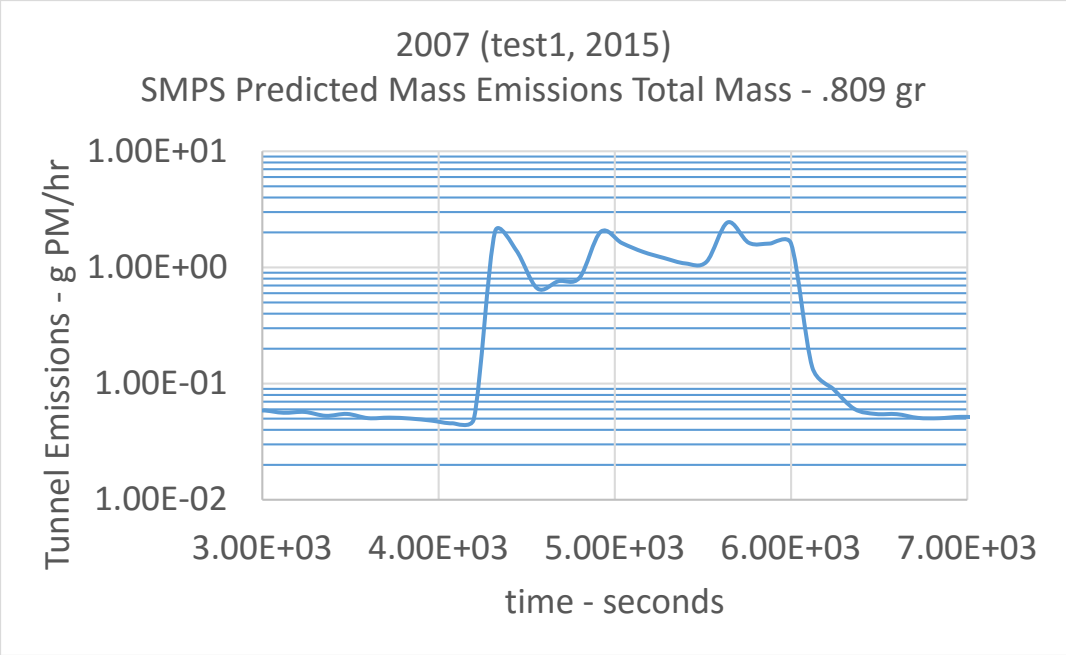

Figure IIIA-9c – Tunnel emissions during test1

Further insight into the results can be gained by studying the SMPS spectral emissions for all 2015 parked regeneration tests with the flashing light on for the DPF in Figures IIIA-10a, IIIA-10b, and IIIA-10c. The results for test3, Figure IIIA-10a, show a significant increase in larger particles at times before the overshoot of the DPF outlet temperature, and this is followed by a sharp decrease in all particle sizes. Test1 and test2 show a relatively uniform distribution of particles with only a slight increase of larger particles at early times. It should also be mentioned that the DustTrak results for all tests showed an insignificant number of particles larger than one micron.

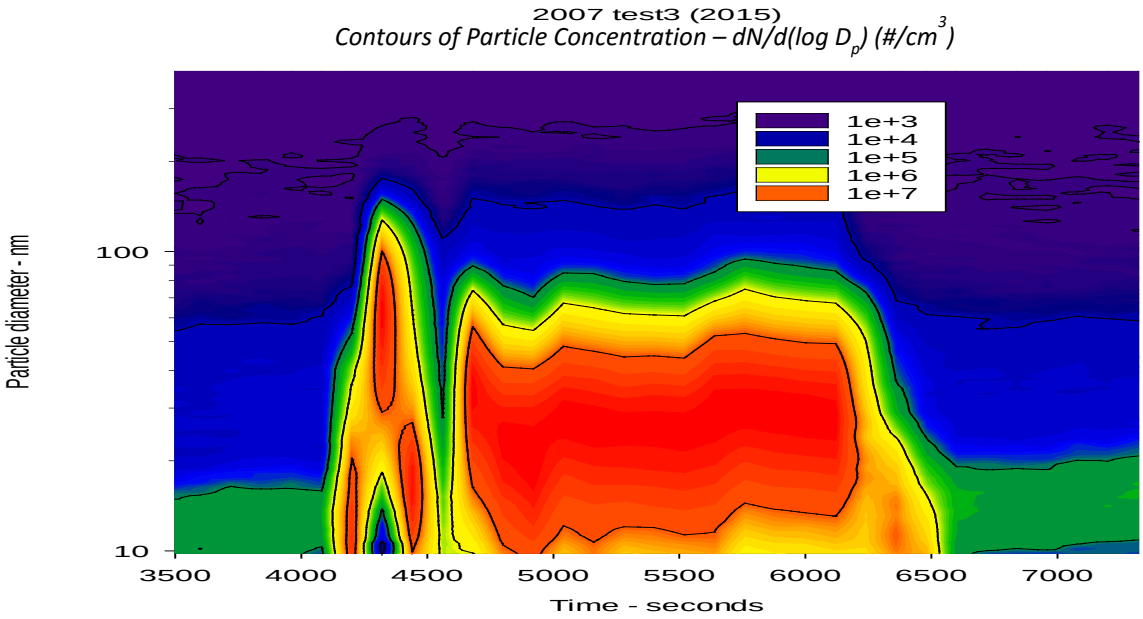

Figure IIIA-10a SMPS spectral data for test3

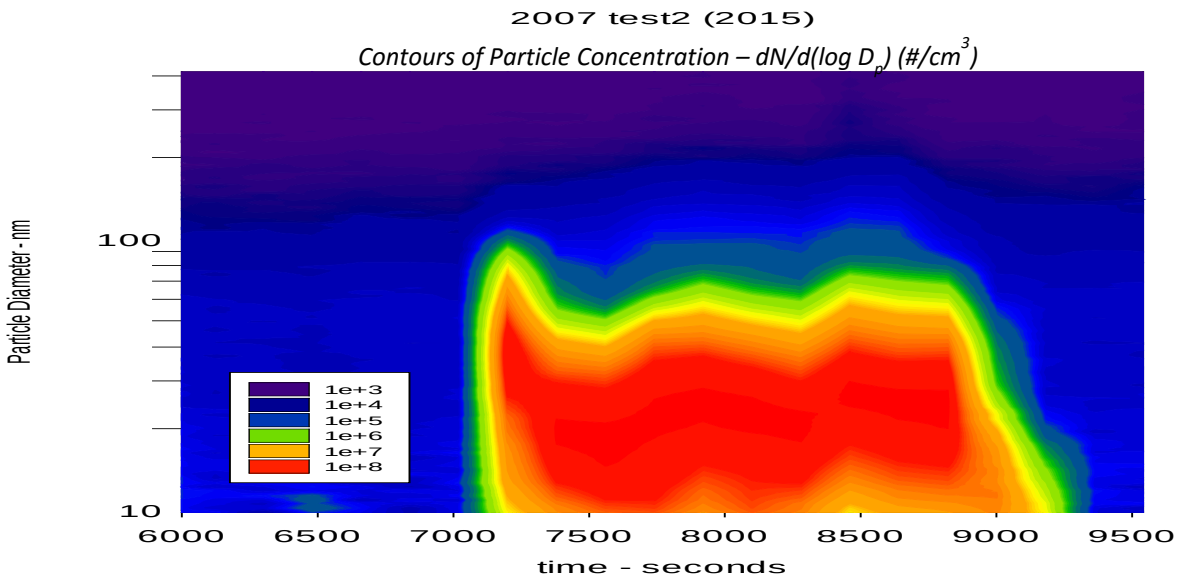

Figure IIIA-10b SMPS spectral data for test2

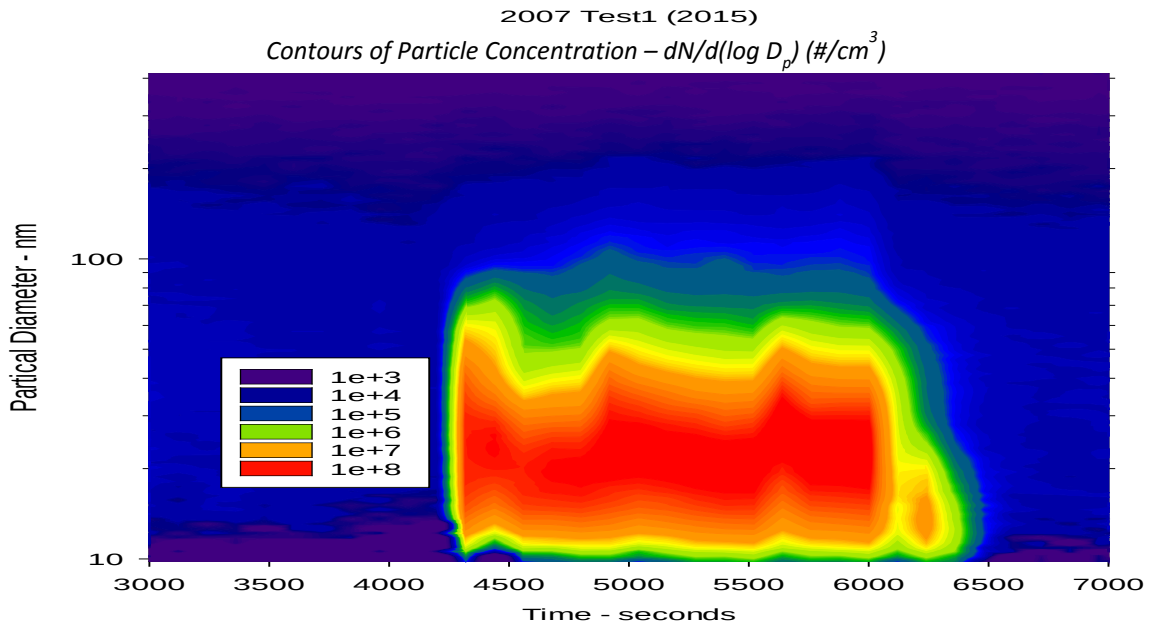

Figure IIIA-10c SMPS spectral data for test1

The final parked regeneration during Phase II was for the 2010 DPF, and only one parked active regeneration was performed, since road active regenerations are more frequent than parked regenerations. As was done previously the parked regeneration of the 2010 DPF in Phase II will be compared to the parked regeneration in Phase I. The major difference in the testing besides the increased mileage on the vehicles is that the DPF was loaded by stop and go traffic on the road in 2013, while for 2015 testing the DPF was loaded with a simulated stop and go cycle on the new CARB chassis dynamometer at Depot Park. It was expected that there would be some differences in the PM collected in the DPF due to the differences between stop and go road driving and simulated driving on the CARB chassis dynamometer.

For the Phase I testing only one complete parked regeneration was performed on the 2010 DPF, and there was much less PM released in the initial soot burning phase of the parked regeneration compared to the 2007 DPF, since the DPF light was only on and not flashing. The 2013 parked regeneration exhibited some large PM particles greater than 2.5 microns in effective diameter, and these particles could only be seen with the DustTrak particle instrument. The PM emissions also had the characteristic of very few particles in the diameter range between 1.0 microns and 2.5 microns.

Shown in Figures IIIA-11a and IIIA-11b are the DustTrak emissions from the 2013 and 2015 parked regenerations of the 2010 DPF, and emissions below 1.0 microns and the total DustTrak emissions up to 10 microns are presented. In general the emissions are similar in magnitude, and both regenerations took approximately 3000 seconds with the 2013 regeneration starting after 4000 seconds and the 2015 regeneration starting after 2000 seconds. The regeneration emissions are slightly higher during the fuel burning phase of the 2015 testing, but during the soot burning phase the 2013 emissions are larger. There is a larger difference between the PM Total emissions and PM 1.0 emissions during the Phase I study. Another point to note is that there are large particles greater than 2.5 microns for the 2010 DPF, but the level of these large particle emissions are less than the 2007 DPF.

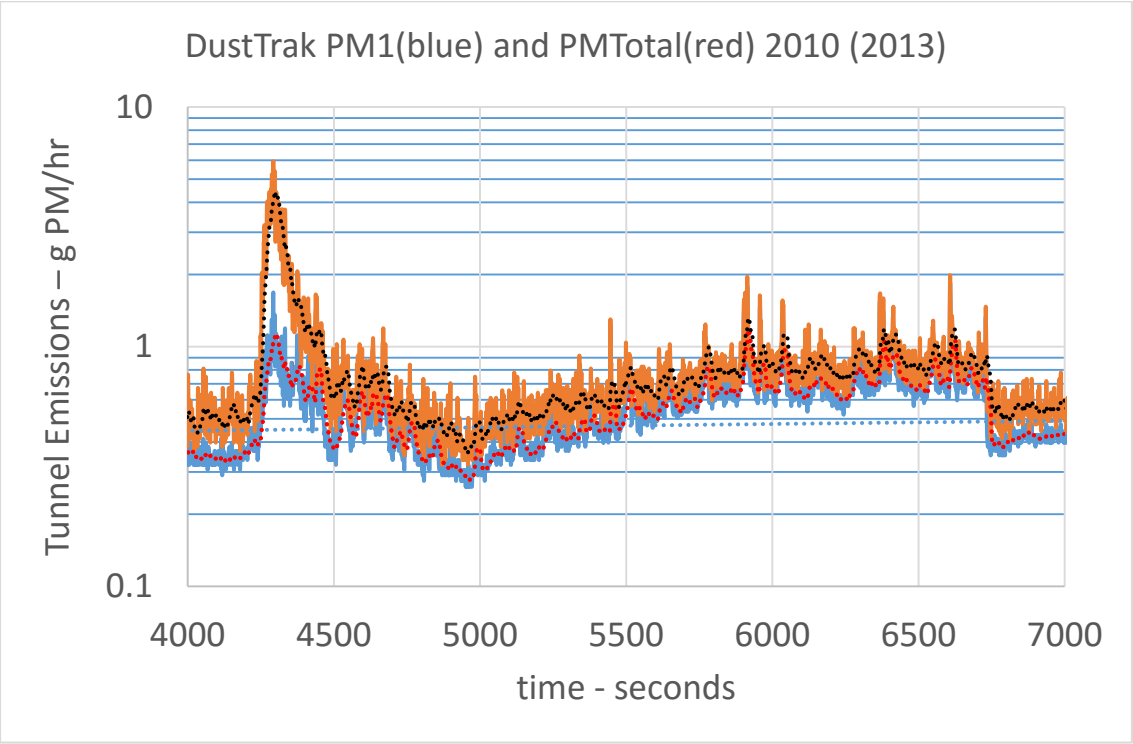

Figure IIIA-11a DustTrak tunnel emissions from the 2010 DPF in Phase I

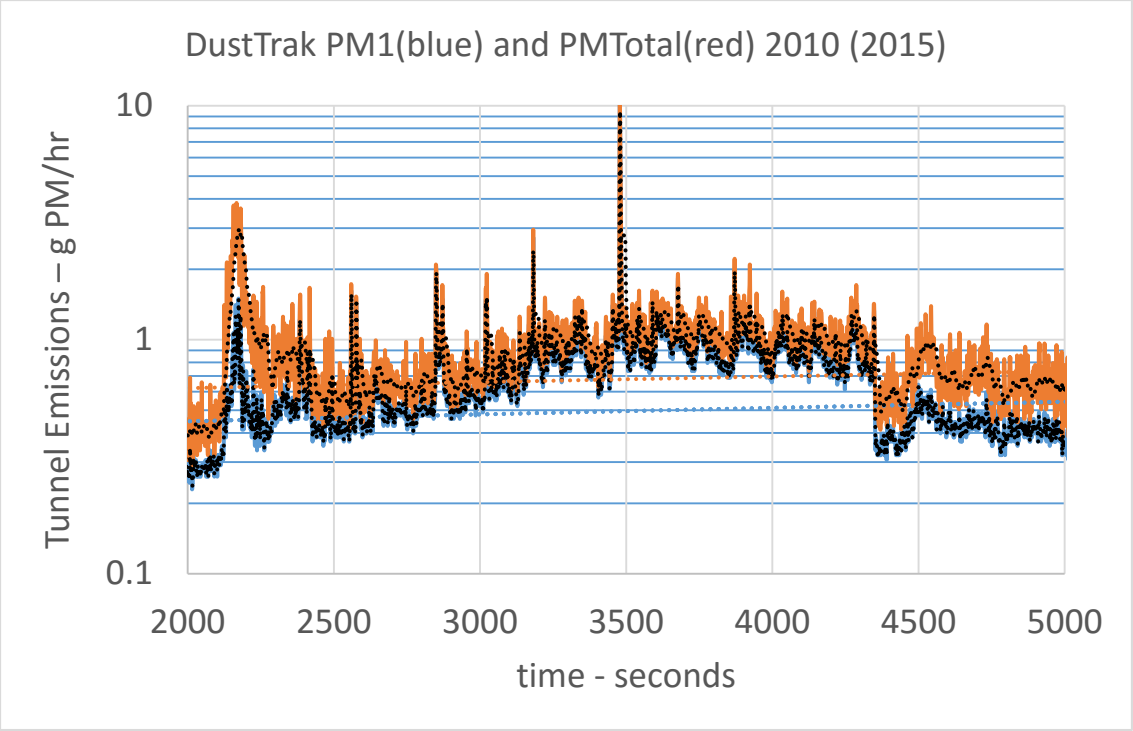

Figure IIIA-11b DustTrak tunnel emissions from the 2010 DPF in Phase II

The particle number concentrations from the SMPS particle instrument for the two tests of the 2010 DPF are presented in Figures IIIA-12a and IIIA-12b, and in general they exhibit similar characteristics. The total number of particles emitted during the regeneration events was larger for the 2015 testing, but there were differences in the particle size distributions which had an influence on the mass emissions in the tunnel. The SMPS integrated local and total mass emissions are shown in Figure IIIA-13a and IIIA-13b, and the total mass emissions are similar even though the particle number emissions were larger for the 2015 testing. It will be shown that the 2015 testing had smaller particles for a longer time at the beginning of the testing and larger particles during the fuel burning phase, and these results are responsible for the similarity of the total mass emissions.

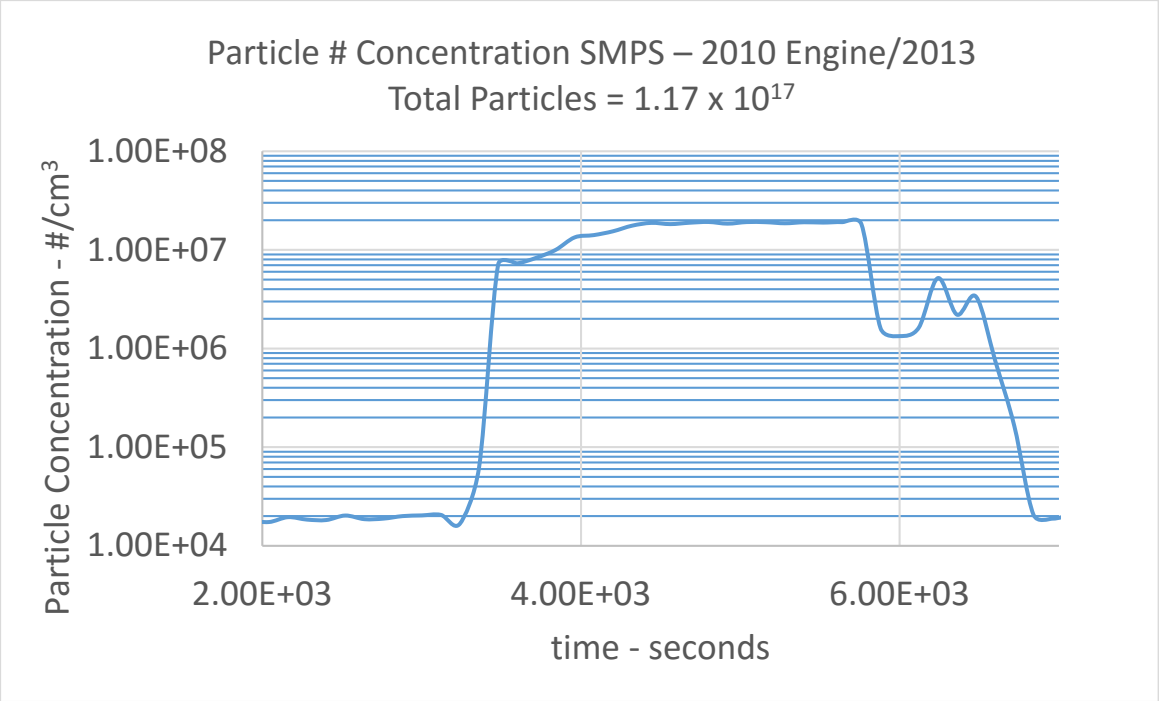

Figure IIIA-12a Tunnel particle concentration for parked regeneration of 2010 DPF, 2013

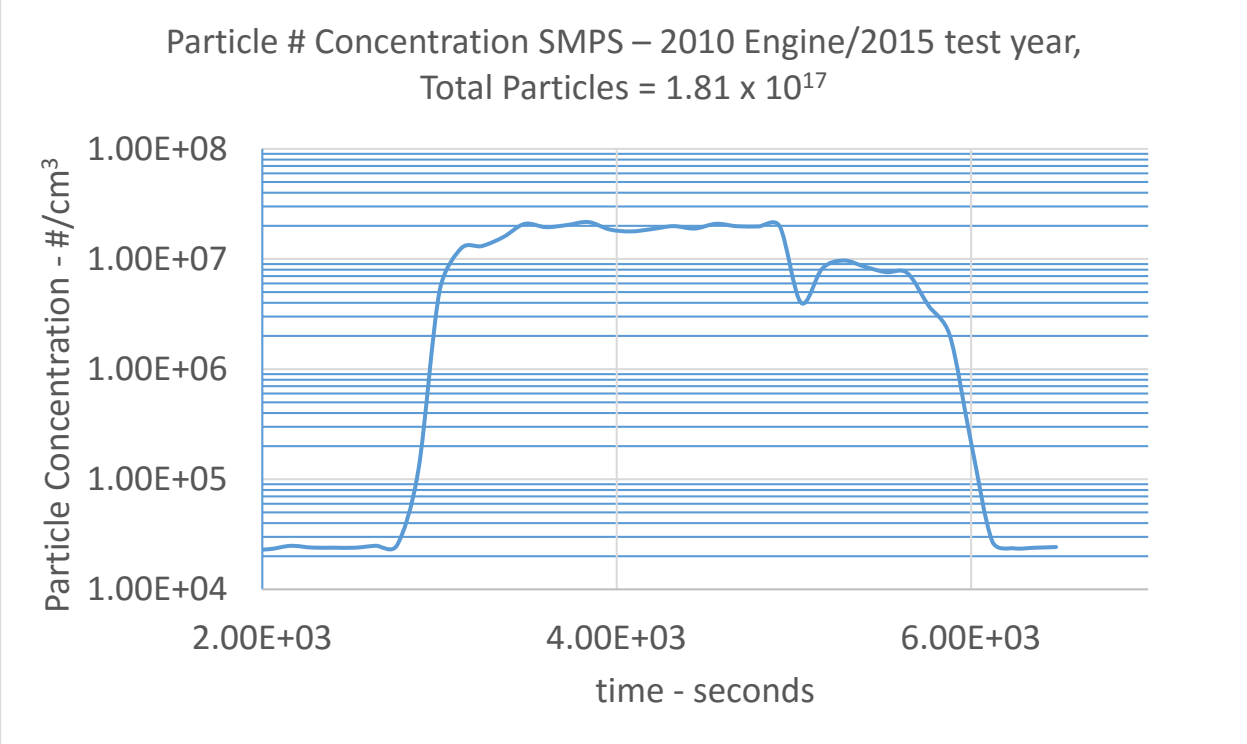

Figure IIIA-12b Tunnel particle concentration for parked regeneration of 2010 DPF, 2015

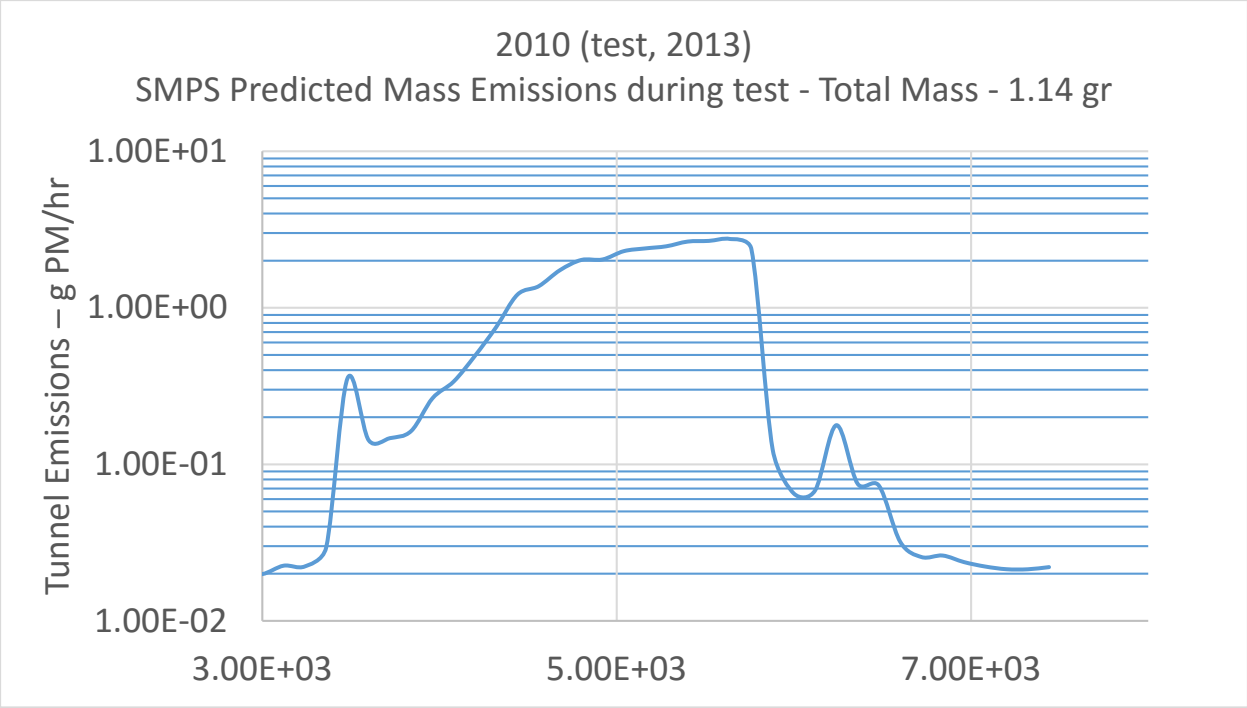

Figure IIIA-13a Tunnel SMPS emissions for parked regeneration of 2010 DPF, 2013

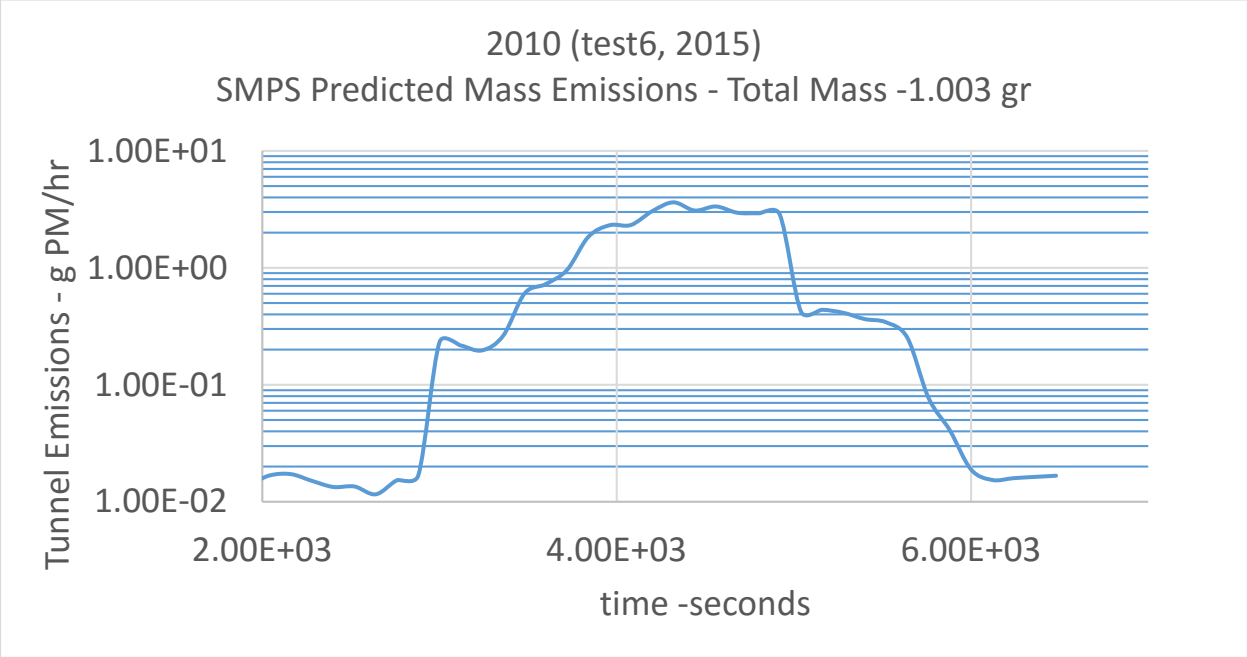

Figure IIIA-13b Tunnel SMPS emissions for parked regeneration of 2010 DPF, 2015

The SMPS spectral content for the 2010 DPF tests are shown in Figures IIIA-14a and IIIA-14b for Phase I and Phase II studies. Again the general spectral content of both the 2013 and 2015 are quite similar, and the differences in the mass emissions are explained by small differences in the

particle size results. The sensitivity of mass emissions to particle diameter is due to the fact that particle mass is proportional to diameter cubed or the volume of the PM particle. At early times in Phase I there are larger particles, while the Phase II had a larger number of smaller particles. Since the total mass emitted in the tunnel is a combination of particle concentration, particle diameter, particle volume, particle density, and time, only a very carefully study will explain the small differences in mass emissions.

