Constant Volume Rapid Exhaust Dilution

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ABSTRACT

The conventional dilution tunnel system for motor vehicle particulate matter (PM) emissions measurement has a number of disadvantages that hamper its use for the testing and development of new "clean" engine / aftertreatment systems: These include 1) the variable delay between the time that emissions exit the tailpipe and the time that they are recorded in the dilution tunnel, 2) the potential interference from storage – release PM artifacts, 3) particle losses, both to the walls and by coagulation, and 4) the possibility of water condensation. These problems originate with the long transfer hose typically used to connect the vehicle tailpipe to the dilution tunnel. The variable delay arises from the changes in vehicle exhaust flows during transient testing, and the artifacts arise when hydrocarbon material and/or sulfuric acid that is trapped on the transfer hose walls during one test is released during subsequent tests.

One alternative is to measure PM concentration directly at the tailpipe. Unfortunately, to convert the concentration measurement into a PM emission rate (particle number or mass per kilometer), one then faces the task of simultaneously measuring, and time aligning, the vehicle exhaust flow rate and PM concentration. In this respect the constant volume sampling aspect of the dilution tunnel is an advantage; by maintaining a constant total flow rate, exhaust plus diluent, a separate measurement of the exhaust flow becomes unnecessary.

The constant volume rapid exhaust dilution (CVRED) system described here avoids the disadvantages of the conventional dilution tunnel, while retaining the advantage of constant volume sampling. This is accomplished by performing the dilution right at the tailpipe. The tailpipe is extended approximately 40 cm and is surrounded by a cylindrical air filter (which can be of HEPA quality). At the downstream end there is an orifice plate to enhance turbulent mixing into a 15.2 cm diameter dilution tunnel. Sampling is performed > 10 tunnel diameters downstream to assure thorough mixing of the exhaust and dilution air. The results of this system thus far appear promising. Nanoparticle artifacts have not been observed for gasoline vehicles. Both soot mode and nucleation mode particles are found from diesel vehicles, depending on speed, load, and fuel sulfur content The diesel PM emissions are consistent with wind tunnel measurements. The accompanying slides describe CVREDS and present test measurements of light duty gasoline and diesel vehicles.

EXPLANATION OF THE SLIDES

Slide 3: There is recognition of the fact that current PM measurement practices may not represent the best methods at the future PM emissions standards. Examples include the Particulates Project and the GRPE-PMP program. Any improvements must consider the entire PM sampling measurement process from the vehicle tailpipe to the measurement instrument.

Slide 4: Because the CVS system operates at a constant total flow of vehicle exhaust plus diluent, the time integrated PM concentration measurement times the total flow rate, and scaled by the distance traveled, directly yields the emission rate in mg/km (or #/mile, or other such combination). Unfortunately, the conventional use of a long (many meter) hose introduces a number of drawbacks including PM (or PM precursor) storage and a variable delay time between when the particles exit the tailpipe and when they are measured.

Slide 5: The CVRED system eliminates the transfer hose from the tailpipe to the dilution tunnel. The tunnel is essentially mounted directly to the tailpipe as shown in Slide 6. The dilution air enters coaxially around the tailpipe and an orifice plate enhances mixing. The constant flow of dilution air through the concentric filter keeps it cool relative to the tailpipe. Although the mixing details differ from those on the roadway, the present system is much closer to real world than a conventional dilution tunnel employing a transfer hose. Allowing 10 times the tunnel diameter before withdrawing an exhaust sample for PM measurement ensures sufficient mixing.

Slide 7: Gravimetric measurement of the PM collected onto filters yield essentially the same mass emissions for two light duty diesel test vehicles utilizing CVRED versus the conventional dilution tunnel. In the case of diesel car 2 there appears to be a small increase in the PM recorded using CVRED, but it may also be that this is simply a small daily increase in vehicle emissions, since the 5 tests displayed follow each other sequentially. Thus, we conclude that CVRED can be used to make accurate PM mass emission measurements at current diesel vehicle emission rates.

