Lower NOx Heavy-Duty Diesel Engines

Technology Assessment

September 2, 2014

Sacramento, California

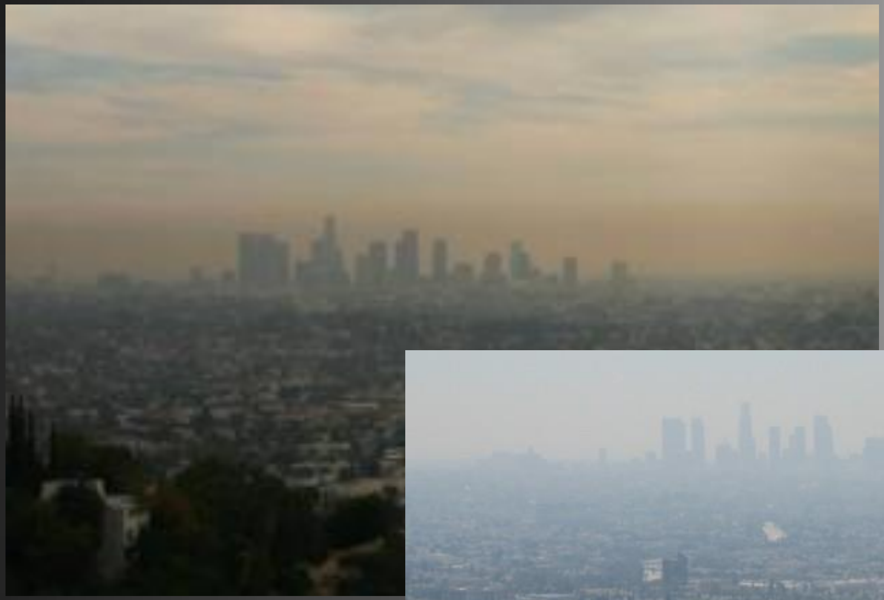
California Environmental Protection Agency

Air Resources Board

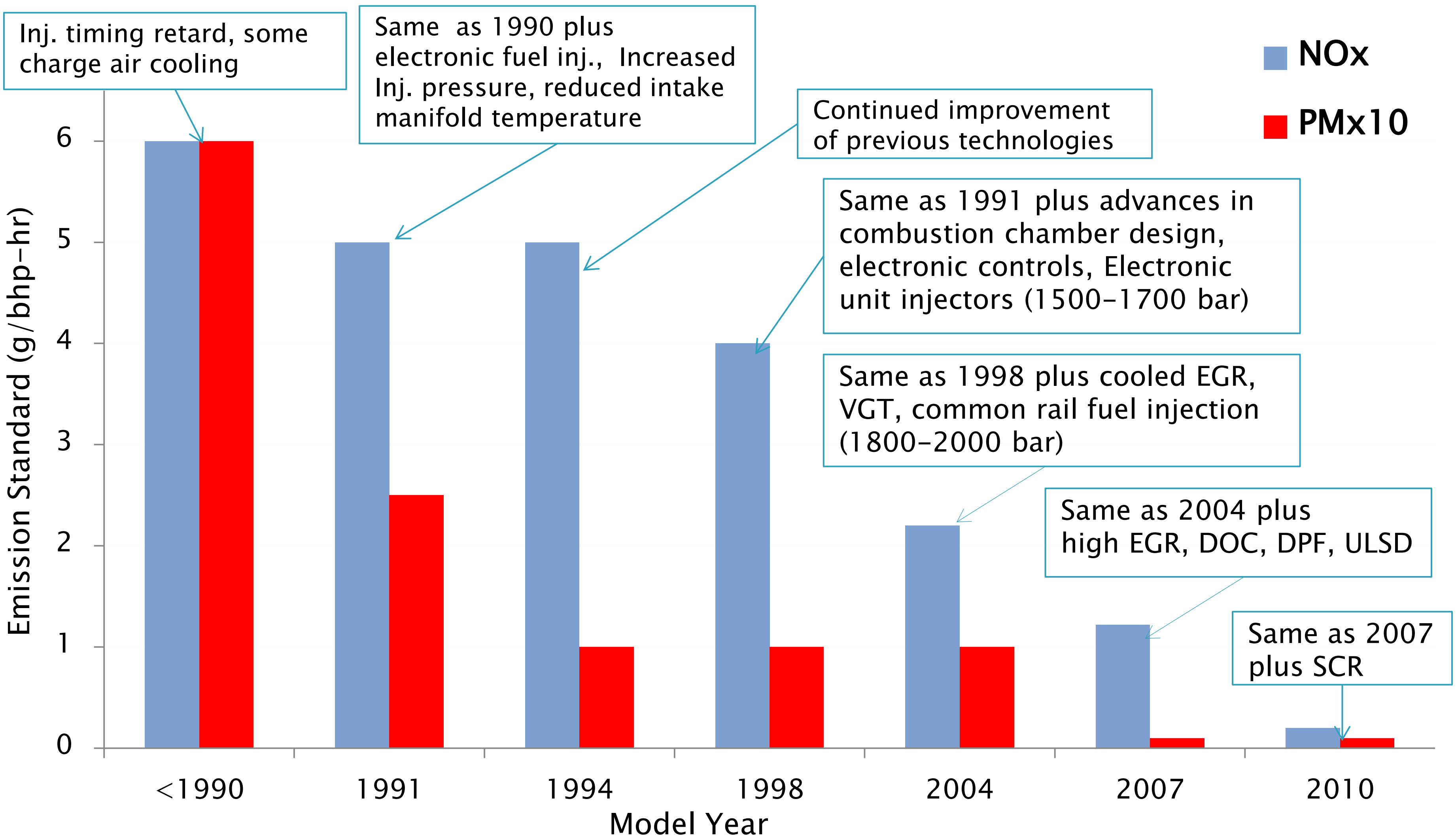
Overview

- Background
- Technologies Evaluated
- Approaches for NOx control
- Conclusion
- Contacts