Although there are minor differences in the 2013 and 2015 parked regeneration testing that can be seen for the testing of the 2010 DPF, the results are basically similar. The testing of the 2010 DPF did not contain the large differences that were obtained for the 2007 DPF, where the PM emissions in the soot burning phase of the regeneration contained a large number of large particles greater than 2.8 microns.

Shown in Table III-1 is a summary of the accumulated mass estimates and filter weights for of the tests in Phase II. The parked regeneration tests are tests 1, 2, 3, and 6, and in general the DMM mass estimates are generally higher than the SMPS. It is expected that the DMM should give higher estimates than SMPS, since it measures particles in a diameter range up to 1 micron. However, there are significant differences in the measurement techniques, as well as the assumed density of the particles as a function of size. In general the filter weights are bracketed by the DMM and SMPS estimates, but for this parked regeneration study there is no clear choice between the DMM and SMPS. Table III-1 will used to compare the filter weights with the particle instruments for all the regenerations carried out in Phase II.

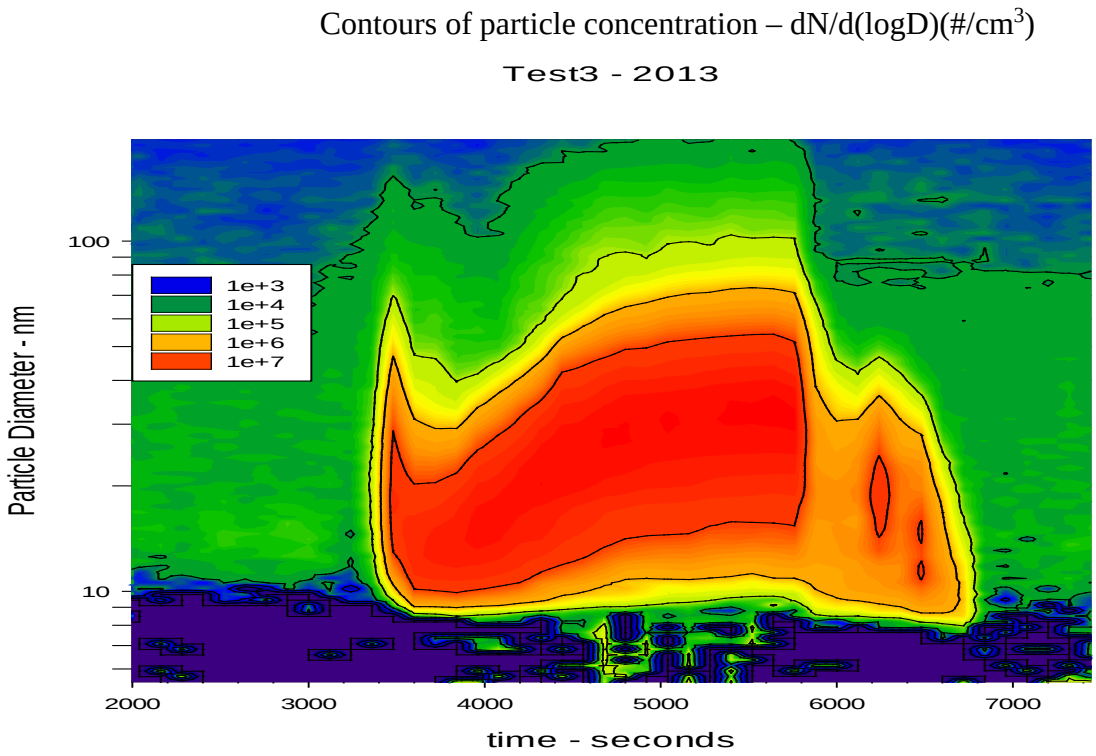

Figure IIIA-14a SMPS spectral content of parked regeneration of 2010 DPF, 2013

Contours of particle concentration – dN/d(logD)(#/cm^3)

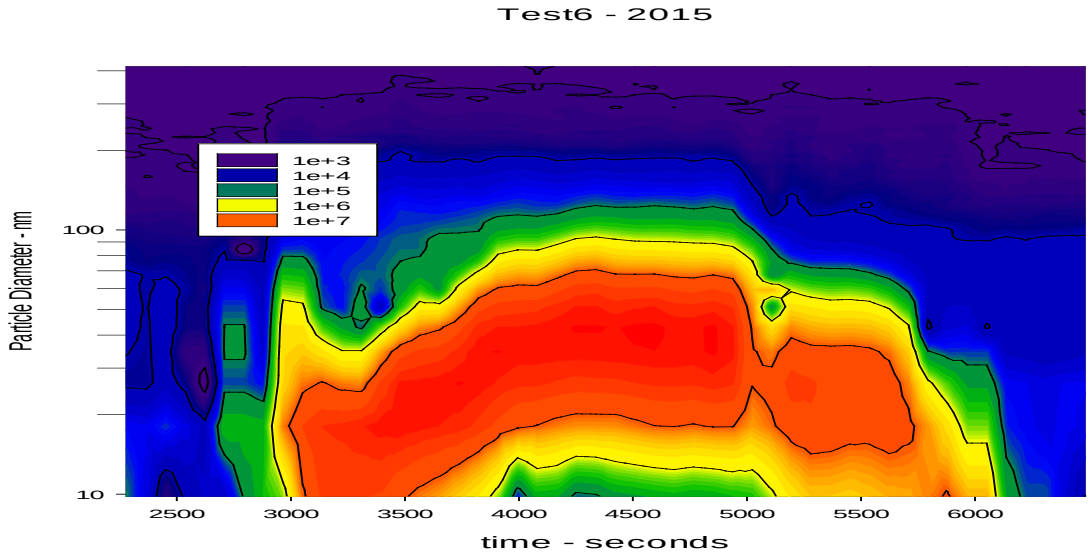

Figure IIIA-14b SMPS spectral content of parked regeneration of 2010 DPF, 2015

Summary Table for Mass Estimates from Particle Instruments and Filters

Vehicle and test type	Test # and date	DMM-g	SMPS-g	Gravimetric Mass-g
2007/flashing light/park	test1-2/23/15	2.49	0.809	0.717
2007/flashing light/park	test2-3/18/15	1.78	1.71	0.981
2007/flashing light/park	test3-4/23/15	5.6	0.91	5.4
2007/light on/road	test4-5/12/15	3.25	0.59	1.87
2007/flashing light/road	test5-5/29/15	7.33	1.33	4.07
2010/light on/park	test6-7/15/15	6.47	1.14	2.64
2010/light on/road	test7-8/5/15	35.1	2.61	16.3
2010/light on/road	test8-8/26/15	23.3	3.32	9.44
2010/light on/passive	test9-9/15/15	0.025	0.012	0.159
2010/light on/passive	test10-9/17/15	XXX	0.036	0.102
2010/light on/passive	Test11-9/22/15	0.120	0.062	0.220

B. Active Road Regenerations of the 2007 and 2010 DPFs

A total of four active road regenerations have been performed, and these regenerations consisted of two on the 2007 DPF and two on the 2010 DPF. The presentation will start with a comparison of a parked and a road regeneration of the 2007 with the light flashing. The road regenerations were carried out on the chassis dynamometer at a speed of 50 mph and a total load of 65,000 pounds. For the parked regeneration the regeneration button was pushed after 10 minutes of engine idling. The road regeneration procedure consisted of ten minutes of engine idling, which was followed by a rapid acceleration to fifty mph. After one minute at fifty mph the active regeneration button was pushed.

Shown in Figures IIIB-1a and IIIB-1b are the CO_2 concentrations and gas temperatures in the wind tunnel at the sampling location as a function of time. Figure IIIB-1a is for the road regeneration, test5, and Figure IIIB-1b is for the parked regeneration, test2. For the road regeneration the tunnel CO_2 concentrations are approximately two times larger. The tunnel temperatures reached a value almost 25 deg F larger for the road test compared to the parked test, and the tunnel temperature increased more rapidly for the road case compared to the parked regeneration. In general it can be said the road active regeneration increased both CO_2 and temperature to significantly larger values over a more rapid time scale, and this changes are due directly to the large amount of engine power needed for road driving

A similar rapid rise in temperature for the DPF outlet temperature is shown in Figure IIIB-2a for test5 compared to test2, Figure IIIB-2b. The DPF outlet temperature reaches its maximum value approximately three minutes after the start of the road regeneration, while it required approximately ten minutes for the maximum DPF temperature to be reached for the parked regeneration, Figure IIIB-2b. For both tests the control system worked well for keeping the DPF at its design condition for both the road and the parked regenerations.

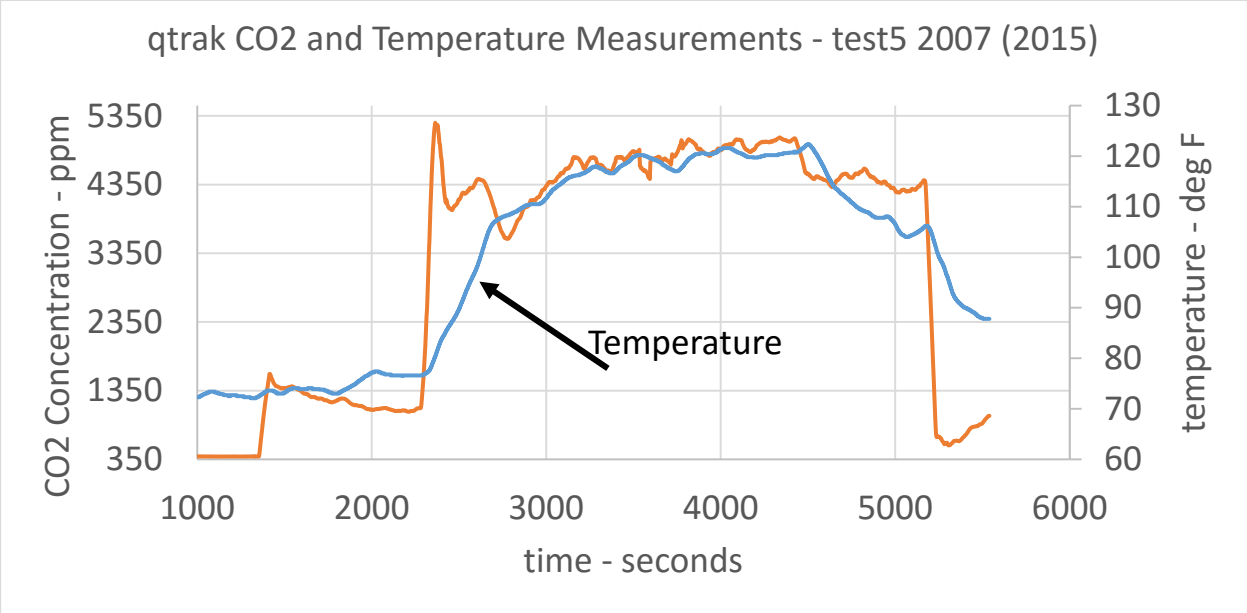

Figure IIIB-1a – Tunnel CO2 and temperature variations during road test5 of the 2007 DPF

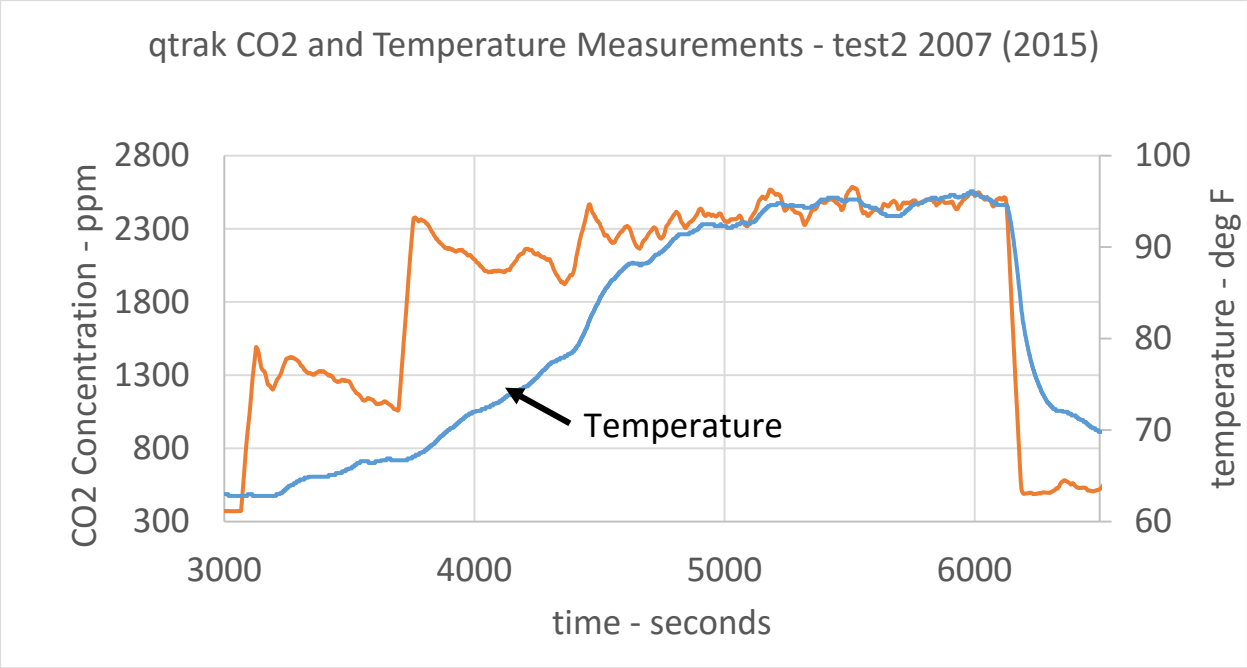

Figure IIIB-1b – Tunnel CO2 and temperature variations during parked test2 of the 2007 DPF

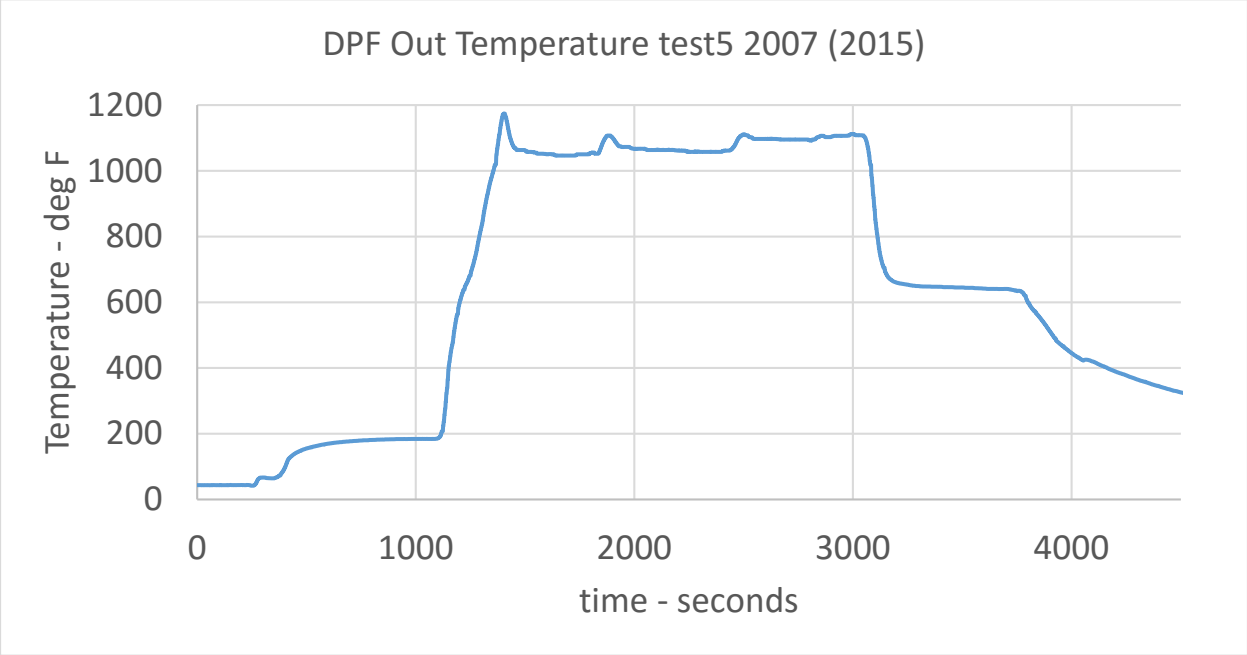

Figure IIIB-2a DPF outlet temperature for the road regeneration of the 2007, test5

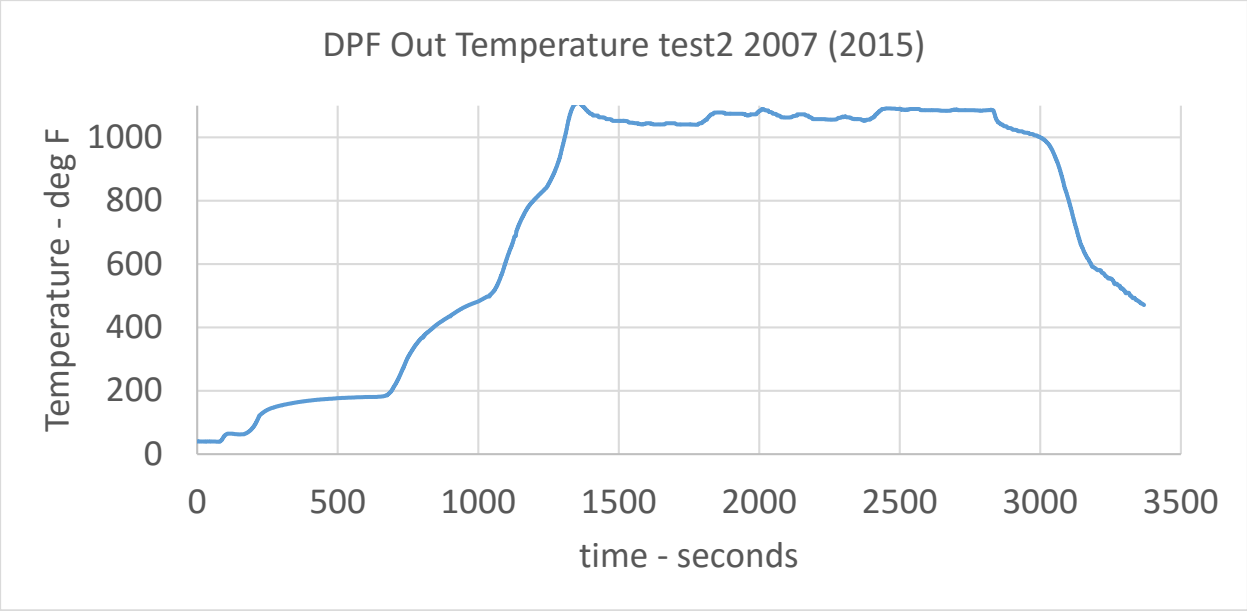

Figure IIIB-2b DPF outlet temperature for the parked regeneration of the 2007, test2

It should be stressed again that an important difference between the road and parked regenerations is the the very substantial power being delivered to truck wheels to power the vehicle for the road regeneration, while for the parked regeneration no power is being delivered to the wheels. This condition implies that the exhaust gases are in a significantly difference state for the two different active regenerations.

The particle emissions from the SMPS instrument are shown in Figures IIIB-3a and IIIB-3b for test5 and test2, respectively. Although there are slight differences in the normalized spectral content, the amount of time for the road and parked regeneration are similar, as well as the level of concentrations and particle size range. A detailed distribution of particle concentration versus size is shown in Figures IIIB-4a and IIIB-4b at similar relative times for test5, 3500 seconds, and test2, 8100 seconds. It is seen again that the particle size distributions for the active parked and road regenerations of the 2007 DPF are quite similar.

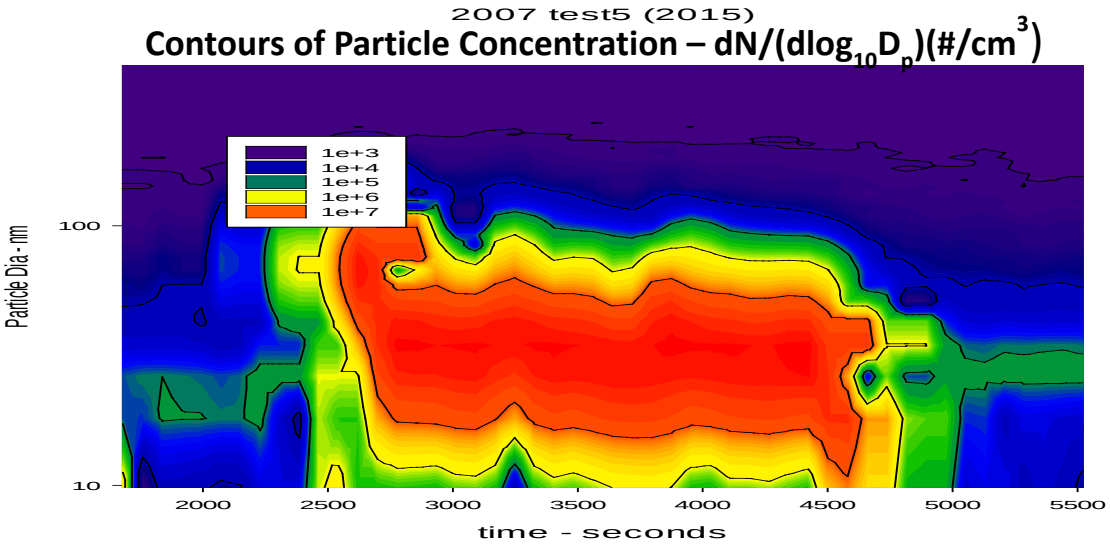

Figure IIIB-3a Contours of particle concentration of the road regeneration of the 2007 DPF, test5

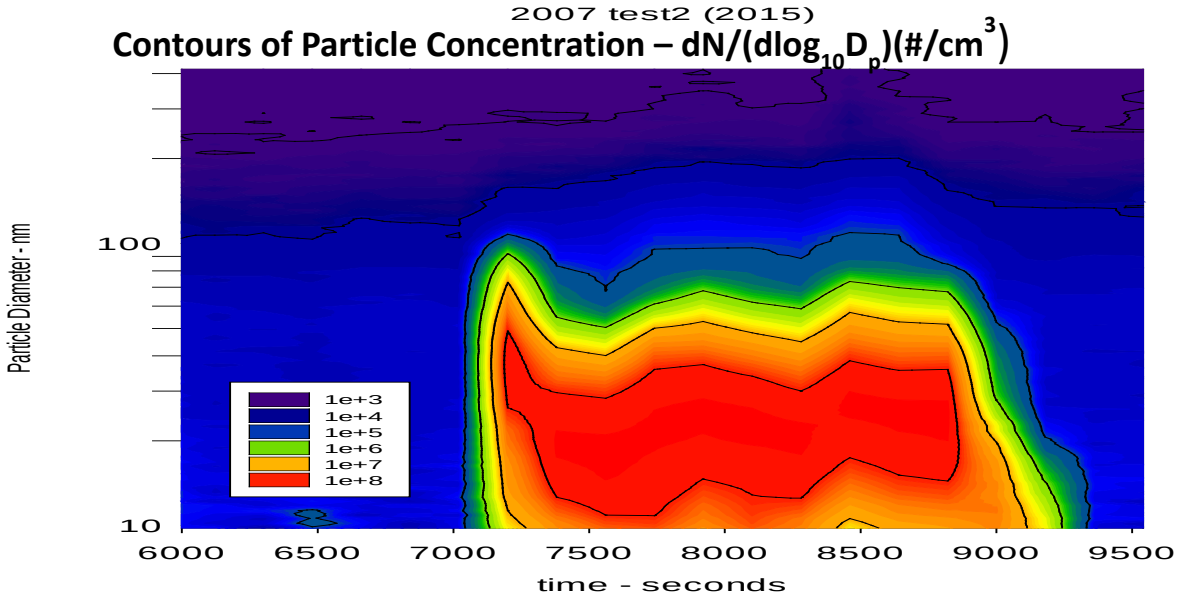

Figure IIIB-3b Contours of particle concentration of the parked regeneration of the 2007 DPF, test2

