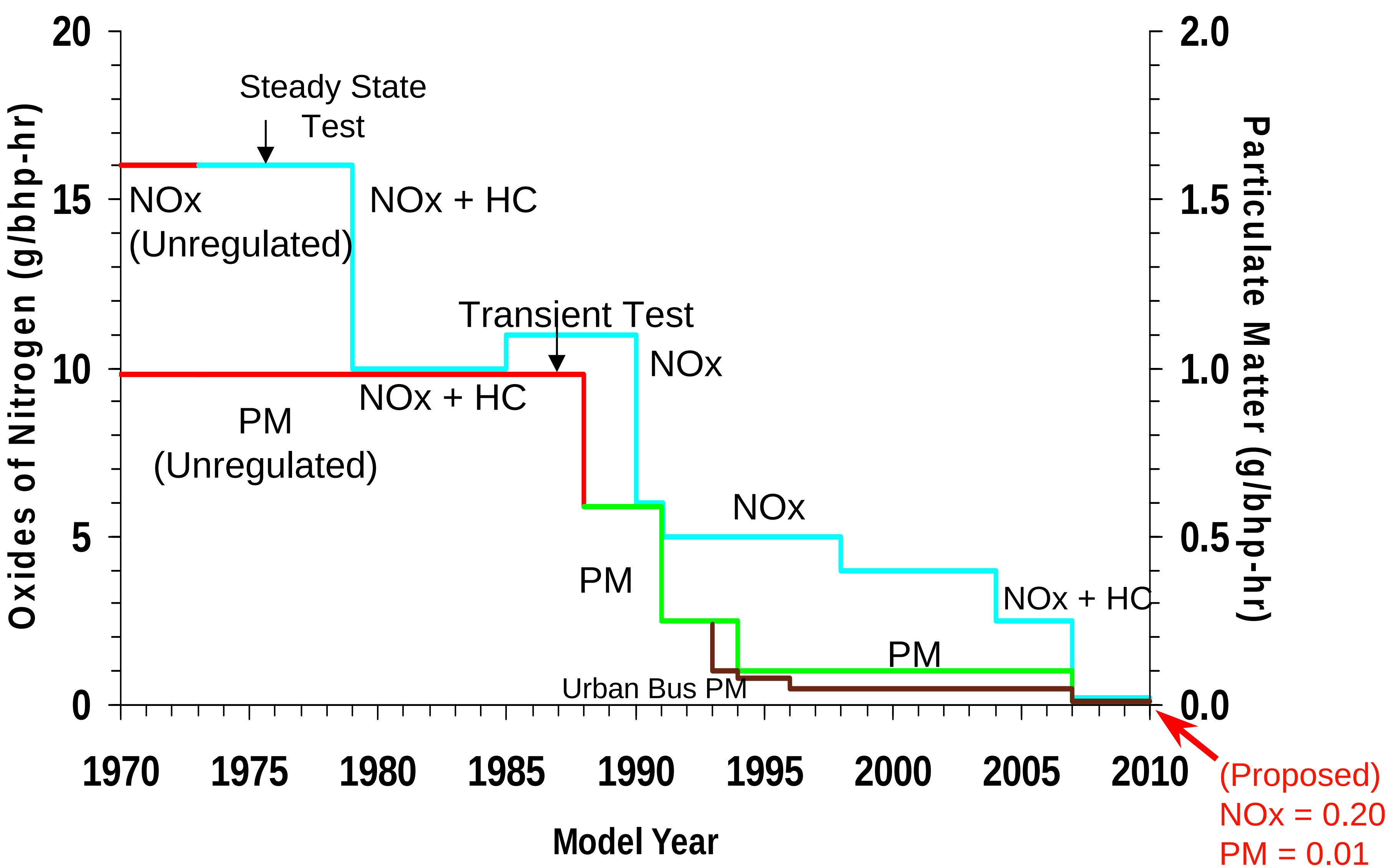
EPA Heavy-Duty Engine Emission Standards



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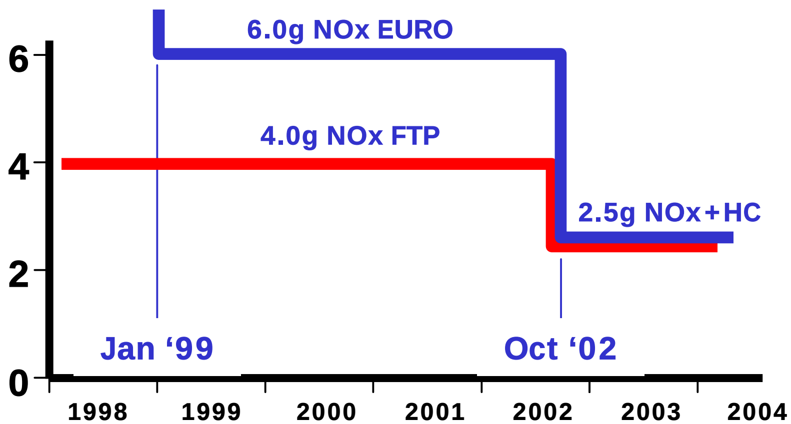
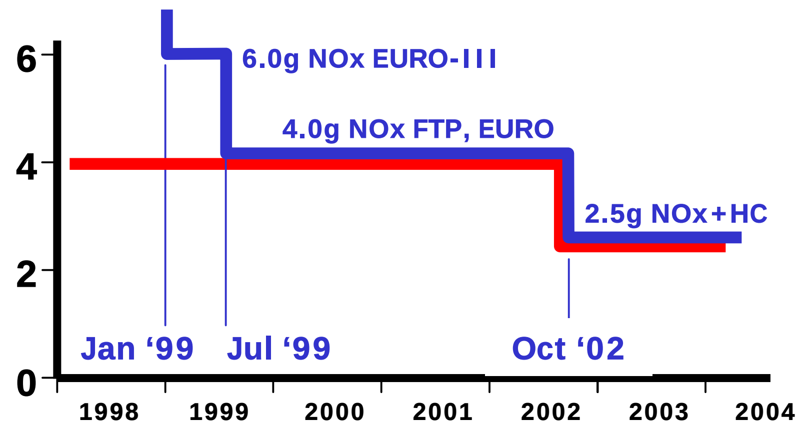
2002 Product Development with Cooled EGR

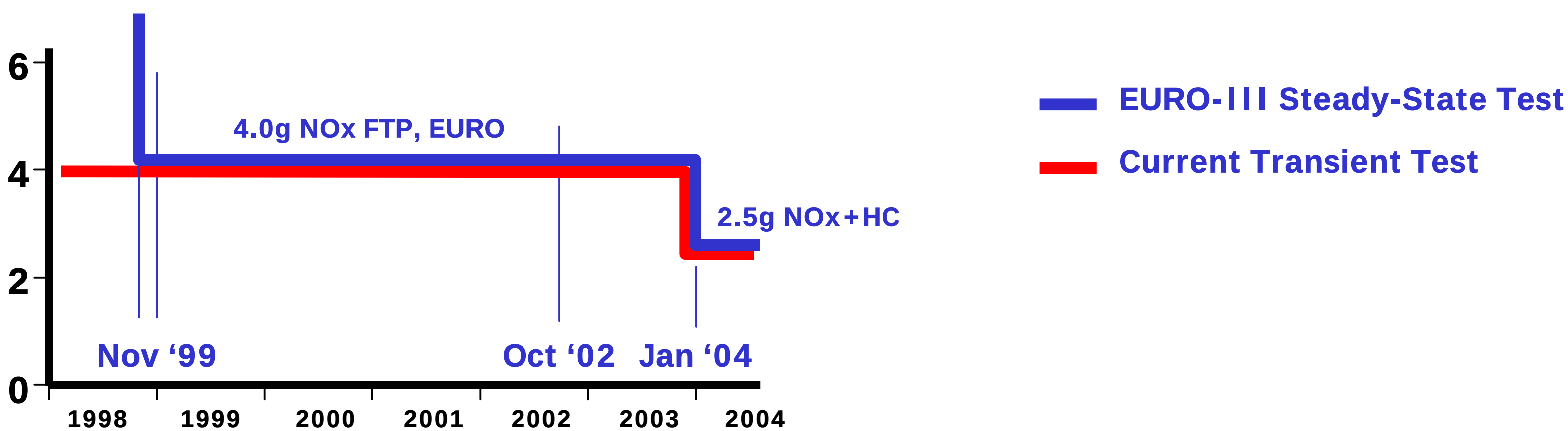
Heavy-Duty Engines
- ISL, ISM, N14, ISX, SIG-600



Medium-Duty Engines
- ISB, ISC, Urban Bus Engines



Chrysler Pick-Up Engines



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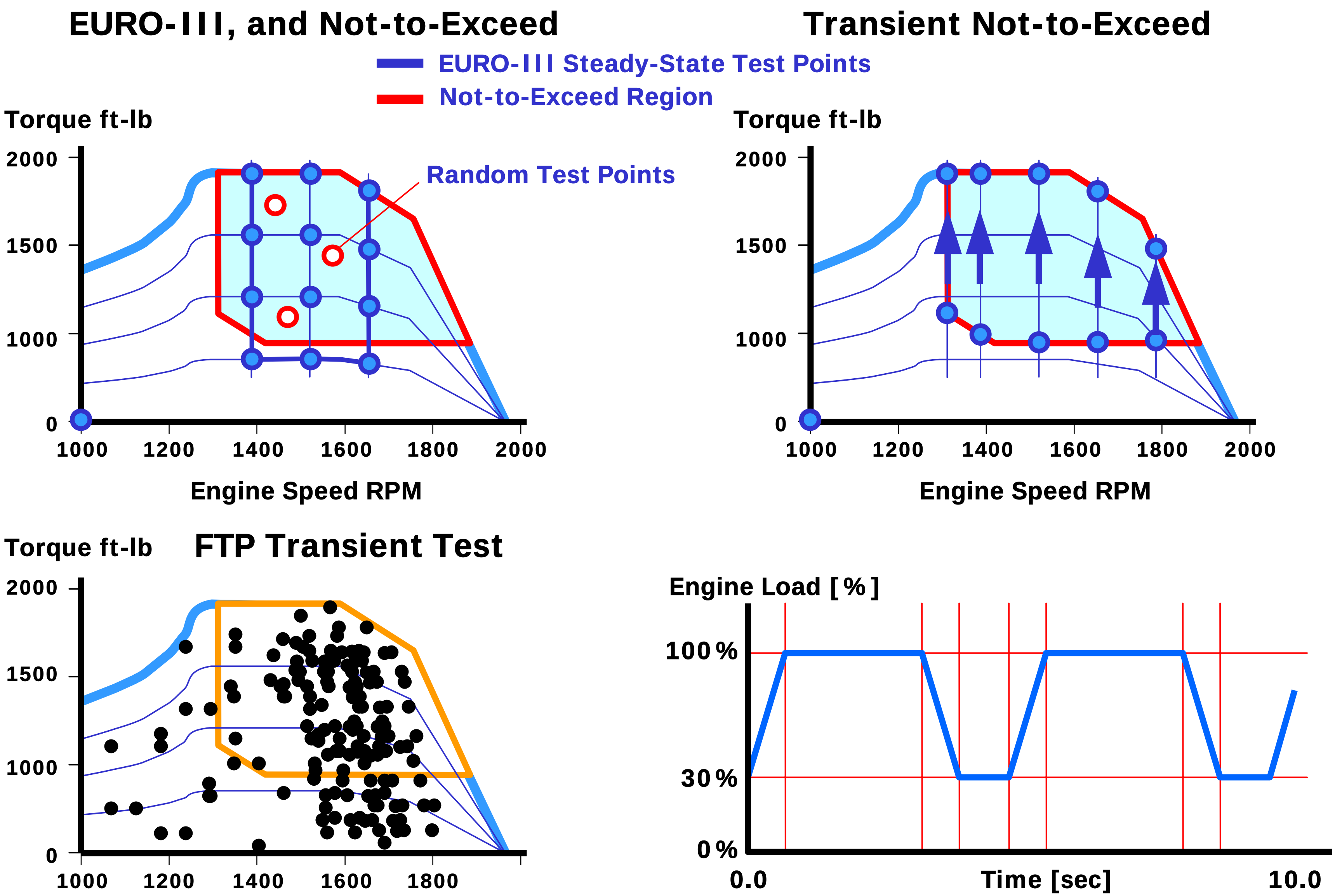


2002 Product Development with Cooled EGR

Emission Certification Test and Requirements

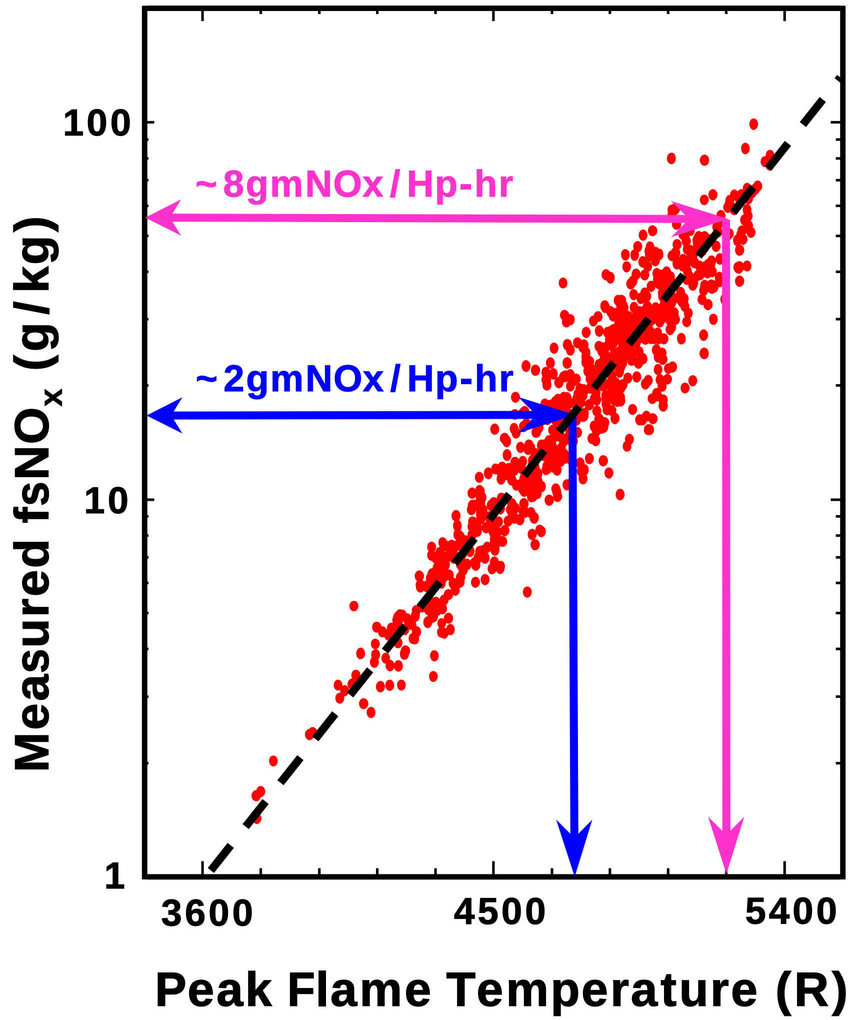
- Current Transient Test
- EURO ESC 13 Mode Steady-State Test
- Not-To-Exceed Requirements
- Transient Not-To-Exceed Requirements
- In-Use Testing and Compliance
- Full disclosure of AECDs (Auxiliary Emissions Control Devices)

Consent Decree emissions requirements apply over a broad range of ambient conditions and altitudes:

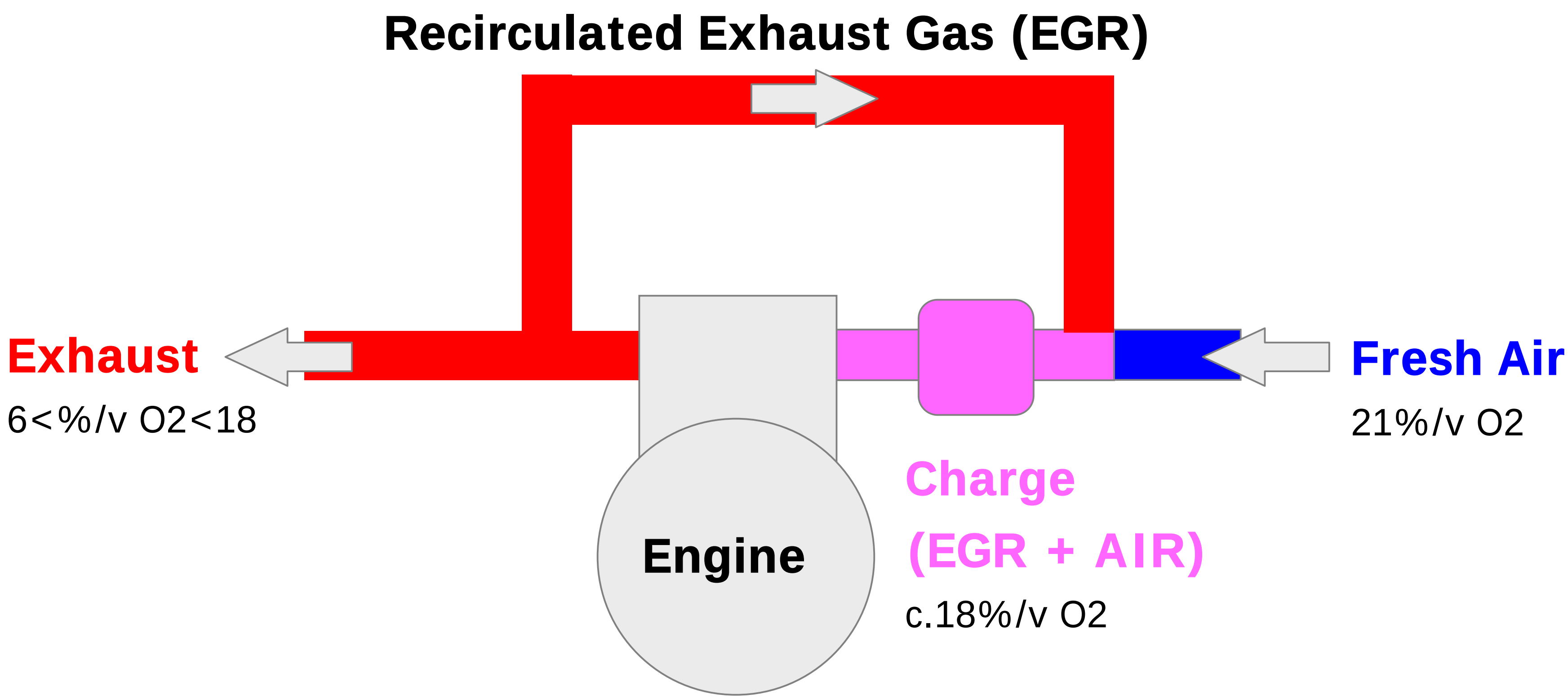
- ambient temperature 55 - 95 degF - full compliance with NTE - no correction factors
- humidity 50 - 75 grains / lb of air - full compliance with NTE - no correction factors
- altitude - full compliance up to at least 5500 feet

Engine NOx Control Basics

- **NOx Emissions Are Very Sensitive To Flame Temperature**
  - **Low Temperatures Required to Achieve 2gm/Hp-hr**
  - **Need To Reduce Flame Temperatures ~400°**
  - **How Do We Cost Effectively Control Temperatures?**

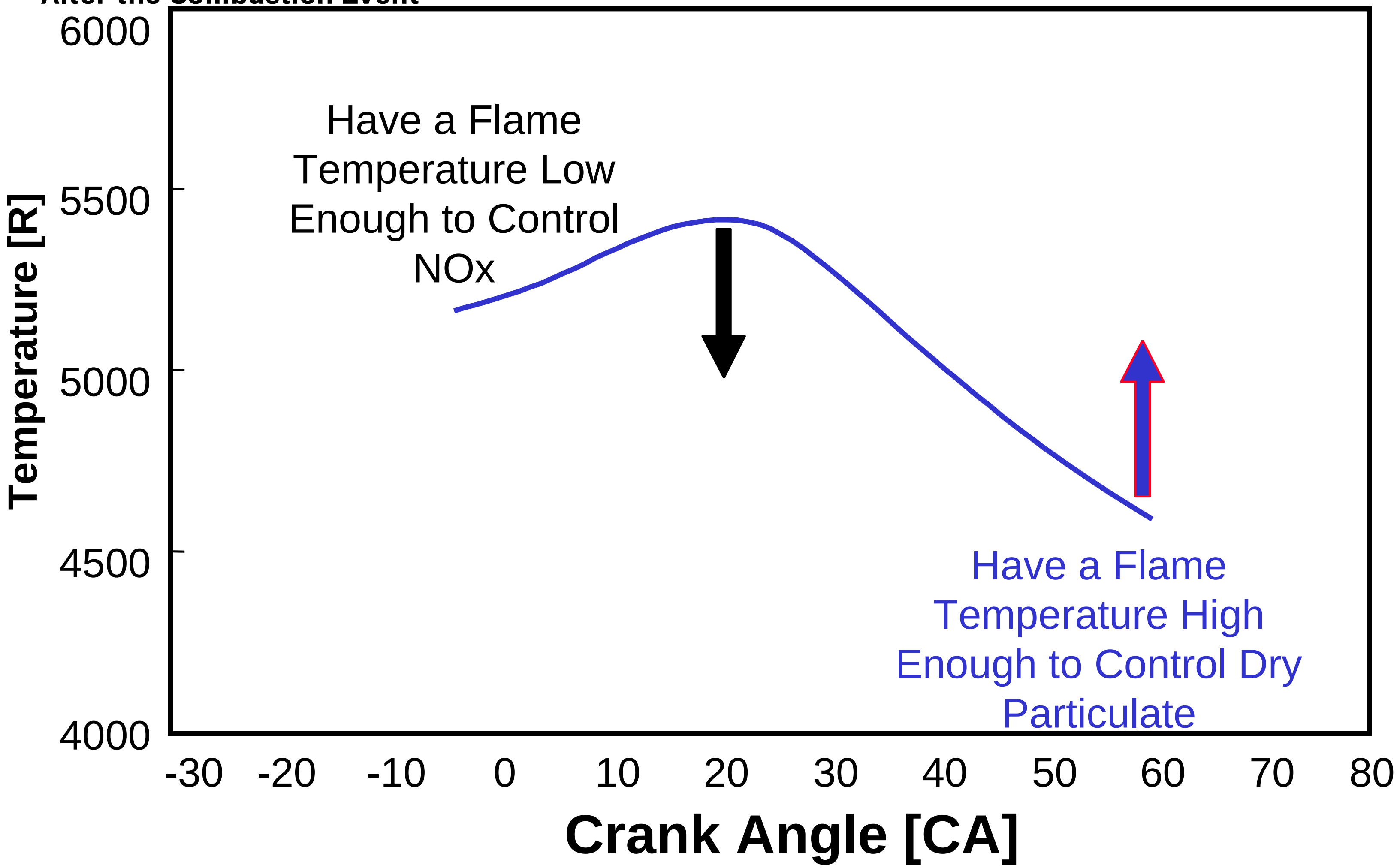


What Is EGR?



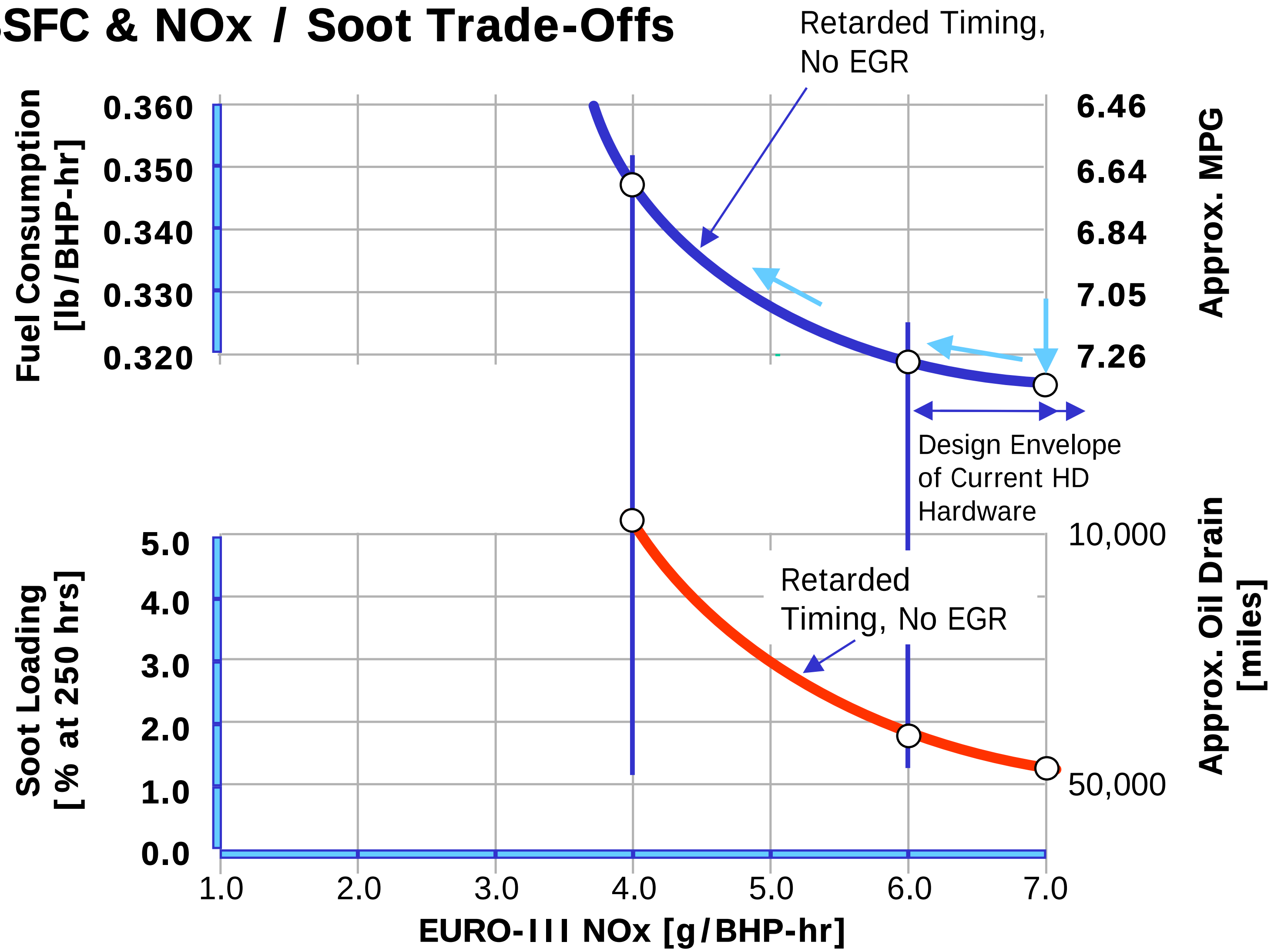
EGR Gives Us A Handy Way To Reduce
- **Oxygen Concentration**
- **Flame Temperature**
- **NOx Emissions**