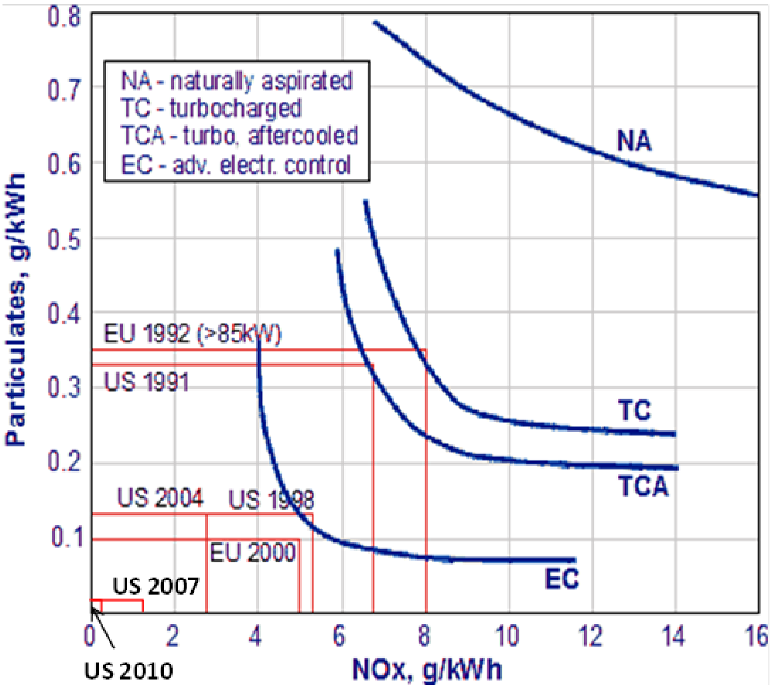
Background



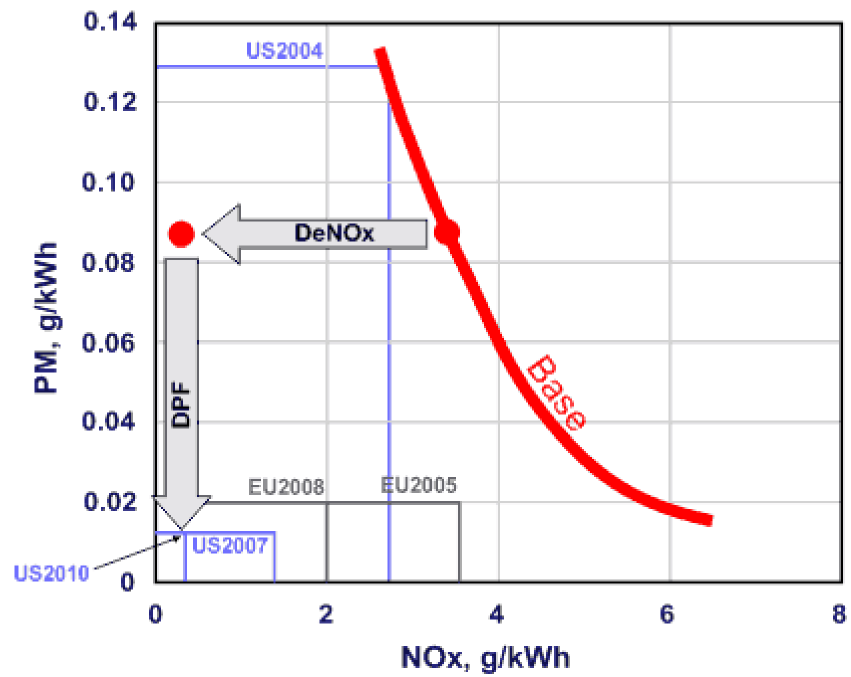
Evolution of Heavy-Duty Engine Standards and Technology



NOx–PM Trade–Off



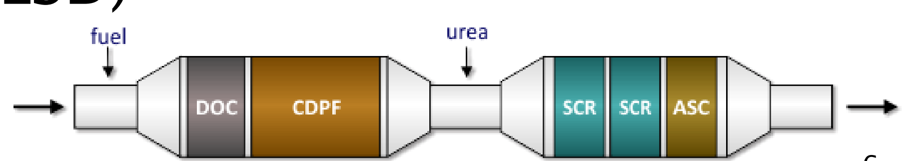
(Needham, 1991)



(dieselnet.com)

Current HDE Emission Control Technologies

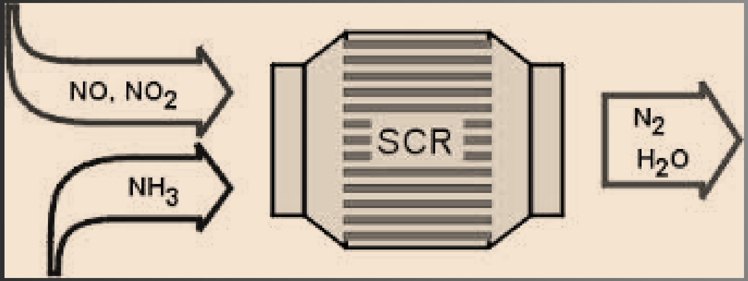
- Current heavy-duty engine emission standards
  - NOx: 0.2 g/bhp-hr; PM: 0.01 g/bhp-hr
- Technologies
  - Diesel Oxidation Catalyst (DOC)
  - Catalyzed Diesel Particulate Filter (CDPF)
  - Urea-Selective Catalytic Reduction (SCR)
  - Ammonia Slip Catalyst (ASC)
  - Cooled Exhaust Gas Recirculation (EGR), Variable Geometry Turbocharger (VGT), high pressure injection, and other engine strategies
  - Ultra low-sulfur diesel (ULSD)

