Particle Number Emissions from In-Use Transit Buses with Advanced SCR Systems

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IREE
Initiative for Renewable Energy and the Environment
Cummins
University of Minnesota
Metro Transit

On-road transit bus emissions

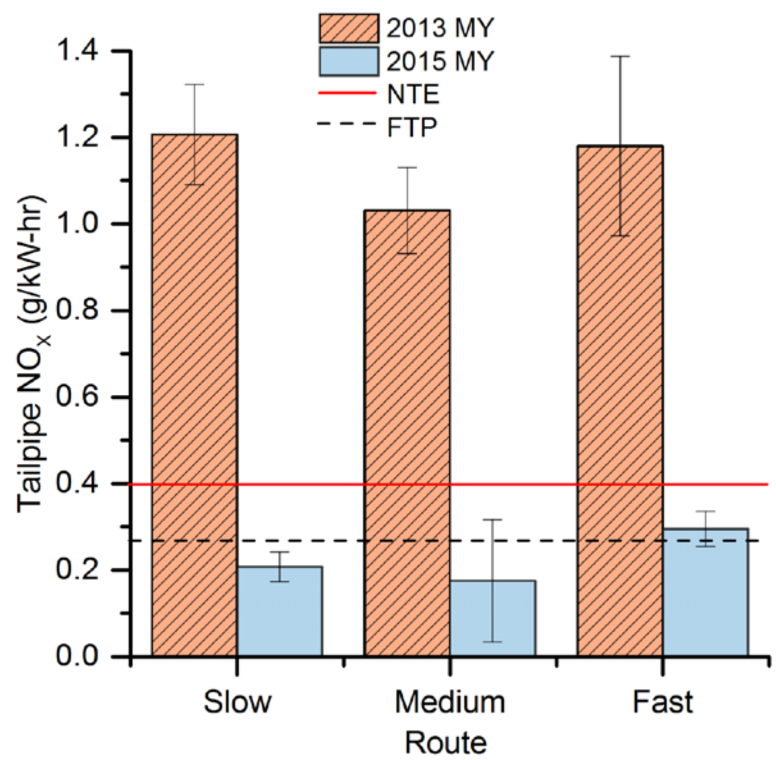
- This is an extension of a project comparing NOx emissions of SCR equipped 2013 and 2015 MY (Model Year) buses
- Increased PM and especially PN have been reported with SCR plus DPF compared to DPF alone*
  - Suggest PN are semi-volatile but still detected by PMP method
  - Suggest PN increases with urea dosing – increasing ammonia to NOx ratio (ANR)
- This motivated us to do preliminary study of on-road PN measurements. That work is the topic of this presentation

*See for example: Carslaw et al. Atmospheric Environment 105 (2015) pages 70-77: Robinson, et al., SAE Technical Paper 2016-01-0995, 2016

Understanding on-road NOx and PN emissions

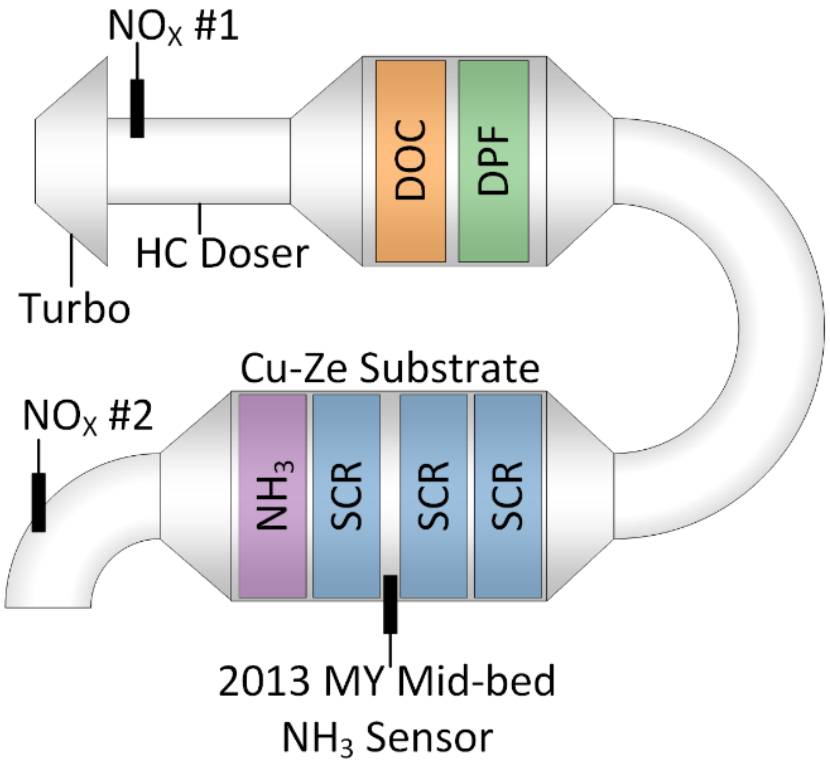
- 2013 engine class met certification, but had high emissions under real-world driving conditions
- Known disconnect with between certification and real-world
- 2015 MY bus had substantially lower real world NOx emissions using model based control with average ANR > 1
- **What about PN?**
  - **2015 vs 2013 MY**
  - **Role of ANR**

