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Status Update on

Evaluating Technologies to Lower Nitrogen Oxide Emissions from Heavy-Duty Engines

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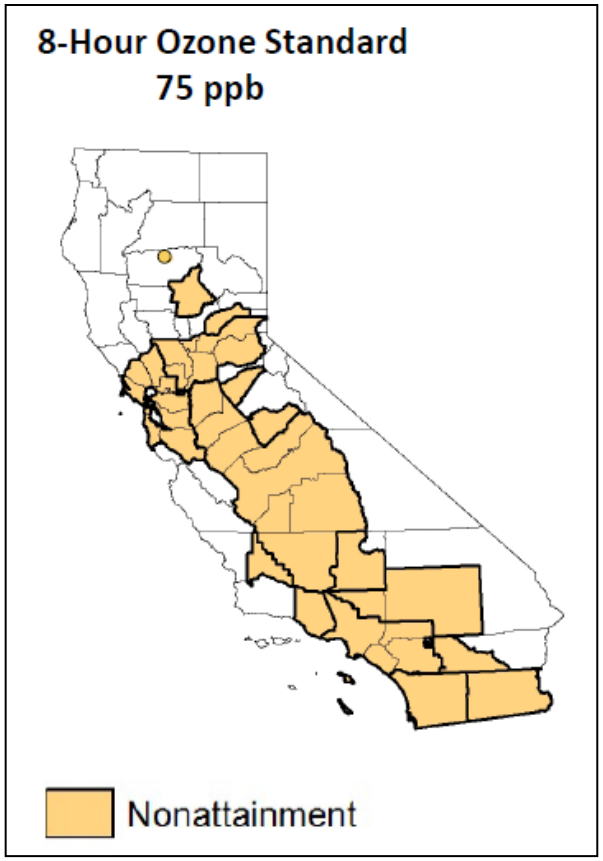
California Needs Significant Reduction in NOx

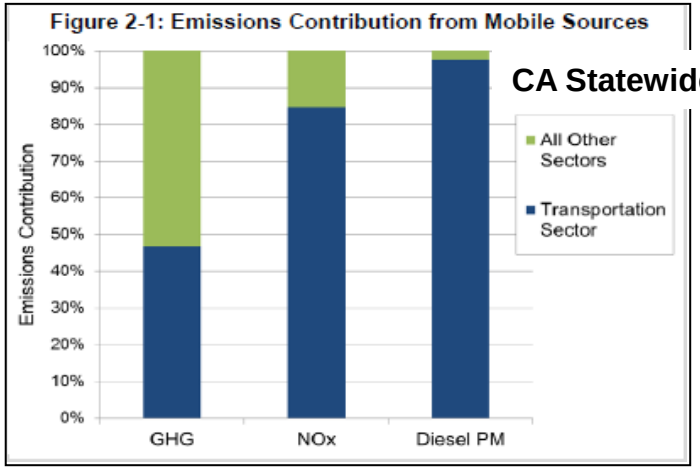
- California needs significant reduction in NOx emissions to meet the NAAQS for PM and Ozone (Source: Mobile Source Strategy, 2015)
  - South Coast Air Basin needs 80% NOx reduction from 2010 level by 2031
  - San Joaquin Valley needs similar magnitude of reduction in NOx

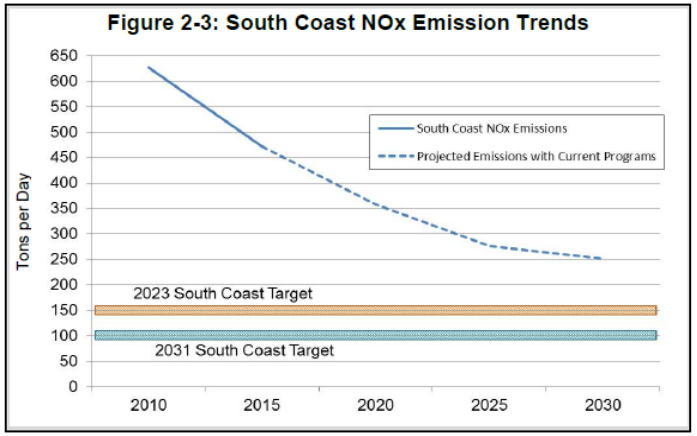


(Source: ARB 1-21-2016 Board Meeting)

