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REAL-WORLD PARTICULATE EMISSIONS FROM A 2010 COMPLIANT HD DIESEL TRUCK TRAVELING ACROSS THE CONTINENTAL UNITED STATES.

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Extended Summary

Engine manufacturers across the US and Europe introduced advanced aftertreatment systems, most commonly comprising Diesel Particle Filters (DPF) and Selective Catalytic Reduction (SCR) systems in order to comply with latest heavy-duty (HD) on-road emissions legislations. With exception of the upcoming Euro VI regulation (2014), current standards do not include limitations for nanosized particle emissions which have been identified by the health science community to increase both morbidity as well as mortality in humans and putting especially the population living in close proximity to major road ways and in densely populated urban areas at elevated risk. Indeed, researchers [1, 2 and 3] reported an increase in nanoparticles from catalyzed DPF's for exhaust temperatures above 380°C even for engines operating on Ultra Low Sulfur Diesel (ULSD) fuel. It has been suggested that these are sulfuric acid-based particles formed as a result of sulfur oxidation (mainly originating from lube oil) over the catalytic surface of DPFs at high temperatures. Furthermore, the introduction of SCR systems augmented the possibility of formation of new particles caused by the ammonia based Diesel Exhaust Fluid (DEF) injection [4].

This work is aimed at gaining insight into real-world particle matter (PM) emissions including both, gravimetric and number specific aspects, from a 2010 compliant heavy-duty Diesel (HDD) tractor equipped with advanced aftertreatment technology. Acquired data allows for, however is not limited to, i) comparison of in-use PM emissions with engine dynamometer based US EPA 2010 emissions certification standards, ii) quantification of PM mass emitted during Not-to-Exceed (NTE) events, and iii) calculation of particle concentrations with regard to the particle number (PN) limit as will be introduced by the EURO VI legislation in 2014. Specifically, a Mack® heavy-duty Diesel Class-8 tractor equipped with a model year (MY) 2011, 12.8liter (MP8-445C) engine, a diesel oxidation catalyst (DOC), a state of the art catalyzed DPF, and liquid urea based SCR aftertreatment system (see Table 1) was under investigation while traveling across the continental US. The tractor was coupled to a flatbed trailer loaded with WVU's Transportable Emissions Measurement System (TEMS) that houses a full-flow CVS tunnel and a multitude of analytical instruments for gaseous and PM emissions characterization, amounting to a gross vehicular weight (GVW) of 66,740lbs.

The driving conditions ranged from the smooth hills of the Appalachian Mountains, the flat steppes of the mid-west, the Rocky Mountains all the way to the busy highways of the greater Los Angeles metropolitan area, resulting in a multitude of operating conditions induced to the aftertreatment system. The total trip distance between Morgantown, WV and Riverside, CA, as shown on the map in Figure 1, was 2450 miles, resulting in a six days journey. Furthermore, the route provided with a range of environmental conditions, including temperature variations from 3 to 36°C (37 to 97°F), relative humidity variations from 12 to 78% as well as changes in ambient pressure between 65.5 to 100.5kPa. Figure 2 depicts the elevation profile of the route as a function of driving distance. The overall net change in elevation between Morgantown and Riverside is only -57ft (final destination lower than start Morgantown), with the highest encountered elevation being ~11,990ft during the Loveland Pass, CO crossing. Note that the elevation profile shows driving from right to left, same as for the map in Figure 1.

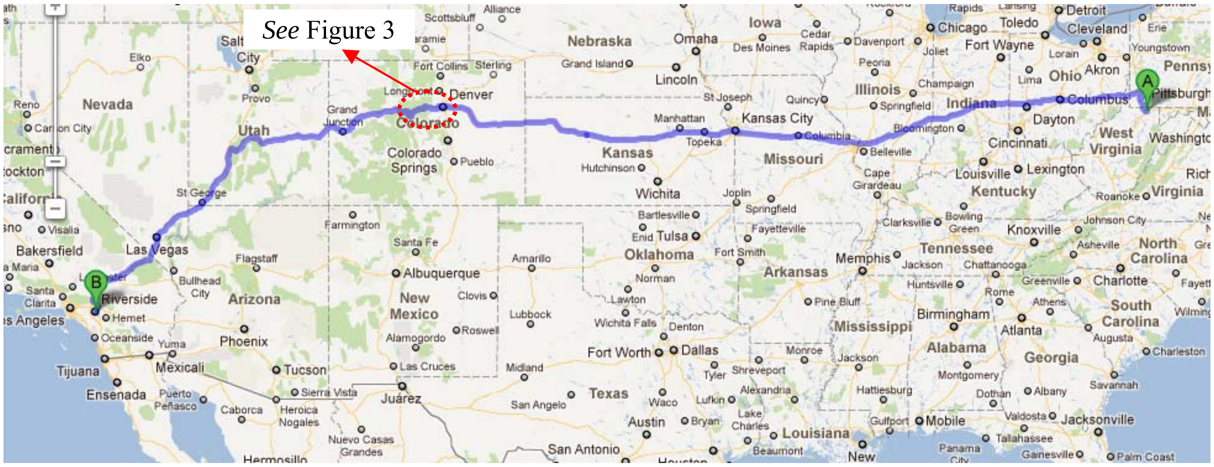

Figure 1: Driving route between Morgantown, WV and Riverside, CA (Google maps)

