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Concentrations and Size Distributions of Particulate Matter Emissions from a Class-8 Heavy-duty Diesel Truck Tested in a Wind Tunnel

Mridul Gautam, Nigel N. Clark, Sandeep Mehta, and James A. Boyce
West Virginia University
Morgantown, WV
Fred Rogers and Alan Gertler
Desert Research Institute
Reno, NV

ABSTRACT

In an effort to develop engine/vehicle test methods that will reflect real-world emission characteristics, West Virginia University (WVU) designed and conducted a study on a Class-8 tractor with an electronically controlled diesel engine that was mounted on a chassis dynamometer in the Old Dominion University Langley full-scale wind tunnel. With wind speeds set at 88 km/hr in the tunnel, and the tractor operating at 88 km/hr on the chassis dynamometer, a Scanning Mobility Particle Sizer (SMPS) was employed for measuring PM size distributions and concentrations. The SMPS was housed in a container that was attached to a three-axis gantry in the wind tunnel. Background PM size-distributions were measured with another SMPS unit that was located upstream of the truck plume. Ambient temperatures were recorded at each of the sampling locations. The truck was also operated through transient tests with vehicle speeds varying from 65 to 88 km/hr, with a wind speed of 76 km/hr. Sampling of the plume with the truck operating at 88 km/hr revealed uni-modal distributions with geometric mean diameter (GMD) values ranging from 55 to 80 nm. When size distributions from five locations in the plume were corrected for concentration with respect to dilution, they were found to be similar. Size distributions and concentrations of PM emissions from the tractor operating at 88 km/hr were found to agree with those from few other heavy-duty diesel vehicles that this team of researchers had previously tested in the field using the WVU Transportable Heavy-duty Vehicle Emissions Testing Laboratory. Under idle operation a distinct nuclei mode was detected with GMD varying from 14 to 24 nm.

INTRODUCTION

Diesel engines are known to produce a substantial fraction of atmospheric PM, particularly in the size range below one micron. Although fine PM has been viewed for decades as detrimental to human health, recent concern that diesel exhaust may contain high number counts of ultra-fine particles has intensified the interest in diesel exhaust products. Whereas traditionally diesel exhaust has been subjected to mass measurement, it has been argued in the literature that it may be the number count and/or surface area and not PM mass alone that is of health concern. Furthermore, although diesel PM mass emissions (whether energy or distance specific for a vehicle) have declined over the last decade, it is possible that emissions control strategies that have been implemented to achieve this mass reduction may not have reduced particle number counts in certain ranges.

Amidst this renewed interest in diesel PM, it was recognized that not only the exhaust dilution and mixing process but also the atmospheric conditions have a profound influence on fine particle formation. Humidity and temperature of the diluting air play a role in determining nucleation and condensation mechanisms. However, it has also been recognized that little is known of the properties of diesel exhaust plumes under real world conditions. Possible disparities between measurements made in the laboratory (using dilution tunnels) and the real world PM formation have been debated.

To enhance understanding of diesel PM characterization, the E-43 program was initiated by the Coordinating Research Council (CRC) and National Renewable Energy Laboratory[1] to elucidate the nature of

[1] Sponsors of this study were the Coordinating Research Council (CRC), National Renewable Energy Laboratory

real world diesel exhaust plumes and provide novel data on real world PM size distributions from both old and new technology trucks under typical operating conditions. Of central interest was the development of PM characterization methodologies. An advantage offered by the tunnel was that it could provide a steady headwind to the vehicle, without crosswinds that can cause the plume to vary unpredictably in position. A further advantage was that the vehicle engine could be reproducibly loaded, using a heavy-duty chassis-dynamometer during both steady state and transient conditions, thus allowing multiple runs with similar plume behavior and composition. Also, the operation of the vehicle in the tunnel allowed the use of stationary equipment and the simultaneous use of a wide variety of equipment, in contrast to the on-road situation, which is limiting. The tunnel test section platform measured 16m (52 feet) in length and 13 m (42 feet) in width, and provided a parallel flow region of approximately 18 m (60 feet) by 9 m (30 feet).

This paper does not seek to review in detail prior health effects studies, prior PM size measurements nor the effect of emissions control technologies on the nature of diesel PM. Some of the more recent studies by this group are reported elsewhere [1, 2, 3, 4, 5, 6, 9, 10]. Reported below are the research effort and results associated with the 1999 experimental program in the Langley tunnel, where the exhaust and plume of a single new technology truck were examined under reproducible conditions.

EXPERIMENTAL SET-UP

West Virginia University was joined by the Desert Research Institute (DRI) and the University of Minnesota (UMN) in the wind tunnel study. DRI measured background PM concentrations and size distributions upstream of the truck. UMN sampled the plume with a probe that was located at a distance of 11m (430 inches) from the truck exhaust stack. This paper will not discuss any UMN results from the wind tunnel nor their chase studies that were associated with the E-43 project[1]. WVU placed a suite of instruments, including Non-Dispersive Infrared Analyzers (NDIR) for CO_2 concentration measurements, and the SMPS configured with CPC 3025, in a traversing gantry mechanism for near real-time three-dimensional measurements. In addition to collecting PM and gaseous data from the plume, CO_2 measurements of raw exhaust in the stack were also being made with the NDIR detector as described in a companion paper [11].

Figure 1 shows the experimental setup for dilution ratio and particle size measurements at the Langley full-scale wind tunnel facility. The gantry-mounted container housed the SMPS. Since the wind tunnel was a recirculating tunnel the background particle levels were continuously monitored by Desert Research Institute at the inlet of the test section with another SMPS. The background levels were also monitored with the remote sampling system after samples were obtained from the plume's centerline and the edge. The sampling container was moved to the inlet of the test section very close to DRI's SMPS. In total, samples were obtained from four locations along the centerline of the plume as well as plume's edge. Coordinates at each location are also show in Figure 1. Data from centerline is presented in this paper.

PARTICLE SIZE DISTRIBUTION MEASUREMENTS

This paper discusses the PM size distributions and concentrations, the dilution ratios in the plume downstream of the exhaust at different wind speeds, as well as temperatures in the exhaust stack, the plume (young and aging), and background, in an effort to highlight the dynamic interaction of the various parameters that govern the physical and chemical processes of particulate matter formation and transformation, and directly affect PM size distributions and concentrations. PM size distributions and concentrations were tracked using the SMPS and CPC throughout the study

Particle sizing measurements were conducted over a period of four days. Prior to obtaining repeatable particle sizing data with the truck operating at a steady-state speed of 88 km/hr and the wind speed maintained at 88 km/hr, the exhaust plume was mapped using CO_2 concentrations measurements to determine the centerline and the dispersion of the plume. The last day of the study was devoted to transient testing. A Scanning Mobility Particle Sizer (SMPS) with an ultra-fine Condensation Particle Counter (CPC) was used for collecting data during steady state runs and also for tracking single particle counts during transient modes of operation.

(NREL), Engine Manufacturer's Association (EMA), South Coast Air Quality Management District, California Air Resources Board, Cummins Engine Company, Caterpillar, Volvo, and National Institute for Occupational Safety and Health (NIOSH). The University of Minnesota was the prime contractor, and West Virginia University, was a subcontractor to the University of Minnesota and to CRC.

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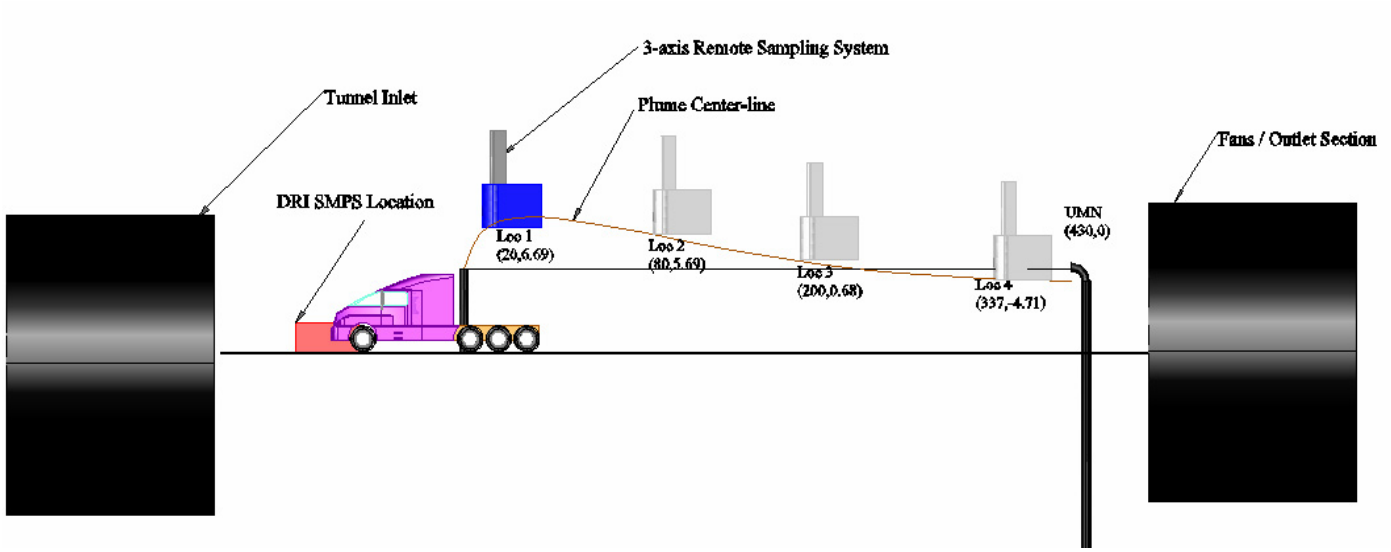

Figure 1: Experimental Setup of the gantry container that housed the SMPS, PM filters and CO_2 sampling equipment for plume exploration.

The SMPS was configured in the under-pressure mode. During under-pressure operation, aerosol is drawn through the Differential Mobility Analyzer (DMA) and is sent to the CPC. This is common practice when sampling from aerosol at or near atmospheric pressure. Symmetric flow conditions were maintained through all measurements. At symmetric flow conditions, flow rates of polydisperse and monodisperse aerosol, as well as sheath air and excess air, were equal. Such flow conditions provided two separate laminar streams inside the DMA, namely the sheath air stream, next to the inner electrode, and the polydispersed aerosol stream, at the outer portion of annulus. Selection of adequate flow rates was found to be crucial for obtaining representative data. The flow rates on the electrostatic classifier were set according to the existing pressure and temperature conditions in the sampling system and the ambient air. A consequence of the deviation of pressure and temperature, with respect to those under which the instrument was calibrated, was that voltages corresponding to those flow rates were different than voltages provided in the calibration sheets. Therefore, flow rates were routinely measured by a bubble flow meter and adjusted accordingly.

