2007-2009 USA Emission Solutions for Heavy-Duty Diesel Engines

Jeffrey A. Leet

Engine Research Department

Engine & Vehicle Research Division

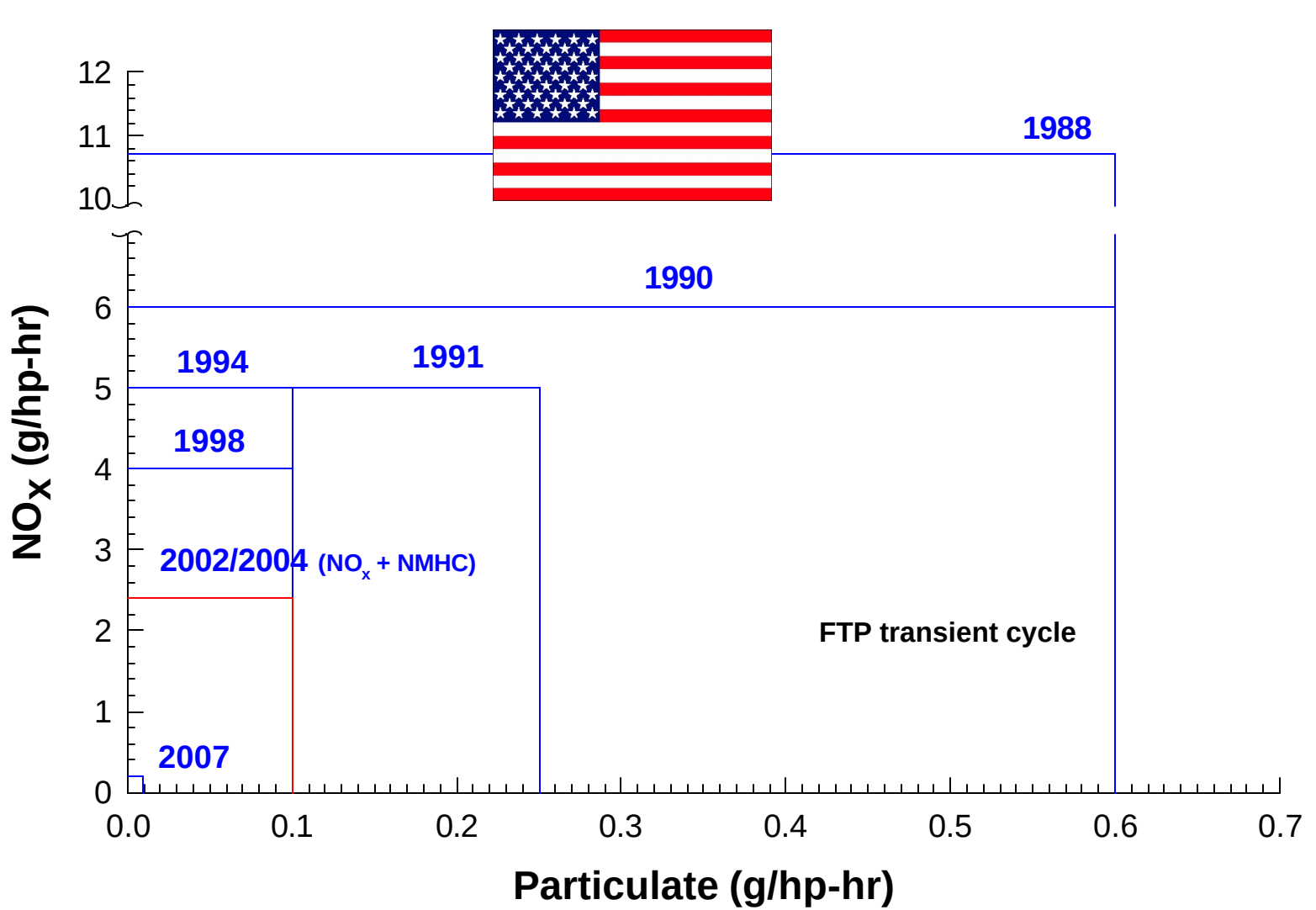
Southwest Research Institute®

2002 Diesel Engine Emissions Reduction Conference
August 26, 2002

Outline

- USA Emissions Standards
- Hypothesis
- Background
- Control Technologies
  - In-Cylinder
  - Exhaust Treatment
- Summary

USA On-Highway Heavy-Duty Emission Standards



EPA Standards for HDE's in 2007

- PM = 0.01 g/hp-hr effective 2007 (100% of engines)
- Phase-in for diesel engine NO_x and NMHC is:
  - 2007: 50%*
  - 2008: 50%*
  - 2009: 50%*
  - 2010: 100%*

  *percentage of fleet sold
- There are no technology provisions for the phase-in engines