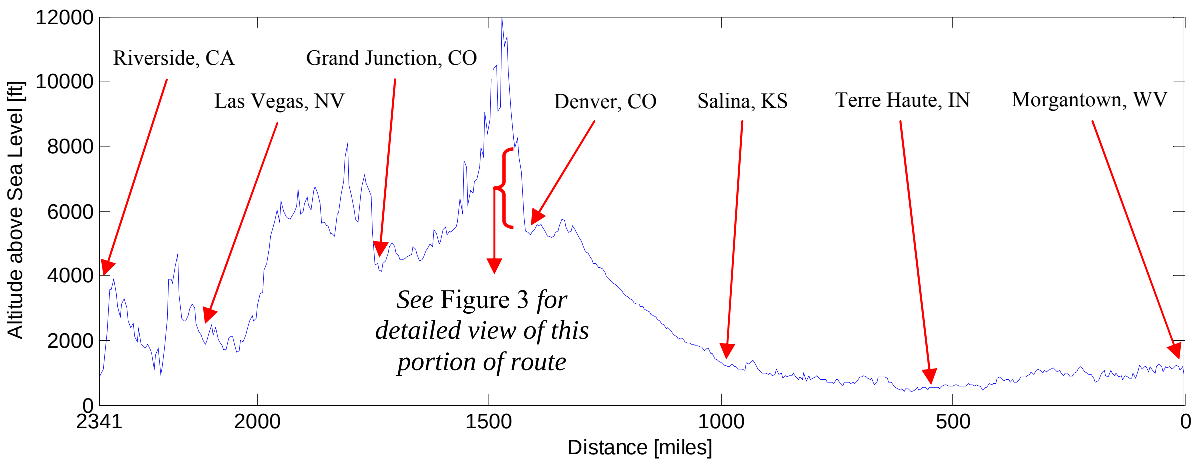

Figure 2: Elevation profile between Morgantown, WV and Riverside, CA

Particulate matter sampling and characterization was performed within the raw and diluted exhaust gas streams. For the purpose of diluted measurements, the exhaust stream was ducted from the vehicle's exhaust stack into the full-flow CVS tunnel of the TEMS which was commissioned and operated according to recommendations outlined in 40 CFR 1065. PM was sampled onto 47mm PTFE-coated glass fiber filters (TX-40, Pall Corp.) using a secondary dilution system, for subsequent gravimetric analysis. Particle number concentrations and size distributions were measured directly from the CVS tunnel using an Exhaust Emissions Particle Sizer (EEPS™) spectrometer from TSI Inc. (model 3090), operating at 10Hz.

Additionally, a slipstream was extracted directly from the truck's exhaust stack in order to quantify gravimetric Not-to-Exceed zone PM emissions using Horiba's portable Transient PM Emissions Measurement System (OBS-TRPM). The OBS-TRPM is a combination of a proportional dilute sampling system for gravimetric PM sampling on 47mm filter media (TX-40, Pall Corp.) and real-time measurements of particle length [mm/cm^3] (including soot, sulfates and volatile particles), which can be defined as the product of total number concentration and average particle diameter, by means of a diffusion charging type sensor called Electrical Aerosol Detector (EAD) from TSI Inc. The underlying assumption is that the mass accumulated on the filter is proportional to the PM length parameter as measured by the EAD, therefore, making the OBS-TRPM ultimately capable of calculating a quasi "real-time" PM mass concentration rate.

To assess real-time particle numbers and mass from the raw exhaust an in-line particle sensor from Pegasor Ltd., Finland, (Pegasor Particle Sensor, model PPS-M) was installed within the exhaust stack downstream the aftertreatment systems. The sensor detects particles based on the escaping current principle at a sample rate of 10Hz and is designed as a flow through device. The sensors output can be subsequently correlated to other aerosol instruments by means of simple linear regression in order to measure the concentration of the mass, surface or number of the exhaust particles, depending on the chosen reference instrument.

Results show a predominant mono-modal particle distribution with a count mode diameter (CMD) in the range of 6.04-15nm and a stable peak number count on the order of 2 x 10^8 [particles/cm^3] during periods where exhaust gas temperatures exceed ~340°C as can be seen from Figure 3. Note that the number concentration displayed on the z-axis (*dN/dlog(Dp)*) in Figure 3 is not corrected for dilution ratio of the CVS tunnel. Figure 4 depicts a normalized exhaust gas temperature histogram for the DPF inlet location from continuous data of the entire route. It can be seen that the temperature of the exhaust stream entering the DPF is exceeding 350°C for ~45% and is between 350-400°C for ~36% of the entire test route, respectively, indicating a favorable temperature range for possible nanoparticle formation over the catalyzed DPF via possible sulfur oxidation [2, 3].