The Challenge:
Alter the Combustion Event

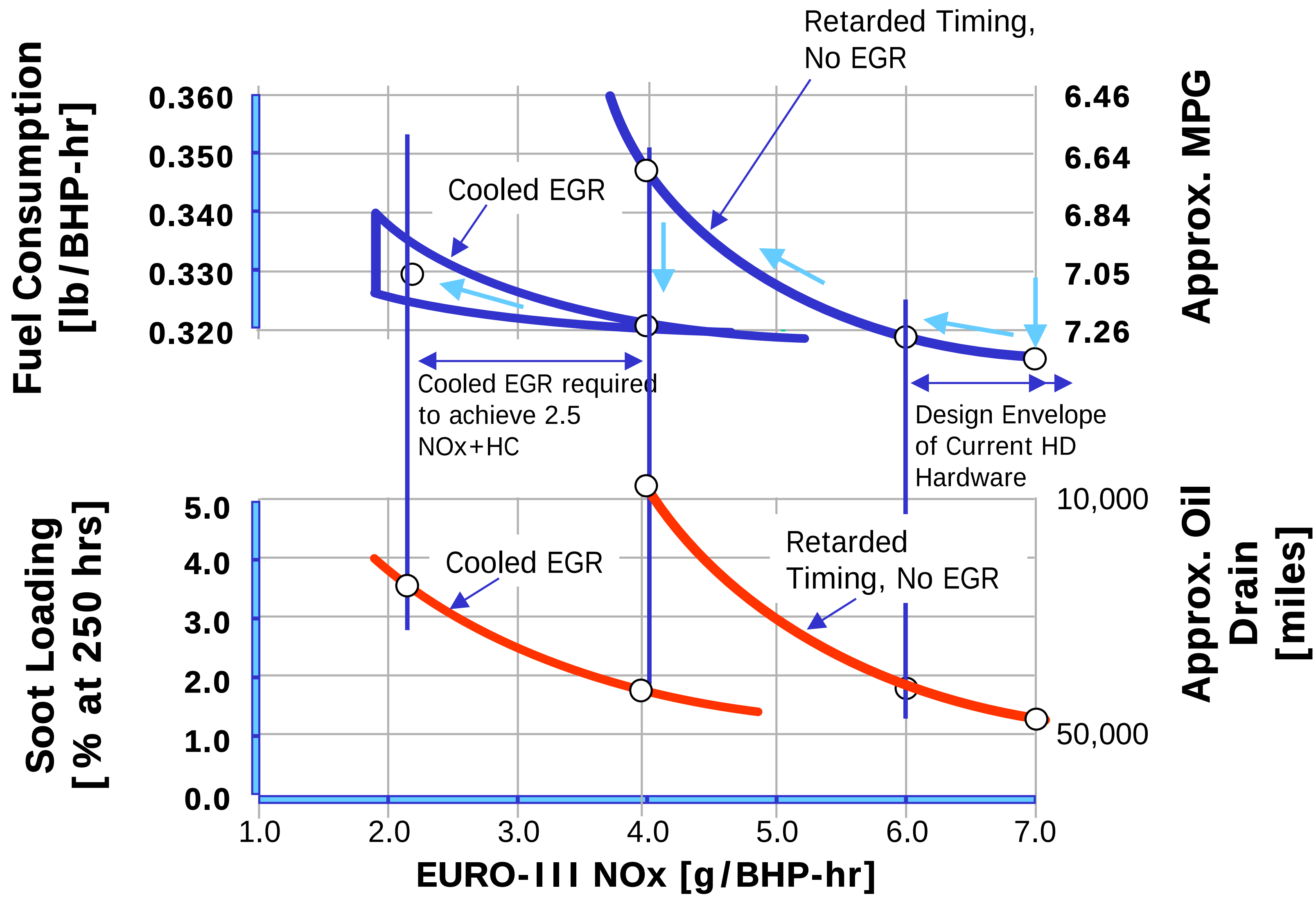


NOx Control with Cooled EGR

NOx / BSFC & NOx / Soot Trade-Offs

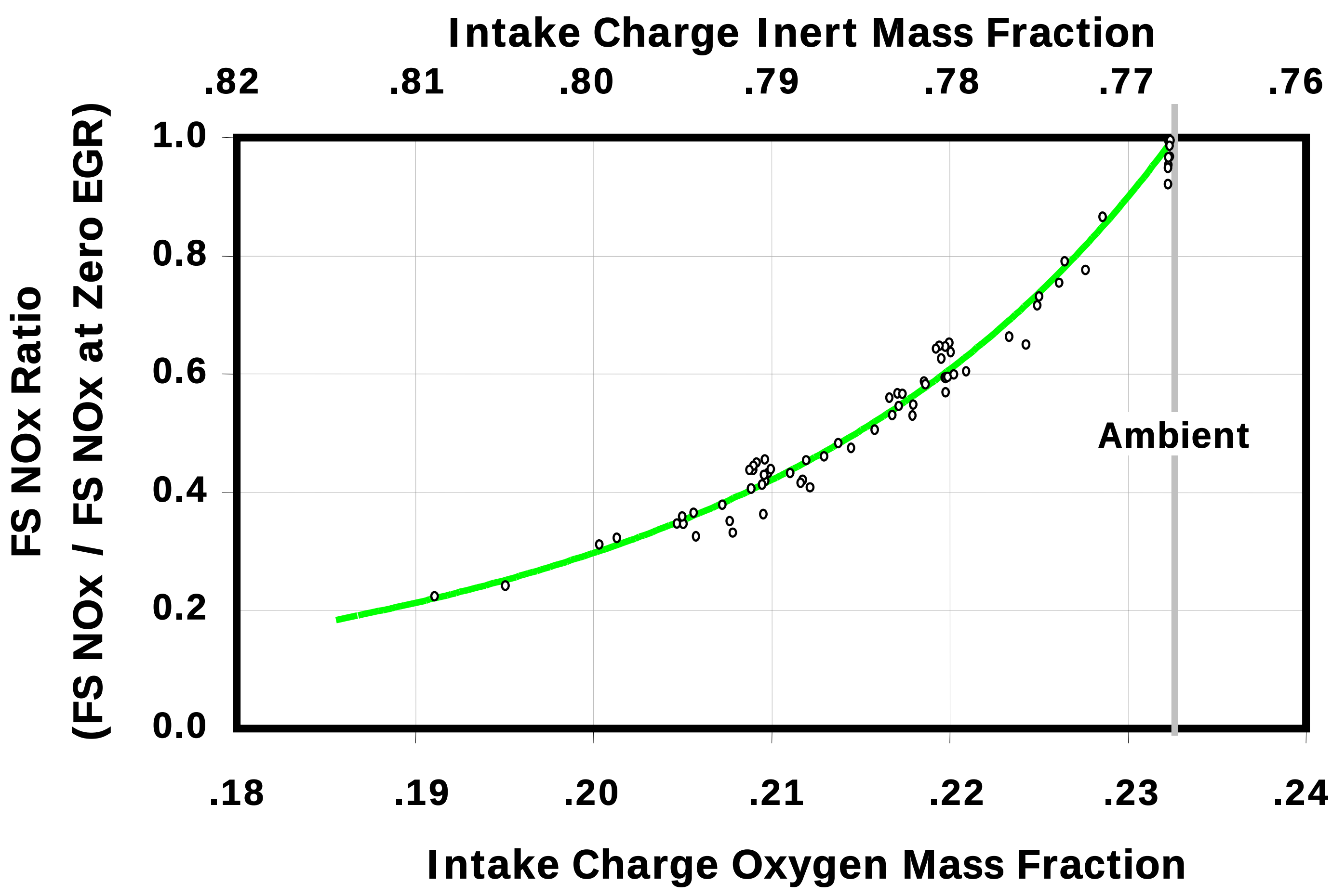


NO_X Reduction Mechanisms



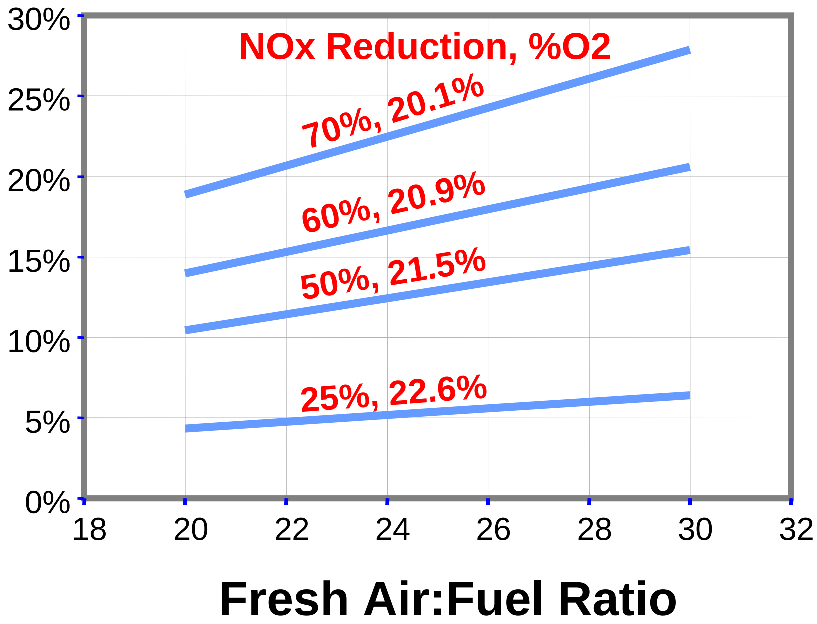
Fuel Consumption is based on EURO-3 weightings, M11 - percentage change based on 0.315 lb/BHP-hr at 7.0g NOx on EURO-3 cycle
Soot loading based on VMS 500 mile Corporate Composite Route / Duty Cycle - EGR soot is extrapolated from available data

Effect of Inert / O_2 Mass Fraction

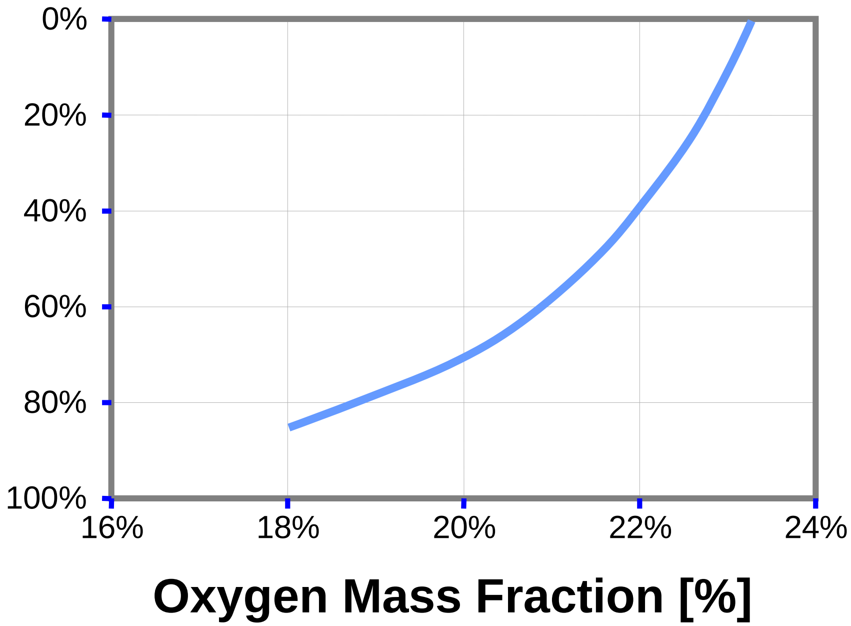


NOx Control with Cooled EGR

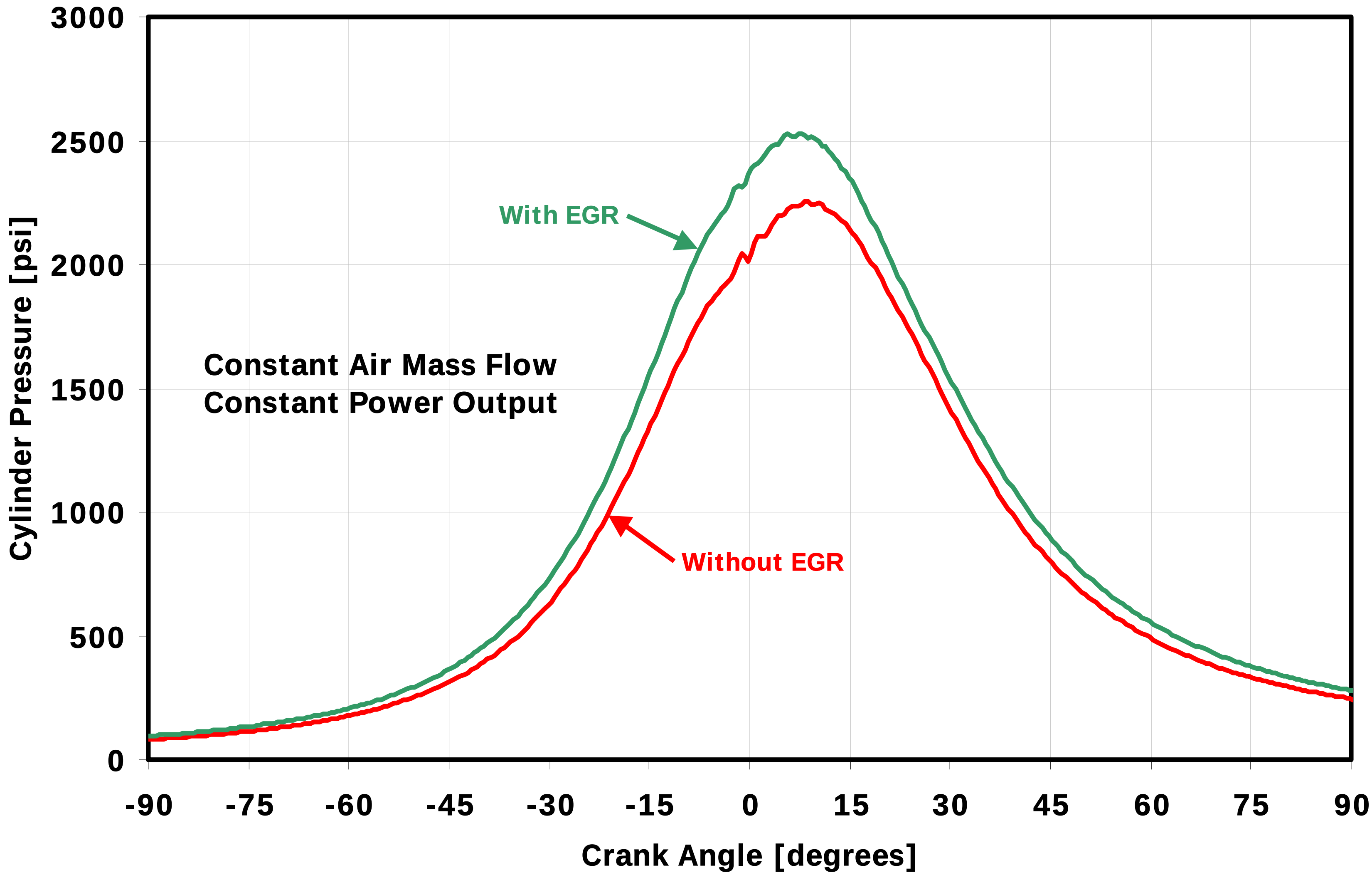
EGR Mass Fraction



NOx Reduction from Non-EGR Case



Cylinder Pressure - Impact of EGR



8.3 L, 2200 rpm, 0 &11% EGR, 53 lb/min fresh air flow

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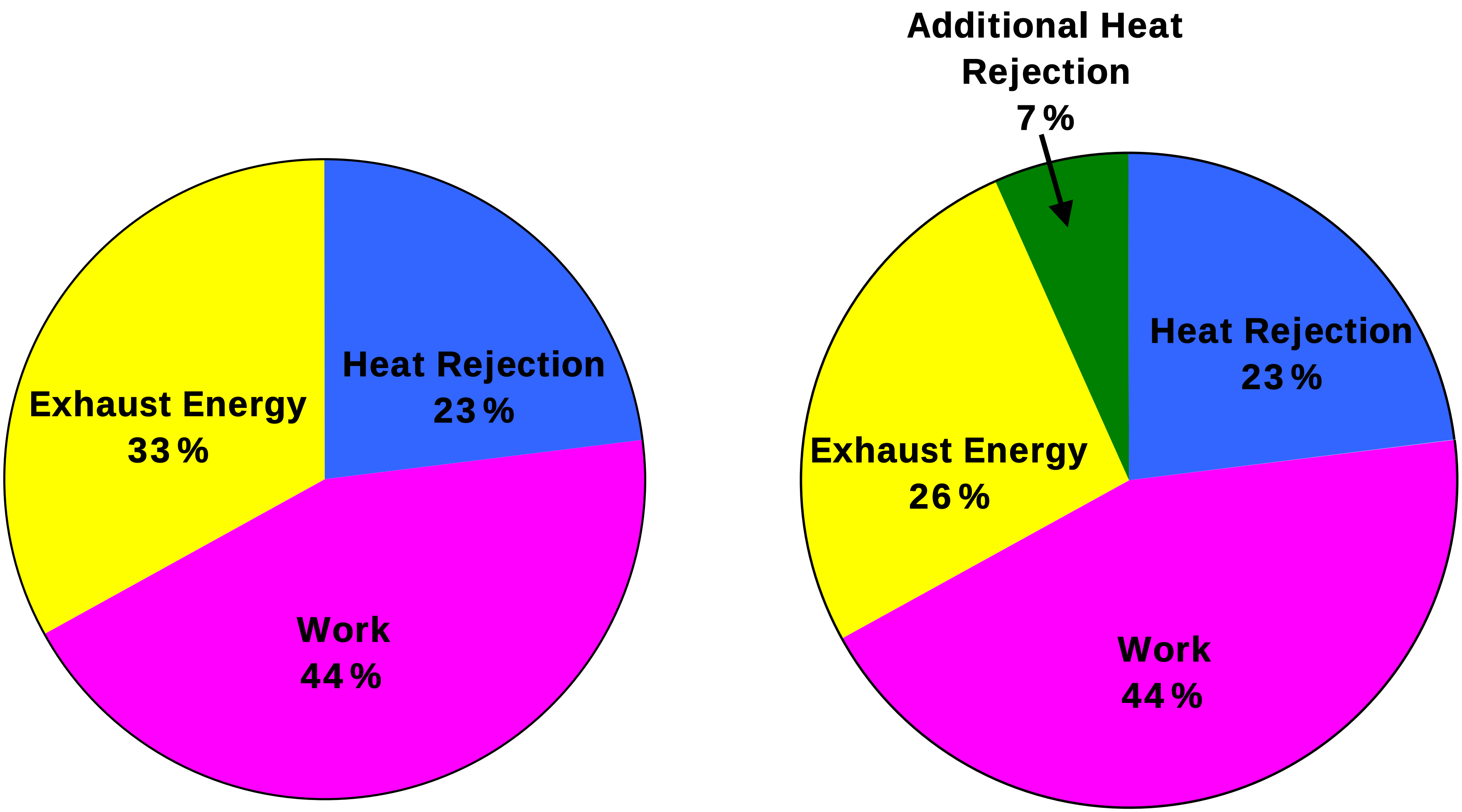
Why so much heat?

With cooled EGR, we take some of the exhaust flow and reject that heat back to the coolant.