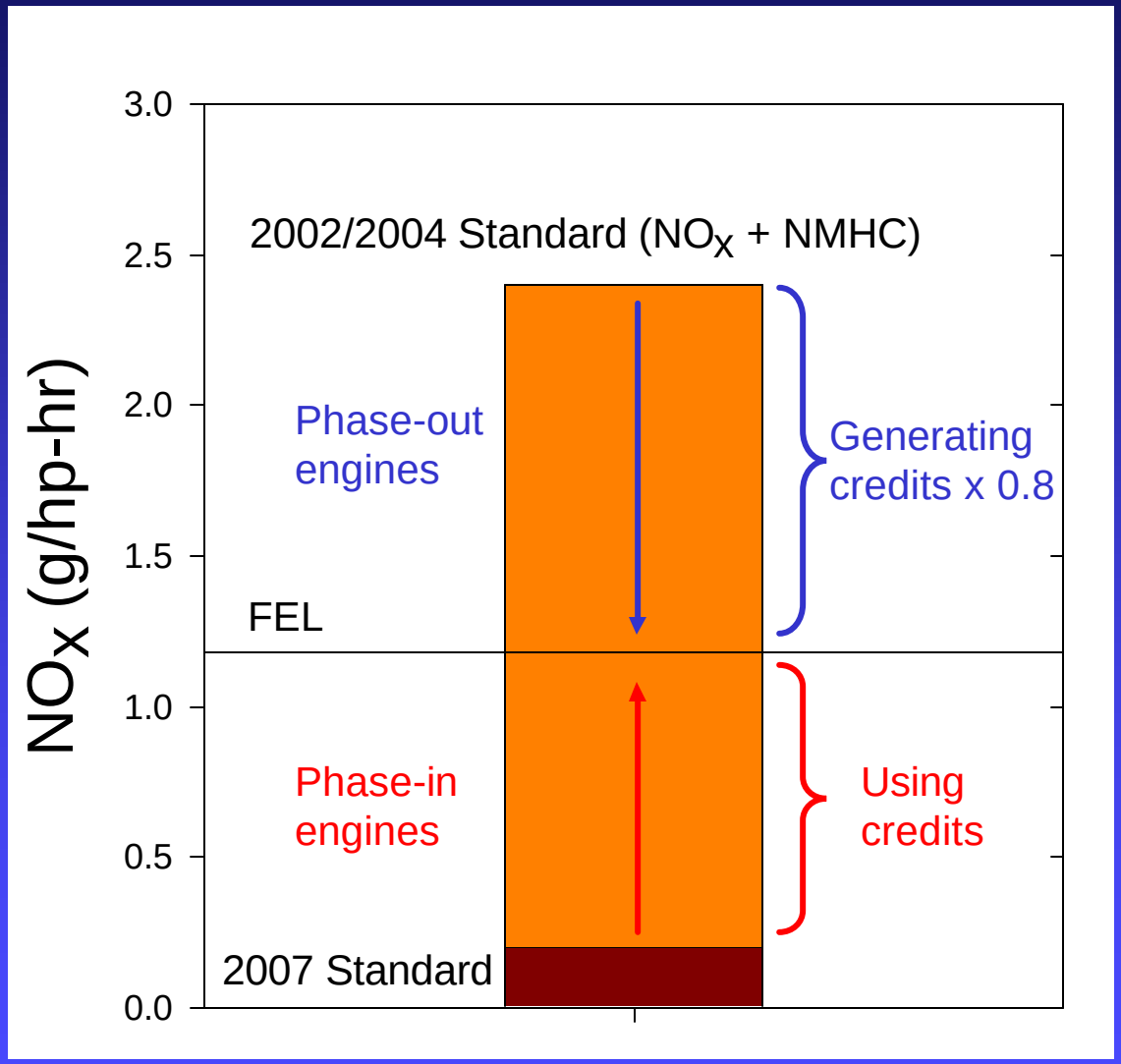
EPA Standards for HDE's in 2007 (cont.)

- Emissions tracked by Family Emissions Level (FEL), similar to "fleet average"
- In addition, engine manufacturers must also comply with:

Procedure	Limits	Emissions (g/hp-hr)
Supplemental Test Procedure (European Stationary Cycle)	1.0 x FTP	NOx = 0.2
		PM = 0.01
		NMHC = 0.14
		CO = 15.5
Not-to-Exceed (NTE)	1.5 x FTP	NOx = 0.3
		PM = 0.015
		NMHC = 0.21
		CO = 23.25

More severe than Euro V!

Implementation of 2007 Standards



Hypothesis

- **The USA 2007-2009 emission standards for heavy-duty diesel engines can be achieved with minimal or no exhaust treatment for NO_x**
  - ***It is assumed that a Catalyzed Diesel Particulate Filter (cDPF) will be required to achieve 0.01 g/hp-hr Particulate Matter (PM)***