Data Presented at 2016 CRC Conference



Test Vehicles

- 40’ GILLIG Buses
  - 8.9L Cummins ISL
  - 2013 certified
  - Emission control system consisting of DOC, DPF, SCR, and NH_3 slip catalyst
- Main differences between 2013 and 2015 MY emission control system, for 2015:
  - Remove NH_3 sensor
  - Model-based dosing



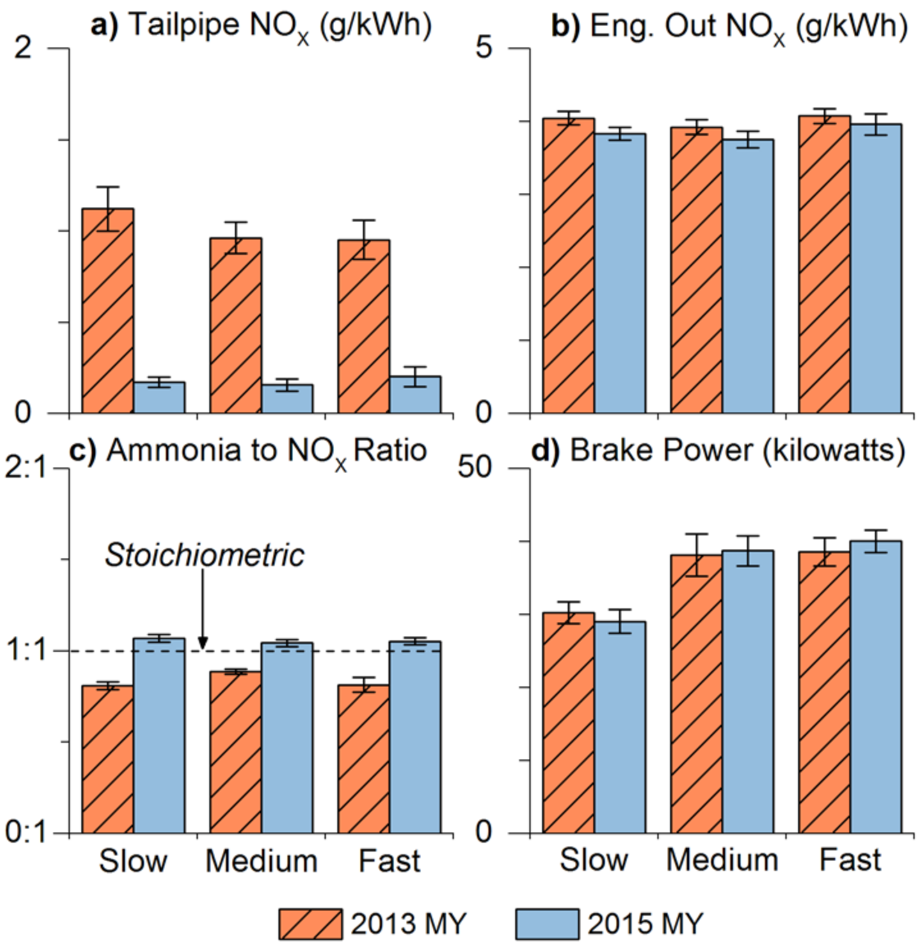
Instruments and Data Acquisition

- Data Acquisition
  - NI cRIO controllers
    - J1939 CAN interface – NO_X Sensors
    - GPS location
    - 1Hz data collection
  - Wireless data streaming
  - TSI NPET 3795
    - Designed for Swiss heavy-duty IM program
    - Not PMP complaint
    - Measures solid particle number greater than ~ 20 nm

