Westport™ INNOVATIONS INC.

Advancing the shift of global commercial transportation to natural gas and hydrogen.

Application of Particulate Filter Technology to a CNG Engine

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Westport Innovations Inc.

Introduction

- Project had three main areas of work;
  - Investigation into the effect of the addition of a Particulate Filter (PF) on the emissions from a CNG-fueled Heavy-duty engine.
  - Investigation into the impact of lubricants on emissions from CNG engines.
  - Assess emission-reduction potential, performance, and reliability of the catalyzed particulate filters during a six-month in-use demonstration program.
- Funded by SCAQMD, Sempra Utilities and NREL.

Introduction

- Project was lead by Westport Innovations with support from the following;
  - West Virginia University (WVU)
    - Chassis Dynamometer facilities and regulated emissions
  - University of Wisconsin (UWI)
    - Chemical speciation
  - University of Minnesota (UMN)
    - Aerosol concentrations and size distributions
  - SunLine Transit Agency
    - Field Trial Partner

Contents

- Suitability of Particulate Filters for use with CNG engines
- Aftertreatment Configuration Selection
- Testcell Setup and Investigation
- Vehicle Installation
- Chassis Dynamometer Testing and Results
- Field Trial Results
- Conclusions

PF Suitability for CNG Engines.

- Composition of PM from CNG engines is significantly different to that from Diesel Engines
- CNG PM in general has:
  - Lower engine out PM levels
  - Larger fraction of Ash and VOF
  - Lower elemental carbon levels
- For Lean Burn SI (LBSI) engines
  - Higher NOx to carbon ratio (vs. diesel)
  - Higher minimum exhaust temperatures (vs. diesel)
  - O_2 in exhaust stream
- LBSI engine exhaust conditions should be favorable to PF continuous regeneration

Selected Engine

- Engine selected is the CWI C Gas Plus.
- Launched in 2001
- Lean-burn Spark Ignited (LBSI) engine.
- Turbocharged
- Fuel metered into intake (fumigation)
- Air to Fuel (AFR) control via oxygen sensor in exhaust stream.
- Drive-by-wire throttle.

Selected Engine

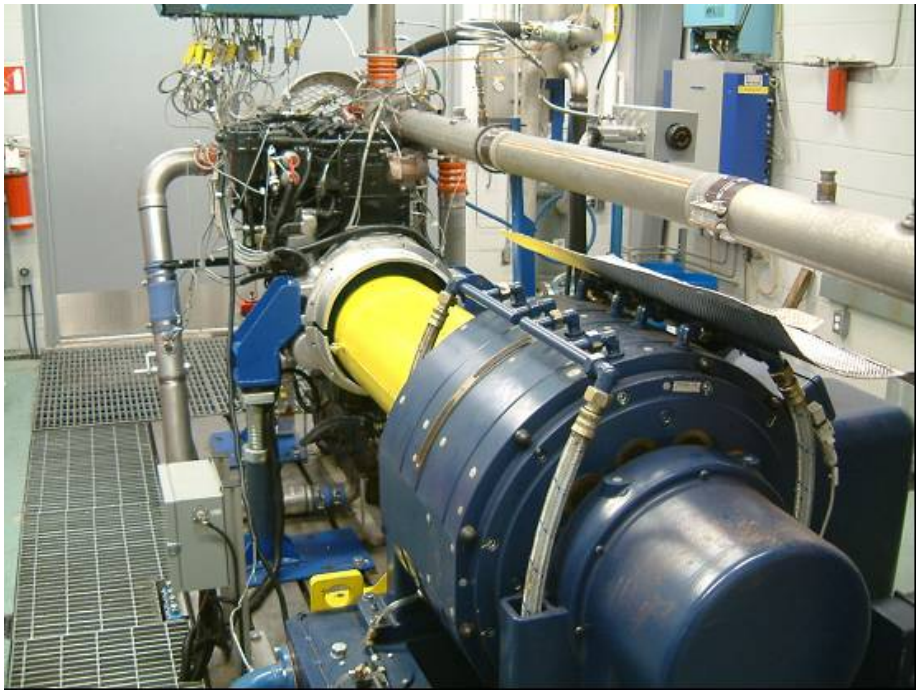
- The CWI C Gas Plus is certified to the following emissions levels:
  - US EPA 2004
  - EPA CFFV ULEV
  - CARB Optional Low NOx (1.8 gm/bhp-hr)
  - Euro 3 (with THC specific catalyst)
- Certification PM emissions < 0.01 g/bhp-hr
- Peak Torque 850 lb-ft (1153 Nm) at 1400 rpm
- Rated Power 280 HP (209 kW) at 2400 rpm.

Aftertreatment Configuration Selection

- Selection to find best combination for CNG operation.
- 2 PF's selected:
  - Engelhard DPX™ [Catalyzed Diesel Particulate Filter]
  - Engelhard PF [Uncatalyzed Particulate Filter]
- 2 Oxidation Catalysts selected:
  - Standard C Gas Plus formulation
  - HEX-1107 [predominantly Palladium]

Testcell Setup

•Testcell located at Westport Innovations in Vancouver, Canada.



•PM emissions measured using Sierra BG-2 Mini-dilution tunnel.

•Horiba emissions bench used for gaseous emissions measurement.