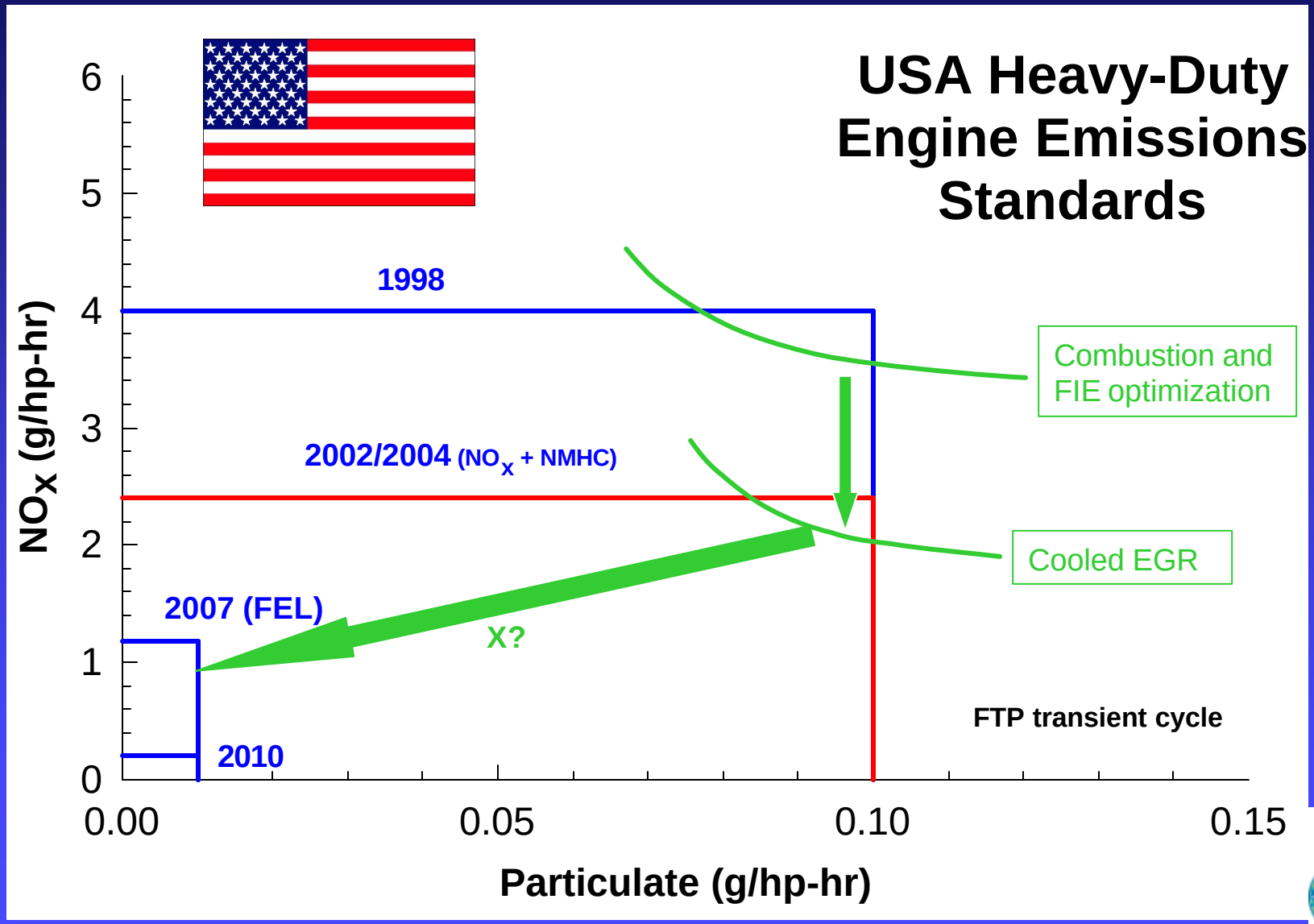
Background

- 90%+ reductions are required in 2010 to be demonstrated across:
  - cold- and hot-start FTP's
  - ESC
  - NTE
- Without Homogenous Charge Compression Ignition (HCCI), in-cylinder controls, alone, will be unable to achieve 2010's levels
- Exhaust treatment systems have demonstrated ability to achieve 2010 but many issues remain:
  - cost
  - regeneration
  - packaging
  - fuel consumption penalty

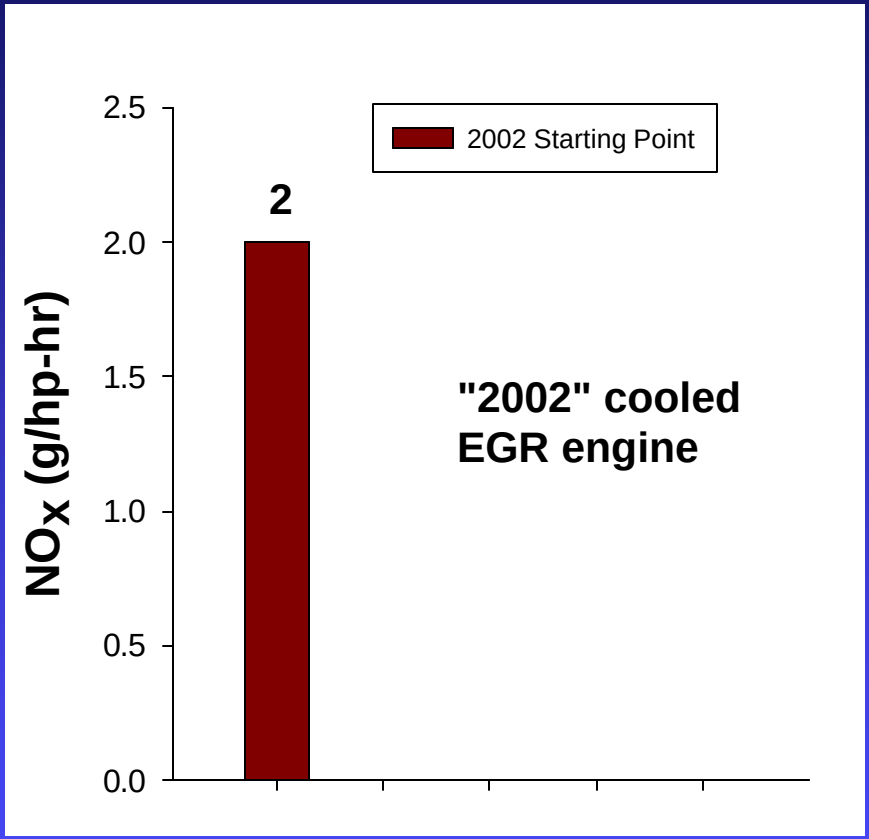
Background (cont.)

- A systems approach will be required in order to comply with the 2007 and 2010 standards
  - In-cylinder methods
  - Exhaust treatment methods
- SwRI believes that further reductions of in-cylinder (engine-out) NO_x emissions are possible and cost effective

2007-2010 Regulations



2007-2009: What's Possible?