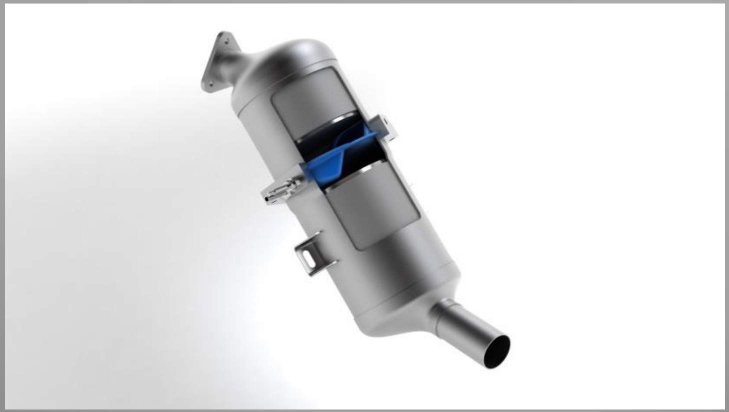


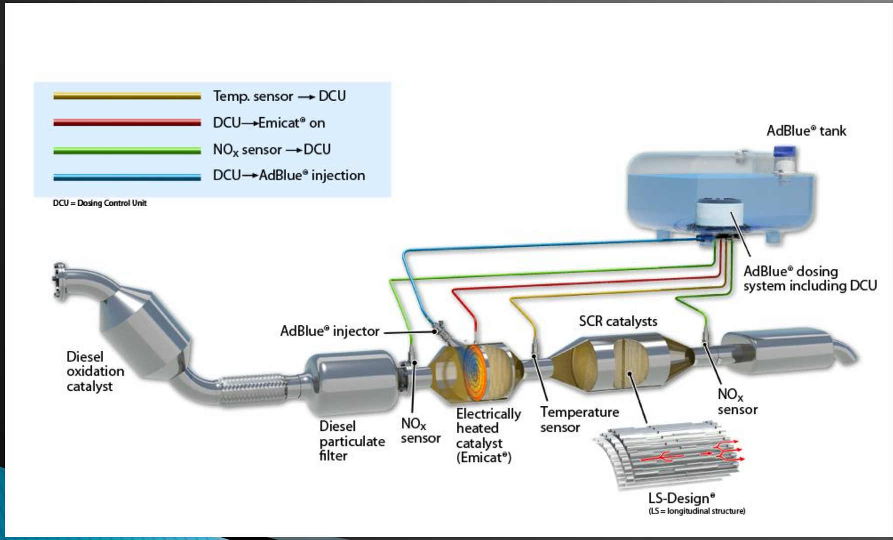
Achieving Low NOx Emissions May Require

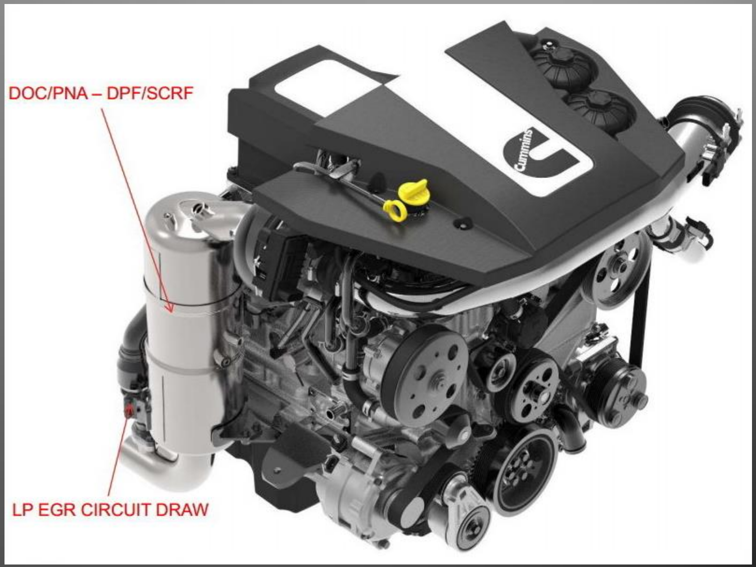
- Controlling cold start conditions
  - Controlling NOx during warm up
  - Accelerating catalyst warm-up
- Controlling NOx at low-load operations
- Maintaining high efficiency NOx control during fully warm operation
- Minimum fuel economy impact
  - Integration of engine control with aftertreatment system control key to achieving GHG and NOx control

Technologies Evaluated





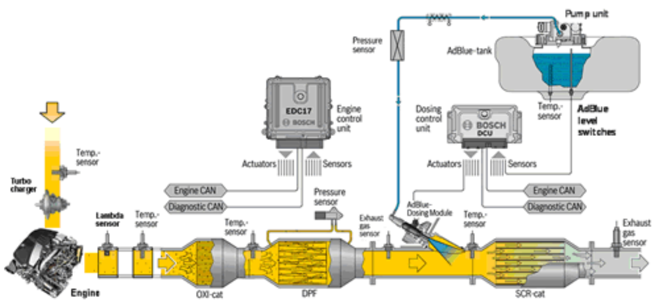




Technologies Evaluated

- Exhaust thermal management
  - Turbocharger control
  - Increased idle speed
  - In-cylinder post-injection
  - Intake throttling
  - More EGR

- Aftertreatment system
  - New SCR catalyst formulations
  - Close coupling
  - NOx storage catalysts
  - Alternatives to urea
  - Urea/ammonia (NH3) gas dosing
  - Exhaust system heat retention
  - Supplemental Heat



Exhaust Thermal Management

- Turbocharger control
  - Turbocharger bypass
    - Avoids heat loss through the turbine housing
    - Suitable at idle and cruise operations
  - VGT
    - Running high expansion ratios across the turbine
    - Imposes high loads on the variable geometry mechanism
    - Engine is made to work harder and therefore elevating exhaust temperature
  - Technology readiness: in production
- Increased idle speed
  - Enables an increase in the amount of fuel injected during idle
  - Technology readiness: in production

Exhaust Thermal Management (cont'd)

- In-cylinder post-injection
  - Fuel injected late in the combustion process, burns at the DOC increasing the exhaust temperature
  - Technology readiness: in production
- Intake throttling
  - Partially close air-intake throttle valve
  - Temporarily increases the fuel-air ratio and raises the exhaust temperature
  - Technology readiness: in production
- EGR
  - Dilute intake air with some fraction of exhaust gas
  - Lowers peak combustion temperatures
  - Lowers engine-out NOx
  - Technology readiness: in production