Slide 8: Scanning mobility particle sizer measurements reveal unimodal size distributions at 40 – 60 mph, and show the appearance of a nuclei mode at 70 mph. The nuclei mode is likely a real one from the test vehicle and not an artifact for two reasons: 1) CVRED has substantially less storage / release possibilities as compared to the transfer hose; yet the nuclei mode is persistent, and 2) Wind tunnel tests, for which artifacts are not possible, also reveal the onset of a nuclei mode under the same vehicle operation as on the chassis dynamometer.

Slide 9: Under the relatively high PM concentrations of conventional diesel vehicles there is sufficient time during transport of the vehicle exhaust through the transfer hose for particle coagulation to occur. The CVRED (red curve) and conventional dilution tunnel (blue curve) size distributions represent identical PM mass emissions. Because the transfer hose has been eliminated, dilution in the CVRED system occurs much sooner than in the conventional dilution tunnel. In the latter case the soot particles grew in size and decreased in number owing to coagulation during transit from the tailpipe to the dilution tunnel. As the particle concentration at the tailpipe is lowered, gasoline vehicles for example, the coagulation rate decreases and both sampling systems would converge to the same particle distribution.

Slide 10: Current technology gasoline PM emissions are so low that other confounding issues become apparent. Thus, whereas the CVRED and dilution tunnel filter based PM mass measurements appear consistent in the top panel, the CVRED shows apparently higher emissions in the lower panel. Yet, ELPI and SMPS measurements show substantially lower PM levels than do the filters, and in this case the CVRED and dilution tunnel results agree. The speculation is that gaseous hydrocarbons are contributing the filter based PM measurements.

Slide 11: The SMPS size distributions here corroborate the conclusion from slide 10, namely up to 60 mph the gasoline vehicle PM emissions are essentially indistinguishable from background levels. At the 70 mph, high load (3%grade) a nanoparticle peak appears. However, the observed increase by a factor of ~5 above background is substantially smaller than the 10^3 increase we have previously observed in the dilution tunnel and attributed to transfer hose artifacts (SAE paper 1999-01-1461).

Slide 12: The results thus far suggest that CVRED overcomes the difficulties of using the conventional dilution tunnel to perform PM measurements at the future reduced emissions standards, yet retains the advantage of providing a direct measure of the extensive mass (or number) emission rate per kilometer traveled.

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Overview

- Pros and cons of Constant Volume Sampling using conventional dilution tunnel.
- Description of Constant Volume Rapid Exhaust Dilution (CVRED) concept.
- Comparison of CVRED and dilution tunnel – light duty diesel vehicles.
  - Gravimetric PM mass.
  - Particle size distributions.
- Comparison of CVRED and dilution tunnel – gasoline vehicles.
  - Gravimetric PM mass.
  - Particle size distributions.
- Conclusions.

Background

- There is currently considerable interest in developing new PM measurement methods, e.g., GRPE-PMP program.
- The need to develop appropriate sampling systems is as important as the need for measurement instruments.
- Current tailpipe PM regulations are based on the dilution tunnel, but this has shortcomings at low PM.
- Other possibilities include:
  - Direct tailpipe sampling.
  - Partial dilution – e.g., bag mini-diluter.

