On-Road Particle Matter Emissions from a MY2010 Compliant HD Diesel Vehicle Driving Across the US

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Background and Motivation

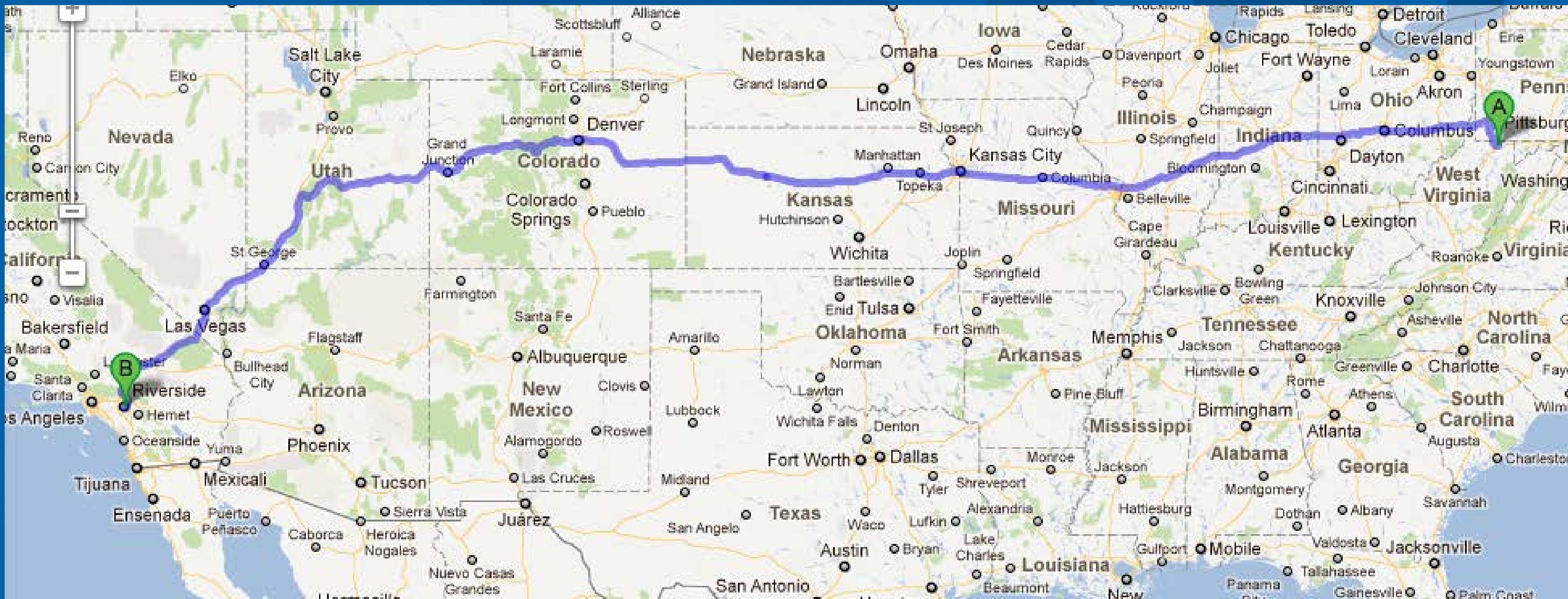
- In-use Emissions Compliance Measurements and On-Road Testing
  - Evaluation of PM emissions from a 2010 compliant heavy-duty Diesel tractor equipped with advanced aftertreatment technology, under real-world conditions
    - Comparison to US EPA 2010 emissions standards (engine dynamometer based)
    - Quantification of PM mass emitted during Not-to-Exceed (NTE) events => PM: 150% of the FTP emissions standard (g/bhp-hr) for the given model year
    - Particle concentration with regard to proposed Particulate Number (PN) limit for Euro VI legislation
  - Reported increase of nano-sized particles for catalyzed DPF's under high temperature conditions (~> 380°C) [1), 2)]
    - Possible sulfuric acid based particles formed as a result of sulfur oxidation (originating from lube oil) over the catalyst surfaces at high temperatures

- Evaluation of In-line, Real-time Particle Sensor
  - On-board Diagnostics (OBD) Applications
    - US EPA HD-OBD in effect by 2013 (all engine families)
    - EU Regulations for OBD effective by 2014
  - Establishing mass reference for aerosol in real-time

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. (2008), 42, 9276–9282.

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., (2011).