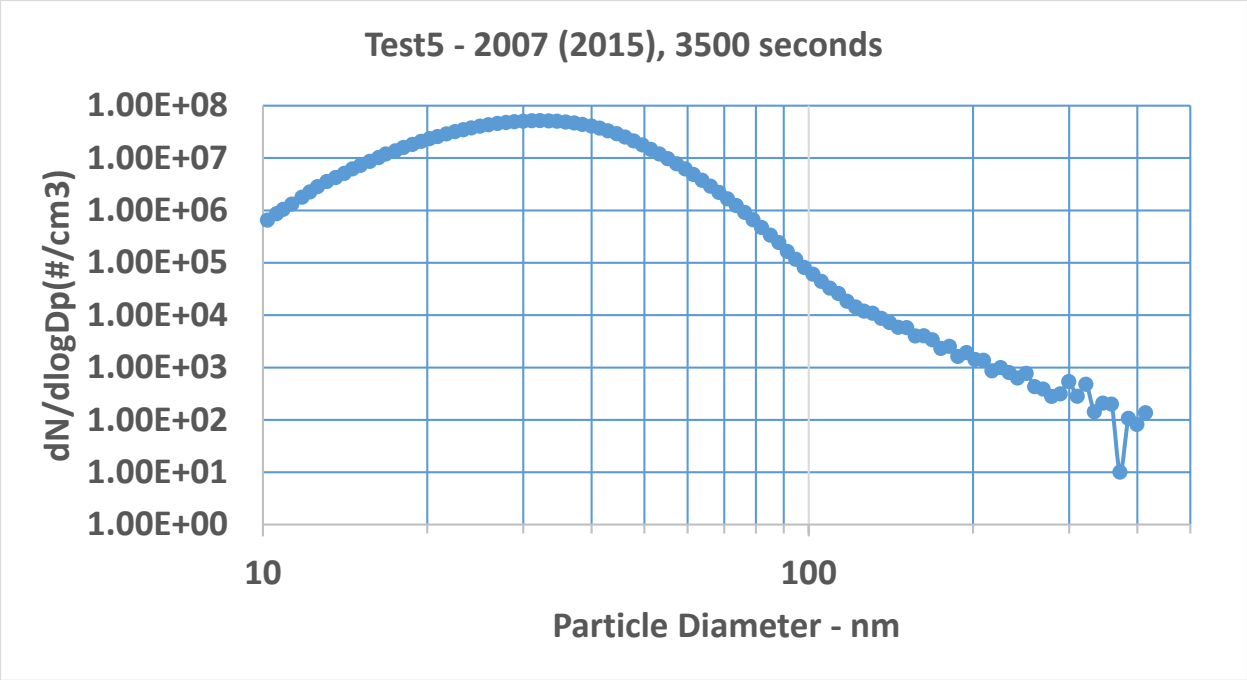

Figure IIIB-4a Particle size distribution during test5

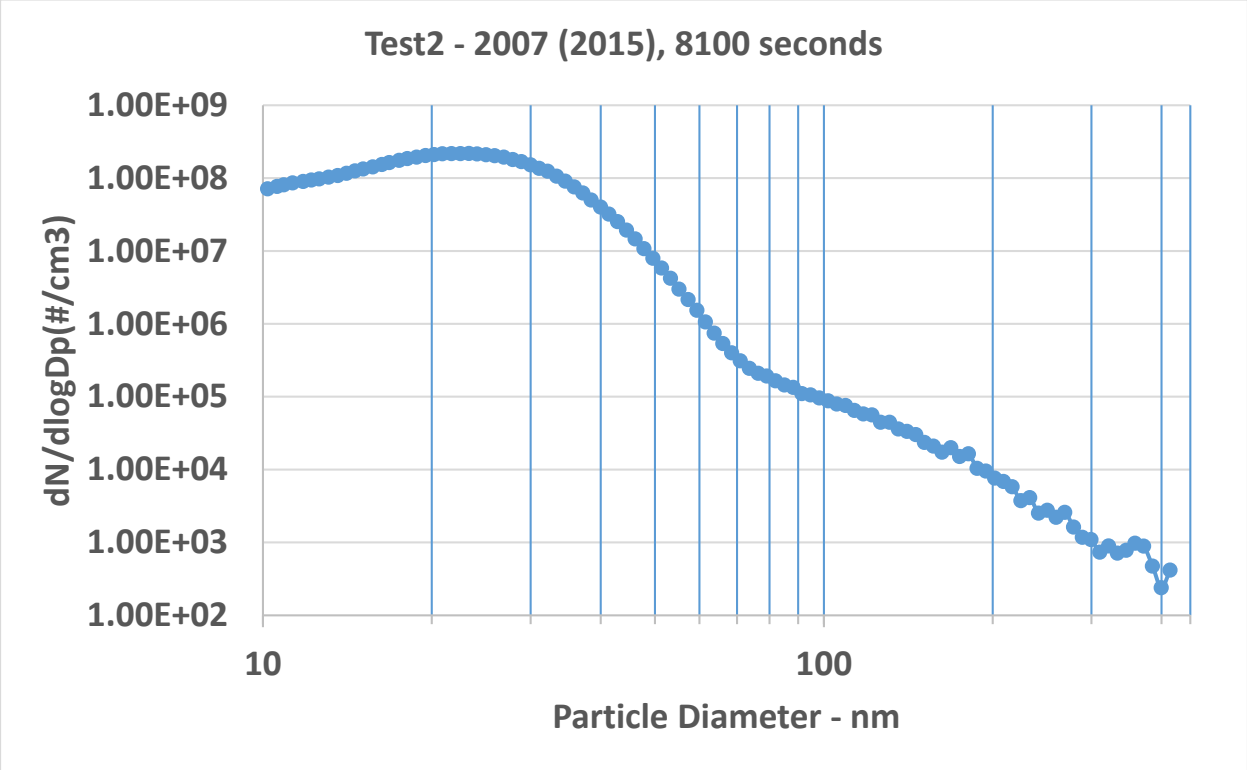

Figure IIIB-4b Particle size distribution during test2

The particle number concentrations during the testing are given in Figures IIIB-5a and IIIB-5b for test5 and test2, respectively, and it is seen that test2 had four times as many particles. However, the total number particles for the road regeneration, test5, is very similar to test1 and test3 for parked regenerations, and test2 gave larger values than all tests of the 2007 DPF. Variations in particle numbers between test1 thru test3 are to be expected since the loading of the DPF occurred during different times of the year with significant variations in atmospheric conditions.

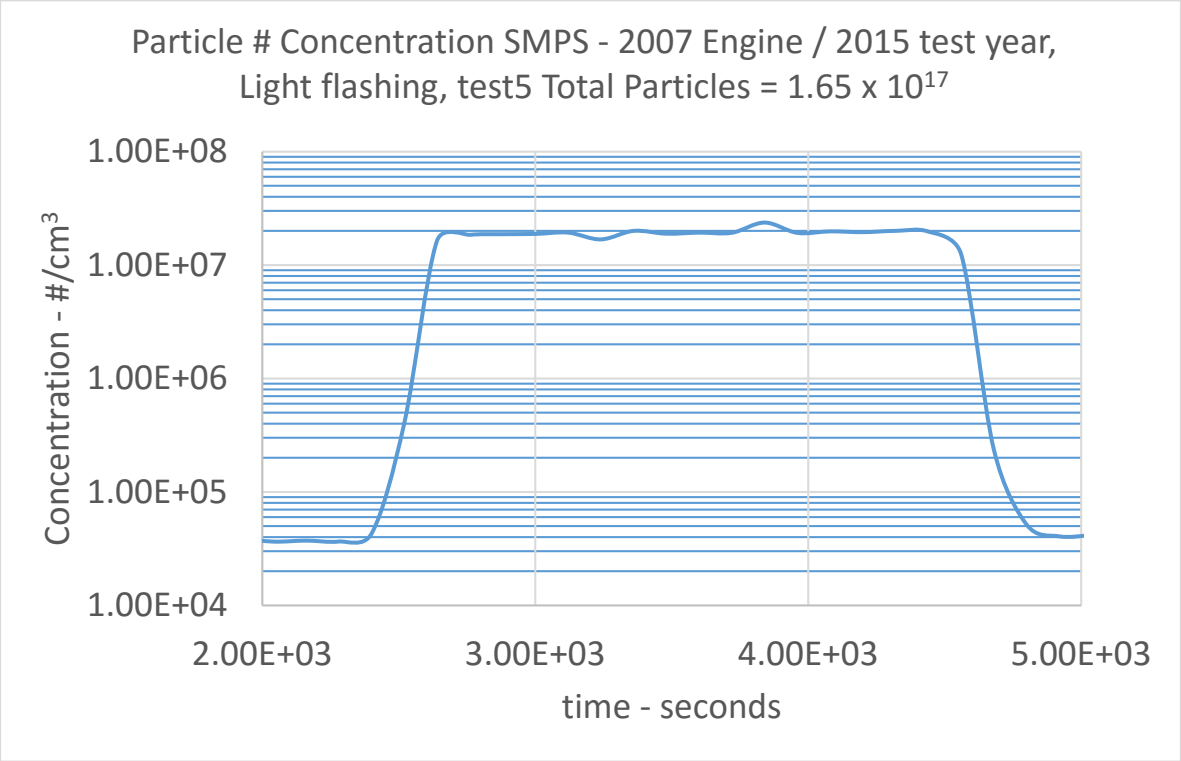

Figure IIIB-5a Particle number concentrations during test5

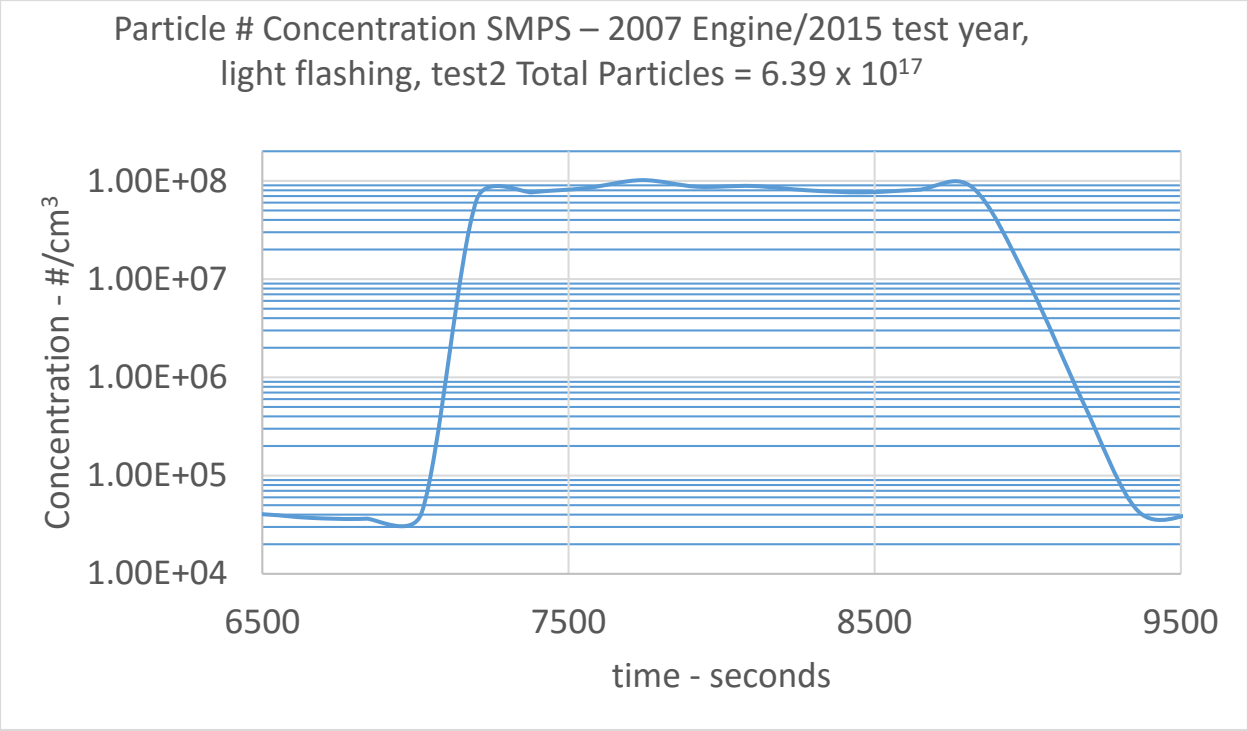

Figure IIIB-5b Particle number concentrations during test2

The SMPS predicted mass emissions are presented in Figures IIIB-6a and III-6b for test5 and test2, respectively, and these mass emissions are similar in value. The reason for this similarity of mass emissions appears to be due to the larger particle sizes in test5 relative to test2, as can be seen in Figures 4A and 4B. Although, there are some differences between the active road and parked DPF regenerations, these difference are small compared to the difference between the parked regenerations in 2013 and 2015 testing of the same 2007 DPF. At the present time it appears that the reason for the differences between the 2013 and 2015 testing is due to the way that the DPF was loaded. The 2013 testing involved stop and go driving on the road, while in the 2015 testing the DPF was loaded on the dynamometer.

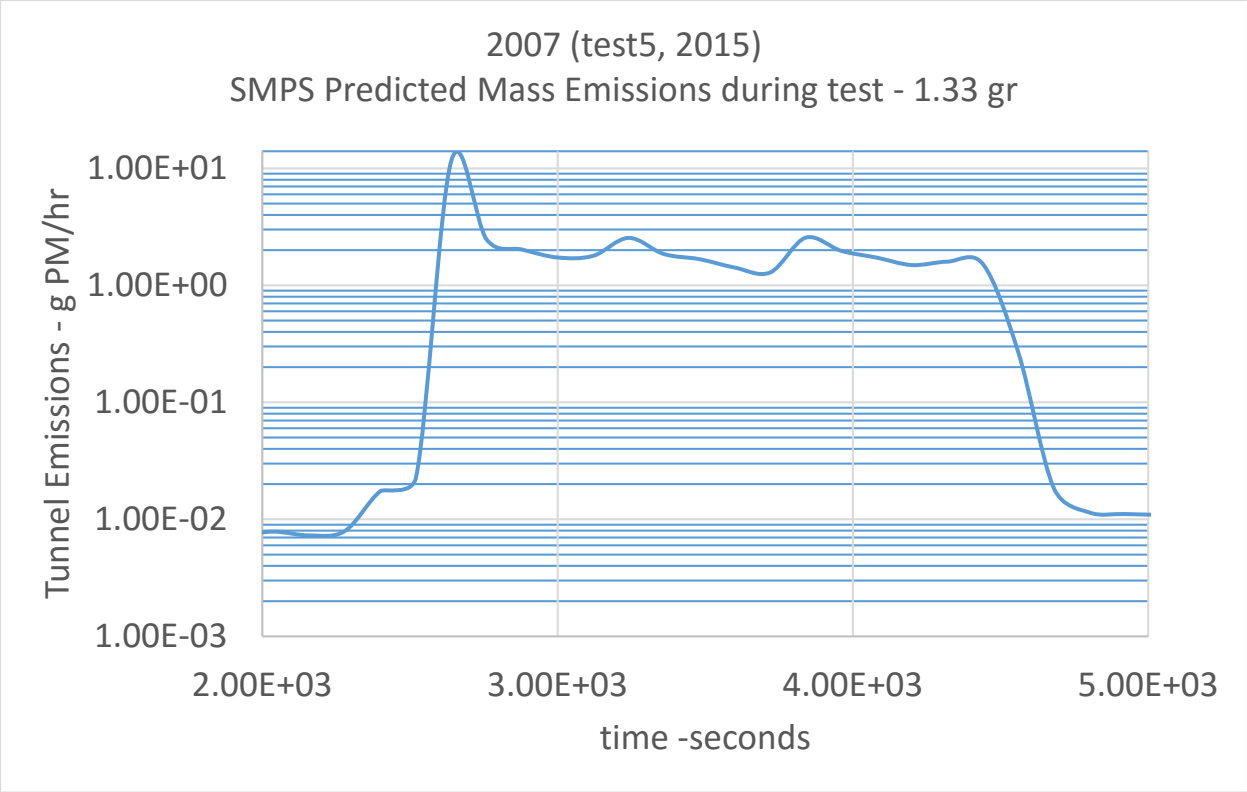

Figure IIIB-6a – SMPS predicted mass emissions during test5

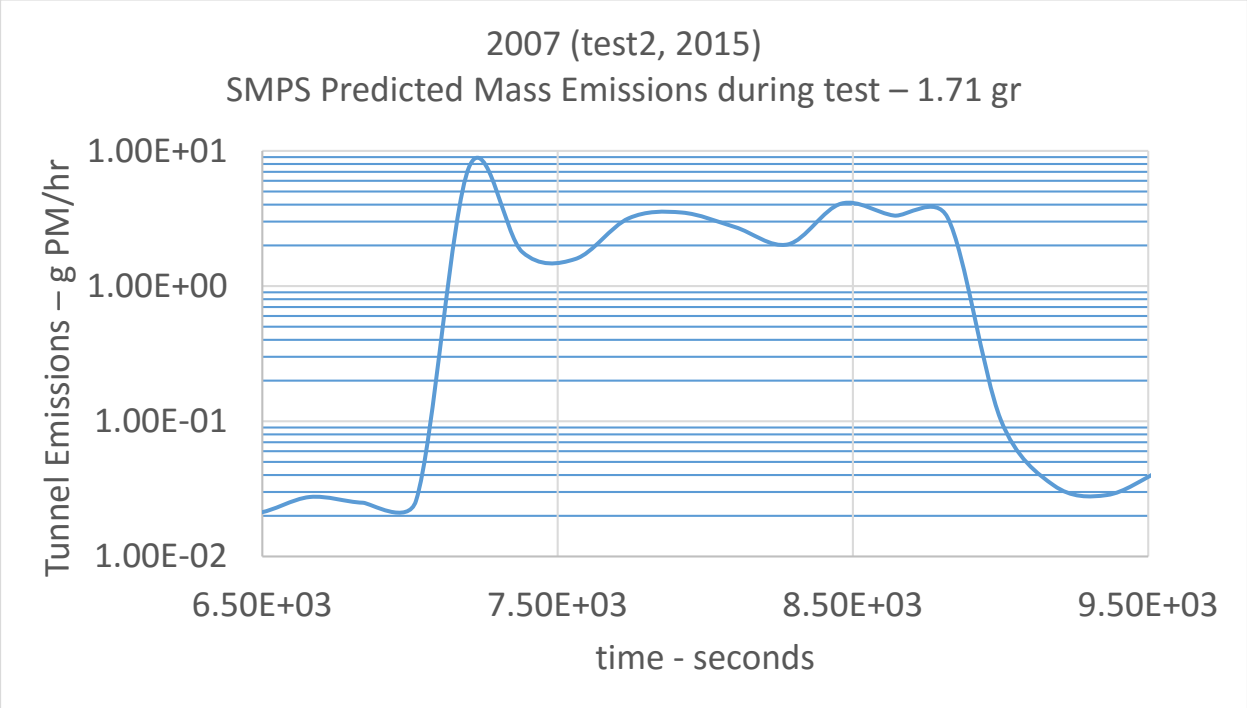

Figure IIIB-6b – SMPS predicted mass emissions during test2

Another point to investigate is the emission of large particles during the road regeneration of the 2007 DPF, and DustTrak emissions from test5 are shown in Figures IIIB-7a and IIIB-7b. Figure IIIB-7a shows the DustTrak emissions, and there is short peak of emissions at approximately 2500 seconds at the beginning of the test5. An expanded view of this peak is shown in Figure IIIB-7b, and it is clearly seen that the PM 1.0, blue, and Total emissions, red, are essentially the same. Therefore, it can be concluded that an insignificant amount of large particles have been emitted during test5 a road regeneration of the 2007 DPF.

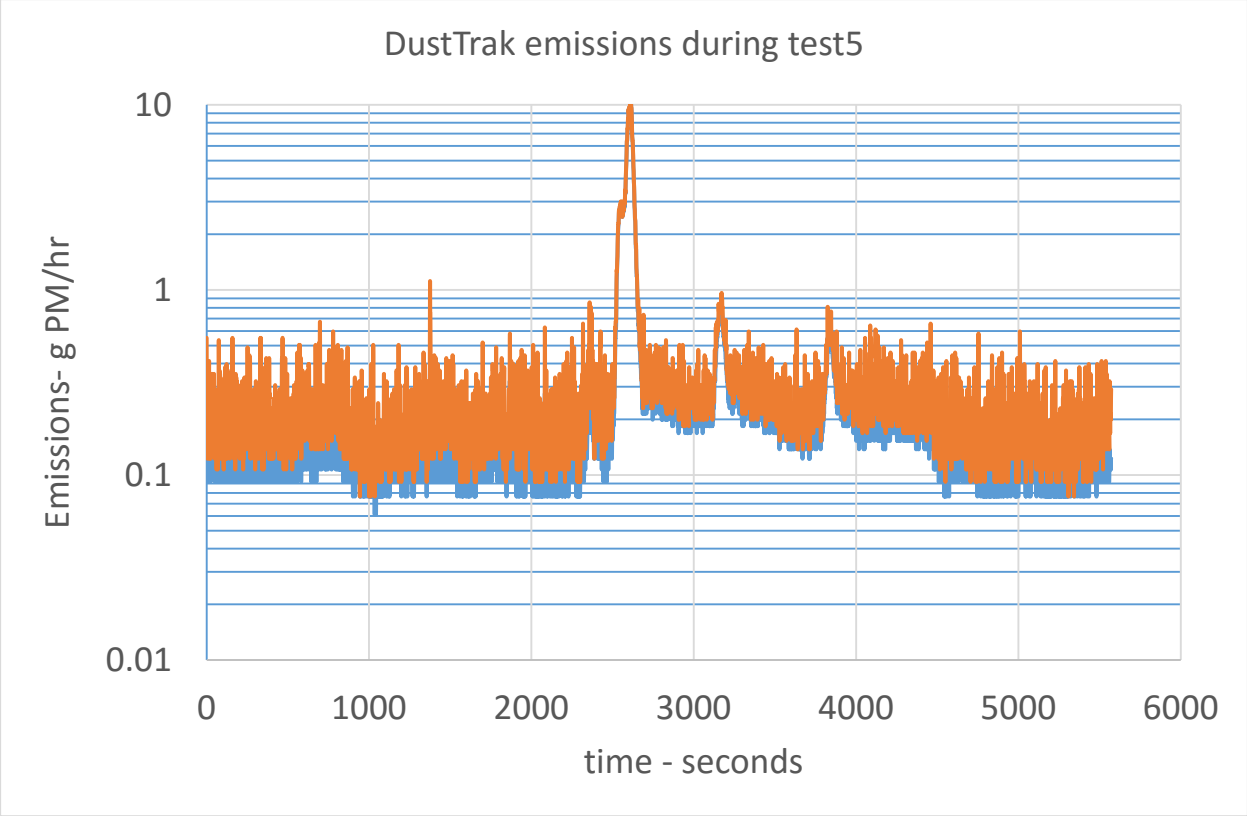

Figure IIIB-7a DustTrak emissions during test5; blue PM 1.0, red PM Total

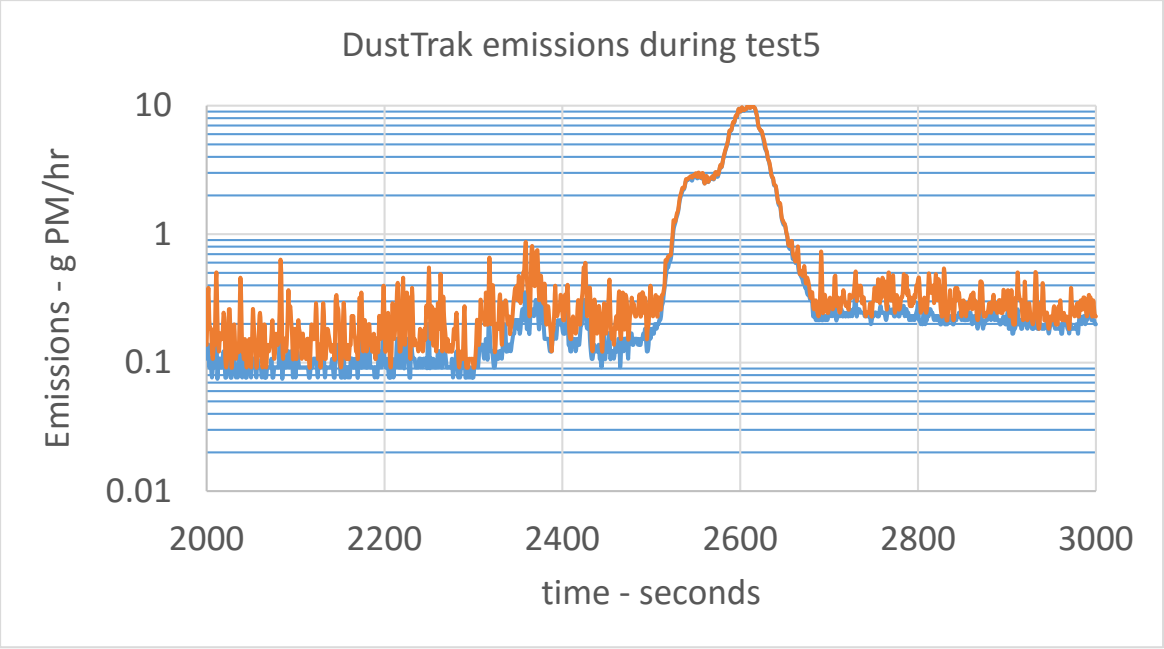

Figure IIIB-7b Time expanded DustTrak emissions during test5; blue PM 1.0, red PM Total

The final point for the 2007 road regeneration, test5, is to compare the estimated SMPS and DMM mass emissions with the amount of mass accumulated on the filter. From Table III….it is seen that the DMM and SMPS mass emission bracket the filter value, and the mass emissions for the road regeneration is similar to test3 of the 2007 DPF parked regeneration during Phase II.

Summary Table for Mass Estimates from Particle Instruments and Filters

Vehicle and test type	Test # and date	DMM-g	SMPS-g	Gravimetric Mass-g
2007/flashing light/park	test1-2/23/15	2.49	0.809	0.717
2007/flashing light/park	test2-3/18/15	1.78	1.71	0.981
2007/flashing light/park	test3-4/23/15	5.6	0.91	5.4
2007/light on/road	test4-5/12/15	3.25	0.59	1.87
2007/flashing light/road	test5-5/29/15	7.33	1.33	4.07
2010/light on/park	test6-7/15/15	6.47	1.14	2.64
2010/light on/road	test7-8/5/15	35.1	2.61	16.3
2010/light on/road	test8-8/26/15	23.3	3.32	9.44
2010/light on/passive	test9-9/15/15	0.025	0.012	0.159
2010/light on/passive	test10-9/17/15	XXX	0.036	0.102
2010/light on/passive	Test11-9/22/15	0.120	0.062	0.220

Two active road regenerations of the 2010 DPF were performed in phase II, and both of these road regenerations, test7 and test8, emitted the largest amount of mass during the testing, see summary mass table. The road active regenerations were carried out in a similar manner to the road regeneration of the 2007 DPF, and the regenerations were started after the truck reached a simulated velocity of 50 mph. However, the tunnel PM mass emissions were considerable larger for the 2010 DPF road regeneration than the 2007 DPF road regeneration. Test7 had a larger SMPS sheath flow of 10 lpm rather than 6 lpm, and the SMPS data had to be corrected for this test. Also, the limit for the SMPS particle size detection was 251 nm for test7, rather than 419 nm for all other test.

Shown in figures IIIB-8a and IIIB-8b are the particle number concentrations for test7 during the testing from the SMPS and the DMM instrumentation, respectively. The limit for the particle size detection was 1000 nm for the DMM, and it can be seen that the DMM recorded approximately two and a half more particles than the SMPS. In general, the DMM has been recording larger mass emissions than the SMPS. Shown in Figures IIIB-9a and IIIB-9b are the particle number concentrations for test8 during the testing from the SMPS and the DMM instrumentation. The SMPS total concentrations in Figure IIIB-9a, test8, are approximately two times smaller than test7, and the DMM has recorded approximately twenty-five percent fewer particles for test8 relative to test7. In general, it appears that test8 generated fewer particles than test7. However, it should also be mentioned that the filter samples were quite dark for both test7 and test8.