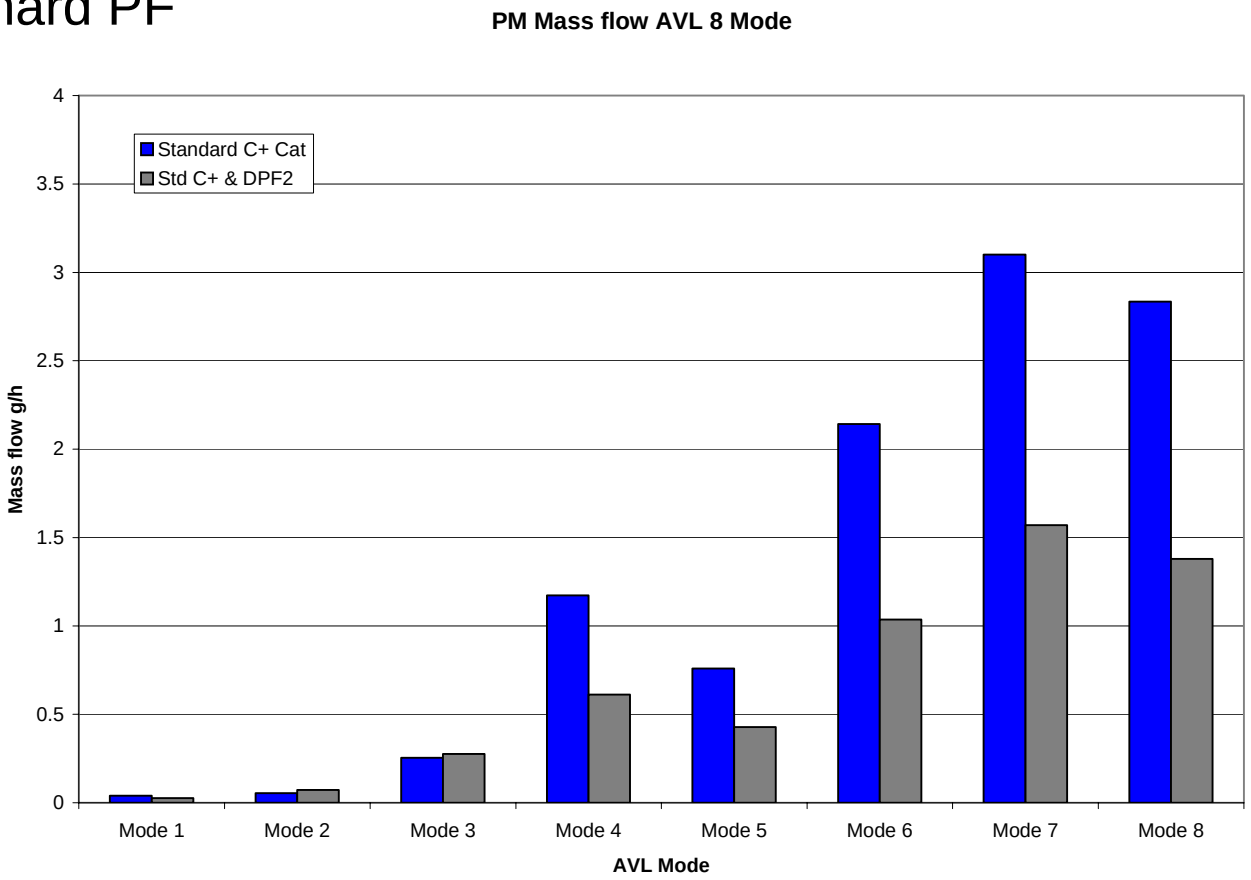
•Modular exhaust system allows for combinations of PF and oxidation catalyst to be tested.

Testcell Investigation

- Engine was base-lined for engine out emissions and with standard OEM Oxidation Catalyst fitted.
- Various aftertreatment configurations fitted and compared by:
  - Measured PM mass emissions.
  - Effect on gaseous emissions.
  - PF mass increase over 100 hours.
- Results allowed selection of configuration for field trial.

Testcell Investigation

- Selected Configuration combined in series:
  - Standard C Gas Plus Oxidation Catalyst + Uncatalyzed Engelhard PF

