MINING DIESEL EMISSIONS COUNCIL

14th ANNUAL MDEC CONFERENCE
Sheraton Parkway, Toronto North, Canada
October 5 – 10, 2008

MDEC SHORT COURSE ON
DIESEL EMISSIONS & CONTROL TECHNOLOGIES

PRESENTED BY: Magdi K. Khair, SwRI

COORDINATED BY: MAHE GANGAL, NRCan

OCTOBER 7, 2008

MINING DIESEL
mdec
EMISSIONS COUNCIL

Diesel Workshop

MDEC Short Course on Diesel Emissions & Control Technologies

Sheraton Parkway, Toronto North
Ontario, Canada

Markham Room

Tuesday, October 7, 2008

Presented by: Dr. Magdi K. Khair, Southwest Research Institute

08:00 – 08:30	Registration & Gathering (Coffee available)
08:30 – 08:35	Welcome (Mahe Gangal, Co-chair MDEC Conference)
10:00 – 10:15	Coffee Break
12:00 – 12:45	Lunch
14:30 – 14:45	Coffee Break
16:30	Adjournment

MDEC Conference
October 2008

Diesel Emissions & Control Technologies

Magdi K. Khair
Southwest Research Institute
San Antonio, TX

Outline

- Introduction
- The Challenge
- Diesel's Achilles' Heel
- Technical Options (for In-Cylinder Control)
- Aftertreatment Technical Options
- Accomplishments

Introduction

Diesel Engines

- Excellent Reliability
- Excellent Durability
- Excellent Fuel Economy
- Low Engine-out HC
- Low Engine-out CO
- Low CO_2 Emission Contribution

But

NO_x and PM Problem

Superior Durability of Diesel Engines

On-Highway

Off-Highway

Superior Fuel Economy of Diesel Engines

	City mpg	Highway mpg	Combined mpg	Combined gal/mi	CO_2 Reduction
Dodge Durango					
-Gasoline	12	17	13.8	0.072	--
-Diesel	20.3	25.0	22.1	0.045	--
			+60% Better	37% Reduced	27%
Dodge Ram 1500					
-Gasoline	12	16	13.5	0.074	--
-Diesel	19.8	24.6	21.7	0.046	--
			+61% Better	38% Reduced	28%

DOE-Funded Research at Cummins

Diesel Engines and the CO_2 Inventory

"The state wants to cut vehicles' output of carbon dioxide by 30 percent over the next decade, limiting a major greenhouse gas thought to contribute to global warming."

California wants to cut vehicle carbon dioxide emissions by 30 percent over the next decade.

California's CO2 Plan Worries Automakers

Cutting Emissions Would Be Costly, Industry Warns

By GREG SCHNEIDER
Washington Post Staff Writer

California loves cars, with more on the road than anywhere else in the country. But the state where the Beach Boys wrote odes to the "Little Deuce Coupe" and "409" struggles to balance romance with environmental responsibility, and now California regulators have come up with a new clean-air guideline that has automakers howling.

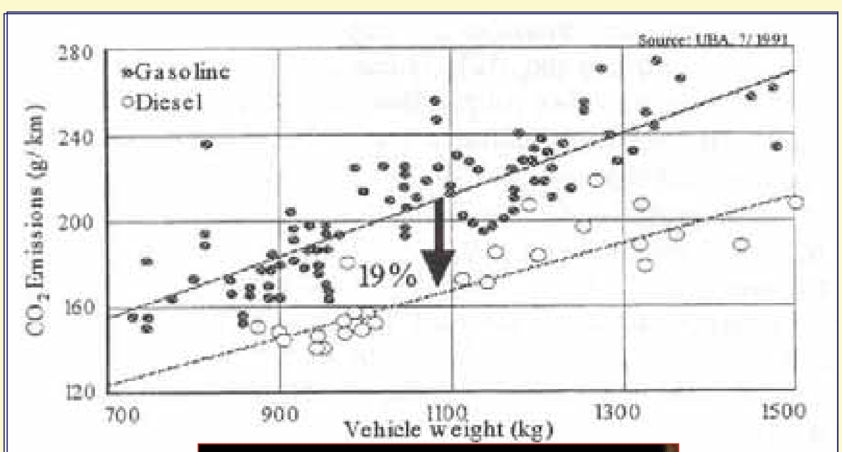
The state wants to cut vehicles' output of carbon dioxide by 30 percent over the next decade, limiting a major greenhouse gas thought to contribute to global warming. It's the first U.S. attempt to address the controversial issue through car emissions, and automakers argue it could boost car and truck prices nationwide without producing much benefit.