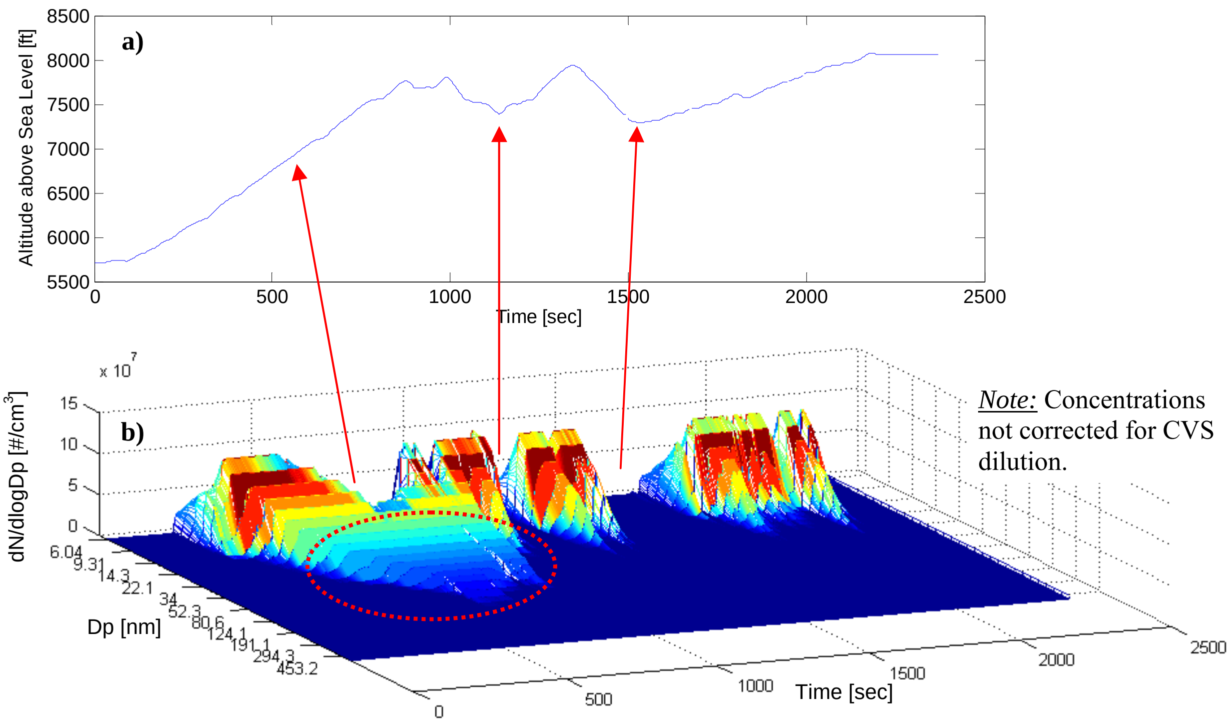

Figure 3: a) Elevation profile for 30min highway section after Denver, CO climbing I-70 into Rocky Mountains (see), b) corresponding particle number and size distribution as measured by EEPS™, data not corrected for CVS dilution, red circle indicating DPF regeneration event.

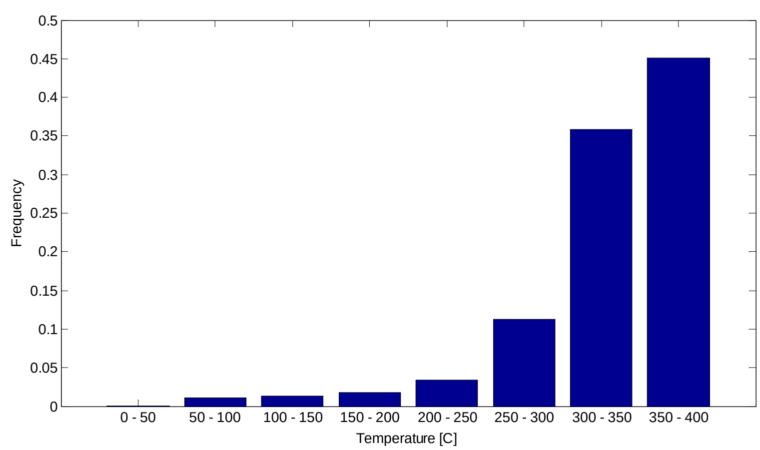

Figure 4: Normalized exhaust gas temperature histogram for DPF inlet location, data from entire route between Morgantown, WV and Riverside, CA

Increased particle number concentrations with a CMD in the size range of 30-40nm were observed periodically during the trip as indicated by a red circle in Figure 3. These events coincided with an increase in in-line particle sensor (PPS) signal along with a reduction in relative DPF soot load, a parameter publicly broadcasted by the engine control unit (ECU) and indicating the percentage of soot loading within the DPF relative to the maximum allowable soot loading value as defined by the engine manufacturer. Based on these data, it was concluded that the increased particle concentrations were indicative of DPF regeneration events.

Finally, Figure 5 depicts distance-specific PM mass emissions in [g/mi] for selected sections along the test route. The PM mass values presented in Figure 5 were not corrected for CVS background PM values which was judged valid since a "clean" CVS tunnel (no prior PM deposition that could re-entrain during the test) was utilized and the dilution air was being filtered by high-efficiency particulate air (HEPA) filters with a minimum collection efficiency of 99.97% prior to entering the CVS. It can be seen from Figure 5 that on average the distance specific PM mass emissions remained below 0.05 g/mi. Test sections with increased PM mass values as seen for test IDs C0035-002-64, 72, and 73 correspond to test portions where increased particle number concentrations in the 30-40nm (CMD) range and in-line particle sensor signals were measured with the EEPS™ and PPS instruments, respectively. Hence, the increased PM mass emissions are attributed to DPF regeneration events that oxidize parts of the soot cake layer on the filter walls and thus, temporarily reduce the filtration efficiency of the DPF.