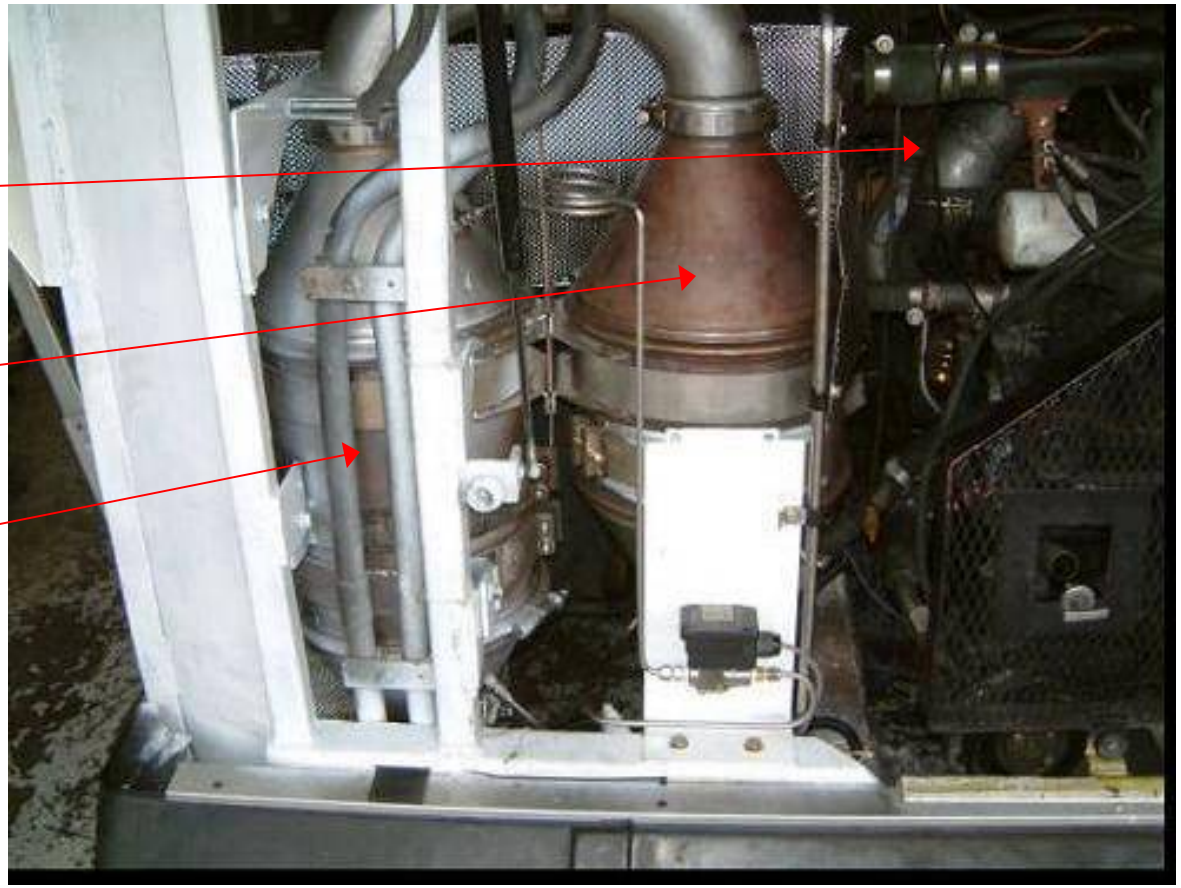


Vehicle Installation

- SunLine Transit supplied a 40-ft transit bus fitted with a CWI C Gas Plus.
- Aftertreatment system fitted for a 6 Month Field Trial in revenue service.

Vehicle Installation

- Available space for packaging was limited in this chassis.

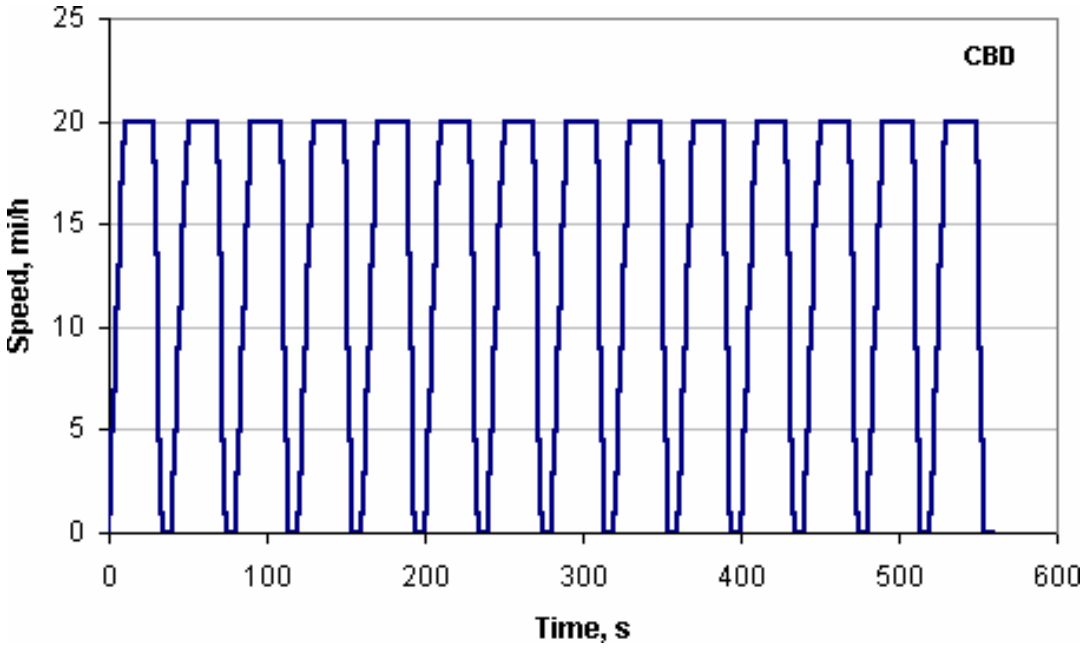


Chassis Dynamometer Testing

- “Real-world” testing of selected Aftertreatment system completed on WVU portable Chassis Dynamometer.
- “Clean” CVS tunnel (reserved for low-emitting applications) was used for this study.