Aftertreatment System Urea-SCR Catalysts

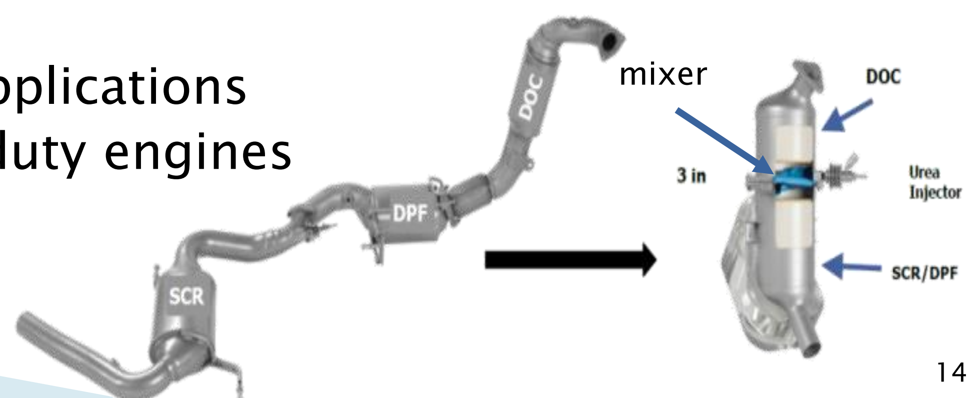
Urea-SCR catalysts in commercial use today	
Copper zeolite	◦ High performance at low temperatures ◦ High efficiency at high space velocity ◦ Little sensitivity to NO_2 concentration ◦ Susceptible to sulfur poisoning /requires occasional desulphation ◦ Does not create dioxins
Iron zeolite	◦ High performance at high temperature ◦ NO_2 management of the inlet gas needed for improved low temperature performance ◦ No sulfur poisoning but susceptible to moderate HC poisoning
Vanadia	◦ Cheapest of the catalysts ◦ Poor high temperature durability (deteriorates at 550°-600°C) ◦ Not utilized in systems with DPFs that require active regeneration (T>650°) ◦ Low temperature performance strongly depends on NO_2 availability

Aftertreatment System (cont'd)
New SCR Catalyst Formulations

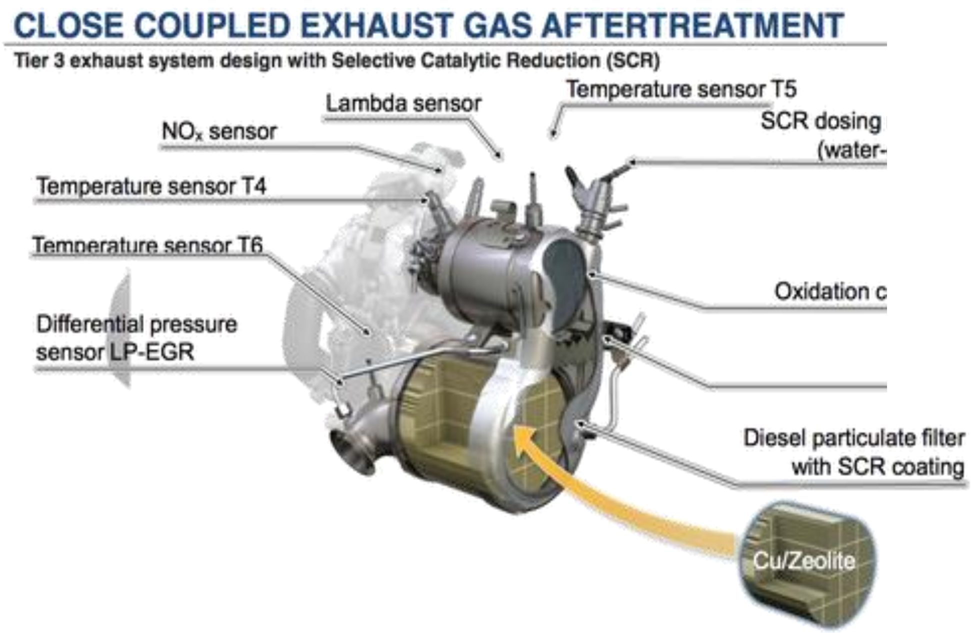
- Higher cell density with thinner substrate walls
  - Reduced thermal mass allowing rapid warm-up during cold start
  - Provide increased surface area per unit volume for efficient distribution of the active coating
  - Allow for sufficient contacting area between the exhaust gas and the active catalytic materials to provide improved performance
- Improved operating temperature windows on both the low temperature and high temperature sides of the SCR operating window
- Technology readiness: in development

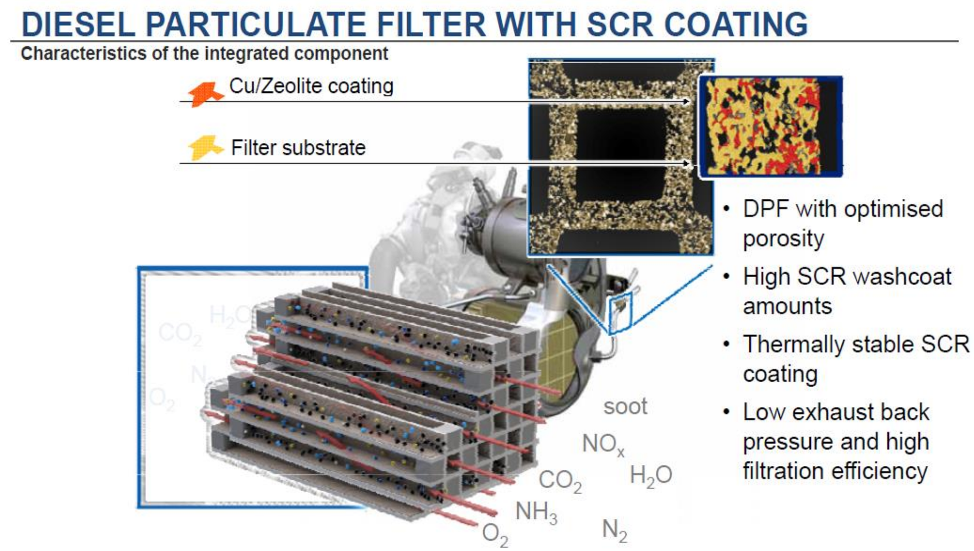
Aftertreatment System (cont'd)
Close-Coupled SCR on DPF