The steady-state SMPS measurements for this study were performed with scan times of 60 seconds and longer. Quant et al. [12] found that scans faster than 60 seconds show a smearing of the measured particle distribution due to the effects of the detector response time. For transient size distribution measurements the SMPS was adjusted to pre-selected fixed narrow size ranges to register the time variation in the size-selective particle emissions.

To assure accurate measurements, the SMPS was tested for possible internal and external leaks prior to each series of runs. Standard leak check procedures were followed for each major component of the SMPS system. By running 300 second long full scan with the HEPA filter attached to the aerosol inlet the integrity of the SMPS configuration was verified. Detection of more than a few dozen particles indicated a potential leak or incorrect flow settings.

Table 1: SMPS Configuration Specifications

Impactor size :	0.508 mm
CPC :	3025 (low flow
Upscan Time :	90 secs
Down SCAN time :	30 secs
Sheath Air Flow :	7 lpm
Aerosol Air Flow :	0.7 LPM
Size Range Bounds :	8.98 nm to 378 nm
Time delay in the column (tf):	3.2 secs
Time delay between the EC	4.2 secs
Impactor Cut Size (D50) :	504 nm

DATA ANALYSIS

DATA INVERSION FOR SMPS MEASUREMENTS

Contemporary aerosol instrumentation uses indirect measurement techniques to determine aerosol size distributions based on their dynamic, electrical or optical behavior. The raw data from these instruments need to be inverted to obtain the aerosol size distribution.

The Electrostatic Classifier of the SMPS classifies aerosol based upon the electrical mobility of the particles. The major factors that affect measurement are the charge of aerosol, influence of the input aerosol characteristics on the output aerosol characteristics, efficiency of the Condensation Particle Counter and efficiency of the inlet impactor. The concentration of the input aerosol (dN/dlogDp) from the number distribution of the classified aerosol (dN_{raw}/dlogDp) as shown in Equation 1 [12]. Corrections must be made for the presence of multiple-charged particles and the transfer function. In addition, corrections for CPC efficiency and inlet impactor efficiency need to be employed:

Equation 1

$$\frac{dN}{d\log D_p} = \frac{\frac{dN_{raw}}{d\log D_p}}{f + (D_p) \cdot \varepsilon_{CPC} \cdot \varepsilon_{IMP}} Tr(D_p).$$

where, $dN/d\log D_p$ is the corrected number(#) concentration of particles (#/cm3), $dN_{raw}/d\log D_p$ is the concentration of particles before the correction (#/cm^3), $Tr(D_p)$ is the transfer function, f is the fraction of single charged particles, ε_{CPC} is the counting efficiency of the Condensation Particle Counter, and ε_{IMP} is the efficiency of the impactor at the inlet to the electrostatic classifier.

An algorithm incorporated into the SMPS software can be used to correct measurements obtained during steady-state engine/vehicle operating conditions. However, real-time single particle tracking software (CPCwin) did not offer this option and the aforementioned corrections had to be performed on the output data.

A transfer function is defined as the probability that an aerosol particle that enters the mobility analyzer via the aerosol inlet will leave via sampling slot, given that its mobility is Z_p [14]. Triangular, Gaussian, and other forms may be used to define this transfer function. The DMA transfer function might significantly deviate from the theoretically-derived function. Brownian diffusion is responsible for degrading the transfer function by causing particle losses in connecting tubing and inlets of the DMA and for broadening the particle trajectories inside the analyzer column [15]. For this investigation, a truncated triangular function was used to provide a DMA transfer function. Experimental results showing the validity of the truncated triangular function are discussed later in the paper

The single-charged particle correction, a truncated triangular transfer function, CPC counting efficiency, and impactor efficiency values were applied to the raw data. Multiple charges on a particle increase its mobility and can make the particle susceptible to incorrect classification as a smaller-sized particle. The raw data from the SMPS can be converted into size distribution if the bipolar charge distribution for the aerosol is known. The calculated values for the concentration are substantially influenced by the choice of the charging theory. The single-charged particle correction applied to this study was based on Fuchs model [16].

DATA PRESENTATION

Results of SMPS measurements of particulate matter size distribution for steady-state vehicle operating conditions are presented as normalized particles/cm^3 (dN/dlogDp). Generally, lognormal distributions have been found to fit the particle size distributions very well. Where necessary, the log-normal fit parameters are used in the following sections. The SMPS measurements for transient engine/vehicle operating conditions are given as time-distributed count base number concentrations of selected size particulate matter for raw exhaust (#/cm^3). PM concentrations are presented as dN/dlogDp. During the transient operation of the vehicle on the chassis dynamometer, the SMPS was locked into a single-particle-size mode, and that particular particle size was tracked for the duration of the cycle. Once the cycle was completed, the SMPS was locked into the next size and the cycle was repeated. Previous studies at WVU have shown that driver variability is a negligible factor in the overall cycle-to-cycle variability. As many as four and as few as three different particle sizes were tracked. Unfortunately, due to time constraints imposed by the testing schedule, more particles sizes could not be tracked. The initial operation of the vehicle on a steady-state mode was used not only to determine the particle size distribution under such operation, but also to select the particle sizes that would need to be tracked during the transient phases.

EXPERIMENTAL RESULTS

The researchers' aim in this particle sizing effort was to collect data that would help explain the effect of background, plume dynamics, mixing in the plume shear layer, dilution ratios, truck's exhaust (in the stack) and plume temperatures, and engine operation (steady state, transient, and idle operations) on diesel particulate formation.

Participation of researchers from the Desert Research Institute (DRI) allowed for the measurement of background PM size distributions and concentrations upstream of the test truck with a SMPS. DRI collected the background throughout the course of the Langley study. In addition to providing valuable insights into the changing background PM size distributions, DRI's data also served as a check on the background data that WVU was collecting between tests. WVU's background data was collected at a location immediately up-stream of the truck's exhaust stack.

Background PM characteristics (concentrations, distributions, morphology, and surface chemistry) may have a profound influence on the fate of particulate matter emitted from diesel vehicles. It is widely recognized that other factors, such as, dilution ratio, rate of dilution, ambient temperature, and humidity coupled with fuel characteristics directly impact the mobile source generated PM. Recent results [4, 5] from various studies show that lubricating oil's chemical composition (base stock and additive packages) plays a major role in the PM size distributions and concentrations. It should be noted that a majority of published literature has focused on studying heavy-duty engine out (exhaust manifold) PM exhaust emissions. Very sparse attempts have been made to conduct repeatable investigations into the PM from the exhaust emitted out of tailpipe of heavy-duty vehicles. The extent of exhaust cooling that occurs in the exhaust system of a heavy-duty vehicle driving at 96.5 km/hr on a highway, and the subsequent gas/particle interactions that occur in the tailpipe have a significant impact on the size distribution and concentration of emitted PM. Maricq *et al*. [6] have shown that particle size distributions obtained in a wind tunnel at vehicle speeds less then 96 km/hr were characterized by a dominant accumulation mode. Their study did yield a nuclei mode at speeds of 113 km/hr. Sasaki [7] conducted a chase study and a wind tunnel study and showed that at 80 km/hr the light duty diesel truck had a PM size distribution with GMD of approximately 50 nm with a concentration of 1 $x10^8$ particles/cm^3.

An impressive body of literature has existed on jet engine exhaust aerosols, and it has explored the formation mechanism of particles during combustion and the environmental effect of exhaust emissions from high flying jet aircraft. Pure carbonaceous aerosol is hydrophobic [16] and it shows almost no water uptake in a humid atmosphere [18]. However, treatment of carbon particles with sulfuric acid improves their hydration properties so that sulfuric acid treated carbon particle become activated at very low super-saturations of less than 0.3% [19, 20]. The oxidation of SO_2 to SO_3 occurs very early in the post-cylinder reactions, leads to formation of gaseous H_2SO4 in the presence of H_2O. Karcher et al. [21] estimated that the formation of SO_3, in aircraft engines, is restricted to a very young plume with less than 10 ms in age. The subsequent binary nucleation of sulfuric acid-water systems has been discussed by several researchers [1, 2, 3, 6, 22,23, 24, 25, 26, 27,]. The binary clusters of H_2SO_4 and H_2O molecules undergo heterogeneous nucleation with the available carbon particles. These carbon particles may have their origin in the fuel, lubricating oil and/or both. Also, ash and heavy hydrocarbons from the lubricating oil participate in the heterogeneous nucleation process. The H_2SO_4-H_2O-carbon complex is now susceptible to growth by condensation of heavier organic species, and a potential decrease in size by evaporation depending upon the partial pressures of the organic species in the exhaust.

Most of the published literature on heavy-duty PM emissions has considered the binary nucleation (via the multi-component route) of water vapor and sulfuric acid, and the subsequent hetero-molecular nucleation and particle growth only in the exhaust dilution systems (laboratory or real-world). Exhaust samples extracted from a location close to the exhaust manifold provides a sample that is at an elevated temperature (approximately 482^OC) compared to a temperature of 204^OC at the exit of the tailpipe of a moving vehicle. It should be noted that sulfuric acid remains in a vapor state at temperatures above approximately 315^OC. The sample extracted from the manifold is then diluted and cooled in a dilution tunnel system that employs filtered dilution air. Characteristics of particles formed in the dilution tunnel under these circumstances would be very different from those of particles formed in the dilution tunnel that used a sample extracted from the end of the tailpipe. The H_2SO_4-H_2O-carbon particles are now subject to growth by condensation, and coagulation. A sample extracted from the high temperature region of the exhaust system (close to the engine manifold) experiences a drop in temperature in a relatively cleaner environment of a dilution tunnel. The sample extracted from the end of the tailpipe has already had a history of cooling in an environment that is rich is carbonaceous particles, organic species and other particles. This paper does not intend to discuss dilution systems, but it should be mentioned that any dilution system that subjects the exhaust sample to vacuum levels significantly below atmospheric pressure will also tend to severely compromise PM size distributions and concentrations measurements.