Chassis Dynamometer Testing

- Test cycles used:
  - 3 steady state modes (idle, 20 mph, 40 mph)
  - Quad Central Business District Cycle (QCBD)



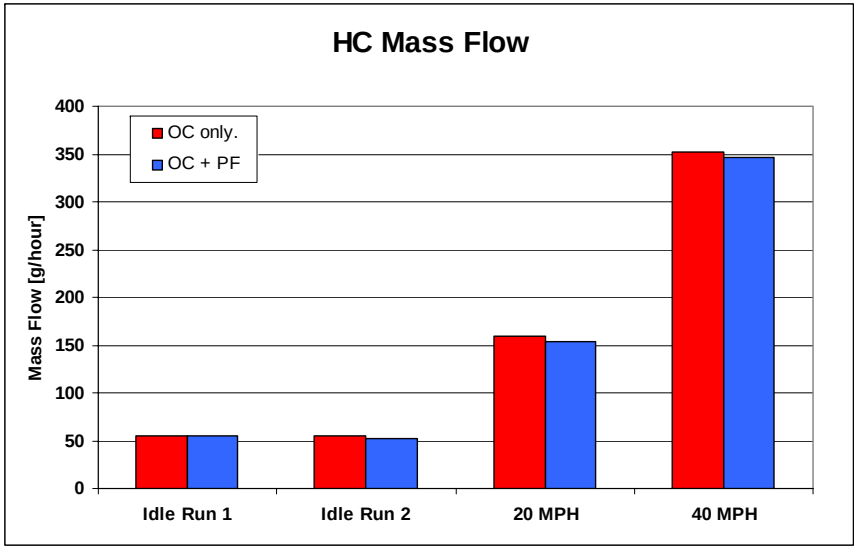
CBD Cycle Profile

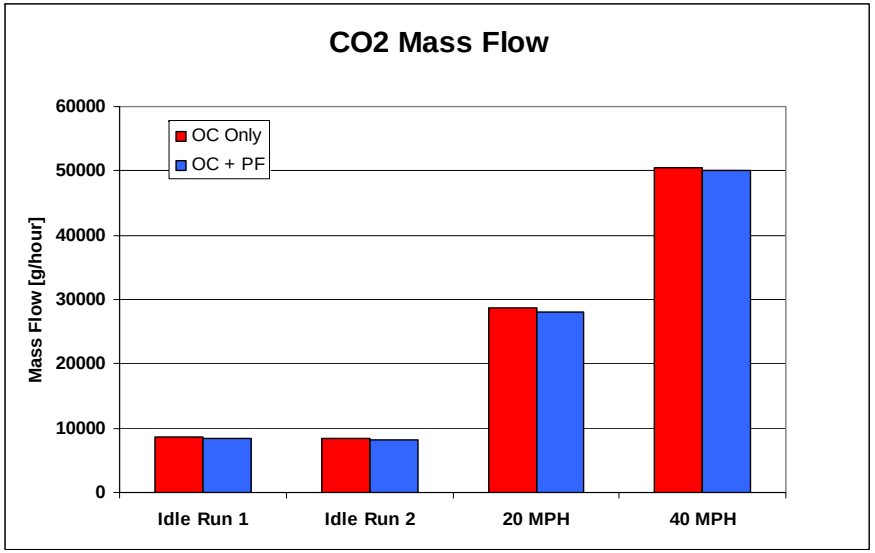
Instrumentation

- UMN (physical characterization)
  - Condensation Particle Counter (CPC)
    - to measure total particle number concentrations]
  - Engine Exhaust Particle Spectrometer (EEPS)
    - Aerosol size distributions
  - Scanning Mobility Particle Sizer (SMPS)
    - 10 to 300 nm for steady state testing only
- UWI (chemical characterization)
  - Media was collected on-site and processed once testing was completed.