Advantages of the conventional dilution tunnel

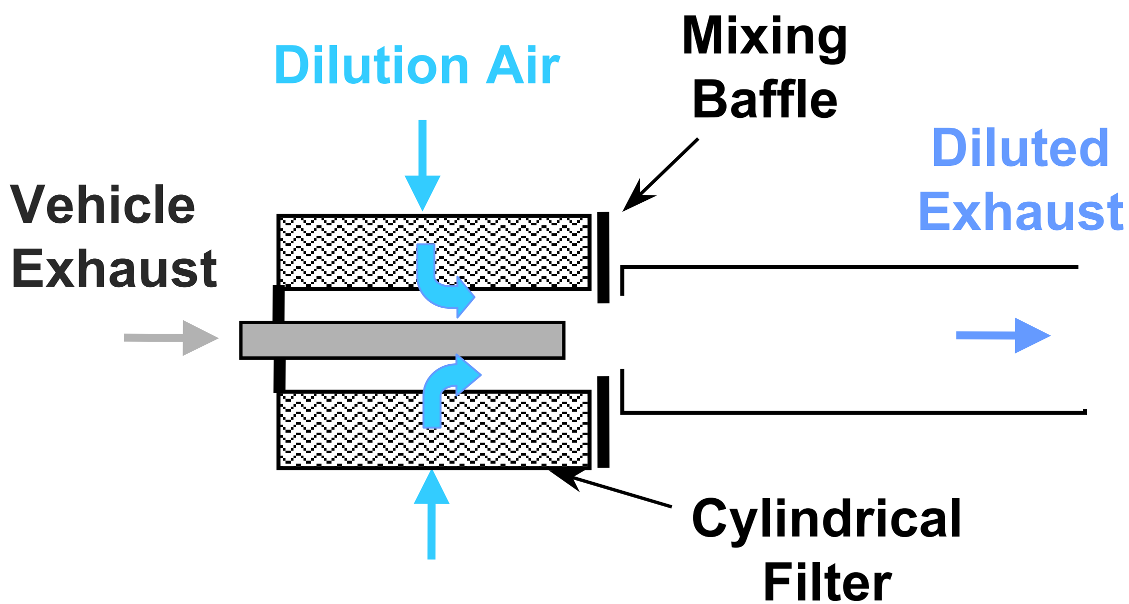
- The constant total (exhaust + diluent) flow directly provides a mass emissions rate (e.g., mg/km).
- In contrast to tailpipe sampling, this avoids the necessity of a synchronized exhaust flow measurement.

Disadvantages of the conventional dilution tunnel

- Introduces variable delay between the time emissions leave the tailpipe and the time they are measured.
- Susceptible to storage – release artifacts.
- Potential chemical and physical changes to PM during transit from tailpipe to measurement point.

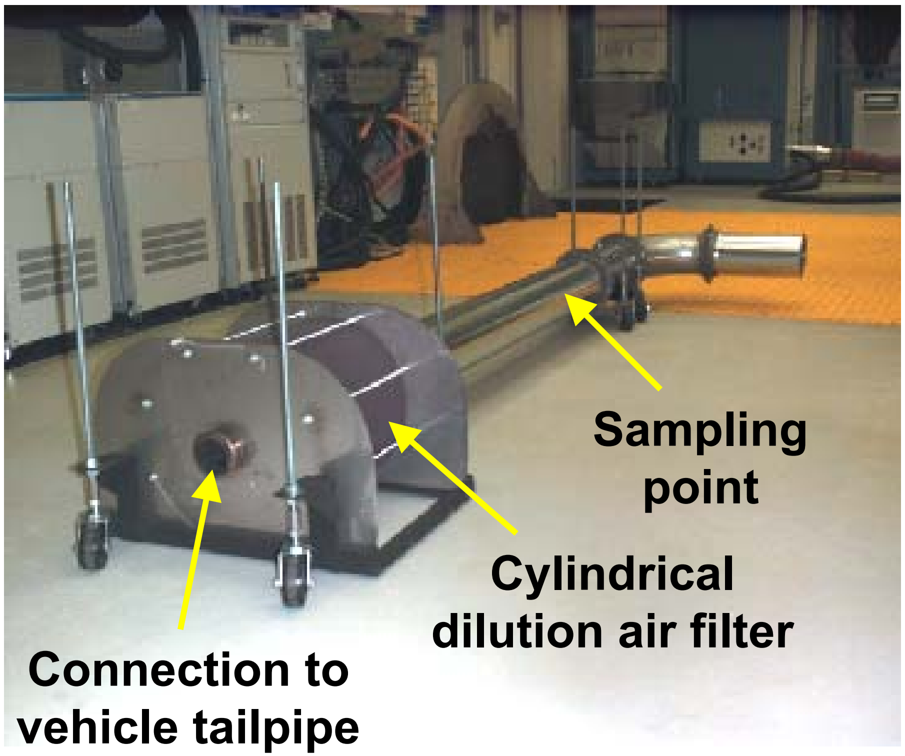
Retain advantage of CVS – fix problems

Provide closer to "real world" dilution by eliminating the transfer hose.