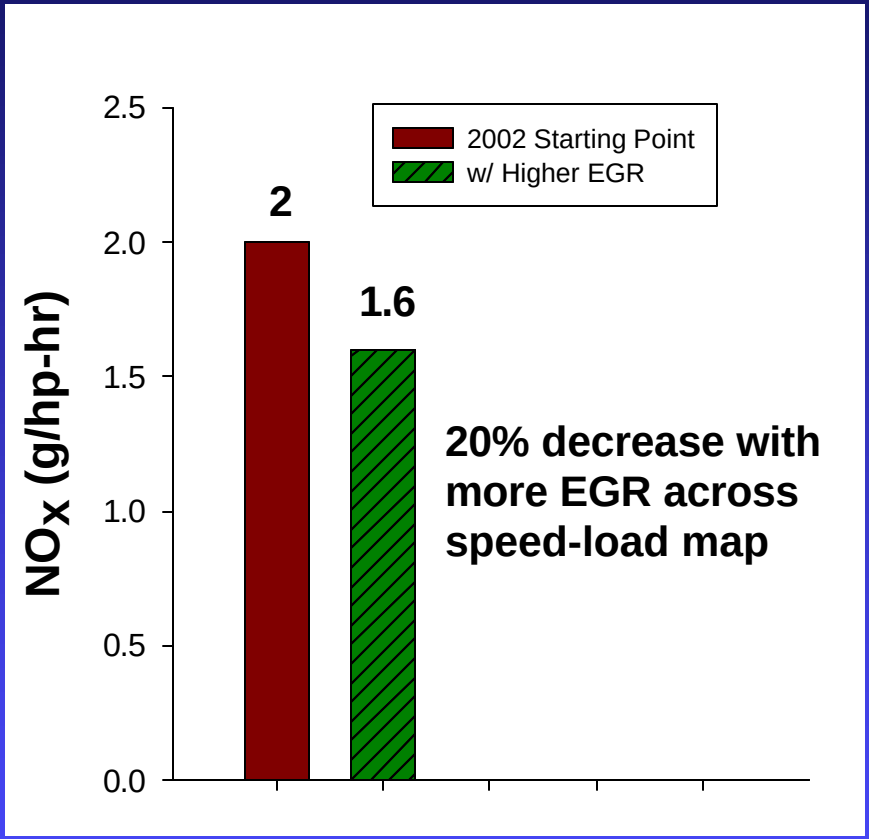
Technologies

- In-Cylinder
  - High boost/high EGR
  - Combustion modifications
  - Fuel injection improvements
  - Variable Valve Actuation (VVA)
  - Model-based controls
  - Water-fuel emulsions
- Exhaust Treatment
  - Lean NO_x catalyst
  - Catalyzed Diesel Particulate Filter (cDPF)

High Boost/High EGR

- External, cooled EGR will predominate in the USA from 2002-2007
- Additional NOx reduction can be achieved especially since a cDPF will remove the soot (assuming h>95%)
- Achieve higher EGR levels while maintaining high BMEP levels via
  - Variable Geometry Turbochargers (VGT)
  - higher boost levels
  - increased peak cylinder pressures (> 200 bar)

2007-2009: What's Possible?

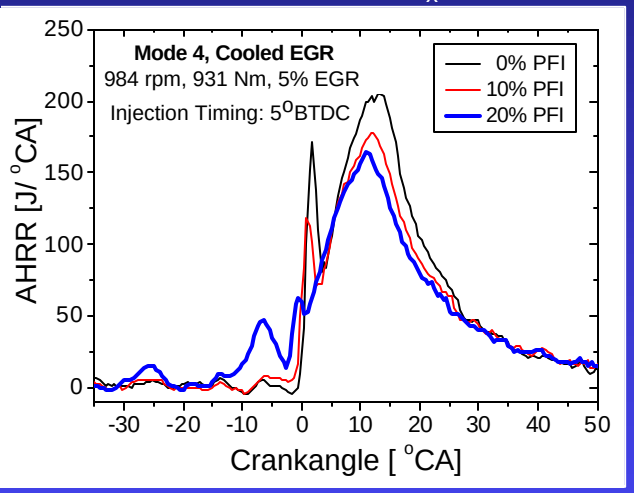


*projections

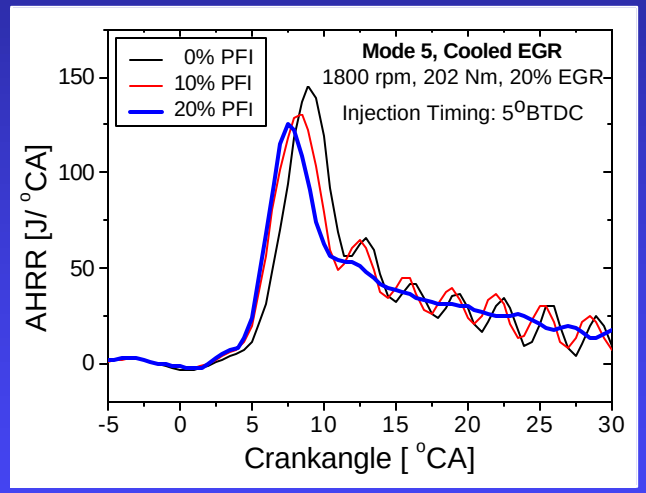
Modified Combustion for NO_x Control

- **Partial Premixed Controlled Compression Ignition (PCCI) - can be used at light- to mid-load to reduce NO_x**