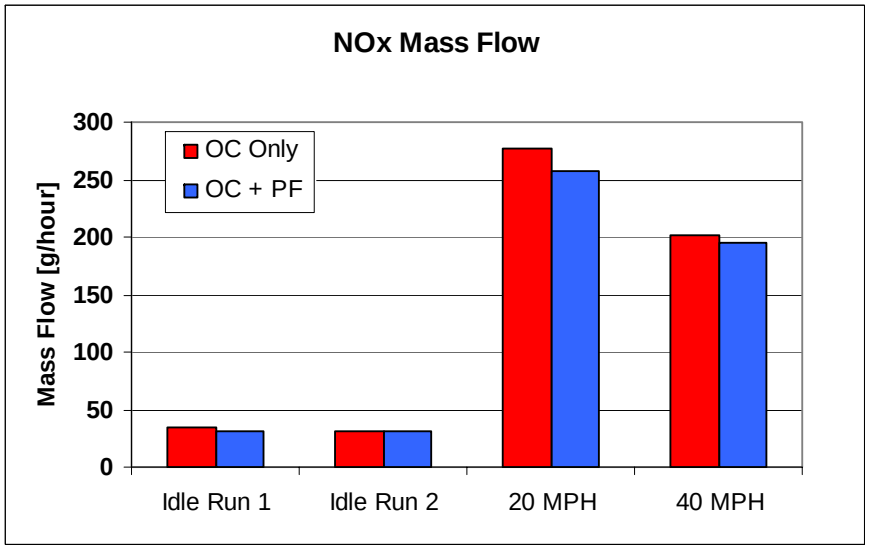
Chassis Dynamometer Results

- Gaseous emission results



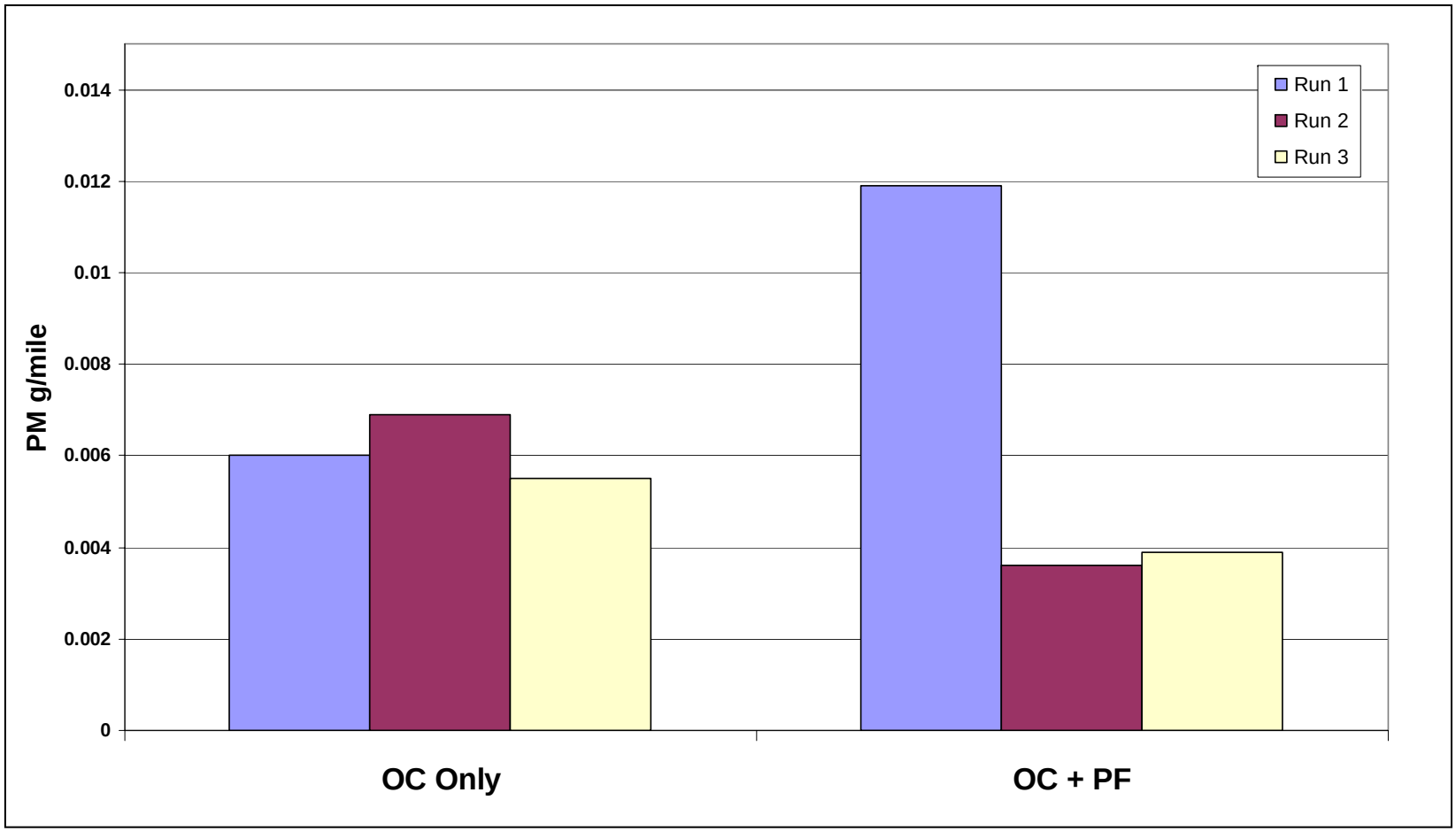


- PF does not adversely affect gaseous emissions from engine.