Methodology - Test Plan



- Morgantown, WV to Riverside, CA => Total distance: ~2450miles (3943km)
- Route: I-70W, I-15S, I-215S
- Journey Total Time: 6 days
- Highest Elevation: 11’990 ft (Loveland Pass, CO)
- Net Elevation Change: -57 ft (final destination lower than Morgantown, WV)
- Environmental Conditions: - Temperature range 37 to 97°F (3 to 36°C)
  - Relative humidity range 12 to 78%
  - Barometric pressure range 65.5 to 100.5kPa

Methodology - Test Vehicle

Test Vehicle Specifications:

Chassis Manufacturer / Model	Mack Trucks Inc. / CXU613
VIN	1M1AW07Y1CM017126
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

Test Engine Specifications:

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*

* Certification values

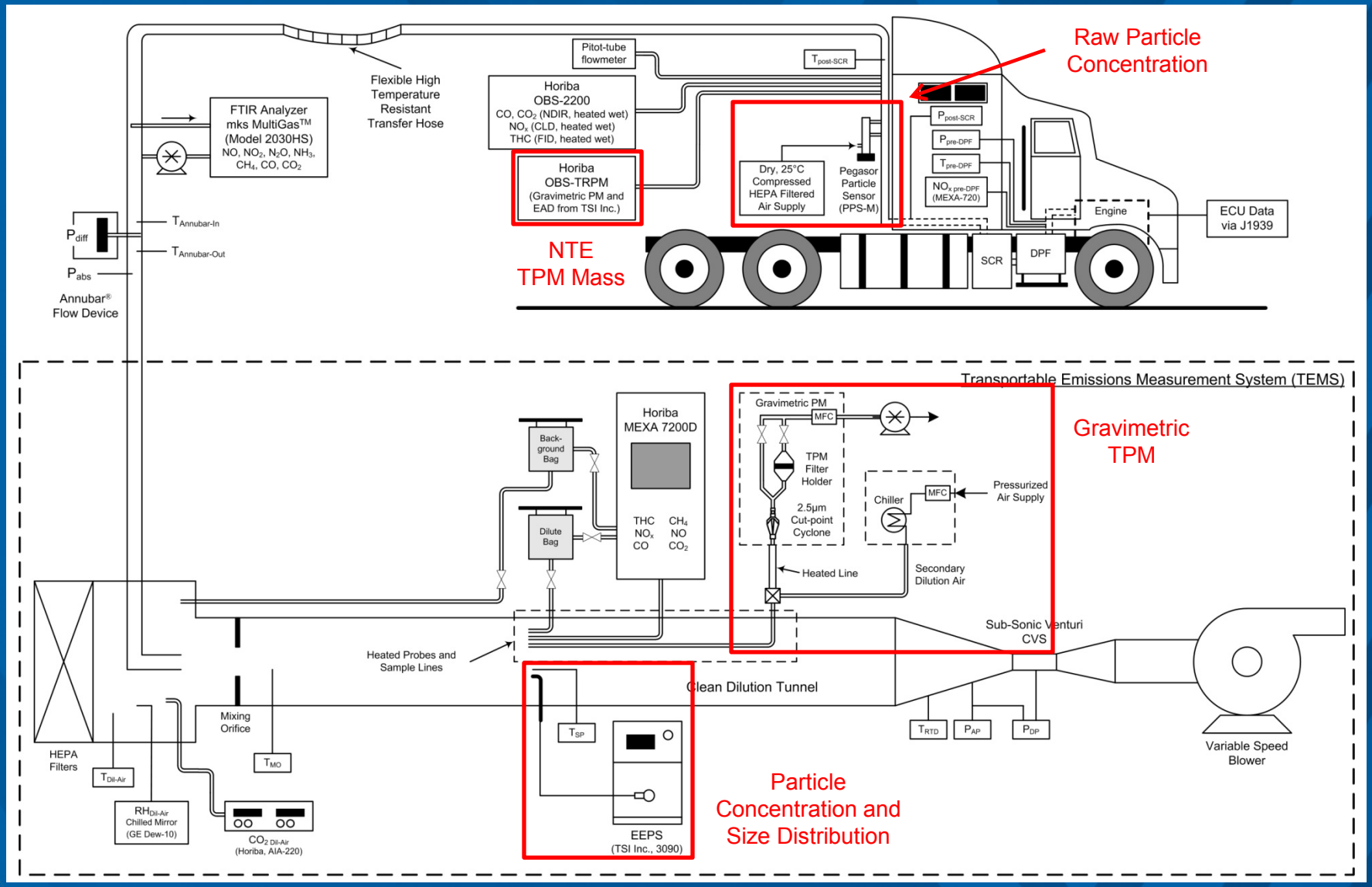
- Engine complies with 2010 EPA HD emission standards (NOx: 0.2 g/bhp-hr, PM: 0.01 g/bhp-hr)
- Vehicle equipped with DOC, DPF and urea based SCR system