High load: little or no NO_x reduction



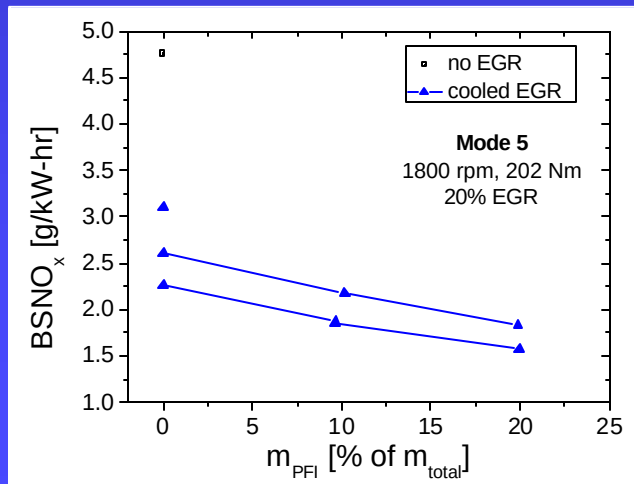
Light load



Simescu, et. al., SAE Paper 2002-01-0963

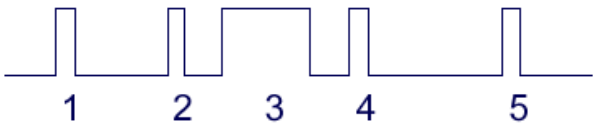
Controlling combustion initiation of the premixed portion allows for simultaneous burning with the diffusion-limited combustion...

...resulting in a 20-30% NO_x reduction at light load

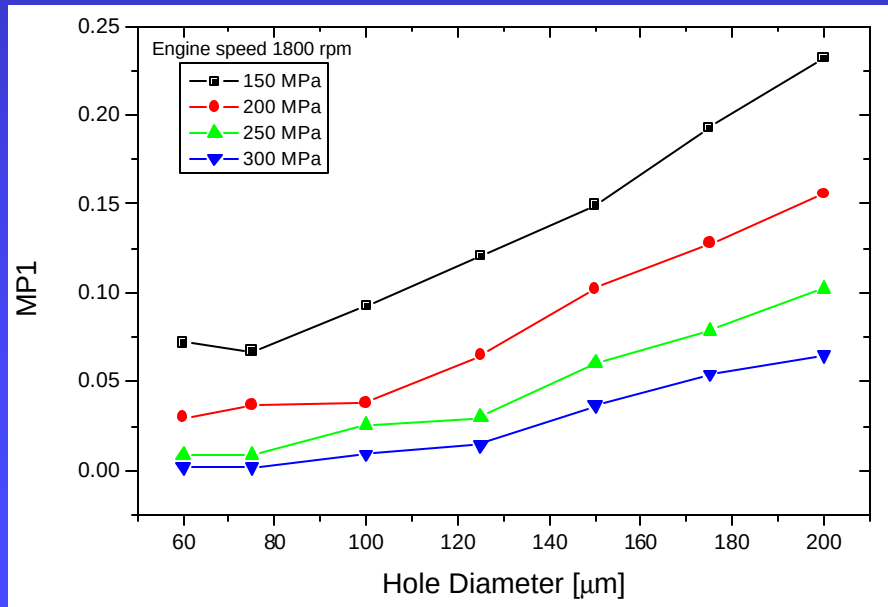


Fuel Injection Improvements

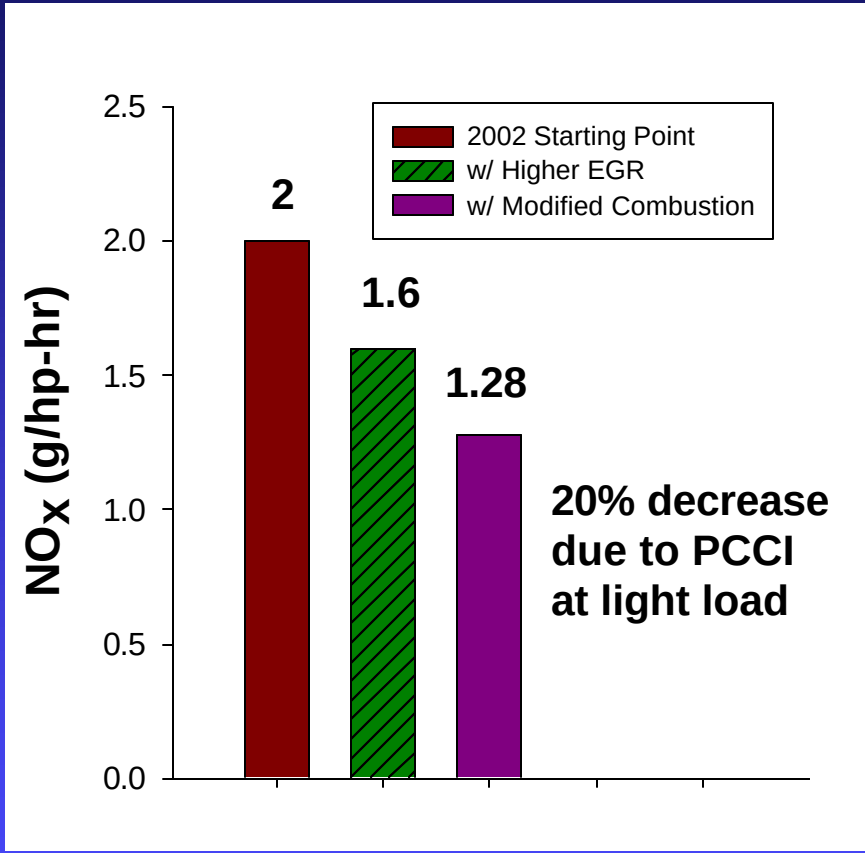
- Important for PCCI
- Multi-injection fuel injection systems *(3-5 pulses per cycle)* for PCCI, noise, cDPF regeneration:
  - E3 unit injector
  - HEUI-C intensifier
  - Common rail
- Fuel-air mixing can still be improved by high injection pressure and smaller injector hole sizes