Data Logger

Cycle Averaged NOx Comparison

- Results by Route
- 2015 MY compared to 2013 MY
  - No change in engine out NOx
  - No change in average power
  - 80% NO_X Reduction
  - 25% Dosing Increase
  - Average ANR >1



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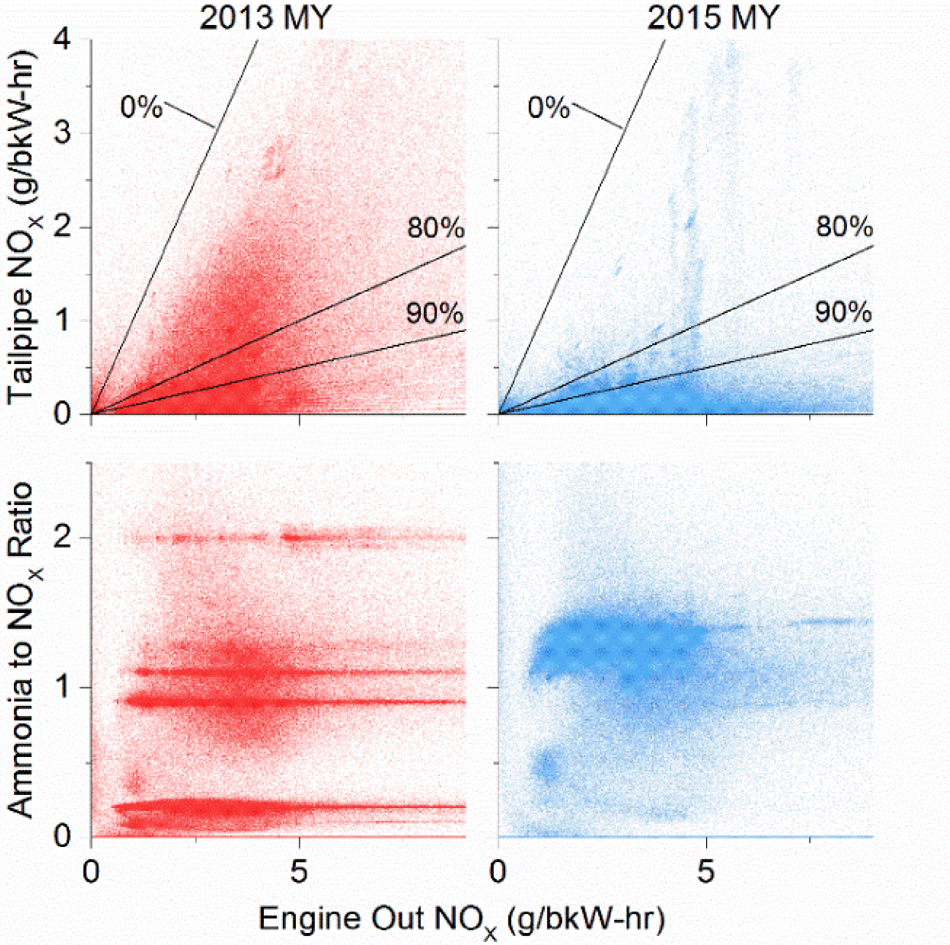
Engine Out vs Tailpipe NO_X