- SCR on filter (SCRF)
  - Reduced system size, weight, and cost
  - Enables close coupling to the DOC
  - Improved cold start operation
  - Higher exhaust temperatures for catalytic activity
  - May require additional downstream SCR to maximize NOx conversion
  - Compact mixer enables close-coupled system
  - Challenge: simultaneously reduce back pressure, improve DPF efficiency, and improve SCR thermal stability to withstand soot burn-off
  - Technology readiness:
    - commercial in light-duty applications
    - In development for heavy-duty engines



Aftertreatment System (cont'd)
Close-Coupled SCR on DPF

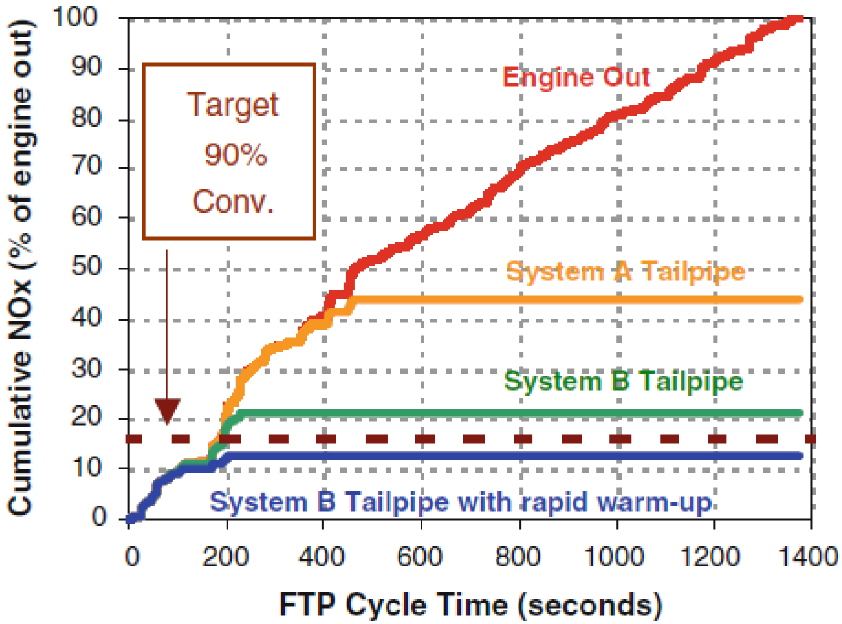




Close-coupled SCR on DPF on a VW diesel engine model EA288, 2015 Golf, Beetle, Passat, and Jetta
http://www.crcao.org/workshops/2014AFEE/2014AFEE.html

Aftertreatment System (cont'd)
Close-Coupled SCR Catalyst

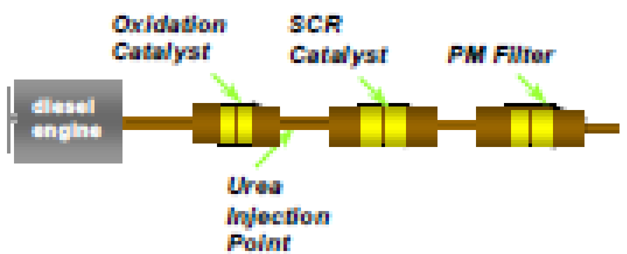
- SCR upstream of the DPF
  - Rapid warm-up
  - Improved NOx performance



Effect of Catalyst Placement in Exhaust System over FTP Light-Duty Cold Start Cycle (Dieselnet.com)

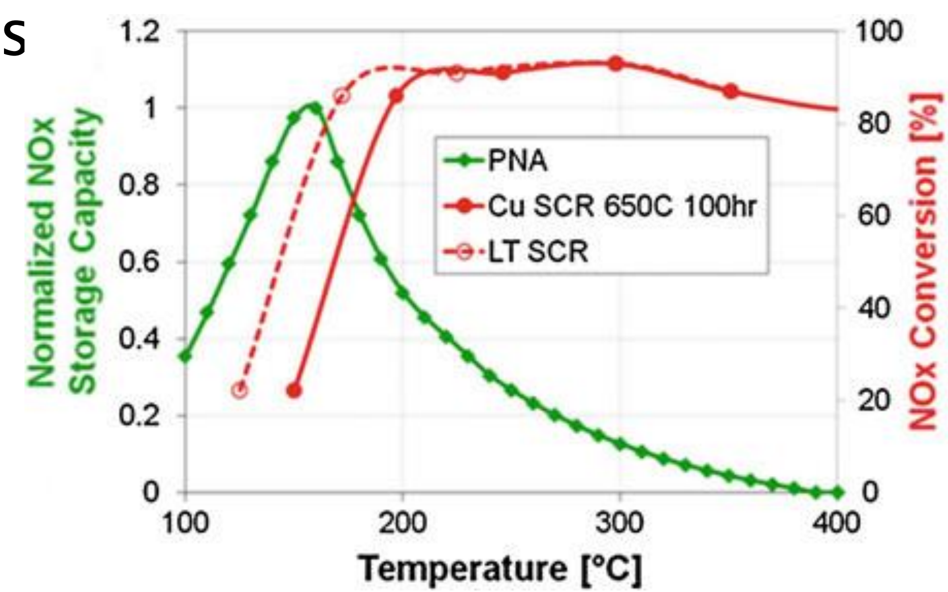
System A: DPF+SCR

System B: DOC+SCR+DPF



Aftertreatment System (cont'd)
NOx Storage Catalysts

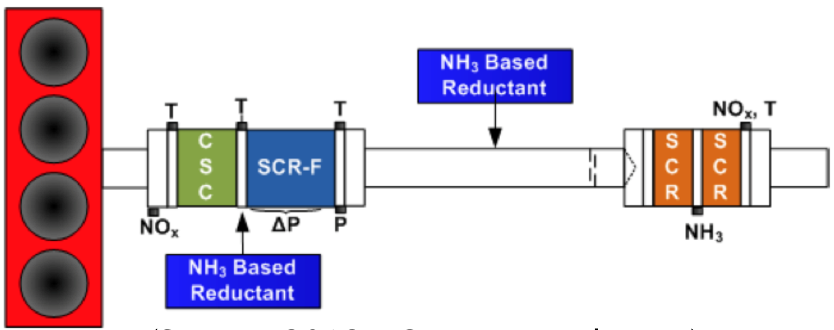
- Passive NOx Adsorbers (PNA)
  - Placed upstream of the SCR
  - Stores NOx during cold operation and releases it as exhaust temperature rises
  - SCR reduces the NOx upon release
  - Technology Readiness
    - in development