Chassis Dynamometer Results

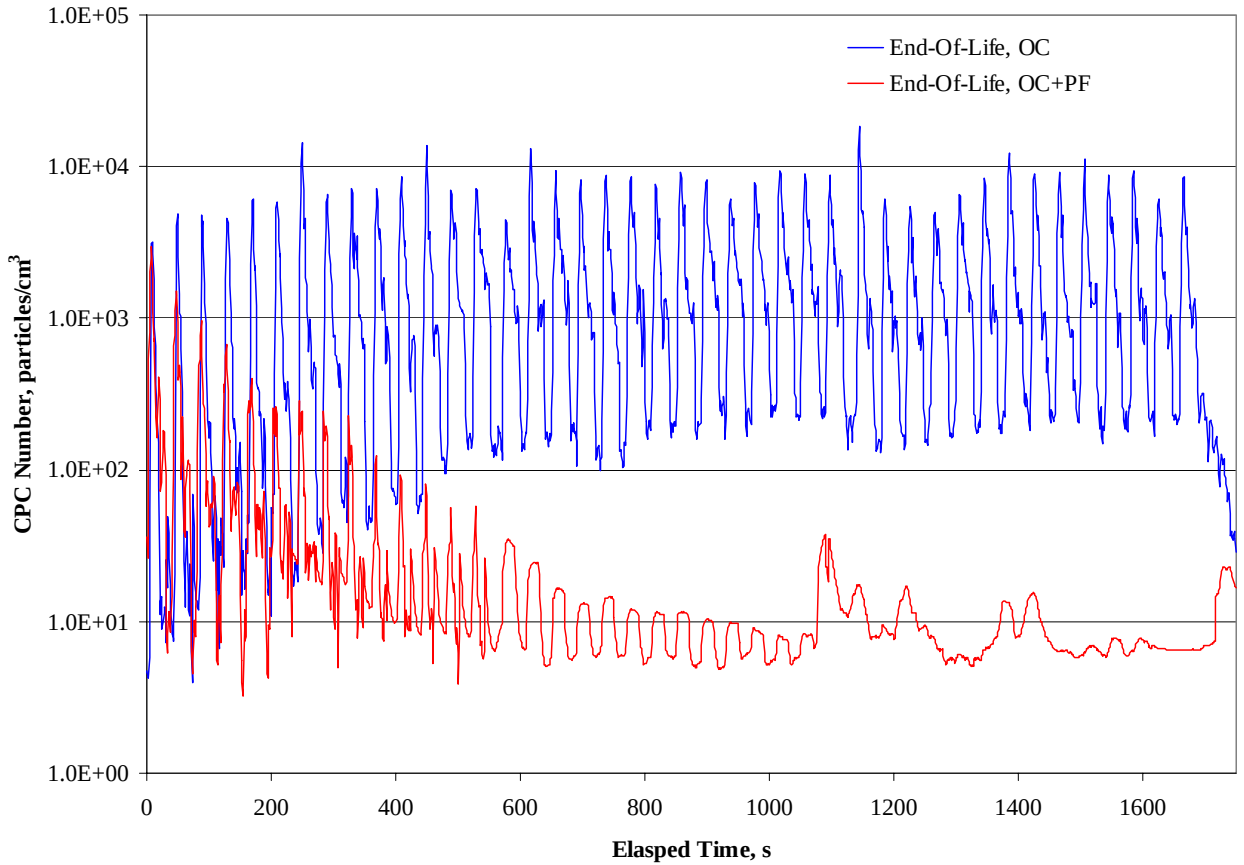
- PM mass emissions



PM Mass Emissions on a g/mile basis from WVU measurements.

Chassis Dynamometer Results

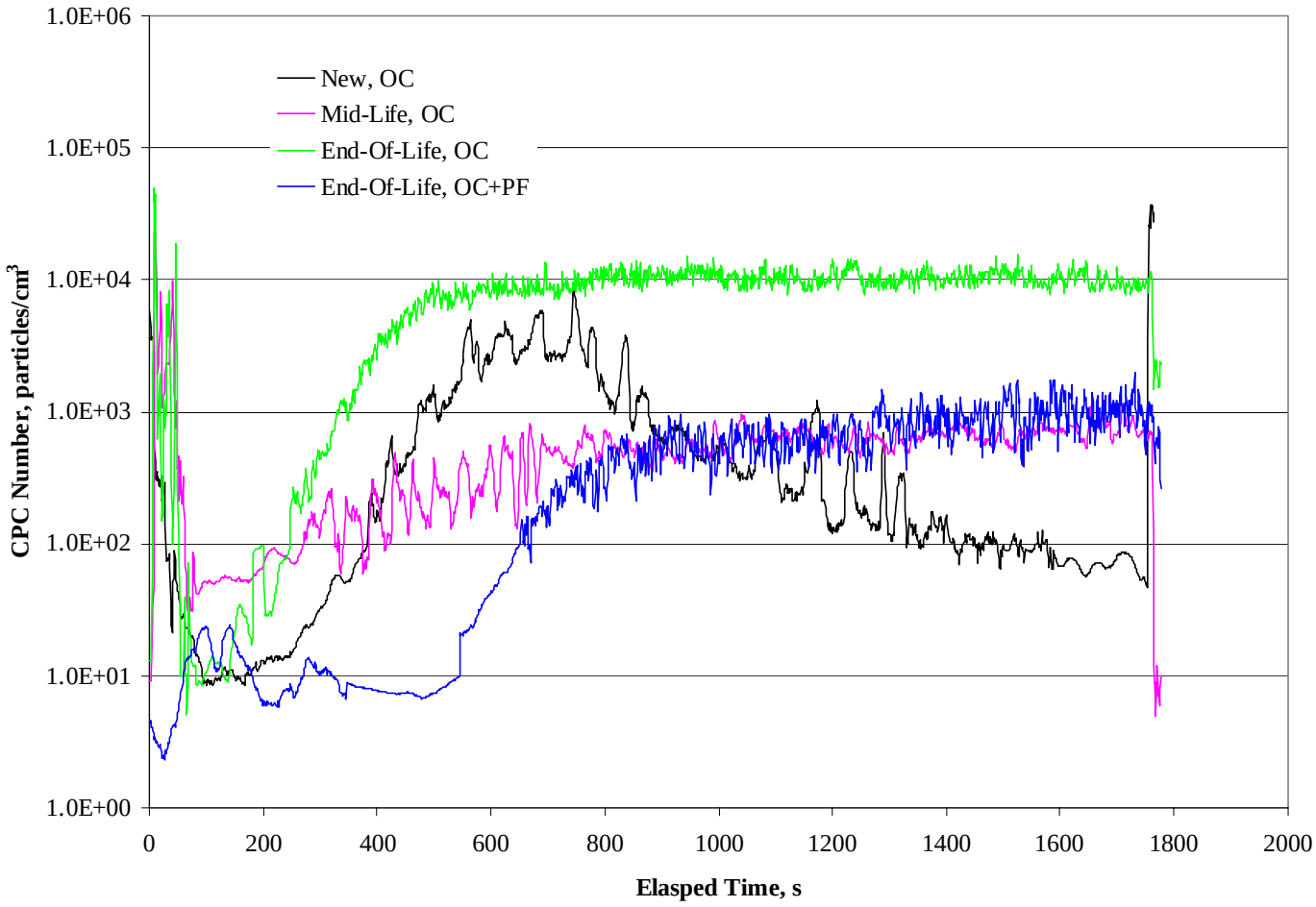
- Particulate Filter reduces particle number.