Need Further NOx Reduction from HDTs

- Introduction of 2010 heavy-duty truck emission standards resulting in substantial reduction in NOx emissions
- Even further significant reduction in NOx emissions from heavy-duty trucks is needed to meet the NAAQS for PM and Ozone in California





(Source: Mobile Source Strategy, 2015)

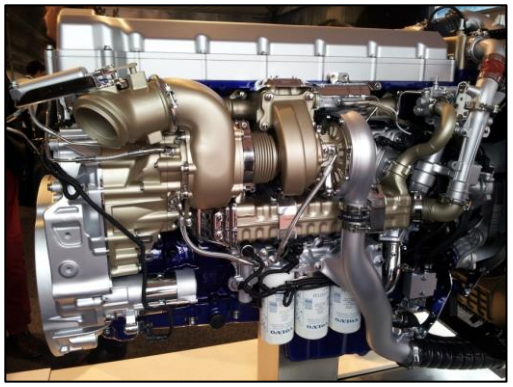
Research Objectives

- Explore and demonstrate the feasibility of significant NOx reduction through heavy-duty engine and aftertreatment (AT) control strategies
- Target the emission rate of 0.02 g/bhp-hr NOx over the FTP cycle
- Continue to meet all applicable emissions standards including HC, CO, PM, and GHG

Engines Selected

Diesel - 2014 Volvo MD13

- A diesel engine with cooled EGR, DPF and SCR
  - 361kw @ 1477 rpm
  - 2050 Nm @ 1050 rpm
- Representative platform for future GHG standards



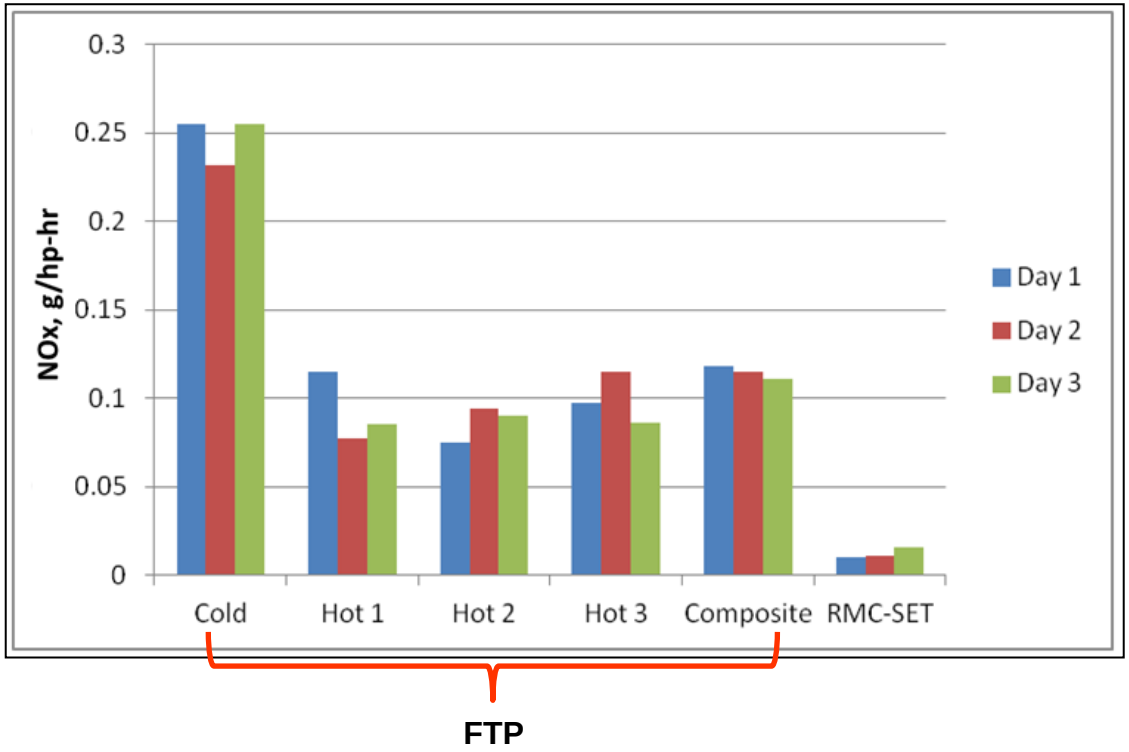
CNG – 2012 Cummins ISX12G

- A stoichiometric engine with cooled EGR and TWC
  - 250 kw @ 2100 rpm
  - 1700 Nm @ 1300 rpm
- Suitable for a variety of vocation types