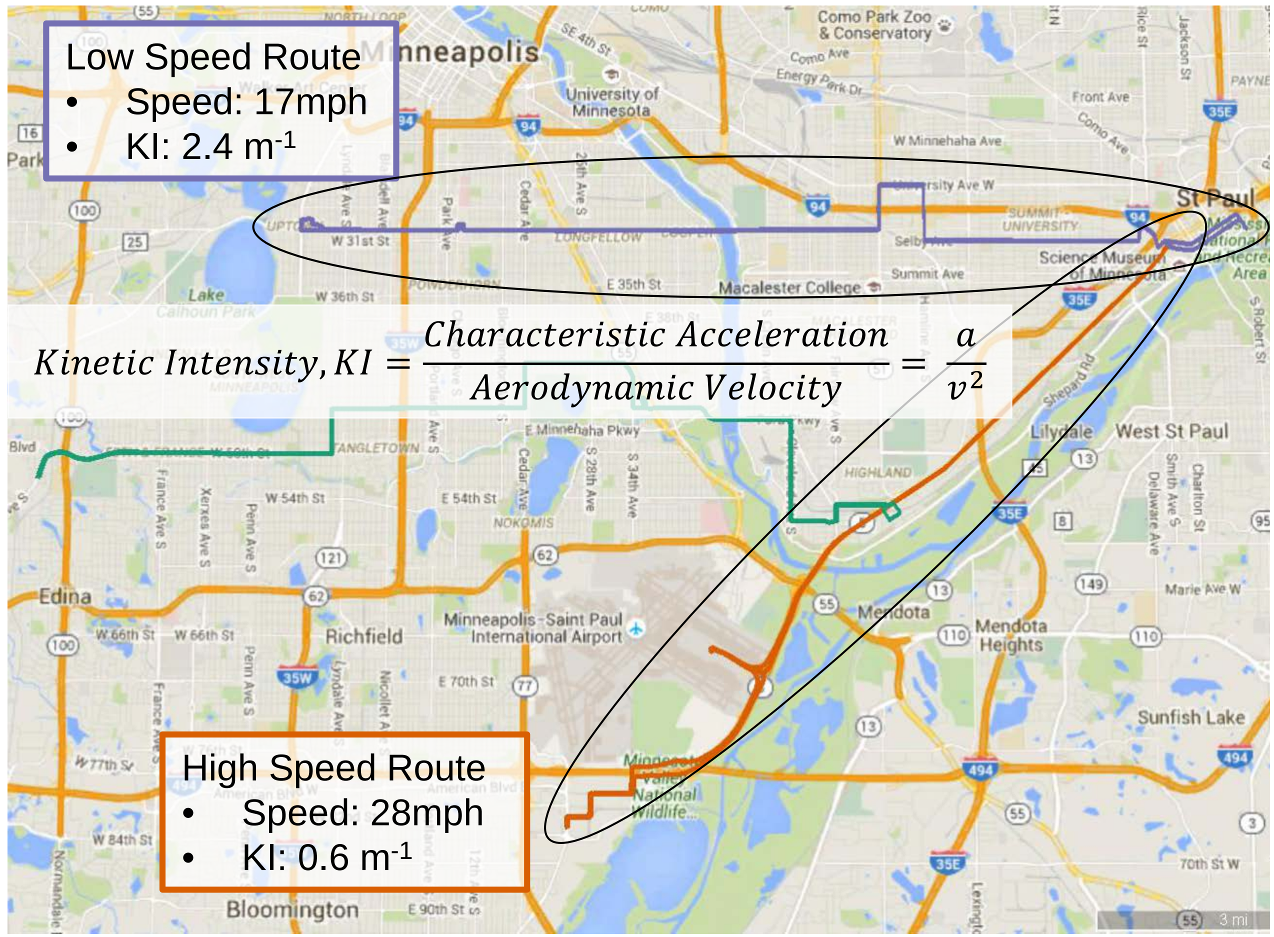
- NO_X Conversion: Tailpipe vs Engine Out Concentration
  - 2015MY
    - Near Constant conversion > 90%
- ANR
  - 2013MY 5 bands
  - 2015MY 1 large band closer to stoichiometric ANR of 1.0



PN Test Conditions

2015 MY Testing
- November 18th, 2015
- Temperature: 48ºF

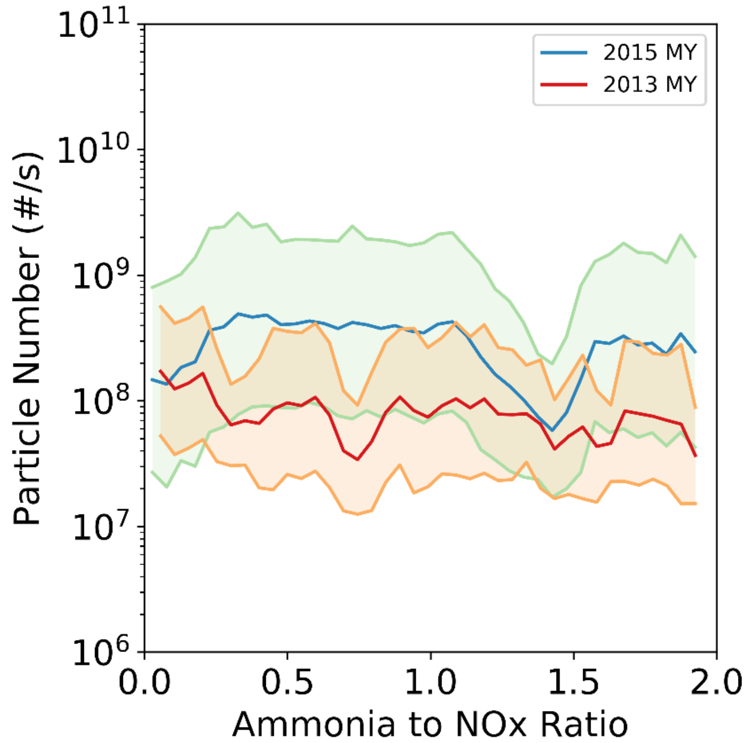
2013 MY Average PN
- November 17th, 2015
- Temperature: 52ºF

