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

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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

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

![Graph showing NOx emissions comparison between 2013 MY and 2015 MY buses for different driving conditions.](image-url)
Test Vehicles

- 40’ GILLIG Buses
  - 8.9L Cummins ISL
  - 2013 certified
  - Emission control system consisting of DOC, DPF, SCR, and NH₃ slip catalyst

- Main differences between 2013 and 2015 MY emission control system, for 2015:
  - Remove NH₃ sensor
  - Model-based dosing
Instruments and Data Acquisition

- **Data Acquisition**
  - NI cRIO controllers
    - J1939 CAN interface – NO\textsubscript{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
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% NOx Reduction
  - 25% Dosing Increase
  - Average ANR >1
Engine Out vs Tailpipe NOX

- NOX 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 18\textsuperscript{th}, 2015
- Temperature: 48\textdegree F

2013 MY Average PN
- November 17\textsuperscript{th}, 2015
- Temperature: 52\textdegree F

\textbf{Low Speed Route}:
- Speed: 17mph
- KI: 2.4 m\textsuperscript{-1}

\textbf{High Speed Route}:
- Speed: 28mph
- KI: 0.6 m\textsuperscript{-1}

\textbf{Kinetic Intensity, }\text{KI} = \frac{\text{Characteristic Acceleration}}{\text{Aerodynamic Velocity}} = \frac{a}{v^2}
Particle Number Measurements

Post SCR Particle Count: Influence of ANR and power

![Graph showing particle number measurements vs. ammonia to NOx ratio and brake power.](image-url)

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Density Plots

- Multiple formation modes
  - No clear trend with ANR
  - Increase with power

- 2015 MY Average PN
  - $1.27 \times 10^{11}$ particles/kW-hr

- 2013 MY Average PN
  - $1.34 \times 10^{10}$ particles/kW-hr

- Why are 2015 emissions higher?
Regen Event

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

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?
Drive Cycles – Fast Route

Cycle Particles: $4.38 \times 10^{10} \text{#/kW-hr}$

2015 MY - Fast Route

Cycle Particles: $9.63 \times 10^{10} \text{#/kW-hr}$

2013 MY - Fast Route

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Drive Cycles – Slow Route

2015 MY - Slow Route

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

107.5 kW

2013 MY - Slow Route

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

122.1 kW