The test vehicle (referred to as Truck 61 by the manufacturer) was operated at speeds up to 88km/hr (55 mph) in the Langley Tunnel with a head wind of 88 km/hr (55 mph). Focusing only on the exhaust that exits the tailpipe, particle size distributions and concentrations are now dictated by dilution ratios, rates of dilution, turbulent mixing, plume dynamics, ambient temperature, lubricating oil and fuel characteristics, and humidity. Availability of a validated computational model to determine the CO_2 concentrations in a truck plume, hence, dilution ratios

would have made the task of designing the study relatively simple. Subsequently, significant modeling work was conducted and reported by this group (1, 2, 6). In the absence of such a model, first day of the four day-testing program in the Langley wind tunnel was dedicated to exploring of the plume and mapping it in space. A considerable amount of effort had to be devoted on the first day of testing to "plume exploration". Plume exploration entailed traversing the overhead gantry across the length, breadth and height of the plume to record CO_2 data. This exercise helped not only in establishing the plume centerline, but also defined the "edge" of the exhaust plume. Four test locations in the plume were then selected on the basis of the results of this exploration. Schematic in Figure 1 shows the relative positions of these locations.

This exercise was carried out on the second day and repeated on the third day. The fourth day of testing was devoted to transient testing. The tunnel testing lasted a total of four days.

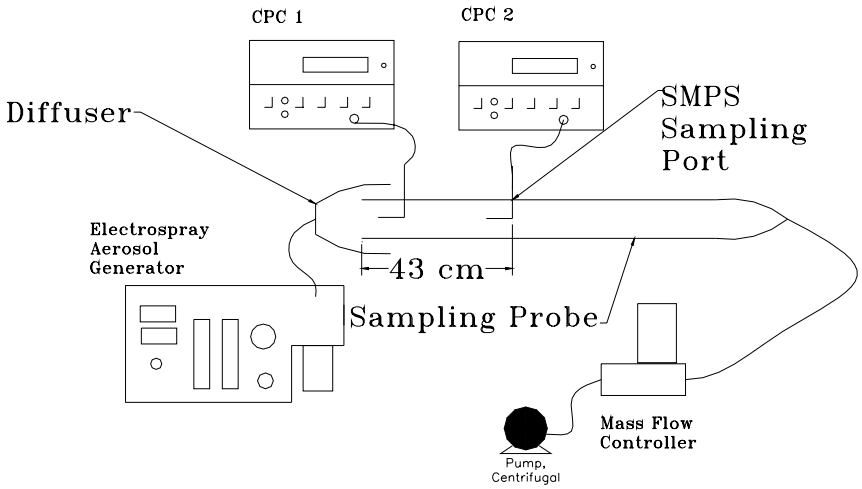

Figure 2: Layout Schematics for Aerosol Loss Study

SYSTEM CHECKS

Aerosol Loss Characterization

The set-up for aerosol loss study is shown in Figure 2. This exercise was undertaken to determine the particle loss (number count) to the walls of the probe and sampling system. An electro-spray aerosol generator (TSI 3480) was used to generate 60 nm sucrose particles. Authors realize that sucrose particles may not exactly represent diesel PM but sucrose (in an electro-spray) was the only available method for generating particles in sizes ranging from 14 nm to 60 nm. These particles were introduced in a 63.5 mm (2.5") NPT diffuser. The diffuser was placed concentric with the inlet of the 37.5 mm (1.5") sampling probe. The clearance between the diffuser and the sampling probe allowed the entry of make-up dilution air for the total sample flow of 144 lpm that was selected for the Langley Tunnel study. It should be noted that the aerosol generator could only produce a flow rate of 1.1 lpm. Aerosol concentrations were measured at the inlet of the probe and also at the SMPS sampling port in the probe that was at distance of 43 cm from the leading edge of the probe.

Two condensation particle counters CPC 3025 were used to simultaneously measure the concentrations at the two sampling ports viz. inlet and SMPS sampling ports. There was a minor discrepancy in the readings between the two CPCs, primarily due to a small discrepancy between the flows in the CPCs. In order to the override the error due to the discrepancy between the CPCs, a set of three repeat tests were conducted with one of the two CPCs at the inlet sample port and the other CPC at the SMPS sampling port. Then, another set of three repeat tests were performed by swapping the CPCs' between the two locations.

Table 2

Test Id.	Inlet Concentations (p/cc)	Test Id.	Sample Concentations (p/cc)	Aerosol loss
INCPC2-1	6969.11	SACPC1-1	7126.30	-2.26%
INCPC2-2	7920.16	SACPC1-2	8062.62	-1.80%
INCPC2-3	8283.57	SACPC1-3	8474.19	-2.30%
		Configuration 1. Average		-2.12%
INCPC1-1	7380.89	SACPC2-1	7213.09	2.27%
INCPC1-2	10887.48	SACPC2-2	10321.33	5.20%
INCPC1-3	14085.10	SACPC2-3	13262.13	5.84%
		Configuration 2. Average		4.44%

Table 2 shows the results from these tests. It can be seen that average loss for configuration 1 is -2.12%, that is, inlet port CPC was reading lower values then the sample port CPC. For the configuration 2 the average aerosol loss was 4.44 % indicating that the sample port CPC was reading a lower value. Hence, the total PM loss (in the sampling system and due to instrument error) was less than 5 %. It was also noted that the significantly high loss of PM can take place if the sample line length between the probe inlet and the classifier is excessively long. The sample line length in the Langley study was maintained at 30 cm.

Validation Of The SMPS "CPCwin" Software For Transient Testing

The manufacturer of the SMPS provides and supports only the full scan software that is applicable only to steady state operations. The full scan SMPS software has built-in routines to implement all the necessary corrections to measurements. However, corrections for the transfer function, multiple–charged particles, CPC efficiency, and inlet impactor efficiency have to be performed on the output data acquired by the real-time single particle tracking software, CPCwin. Details of the corrections have been discussed above.

Presented here are the results of tests that were conducted to confirm the use of a truncated triangular transfer function. These tests were conducted at WVU prior to the Langley Tunnel study. These results have also been used in other studies conducted by WVU. A Navistar T444-E, turbocharged diesel engine was operated over four modes of steady state operation. Table 1 shows the four test modes employed:

The SMPS was operated in a full scan mode and a particle size distribution was obtained. While the engine continued to operate through the given mode, the SMPS was switched to operate in the real-time single-particle tracking mode (using the CPCwin software). Six to seven particle sizes were tracked over the same steady state engine operating condition. The output data from the single-particle tracking exercise was post-processed using different types of transfer functions and the results were compared with the full scan distributions. It was found that the truncated triangular transfer function gave results that were in excellent agreement with the full scan mode of SMPS operation. Figure 3 shows the differences in the distributions from one of these modes when the triangular or the truncated transfer functions were used. The results from the other modes were similar in nature.

Table 3 Navistar T444-E Engine Evaluation Conditions

Steady State Mode	Engine Speed rps (rpm)	Engine Torque N-m (ft-lb)
2	16.7 (1000)	110 (81)
3	20.8 (1250)	165 (122)
7	33.3 (2000)	165 (122)
9	36.7 (2200)	550 (406)

Calibration and Cross-check

Figure 4 shows results of a calibration exercise on the WVU SMPS using an electrospray monodispersed particle generator. An effort was made to ensure that all the SMPS units that were used in this study, were compared with each other. Also, UMN used a nebulizer that produced an ammonium sulfate aerosol to check the size distributions measured by each of the SMPS units.

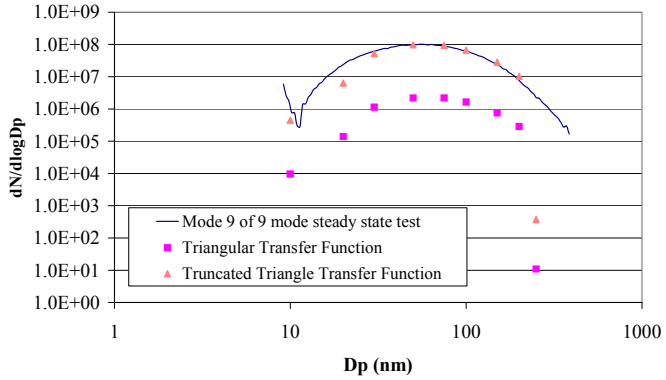

FIGURE 3: Comparison Between The Full-Scan Program And The CPCwin Program Using The Triangular, And Truncated Triangular Transfer Functions Effect Of Transfer Functions On Data Collected With The Single-Particle Size Tracking Program (Mode 9 Of Steady State Cycle On A Navistar T444 Diesel Engine)

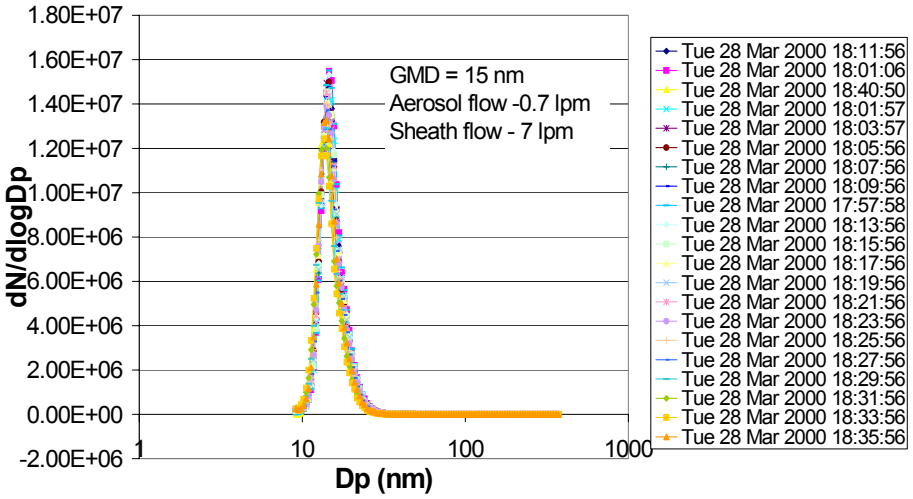

FIGURE 4: Aerosol generated by Electro-spray aerosol generator.