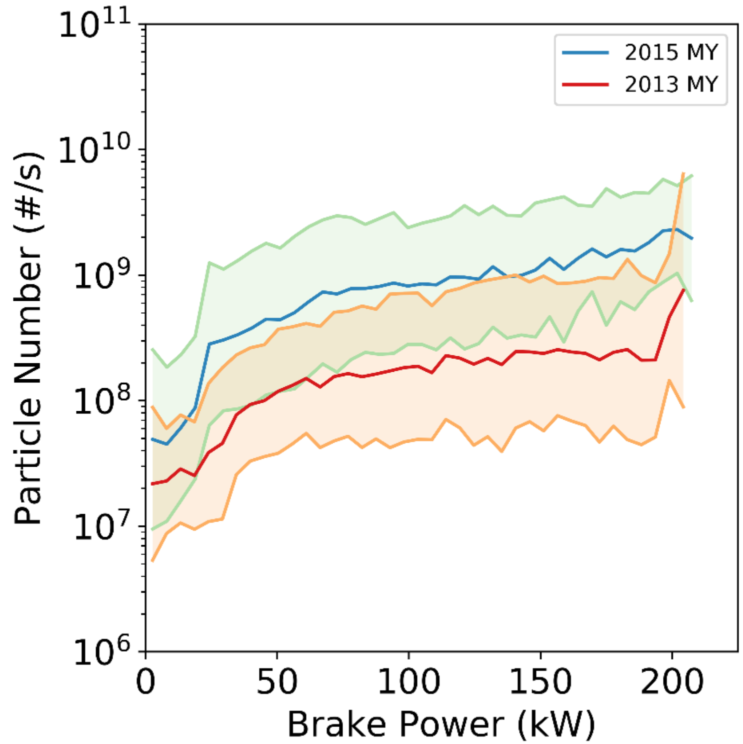


$$Kinetic\ Intensity, KI = \frac{Characteristic\ Acceleration}{Aerodynamic\ Velocity} = \frac{a}{v^2}$$

Particle Number Measurements

Post SCR Particle Count: Influence of ANR and power





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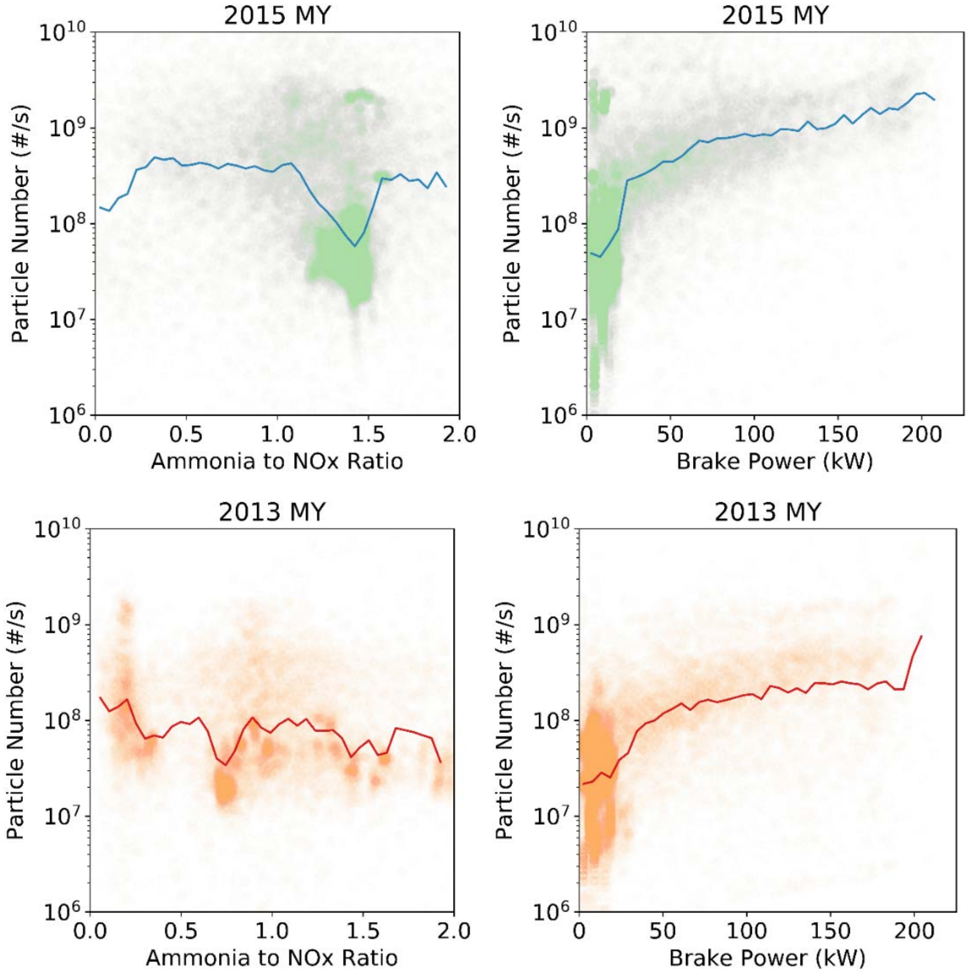
Density Plots