Unlike other engine emissions, carbon dioxide can't be filtered away, so the only way to cut it back is to improve efficiency – in-creasing the distance a car can go on a gallon of gasoline. California regulators estimate that achieving their goal would cost roughly $1,000 per vehicle, but carmakers say that figure is low.

"We would certainly consider it one of the most, if not the most, comprehensive and costly environmental programs that's ever been adop-ted -- not just by California, but by any-one," said John M. Cabaniss Jr., director of envi-ronment and energy at the Association of In-

See **AUTOS**, *E5, Col.1*

Diesel Engines and the CO_2 Advantage



Diesel Engines and Global Warming

Not a lot of lobster

Global warming blamed

By Jeff Donn
ASSOCIATED PRESS

Business is booming for Maine lobsterman Ben Lash, but is falling off in southern waters.

“…about 60 lobster researchers brainstormed in Groton, Conn. They agreed that…warming water seems to account for the lobster’s decline.

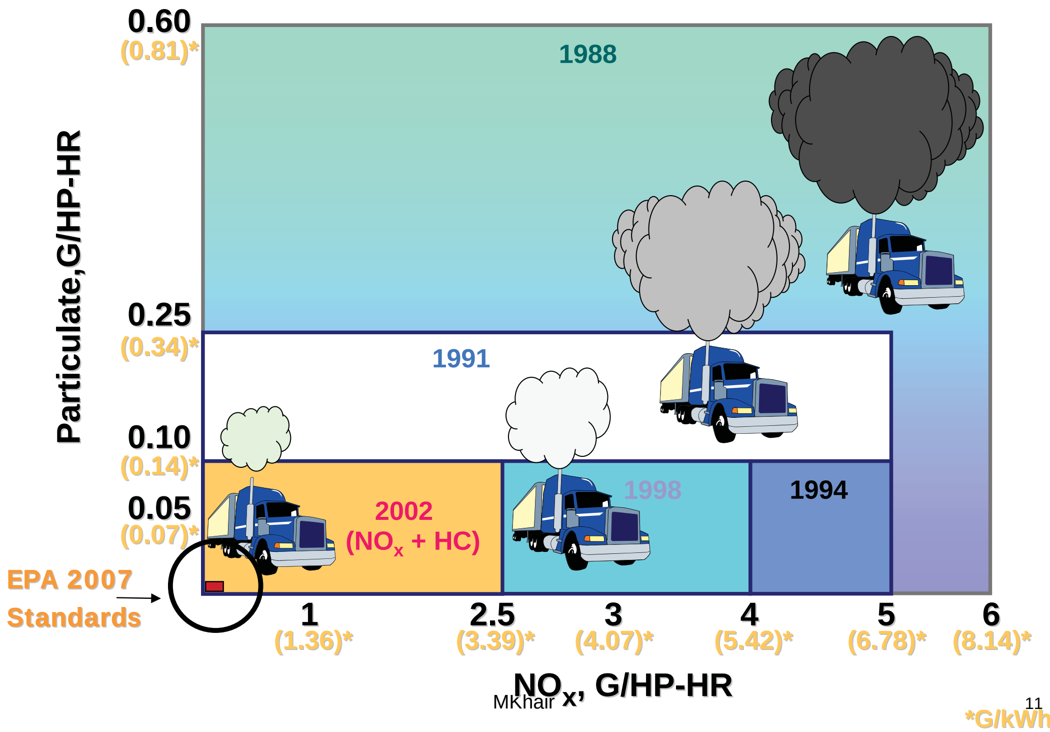
“…Last year’s state (Maine’s) catch fell back almost 14% to 53.9 Million pounds.