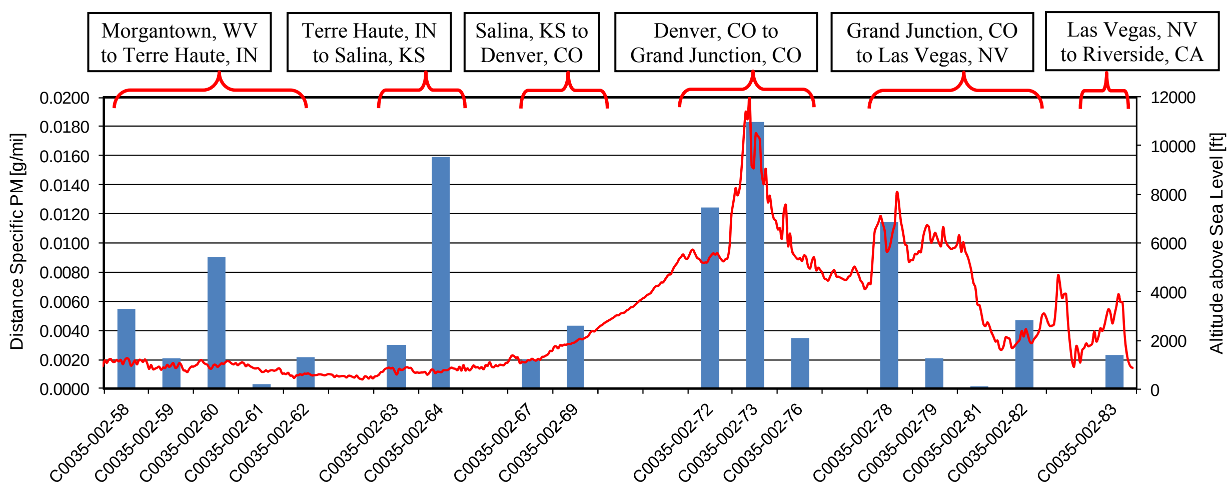

Figure 5: Distance specific gravimetric PM emissions in [g/mi] for different portions of the route

<u>Outlook</u>

Data reduction and analysis efforts are currently on-going and will focus on, but are not limited to following areas of interest:

- Calculation of NTE PM rates using the Horiba TRPM system and comparison of results to an alternative NTE PM mass calculation method based on the in-line particle sensor (PPS) signal.
- Calculation of total particle number concentration per mile driven, using the EEPS™ and investigate the possible influence of aftertreatment temperature, vehicle speed, elevation, and road grade on particle number emissions and DPF filtration efficiencies.
- Evaluate the durability and applicability of the in-line, real-time particle sensor (PPS) with regard to its possible application in the On-Board Diagnostics (OBD) environment.

Table 1: Test vehicle and engine specifications

Chassis Manufacturer / Model	Mack Trucks Inc. / CXU613
Class	8
Vehicle Model Year (MY)	2011
Aftertreatment System	DOC / DPF / urea-SCR
Fuel	Standard ULSD (<15ppm)
Emission Family	BVPTH12.8S01
Curb Weight [lbs]	15’000
Gross Vehicle Weight (GVW) [lbs]	66’740
Engine Manufacturer	Mack Trucks Inc.
Engine Model	MP8-445C
Engine Model Year	2011
Displacement [L]	12.8
Configuration / # of Cylinders	In-line / 6 cylinder
Rated Power [hp]	445 @ 1500rpm
NOx [g/bhp-hr]	0.2*
PM [g/bhp-hr]	0.01*

**Engine complies with 2010 EPA HD emission standards (NOx: 0.2 g/bhp-hr, PM: 0.01 g/bhp-hr)*

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[1] Kittelson, D. B., Watts, W. F., Johnson, J. P., Thorne, C., Higham, C., Payne, M., Goodier, S., Warrens, C., Preston, H., Zink, U., Pickles, D.; Goersamnn, C., Twigg, M. V., Walker, A. P., Boddy, R., “Effect of fuel and lube oil sulfur on the performance of a diesel exhaust gas regenerating trap,” Environ. Sci. Technol., Vol. 42, pp. 9276−9282, (2008).

[2] Thiruvengadam, A., Besch, M.C., Carder, D.K., Oshinuga, A., and Gautam, M., “Influence of Real-World Engine Load Conditions on Nanoparticle Emissions from a DPF and SCR Equipped Heavy-Duty Diesel Engine,” Environ. Sci. Technol., Vol. 46 (3), pp. 1907-1913, (2012).

[3] Vaaraslahti, K., Keskinen, J., Giechaskiel, B., Solla, A., Murtonen, T., and Vesala, H., “Effect of Lubricant on the Formation of Heavy-Duty Diesel Exhaust Nanoparticles,” Environ. Sci. Technol., Vol. 39, pp. 8497-8504, (2005).