- Perform dilution at tailpipe .
- Dilution air enters concentrically around tailpipe.
- Sample taken 10 tunnel diameters downstream
  (~0.2 s residence time at 9.9 m^3/min in 15 cm dia. duct)

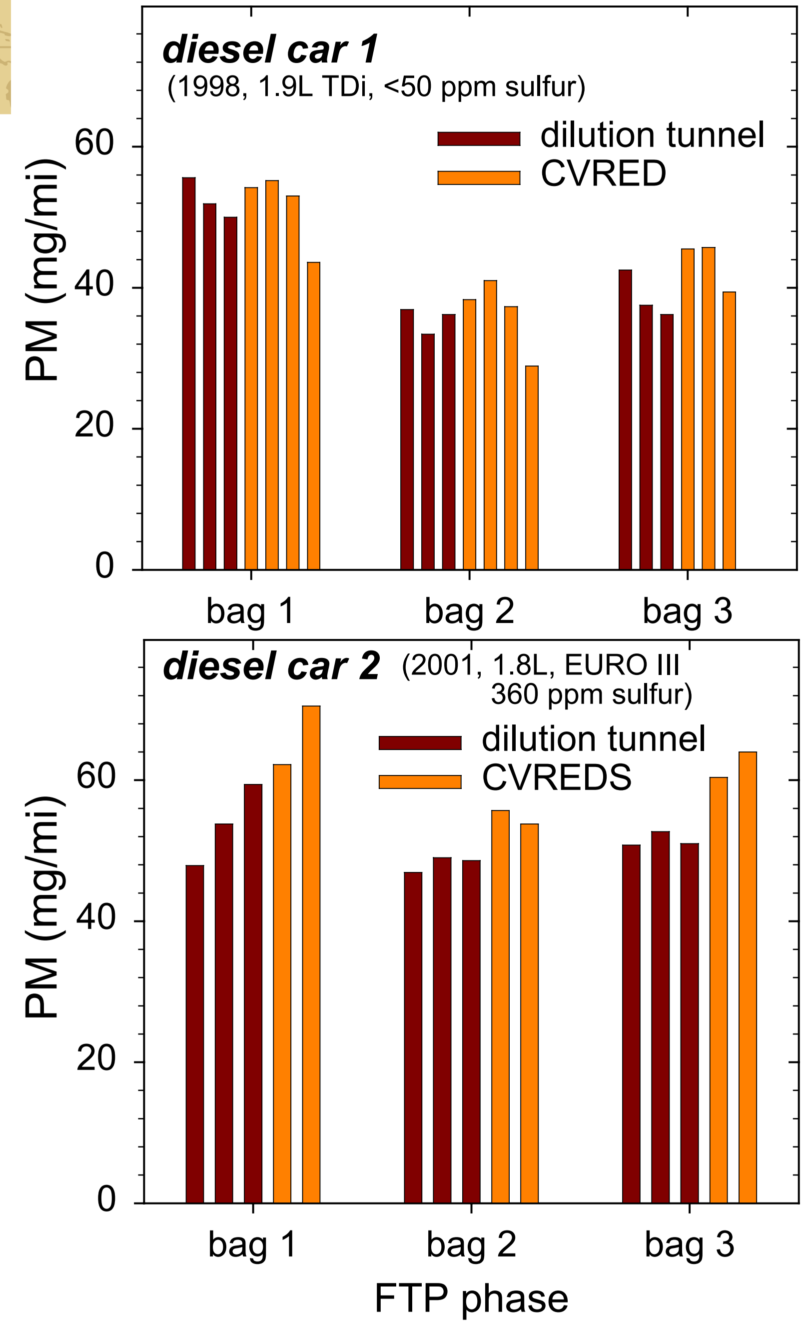
Prototype CVRED system



CVRED vs dilution tunnel

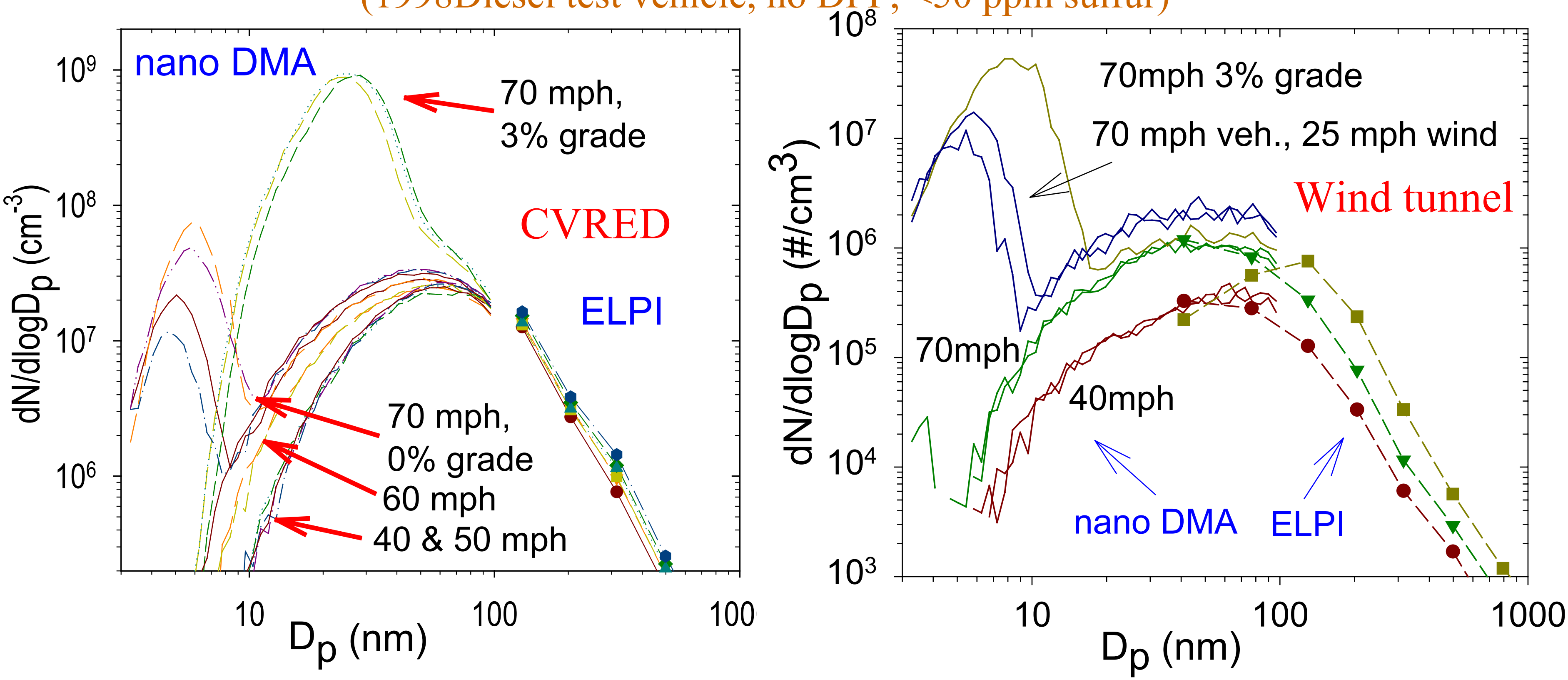
Light duty diesel PM mass by filter collection.