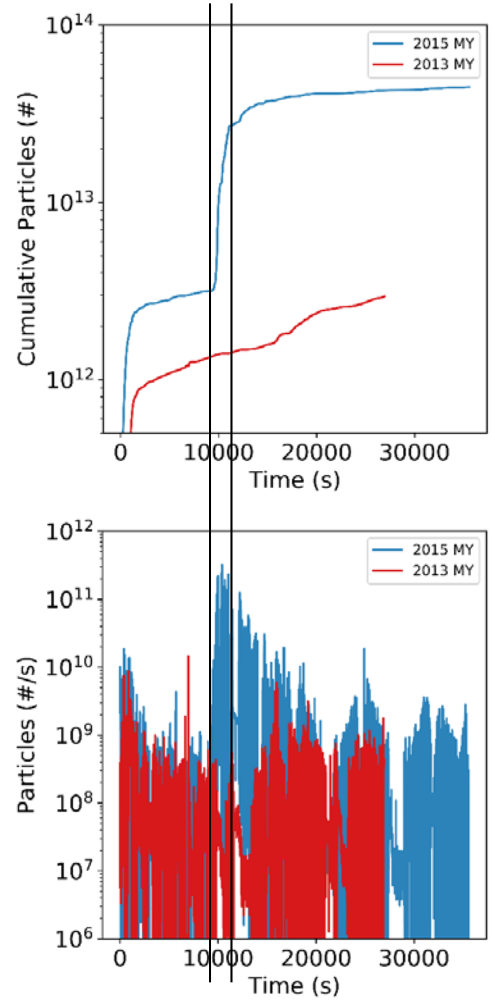
- Multiple formation modes
  - No clear trend with ANR
  - Increase with power
- 2015 MY Average PN
  - $1.27X10^{11}$ particles/kW-hr
- 2013 MY Average PN
  - $1.34X10^{10}$ particles/kW-hr
- Why are 2015 emissions higher?



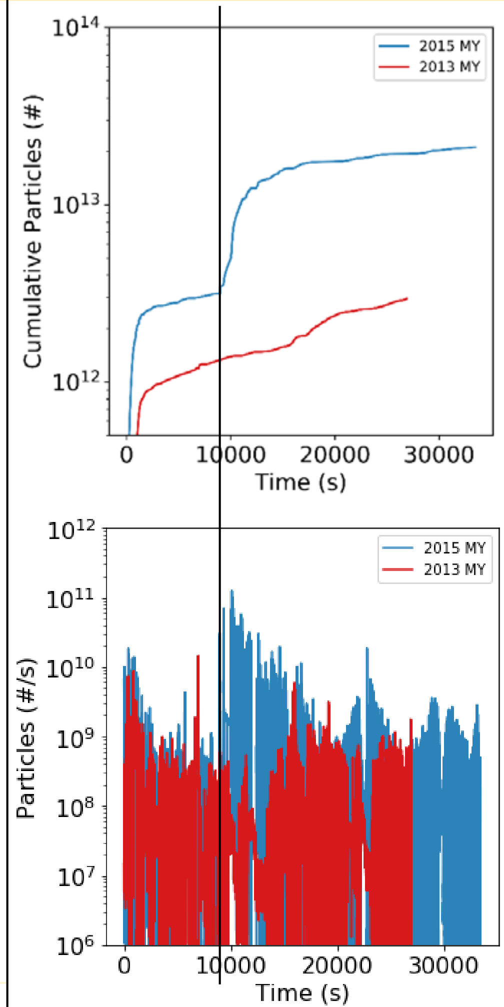
Regen Event

- 2015 MY Average PN
  - 1.27×10^{11} particles/kW-hr
- 2015 Regen Removed
  - 7.81×10^{10} particles/kW-hr
- 2013 MY Average PN
  - 1.34×10^{10} particles/kW-hr
- All values well below PMP heavy-duty standard
  - 6×10^{11} particles/kW-hr
- Strong influence of regeneration
  - Higher emissions continue after regeneration until soot cake develops
  - Somewhat higher emission even in absence of regeneration