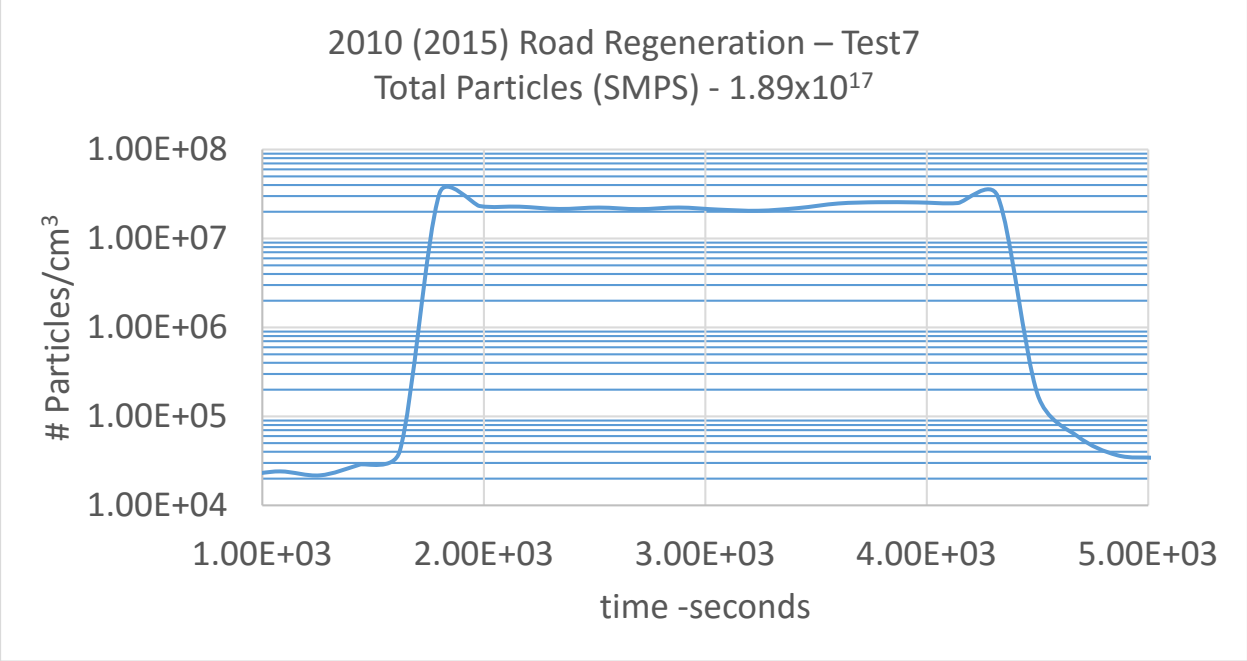

Figure IIIB-8a SMPS tunnel concentration data, test7

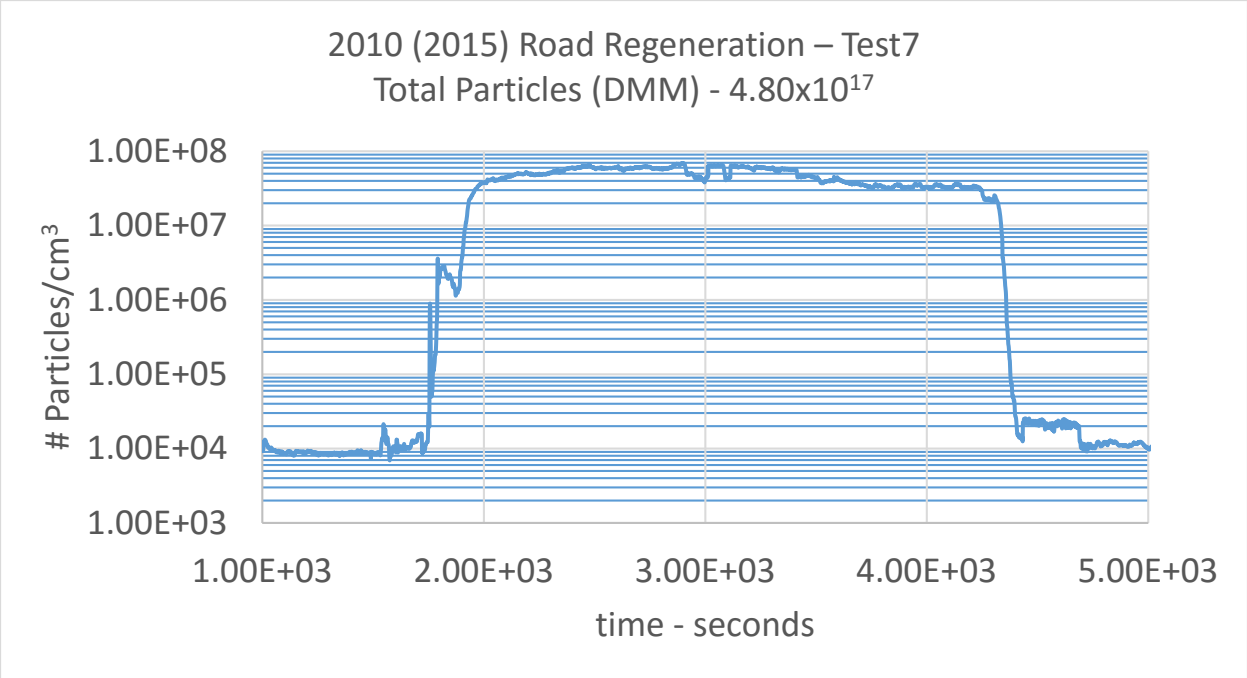

Figure IIIB-8b DMM tunnel concentration data, test7

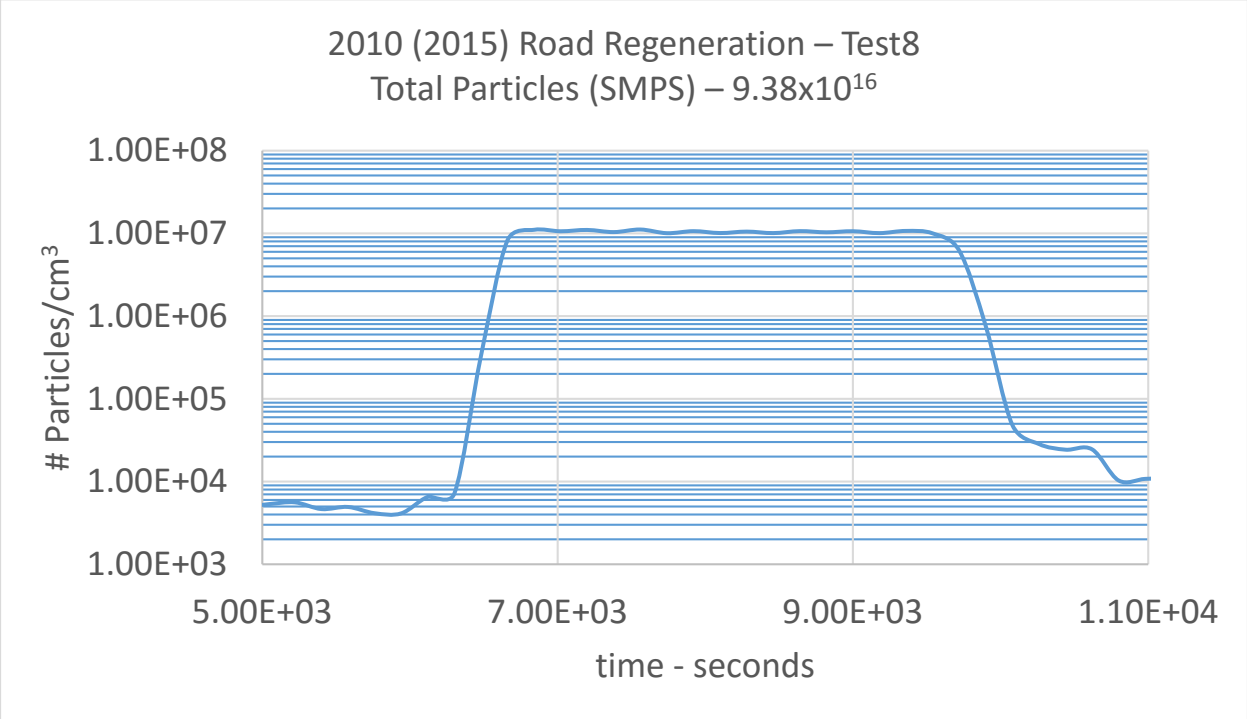

Figure IIIB-9a SMPS tunnel concentration data, test8

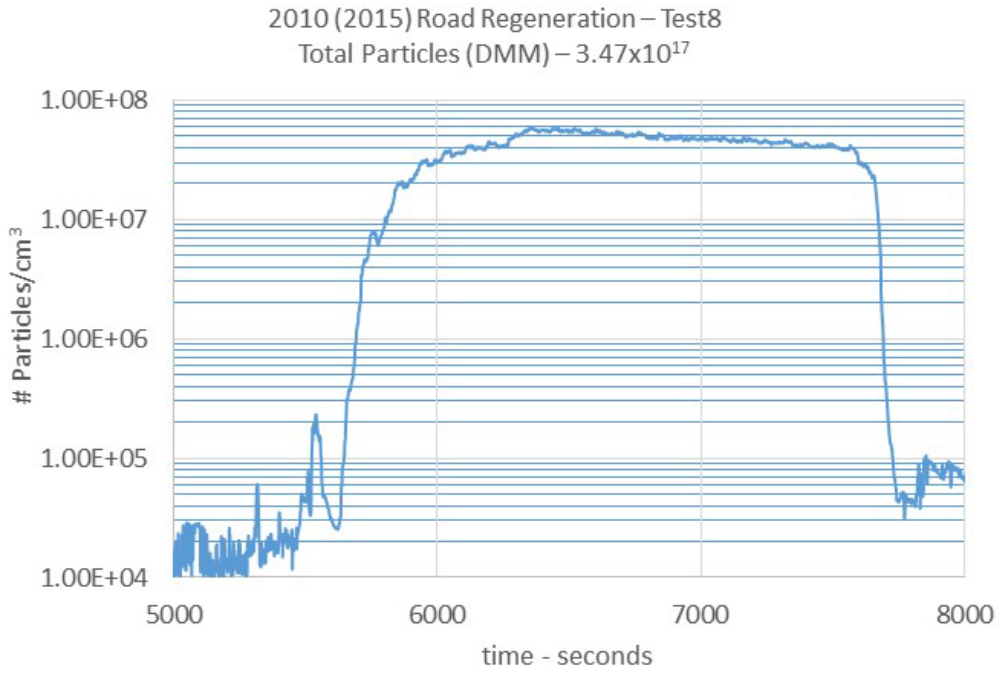

Figure IIIB-9b DMM tunnel concentration data, test8

The tunnel mass emissions predictions depend on the particle concentration, particle size distribution, and the density size distribution, and these emissions are shown in figures IIIB-10a and IIIB-10b, test7, for the SMPS and DMM respectively. The DMM predicted PM tunnel emissions are more than ten times larger than the SMPS values, 35.1 grams versus 2.61 grams, and this larger value for the DMM is consistent with most of the predictions from the other tests carried out with the DPF loading applied by the Depot Park chassis dynamometer. The SMPS mass data in figure IIIB-10a is lower due to the smaller sampling size range. It should also be noted that the DMM recorded data on a one second interval and the SMPS had a three minute recording interval. Shown in Figures IIIB-11a and IIIB-12a are the PM tunnel mass emissions for test8, and both the SMPS and the DMM reported lower values than test7. The SMPS total PM mass is similar between tests, while the DMM predicted total PM mass decreased by approximately one third. Again, it should be noted that the filter weights is useful for evaluating the accuracy of the SMPS and DMM predictions.

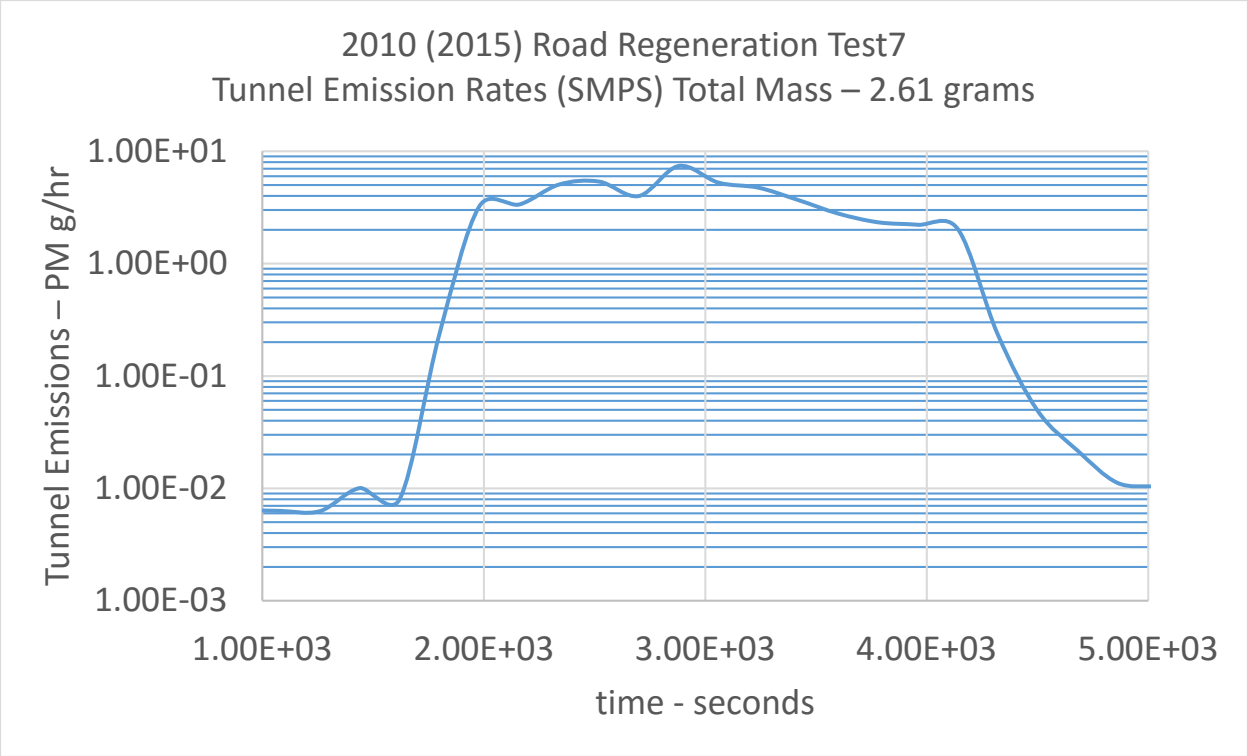

Figure IIIB-10a SMPS mass emission predictions, test7

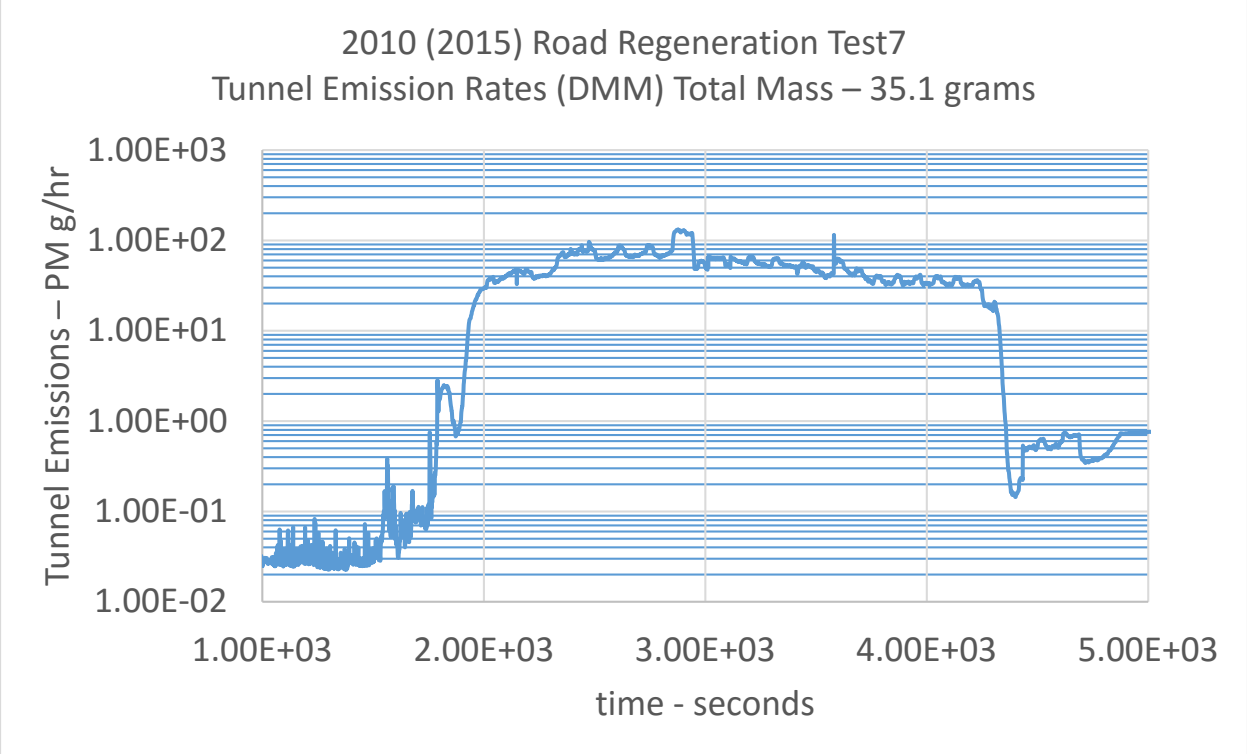

Figure IIIB-10b DMM mass emission predictions, test7.

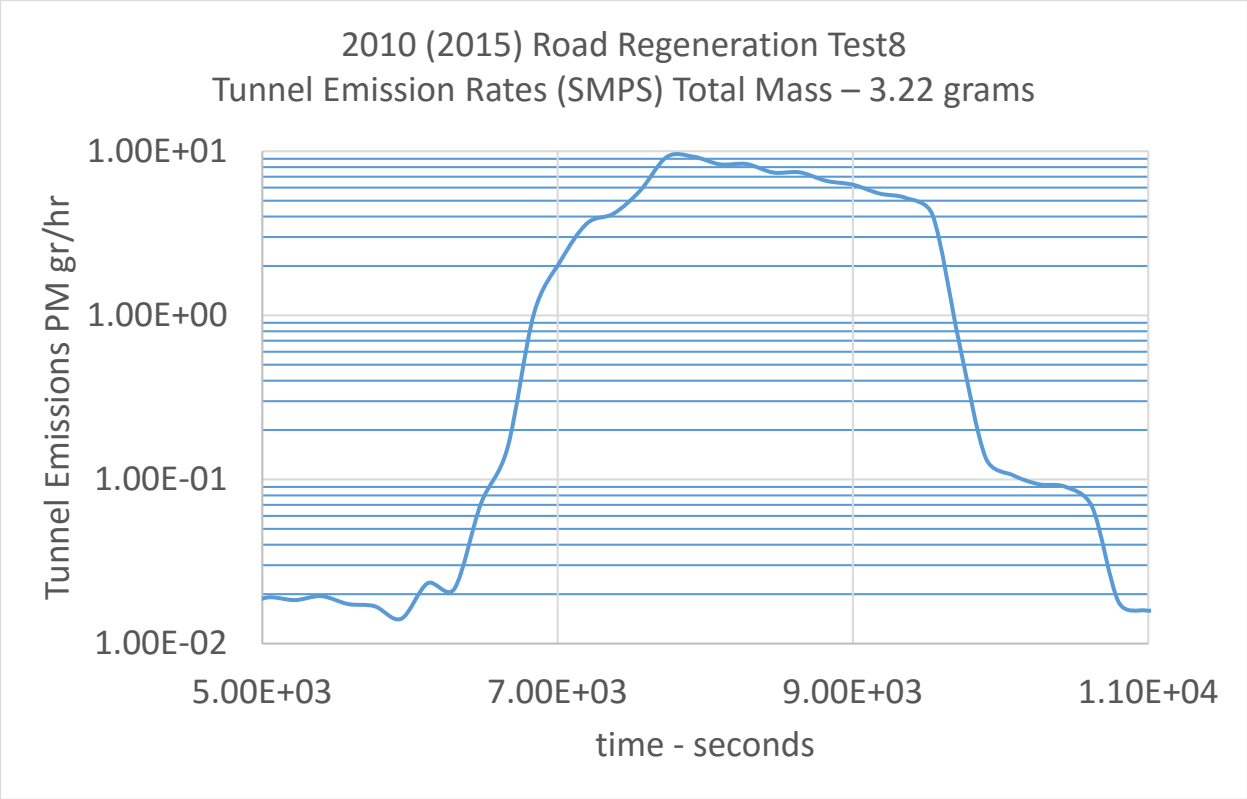

Figure IIIB-11a SMPS mass emission predictions, test8

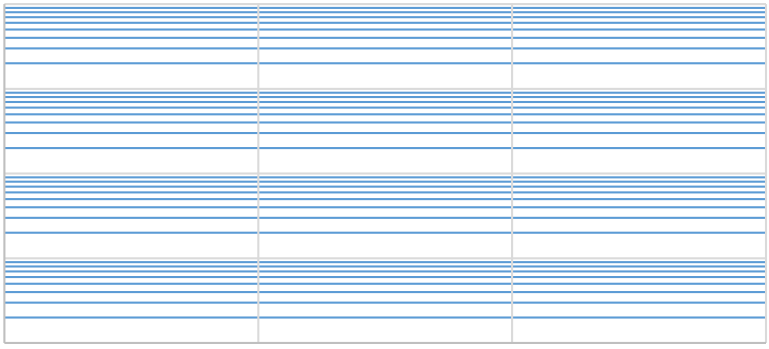

Figure IIIB-11b DMM mass emission predictions, test8

The DustTrak emissions are shown in Figures IIIB-12a and IIIB-12b for test7. The predicted DustTrak tunnel emissions in Figure IIIB-12A are considerable, 2.21 grams, but less than both the

DMM and SMPS emissions. The DustTrak instrument only records particles larger than 100 nm, and it uses a constant density of approximately 2.8 grams/cm^3, which is much larger than typical PM particles in the size range from 100 to 1000 nanometers. However, the DustTrak does record particles greater than one micron with a limit of ten microns, and the DustTrak predictions for both PM1.0 and PMTotal are shown in Figure IIIB-12a. In general the DustTrak PM emissions for PM1.0 and PMTotal have similar values except for the beginning of the regeneration, Figure IIIB-12b, which has previously been called the soot burning phase in the DPF. Considering the large density used in the DustTrak predictions, it can be reasonably estimated that the DustTrak predicts much less than one gram of emissions in the particle diameter range larger than the PM 1.0 micron limit. Therefore, the DustTrak emissions does very little to explain the differences between the SMPS and DMM predicted emissions. The DustTrak emissions for test8 are shown in Figure IIIB-12c, and they are very similar to test7.