Main Tasks

- Measure baseline emissions
  - Certification cycles: CARB Idle, FTP, RMC-SET, and WHTC
  - Low-load vocation cycles: NYBC, ARB Creep, and OCTA
- Develop engine and aftertreatment control strategies using:
  - A diesel engine provided by Volvo Group
  - A CNG engine provided by Southwest Research
  - Aftertreatment control systems provided by MECA
- Screen potential aftertreatment control strategies with a hot gas transient reactor (HGTR) burner system developed by Southwest Research
- Select final engine and aftertreatment control strategies
- Demonstrate the low NOx emissions with the final strategies

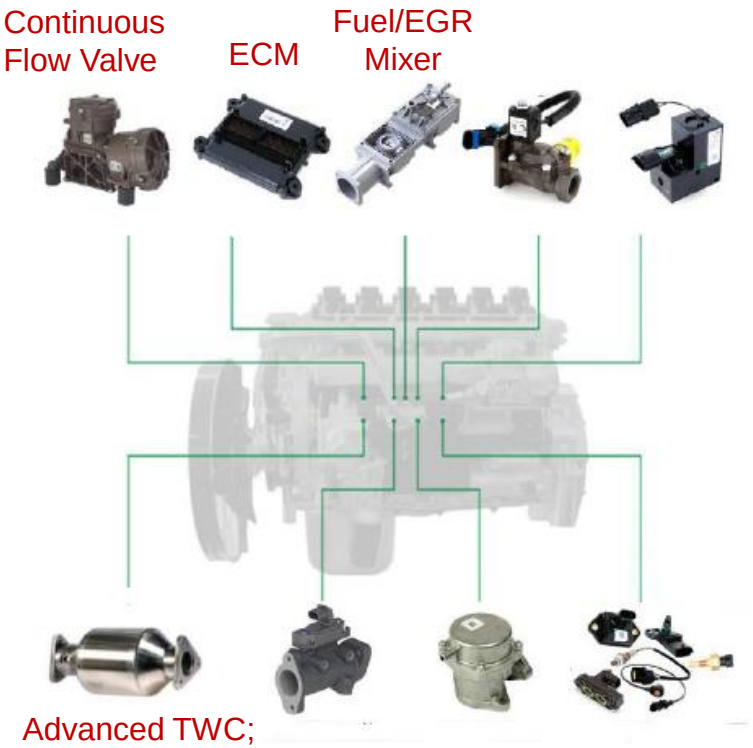
CNG Engine Baseline Emissions



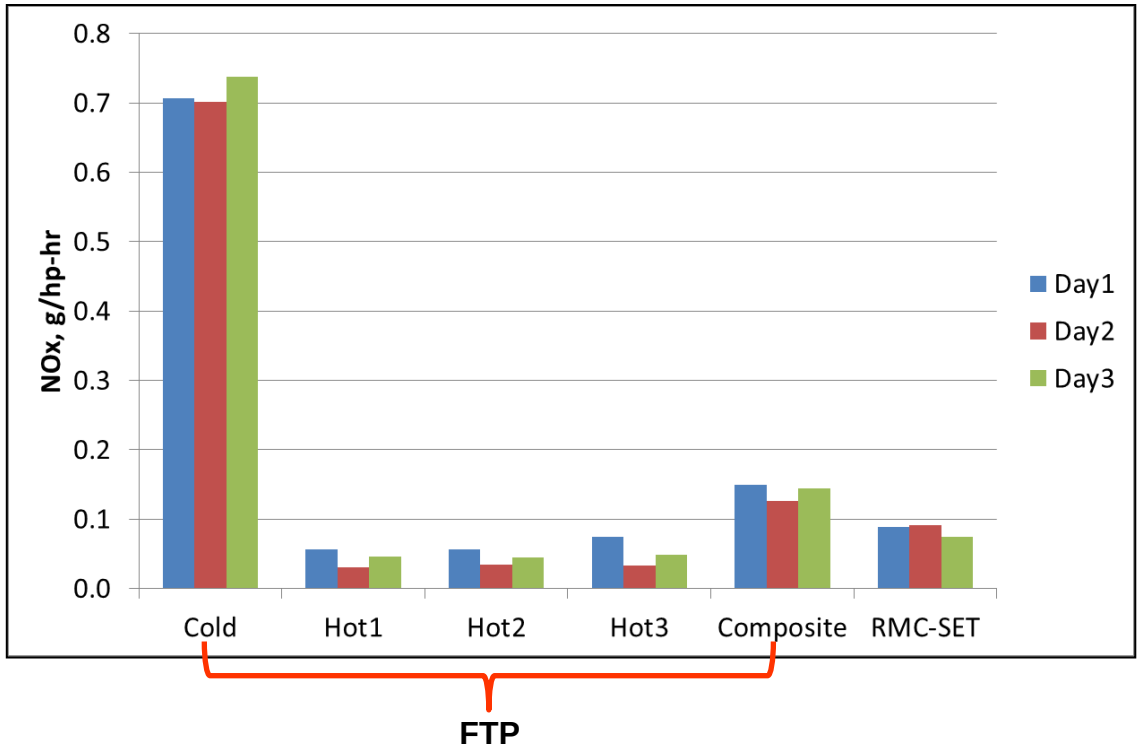
~3 times higher cold start NOx than hot start NOx