Regen Event



Regen Removed



Expectations – VPR (CS) should remove semi-volatile particles

- On regeneration
  - Release of stored ***semi-volatile*** material
    - Sulfuric acid, ammonium sulfate
    - Heavy hydrocarbons adsorbed on soot
  - Removal of soot cake, ***solid particle release***
      - Some penetration of fragments of soot cake
      - Increased fresh soot penetration as soot cake is reestablished
  - Particles related to urea dosing
    - Incomplete evaporation / conversion leading to urea decomposition products, ***"solid" or semi-volatile***
    - At ANR > 1 ammonia penetration leading to ammonium sulfate, ammonium nitrate, ..should be ***semi-volatile***

Issues

- Nature of SCR related particles
  - Urea, ammonia related compounds “solid” or semi-volatile
    - TGA shows some urea related compounds less volatile than tetracontane
    - TGA may be poor predictor of behavior of suspended particles
    - Was PMP method intended to classify such particles as “solid”?
- Removal of semi-volatile material by VPR in this case catalytic stripper
  - Meets tetracontane removal specifications
  - Are “solid” particles during regeneration real or VPR overload*
- It would be useful to compare PN emissions from urea spray and gaseous ammonia SCR

*See for example: Johnson, et al., Aerosol Science and Technology, 43:962–969, 2009.
Swanson et al., Journal of Aerosol Science, Volume 41, Issue 12, Pages 1113-1122.

Summary

- Changes in SCR system between 2013 and 2015 MY led to more than 80% reduction in on-road NOx emissions
  - FTP certification levels essentially unchanged
  - Great improvement in real driving emissions
- However, these changes were associated with significantly higher PN emissions for 2015 MY bus
  - Not designed to meet PMP standard, but still well below standard
  - Increased ANR may play a role but decrease in emissions with ANR unexpected
  - Regeneration and associated higher emissions as soot cake redevelops main difference between 2015 and 2013 results but difference remains without regeneration
- This was preliminary study – additional work needed

Thank You

Questions?