2002 Product Development with Cooled EGR

Mutually Dependent Design Targets

Base Engine
- Peak Cylinder Pressure
- Cylinder Liner & Ring Pack
- Lube Oil Formulation

Vehicle Integration
- Cooling System
- Packaging
- Engine Power Density

Mutually Dependent Design Elements

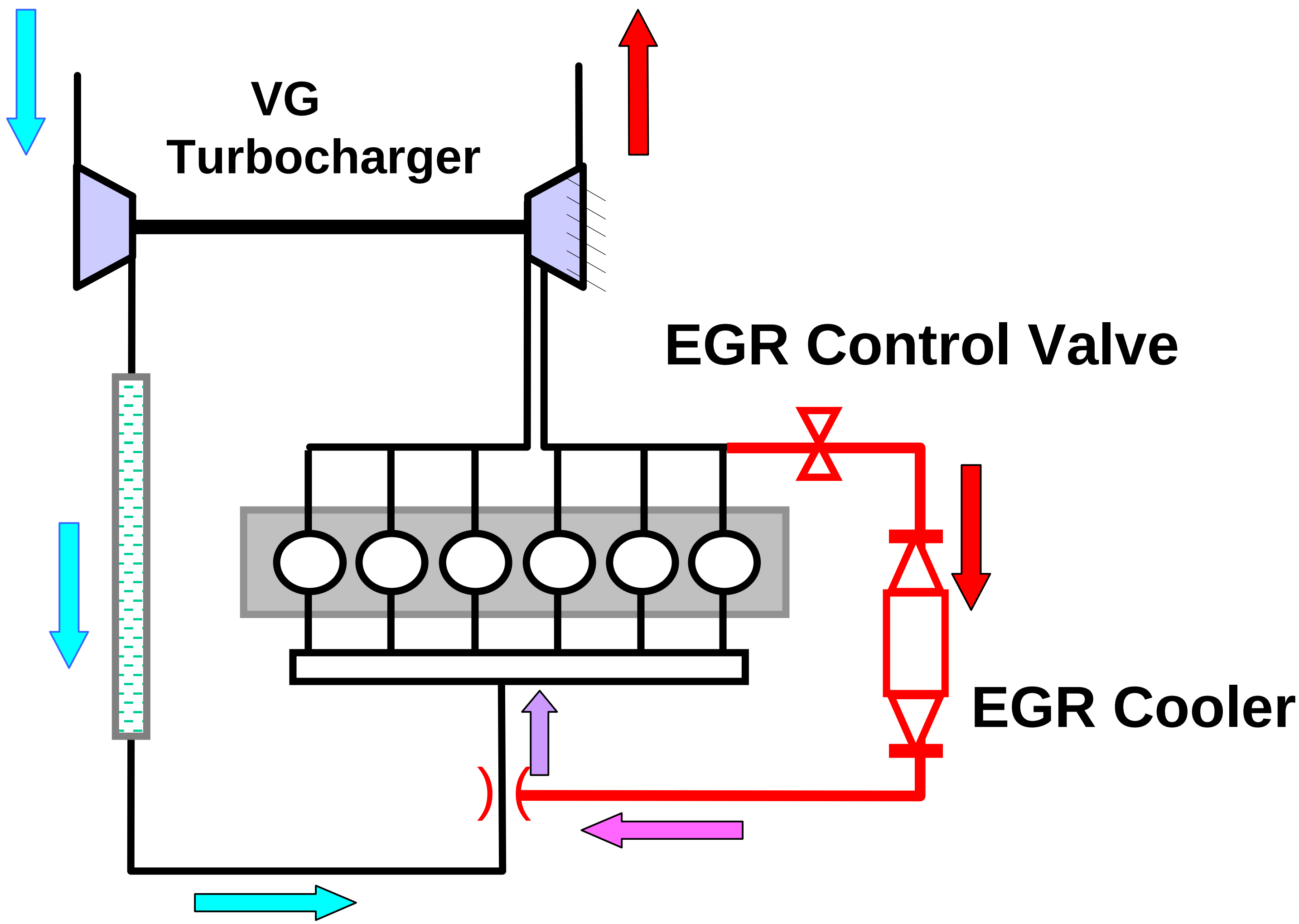
Fuel Injection System
- Injection Pressure
- Multiple Injections
- Low Soot Combustion System

Air Handling System
- Turbocharger
- EGR System
- Controls and Diagnostics

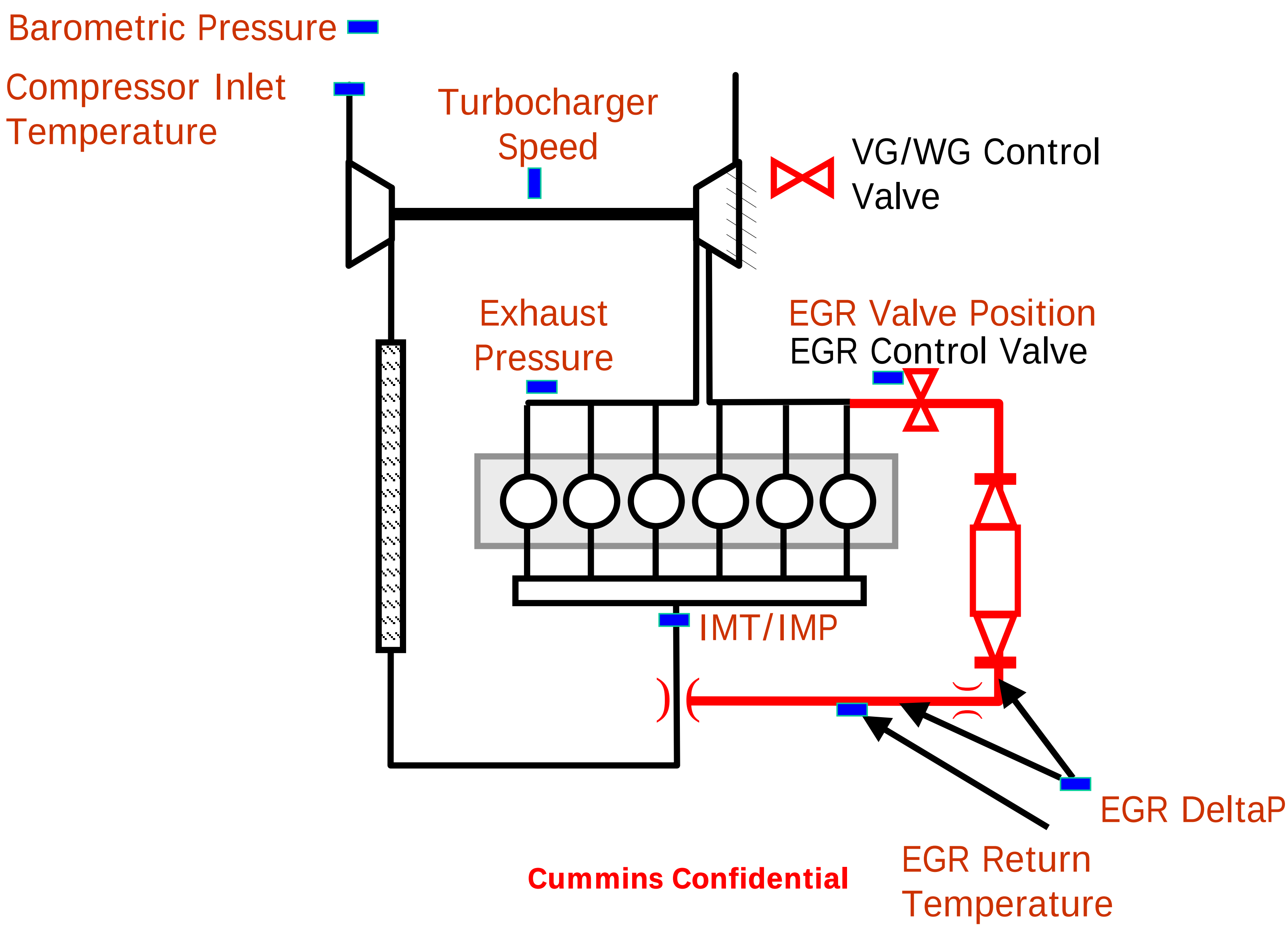
Description of an EGR System

- Turbomachinery and assist devices for increasing exhaust manifold pressure sufficiently above intake manifold pressure to allow scheduling of charge mass and EGR fraction
- EGR take-off, transport, and return to intake
- EGR valve and actuator to regulate amount of exhaust to be re-circulated
- EGR cooler
- Actuators, sensors, controls
- Attachment hardware

EGR System Schematic



System Sensors / Actuators



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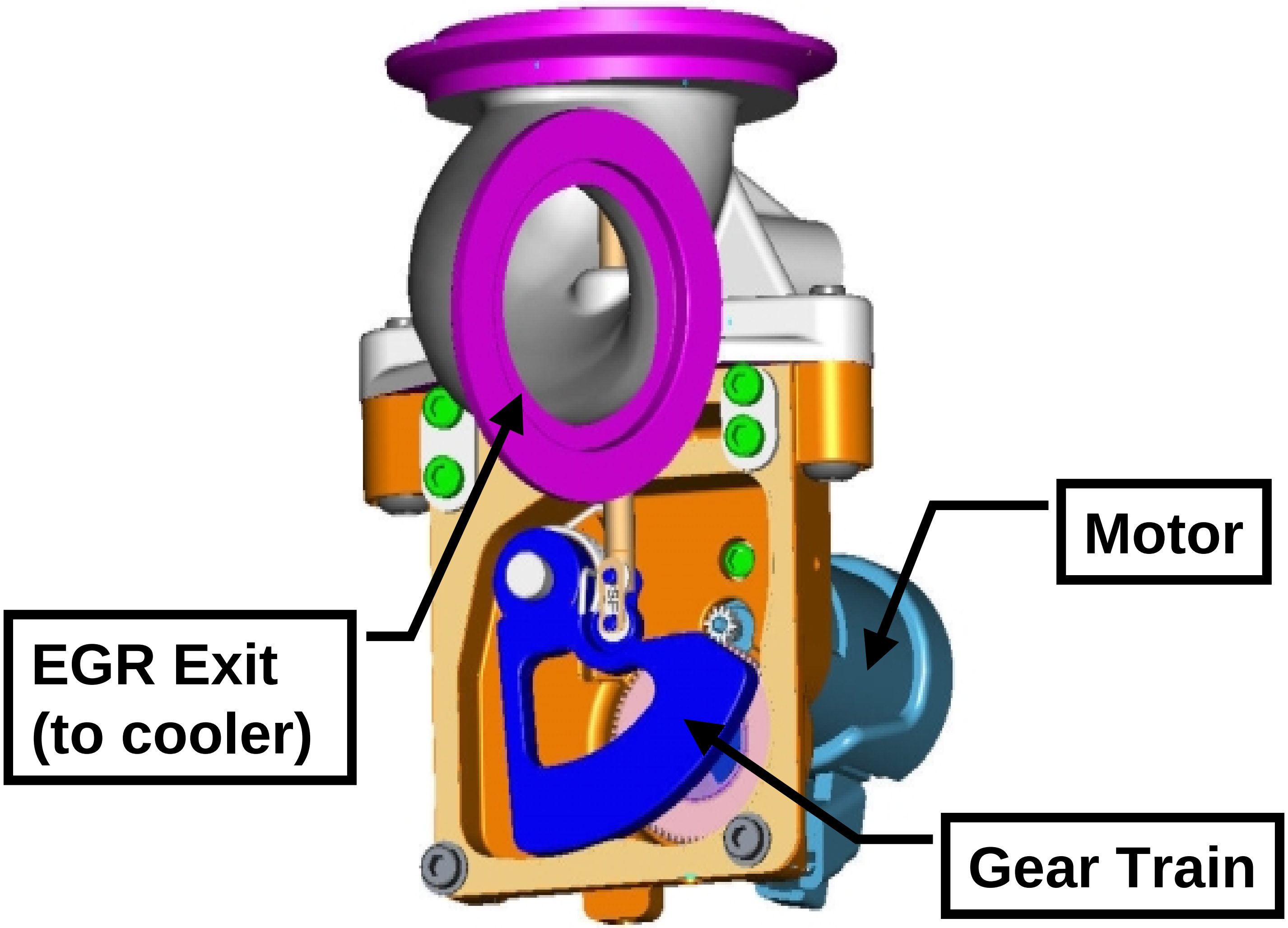
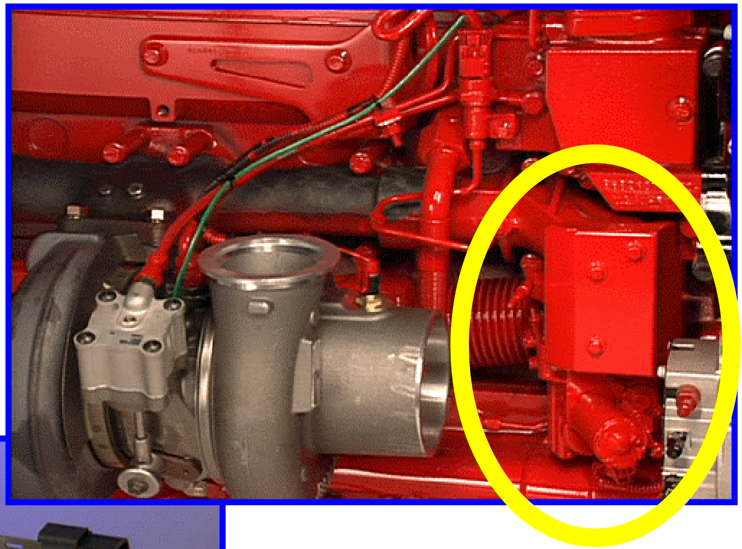
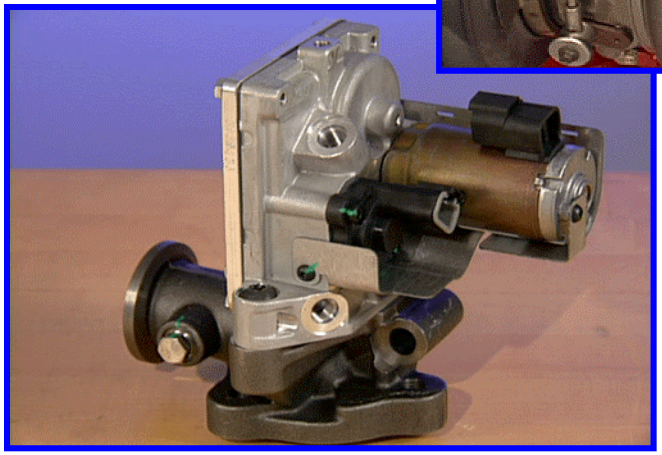
EGR Valve



EGR Hardware - EGR Valve

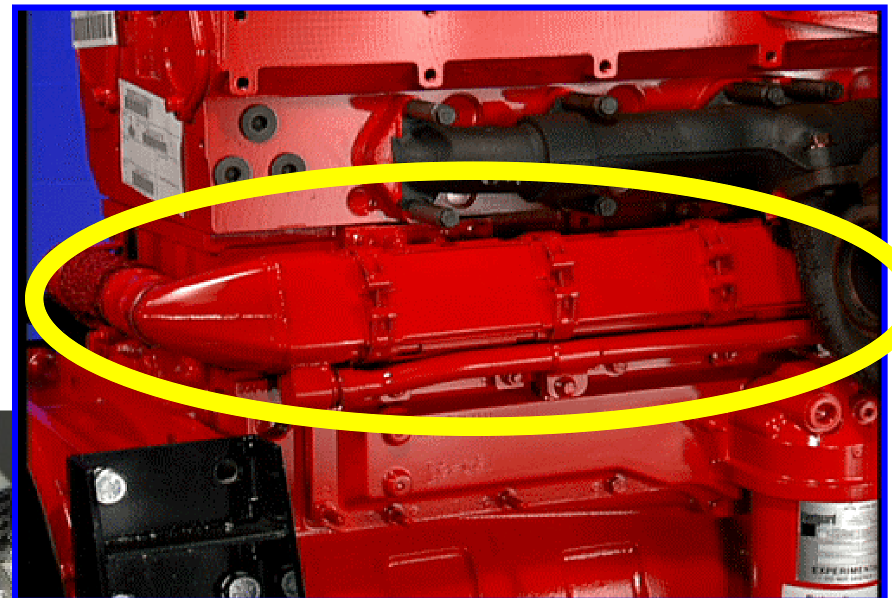
- **The EGR valve regulates the amount of exhaust gas that is recirculated into the intake system.**