CNG Engine+Aftertreatment Control Strategies

- Cold start strategies
  - Faster light-off catalysts
  - Retard ignition timing
  - Increase idle speed
- Hot start strategies
  - Calibrate for close to zero NOx
  - Accurate air/fuel ratio control, including transients
  - Production/production intent hardware/software
- All CNG strategies will be considered as final without AT screening analysis



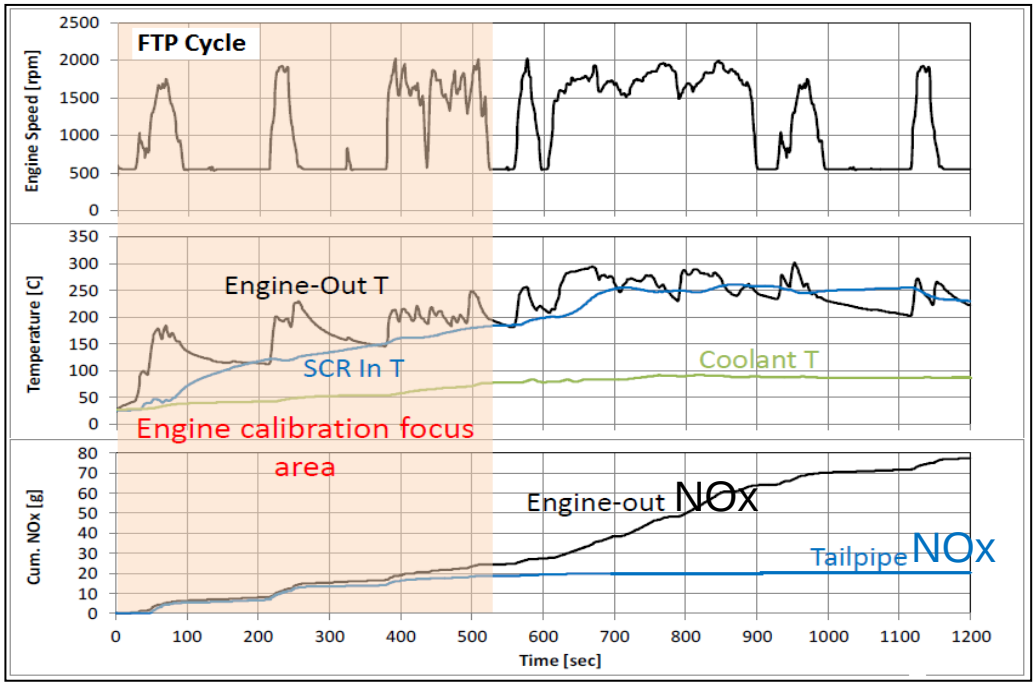
Diesel Engine Baseline Emissions



~14 time higher cold start NOx than hot start NOx

Diesel Engine+Aftertreatment Control Strategies

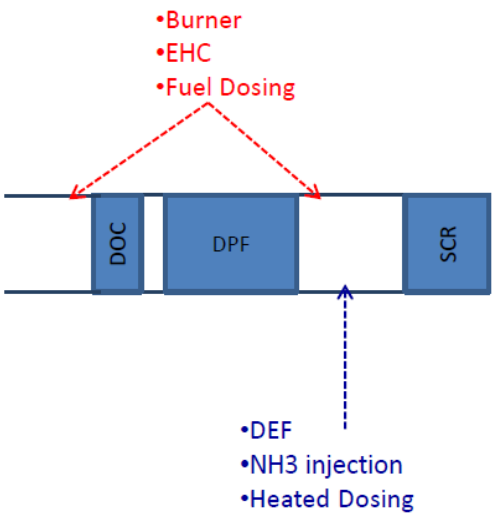
- Cold start strategies
  - Elevated idle speed
  - Early and increased EGR
  - Close-coupled SCR
- Hot start strategies
  - Configure AT for close to zero NOx
- Using the HGTR system* extensive AT screening analysis underway for selecting optimum NOx reduction configurations
  - Traditional system: DOC; DPF; SCR
  - Advanced system: SCRF; light-off SCR (LOSCR); passive NOx adsorber (PNA)
  - Low temperature control: heated DEF dosing; gaseous NH_3
  - Supplemental heat addition: EHC; burner