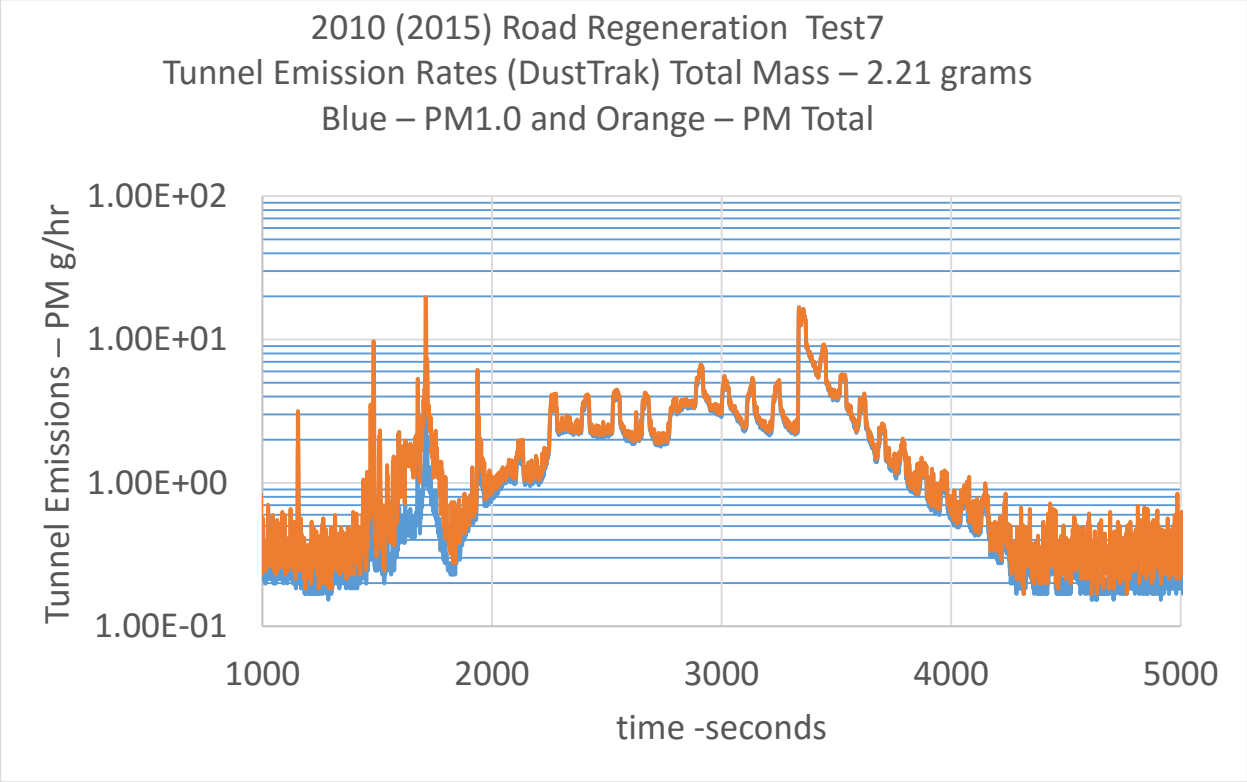

Figure IIIB-12a DustTrak emissions during test7

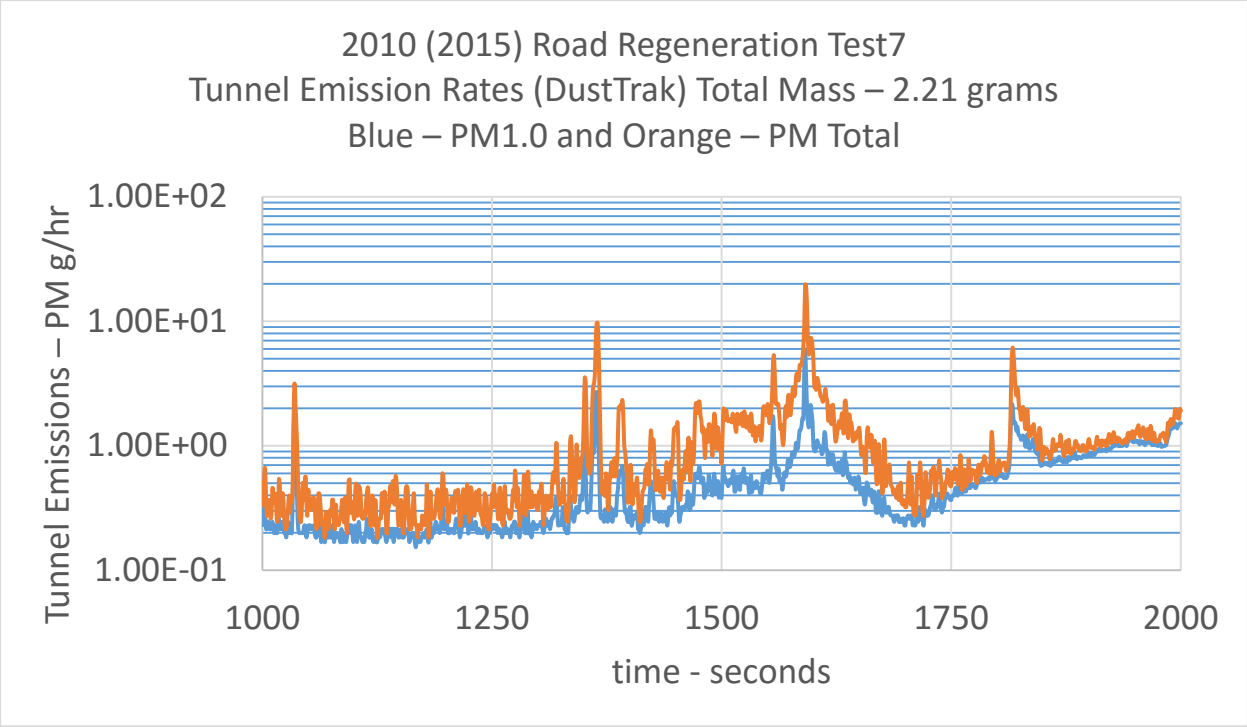

Figure IIIB-12b Expanded scale for DustTrak emissions during test7

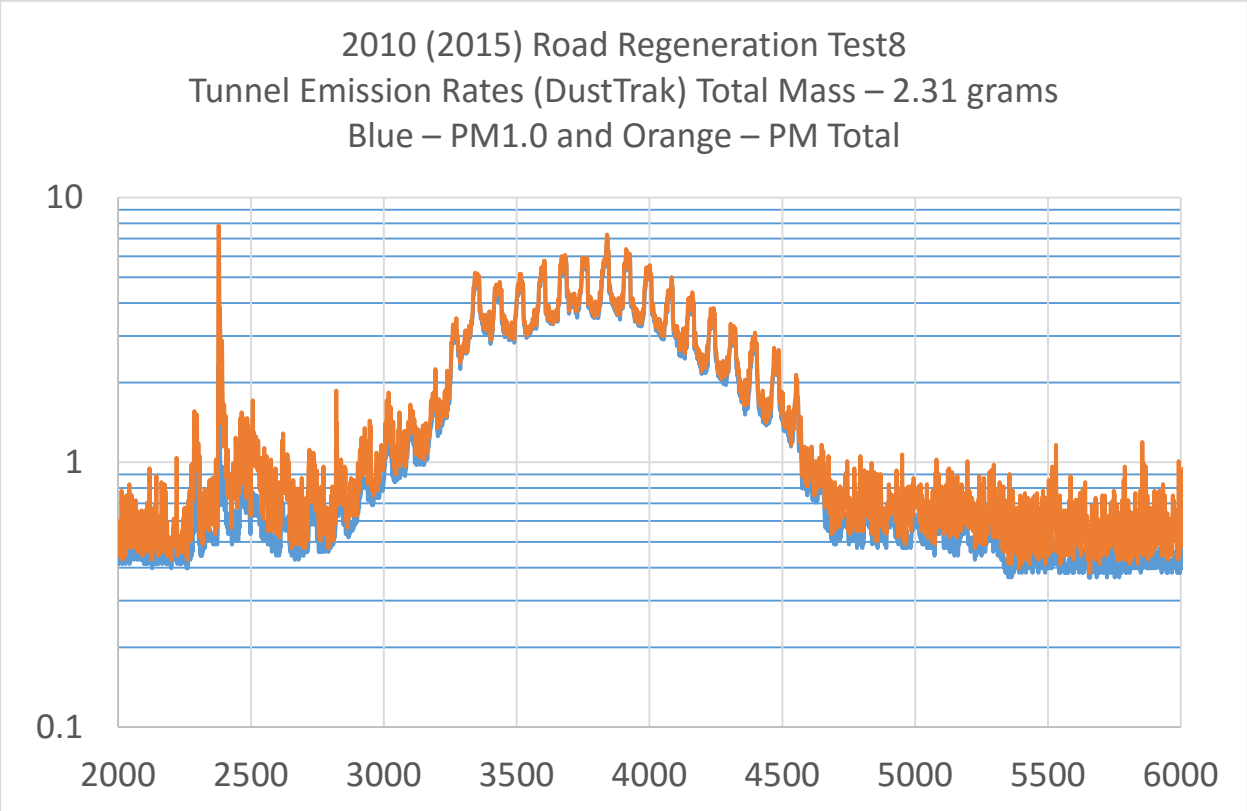

Figure IIIB-12c DustTrak emissions during test8

An important part of estimating the tunnel emissions is the particle size distribution, and the normalized size distributions from the SMPS are shown in Figure IIIB-13, test7. Compared to all previous testing the results in Figure IIIB-13 show increased emissions of larger particles in the size range between 20 and 60 nm than any previous testing, and these large particles are responsible for the larger amount of mass predicted by the SMPS, which was larger than any other test this year. Also, the SMPS results indicate that there are significant particle numbers and mass larger than the size range limit of the SMPS instrument. The normalized size distribution for test8 is given in Figure IIIB-14, and it is qualitatively similar to test7, but with somewhat lower particle concentrations.

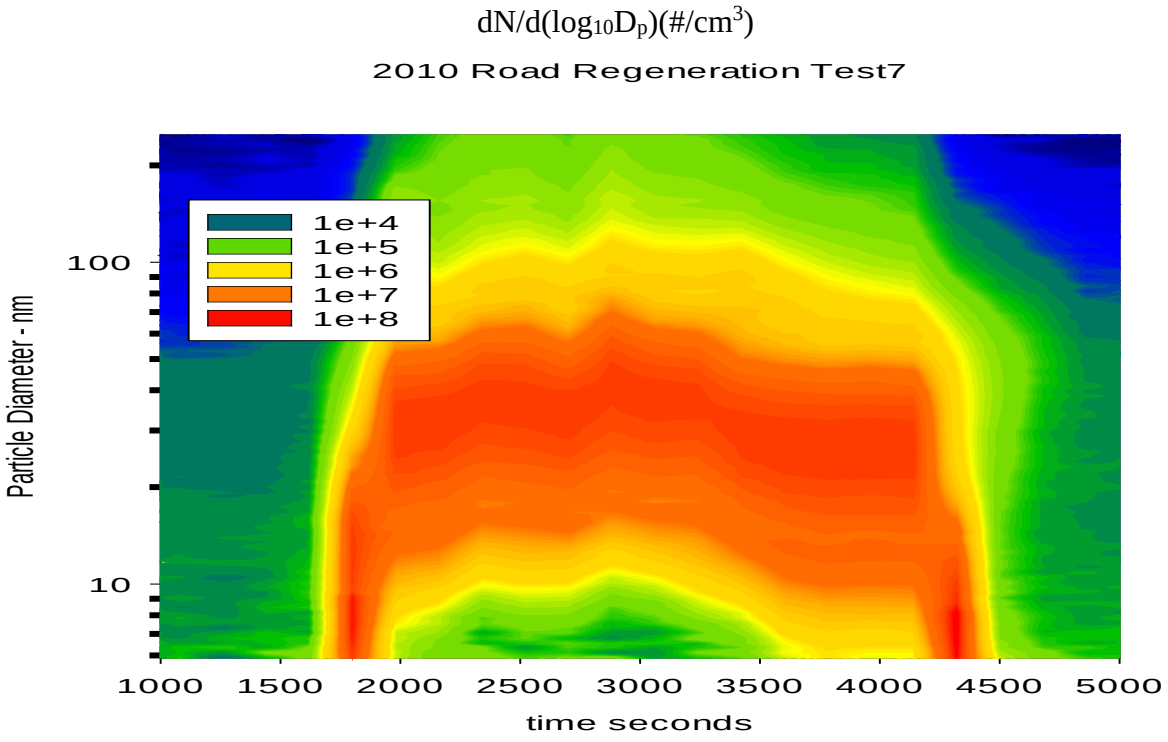

Figure IIIB-13 Normalized spectral particle concentration, test7

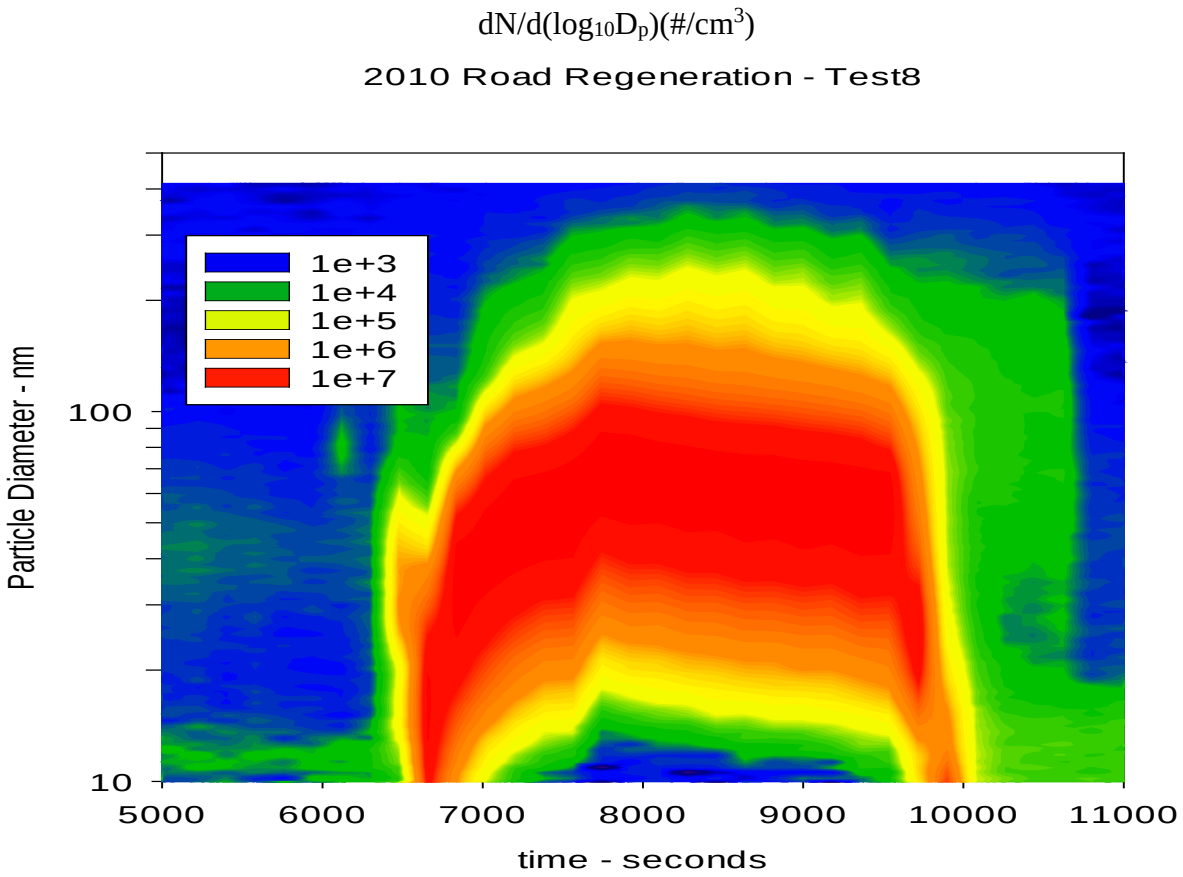

Figure IIIB-14 Normalized spectral particle concentration, test8

Shown in Figure IIIB-15, test7, is the normalized volume distributions from the SMPS as a function of size and time, and it is clear that the particle volume is quite large at the size limit of the SMPS, 251 nm for test7. The primary reason that the particle volume is remaining large when the particle concentration is decreasing is due to the fact that volume is proportional to the diameter cubed. For test8 the normalized volume distribution is shown in Figure IIIB-16, and the results are similar to test7, but with lower volume due to smaller concentrations. Further insight into these results can be obtained by observing a slice of Figures IIIB-13 at 2800 seconds, test7, and Figure IIIB-14, test8 at 8100 seconds, and these results can be seen in Figures IIIB-17a and IIIB-17b, test7, and Figures IIIB-18a and IIIB-18b, test8.

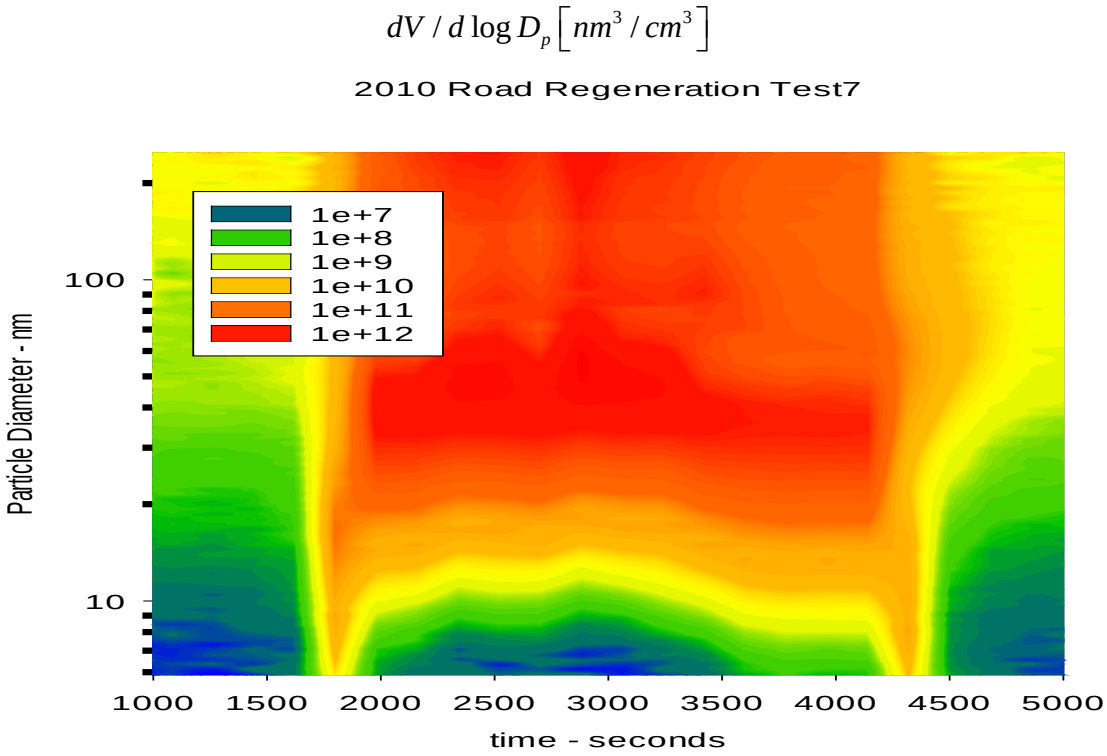

Figure IIIB-15 Normalized volume distribution during test7

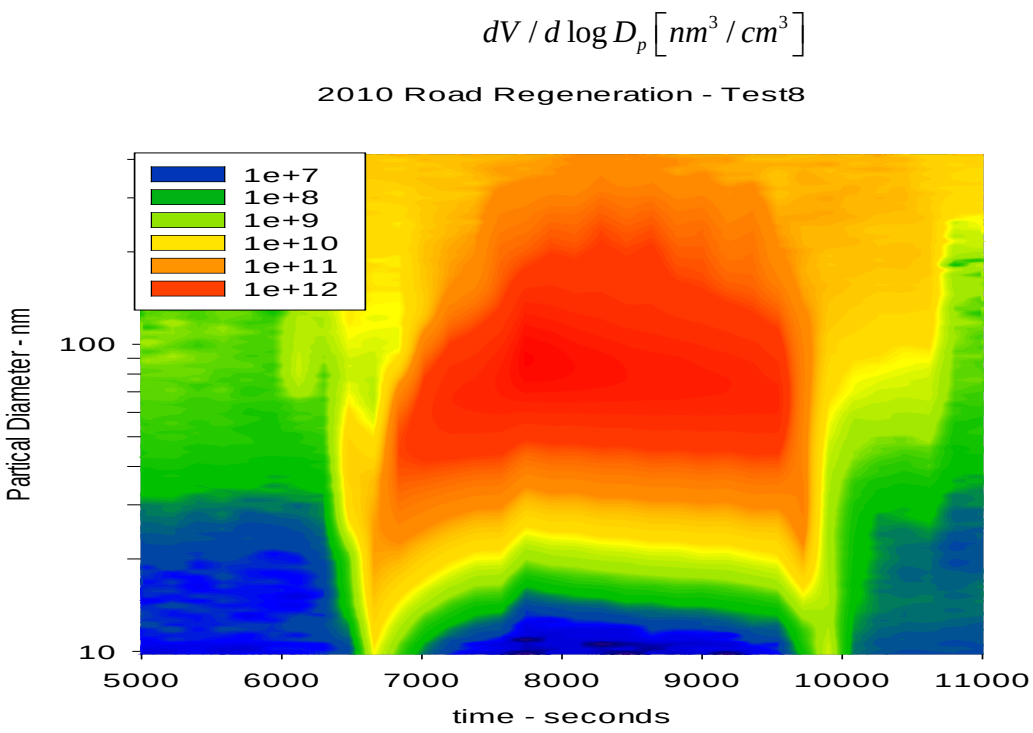

Figure IIIB-16 Normalized volume distribution during test8

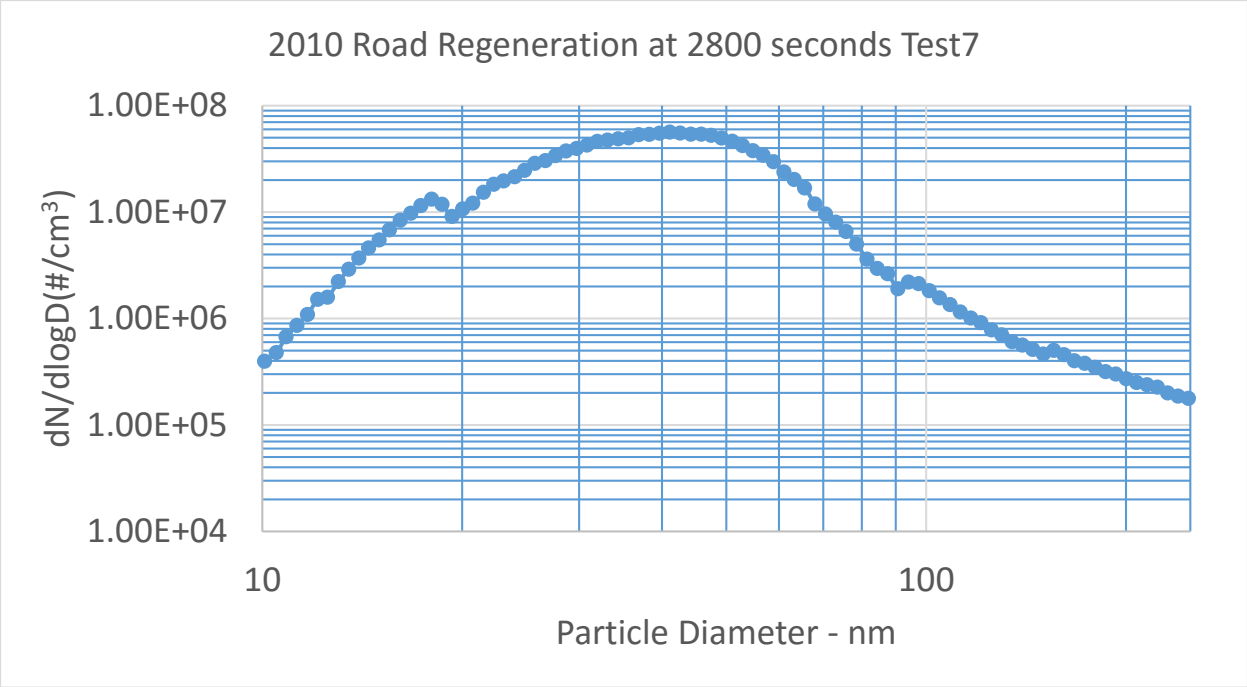

Figure IIIB-17a Normalized particle number concentration at time 2800 seconds, test7

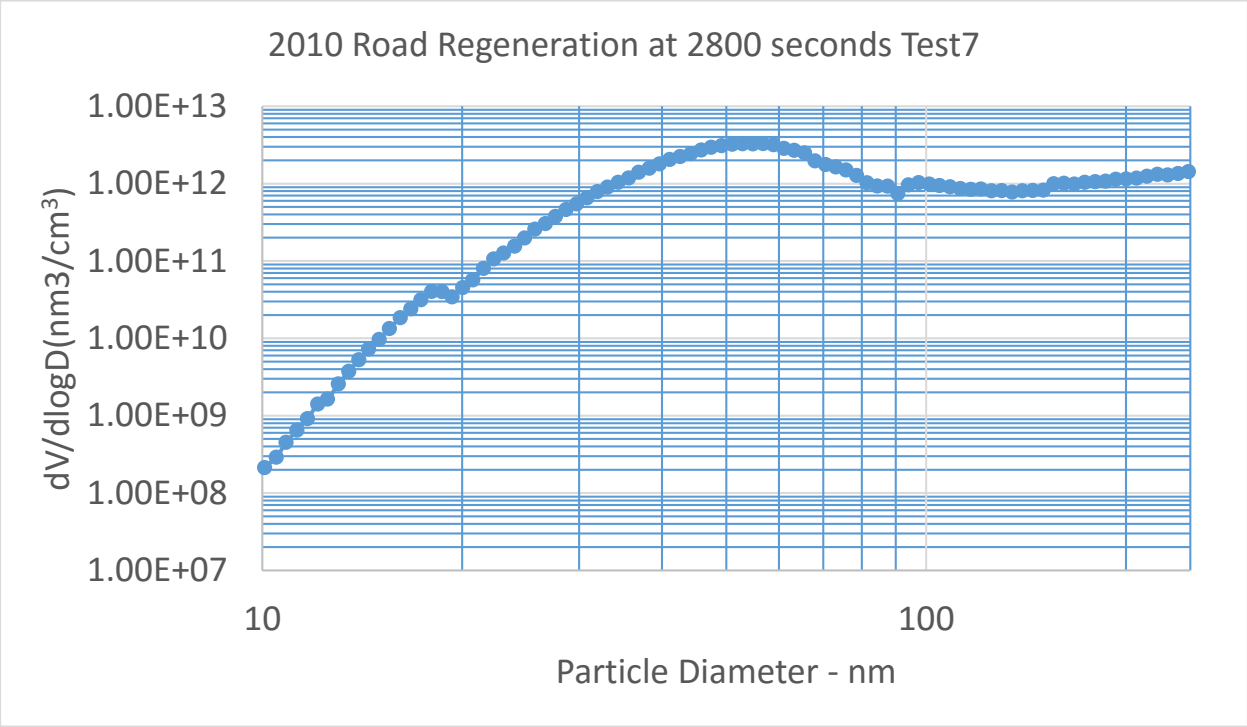

Figure IIIB-17b Normalized particle volume concentration at time 2800 seconds, test7

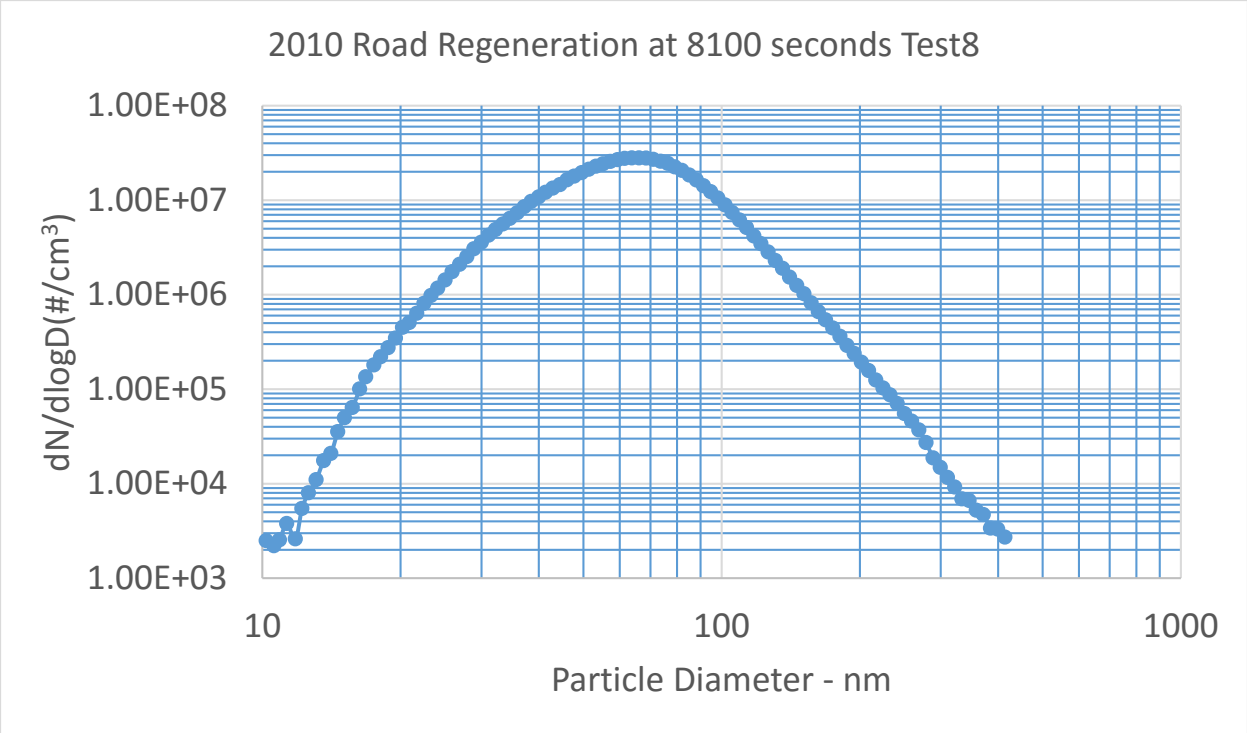

Figure IIIB-18a Normalized particle number concentration at time 8100 seconds, test8

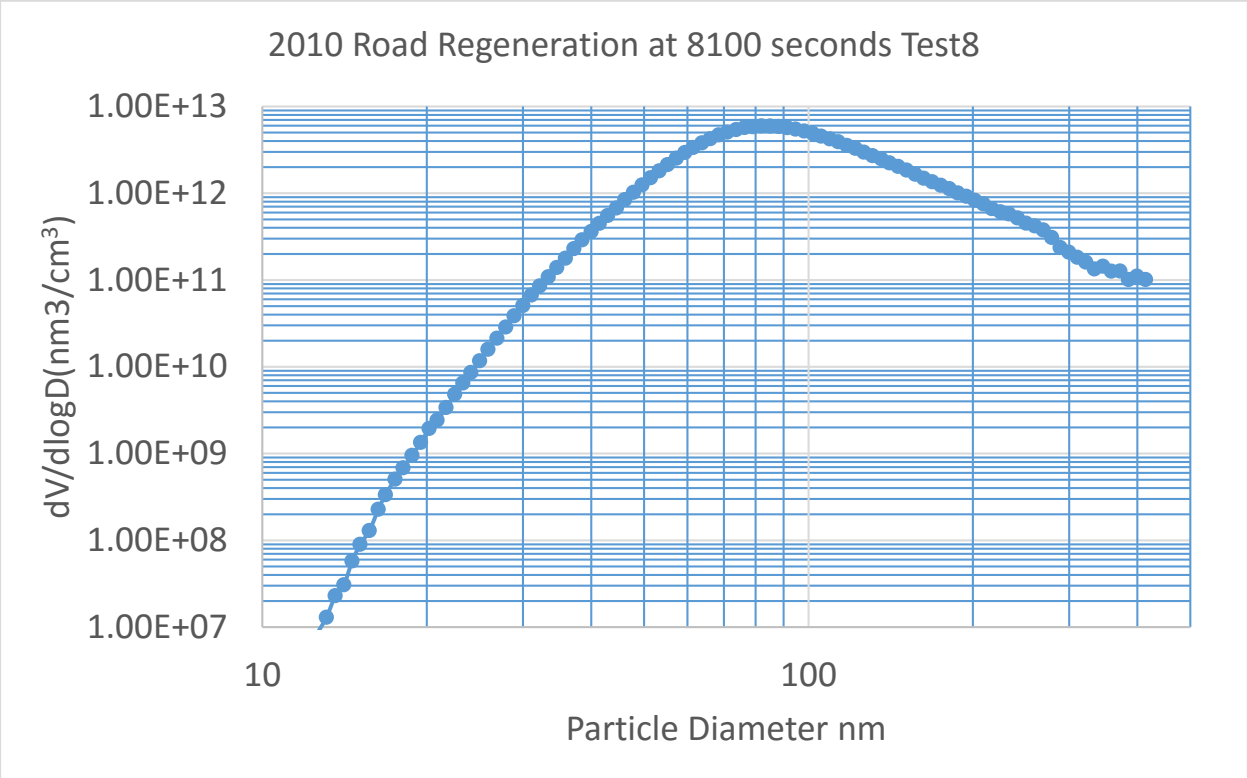

Figure IIIB-18b Normalized particle volume concentration at time 8100 seconds, test8

Figure IIIB-17a shows that the maximum particle concentration for the SMPS occurs between 40 and 50 nanometers, and Figure IIIB-17b shows that the maximum particle volume is between 50 and 60 nm at 2800 seconds. These results for the active road regeneration are distinct from all previous testing, and they will have to be confirmed with future testing. Figure IIIB-17b is also showing that the particle volume is increasing slightly above 200 nm, and this is significant. However, the results at 2800 seconds are near the maximum of the particle concentrations, and the particle concentrations decrease in level and size as time proceeds. Although the SMPS results indicate that there is substantial mass emitted in the tunnel above the size limitation of the SMPS, it appears to not fully explain a difference of ten times between the DMM and the SMPS.