Injection	Name	Function
1	Pilot 1	Noise control / rate shaping
2	Pilot 2	Noise control / rate shaping
3	Main	Load control
4	After	Soot oxidation at higher load
5	Post	After-treatment activation



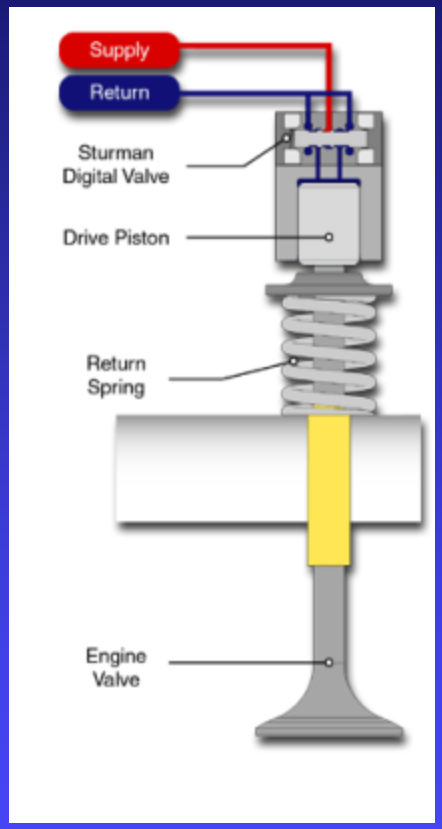
2007-2009: What's Possible?