Source: DEER 2011, Henry et al

Aftertreatment System (cont'd)
NOx Storage Catalysts

- Cold Start Concept Catalyst (CSC™)
  - Advancement beyond PNA
  - Stores HC/NOx at low temperatures at high storage efficiency
  - Converts a significant portion of the stored HC/NOx during the warm up period
  - High HC/NOx release temperature enabling further conversion by downstream catalyst
  - Also functions as a DOC, after warm-up
  - Technology readiness:
    - in development

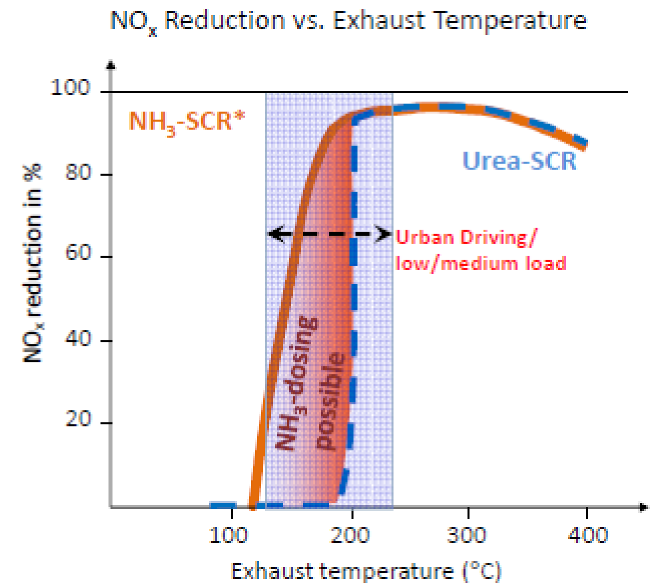


(Source: 2012 DOE AMR, Ruth, M.J.)

*CSC™ is a trademark owned by Johnson Matthey (SAE 2013-01-0535)

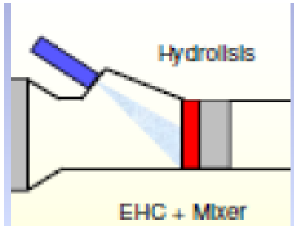
Alternative Sources for Ammonia

- Solid ammonia storage materials
  - Ammonium salts and Metal ammines
- Direct dosing of NH3 gas
- Enable SCR to function better at low exhaust temperatures
- Decrease the size/cost of the dosing system
- Enable use of the system at very low ambient temperatures
- Low risk of deposits in the exhaust line
- Technology readiness:
  - in demonstration (Amminex™ System)

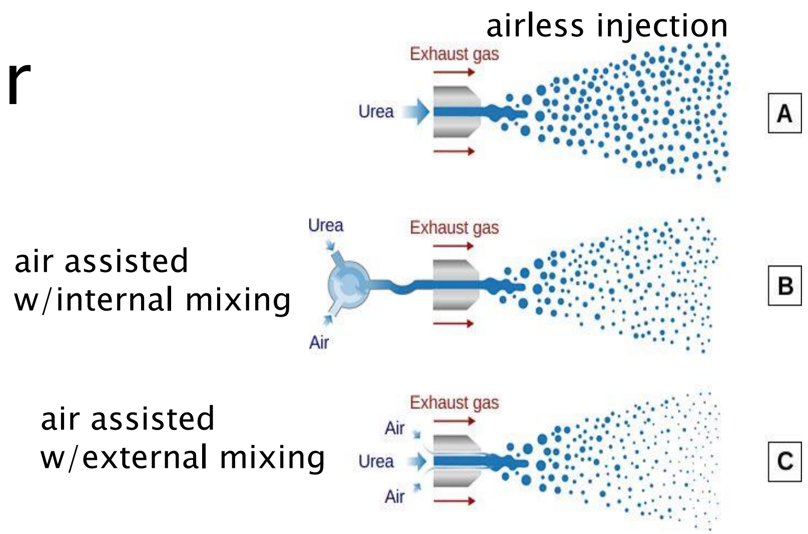


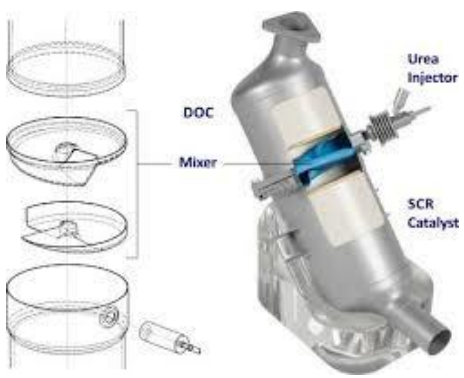
Urea Delivery System

- Heated doser
- Air assisted/ Airless doser
- Compact mixer
- Urea injectors
- Control Strategies
  - Open loop control
  - Closed loop control
  - Sensors for SCR Control
    - NOx sensors
    - NH3 sensors
  - Technology readiness:
    - in production/continuous development