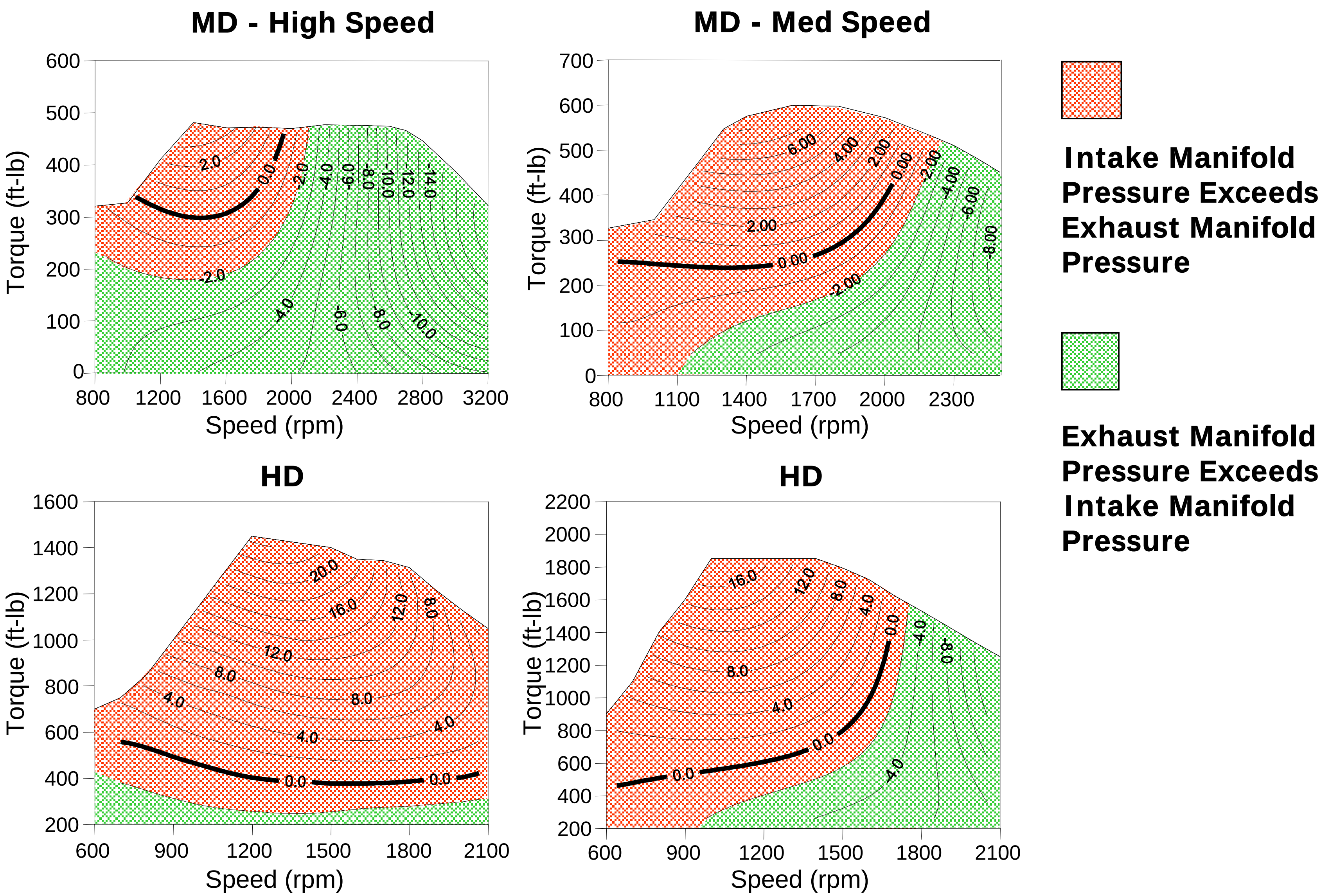


EGR Cooler

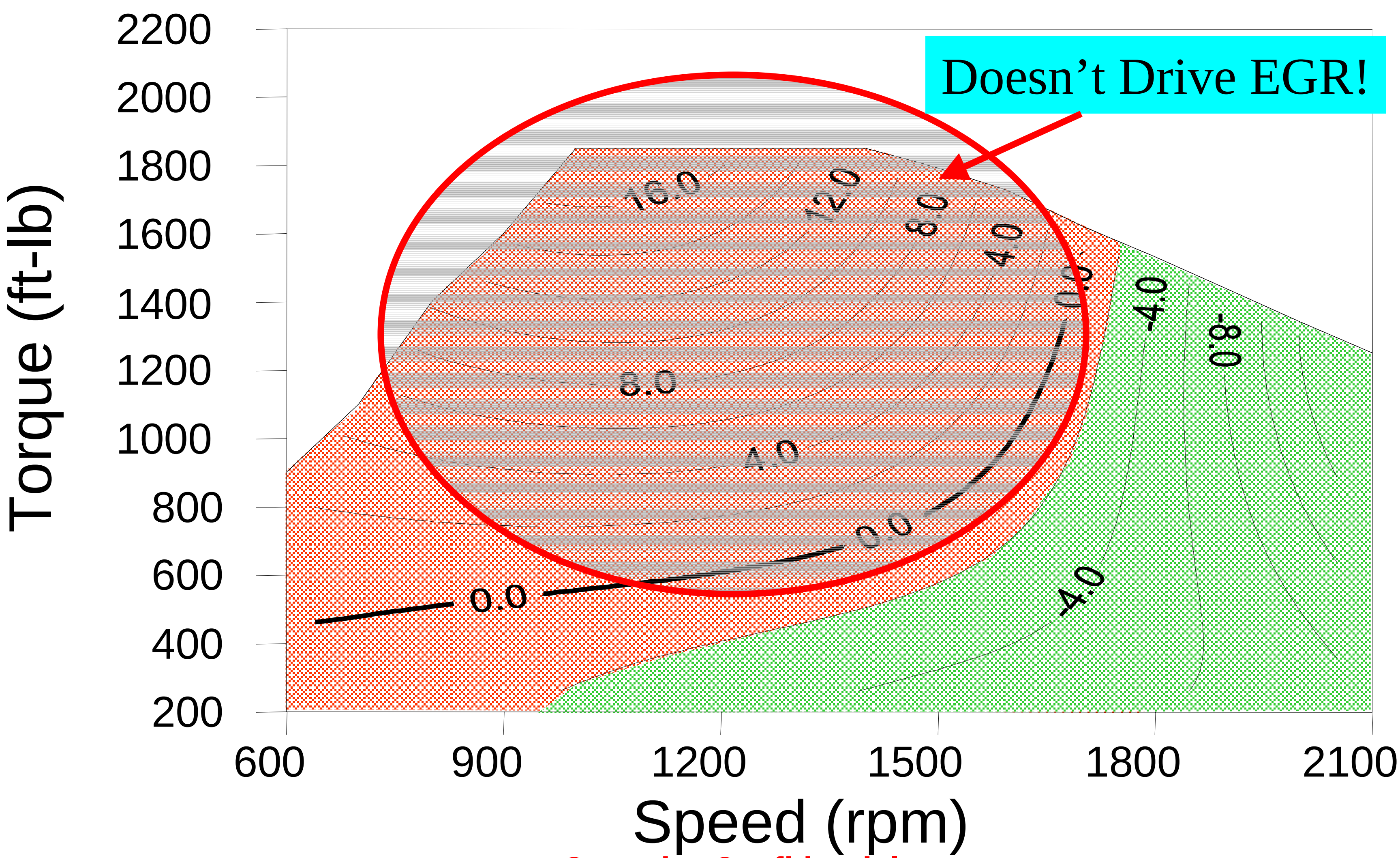
- **Tube-and-shell design**
- **Stainless steel**
- **Engineered by**
- **Behr…a leader**
- **in heat**
- **exchangers**



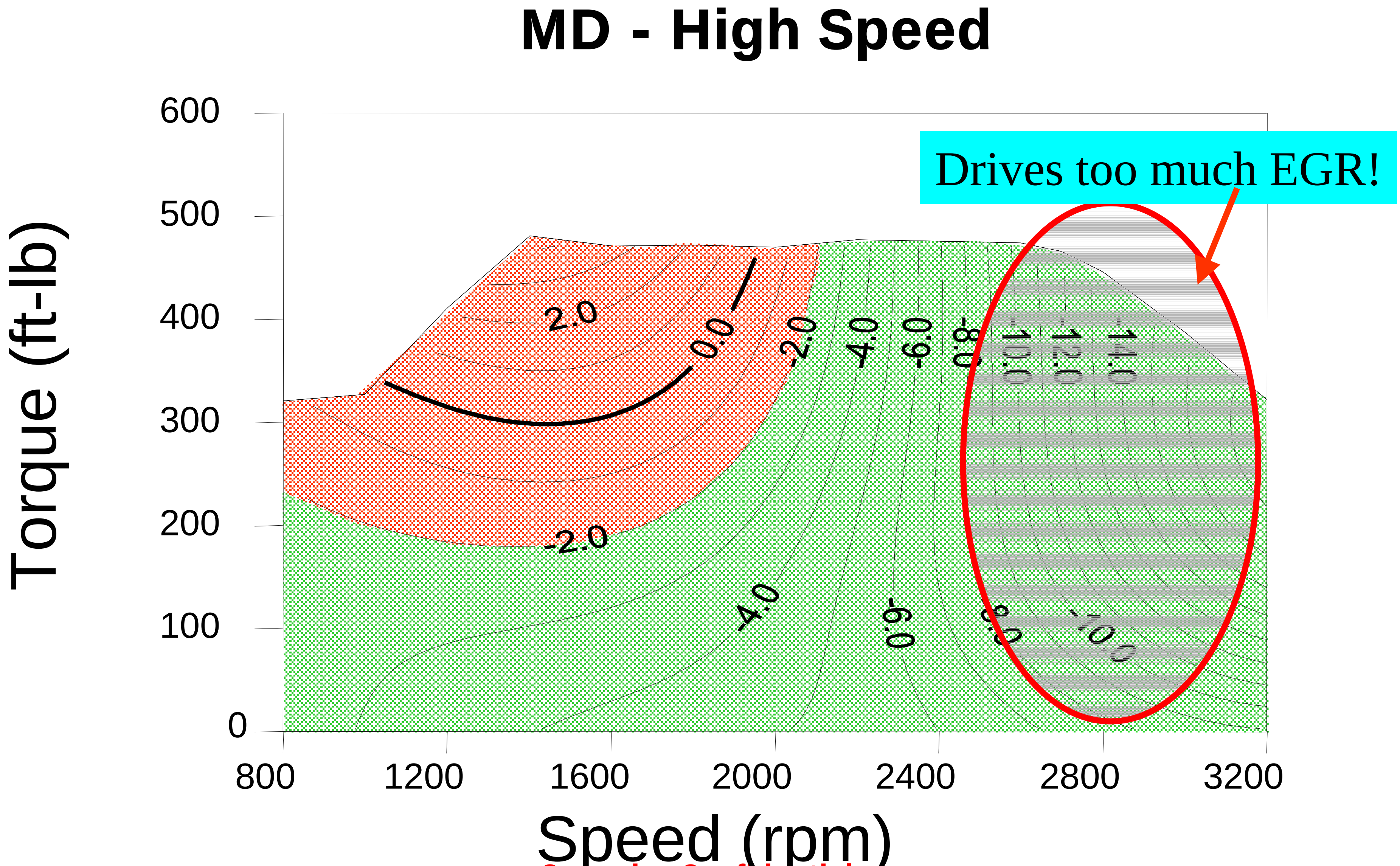
Exhaust-to-Intake Pressure Difference - Current Engines