Plot of CPC number concentration for the average quad-CBD cycle for the end-of-life oil condition, with the OC and with the OC and PF together.

Chassis Dynamometer Results

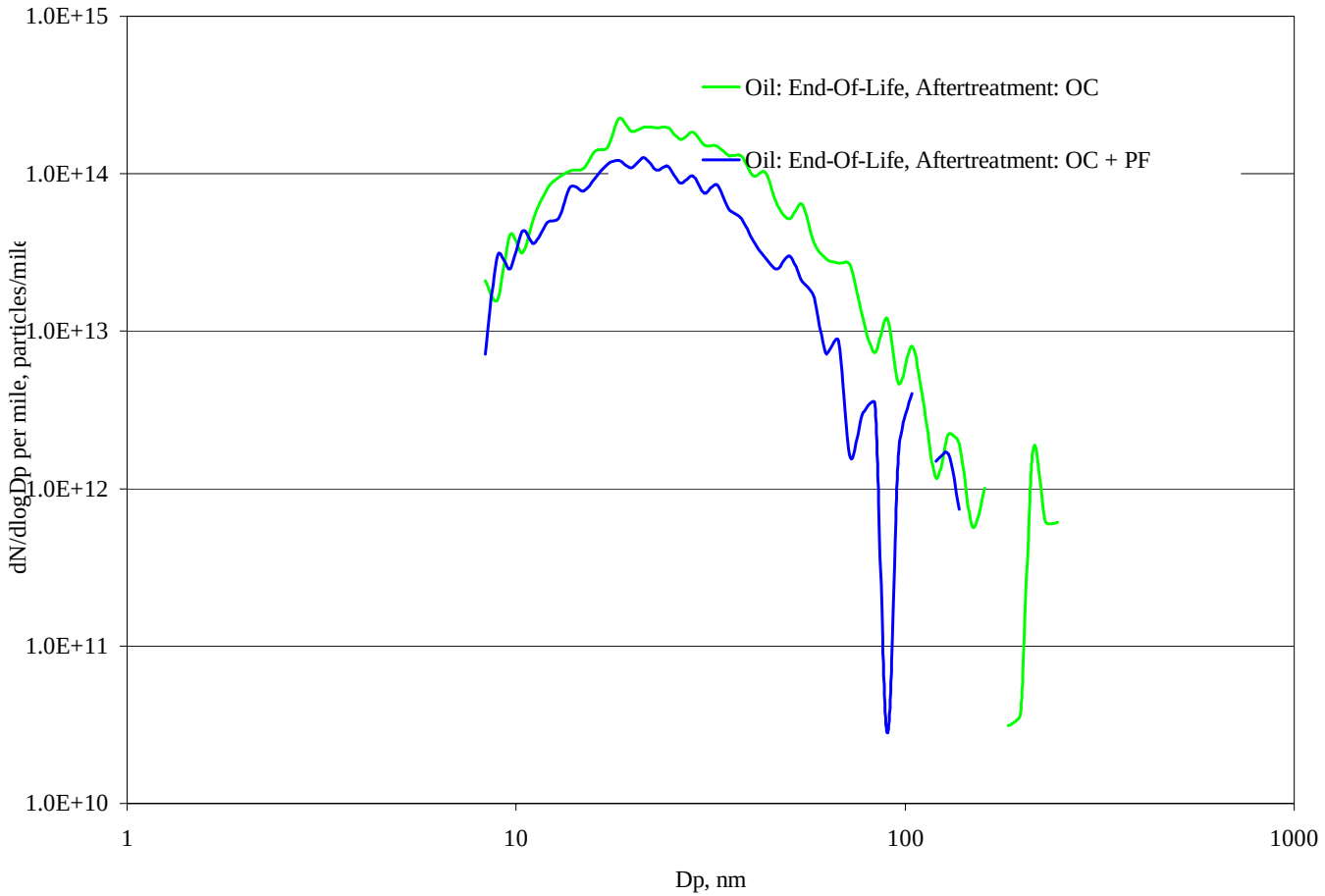
- Start up spikes removed with addition of PF



Particle number measured during 40 mph tests, not corrected for dilution ratio.