Heated doser

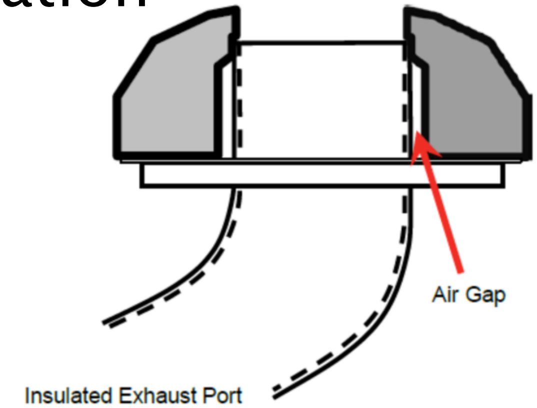




Compact Mixer

Exhaust System Heat Retention

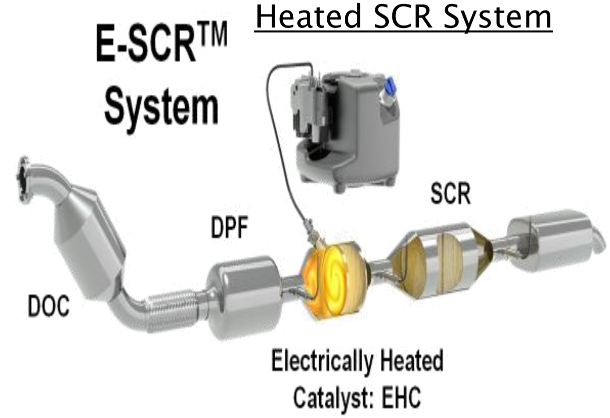
- Air gap-insulated, double-walled exhaust manifolds
  - Reduces the amount of heat absorbed by the walls
  - A very thin inner wall (low thermal mass) to limit heat loss to the walls
  - An air gap between the inner and outer wall
  - Disadvantages: Cost and durability
  - Technology readiness: in demonstration

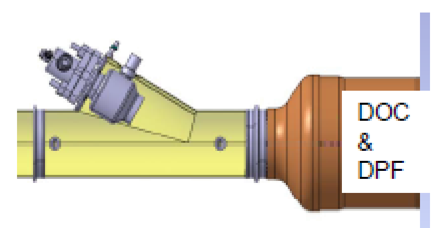


Supplemental Heat

- Electrically heated catalyst (EHC)
  - Fast light-off during cold start or light load operations
  - No secondary emissions
  - Limited power
  - Technology readiness:
    - in production
- Fuel burners
  - Very rapid light-off
  - High power Output
  - Issues:
    - Coking
    - Air Supply/complex
    - HC slip may affect cold SCR efficiency
  - Technology readiness:
    - in production (for DPF regeneration)