The Washington Times, August 24, 2004

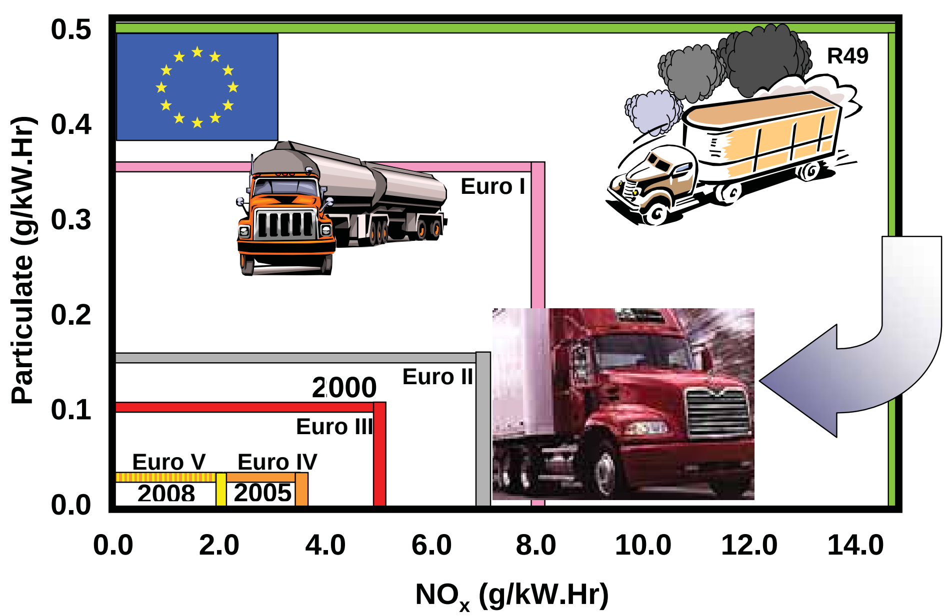
9

The Challenge

On-Highway Emission Limits - USA



On-Highway Emission Limits - Europe



Off-Highway Emission Limits

Tier 4 Emission Standards—Engines Up To 560 kW, g/kWh (g/bhp-hr)

Engine Power	Year	CO	NMHC	NMHC+NOx	NOx	PM
kW < 8 (hp < 11)	2008	8.0 (6.0)	-	7.5 (5.6)	-	0.4[a] (0.3)
8 ≤ kW < 19 (11 ≤ hp < 25)	2008	6.6 (4.9)	-	7.5 (5.6)	-	0.4 (0.3)
19 ≤ kW < 37 (25 ≤ hp < 50)	2008	5.5 (4.1)	-	7.5 (5.6)	-	0.3 (0.22)
	2013	5.5 (4.1)	-	4.7 (3.5)	-	0.03 (0.022)
37 ≤ kW < 56 (50 ≤ hp < 75)	2008	5.0 (3.7)	-	4.7 (3.5)	-	0.3[b] (0.22)
	2013	5.0 (3.7)	-	4.7 (3.5)	-	0.03 (0.022)
56 ≤ kW < 130 (75 ≤ hp < 175)	2012-2014[c]	5.0 (3.7)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)
130 ≤ kW ≤ 560 (175 ≤ hp ≤ 750)	2011-2014[d]	3.5 (2.6)	0.19 (0.14)	-	0.40 (0.30)	0.02 (0.015)

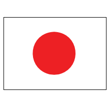
a - hand-startable, air-cooled, DI engines may be certified to Tier 2 standards through 2009 and to an optional PM standard of 0.6 g/kWh starting in 2010
b - 0.4 g/kWh (Tier 2) if manufacturer complies with the 0.03 g/kWh standard from 2012
c - PM/CO: full compliance from 2012; NOx/HC: Option 1 (if banked Tier 2 credits used)—50% engines must comply in 2012-2013; Option 2 (if no Tier 2 credits claimed)—25% engines must comply in 2012-2014, with full compliance from 2014.12.31
d - PM/CO: full compliance from 2011; NOx/HC: 50% engines must comply in 2011-2013