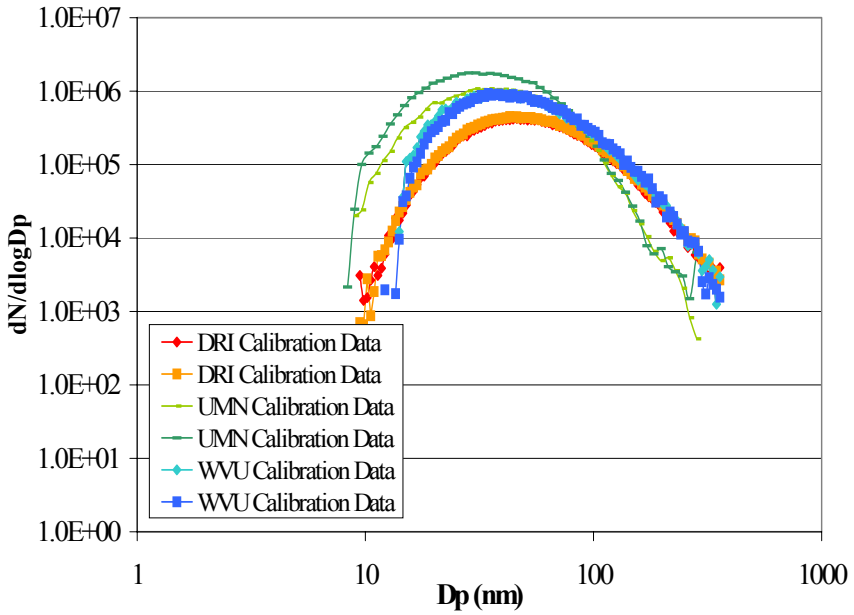

Figure 5: Calibration check on the three SMPS with ammonium sulfate aerosol generated with a nebulizer.

Figure 5 shows the size distribution and concentration of the ammonium sulfate aerosol that was generated using UMN's nebulizer. The WVU SMPS was operated at 60 second and 90 second upscans, and a 30 second downscan. It is seen that the WVU distributions were very repeatable at both the SMPS scan time settings. Figure 5 compares the distributions obtained by UMN, DRI and WVU. The differences in concentrations observed with the DRI and UMN SMPS can be attributed to non-uniform poly-dispersed aerosol generated by the nebulizer at different times as well as the unaccounted time delay in the SMPS configuration. The SMPS units were in two different locations, and the nebulizer was moved from one unit to the other. WVU and DRI SMPS were placed at the same location and simultaneously sampled the same aerosol. The WVU SMPS was configured as per the manufacturer's specification and the default time delay constants were used in the software.

In addition to calibrations with the nebulizer, WVU and DRI conducted comparison with each other's SMPS units. Figure 6 shows the background aerosol distributions that were measured on the first day at the Langley tunnel. Both, the DRI and WVU SMPS units were sampling from approximately the same location prior to any testing in the tunnel. The background PM distributions were similar and in fairly good agreement with each other. The Geometric Mean Diameter (GMD) values were approximately 74 nm. A discrepancy is obvious at the 10-11nm size range, and was attributed to the lower counting

efficiency (in this size range) of the CPC 3022 that was used by DRI.

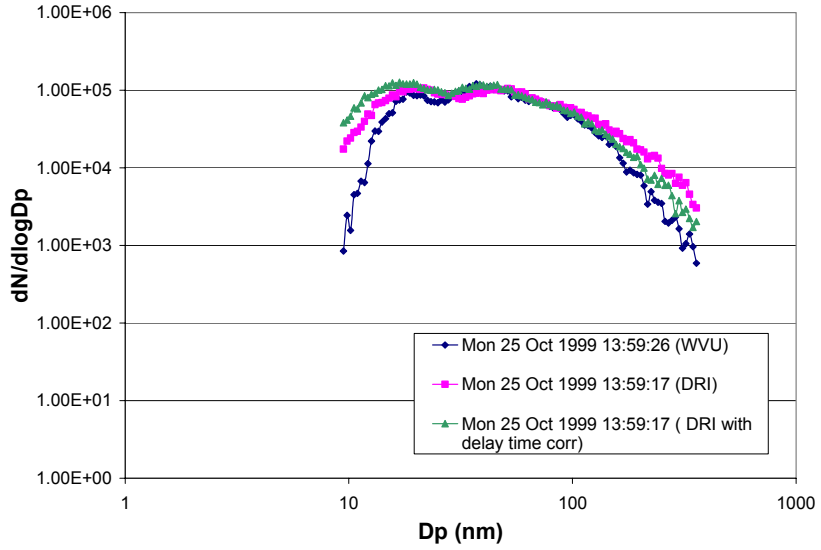

Figure 6: Comparison of between DRI's SMPS and WVU's SMPS

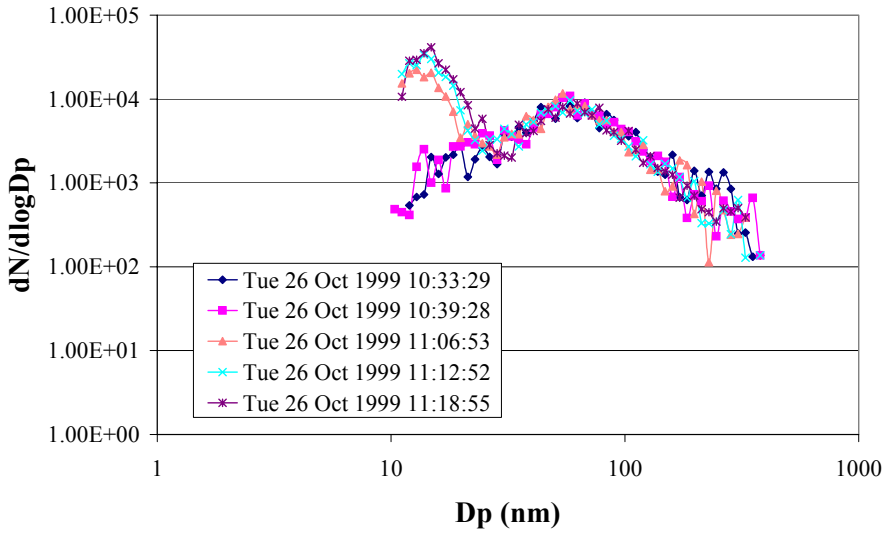

Figure 7: Background at beginning of the day on Day2, without the truck running at location 1 (20, 6.69)

BACKGROUND PARTICLES SIZE DISTRIBUTIONS AND CONCENTRATIONS

This section attempts to characterize the background particle size distributions and concentrations during the course of the Langley study. Background measurements were acquired throughout the duration of the Langley Tunnel study. Background measurements were made upstream of the truck, between tests and at various locations in the plume. One of the more interesting plots is shown in Figure 7. The background aerosol was probed during the morning of Day 2. The truck was turned off and the tunnel fans continued to operate. The sampling probe of WVU's instrumentation gantry was at a location 20 inches downstream of the truck exhaust stack outlet, and 6.69 inches above the geometric centerline of the exhaust outlet. It should be noted that a distinct nuclei mode was absent during the first two runs. However, twenty minutes later, three consecutive runs (at 11:06 am; 11.12 am, and 11:18 am) did show a distinct nuclei mode (GMD of approximately 15 nm). Even more interesting is the fact that these particles persisted in the recirculating tunnel for at least the duration of the background testing, that is for approximately 12 minutes. A quick investigation suggested that these particles could have been emitted from a source, possibly aircraft taking off from the Langley Air Force Base, outside of the Langley tunnel. Without the nuclei mode, the distributions and concentrations looked very similar to what was observed with the very first sample obtained prior to any form of contamination of the background aerosol.

Before discussing WVU's background data any further, DRI's background distributions will be discussed as they show how the distributions

changed during the course of the day. It should be recalled that all of DRI's background data were collected from a location next to the vehicle immediate upstream of the exhaust stack. Figure 8 shows the tunnel background PM size distributions and concentrations as measured on day 3. Figure 8 shows distributions beginning at 8:34 in the morning, prior to starting up the truck and the wind tunnel fans. The tunnel fans were switched on at 9:23 am. Prior to the fans being turned on, the observed bi-modal distributions showed the presence of a nuclei mode. Immediately after the tunnel fans were turned on, there was a reduction in the nuclei mode. However, after a few minutes the distribution became bi-modal again. It should be pointed out that the number concentrations of the nuclei mode particles were very low (approximately 5 $x10^3$ to $5x10^4$ particles/cm^3). This is typical of an indoor setting. The concentration of the accumulation mode particles was slightly less than $1x10^3$ particles/cm^3). At 10:39 am, the fan speed was dropped to 40 km/hr, the truck engine was started. The truck was then allowed to warm-up with the fan speeds varying at 40 km/hr to 88 km/hr. At this point the introduction of engine exhaust into the tunnel began to change the background characteristics. At approximately 10:58 am the truck was operated at cruising speeds of 88 km/hr and the fan speed was increased to match the vehicle speed. At this point the GMD of the distributions shifted to a larger size and exhibited a dominant accumulation mode. Concentrations of the accumulation mode particles remained under 1 x 10^5 particles/cm^3. PM size distributions were very similar for the next several hours.