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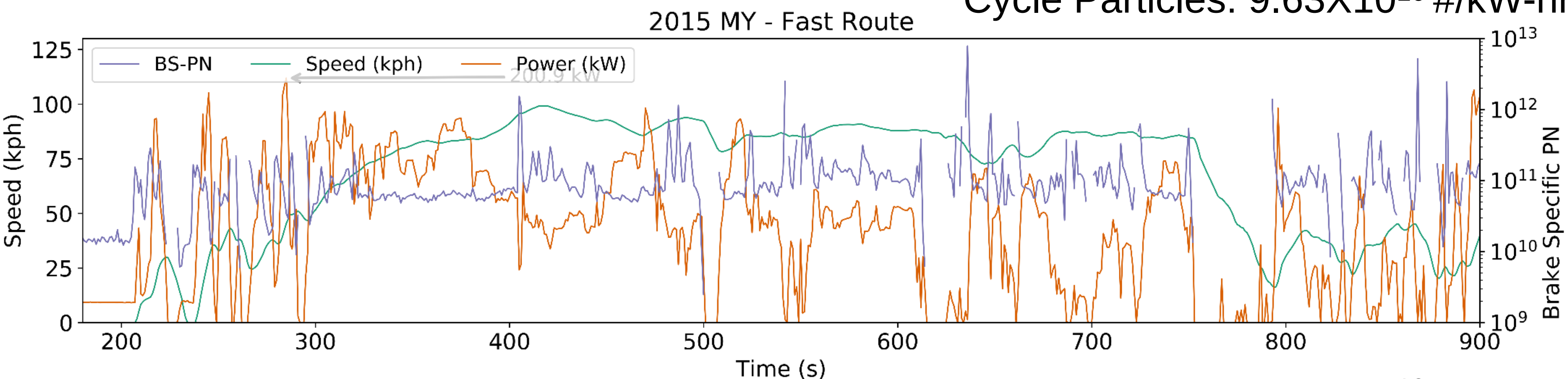
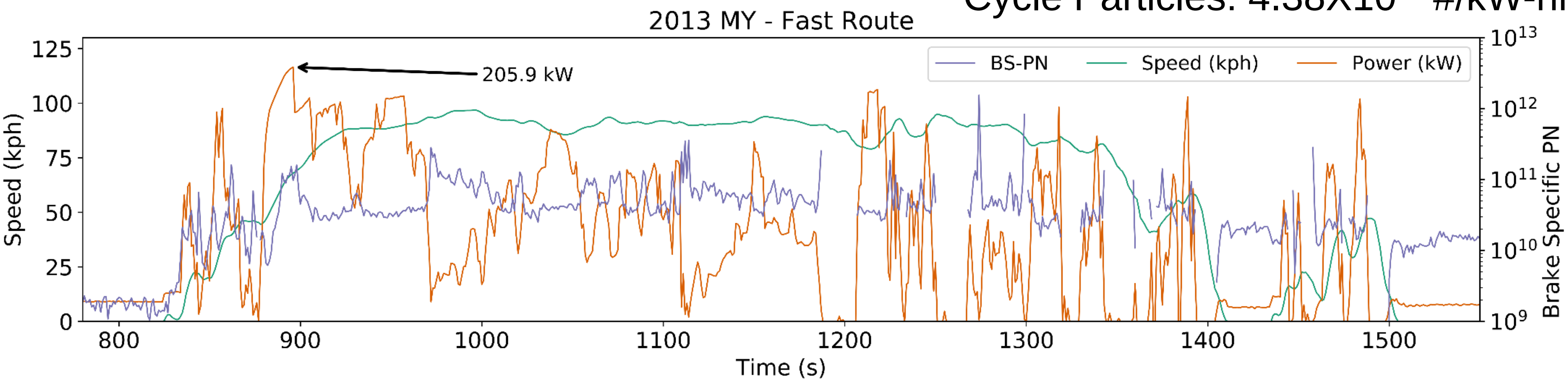
Drive Cycles – Fast Route

Cycle Particles: $9.63X10^{10}$ #/kW-hr



Cycle Particles: $4.38X10^{10}$ #/kW-hr



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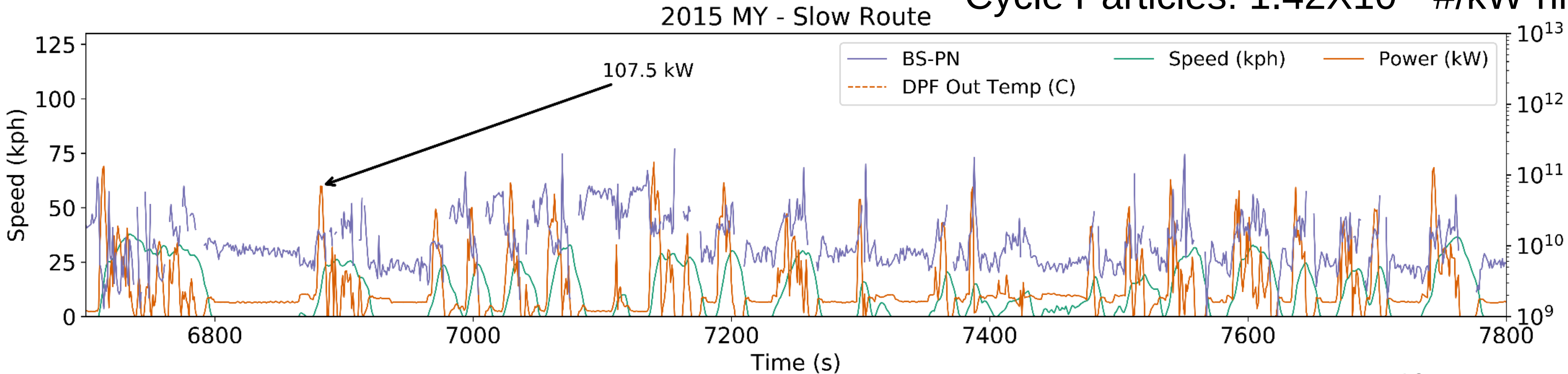
Drive Cycles – Slow Route

Cycle Particles: $1.42X10^{10}$ #/kW-hr



Cycle Particles: $1.00X10^{10}$ #/kW-hr