Utah

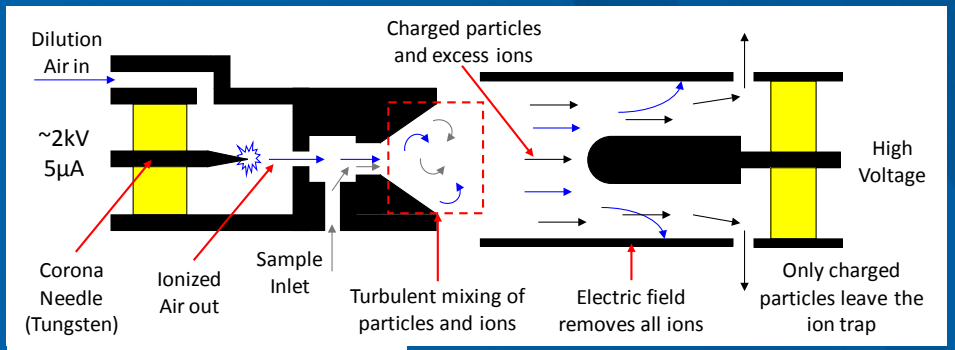
Terra Haute, IN

Rocky Mountains, CO

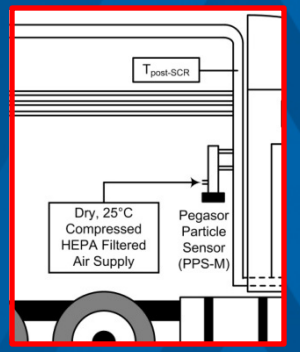
Laboratory and Measurement Setup



Setup - Real-Time Particle Sensor (PPS)



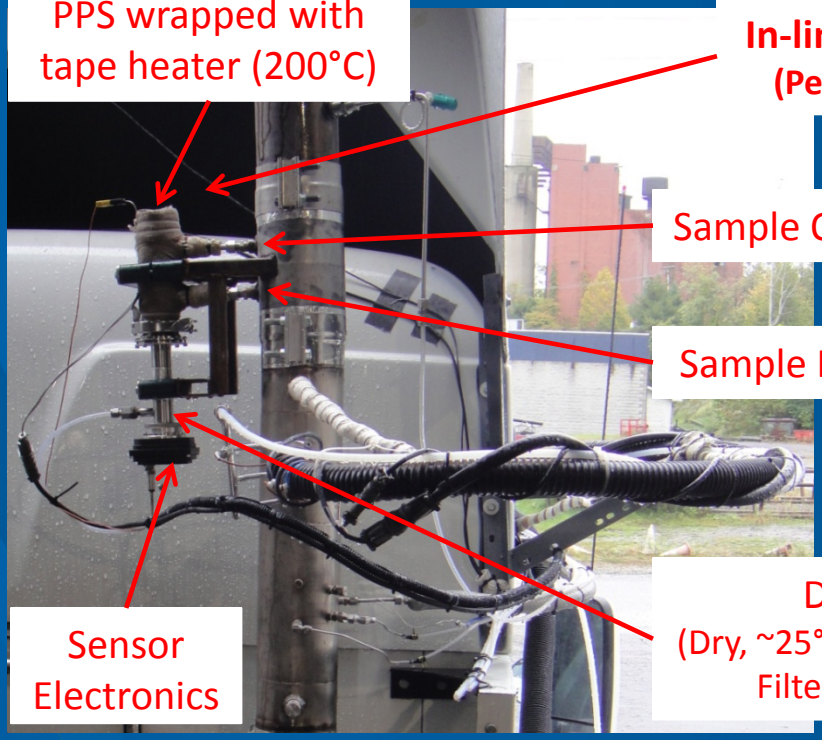
[Picture provided by Pegasor Oy]



- PM detection based on diffusion-charging and escaping current principle
- Constant dilution air pressure leading to constant sample inlet flow (const. dilution ratio)
- Flow through device
- Sensor shows proportional response to particle surface area concentration

PPS wrapped with tape heater (200°C)

In-line PM Sensor (Pegasor PPS-M)