Figure 8 suggests that in the absence of an operating vehicle, and the tunnel fans turned on, the background does exhibit a distinct nuclei mode. Hence, the uni-modal distributions centered at 14 nm (shown in Figure 8) may be representing an aerosol that was disturbed by extraneous sources possibly from the jets taking off from base in the vicinity

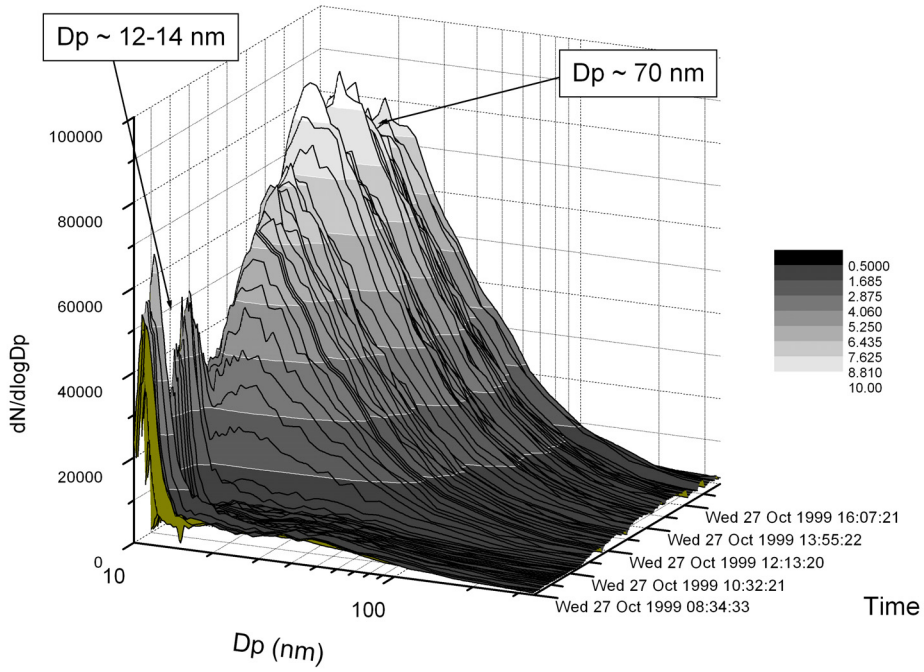

Figure 8: Background particle size distribution with DRI's SMPS between 8:33 to 16:58

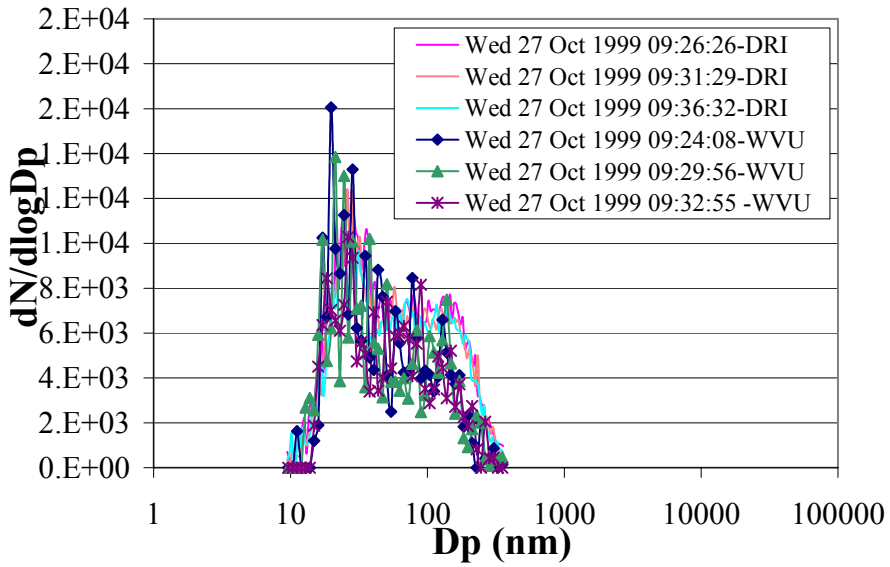

Figure 9: Comparison of background at beginning of the day with the truck not operating and wind speeds of 88 km/hr (55 mph)

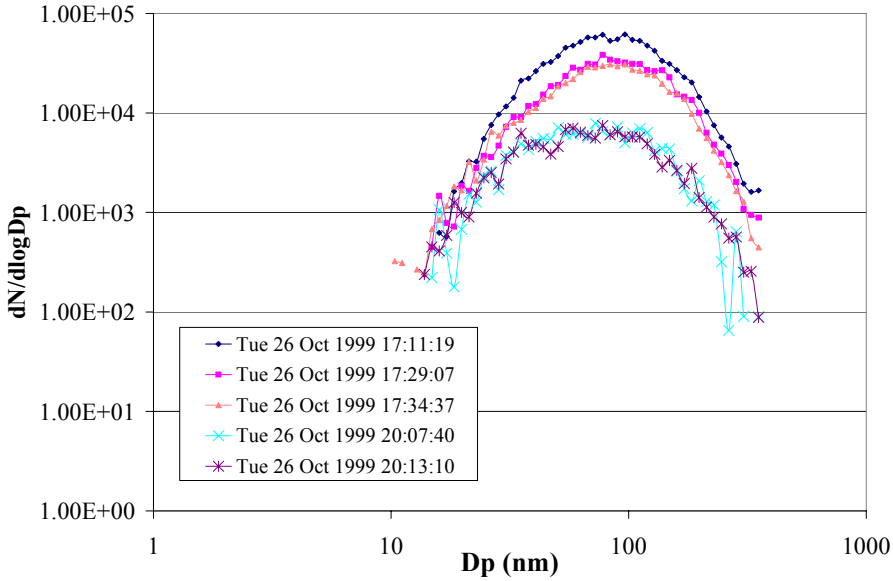

FIGURE 10: Background at the end of the day with the truck not operating and the fans at 88 km/hr (55 mph)

WVU researchers also measured background PM size distributions and concentrations at various locations throughout the course of the testing. Figure 9 shows data from location 4 (337 inches downstream of the exhaust stack outlet) that was acquired by WVU. Simultaneously, DRI was sampling at the inlet to the tunnel. Figure 9 shows that WVU and DRI's results are in fair agreement

Figure 10 shows background distributions measured by WVU towards the end of day 1. The truck was turned off and the tunnel fans continued to operate. It is seen that the distributions were dominated by the accumulation mode particles (GMD of approximately 88 nm). Tests at 5:11 pm, 5:29 pm and 5:34 pm, were conducted immediately after the truck was turned off and the results are shown in Figure 10. Tests at 8:07 pm and 8:14 pm were conducted after the tunnel was purged (by opening up the building doors. Concentration levels dropped but the distribution remained unchanged.

PM SIZE DISTRIBUTIONS AND CONCENTRATIONS DURING STEADY STATE AND TRANSIENT OPERATIONS

PM size distributions and concentrations were measured at each of the four locations (see companion paper [11]) along length of the plume. Further, the plume was traversed vertically at each of the locations in an effort to identify the effect of rapid mixing in the shear layer on size distributions. Data were collected when the vehicle was operated at a

steady state condition of 88 km/hr (55 mph), and also during the transient operations.

At steady state conditions of 88 km/hr, GMD of the size distributions were found to be very similar at each of the locations. The major difference was observed in the concentration of particles at each of the locations. The distributions were dominated by the accumulation mode particles and were primarily uni-modal with GMD values ranging from 55 nm to 80 nm. Figure 11 and Figure 12 show the size distributions at locations along the plume centerline. It is expected that the ambient temperature or perhaps the temperature at a certain location in the plume would have an influence over the particle size distribution and concentrations. Looking further into the effect of temperature, all the particle distributions (from all the locations) were multiplied by the measured dilution ratios and the distributions were reduced back to the vehicle tailpipe emissions Figure 13 shows distributions for five cases that were reduced back to the engine tailpipe out values. PM concentrations in excess of 1 x 107 with a GMD of about 58nm were obtained and demonstrated that the particle size distributions were consistent and merely diluted differently at these various locations. While these results are extremely interesting, it is not clear what the effect of background PM was on the measured size distributions at each of the locations. There were distributions from some of the locations that did not agree with the rest when they were reduced back to the engine. These discrepancies were attributed to inaccurate dilution ratio computations because the dilution ratio at high dilution was influenced by the background CO2 concentration measurements.

Table 4 lists the temperature values in the exhaust pipe, plume temperature (at the sampling point), and ambient temperatures as well as dilution ratios. As expected, the exhaust temperatures in the exhaust stack were fairly uniform (approximately 243^{O}C at a distance of 1.52m upstream of the tailpipe exit) and the ambient temperature was approximately 24^{O}C throughout the tests. However, the plume temperature varied as a function of measurement the location. At location 1 the plume temperature was approximately 46OC. Plume temperatures along the centerline at locations 2, 3 and 4 were approximately 34^{O}C, 27^{O}C, and 25^{O}C, respectively. The temperatures along the edges at most of the locations were similar to the centerline temperature at location 4. At location 4, that is 8.2 m (337 inches) downstream of the stack, the plume temperatures (25^{O}C) were approximately equal to the ambient temperatures (24^{O}C).

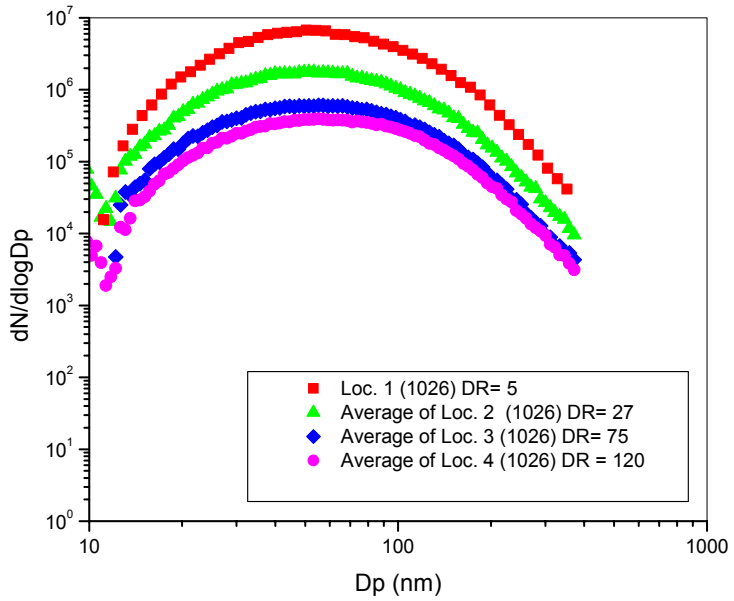

Figure 11: Particle Size Distribution at the four locations on Day 1

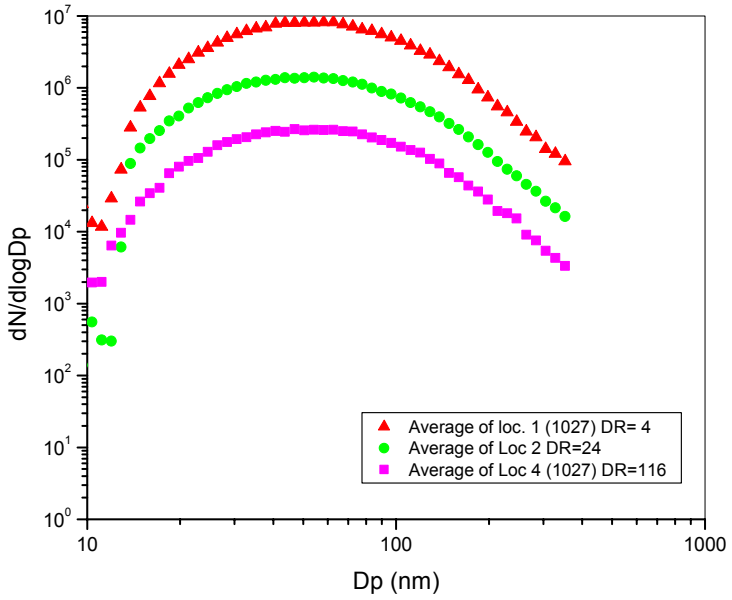

Figure 12: Particle Size Distribution at three locations on Day 2.