- Diesel 1 – PM emissions using CVRED vs dilution tunnel are equal within the data scatter.
- Diesel 2 – CVRED PM mass appears 10-20% higher than measured in dilution tunnel.
- Number of tests insufficient to tell if difference is systematic or random.



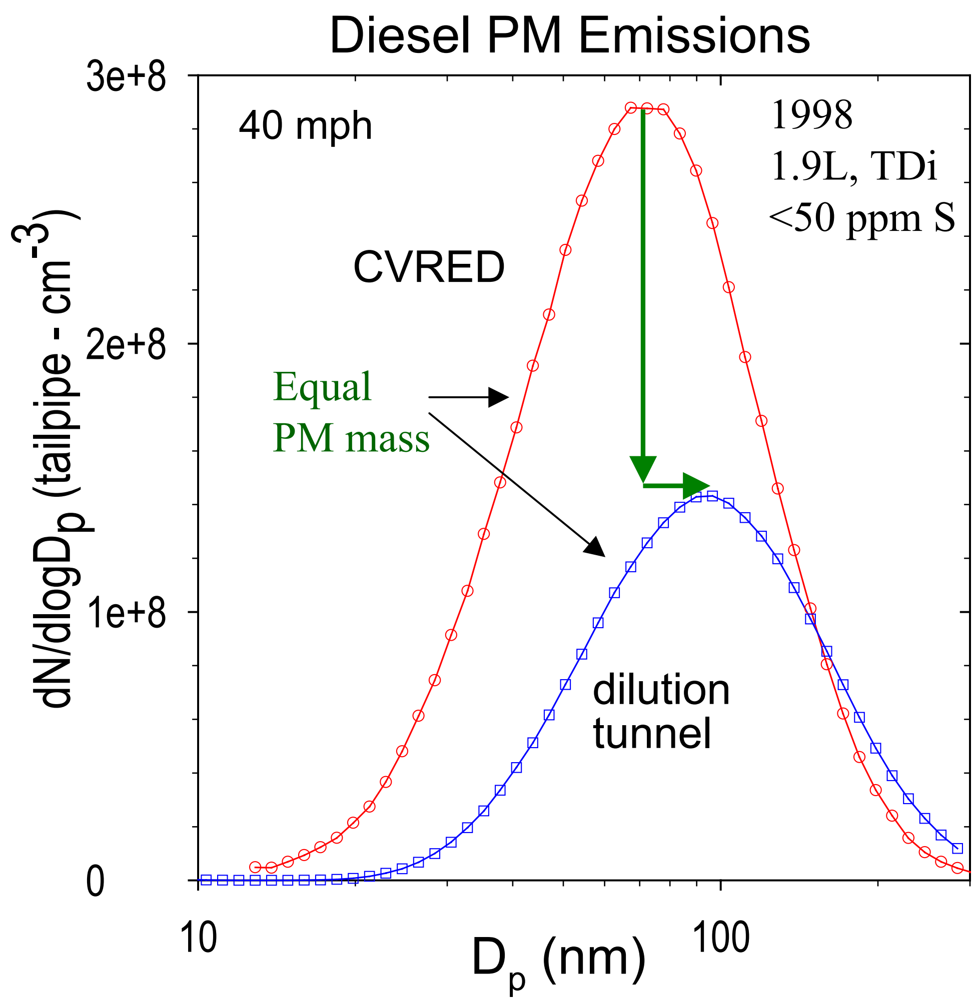
- CVRED is consistent with wind tunnel PM measurements (not all diesel nanoparticles are artifacts).
- Both show stable soot mode at 40-60 mph. No nucleation.
- Nuclei mode observed at 70 mph:
  - Increases with load. Depends on dilution.