[4] Ardanese, R., Ardanese, M., Besch, M.C., Adams, T.R., Thiruvengadam, A., Shade, B.C., Gautam, M., Miyasato, M., and Oshinuga, A., “PM Concentration and Size Distributions from Heavy-Duty Diesel Engine Programmed with Different Engine-Out Calibrations to Meet the 2010 Emission Limits,” SAE Technical Paper No. 2009-01-1183, (2009).

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CAFEE

Center for Alternative Fuels, Engines and Emissions

Introduction

Engine manufacturers across the US and Europe introduced advanced aftertreatment systems, most commonly comprising Diesel Particle Filters (DPF) and Selective Catalytic Reduction (SCR) systems in order to comply with latest heavy-duty (HD) on-road emissions legislations. With exception of the upcoming Euro VI regulation (2014), current standards do not include limitations for nanosized particle emissions which have been identified by the health science community to increase both morbidity as well as mortality in humans and putting especially the population living in close proximity to major road ways and in densely populated urban areas at elevated risk. Indeed, researchers [1, 2 and 3] reported an increase in nanoparticles from catalyzed DPF's for exhaust temperatures above 380°C even for engines operating on Ultra Low Sulfur Diesel (ULSD) fuel. It has been suggested that these are sulfur derived particles formed as a result of sulfur oxidation (mainly originating from lube oil) over the catalytic surface of DPFs at high temperatures. Furthermore, the introduction of SCR systems augmented the possibility of formation of new particles caused by the ammonia based Diesel Exhaust Fluid (DEF) injection [4].

Objective

This work is aimed at gaining insight into real-world particle matter (PM) emissions including both, gravimetric and number specific aspects, from a 2010 compliant heavy-duty Diesel (HDD) tractor equipped with advanced aftertreatment technology. Specifically, the acquired data allows for:

i) **comparison of in-use PM emissions with engine dynamometer based US EPA 2010 emissions certification standards,**

ii) **quantification of PM mass emitted during Not-to-Exceed (NTE) events,** and

iii) **calculation of particle concentrations with regard to the particle number (PN) limit** as will be introduced by the EURO VI legislation in 2014.

Vehicle Technology and Test Route

A Mack® heavy-duty Diesel Class-8 tractor equipped with a model year (MY) 2011, 12.8liter (MP8-445C) engine, a diesel oxidation catalyst (DOC), a state of the art catalyzed DPF, and liquid urea based SCR aftertreatment system (see Table below) was under investigation while traveling across the continental US. The tractor was coupled to a flatbed trailer loaded with WVU's Transportable Emissions Measurement System (TEMS) that houses a full-flow CVS tunnel and a multitude of analytical instruments for gaseous and PM emissions characterization, amounting to a gross vehicular weight (GVW) of 66,740lbs.

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Vehicle Specifications

Chassis Manufacturer / Model	Mack Trucks Inc. / CXU613
VIN	1M1AW07Y1CM017126
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Vehicle Model Year (MY)	2011
Aftertreatment System	DOC / DPF / urea-SCR
Fuel	Standard ULSD (<15ppm)
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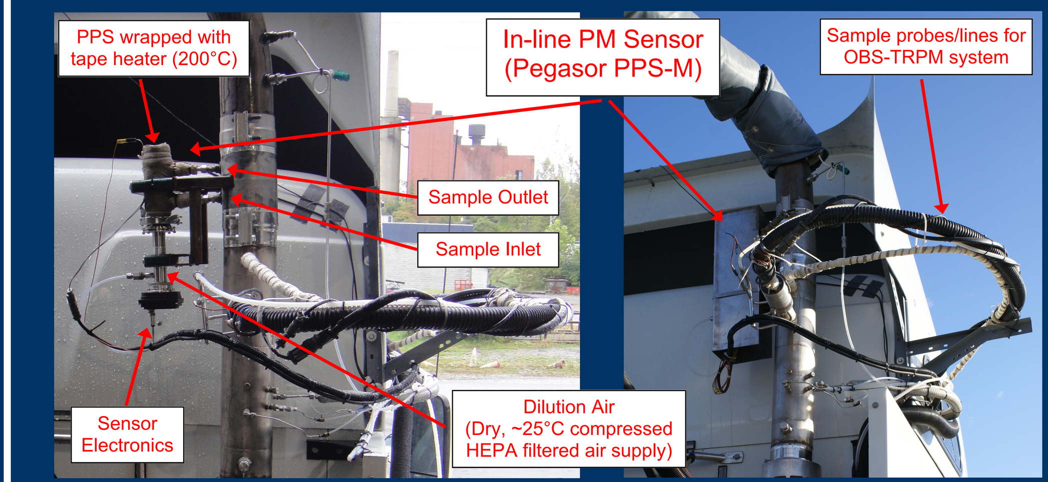
Rated Power [hp]	445 @ 1500rpm
NOx [g/bhp-hr]	0.2*
PM [g/bhp-hr]	0.01*

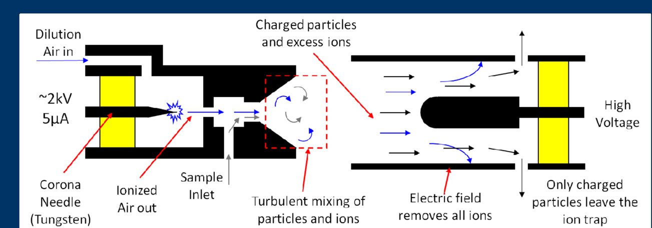
Scientific Approach

Particulate matter sampling and characterization was performed within the raw and diluted exhaust gas streams.