*projections

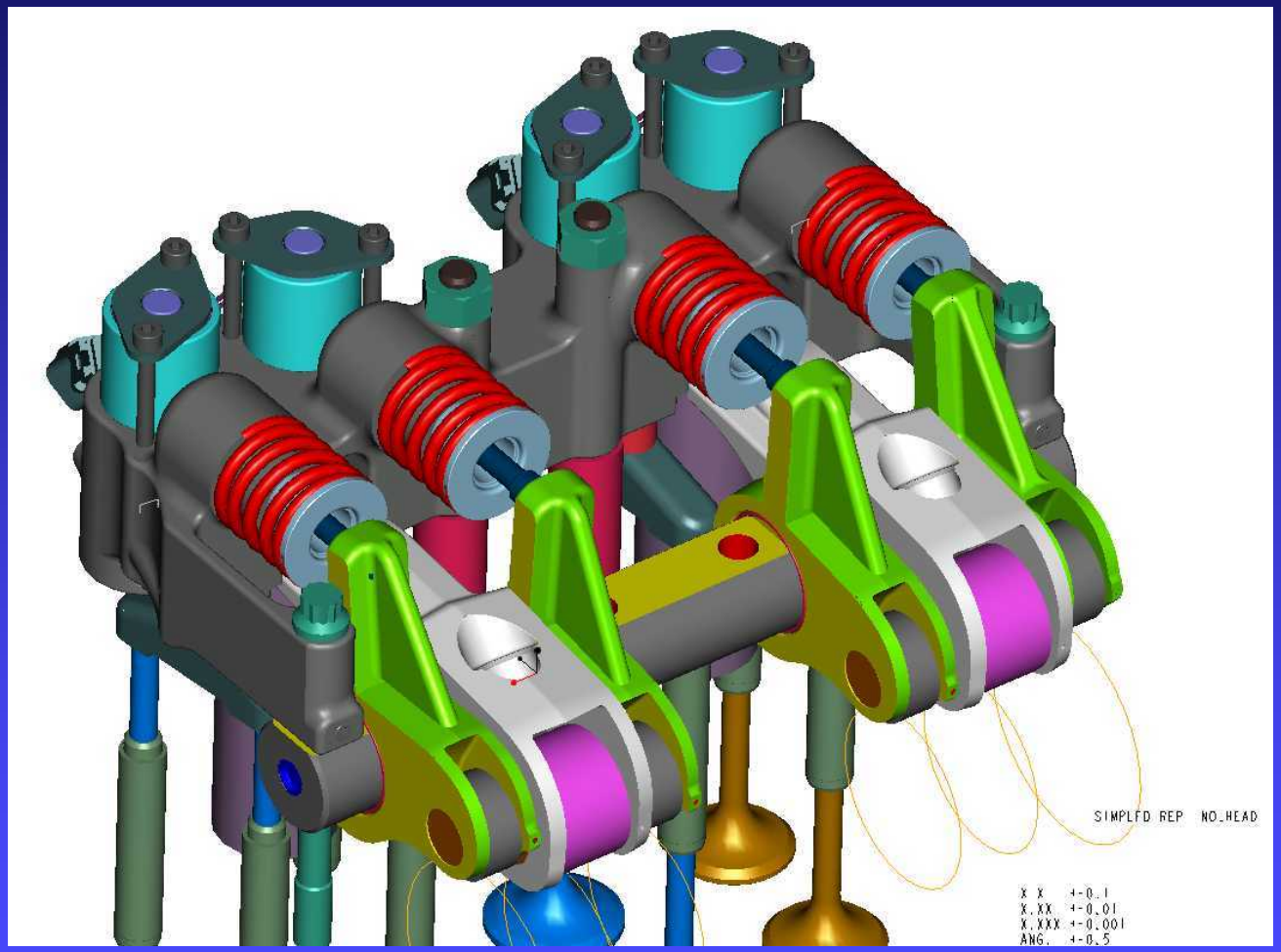
Variable Valve Actuation

- VVA has many advantages for HD diesel engines
  - NOx control:
    - lower NO_x via Miller Cycle
    - better residual control for PCCI
  - Secondary:
    - better cold-starting
    - cylinder de-activation
    - part load BSFC improvement
    - variable swirl ratio
    - ability to increase exhaust temperatures for exhaust treatment devices
    - engine braking
- Near-production systems are becoming available now



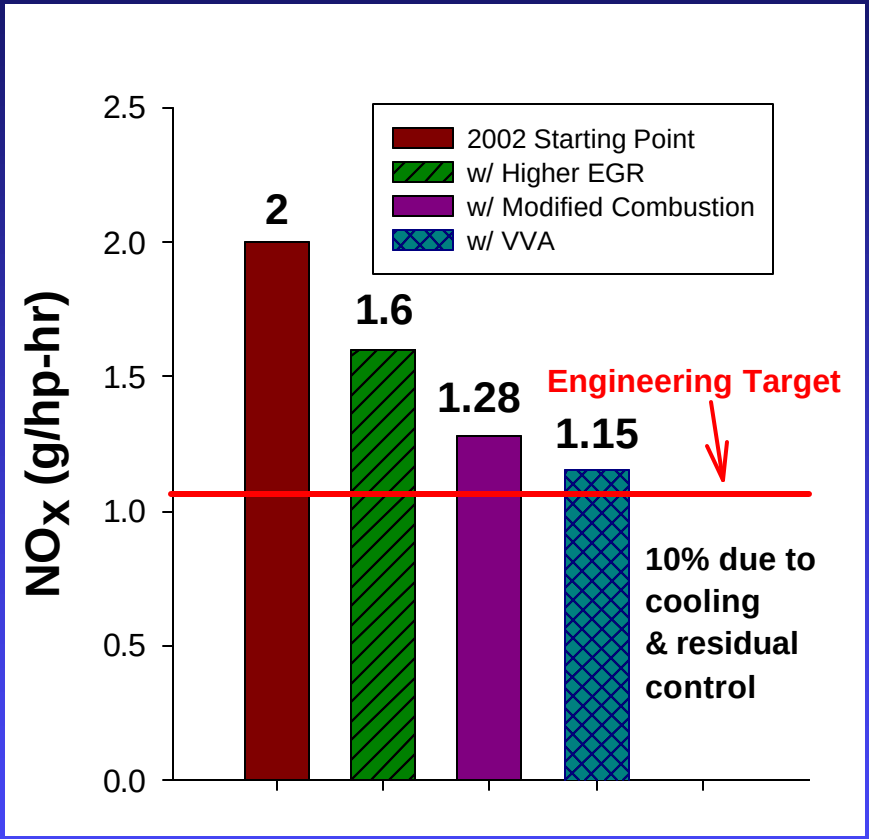
Hydraulic Valve Actuation from Sturman Industries

Jacobs' Lost Motion Hydraulic Valve Actuation System



Jacobs Vehicle Systems™

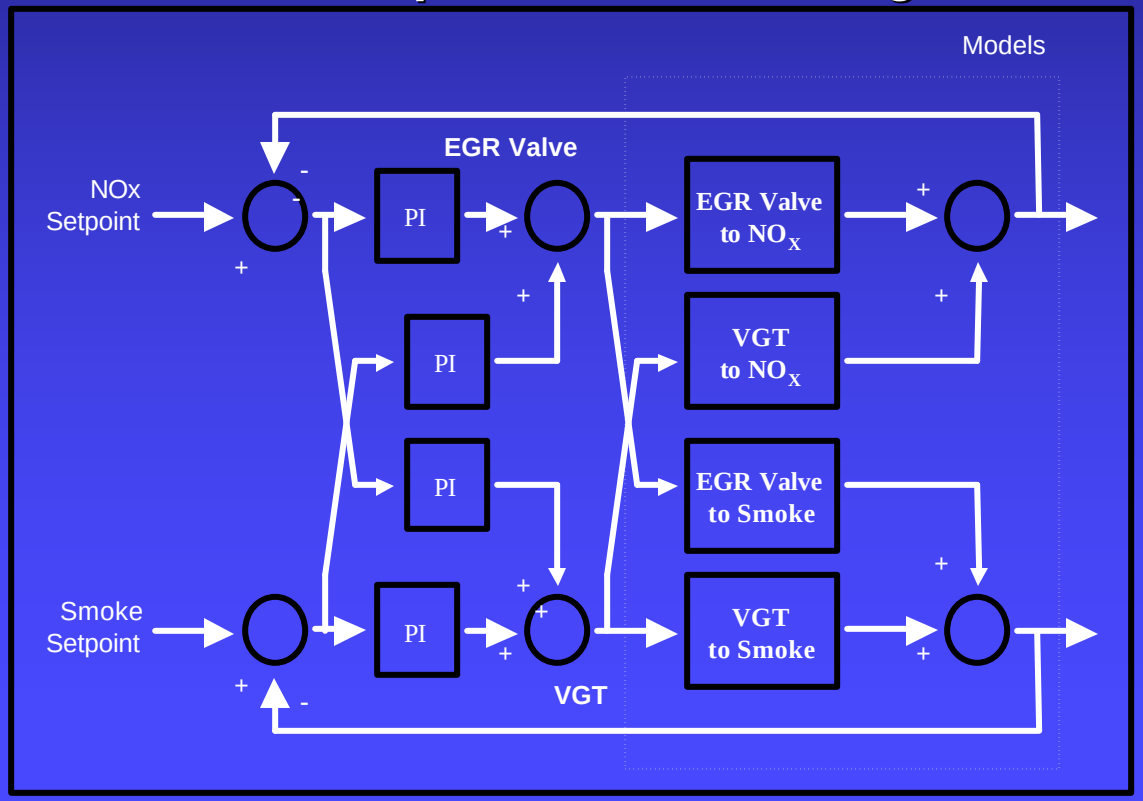
2007-2009: What's Possible?