(1998Diesel test vehicle, no DPF, <50 ppm sulfur)



Transfer hose coagulation – diesel vehicle

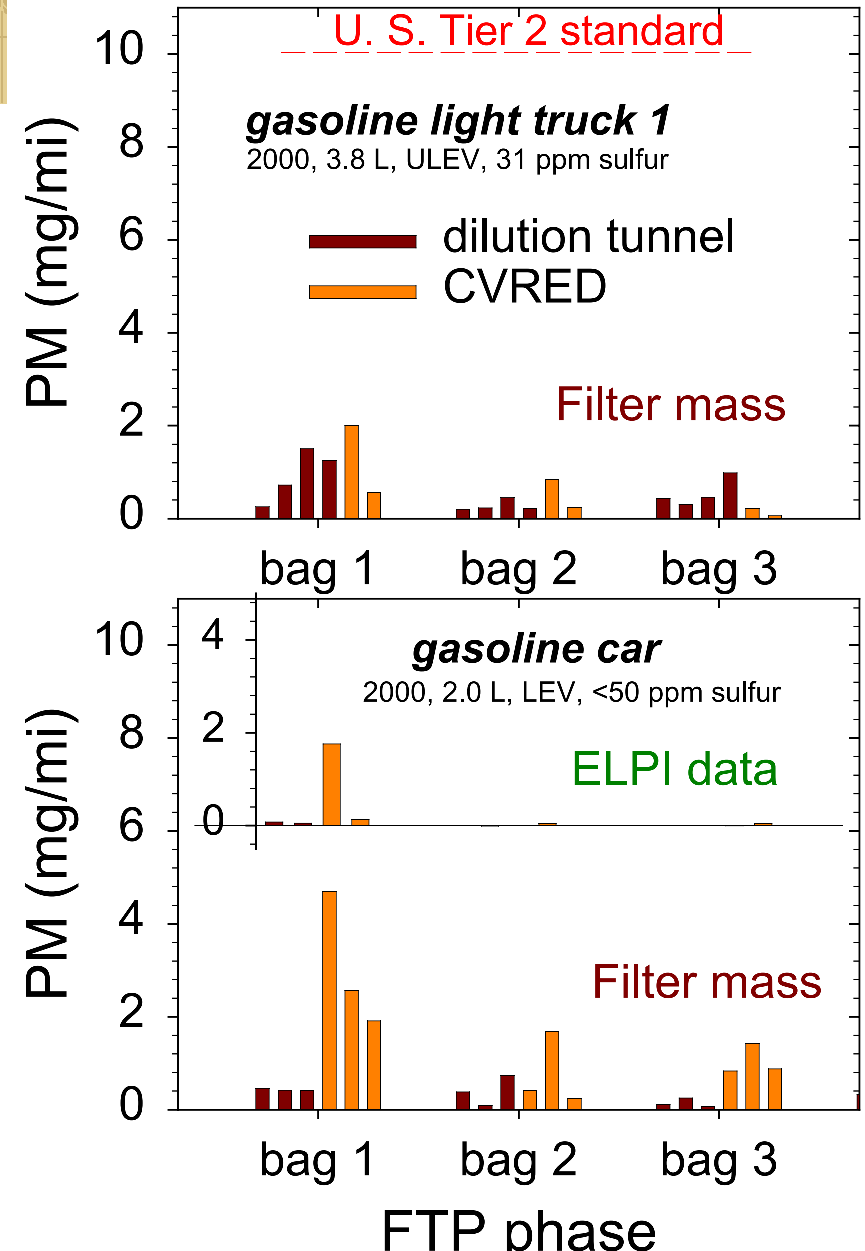
- CVRED and dilution tunnel yield the same PM mass.
  - CVRED shows 2x the number of particles.
  - But they are 25% smaller than in the dilution tunnel.
- Particles coagulate in transfer hose (at ~ 1×10^{-9} cm^3/s). During ~5 s transit size calculated increase is ~16 nm.
- Coagulation effect will not occur for gasoline or DPF equipped diesel particle number since PM emissions are 100 times lower.