Figures IIIB-18a and IIIB-18b, test8, show a similar nature to test7, but with smaller particle concentrations and larger particles. The SMPS particle concentration and volume distributions clearly show that test7 emitted similar mass to test8, but the SMPS particle size distribution limit relative to the DMM may be important. Again it should be noted that the final determination of the accuracy of the different particle instruments will come from the filter measurements.

Important Note: Besides the sheath flow of 10 lpm for test7 there was another difference between test7 and all other tests carried out this year. Test7 employed an older CPC than all other tests, and the use of a different CPC could be responsible for some of the differences between tests 7 and 8.

C. Passive Road Regenerations of the 2010 DPF

The passive regeneration study was designed to investigate passive DPF regeneration after substantial stop and go driving on the Depot Park chassis dynamometer. Three tests were performed and the first two test yielded only very small amounts of PM after twenty five minutes of high power road driving. For the first two tests the DPF was loaded with five hours of stop and go traffic, and the high power driving was carried near maximum power, 405 hp, and the DPF outlet temperature was 405 deg C. These results were very puzzling, since the ACEs II results, Ref. , gave substantial amounts of passive PM with much less stop and go driving.

For the final test the DPF was loaded with ten hours of stop and go traffic, and substantial PM emissions were emitted near the end of the test. During the test it was not very clear that PM was being emitted since the particle instruments real time displays were dominated by large numbers of particles less than 20 nm in diameter. Only after post processing of the data was the substantial amount of large particle PM discovered. Unfortunately, this test, test11, was the final test of the project, since the 2010's DPF and vehicle was needed for other testing at CARB facilities.

After considerable time and effort test11 results were able to be analyzed, and the results showed substantial amount of passive regeneration. The analysis indicates that it takes considerable road driving before passive regeneration fully starts, and test11 was stopped before maximum passive regeneration was reached. This result can be best seen by observing the spectral particle number results from the SMPS and the FMPS in Figures IIIC-A and IIIC-B. The test started with some idle and thirty minutes of stop and go driving, and very little PM was emitted until the high power road driving was started. Almost immediately large numbers of very small particles less than 20 nm were observed by both the SMPS and FMPS as shown in the figures. Between 3500 and 4500 seconds the particle concentrations are dominated by the small particles, while at approximately 4500 seconds larger particles due to passive regeneration are emitted by the 2010 DPF. The large particle concentrations continue to grow until 5000 seconds when the test was terminated. It is quite clear from Figure IIIC-A and IIIC-B that test11 was stopped prematurely! The maximum concentration for the large particles during passive regeneration is between 30 and 120 nanometers, and this size range was expanding when test11 was stopped.

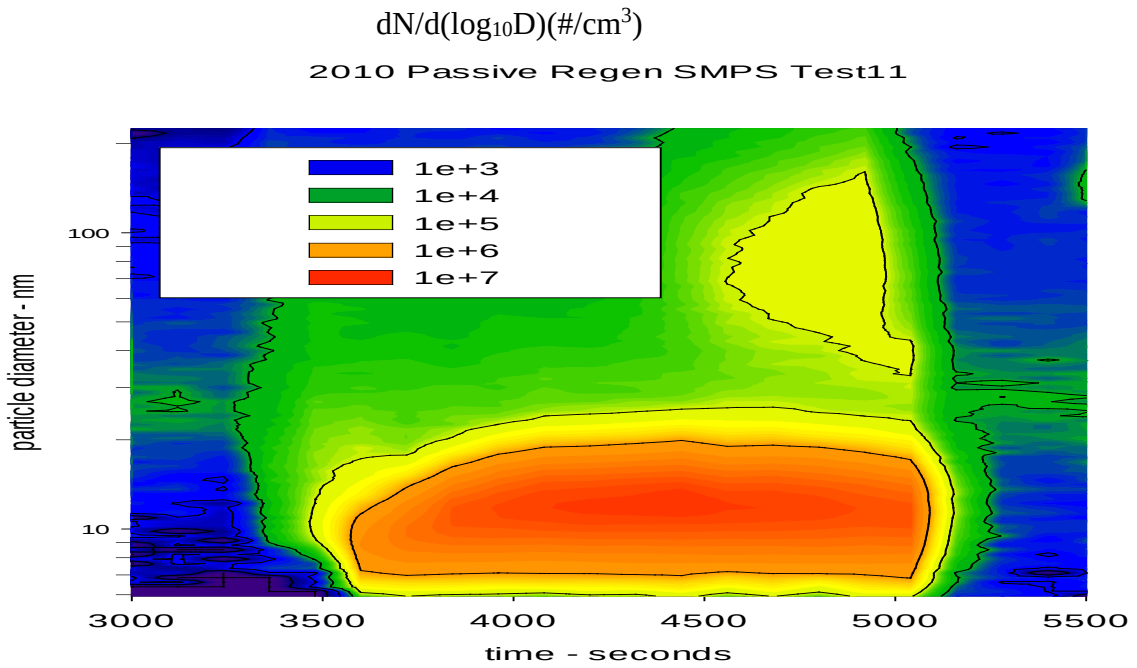

Figure IIIC-1 SMPS spectral particle number results for test11

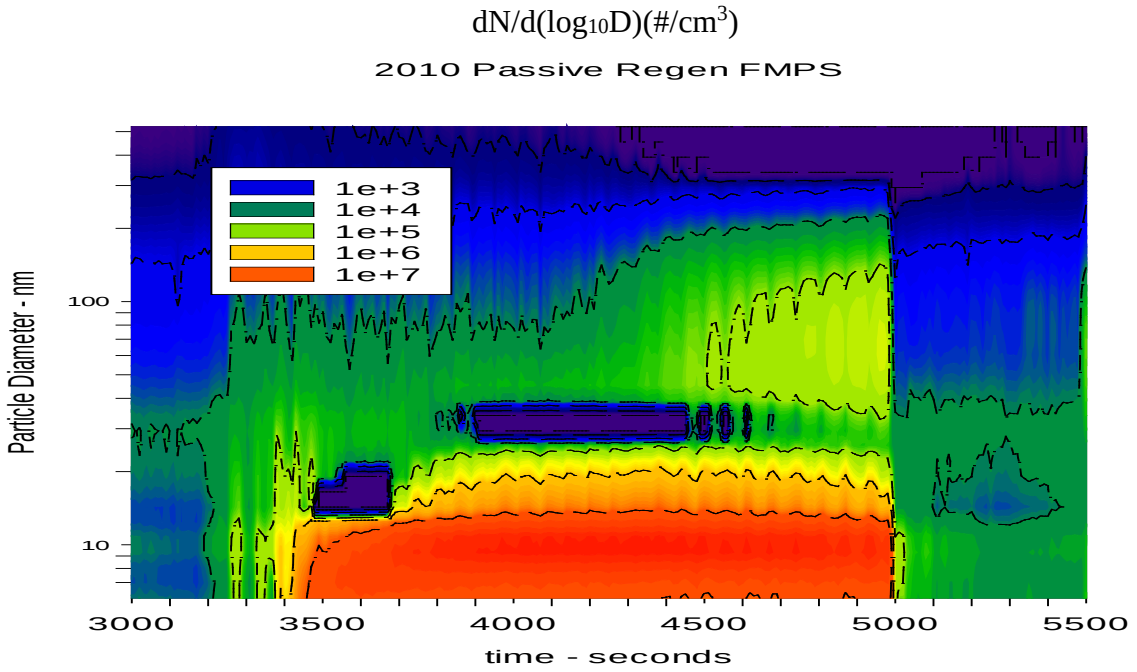

Figure IIIC-2 FMPS spectral particle number results for test11

The predicted mass emission rates from the SMPS and the DMM are shown in Figure IIIC-3 and IIIC-4, and the increase emissions are clearly seen at 4500 seconds. The particle size range for the SMPS was reduced to 225 nm in order to resolve the very fine particles less than 10 nm, and the DMM had the normal size range. The mass emissions rates are increasing until the test was

stopped, and the DMM has almost double the total amount PM emissions (Note: the times for the SMPS and DMM are not aligned). The accumulation of PM mass during test11 is shown in Figure IIIC-5 and IIIC-6 for the SMPS and DMM, respectively. The accumulation rate for both the SMPS and DMM are both increasing in time, and the DMM has larger mass estimates presumably due to recording of larger diameter particles. Also, it should be pointed out the DMM was not able to record the very small particles recorded by the SMPS in test11.

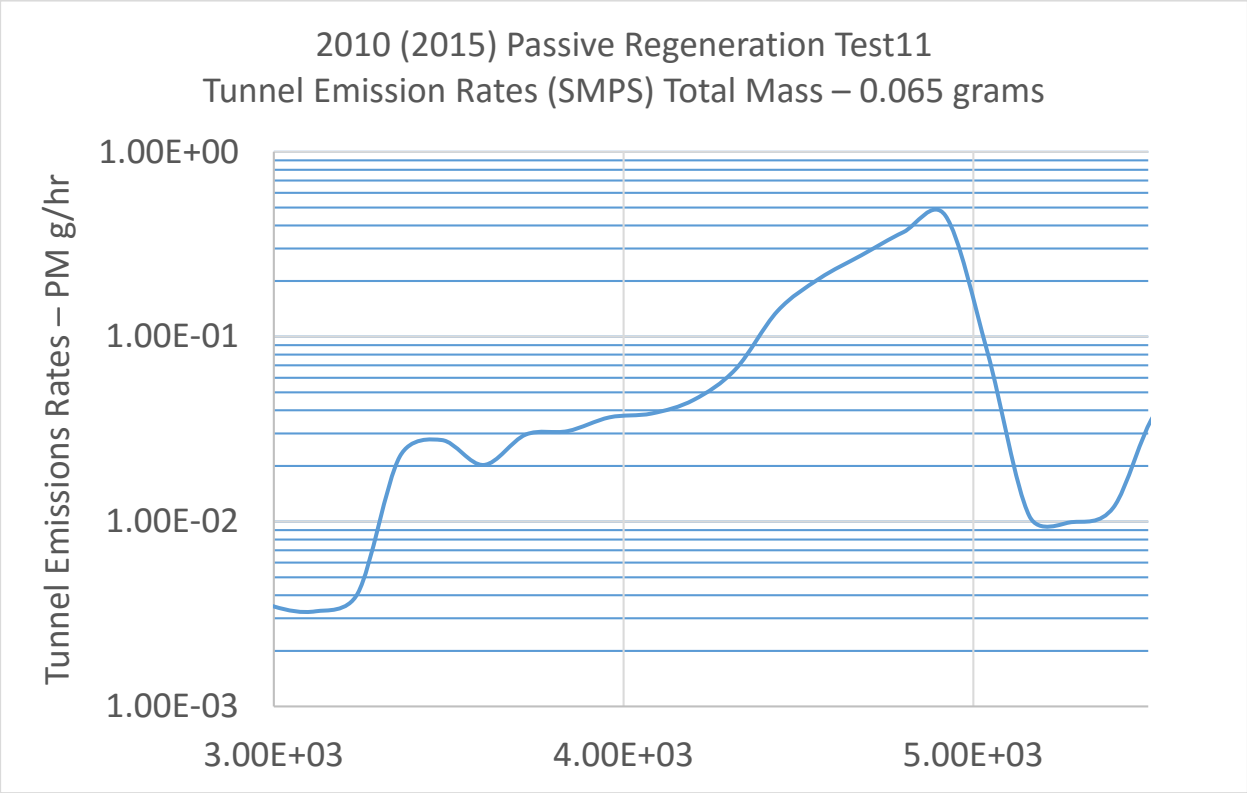

Figure IIIC-3 SMPS predicted mass emissions rates during test11

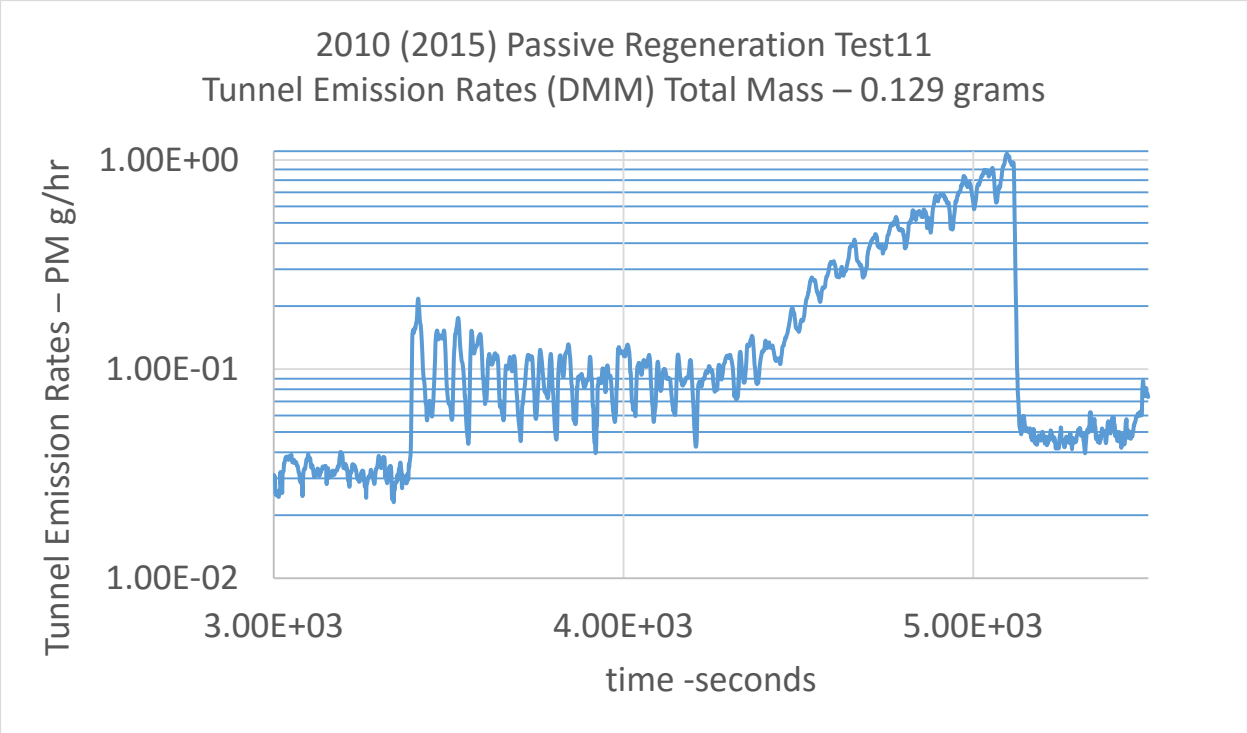

Figure IIIC-4 DMM predicted mass emissions rates during test11

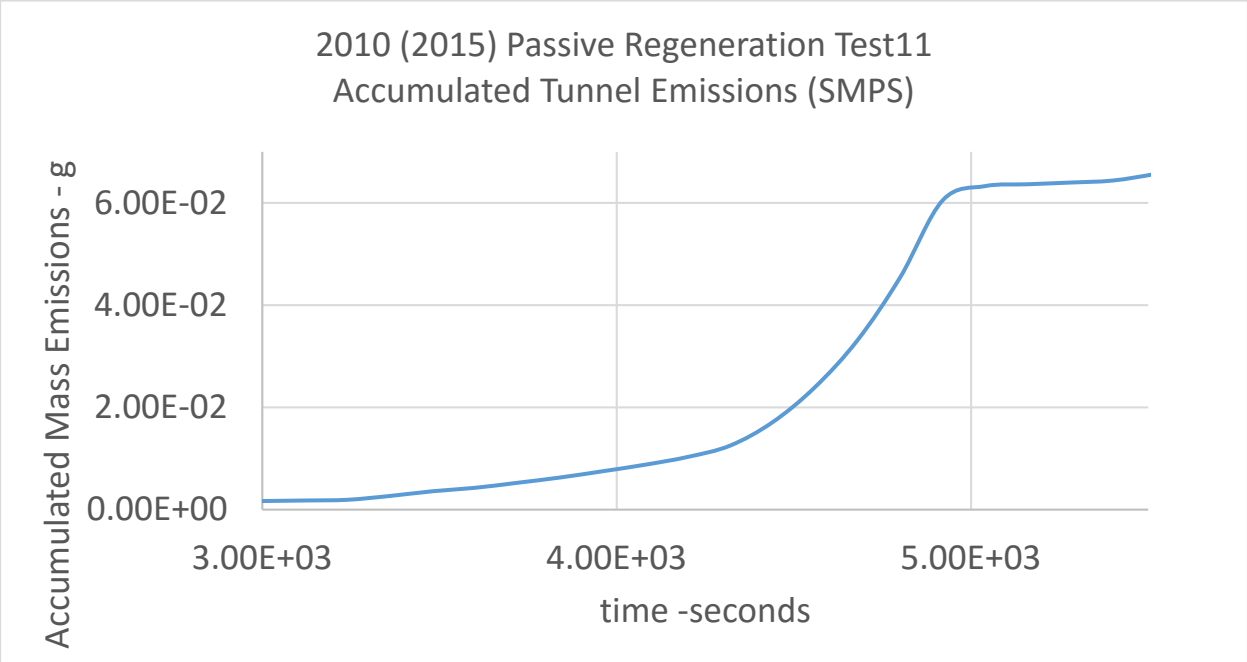

Figure IIIC-5 Accumulated mass emission rates for the SMPS

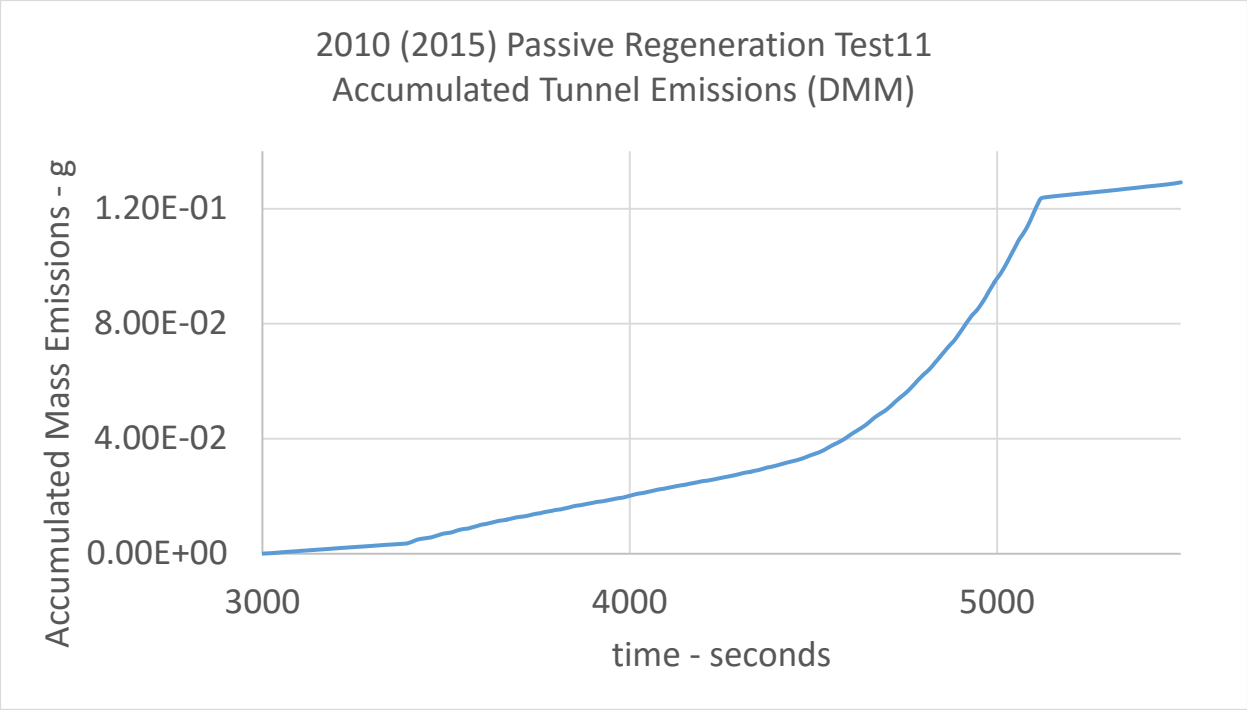

Figure IIIC-6 Accumulated mass emission rates for the DMM

It is interesting to study the time dependent particle concentrations from the SMPS and the DMM during test11, and these are shown in Figure IIIC-7 and IIIC-8. At very early times the SMPS recorded concentrations rise very rapidly to more than two million, and they remain at this value until the end of the test. The reason for this behavior is that the SMPS concentrations are dominated by particles between 20 and 5 nm, which have very little mass. The DMM concentrations do not significantly rise until the passive regeneration starts, and the larger particles are emitted due to passive regeneration. However, during the passive regeneration part of test11 both the SMPS and the DMM are accumulating PM mass at an increasing rate.

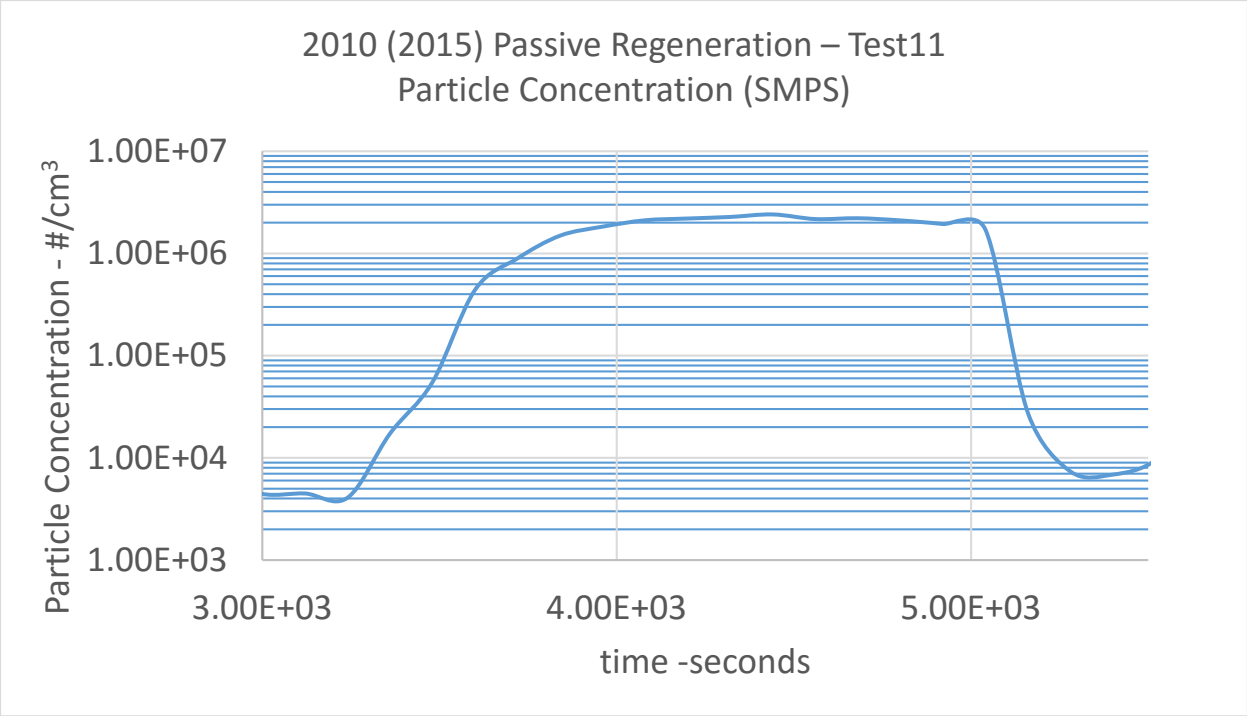

Figure IIIC-7 SMPS particle concentrations during test11

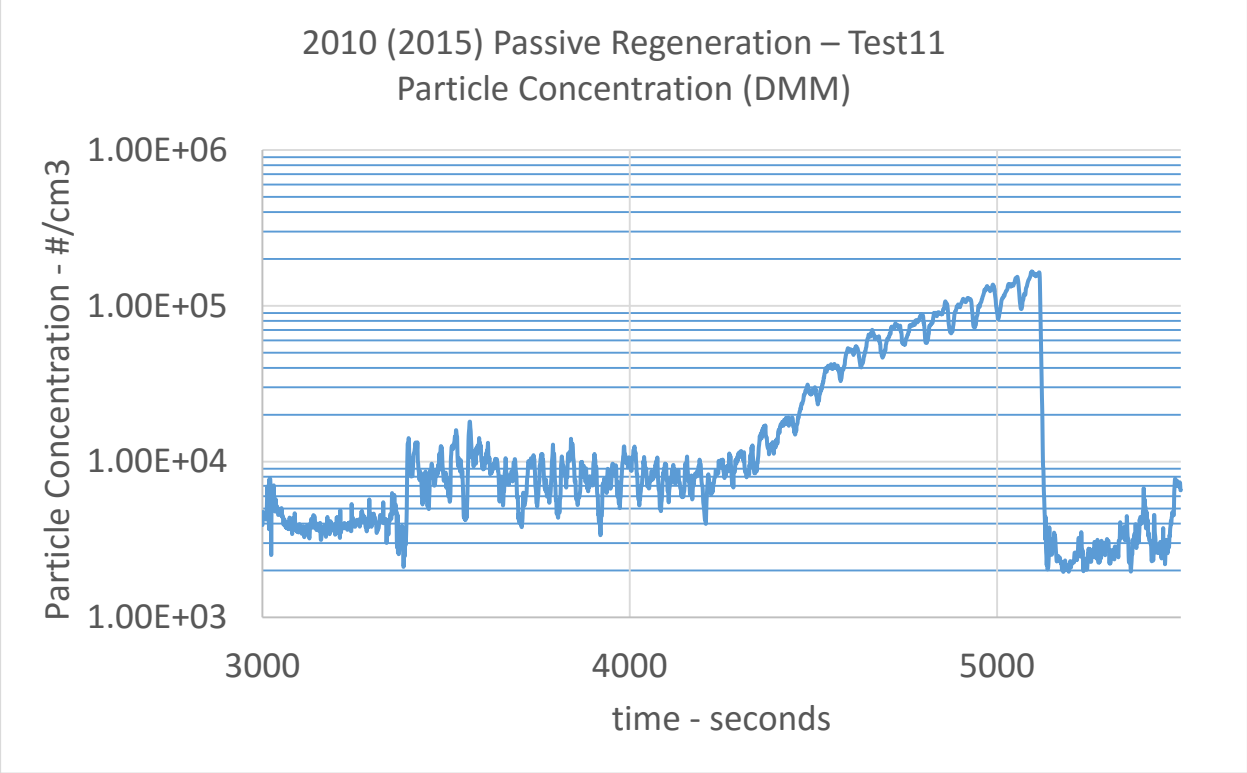

Figure IIIC-8 DMM particle concentrations during test11

Test9 and test10 during passive regeneration were stopped prematurely, since it was not expected that passive regeneration would take so much time to get started. However there were some indications that significant passive regeneration was about to begin. Shown in Figures IIIC-9, IIIC-10, IIIC-11, and IIIC-12 are the SMPS spectral particle number concentrations, total particle number concentrations, tunnel mass emissions, and accumulated tunnel mass emissions from test10. Although these results do not show an obvious passive regeneration regime, they do indicate that passive regeneration may be close to starting. Also, the initial parts of test 9 thru 11 all have a very similar quantitative and qualitative nature.