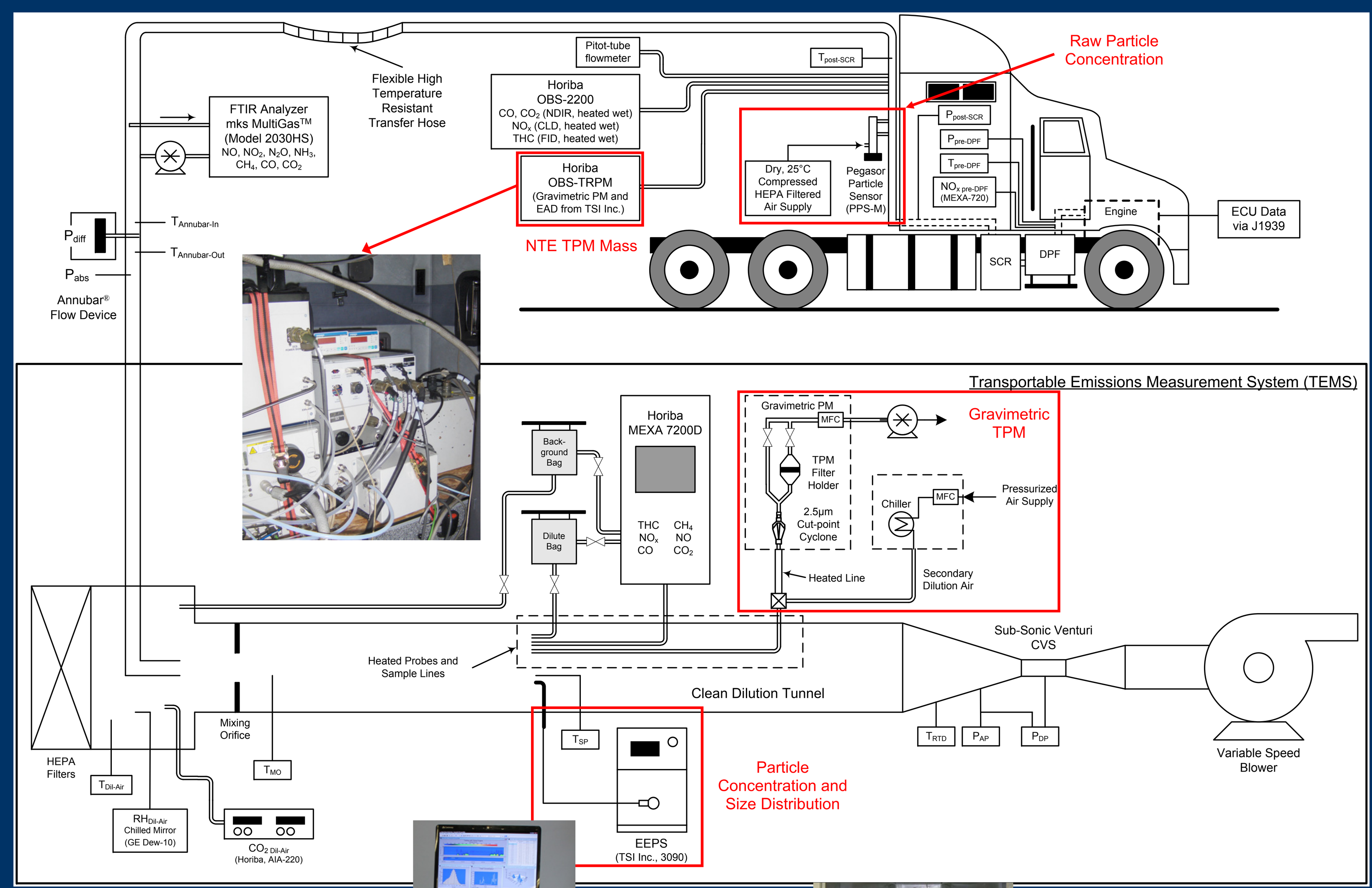
- **Diluted Exhaust Measurements (full-flow CVS tunnel):**
  - PM sampled onto 47mm PTFE-coated glass fiber filters (TX-40, Pall Corp.) using a secondary dilution system, for subsequent gravimetric analysis.
  - Particle number concentrations and size distributions measured directly from the CVS tunnel using an Exhaust Emissions Particle Sizer (EEPS™) spectrometer from TSI Inc. (model 3090), operating at 10Hz.
- **Partially Diluted Exhaust Measurements:**
  Slipstream extracted from raw exhaust to quantify gravimetric Not-to-Exceed (NTE) zone PM emissions using Horiba's portable Transient PM Emissions Measurement System (OBS-TRPM). The OBS-TRPM is a combination of a proportional dilute sampling system for gravimetric PM sampling on 47mm filter media (TX-40, Pall Corp.) and real-time measurements of particle length [mm/cm^3] (including soot, sulfates and volatile particles), which can be defined as the product of total number concentration and average particle diameter, by means of a diffusion charging type sensor called Electrical Aerosol Detector (EAD) from TSI Inc.
- **Raw Exhaust Measurements:**
  Measurement of real-time particle numbers and mass from the raw exhaust using an in-line particle sensor from Pegasor Ltd., Finland, (Pegasor Particle Sensor, model PPS-M) The sensor detects particles based on the escaping current principle at a sample rate of 10Hz and is designed as a flow through device. The sensors shows a proportional response to particle surface area concentration and can be subsequently correlated to other aerosol instruments by means of simple linear regression in order to measure concentration of particle mass or numbers.