Sample Outlet

Sample Inlet

Sensor Electronics

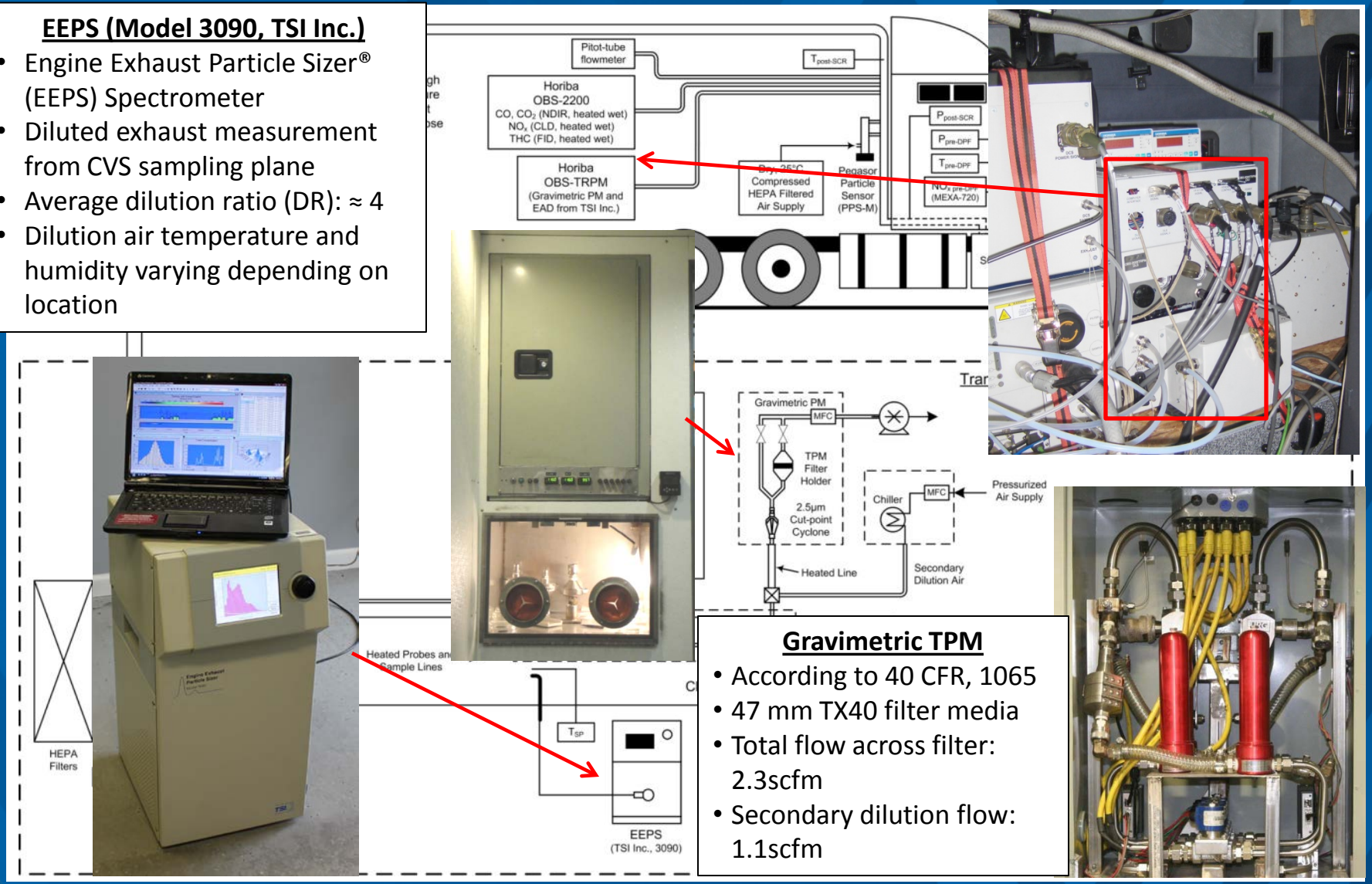
Dilution Air (Dry, ~25°C compressed HEPA Filtered Air Supply)

=> with weather protection cover

Setup - PM Measurement Instrumentation

EEPS (Model 3090, TSI Inc.)

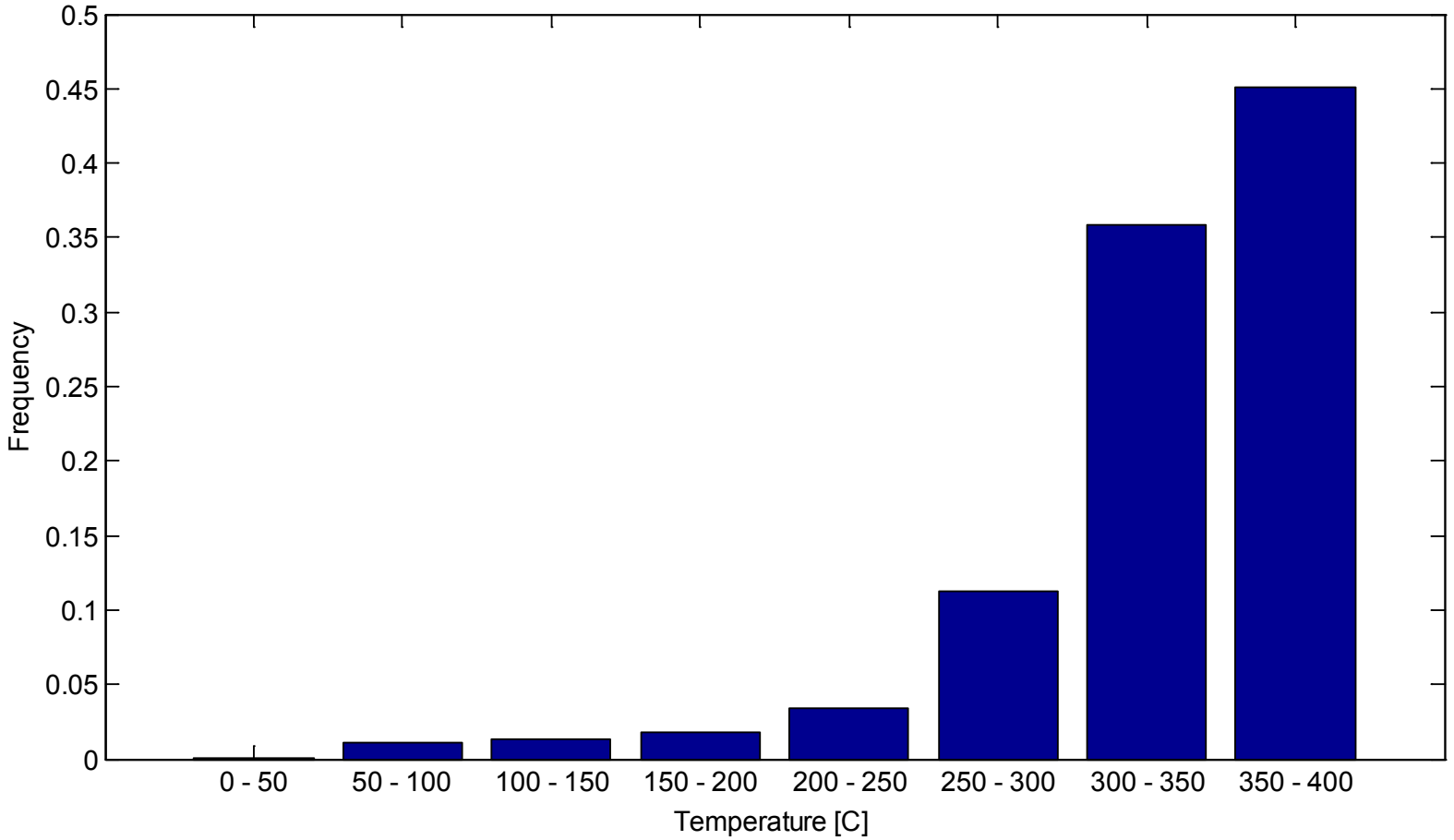
- Engine Exhaust Particle Sizer® (EEPS) Spectrometer
- Diluted exhaust measurement from CVS sampling plane
- Average dilution ratio (DR): ≈ 4
- Dilution air temperature and humidity varying depending on location