It is expected that the ambient temperature or perhaps the temperature at a certain location in the plume would have an influence over the particle size distribution and concentrations. Looking further into the effect of temperature, all the particle distributions (from all the locations) were multiplied by the measured dilution ratios and the distributions were reduced back to the vehicle tailpipe emissions Figure 13 shows distributions for five cases that were reduced back to the engine tailpipe out values. PM concentrations in excess of 1 x 10^7 with a GMD of about 58nm were obtained and demonstrated that the particle size distributions were consistent and merely diluted differently at these various locations. While these results are extremely interesting, it is not clear what the effect of background PM was on the measured size distributions at each of the locations. There were distributions from some of the locations that did not agree with the rest when they were reduced back to the engine. These discrepancies were attributed to inaccurate dilution ratio computations because the dilution ratio at high dilution was influenced by the background CO_2 concentration measurements.

Table 4

Location	Location Coordinates (inches)	Dilution Ratio	Exhaust Temp (C)	Plume Temp (C)	Ambient Temp (C)
1	(20,6.69)	1:4-1:5	245	46	24
2	(80,6.69)	1:24-1-27	244	36	24
3	(200,0.68)	1:75	244	27	24
4	(337,-4.7)	1:116-1:130	244	25	24

In an attempt to compare these results with WVU's findings from other studies, size distributions from five Cummins M-11 powered heavy-duty buses from Dallas were selected. WVU had investigated these vehicles in spring of 1999 under a study funded by the U.S. Department of Energy. All of the Dallas vehicles were equipped with Cummins M-11-280E+ (CPL 2425), turbocharged, compression ignited engines that were equipped with a Nelson catalytic converter. Vehicles were tested at an inertial weight of 39,500 lbs. over a steady state operation of 20 mph. PM size distributions in the exhaust of Dallas vehicles were measured with WVU's mini-dilution tunnel that controls dilution rates using mass flow controllers. WVU has avoided the use of ejectors in our mini-dilution tunnels owing to the excessively high vacuum levels in the ejector throat, and the consequent effect on volatilization of hydrocarbon from PM. It is hypothesized that the volatilized heavy hydrocarbons would nucleate downstream of the throat in the more dilute, cooler and considerable "cleaner" environment. The dilution ratios (between 1:24-1:27) at location 2 in the Langley Tunnel study were comparable to those used in the Dallas study. Figure 14 shows PM size distributions and concentrations from multiple runs that were conducted on each of the 5 vehicles in Dallas. It is seen that the vehicles in Dallas had PM size distributions that showed particles in the nuclei mode (20 nm to 50 nm). It should be noted that unlike the test truck in the Langley tunnel, the Dallas vehicles were equipped with a catalytic converter. But, the catalytic converters were probably not designed to oxidize the lubricating oil based heavy hydrocarbon that would contribute to nano-particle formation. The size distribution from location 2 in the Langley tunnel exhibited a uni-modal distribution with a GMD of 54 nm, and the concentrations were relatively higher. Dallas Bus no. 1 did exhibit a bi-modal distribution with a mode centered at 20 nm. While none of the Dallas buses exhibited a peak in the 10-15 nm range, it should be noted that the particle concentrations (in the 10-15

nm range) for Bus no. 5 ranged from 1 x 10^6 to greater than 1 x 10^7 particles/cm^3.

Idle Operation

Unlike the size distributions from the 88 km/hr operations, the idle emissions showed distinct nuclei modes. The very first test, under idle conditions, was conducted at 4:28 pm (see Figure 15). This bi-modal distribution shows nuclei mode centered at 14 nm. Subsequent samples (collected at intervals of approximately 3 minutes) show a slight increase in the concentration and also the particle size. However, a sample collected after nearly 30 minutes of engine operation showed a GMD of 24 nm. This is significantly lower than that observed at 88 km/hr operation.

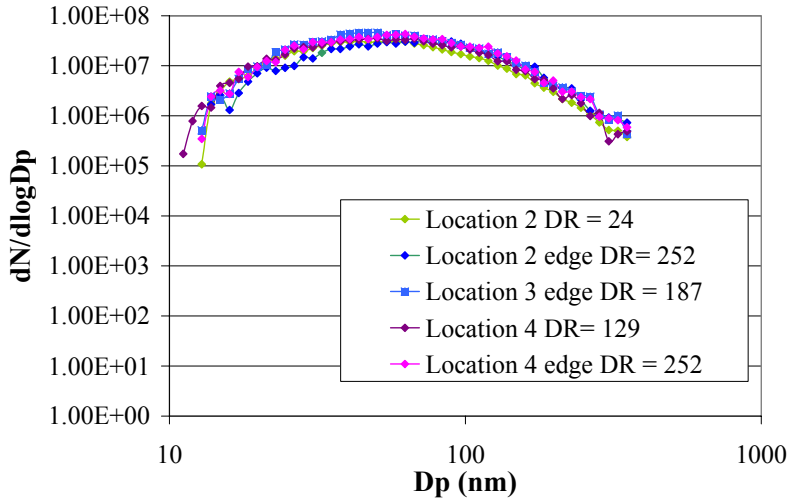

Figure 13: Particle size distribution reduced back to the engine for few of the locations

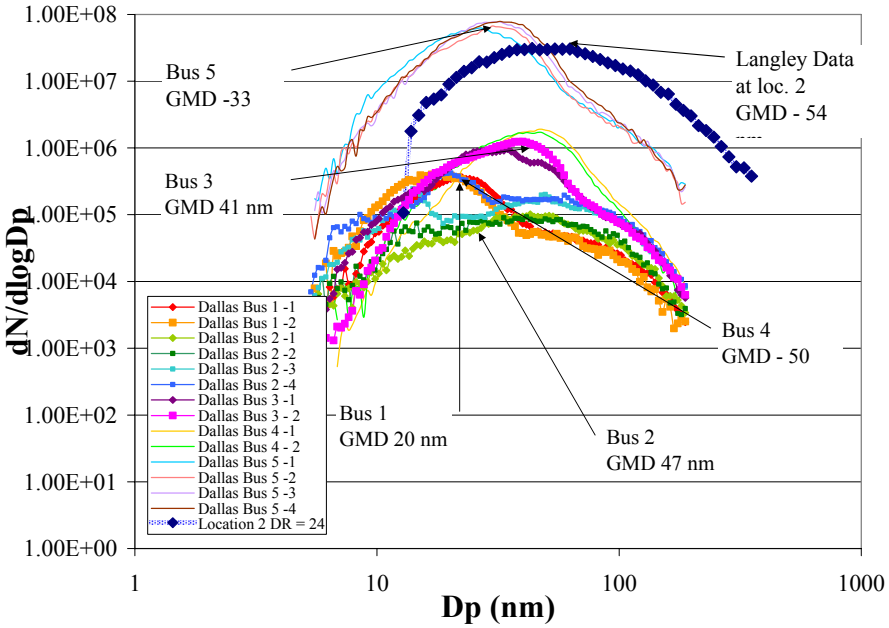

Figure 14: Comparison of particle size distributions from five Cummins M11-equipped transit buses (DART, Dallas TX) and particle size Distribution from Truck 61 (Langley Tunnel-CRC E43 Study) at comparable dilution ratios

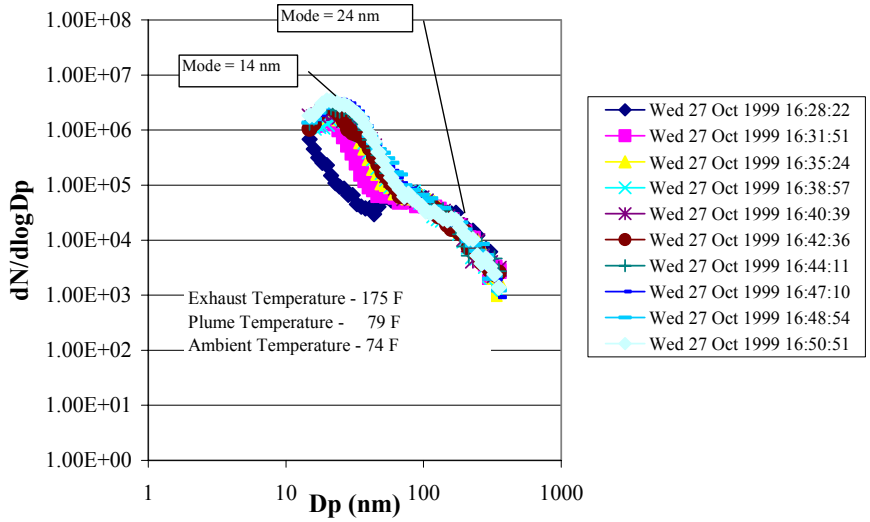

Figure 15: Particle size distribution at location 1 (20, 6.69) with truck idling and the fans at the 40 km/hr (slowest allowable speed)

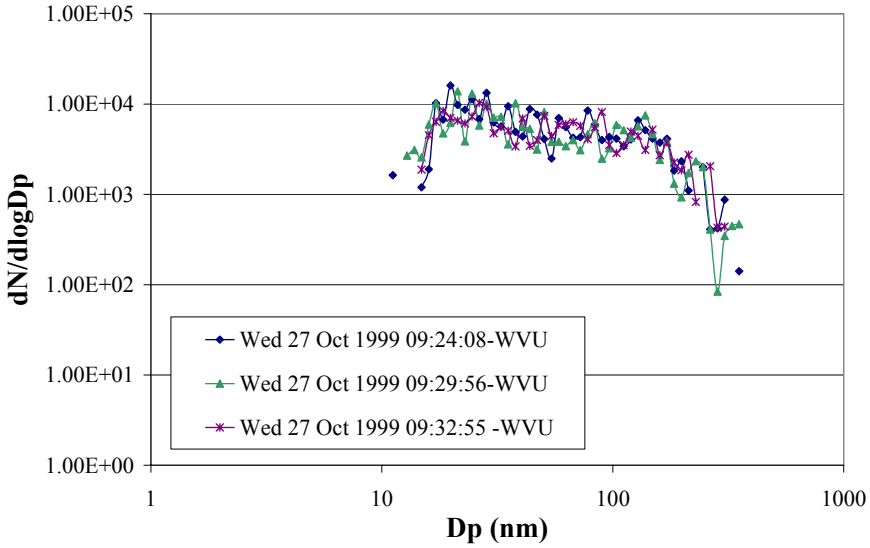

Figure 16: Background at beginning of the day on Day 3, without the truck running at location 4 (337,10.69)

This set of data sheds light on the effect of engine operation on the particle formation. It is expected that the idle mode emissions will have a higher relative concentration of heavier organic species than those from 88 km/hr operation. Also, the carbon particle concentration in the idle operation will be relatively lower than that at the 88 km/hr operation. Hence, idle operation PM emissions are driven by the lower exhaust temperature and the higher saturation ratios. The heavier organic species undergo condensation on the hetero-molecular complex of water, sulfuric acid and lubricating oil based nano-sized ash particles.