Pegasor Operating Principle:



Picture provided by Pegasor Ltd.



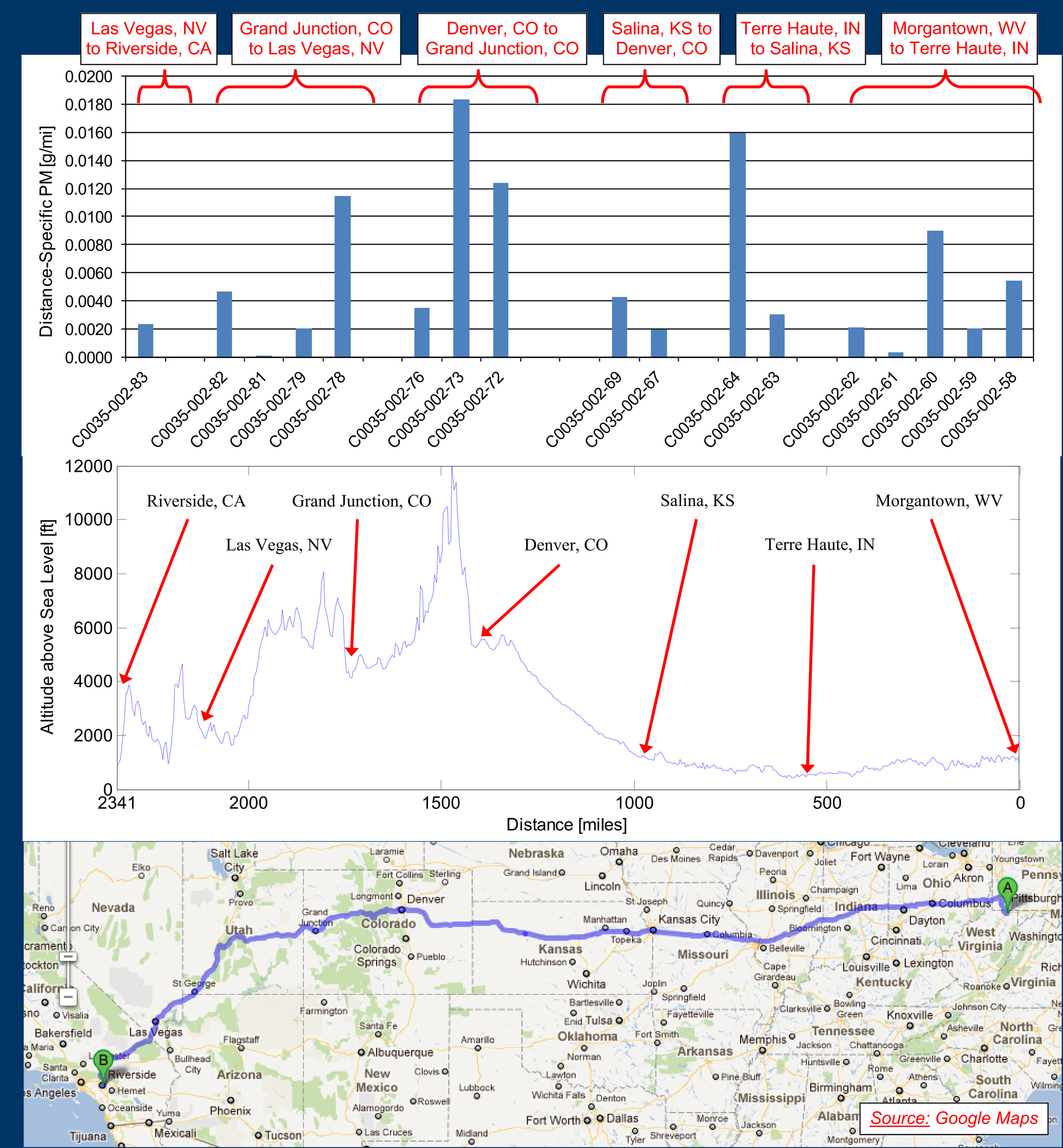
EEPS (Model 3090, TSI Inc.)