Gravimetric TPM

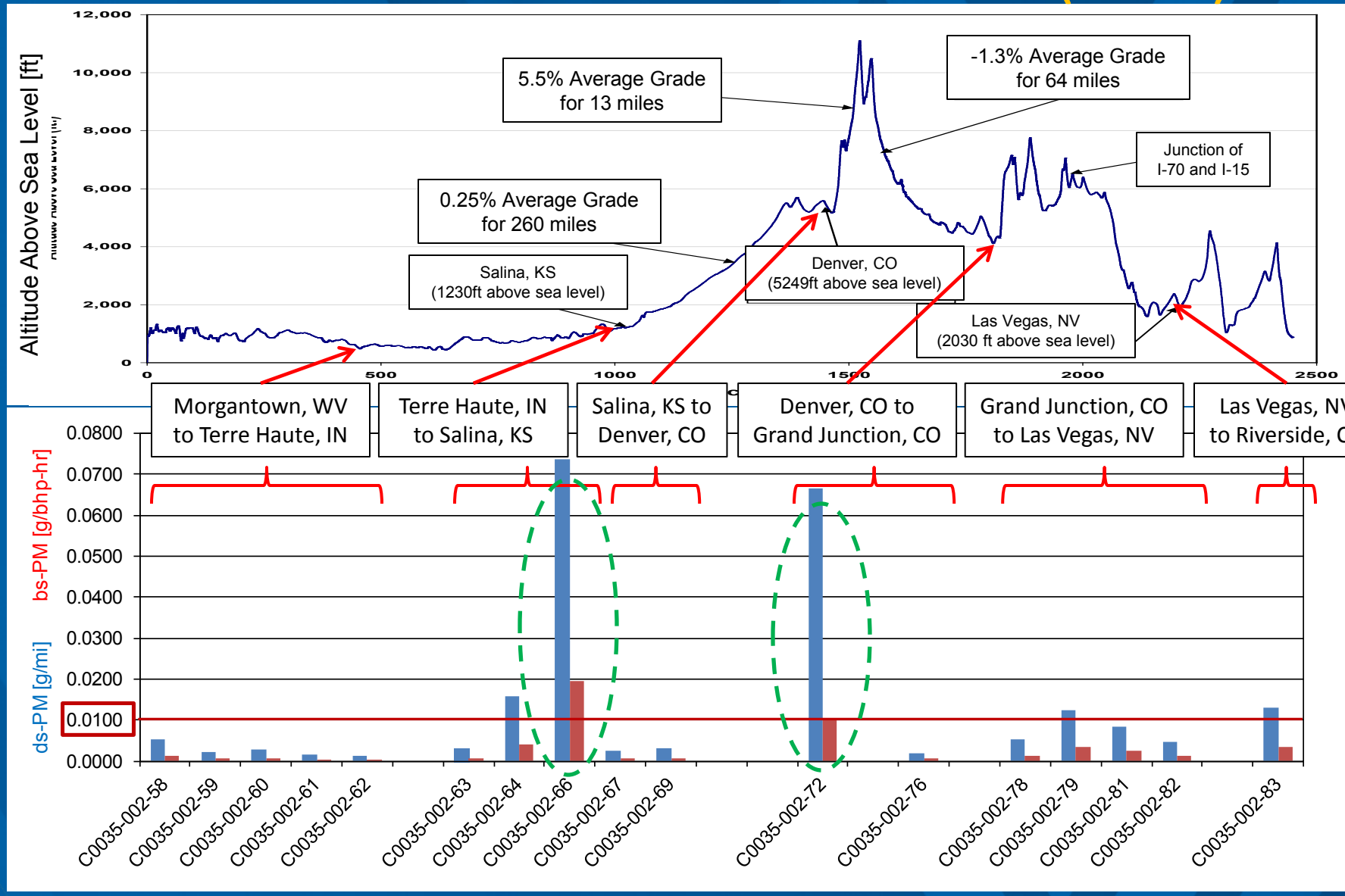
- According to 40 CFR, 1065
- 47 mm TX40 filter media
- Total flow across filter: 2.3scfm
- Secondary dilution flow: 1.1scfm