CVRED vs dilution tunnel

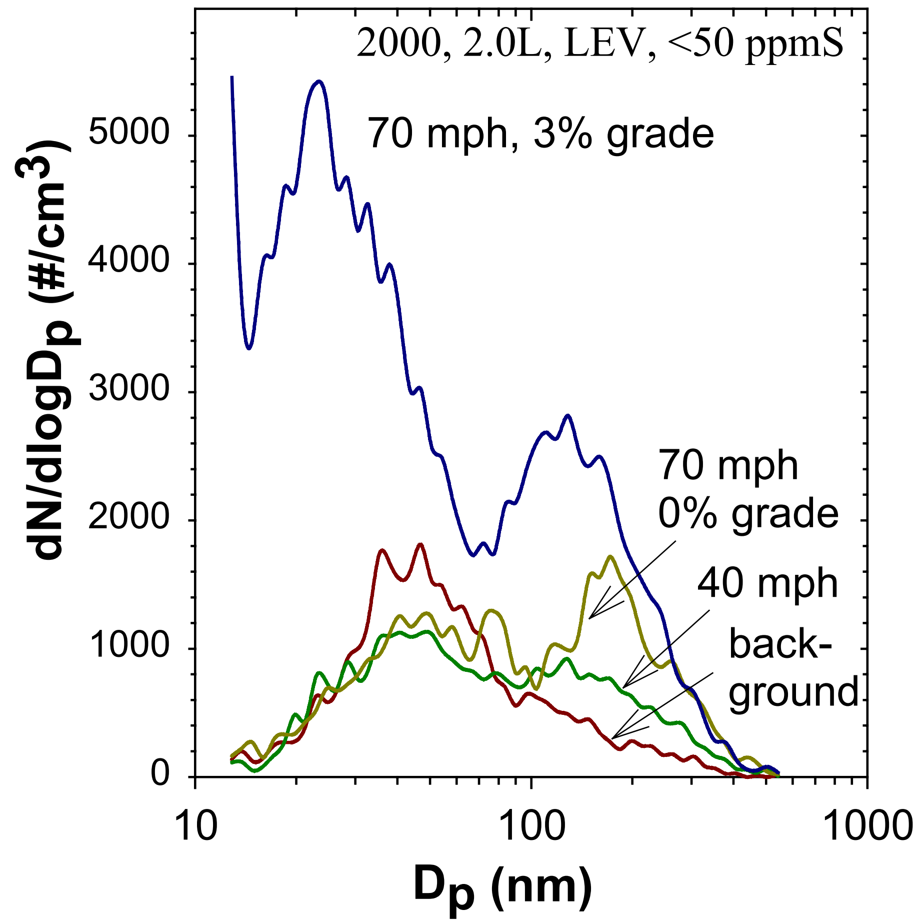
Gasoline vehicle PM mass by filter and by ELPI.

- Filter PM mass is
  - comparable for light truck
  - higher for the test car.
- But, PM mass calculated from ELPI (inset) is ~0 in bags 2 and 3 for both dilution tunnel and CVRED. SMPS also indicates very few particles (see next slide).
- Further work needed to clarify exactly what the filters are measuring.



CVRED – Gasoline vehicle

- Figure displays diluted PM # concentration in CVRED system.
- Steady state PM at 40 – 70 mph nearly indistinguishable from background test cell air.
- At 70 mph and a 3% grade, an increase of 20-30 nm particles is noted.
  - # remains orders of magnitude smaller than diesel PM.
  - # is orders of magnitude smaller than transfer hose artifacts.
  - Possibly due to residual heat release PM from exhaust and/or CVRED.



Conclusions

- Prototype CVRED system shows promise at overcoming disadvantages of conventional dilution tunnel.
- Transfer hose artifacts during high speed gasoline vehicle operation are substantially reduced.
- Distortion of the PM size distribution for diesel vehicles by particle coagulation is substantially reduced.
- Rapid dilution process is more realistic than that of conventional dilution tunnel.
- Future improvements:
  - HEPA filter to remove ambient PM for low level measurements.
  - Pre-condition dilution air for temperature and humidity.
  - Dilution air flow measurement capability.