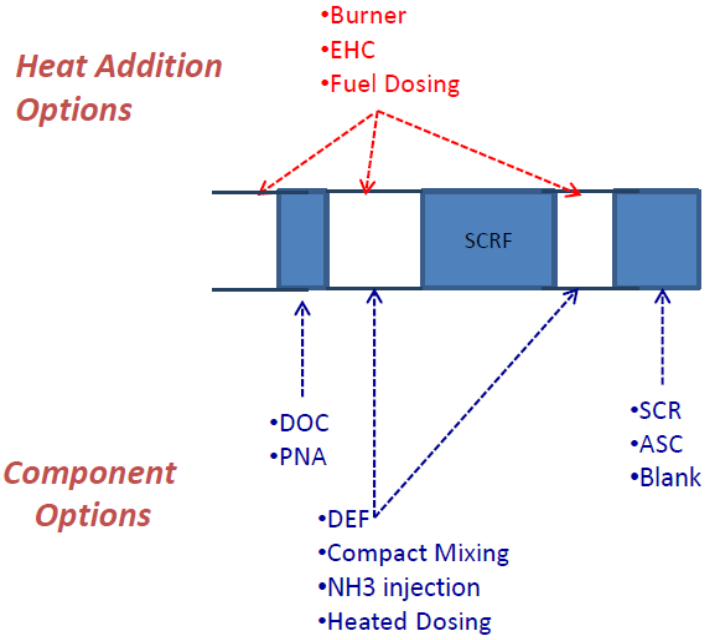
* See Appendix

Diesel Aftertreatment System Configurations

Traditional Approach

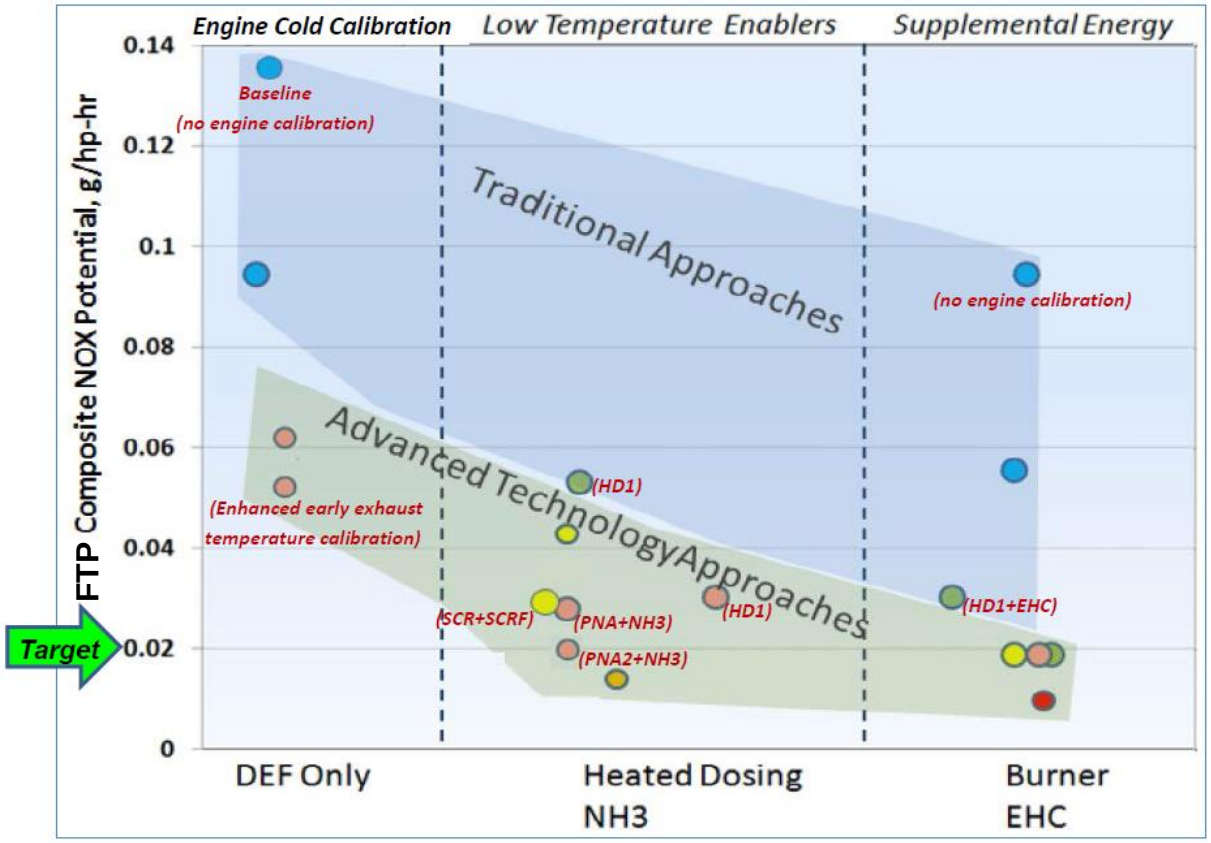


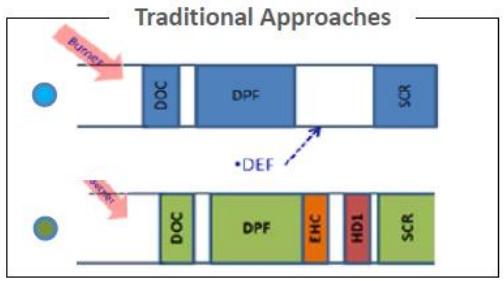
Advanced Approach

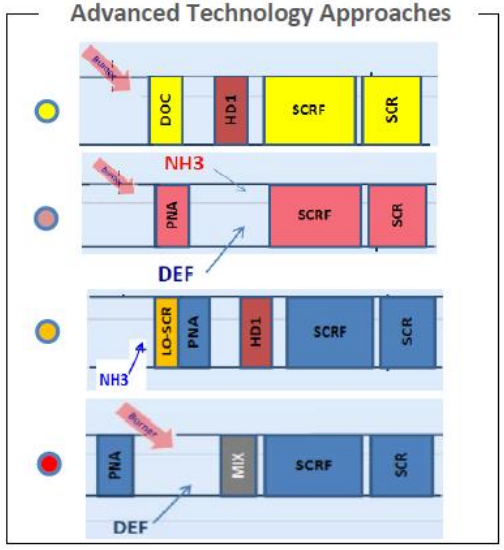


Examined 33 out of 500 possible configurations of component and heat addition options

Preliminary Test Results for Diesel Aftertreatment System Configurations







Acronyms

DOC: diesel oxidation catalyst; ***DPF***: diesel particulate filter; ***SCR***: selective catalyst reduction; ***Burner***: 10kw mini-burner; ***EHC***: electrically heated catalyst; ***HD1***: heated DEF dosing; ***SCRF***: SCR catalyst coated DPF; ***PNA***: passive NOx adsorber; ***PNA2***: PNA with altered catalyst formulation; ***NH3***: gaseous ammonia injection; ***LO-SCR***: close-coupled light-off SCR

Multiple pathways to achieve NOx emissions below 0.02 g/bhp-hr

Next Steps

- Select the final aftertreatment system configurations
- Fine-tune the engine calibrations to optimize for each final configuration selected
- Demonstrate low NOx emissions with the final engine and aftertreatment configurations
- Release the final study report to the public by the end of 2016
- Continue to update research progress through a public website at http://www.arb.ca.gov/research/veh-emissions/low-nox/low-nox.htm

Appendix

Hot Gas Transient Reactor (HGTR) Burner System for Screening Aftertreatment Configurations

- A computer controlled diesel-fueled burner system
- Designed to simulate the exhaust conditions for a wide range of engines and cycles
- A full size, continuous gas reactor for testing of full-sized catalyst systems