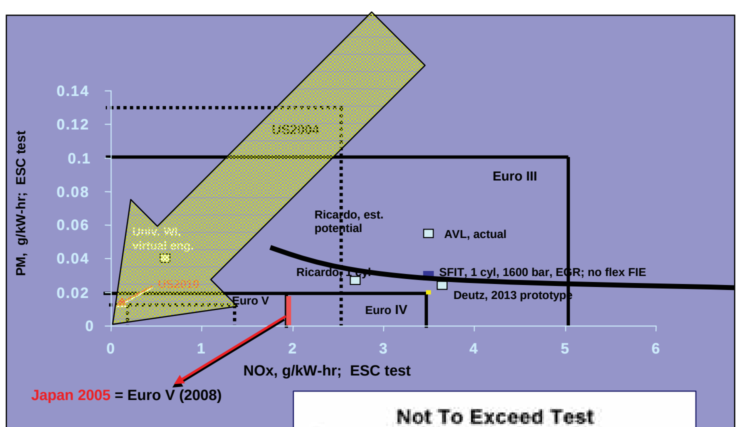
Regulatory Constraints

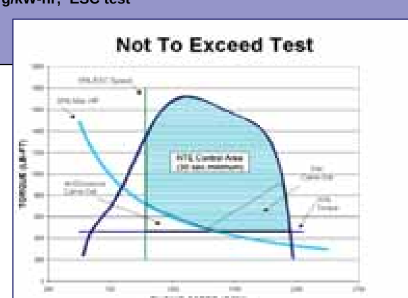
- **USA**
  - EPA FTP
  - EPA SET
  - N-T-E
  - NOx Checks
  - IUT
  - Non-Road (Tier 4a & b)
  - Locomotive & Marine
  - CO_2 Limits
  - OBD

- **Europe**
  - EURO IV
  - EURO V
  - EURO VI
  - CO_2/Kyoto Agreement
  - ESC
  - ETC

- **Japan**
  - New Japanese Transient Cycle
  - Steady-State 13-Mode
  - Etc………….







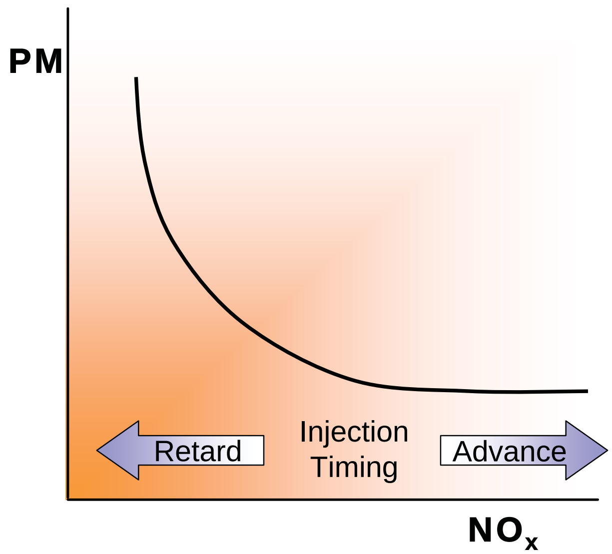
What is Needed?

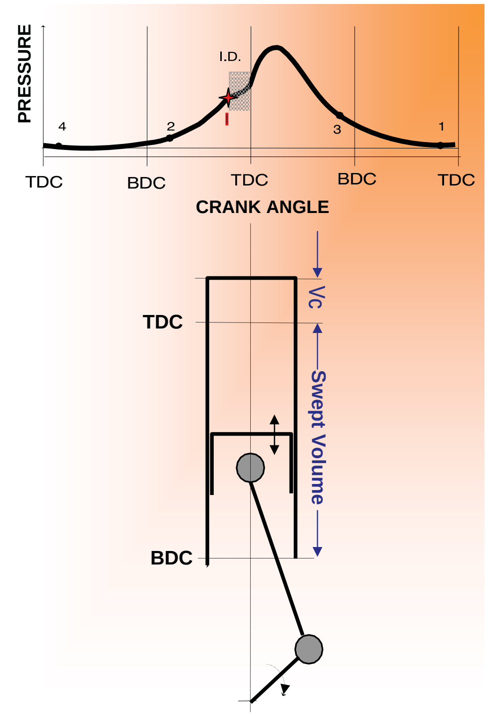
A prosperous future with transportation Systems That are economically- and ecologically-friendly
(ECO^2)

Can the Diesel Engine Satisfy This Requirement?