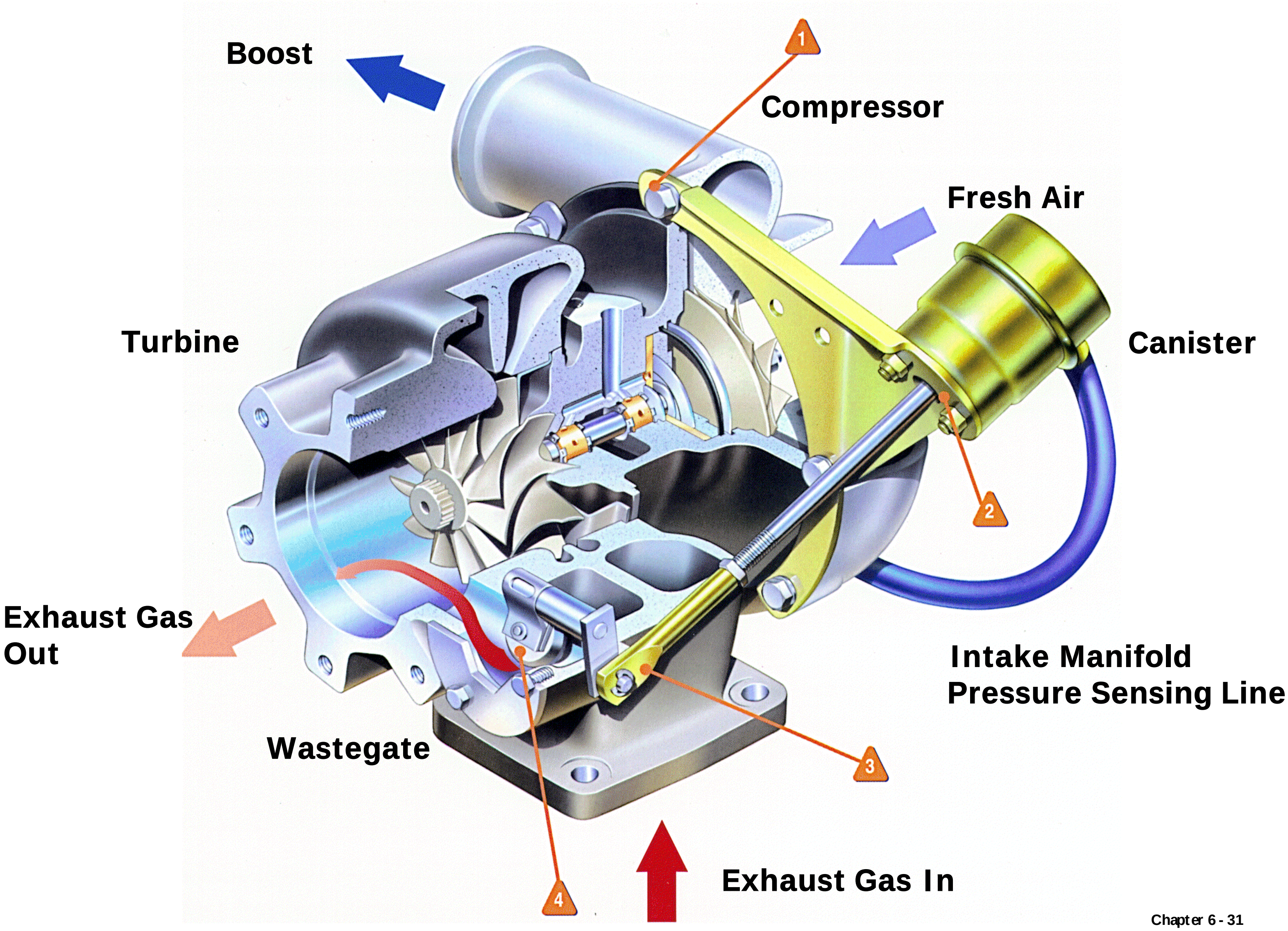
Driving EGR - Engine DeltaP



Driving EGR - Engine DeltaP



Wastegate Turbocharger with Pneumatic Actuation



Variable Geometry Turbocharger with Pneumatic Actuation

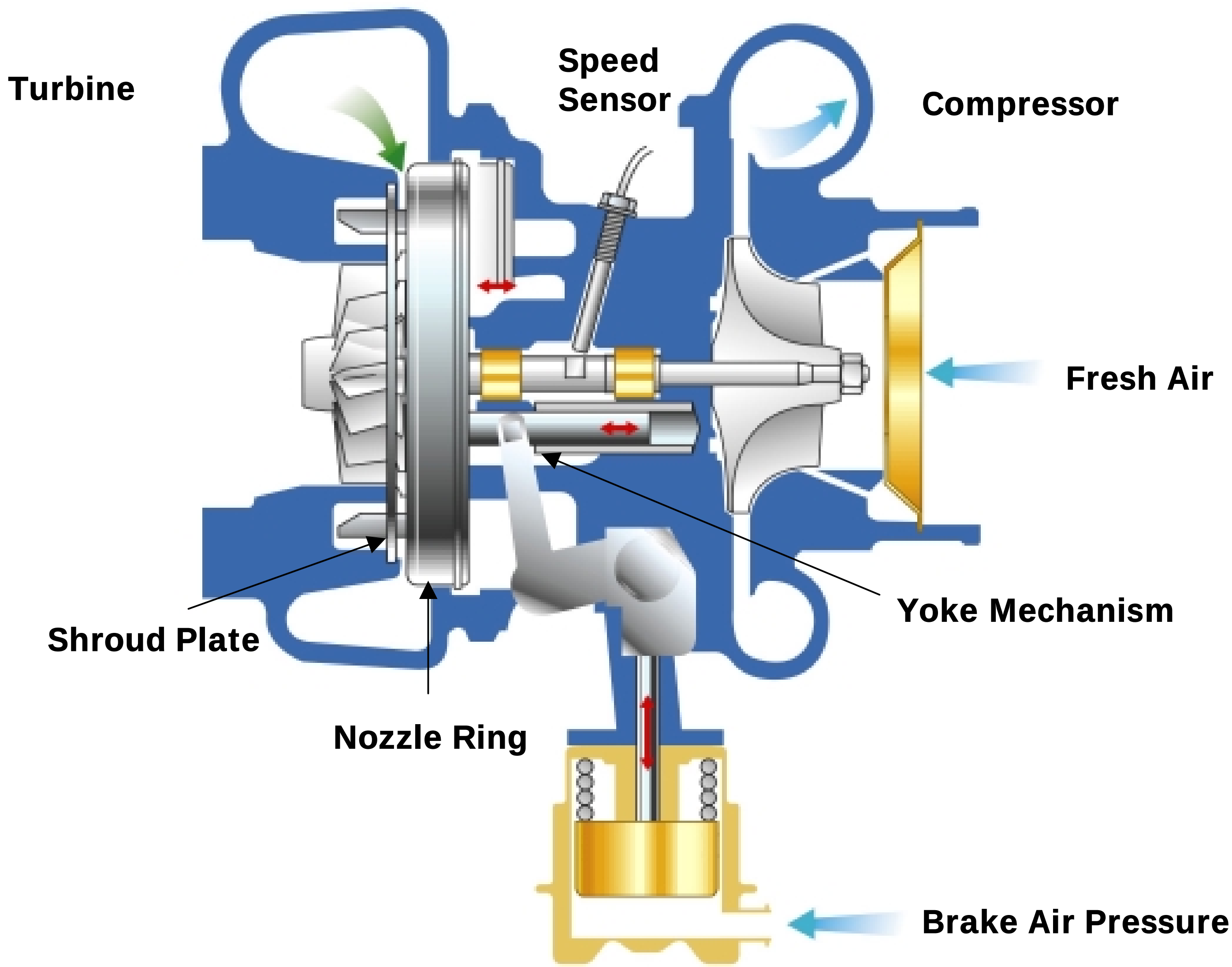
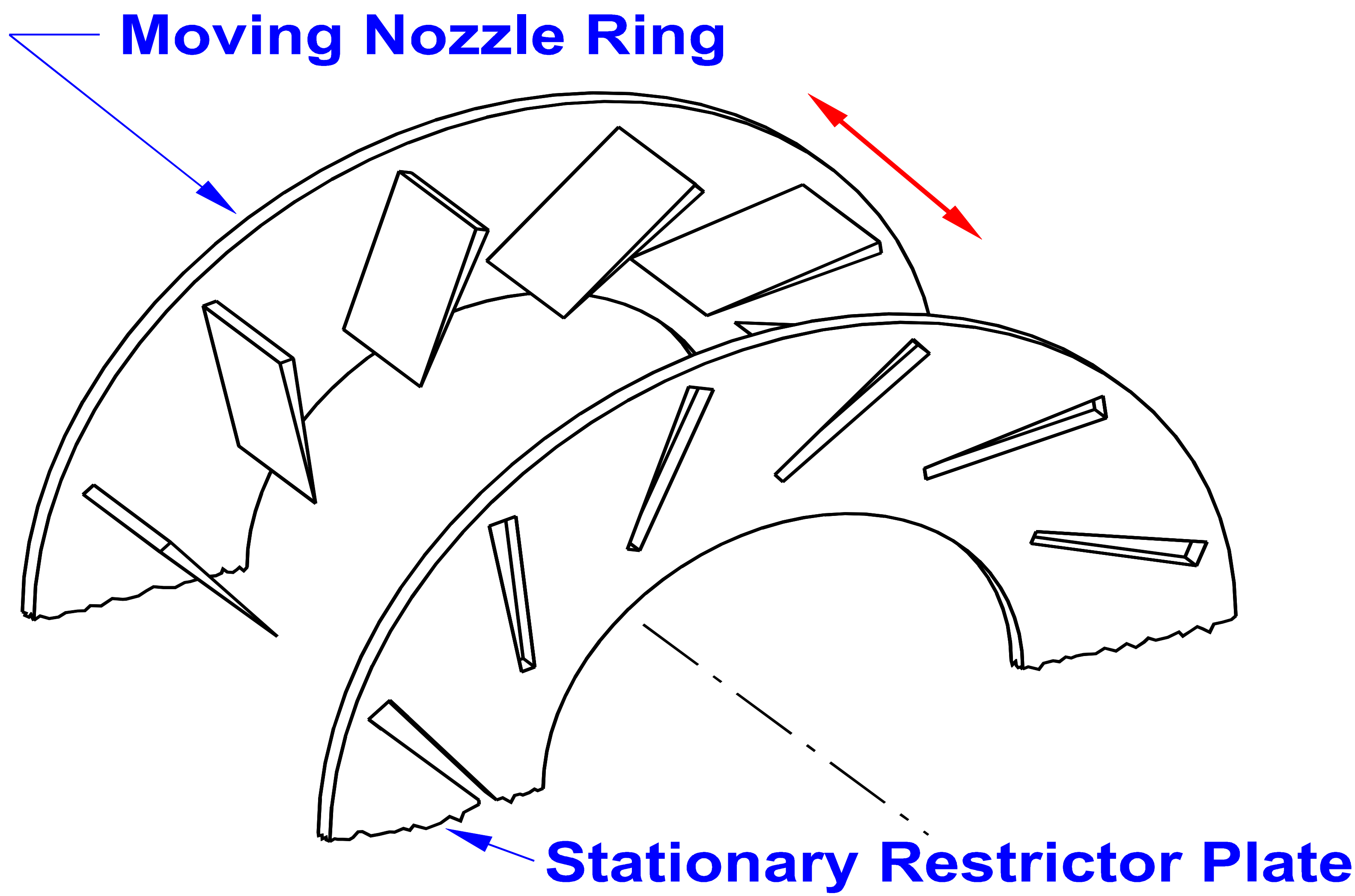
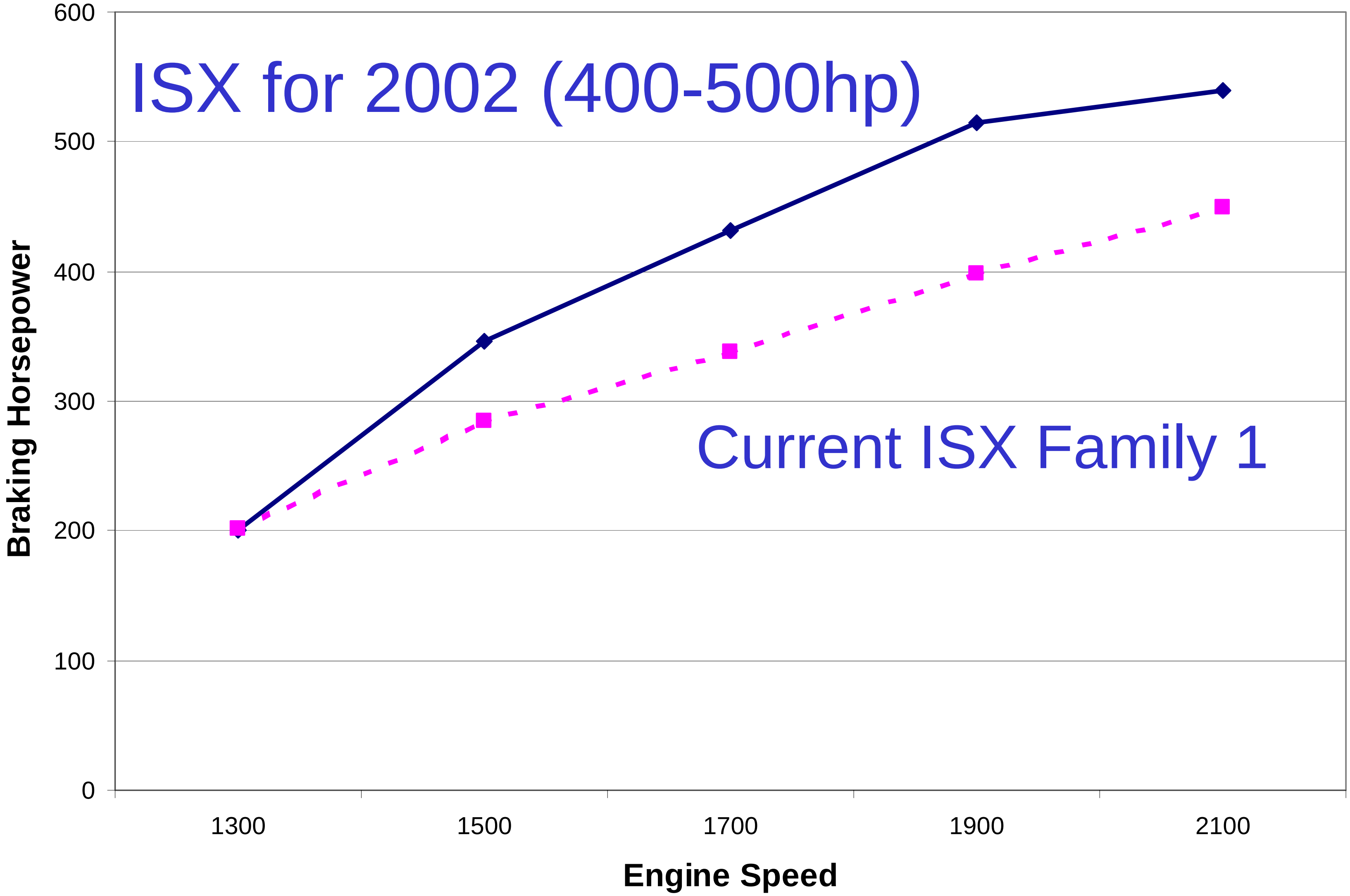


Illustration of VG Nozzle Ring and Restrictor Plate



ISX Compression Braking



Control System Responsibilities

- **Manage Engine Operation**
  - **Produce Torque**
    - Performance (fuel consumption, transient operation, throttle response)
    - EGR on and off
    - Compensate for ambient condition variation, variability, and system deterioration
  - **Limit emissions output to legislated levels**
    - Meet FTP and SET requirements
    - Implement Approved AECD's
    - Least Practicable
    - In Use compliance
  - **Optimize tradeoffs (fuel consumption, heat rejection, etc.) if hardware is capable**

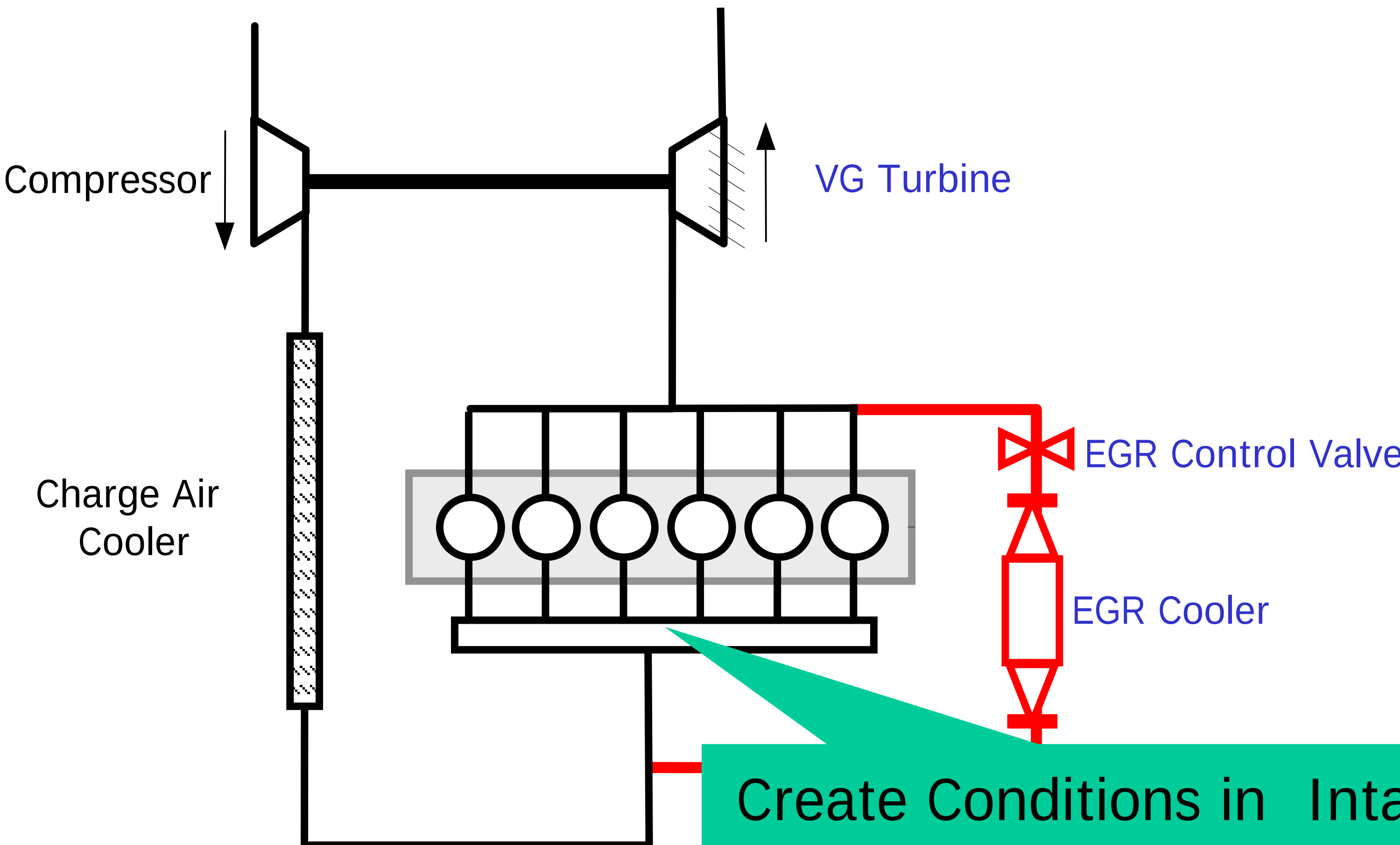
Control System Responsibilities (cont.)