Results - Exhaust Temperatures (Post DPF)



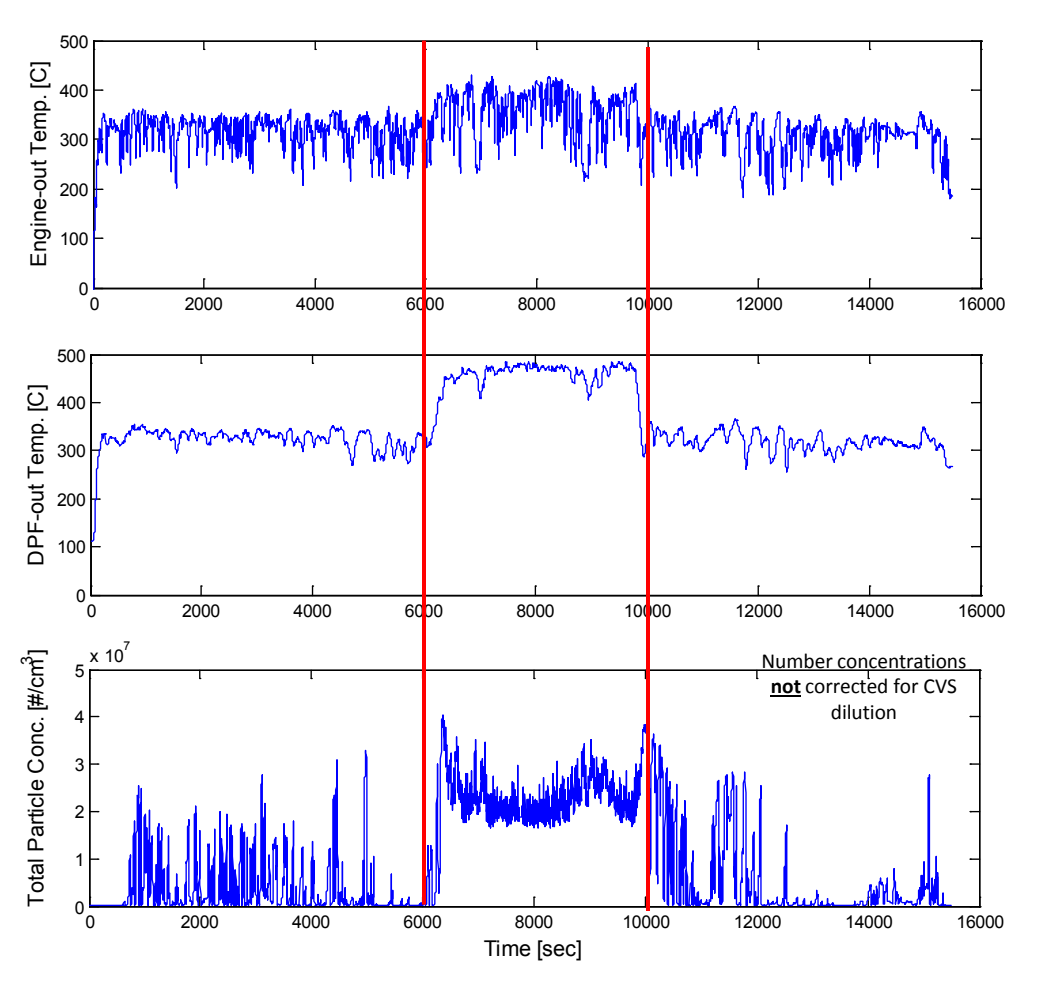
- Pre DPF (post DOC) exhaust temperatu
  (Morgantown, WV to Riverside, CA)

Results - Total Particle Matter (TPM)