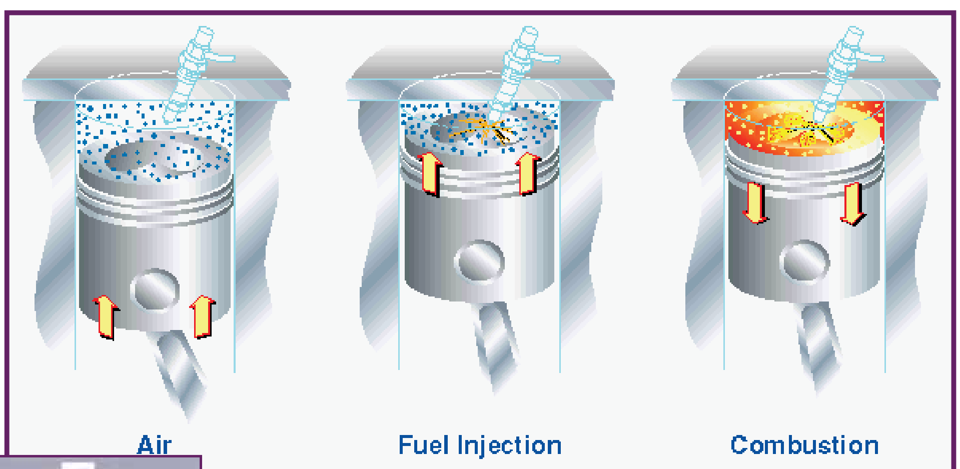
Diesel’s Achilles’ Heel

NO_x-PM Tradeoff



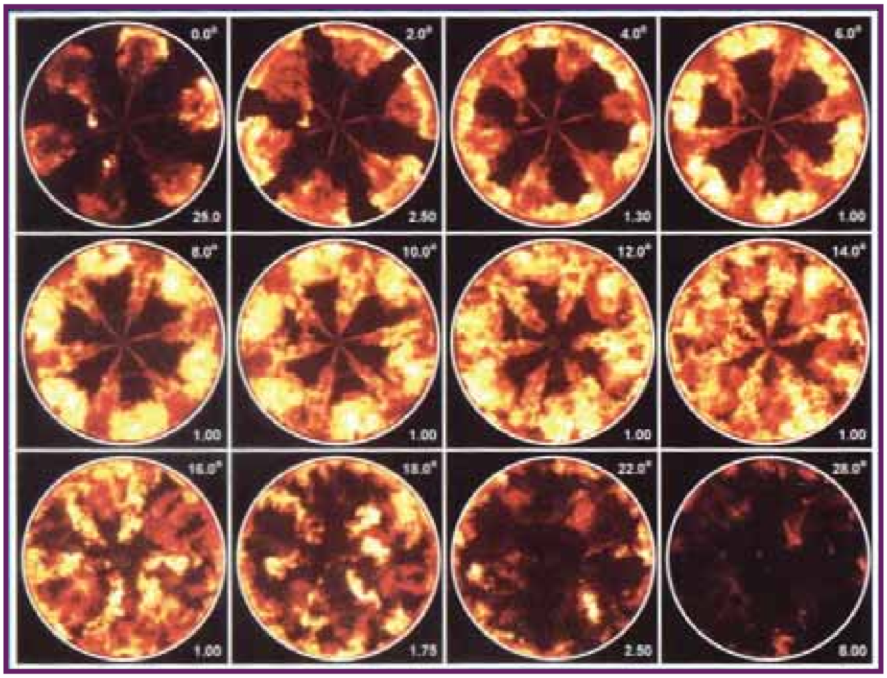


Source of PM / NO_x Problem

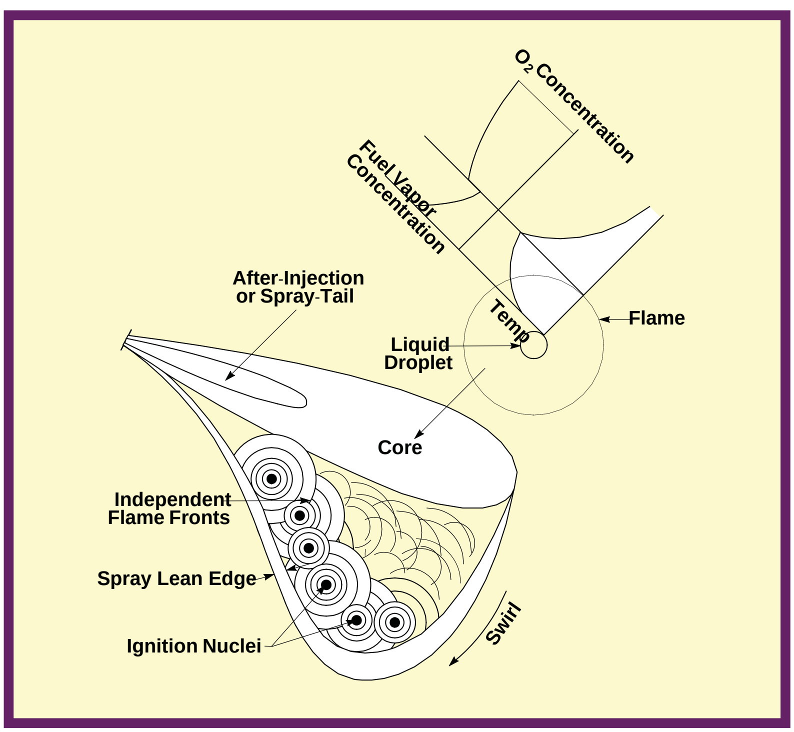


- Start of Injection Controls Timing of Ignition
- High Temp. Diffusion Flame Creates NO_x
- Incomplete Combustion in Fuel Rich Zones Causes Soot Formation