- **Manage Subsystems**
  - **Fuel System (HPCR and HPI)**
  - **Charge Management (Several configurations)**
  - **Braking**
- **Provide Component Protection**
  - **New for 2002**
    - Condensation (Intake Manifold, EGR Cooler)
    - EGR Cooler Fouling
    - EGR Valve
    - Turbocharger
      - Compressor Outlet Temperature
      - Speed
      - Turbine Inlet Temperature
  - **Manage emission compliance during protection**

Control System Responsibilities (cont.)

- **Manage Sensor Inputs and Actuator Outputs within ECM resource constraints**
- **Recognize and accommodate component faults**
  - **Prevent operation outside of design limits while fault condition present**
  - **Provide data necessary to isolate and repair engine**
    - Requires more ‘in range’ fault detection and accommodation due to system complexity
  - **Meet legislated requirements (OBD II)**
- **Provide a system that can be calibrated in an expedient manner**

Objective for Charge Handling Control



Create Conditions in Intake Manifold to support Combustion Goals!

The Automotive Control Approach

- $M_{EGR} = M_{charge} - M_{air}$
- Use Speed-Density to calculate charge mass
- Measure M_{air} using a sensor
- But……, for high output diesels
  - If EGR is roughly 20% and errors in mass flows are about 5%
  - Error in EGR rate estimation becomes a whopping 25% or so of calculated value!
  - Obviously, this is unacceptable

Other Control Approaches

- **Our approach to controls has evolved over time**
- **Generally, the simplest control systems relate a measured parameter directly to an actuator output command**
  - **First Try**
    - Operate EGR valve On/Off
    - VG Position = f(Delta P across engine)
  - **Later**
    - EGR valve modulation was added
- **Our current controls approach significantly more sophisticated**

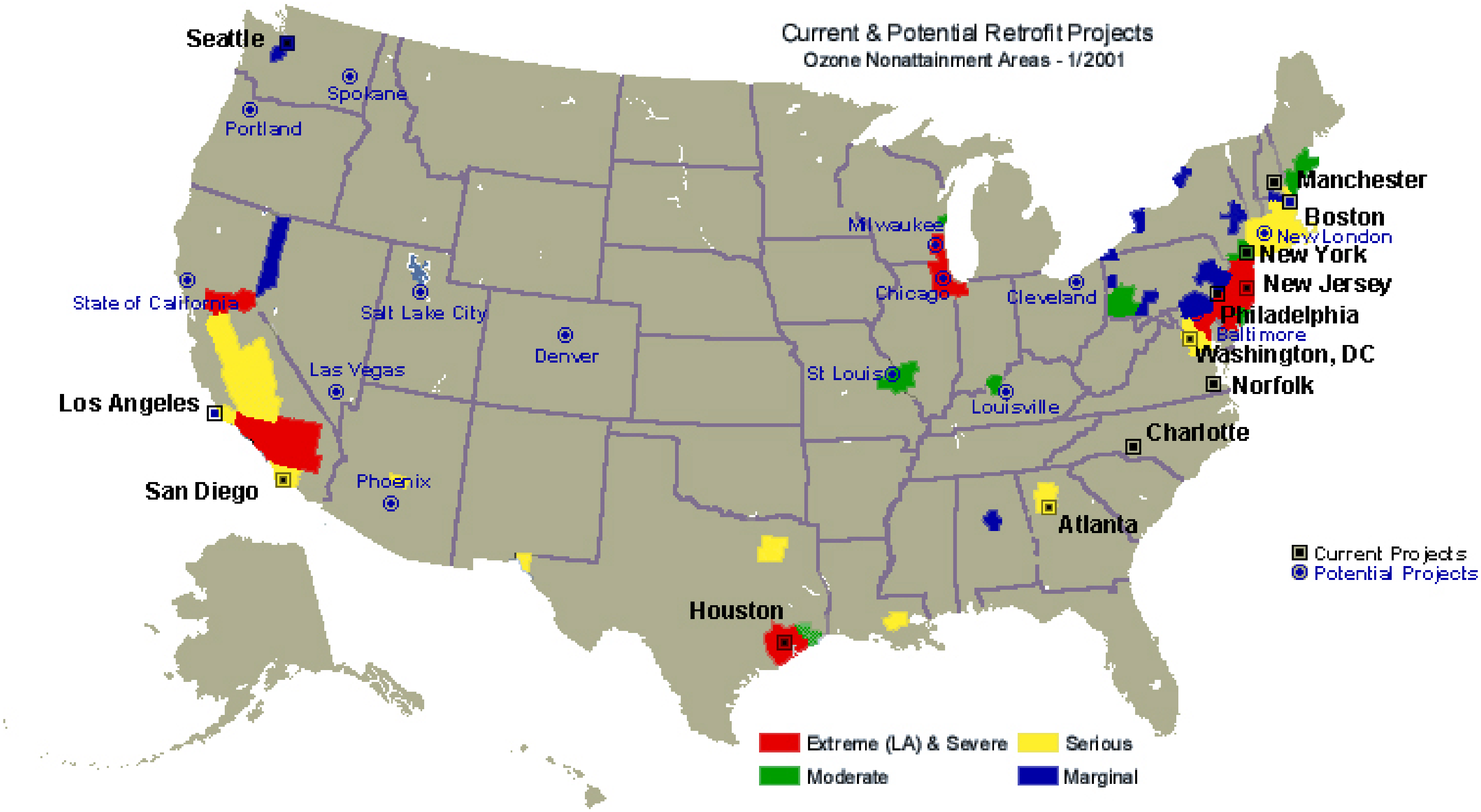
Component Protection Functions

- The following component protection algorithms are necessary in the controls
    - Compressor Outlet Temperature
    - Turbocharger Speed
    - EGR Cooler Condensation
    - Intake Manifold Condensation
    - Turbine Inlet Temperature
    - EGR Valve

Diagnostics and Fault Accommodation

- Sensor Out of Range Testing
- Actuator short/open
- Actuator Temperature
- In Range fault detection and accommodation - e.g.
  - EGR Valve Position
  - Intake Manifold Pressure (High/Low)
  - Charge Temperature
  - VG Actuation
  - EGR Cooler fouling

Ozone Nonattainment Areas



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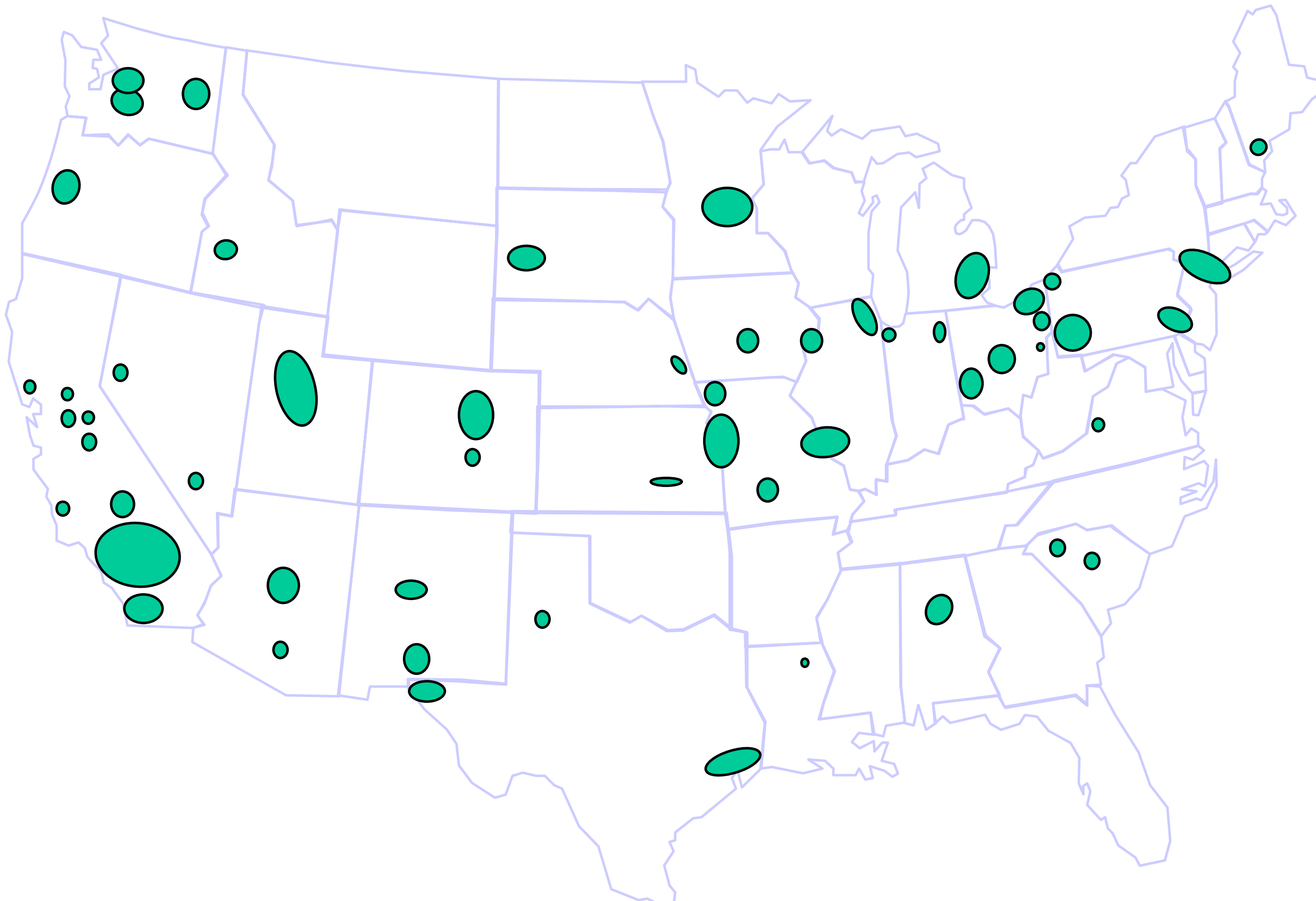
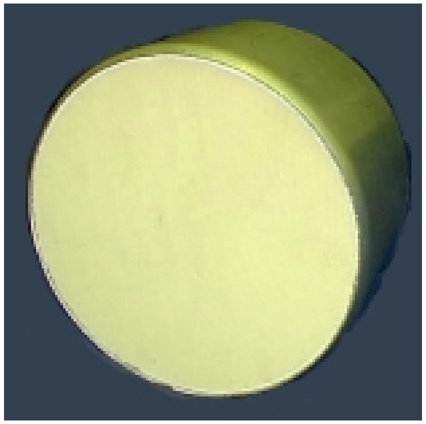
Particulate Nonattainment Areas

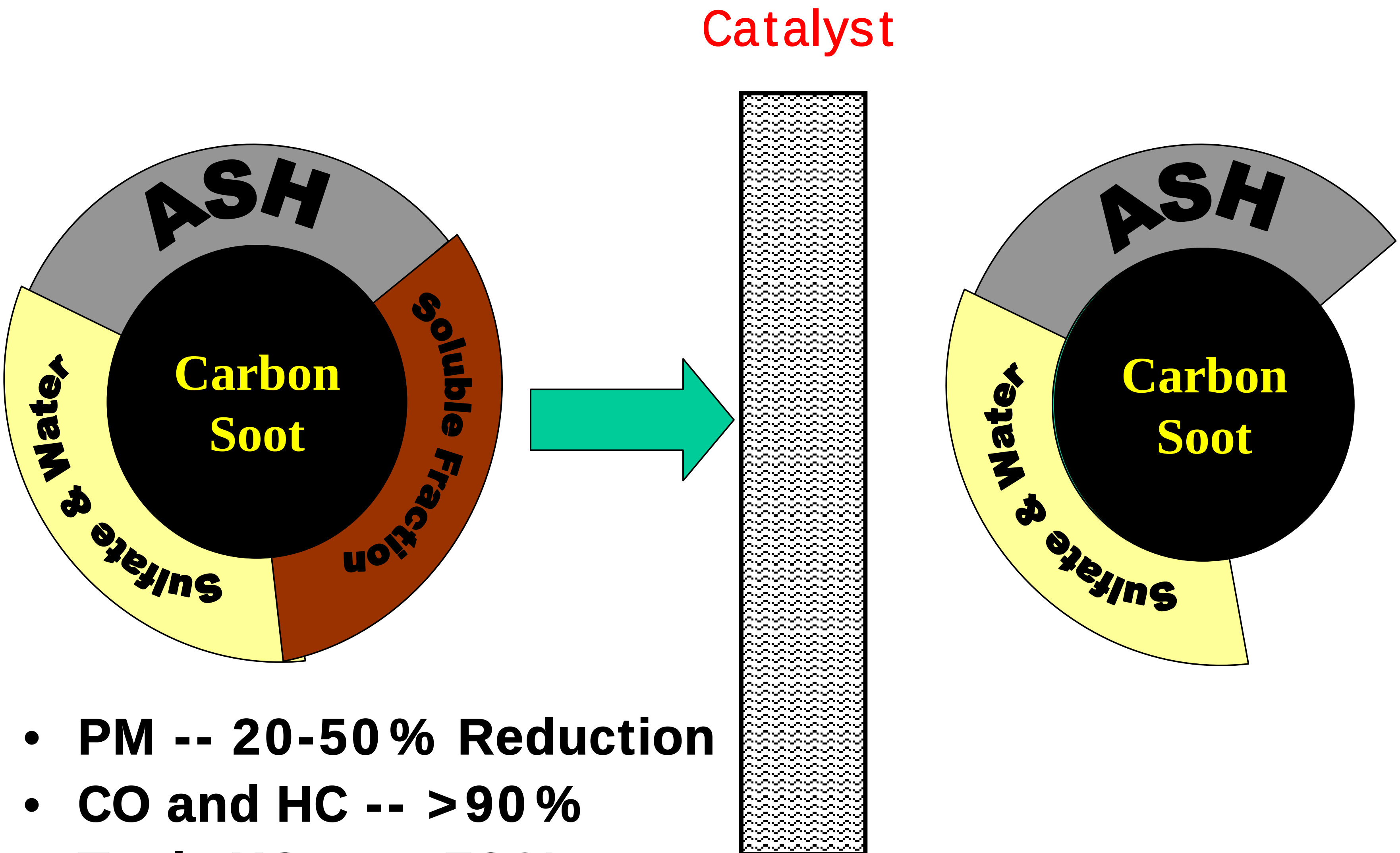


Diesel Oxidation Catalyst

- Cummins and diesel industry have extensive experience with this technology
- Effective at removing unburned fuels and lube (soluble organic fraction)
- Compatible with higher level sulfur fuels
- Maintenance free
- Through flow design