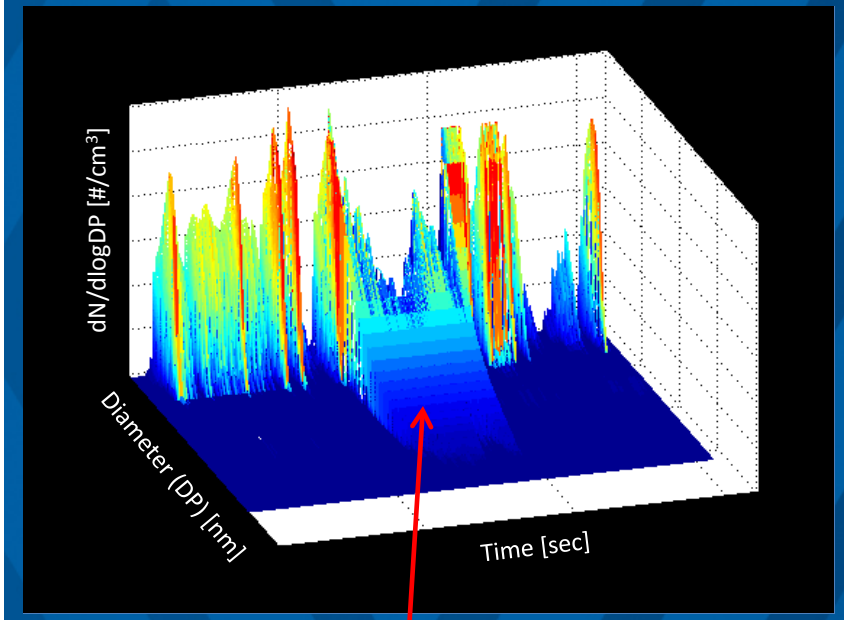


Results - DPF Regeneration Event

Data from test portion C0035-002-66:

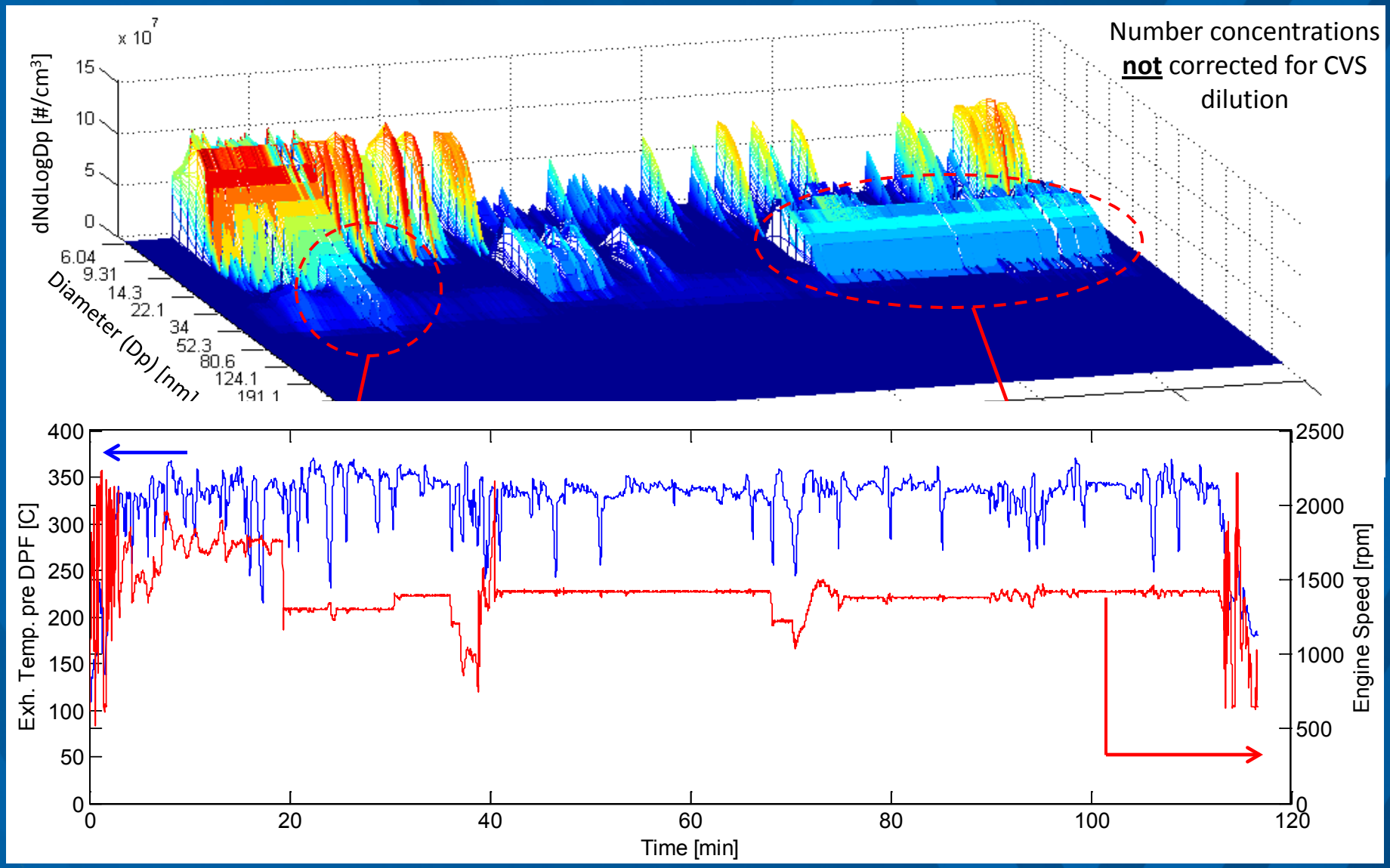


Number concentrations **not** corrected for CVS dilution

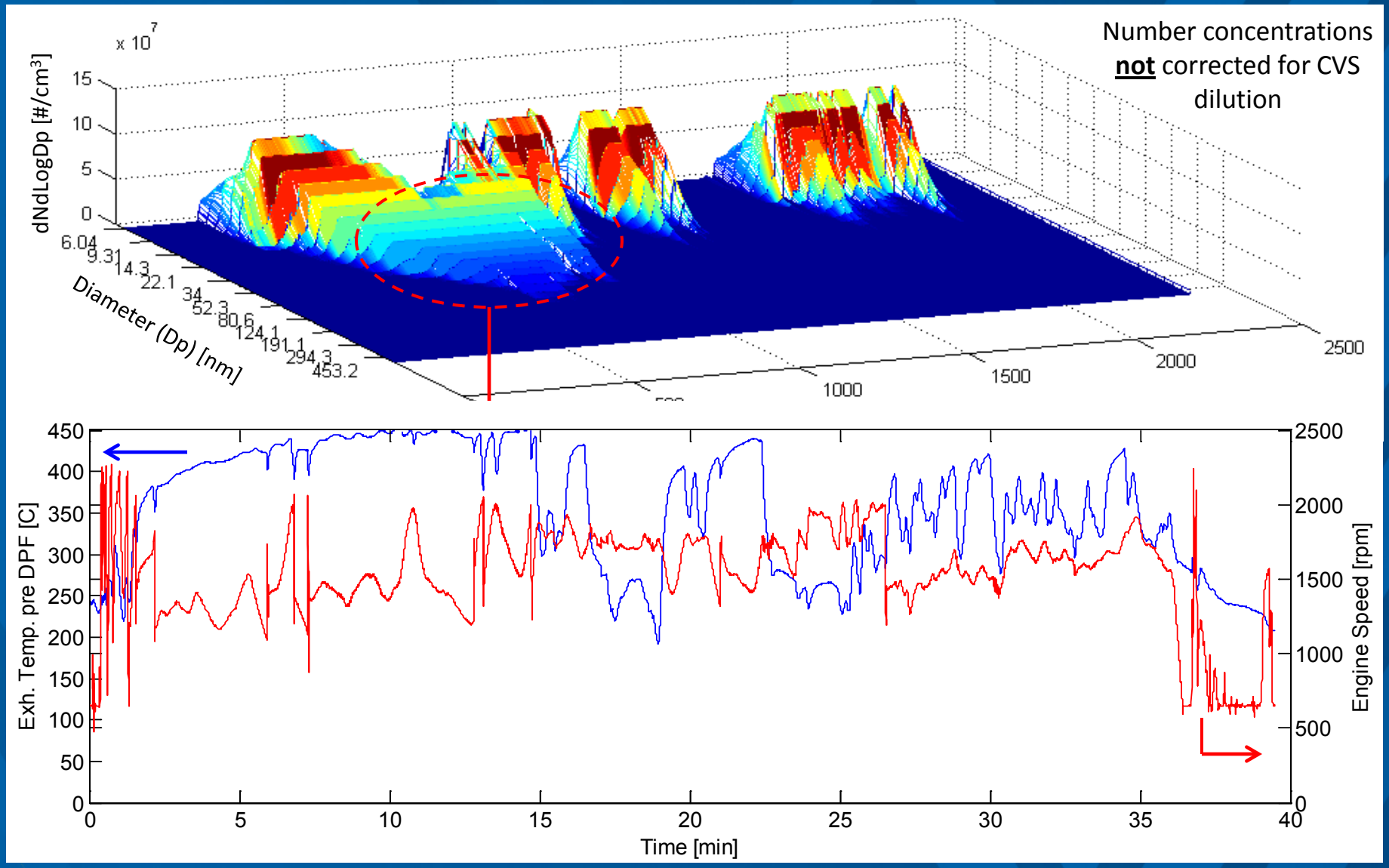


Particle distribution shifting to larger particle size

Results - Flat Highway, Midwest (I-70, MO, KS)



Results - Mountain Highway (I-70, CO)



Conclusions

- Measuring particle emissions from a 2010 compliant HD Diesel tractor while traveling on-road for 2300 miles between Morgantown, WV to Riverside, CA.
- Average gravimetric TPM over entire route was 0.0056 g/mile and 0.0015 g/bhp-hr => well below EPA 2010 PM standard (0.01g/bhp-hr)
- Increased TPM observed for portions that included DPF regeneration events (~0.0735g/mile or ~0.019g/bhp-hr).
- Increase particle concentration (up to three orders of magnitude) in raw exhaust during DPF regeneration events as measured by the PPS (up to 250mV vs. 0.2mV during regular operation).
- Nanoparticle concentration on the order of 2 x 10^8 [#/cm^3] (CMD ~5-15nm) as measured in diluted exhaust (not dilution corrected) under high exhaust/aftertreatment temperature (>~340°C) conditions.
- DPF inlet temperatures exceeding 350°C for ~45% and are between 350-400°C for ~36% of entire test route => indicating a favorable temperature range for possible nanoparticle formation over catalyzed DPF via possible sulfur oxidation

Thank You for Your Attention

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