It was observed that owing to the recirculating tunnel the background levels of PM were indeed increasing throughout the day. There is a concern that background particles may have suppressed the nano-particle formation. However, Figure 17 shows that particle size distributions that were measured at three different times of the day did not deviate much from one another. Particle size distribution was measured at 10:45 am during the warm-up routine of the truck immediately after the truck was started. Prior to running the truck the wind tunnel was purged of any residual particles and the background was measured without the truck operating.

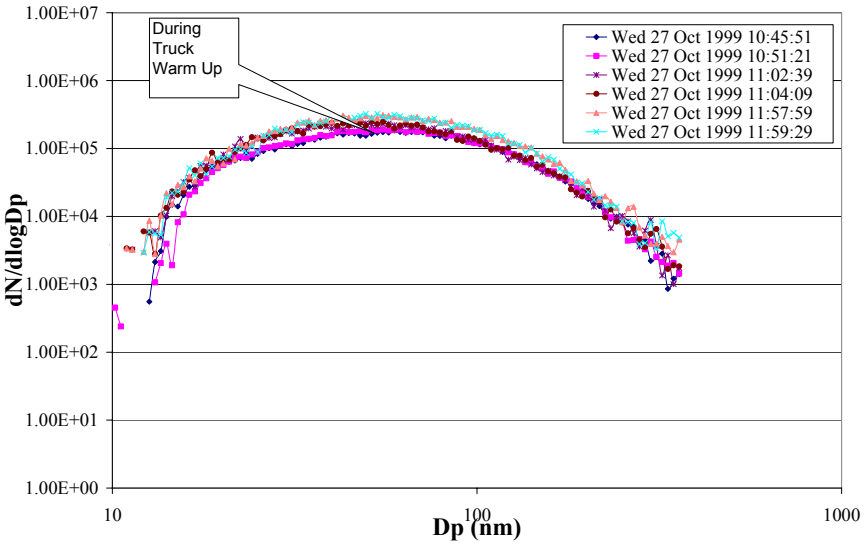

Figure 17: Particle size distribution at location 4 measured at different times of the day

It has been speculated that due recirculation of the air in the Langley wind tunnel there might have been a steady increase in concentrations of accumulation mode particles in background. These particles in turn may have undergone coagulation. The idle data presented herein provides evidence that background PM did not contribute to scrubbing of the nuclei mode particles, which are present in the diesel exhaust plume. The lower in-cylinder temperatures under idle operation, lower stack temperatures, and higher saturation ratios contribute to nuclei mode PM at idle.

Transient Testing

The effects of vehicle acceleration on particle size distribution were also studied. It was expected that the rapid fueling would produce high levels of PM.

A transient chassis dynamometer cycle was designed to simulate an on-road transient operation. The cycle consisted of 5 transient peaks, with each peak requesting the truck to drive from 64.4 km/hr to 88.5 km/hr (40 mph to 55 mph) during an eight second period. At the beginning of each peak, a maximum possible loading was applied to the power absorber. As soon as the truck reached 88.5 km/hr (55 mph), it was brought down to 64.5 km/hr (40mph) using service brakes with a moderate power absorber loading. This procedure was repeated 5 times with about 40 seconds idle time between.

The transient testing of the test truck was intended to mimic transient tests conducted in a loaded condition on the road by University of Minnesota. The study by UMN is not discussed in this paper. West Virginia University's medium duty dynamometer was configured to apply the maximum load to the truck wheels during a full pedal acceleration, in a single gear, from 64.4 km/hr to 88.5 km/hr (40 mph to 55 mph). UMN accelerations on the road elicited 1692 N-m (1248 ft-lb) of torque from the wheels during acceleration, whereas the dynamometer, bereft of flywheels due to weight restriction in the wind tunnel, could raise only 1288 (950 ft-lb) of retarding torque at the wheels. In consequence, the truck accelerated more rapidly and may not have developed as long a sustained turbocharger boost as during the on-road testing. It was also observed that fueling rates differed between the on-road and Langley operation in sympathy with the torque values, implying a lack of full boost operation. Nevertheless, the transient operation should have elicited sufficiently similar operation, with low air to fuel ratios, in both instances.

Figure 18, Figure 19, Figure 20, Figure 21, and Figure 22 show traces of single particle sizes tracked during the transient cycle operation at different locations. It can be seen from Figure 18 that the 65nm particles were prominent at this location. This location was closest to the exhaust stack and the transient data indicate that no nano-particles detected at this location. Figure 19 also shows 65 nm as the prominent size in the shear layer zone. Even though, very rapid mixing and cooling takes place at this location, elevated levels of nano-particles were absent. Given the logistical constraints only three particle sizes could be measured at location 2. It can be seen in Figure 20 that 25 nm was the prominent size. It is quite possible that nano-particles were produced at this location due the higher dilution and cooling taking place at this location. However, Figure 21 shows that the 65 nm re-appeared as the prominent particle size.

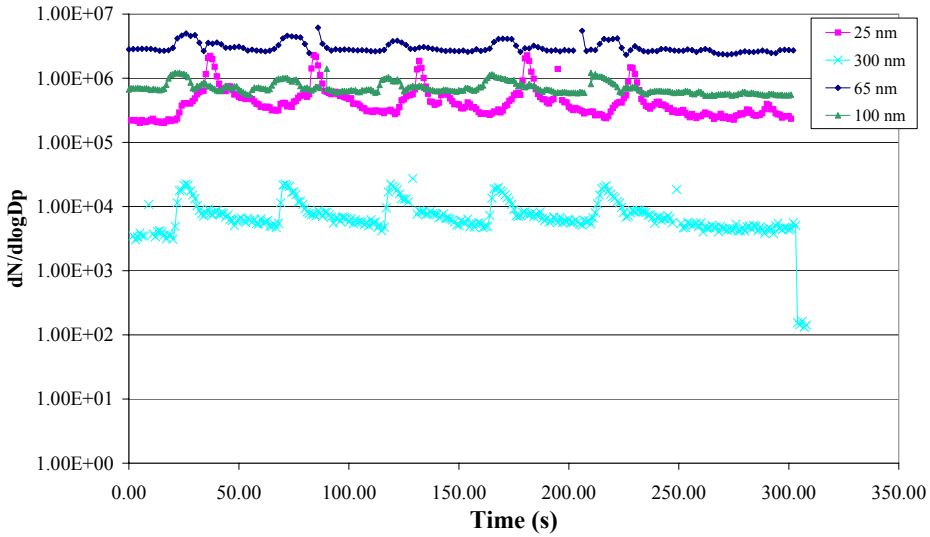

Figure 18 : Traces of few particle sizes at location 1 (20, 6.69) during the transient operation of the truck

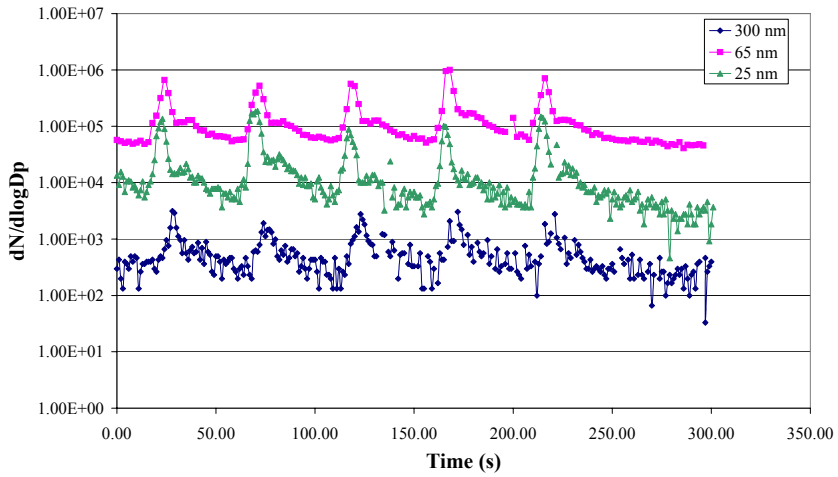

Figure 19: Traces of few particle sizes at location 1 at the detected edge (20, 15.5) of the plume during the transient operation of the truck

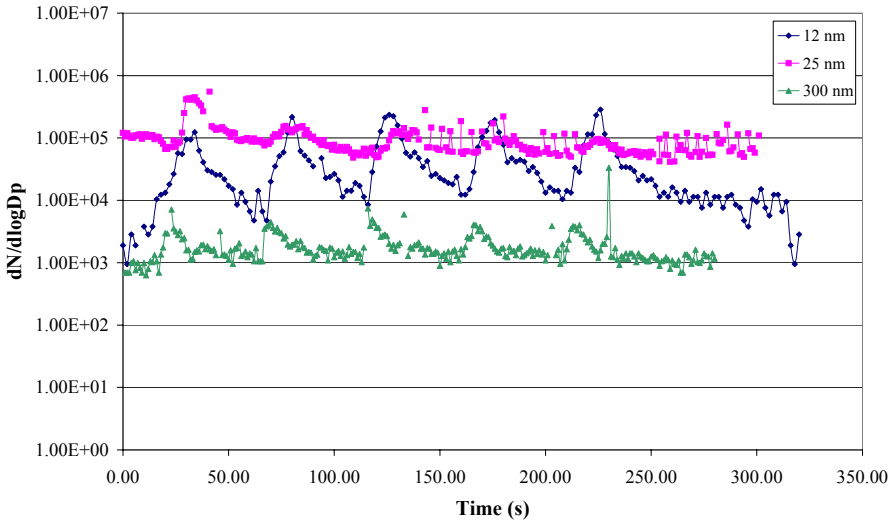

Figure 20: Traces of few particle sizes at location 2 (80.6.69) during the transient operation of the truck