Chassis Dynamometer Results

- Distribution of particles unaffected by addition of PF



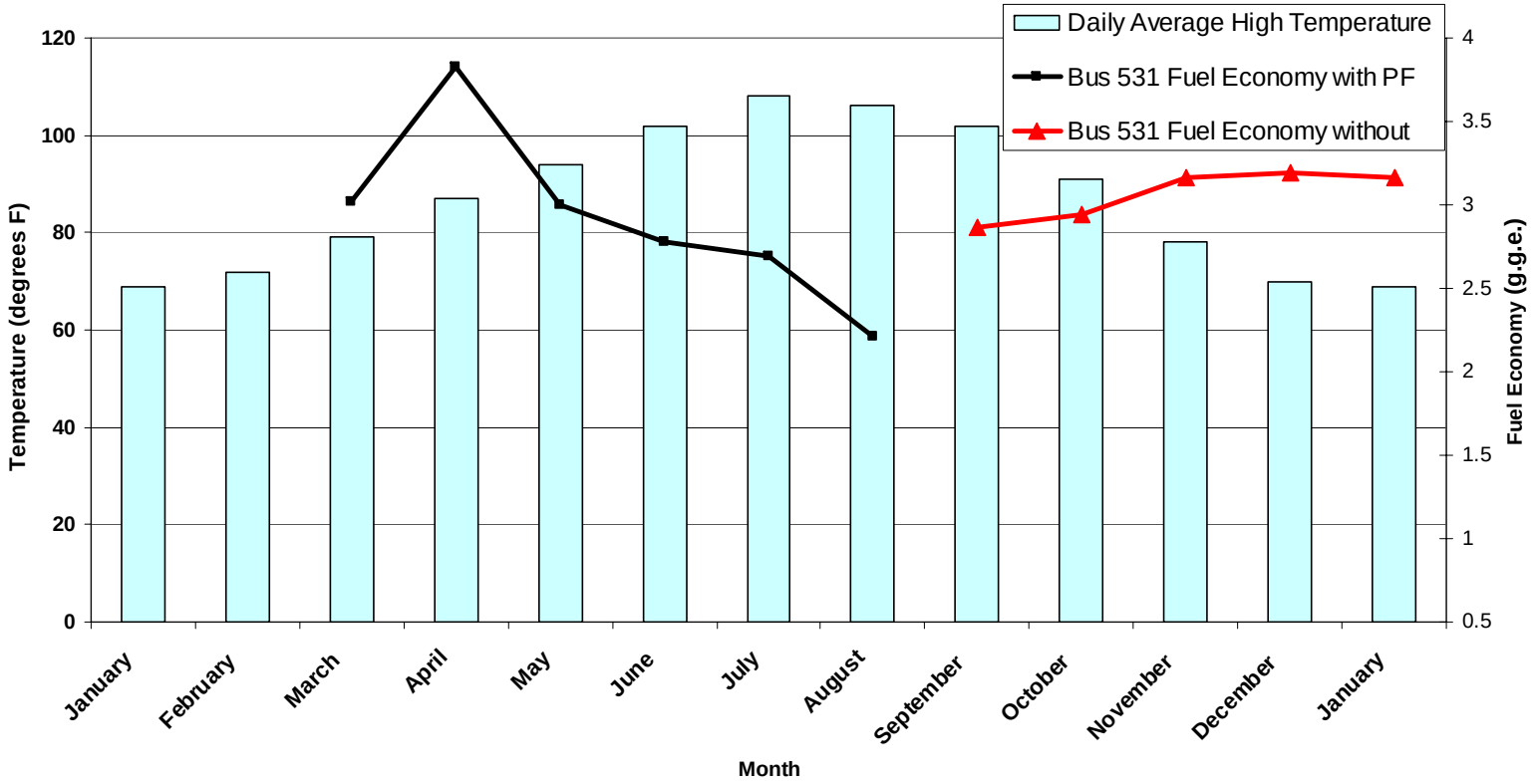
40 mph cruise condition SMPS size distribution with and without the particle filter (PF).

Chassis Dyno Results Summary

- The addition of the PF does not produce a statistically significant change in PM mass emissions
- In many cases and under many conditions, particle number concentrations were not detectable above background.
- The addition of a particulate filter is effective at removing start-up spikes in particle number concentration
- By adding the particulate filter the size distribution is unchanged but the overall number is reduced.

Field Trial Results

- SunLine Bus 531 covered over 30,000 miles in 6 months.
- No mechanical issues incurred.
- Fuel consumption effect minimal.



Conclusions

- The experience of the 6-month field trial was positive with no serious issues encountered during operation.
- The addition of the Particulate Filter to the Aftertreatment system reduced the particle number emissions from the engine.
- During engine and vehicle dynamometer emissions testing, the addition of the Particulate Filter did not adversely affect the standard engine operation.
- The filter used in the 6-month field trial has been stored and could be examined (for ash content / composition etc.) further if a suitable opportunity arose.