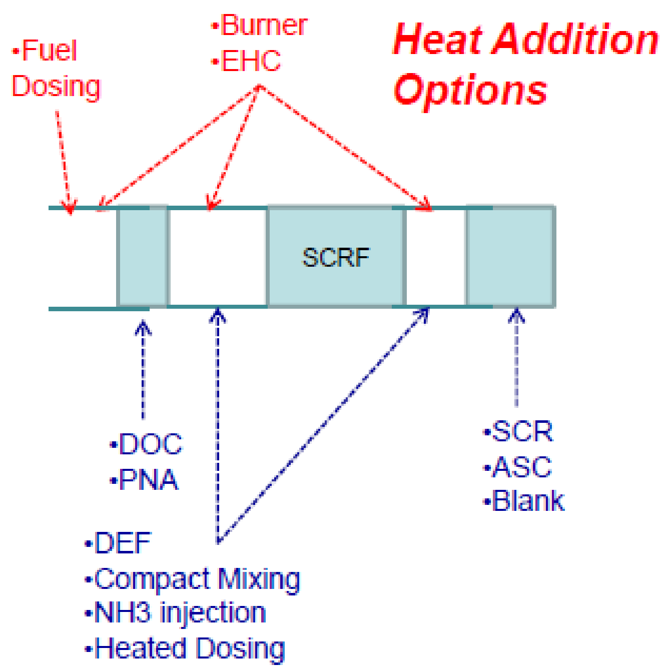
Emitec Heated SCR System





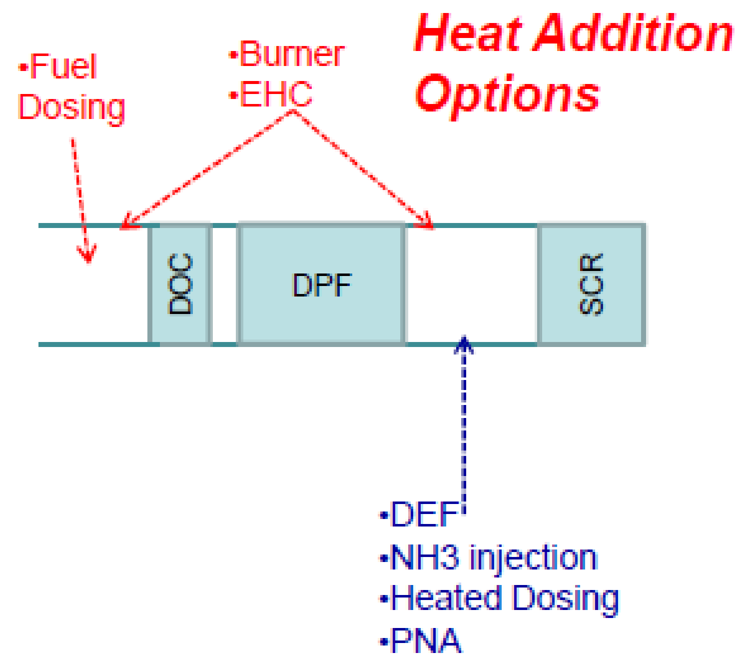
Options for Advanced SCR Configurations

Advanced Technology Approaches



Component Options

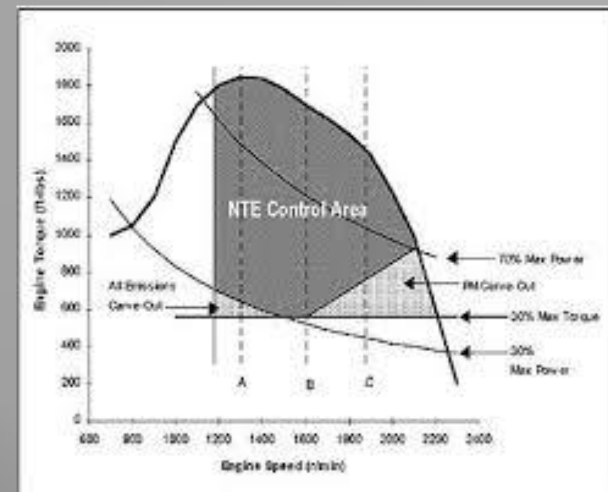
Traditional Approach with Options

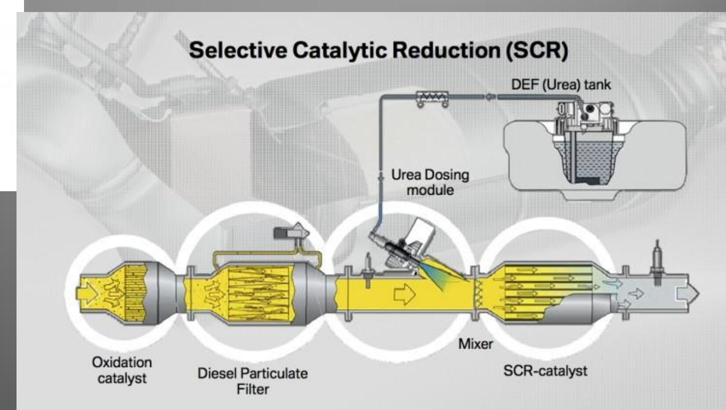


Component Options

Technology options currently being screened as part of the ARB/SwRI Low NOx program.

Approaches for NOx Control





Future Approaches for NOx Control

- Reduced NOx standard
- Strengthen standards
- Encourage innovations

Reduced NOx Standards

NOx–GHG Trade-Off

- Possible GHG impacts from some NOx control measures
  - Exhaust thermal management
  - Supplemental heat for aftertreatment system
- Possible NOx impacts from some GHG control measures
  - Waste heat recovery
- Many NOx reduction technologies have no GHG impacts
  - Catalysts, exhaust system insulation
- Some technologies reduce both GHG and NOx emissions
  - Stop-start technology, Reduced engine friction

Reduced NOx Standards

- Need for a balanced approach to maximize both NOx and GHG reductions
  - System integration critically important
  - Engine management/aftertreatment control need to accommodate engine use variability for in-use performance and emissions control
- ARB funding study with SwRI
  - Target: 0.02 g/bhp NOx with minimal GHG impact
- Optimistic that diesel engines can meet very low NOx levels of 0.02 g/bhp-hr

Strengthen Standards

- Improve certification and durability requirements
  - Durability testing
  - Warranty
- Address low-temp/low load NOx issues
  - Supplementary certification test cycles
  - Expand NTE zone(s) to capture broader events
  - PEMS-based in-use compliance testing

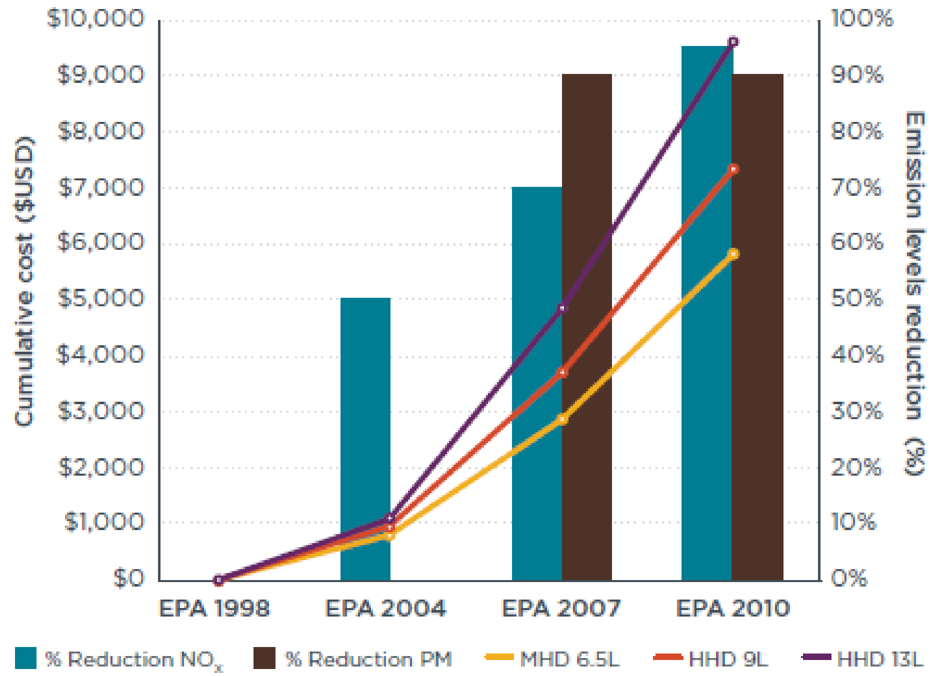
Encourage Innovation

- Evaluate ways to encourage zero and near-zero technology development and commercialization
- Public sector investments
- Recognize innovative technologies
  - Develop tiered certification process for new technologies, ramp up requirements as market develops
- Encourage efficiencies
  - Automation, packaging, communications
- Foster sustainable transportation solutions
  - Engines, vehicles, fuels, efficiencies

Conclusions and Contacts

Cost

- US 2010 HD engine
  - Urea-SCR system
  - $3,000 to $4,500 more expensive than 2007 HD engine, depending on engine size



*Source: Revising Mexico's NOM 044 standards, ICCT, 2014

Conclusions

- Even with advanced technologies (hybrid, battery, fuel cell), combustion engines will continue to play major role
- Diesel engines are significantly cleaner than they were in the past decade
  - Additional reductions needed to meet air quality and GHG goals
- ARB funding research to demonstrate feasibility of low-NOx
- Technology developments are promising
  - Further engine refinement and improvement in exhaust aftertreatment and control
  - Integrating OBD, improved sensors with lower NOx engines
- Need to both reduce new engine standards and address in-use emissions to ensure standards achieved in real world
  - Systems integration necessary to achieve maximum NOx and GHG reductions

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- Submit comments by Oct. 1 to: http://www.arb.ca.gov/msprog/tech/comments.htm