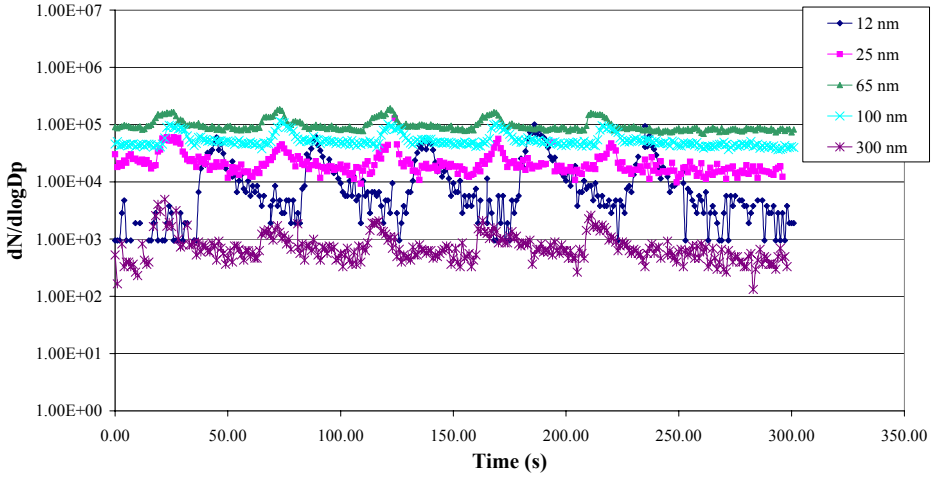

Figure 21: Traces of few particle sizes at location 3 (200, 0.68) during the transient operation of the truck

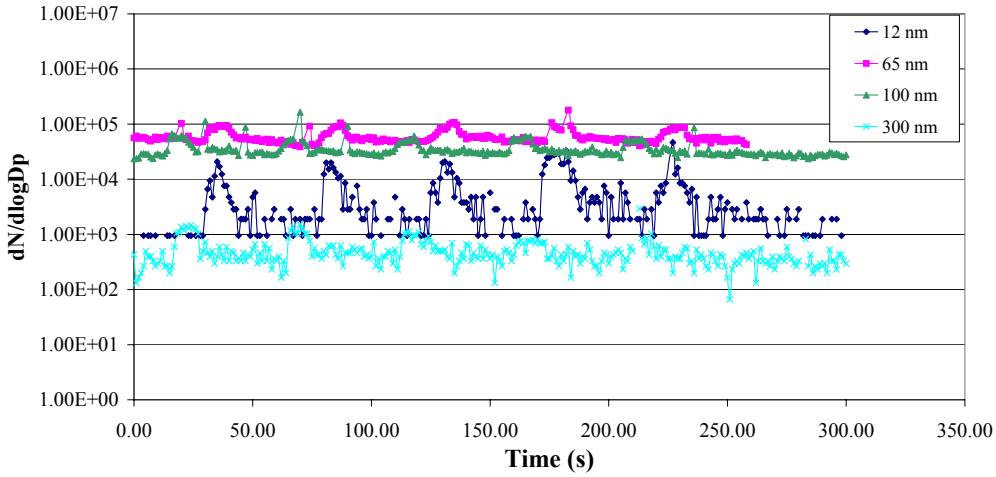

Figure 22: Traces of few particle sizes at location 4 (337, -4.71) during the transient operation of the truck

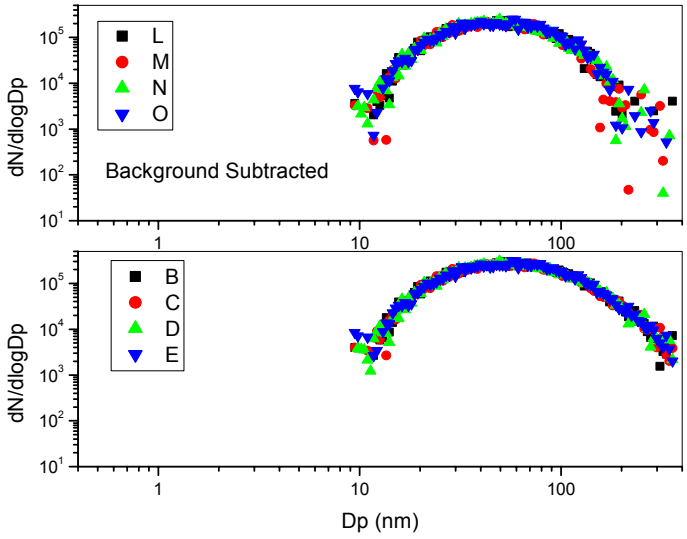

Figure 23: Particle size distributions at the location 3 (337, 4.71) on the Day 3 with the background subtracted, dilution ratio= 130:1

Effect of Background on PM Size Distributions

Typical background size distributions are shown in Figure 8 and Figure 16. A prominent nuclei mode was observed by both, WVU and DRI. These nuclei mode particles completely disappeared during the engine warm-up period. Particle size distributions were measured at the same location at two other times during the day, and similar size distributions were observed. It can be seen from these distributions that while concentration increased marginally over the day, the GMD did not deviate significantly. Based upon this observation it appears that the background particles in the tunnel did not distort the size distributions during these experiments. A few data sets from day 2 and day 3 were selected and corrected by subtracting the background particle concentrations. These included the first data set of the day, a data set from the middle of the day and one from end of the day's testing. Figure 23 shows that the particle size distributions are relatively unaffected after applying background corrections. This exercise did not indicate that nano-particle formation was suppressed by background PM in the tunnel. The idle data suggests that the background had no impact on the presence of nuclei mode particles, which may very well have formed in the exhaust stack itself.

CONCLUSIONS

A truck tractor representing current in-use vehicles and with an electronically managed diesel engine was installed on a dynamometer in the ODU/Langley full scale aircraft testing wind tunnel. These arrangements permitted repeat measurements of diesel exhaust under realistic and reproducible conditions, and permitted examination of the steady exhaust plume at multiple points. Recirculation in the tunnel led to an increase in the GMD of the background PM distribution in comparison to the background PM distribution before the truck was started in the mornings. However, these distributions may by representative of the accumulation mode that exists in the background in urban metropolitan areas. The temperature in the tunnel varied from 66°F to 75°F, which again is the average ambient temperature in the summer across most of the US. Background particle size distribution was characterized using a Scanning Mobility Particle Sizer (SMPS) set up near the truck front wheel, away from the exhaust stack. Another SMPS, a filter arrangement and gas (CO_2) analysis equipment were installed in a roving three-axis gantry container that could sample at various points in the plume. Steady state PM size measurements were made at scan rates of 90 seconds. Comparative testing with a nebulizer between the WVU and UMN SMPS units confirmed agreement between the two units. Also, by measuring background concentration simultaneously, the SMPS units of WVU and DRI were found to be in agreement. Raw exhaust CO_2 levels were also measured during the testing period. Results showed GMD values of 54-58 nm with peak concentrations in the range of 10^6 – 10^7 particles/cc. When distributions from four positions in the plume were corrected for concentration with respect to dilution ratios, they were found to be similar. This suggested that no appreciable evolution of size distribution occurred in the plume. Subtraction of background PM distributions from the plume distributions provided only negligible correction.

The test vehicle was also operated through repeated transient tests, from 65 to 88 km/hr, with a wind speed of 75 km/hr (47 mph). During transient operation, three to five single particle sizes were tracked as the vehicle was operated through a series of accelerations. Increased PM production during the accelerations was evident, and close to the stack on the plume centerline the number count of 65 nm particles dominated the counts of 25, 100 and 300 nm particles throughout the transient operation. Near the edge of the plume close to the stack 65 nm particles were also most prolific. Measurements on the plume centerline at 200 and 337 inches behind the stack confirmed that 65 nm particles were highest in count, and were one to two orders of magnitude higher in count than 12 nm particles. In two of the cases only 12 nm, 25nm and 300 nm particles were measured, so no conclusion can be drawn regarding the 65 nm particles concentrations.

Background PM size distributions were dominated by accumulation mode particles, although the nuclei mode, at low concentrations, was detected early in the test day prior to starting the engine.

Under idle operation a nuclei mode was found, with GMD varying from 14 to 24 nm. It is likely that at the lower exhaust stack temperatures under idling conditions, nuclei mode particles may have formed and matured considerably in the exhaust stack itself. The nuclei mode particles persisted and were detected in the background after several passes through the tunnel. The presence of nuclei mode particles during idle operation leads one to believe that lubricating oil control and in-cylinder temperatures play a major role in nano-particle formation. The in-cylinder condition and its effect on the effectiveness of oil control ring may lead to presence of higher levels of products of partial combustion of lubricating oil in the exhaust, and the subsequent nano-particle formation.

In summary, during the Langley tunnel research no appreciable count of nuclei mode particles was detected

during both steady state and transient operation. However, consistent with WVU's findings in other studies, the Langley tunnel study revealed a very distinct nuclei mode during idle operation. We believe that the nuclei mode particle formation in diesel engine exhaust is strongly dependent upon, lubricating oil formulation and control, dilution conditions, including the type of dilution system that is employed.

RECOMMENDATIONS

Though the background particle concentration were observed in this study were typical of urban area, it was seen the high backgrounds did not have any significant effect on the particle size distributions. Similar experiments could be conducted in a single pass wind tunnel where this study will offer an opportunity to observe the effect of background particles on evolution of particle size distribution if any. The background particle concentration could be contaminated by operating other vehicles or generating aerosol at the inlet of tunnel to study the effect of various sources of background particles on particle size distributions in the diesel exhaust plume.

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