*projections

Model-Based Controls

- Advanced model-based algorithms include both engine and exhaust treatment control
- Multivariable control in diesel engines
  - Engine control variables have increased
  - Look-up tables are no longer sufficient



EGR/VGT control strategies development using multivariable control design techniques

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- ➔ Exhaust Treatment
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Lean NO_x Catalysts

EXHAUST CATALYSIS PROCESS

$HC+CO+NO_X+O_2$ + HC → [ ] → $H_2O+CO_2+N_2+O_2$

SUPPLEMENTAL

SUBSTRATE + (Cu-ZSM-5)

IDEAL

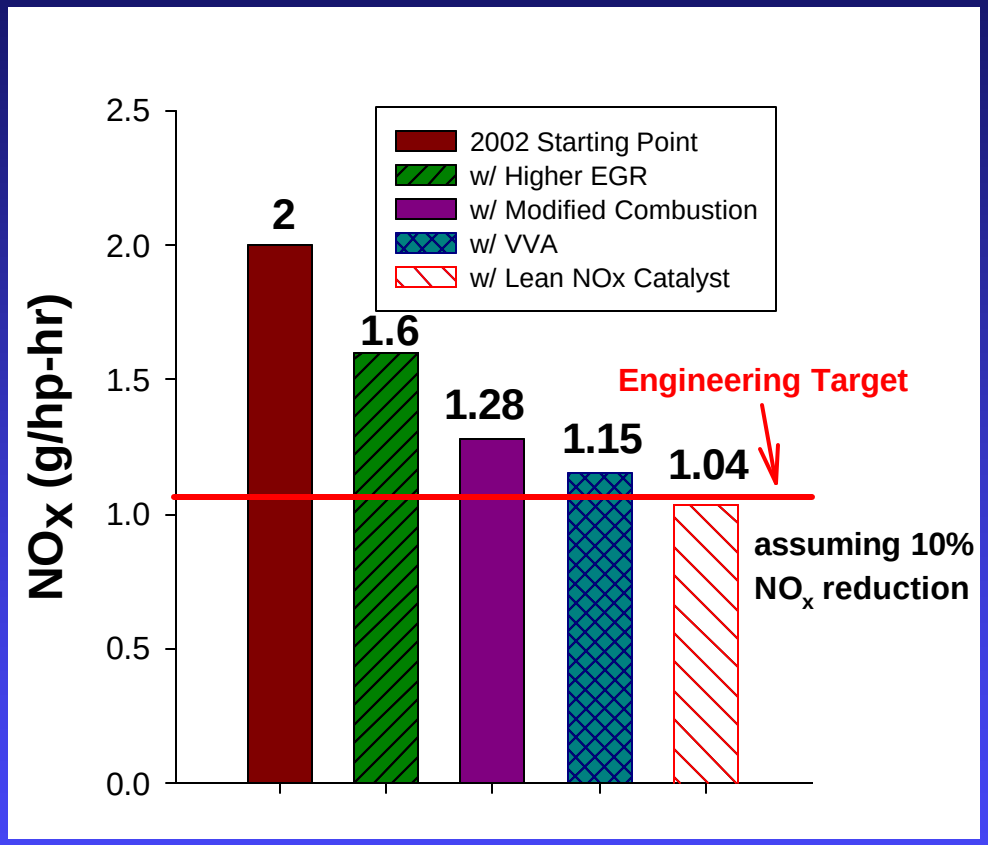
Advantages

- **Uses same on-board reductant**
- **Good sulfur tolerance**
- **Provides added margin for calibration, if needed**

Disadvantages

- **Low cycle NOx conversion (<30%)**
- **Narrow exhaust temperature range of operation**
- **High fuel consumption penalty (~10%)**
- **Durability**

2007-2009: What's Possible?



*projections

Summary

- Future emission standards in the USA are very severe requiring a systems solution
- Lean NO_x adsorbers may not be sufficiently developed for 2007-2009 timeframe and may not be necessary
- In-cylinder controls should be sufficient for 1.18 g/hp-hr NO_x in 2007
  - possible need for additional NO_x control via a lean NO_x catalyst to provide a margin

Summary (cont.)

- Offering an engine with minimal exhaust treatment and further improved in-cylinder controls will:
  - Reduce the costs of exhaust treatment portion
  - Improve the durability of exhaust treatment
  - Reduce the packaging volume
  - Show an engine manufacturer as a technological leader
  - Provide a product distinction in a crowded market