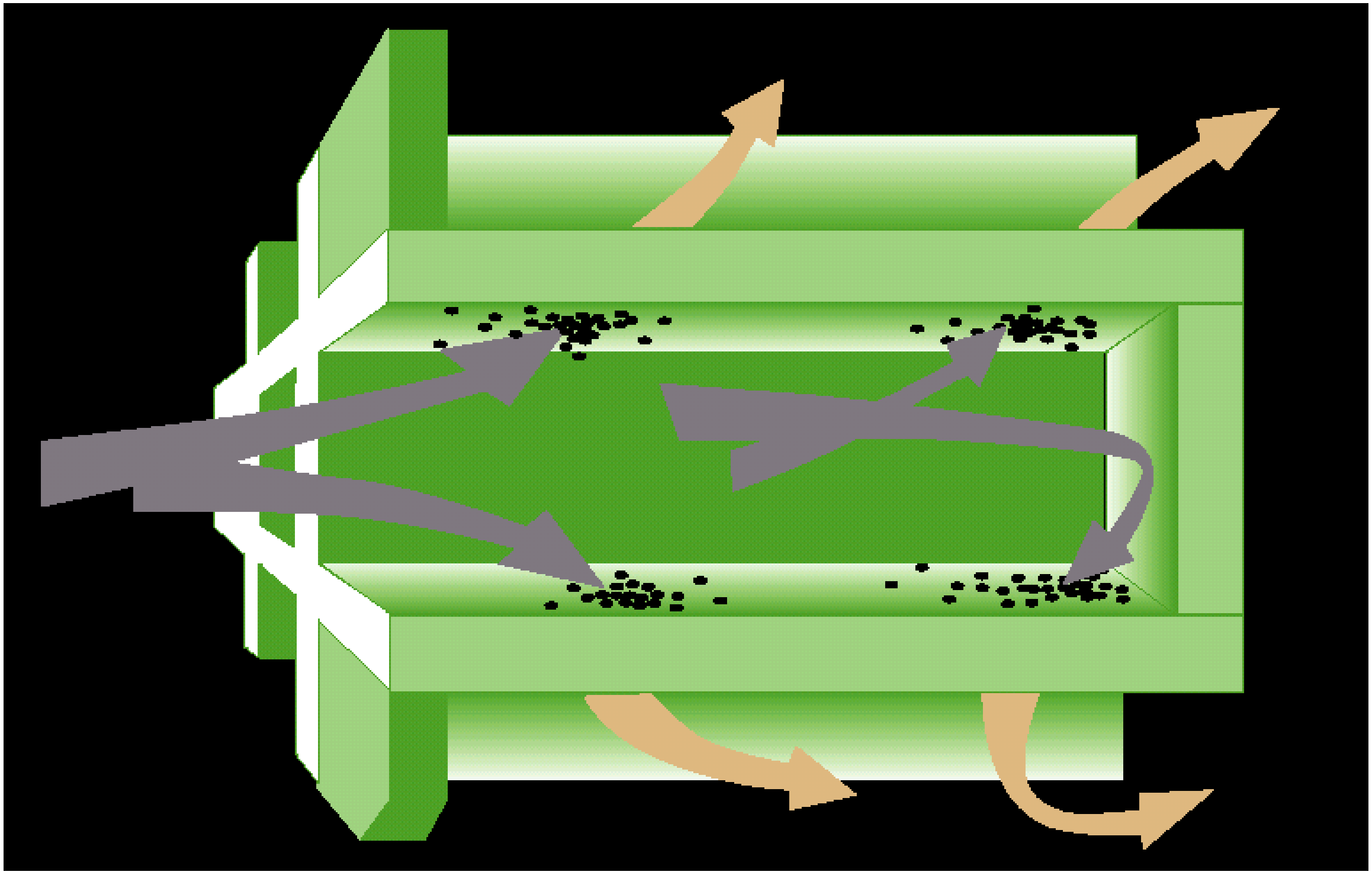


Diesel Oxidation Catalyst



- PM -- 20-50% Reduction
- CO and HC -- >90%
- Toxic HCs -- >70%

Catalyzed Soot Filter

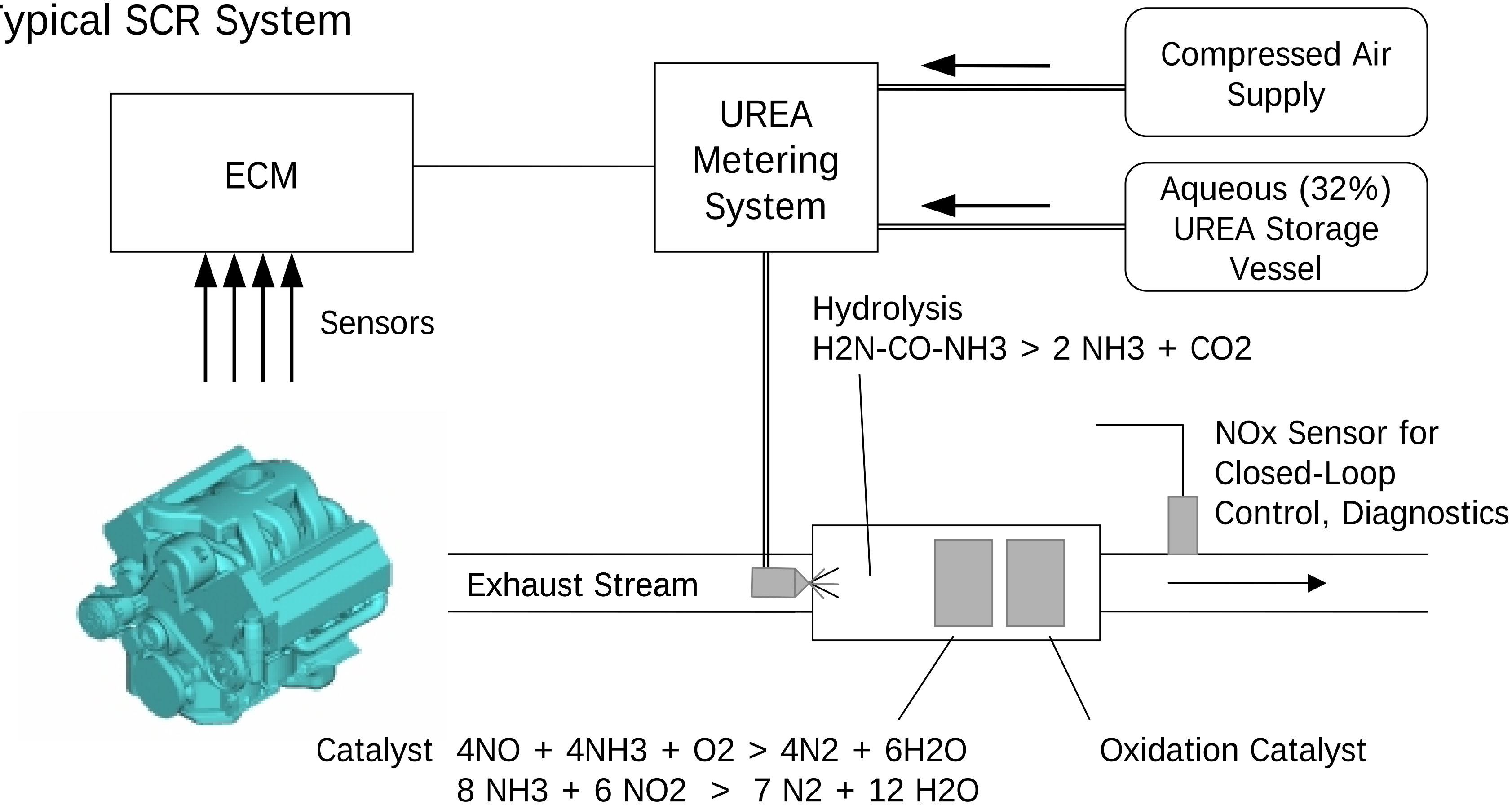


NOx Reduction Technologies

- Exhaust Gas Recirculation (EGR)
- Selective Catalytic Reduction
- Lean NOx Catalyst Technology
- NOx Adsorber Technology

SCR Aftertreatment

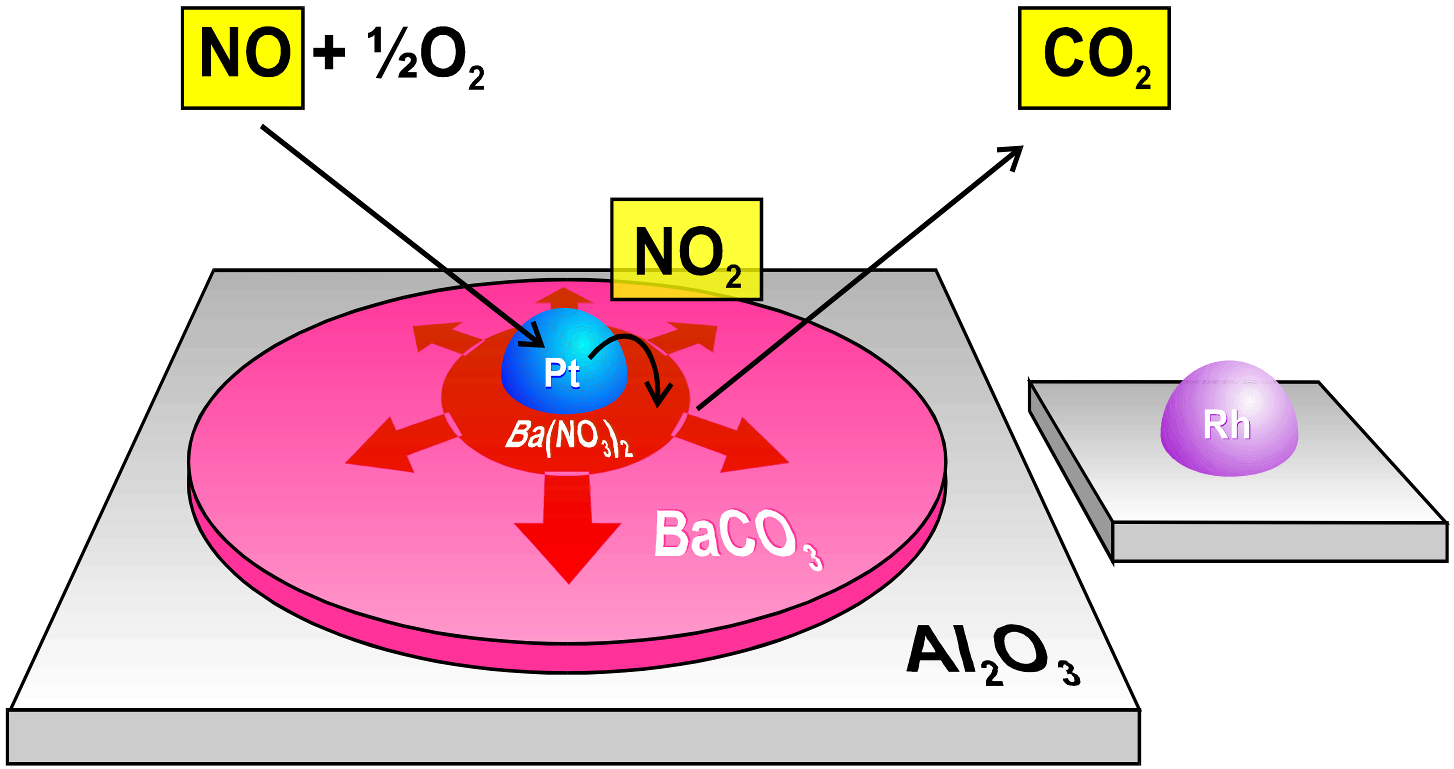
Typical SCR System



- **Urea solution is added to exhaust with compressed air for atomization**
- **Urea decomposes to ammonia and reduces NOx over catalyst**

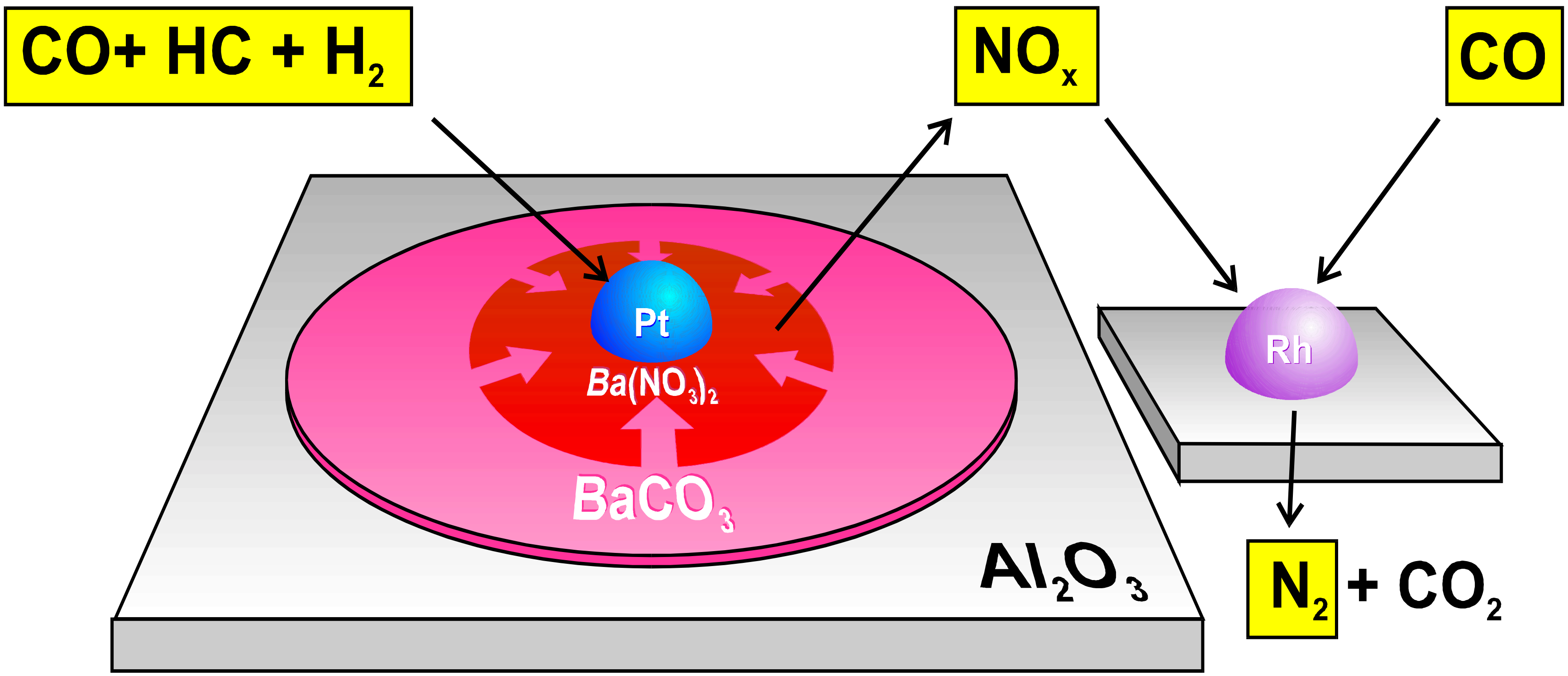
NOx Storage Catalyst Operation

Lean Conditions



NOx Storage Catalyst Operation

Rich Conditions



NOx Adsorber / SCR Comparison

NOx Adsorber

- >50% NOx conversion on light-duty European cycle
- Requires complex engine calibration linked to catalyst regeneration and desulfation
- 3-5% reduction in fuel economy
- Ultra low sulfur fuel is required - sulfur traps probably required
- Complex, parallel system required for HDD - exhaust switching
- Additional PM control burden during NOx regen and desulfation
- No secondary reductant needed

SCR

- >60% NOx conversion on European LD cycle; > 85% on European and US heavy duty cycles
- Engine may be tuned for increased fuel efficiency - EGR synergy
- Ultra low sulfur fuel required
- No high temperature desulfation strategy required
- No additional PM control burden
- On board storage of urea or other NH3 source required