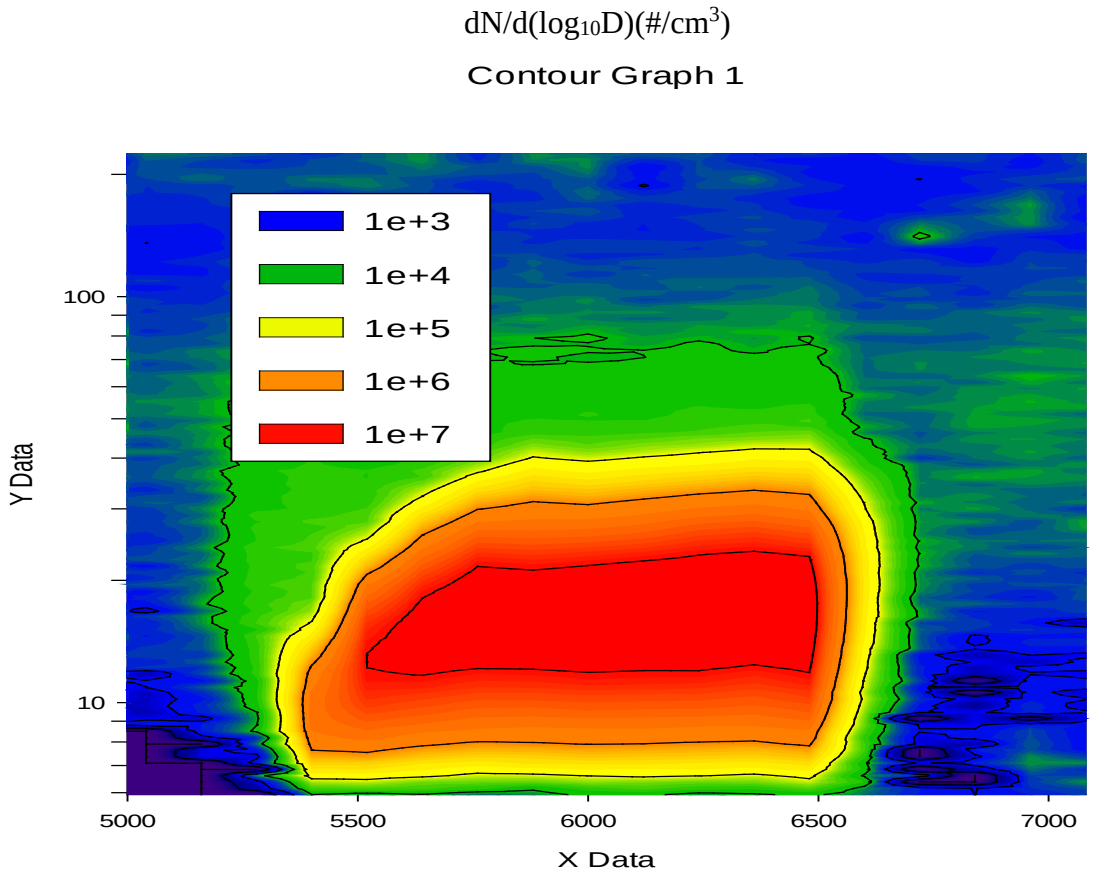

Figure IIIC-9 Spectral particle number concentrations versus time for test10.

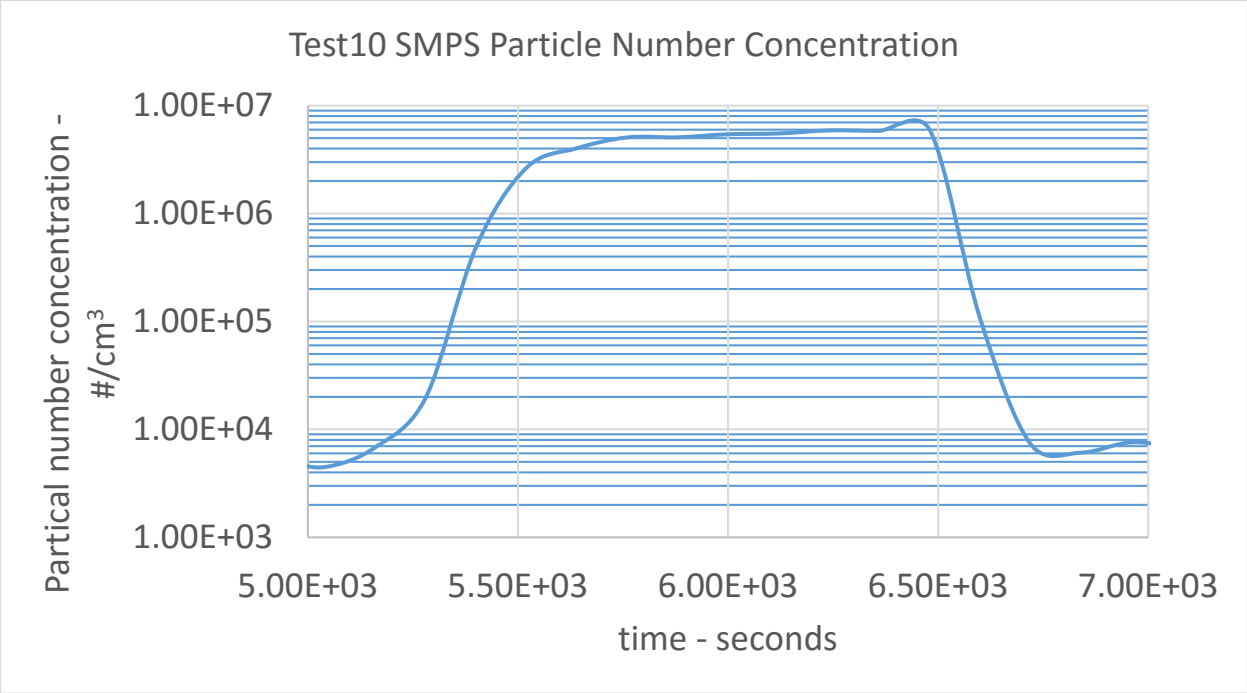

Figure IIIC-10 Total particle number concentrations versus time for test10.

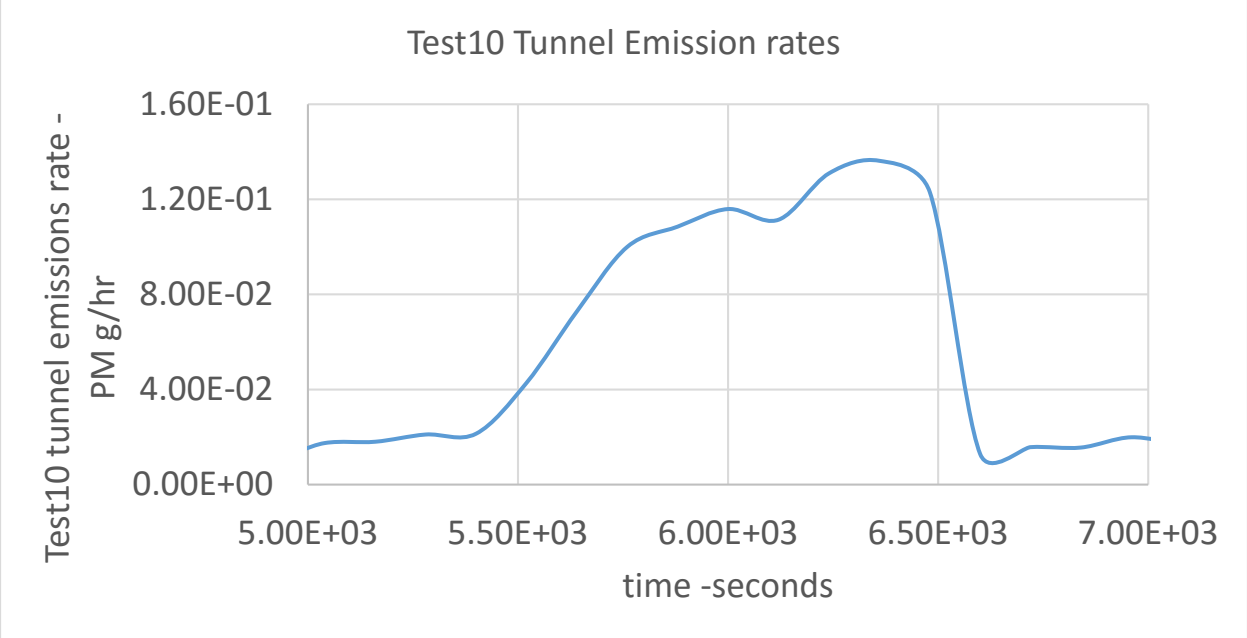

Figure IIIC-11 Tunnel emissions rates versus time for test10.

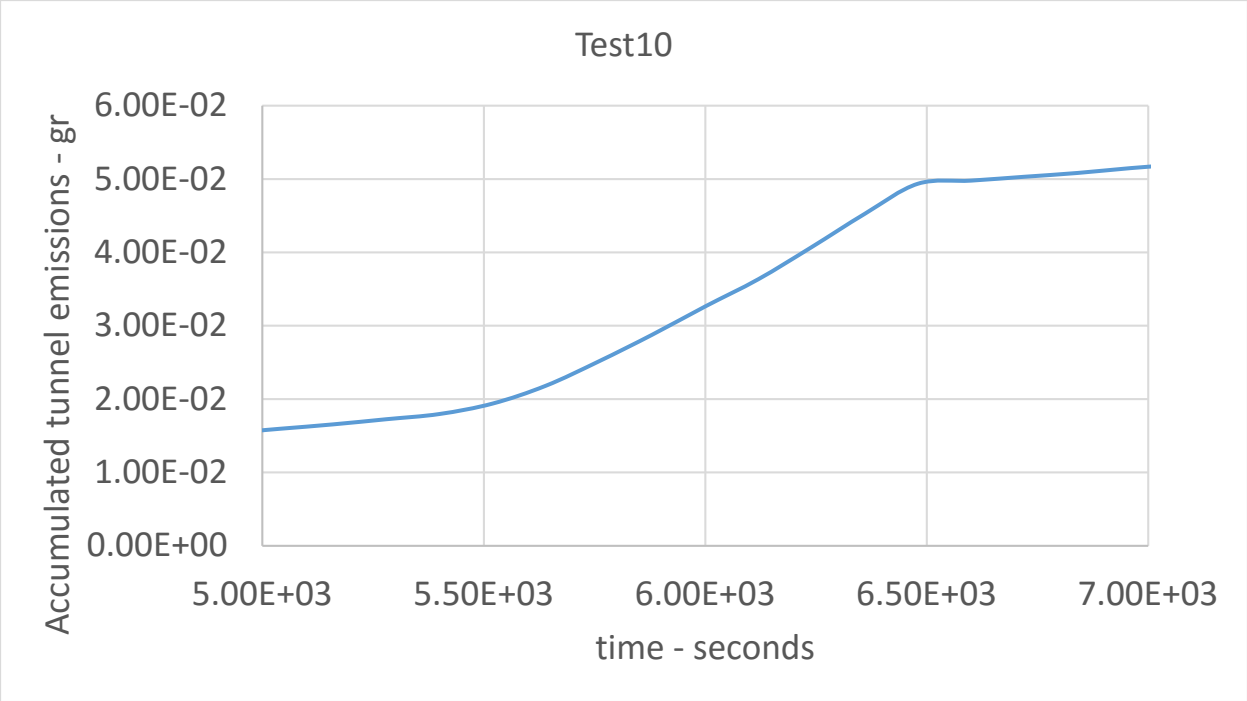

Figure IIIC-12 Accumulated tunnel emissions rates versus time for test10.

In summary the passive regeneration dynamometer testing at Depot Park has indicated that the PM deposited in the 2010 certified DPF during stop and go driving requires substantial effort to remove by passive regeneration. For example, it required more than 20 minutes of driving at maximum engine load to start the passive regeneration, even though the DPF temperature reached 400 deg C very quickly. There is increasing evidence that all PM deposited in a DPF is not equal, and the PM deposited depends strongly on the duty cycle. This type of study may be important for HD diesel trucks that have a primary intercity driving cycle.

D. Chemical analyses on PM filter samples

PM filter samples from the dilution tunnel were subject to four analyses including gravimetric mass, thermo-optical carbon, ion chromatography (IC), and X-ray fluorescence (XRF). Thermo-optical carbon is comprised of Organic Carbon (OC) and Elemental Carbon (EC); ion chromatography detects Na^{+}, K^{+}, NH_4^{+}, Ca^{2+}, Mg^{2+}, Cl^{-}, NO_3^{-}, SO_4^{2-}, and PO_4^{3-}; and XRF detects 44 total elements. The results of these analyses, with ambient concentrations subtracted and presented as grams of each species emitted, are given in Table below and also displayed in Figure 1.

Table - Mass of various chemical species emitted during each stage of all regeneration events.

					grams emitted				
date	truck	lamp	type	phase	gravimetric	OC	EC	SO_4	NH_4
Test1	2007	flashing	parked	soot	0.091	0.015	0.000	0.121	0.022
				fuel	0.626	0.069	0.019	0.505	0.150
Test2	2007	flashing	parked	soot	0.253	0.001	0.015	0.164	0.032
				fuel	0.728	0.029	0.034	0.465	0.125
Test3	2007	flashing	parked	soot	2.430	0.058	0.011	1.190	0.040
				fuel	2.970	0.100	0.013	1.701	0.162
Test4	2007	light on	road	total	1.873	0.057	0.016	0.934	0.082
Test5	2007	flashing	road	soot	1.905	0.041	0.007	0.925	0.034
				fuel	2.171	0.115	0.016	1.212	0.115
Test6	2010	light on	parked	forced	3.538	0.382	0.064	1.940	0.341
Test7	2010	light on	road	soot	0.000	0.071	0.000	0.000	0.000
				fuel	2.640	0.055	0.059	1.501	0.200
Test8	2010	light on	road	soot	0.747	0.074	0.007	0.427	0.060
				fuel	15.579	0.247	0.241	5.732	0.227

Due to relatively high ambient concentrations of several species including Na^+, Cl^-, and NO_3^-, only four species contributed to the speciated emitted mass: OC, EC, NH_4^+, and SO_4^{2-}. A total of 14 filters from 8 test were analyzed, and the percentage of gravimetric mass that was speciated was 79 ± 10% (quoted uncertainty is the standard error). Several factor could be contributing to the "missing mass." Thermo-optical carbon does not include any other elements (besides C) incorporated into the organic matter, and so any O, N, S, H, etc. that comprises this matter is not detected. IC only detects water-soluble ions, and so insoluble material is not included in this analysis. Also, XRF analysis occurs under a vaccum, and so any volatile PM may evaporate before it is detected. Finally, if any ambient PM entering the tunnel evaporates as it is warmed ~10-20 degrees above ambient temperature, the background subtraction will cause emitted PM to be biased low

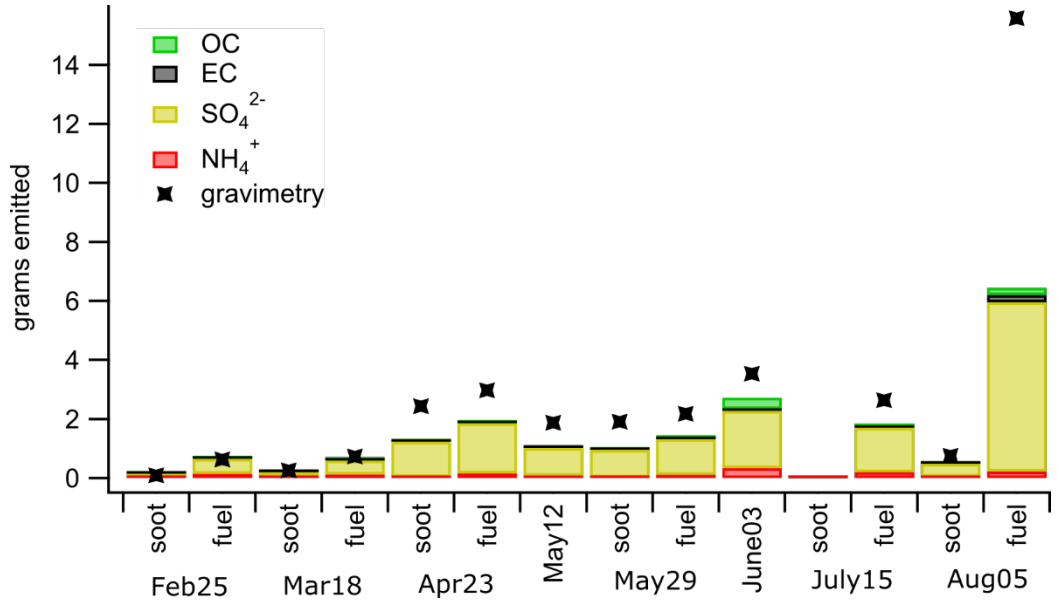

Figure IIID-1. Mass of various chemical species emitted during each stage of all regeneration events.

The molar ratio of NH_4:SO_4 was quite low, only 0.37 ± 0.07 for all tests, and was slightly lower for the 2010 truck (0.28 ± 0.11) than for the 2007 truck (0.39 ± 0.08). Since fully-neutralized

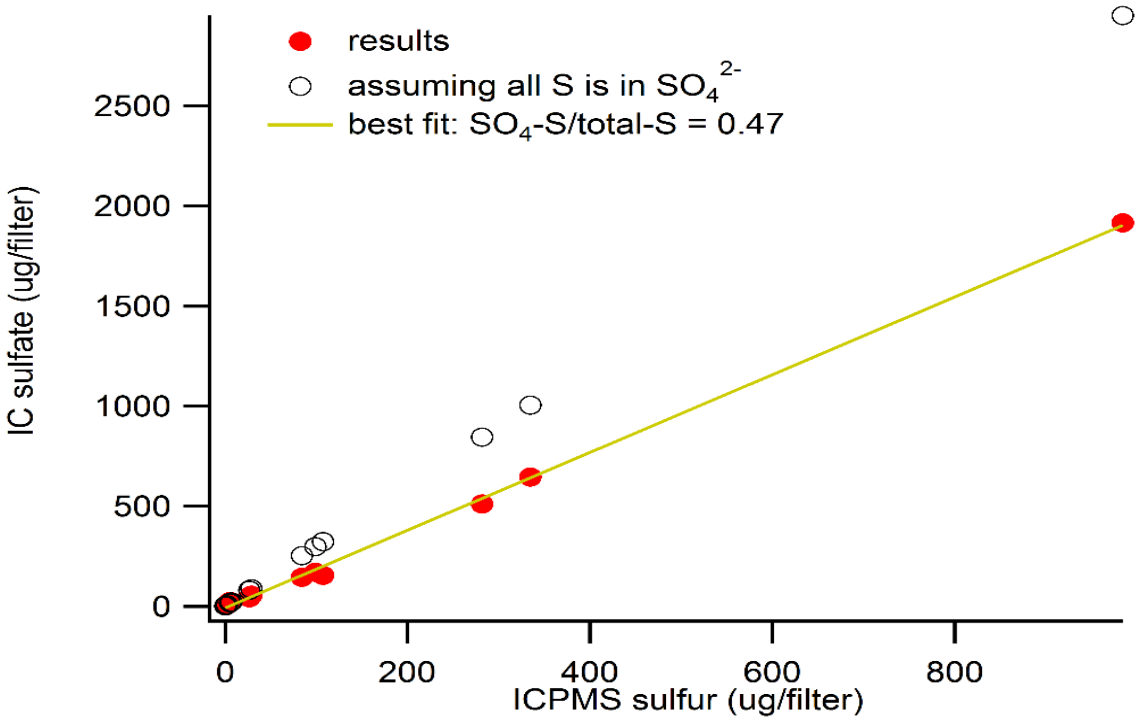

Figure IIID-2. Comparison of sulfate detected by ion chromatography and sulfur detected by X-Ray Fluorescence.

sulfate has an NH_4:SO_4 ratio of 2, this indicates that the PM emitted during DPF regenerations is highly acidic. It is possible that some basic material besides ammonium is present in this PM analyses (such as organic amines).

The quantified mass was dominated by sulfate, which comprised 81 ± 2% of speciated emissions. This was true for both the 2007 (80 ± 3% sulfate) and 2010 (82 ± 5% sulfate) HDDV. This is consistent with previous studies of high-speed driving of 2010-compliant HDDVs. Carbon only comprised 9 ± 1% of the PM by mass, suggesting that engine-out PM stored on the DPF was converted to CO_2 very efficiently. Sulfur was also detected by XRF, and a comparison between IC SO_4^{2-} and XRF S is presented in Figure 2. The amount of sulfate detected by IC was consistently less than that predicted if all XRF sulfur was assumed to be in the form of sulfate. This suggests that about half of the sulfur is in a different form, perhaps incorporated into the organic material and/or in an insoluble organic form. Other than sulfur, the only XRF elements detected above ambient levels were phosphorus (4 tests), nickel (2 tests), and chromium and manganese (one test each). None except for sulfur contributed significantly (>1%) to quantified mass.

E. DPF Efficiency

RD and MLD staff were able to measure the DPF PM loading, and this measurement took considerable time and effort. The measurement required the DPF to be taken off the truck and carefully weighed. The DPF was then put back on the truck, and the truck was then placed on the dynamometer to collect the engine PM. After the DPF accumulated enough mass for a regeneration to be carried out, the DPF was again taken off the truck and weighed. If no PM was collected on the tunnel filter, the efficiency of the DPF would be 100%, since all the PM was converted in gaseous products. Therefore, the mass collected on the tunnel filter represents PM that was not converted to gaseous products. With both the amount of mass collected by the DPF and the tunnels filters, a DPF efficiency can be defined as the DPF mass converted to gaseous products divided by DPF mass collected, which is given below.

$$DPF\,(efficiency) = \frac{DPF\ Mass\ Collected - Tunnel\ Filter\ Mass}{DPF\ Mass\ Collected} x100$$

The results of these measurements are shown in the table given below, and it can be seen that the DPF efficiency is high except for the road act regenerations of the 2010 DPF. Since these results are for two tests general conclusions cannot be made. A possible recommendation for future research is to continue DPF loading studies with stop and go traffic. There is a possibility that stop and go traffic could lead to a different type of PM in the DPF.

Summary Table for Gravity Mass and DPF Efficiency Measurements

Vehicle and test type	Test # and date	Filter Mass-g	DPF Mass-g	Ratio PM/DPF	DPF Efficiency
2007/flashing light/park	test1-2/23/15	0.717	168.7	.00426	99.57
2007/flashing light/park	test2-3/18/15	0.981	137.1	.00715	99.28
2007/flashing light/park	test3-4/23/15	5.4	136.5	.03956	96.04
2007/light on/road	test4-5/12/15	1.87	100.9	.01856	98.14
2007/flashing light/road	test5-5/29/15	4.07	141.9	.02871	97.13
2010/light on/park	test6-7/15/15	2.64	120.3	.02172	97.83
2010/light on/road	test7-8/5/15	16.3	93.60	.17436	82.56
2010/light on/road	test8-8/26/15	9.44	89.15	.10846	89.15

IV. Some Suggestions for Future Projects from H. A. Dwyer

- **Passive DPF Regeneration and Stop and Go Driving** – The dynamometer testing at Depot Park has indicated that the PM deposited in the 2010 certified DPF during stop and go driving requires substantial effort to remove by passive regeneration. For example, it required more than 20 minutes of driving at maximum engine load to start the passive regeneration, even though the DPF temperature reached 400 deg C very quickly. There is increasing evidence that all PM deposited in a DPF is not equal, and the PM deposited depends strongly on the duty cycle. This type of study may be important for HD diesel trucks that have a primary intercity driving cycle.
- **Active Road Regeneration of 2007 and 2010 DPFs** – The active road and parked regenerations carried out at Depot Park have shown that the 2010 DPF released more mass and larger particles than the 2007 DPF during road regenerations. The parked regenerations carried out in 2013, Phase I, gave the opposite result, and for the 2013 study there was a large amount of mass released by particles larger than 2.5 microns in diameter. The major difference between the 2013 and 2015 studies was the manner in which the DPF was loaded. For the 2013 study the DPF was loaded by stop and go road driving in the Sacramento region, while the 2015 study loaded the DPF with the Depot Park dynamometer. This a good example of the DPF PM depending on the engine duty cycle.
- **Toxicology Studies of Semi-Volatile Particles under Real World Conditions** – During Phase II of our recent testing Hepa Filters have been purchased for the Ambient Tunnel at Depot Park. In order to complete the installation of the Hepa Filters an interchangeable entrance section must be constructed at a cost of approximately $3000. The Hepa filter capability will allow for ***"CVS Type Studies"*** to be carried out under real world conditions, instead of the highly controlled and expensive CVS studies. An important possibility is to take filter samples of PM under winter and summer conditions in the Sacramento area, and the toxicology of the filters will be analyzed. It is expected that winter conditions would deposited more semi-volatile particles on the filters. Of course, the same type of study could be carried out with ambient air and diesel engine exhaust, in order to investigate any interactions between the diesel exhaust with ambient air.
- **Emission measurements of Tier IV TRUs** – Recently, many manufacturers of diesel exhaust systems have been able to meet Tier IV standards without the use of a DPF. The diesel engines employed for some TRUs are a good example of Tier IV system without DPFs , and due to TRUs availability and mobility, TRUs are a good candidate for testing. The TRU exhaust system for the diesel engine could be attached to a PEMs system or the ambient wind tunnel at Depot Park. Maximum power for TRUs are usually required during temperature pulldown, which occurs before a load is placed in the refrigerated trailer. Without a load in the TRU there is no possible damage to a valuable load, and it should be mentioned that UC Davis carried out a study of this type with a Sacramento area company ten years ago. The emission instrumentation ten years ago had much less capability than currently exits.