- Engine Exhaust Particle Sizer® (EEPS) Spectrometer
- Diluted exhaust measurement from CVS sampling plane
- Average dilution ratio (DR): ≈ 10
- Dilution air temperature and humidity varying depending on location

Gravimetric TPM

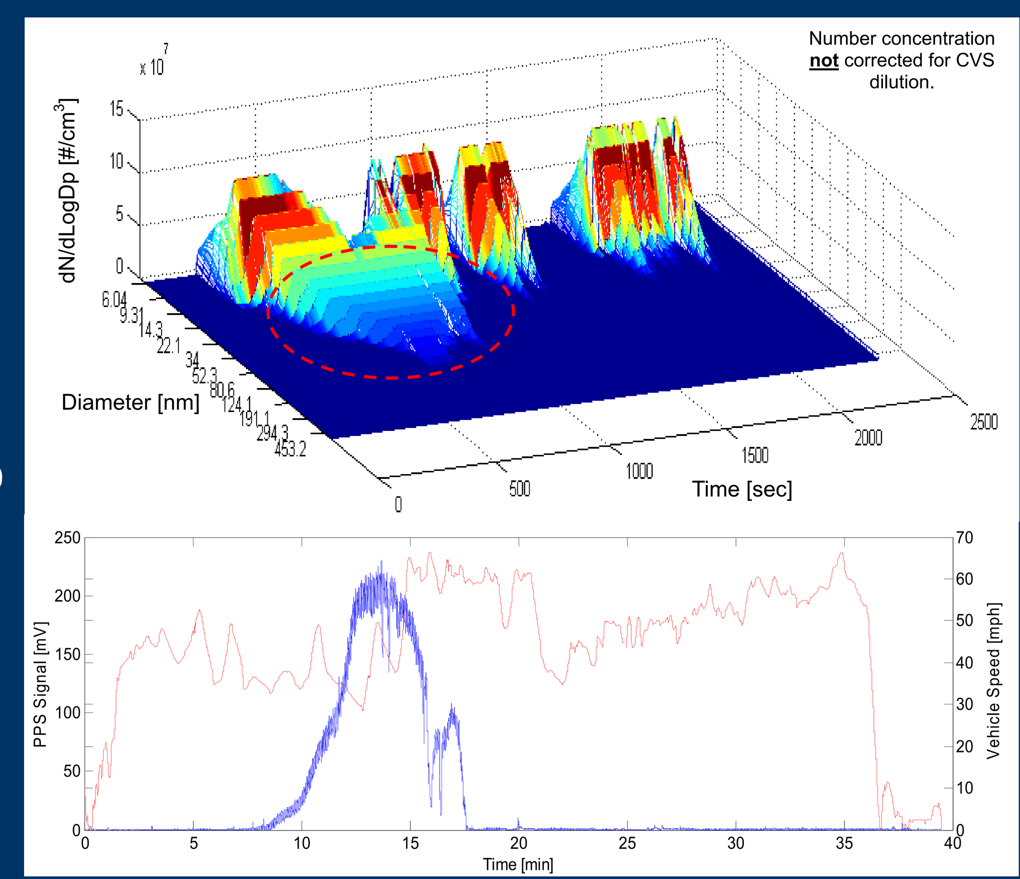
- According to 40 CFR, 1065
- 47 mm TX40 filter media
- Total flow across filter: 2.3scfm
- Secondary dilution flow: 1.1scfm

Results and Discussion



- Distance-specific PM mass emissions in [g/mi] for selected sections along the test route.
- Values are not corrected for CVS background PM since HEPA filtered dilution air was utilized.
- On average the distance specific PM mass emissions remained below 0.05 g/mi.
- Test sections with increased PM mass (e.g. *C0035-002-64*, *72*, and *73*) correspond to test portions where increased particle number concentrations in the 30-40nm (CMD) range and in-line particle sensor signals were measured with the EEPS™ and PPS instruments, respectively. Hence, the increased PM mass emissions were attributed to DPF regeneration events.
- Active DPF regeneration (addition of HC via 7th injector) occurred during test section *C0035-002-64.*
- Note that PM mass graph and elevation graph show driving from right to left, thus corresponding to map.

- Results show a predominant monomodal particle distribution with a count mode diameter (CMD) in the range of 6.04-15nm and a stable peak number count on the order of 2x10^8 [#cm^3] during periods where exhaust gas temperatures exceed ~340°C.
- Exhaust temperature at DPF inlet is exceeding 350°C for ~45% and is between 350-400°C for ~36% of the entire test route.
- Increased particle number concentrations with a CMD in the size range of 30-40nm were observed periodically during the trip, as indicated by a red circle, coinciding with an increase in in-line particle sensor (PPS) signal of up to two orders of magnitude.
- Increased particle concentrations are considered to be good indicators of DPF regeneration events, leading to a temporary reduction in DPF filtration efficiency.



Project Outlook

Data reduction and analysis efforts are currently on-going and will focus on, but are not limited to following areas of interest:

- Calculation of NTE PM rates using the Horiba TRPM system and comparison of results to an alternative NTE PM mass calculation method based on the in-line particle sensor (PPS) signal.
- Calculation of total particle number concentration per mile driven, using the EEPS™ and investigate the possible influence of aftertreatment temperature, vehicle speed, elevation, and road grade on particle number emissions and DPF filtration efficiencies.
- Evaluate the durability and applicability of the in-line, real-time particle sensor (PPS) with regard to its possible application in the On-Board Diagnostics (OBD) environment.

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