V. Conclusions and Summary

A short summary of the four main tasks that were accomplished in this project are the following:

1. Parked active regeneration of 2007 and 2010 DPFs – The large particles emitted in the Phase I study were not found in large numbers in the Phase II investigation. It is surmised that this result is due to the loading of the DPF with the chassis dynamometer as opposed to stop and go driving in the city of Sacramento. The fuel burning phases of the parked regenerations are very similar to Phase I investigation.
2. Road Active regeneration of the 2007 and 2010 DPFs – The road regeneration of the 2007 DPF gave emissions very similar to the parked regeneration of the 2007 DPF in Phase II. The road regeneration of the 2010 DPF resulted in a large amount of PM, and this PM contained large numbers of particles in the 50 to 100 nanometer size range.
3. Passive road regeneration of the 2010 DPF – The passive regeneration of the 2010 DPF appears to take a considerable amount of high power and temperature driving after the DPF was loaded with 5 to 10 hours of stop and go driving. This part of the investigating needs more testing in a future possible study.
4. Chemical analysis of PM filters – The filter system attached to the small ambient wind tunnel was constructed and performed very well. The majority of the PM was determined to be sulfates, and further analysis will be performed by RD and MLD staff.

A detailed summary of the above material is contained in the executive summary at the beginning of this report.

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Appendix I: Carb Depot Chassis Dynamometer Brief Description

The Depot Park Chassis system is a basic Burke E. Porter Dynamometer System is designed to meet the technical requirements of the specifications as provided by CARB for this project. Acceptance tests are proposed to be conducted according to the AAMA procedures during the commissioning of the system. These tests will prove that the performance of the dynamometer meets or exceeds the requirements set forth in specifications that were provided. These procedures are considered the industry standard for emissions and other class dynamometers. The exact performance criteria for this testing will be adjusted relative to the EPA standards based on the extreme high capacity of the rear dynamometer axle. See the technical data section that follows for more details.

Basic Technical Data

The following table provides a summary of the basic technical data upon which the proposed dynamometer systems are based. Some data is assumed at this point based on the fact that no specific information was supplied by CARB.

Test Site / Pit (Basement) Environment - Recommended

- Test Area Temperature — 0º C to 35º C
- Test Area Relative Humidity — 10% to 95% RH @ 35º C; 10% to 50% RH @ 45º C
- Pit Ventilation — 6 Air Exchanges per hour @ 20º C; -45º C dewpoint

Environmental requirements (by BEPCO)

- Pit Temperature — <40º C must be maintained
- Elec Panel Location Temperature — <40º C must be maintained

Utilities Available from Customer (to be confirmed)

- Electrical — 460V, 60 Hz, 3 phase
- City Water — 4 bar pressure
- Compressed Air — 6 bar (88 psi)

Utility/Configuration Requirements (BEPCO specified)

- Electrical Power Drop — 800A (Base Bid – 500 HP Motor); 1000A (Optional – 650 HP Motor); 60A (additional power drop for Optional Shear Brake)
- Compressed Air Flow — <50 SCFM @ 80 PSI for normal operation
- Cooling Water (max) — 40-60 GPM for Optional Shear Brake (300 HP)
- Interconnecting Cables (46m) ** — Quote is based on lengths not to exceed 150 ft

** If substantially longer cables are ultimately required based on the facility layout (especially for the large motor power leads), we will need to re-evaluate our pricing of the system.

Test Vehicle Specifications (estimated)

- Vehicle Types MD/HD Trucks, RV's, Buses, Military
- Weight Classifications Class 4 through 8
- Weight Range (simulated) 10,000 to 80,000 lbs
- Axle Configurations Single and Tandem Axle
- Wheelbase Range tbd
- Tandem Axle to Axle Dim 52" to 60" (estimated range)
- Maximum Axle Load 40,000 lbs (max dyno shaft loading)
- Maximum Vehicle Speed 100 MPH

Dynamometer Specifications

- Nominal Dyno Roll Diameter 75"
- Concentricity / Runout not to exceed 0.25 mm (0.010")
- Maximum Taper less than 0.254 mm (0.010")
- Balance Specification G2.5 per ISO1950 standard
- Roll Surface Material Sealed, Tungsten Carbide (Flame Spray)
- Roll Surface Finish aggressive 300-400 microinch
- Roll Spacing / Width 36" / 38"
- Maximum Dyno Shaft Load 40,000 lbs
- Estimated Base Inertia 6,000 lbs (equivalent weight)

- AC Motor Configuration Inline, Direct Coupled
- Motor Support Trunnion Mounted
- Nominal Power Capacity 500 HP Motoring & Absorbing @ 220 RPM
- Continuous Tractive Effort 3,920 lbf (0 to ~49 MPH)
- Continous HP Rating 500 HP from 49 to 100 MPH
- Torque Overload Available 150% for 10 Sec (Frame 3A drive) – Motor+Absorb

OPTIONAL higher HP AC Motor Specifications

- Nominal Power Capacity 650 HP Motoring & Absorbing @ 220 RPM
- Continuous Tractive Effort 5,096 lbf (0 to ~49 MPH)
- Continous HP Rating 650 HP from 49 to 100 MPH
- Torque Overload Available 150% for 30 Sec (Frame 3B drive) – Motor+Absorb

OPTIONAL Shear Brake System Specifications

- Shear Brake System Provides absorbing power only
- Nominal Capacity (equiv) 300 HP @ 112 RPM
- Continuous Tractive Effort 4,480 lbf ("0" to ~25 MPH)
- Continuous HP Rating 300 HP from 25 to 100 MPH

- Torque Overload Available ~200% for 30 seconds – Absorbing Only

Note: Performance Evaluation Criteria are shown on the next page

General Performance Specifications based on modified US-EPA/AAM Test Criteria

AAMA Modified Acceptance Test Criteria for Model 9248 Inline Dynamometer with 75" Rolls	
Test #) Description	**Acceptance Criteria**
1) Roll Diameter Determination	Diameter = 75.000 +/-0.010 inches Maxiumum Runout = 0.010 inches
2) Encoder Pulse Verification	Accuracy: +/- 5 pulses out of 10 turns due to manual technique Distance Resol with 5K PPR encoder w/ 75" roll diam < 0.047"
3) Computer Time Accuracy Test	Time: +/-0.01 seconds out of 1000 seconds or 0.001%
4) Dyno Speed Performance Eval	Accuracy: +/-0.05 MPH (0.08 KPH) averaged for 5 seconds <0.16 MPH (0.1 KPH) instantaneous variation during 10-100 MPH test in 10 MPH increments
4a) Speed Measurement Accuracy	+/-0.01% based on the allowable error in roll diameter and the allowable time measurement error
5) Torque Transducer Accuracy Evaluation	Overall Accuracy (Single Load Cell for AC Motor or Shear Brake) +/-0.05% of Full Scale Loading: 10,000 lbf x 0.05% = +/-5.0 lbf
6) Response Time Evaluation	Motor Response Time (to reach 90% of final value) < 200ms Shear Brake Response Time (to reach 90% of final value) < 3 seconds Note: Control algorithm can request 180% of motor torque for 3 seconds to make up for the latency of the shear brake
7) Base Inertia Verification	Accuracy: Mean inertia deviation from Set Inertia < +/-0.5%
8) Acceleration Performance Eval	Accuracy: Accel and Decel Should be Accurate to +/-2.5% Max Deviation of <0.1 KPH during 10 to 40 MPH accel/decel test @ 0.5 MPH/s
9) Parasitic Friction Compensation	Accuracy: +/-0.05% of Full Scale
10) Road Load Simulation Accuracy	Accuracy: +/-0.05% of Full Scale

Appendix II: Test Plan

Measurement of Emissions from both Active and Passive Regenerations of Diesel Particulate Filters from Heavy Duty Trucks

MLD Project Number:

August 2014

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Introduction

This proposed investigation is concerned with emissions associated with DPFs on heavy duty diesel engines that are certified for compliance with 2007 and 2010 emission standards. A recent investigation, Ref. [1], which was concerned with active parked regenerations of both 2007 and 2010 DPFs, has shown that there are very significant differences between the quality and quantity of PM mass and particle number for the two technologies. For example the 2007 DPF emitted a large amount of mass at the beginning of DPF regeneration, and this was followed by a relatively long period of a very large number of ultrafine particles. An unexpected result from the investigation was the emissions of very large particles emitted in the PM_{10} range. During this recent testing filter samples were not collected to determine the chemical composition of the PM emitted, and there are large uncertainties concerning the chemical composition of the emitted PM during the entire parked regeneration process.

As was expected the 2010 DPF emitted much less PM than the 2007 DPF during the active parked regeneration. The level of the DustTrak emissions at all times was orders of magnitude lower than the early time emissions of the 2007 DPF, and the results clearly show that there has been a dramatic improvement in the 2010 technology relative to the 2007 technology. However, the particle number results for the 2010 DPF are surprisingly similar to the 2007 results during the parked regeneration. Although the mass emissions are less for the 2010 DPF, the total time for the active regeneration is very similar for the 2010 DPF, and the level of particle number concentration is very similar to the parked active regeneration of the 2007 DPF. A direct comparison of the ultrafine particle phase is very similar for both technologies. Since these ultrafine particles are significantly larger than some previous studies, Ref. [2], there is a need for further studies to determine their chemical composition with the use of filters.

A parked active regeneration is a special operating condition for a diesel engine, since no power is being generated by the diesel engine to power the tractor and trailer on the road. With significant power generated by the engine for road travel the exhaust gases into the DPF will be in a significantly different state. Therefore, it is expected that an active regeneration on the road will have different characteristics than a parked regeneration for both the 2007 and 2010 DPF technologies. At the present time there have been very few investigations of active road regenerations into ambient air, and the development of the ambient dilution tunnel and the chassis dynamometer at CARB's Depot Park facility will give detailed information on the emissions into ambient air.

Recent advances in DPF technology have significantly increased passive regeneration in DPFs, as was observed in ACES 2 testing, Ref. [3], during extensive testing of 2010 DPFs. In fact, during a sixteen hour testing cycle no active regenerations were observed during the testing. However, there were periods where the passive regeneration resulted in the release of a large number of particles. An important variation on the ACES 2

investigation will be to have an extended period of stop and go traffic in order to build up a larger PM load in the 2010 DPF. For example, five to ten hours of stop and go traffic followed by high temperature road driving. It is expected that this type of driving pattern will lead to a larger release of passive PM regeneration and particle numbers from the 2010 DPF. Also, with the use of the small ambient dilution tunnel there could be more semi-volatile particles due to the lower temperatures in the mixed ambient air and exhaust gases. Again it should be mentioned that the new chassis dynamometer at the Depot Park facility allows for this type of novel emission testing to be carried out.

The ambient dilution tunnel at Depot Park does not interfere with the normal emission testing with the chassis dynamometer, and it can be connected and used when cycles such as the FTP, UDDS, and others are being performed. Therefore, there is the opportunity of relating Constant Volume Sampling, CVS, testing with filtered air to real world testing with ambient air and higher dilutions ratios. Also, the small wind tunnel can be modified to place HEPA filters at the tunnel's entrance.

Project Objectives

The project objectives will be to measure and characterize the emissions from 2007 and 2010 certified HDD vehicles during active and passive regenerations of the DPFs. Furthermore, this study will collect a separate set of PM filter samples during the initial "soot-burning" (high mass) phase and the second "fuel-burning" (high number) phase of DPF regeneration. The testing required will involve controlled PM loading of the DPFs and the determination of total particle numbers, size distribution, chemical composition and regulated emissions during two different testing situations. These situations are active DPF regenerations under the following conditions: (1) A high temperature driving cycle with the use of the chassis dynamometer at Depot Park connected to the small ambient dilution tunnel; and (2) A parked regeneration with the small ambient dilution tunnel connected to the engine exhaust. For the parked regeneration study the determination of the chemical composition of the PM is a major objective of the testing, and this testing will be carried out for both 2007 and 2010 DPF technologies.

The testing of the 2010 DPF with 3 to 6 hours of stop and go traffic loading will be somewhat experimental since it is not known how substantial the PM emissions from the passive regeneration in the DPF will be. Depending on the results obtained this PM emission mode could be studied more extensively in the future. Loading times of the order of 3 to 6 hours are typical of a heavy duty truck making a series of deliveries in an intercity region.

Test Facility and Emissions Measurement

All of the emissions testing for this study will be carried out at the Depot Park facility of MLD's Freight Emissions Assessment and Testing (FEAT) section. Modal emissions

data will be collected with real time analyzers of the truck's raw exhaust. The emissions to be collected are PM mass, total particle numbers, particle size distribution, temperature, as well as engine parameters. Table 1 provides a list of emissions data that will be collected.

Table 1 Engine and Emission Parameters	
Parameter	**Units**
Engine Speed	rpm
Engine Torque	lb-ft
Fuel Flow Rate	gal/sec
Exhaust Mass Flow Rate	kg/hr
Percent Load	%
Oil temperature	deg C
Coolant temperature	deg C
Exhaust temperature	deg C
Pre and Post DPF and SCR temperatures-if feasible	deg C
Pre and Post DPF pressure-if feasible	mbar
Pre and Post DPF mass-if feasible	mg
PEM Gaseous Engine Emissions	g/hr
Ambient Dilution Tunnel inlet and outlet temperatures	deg C
Ambient Dilution Tunnel inlet and outlet $PM_{1.0}$, $PM_{2.5}$, $PM_{10.}$	mg/m^3
Ambient Dilution Tunnel inlet and outlet total particle concentration	#/cc
Ambient Dilution Tunnel inlet and outlet size distribution	#/cc
Filters for PM: mass, EC/OC composition, and Sulfate	mg

The instrumentation for the small wind tunnel is listed in Table 2.

Table 2 Instrumentation				
Instrument	Location	Emissions	Provider	Required?
EEPS	Tunnel inlet air	Total particle and size distribution		
FMPS	Tunnel exit air	Total particle and size distribution		Y
DMM	Tunnel exit air	Total particle and size distribution		

Three Thermocouples	Inlet diesel exhaust & air, exit gases	Temperature		Y
PEMS	Engine truck exhaust	Engines gaseous emissions		
DustTraks	Inlet air and exit gases	PM mass		Y
Q-Trak	CO_2, Relative Humidity	0-5000 µg/m^3, %		
Secondary Dilution	Before FMPS sampling	Additional 100 times dilution air		

The FMPS, EEPS, and DMM will record particle size and concentrations, which are very important for the very small and semi-volatile particles released during DPF regeneration. The use of these instruments will yield a very good characterization of the inlet air and the exhaust products.

It is proposed that PM mass, PM sulfate, PM elemental and organic carbon (EC/OC), and elemental composition will be analyzed by ECARS from the filters collected, and the methods employed will be similar to Ref. [2]. Listed in Table 3 are the analyses that will be performed, and in Table 4 the planned tests and total number of filters of each type needed. In order to carry out the filter measurements a new filter holder system will be built and designed by Professor Dwyer, RD staff, and Depot Park staff, and this will require additional pumps and filter holders. The pumps and filter holders will be supplied by RD and MLD.

Table 3 – Types of PM analyses

	gravimetry	IC (ions)	OC/EC	XRF (elemental)
Filter media	Teflon (1st set)	Teflon (1st set)	Quartz	Teflon (2nd set)
Flow rate (lpm)	80	80	80	80
Face velocity (cm/s)	85	85	85	85
Estimated mass, soot burning phase[1] (mg)	0.25	0.25	0.25	0.25
Estimated mass, fuel burning phase[1] (mg)	0.75	0.75	0.75	0.75

1. Based on results from ARB project 11-329 (2 g total per regeneration, 25% in soot burning phase, 75% in fuel burning phase for 2010 truck)

Table 4 - Expected Tests and Filter Samples Required			
Test Type	# Tests	# PTFE Filters[1,3]	# Quartz filters[2,3]
2007 Parked Regeneration	2	12	6
2007 Road Regeneration	2	12	6
2010 Parked Regeneration	1	6	3
2010 Road Regeneration	1	6	3
2010 Partial Road Passive Regeneration	3	18	9
Trip blanks		6	3
Total	9	60	30

1. Half the PTFE filters will be analyzed for PM mass and ion content, the other half will be analyzed by XRF.
2. Quartz filters will be analyzed for EC/OC content
3. For each test, three filters of each type will be collected: soot burning phase, fuel burning phase, and background

The instrumentation will be operated and maintained by MLD's staff per the requirements of the manufacturer, and the majority of the instruments will be provided by the Research Division. A diagram of the small wind tunnel and the instrumentation locations are shown in Figure 1.

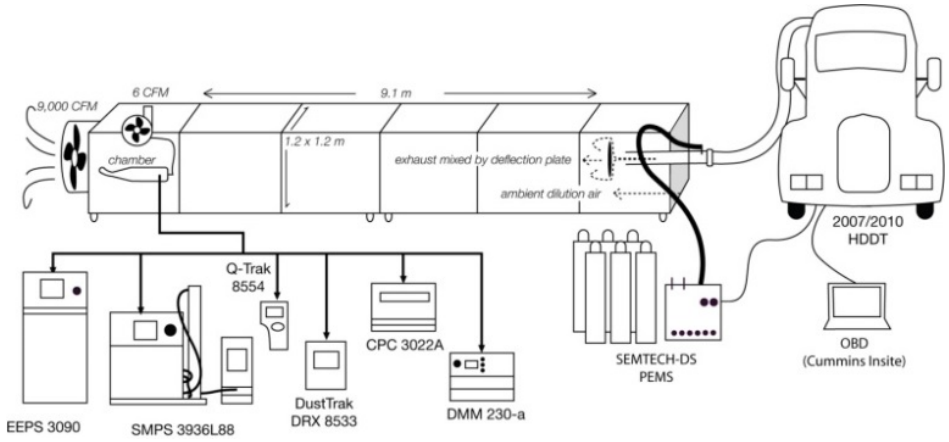


Figure 1. Diagram of small ambient dilution tunnel and locations of the instrumentation.

A diagram of the sampling manifold can be found in Appendix I.

Schedule and Tasks

Based on the availability of MLD and RD staff, the functionality of the emissions equipment, and the availability of the trucks, the construction of the tunnel and sampling system modifications, as well as emissions testing, will take place over a 6 month period from December, 2014 thru May, 2015 (Table 4). The actual time for the regeneration process to occur will be between 20 and 40 minutes, but it will take substantial driving time to acquire enough soot in the DPF to create the conditions for a DPF regeneration. It is estimated that it will require approximately 30 hours of creep and low speed transient driving to generate the soot in the DPF, and it is expected that 2007-2009 trucks will accumulate substantially more soot than 2010+ trucks due to improvements in passive regeneration in the 2010+ DPFs as well as lower engine out PM.

Table 4: Preliminary timeline for testing

Vehicle	Test Month
2007-2009	December to May – 2014/2015
2010+	December to May – 2014/2015

A summary of the Schedule of Tasks is presented in Table 4 below:

Table 5 Schedule of Tasks

Task	Sept.-Nov.	Dec.-Jan.	Feb.-Mar.	Apr.-May
Building of Instrumentation Console(HD, CR, MB)	XXXXX	XXX		
Testing of emissions instrumentation under idle conditions(HD, CR, DQ)	XXXXX	XXX		
Test Driving to load DPF for a parked Regeneration (MB)	XX	XXXXXXX	XXXXXXX	XXXX
Analysis of Data Files produced by Emissions Console (HD, CR)		XXXXXXX	XXXXXXX	XXXXXXX
Emissions Testing of 2007 Truck (MB, CR, HD, DQ)		XXXXXXX	XXXX	XXXX
Emissions testing of 2010 Truck (MB, CR, HD, DQ)		XXXXXXX	XXXXXXX	XXX
HD- Harry Dwyer; CR-Chris Ruehl, MB-Mark Burnitzski, DQ – Davis Quiros				

Test Vehicles Selection/Procurement/Acceptance Criteria

Table 6 lists the vehicle categories to be tested in this study, and it is expected that the vehicles used in a previous CARB study will be used in the present investigation [1]. One of the vehicles will be powered by an engine that does not use SCR technology, and it is certified to the 2007 standard (0.01 g/bhp-hr PM). The other vehicle will be powered by an engine certified to 2010 interim or full certification standards for NO_x using OEM SCR technology. MLD will be responsible for acquiring the test vehicles. Acquisition of these vehicles will be by rental, or through the ECARS vehicle procurement contract, or through loan of ARB-owned vehicles. The test vehicles will be housed at the Depot Park facility located in Sacramento. MLD will be responsible for instrumenting the truck with gaseous PEMS and the wind tunnel with emission instrumentation provided by RD.

Table 6: Summary overview of test vehicles

Category	Class	NO_x Control	PM Control	Number of trucks
1-2007	8	None	DPF	1
2-2010	8	SCR	DPF	1

Fuel Requirements

All the testing on these two trucks will be performed using commercially available No. 2 diesel fuel in California. The entire emissions testing for the vehicles will be performed with fuel mixture obtained from the same commercial outlet if practical.

Vehicle Preparation and Conditioning

In order to get the vehicles into a condition where a “Parked” and active road regeneration can occur, it is expected that 30 hours of creep and low speed FTP transient driving will be required. Such conditions may be limited to drayage shipping, although it is not known if or how regeneration characteristics (e.g., active vs. passive) will change with age in 2010-compliant HDDV. Although the above cycles have been designed for engine dynamometers, they will serve as a guide for the driving necessary to obtain the conditions for a “Parked” regeneration. Again, it should be mentioned that MLD staff at Depot Park have acquired considerable experience in loading the DPFs in a previous study [1].

Emissions Testing and Test Sequence

Emission testing for each truck will be carried out in the active parked and active road regeneration mode, and the manufacturer’s instructions will be followed to create the

manual regeneration of the DPF. The regeneration will be preceded by an idle of sufficient length to warm up the engine and to prepare the ambient dilution tunnel and emissions instrumentation for testing. It is expected to measure two parked regenerations for each 2007 and 2010 truck.

Due to the availability of trucks and the time needed to create the conditions for a regeneration, it is not possible to specify in advance the test sequence for each truck. That is the primary reason that the testing has been spread out over 11 months, even though a single regeneration test will take between 20 and 40 minutes. Also, there is a substantial amount of time required for the processing and analysis of the filter samples.

Data Handling and Processing

MLD and RD will perform an analysis of all emissions testing, and the data will be placed on the MLD shared drive (I:\) for analysis by RD. RD will perform the data analysis which at a minimum will include the following:

1. Analyze emissions data during the regenerations as a function of time, engine speed, and exhaust temperatures.
2. Compare regeneration exhaust emissions between 2007 and 2010 engines.

Valid raw files, cleaned files, and analyzed data will be stored on a shared drive. The data will be available to RD and MLD who may perform additional analysis for their programmatic needs. In the event that there are discrepancies in the data, they will be resolved in collaboration with the PI, MLD, ad RD staff.

Vehicle Release

The Test Engineer will notify RD after all scheduled testing has been completed at Depot Park. The Project Engineer will consult with MLD staff to determine when the test vehicle can be released.

Test vehicles may be released prior to completion of all testing, if MLD staff and the Test Engineer concur that the vehicle is untestable. Vehicles may also be released before the completion of all tests based on the vehicle owner's demands. In such cases the Test Engineer, MLD staff, and RD staff will do their best to expedite the testing of the vehicle before releasing it.

Data Summary and Report

RD will compile a report summarizing the data and the analyses performed for internal distribution and posting to the Emissions Lab Coordination (ELC) web page for this project. A presentation on the major findings from this study will be provided if requested by management. Any journal publications resulting from this study will be collaborative

effort among the participating divisions, and they will be reviewed by management prior to submission.

Staffing

The Project Engineer for this project will be Chris Ruehl. The Project Engineer and the Principle Investigator, Professor Dwyer, will assist with or at least observe the tests for each vehicle. They will also assist in the design and operation of the instrumentation package. The test engineer will be Mark Burnitzki, and he will be in charge of operating the vehicles and organizing the schedules for driving the vehicles in order to load the DPFs. PM filters will be provided and analyzed by Oliver Chang and Yilin Ma (ECARS).

The project has the good fortune to have both David Quiros and Oliver Chang from MLD as participants in the study, and their supervisor, Shaohua Hu, will be a consultant. Both David and Oliver have extensive experience with the use of particle instruments, and Shaohua has extensive experience with the analysis of filter samples. These additional staff members will allow for flexibility in scheduling tests, and it will also be possible to have a detailed comparison of the particle instruments being used in the investigation.

References

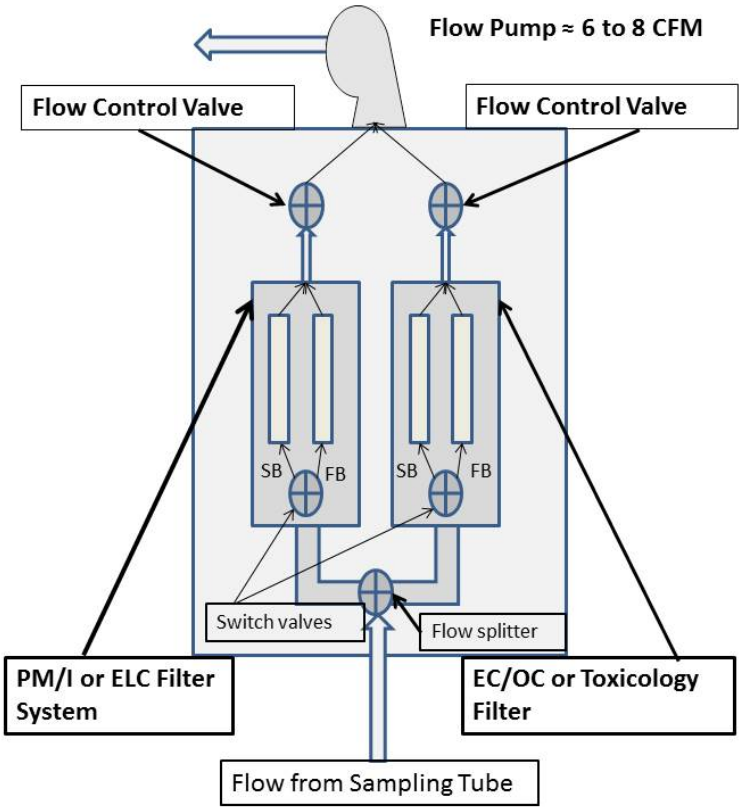
1. Dwyer, H. (2013). Final Report, Agreement Number 11-329. In Measurement of Emissions from both Active and Parked Regenerations of a Diesel Particulate Fitler from Heavy Duty Trucks. California Air Resources Board.
2. M. Yusuf Khan, Kent C. Johnson, Thomas D. Durbin, Heejung Jung, David R. Cocker III, Dipak Bishnu, Robert Giannelli, “Characterization of PM-PEMS for in-use measurements conducted during validation testing for the PM-PEMS measurement allowance program”, Atmospheric Environment 55 (2012) 311-318.
3. CRC Report: ACES PHASE 2 OF THE ADVANCED COLLABORATIVE EMISSIONS STUDY, November 2013.

Conceptual Design and Requirements for Filter Sampling System

The primary objectives for ambient dilution tunnel filter sampling system are the following:

- Construct a robust sampling system that can collect emission samples on filters for the following four emission categories: (1.) PM mass and Ions; (2.) EC/OC; (3.) Elemental Composition; and (4.) Possible additional sampling (e.g., toxicological assays, MOUDI).
- A panel showing the flow rates (rotometers and pressure gauges) into the filters should be centrally located and visible for staff to adjust and control a proper filter face velocity into each filter.
- The filter system for the active regeneration study should be capable obtaining separate filters for the soot burning phase and the fuel burning phase of the regeneration process.

A schematic of a filter possible system is shown below, and this system handles two of the emission categories with one pump.



1. SB – Soot Burning Filter
2. FB – Fuel Burning Filter
3. PM/I - PM Mass/Ions Filter
4. EC/OC – Elemental Carbon/ Organic Carbon Filter
5. ELC – Elemental Composition Filter
6. TOX – Toxicology Filter