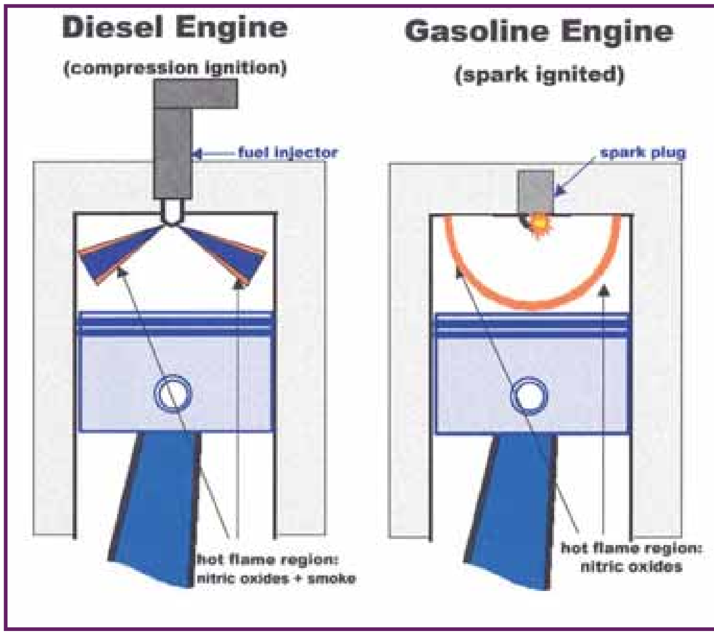
Flame Progression in Diffusion Combustion



A Closer Look at Diffusion Combustion



Comparison Between Diesel & Gasoline Combustion



Diesel
- Heterogeneous Mixture*
- High Compression (16-20:1)
- Auto-ignition (Chem-T_{air}-t_{inj}).
- High A/F Ratio (23->150:1)
- Unthrottled
- Low Speed (4-5K)
- High PM
- Tends to Smoke

Gasoline
- Homogeneous Mixture*
- Low Compression (8-10:1)
- Spark-ignition
- Fixed A/F Ratio (14.5:1)
- Throttled
- High Speed (6-9K)
- Low PM
- Smokeless Operation

****Heterogeneous: Fuel is injected into air***
****Homogeneous: Fuel is pre-mixed with air***

Adapted From Caterpillar-K. Duffy-DEER 2002

The Zeldovich Mechanism

$$O_2 \rightleftharpoons 2O$$

$$O + N_2 \rightleftharpoons NO + N$$

Modified

$$N + O_2 \rightleftharpoons NO + O$$

Note:

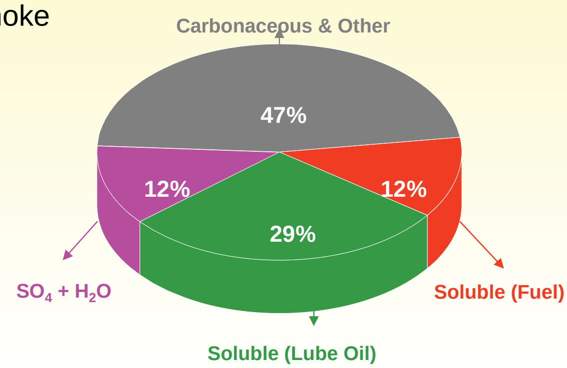
N_2, O_2, $T_{combustion}$ & $t_{residence}$

Definition of Particulate Matter

Any Matter In The Exhaust Of An Internal Combustion Engine *(excluding water vapor)* That Can Be Filtered at 125 Degrees (F) Or Less After Equilibration In Conditioned Air

Constituents of Particulate Matter

- Carbonaceous-Soot-Black Smoke
- Trace Metals
- Soluble Organic Matter
  - Lube Oil
  - Fuel
- Sulfates



Is Smoke PM?
Is PM Smoke?

Sources of Particulate Matter

1. LOSS OF OIL CONTROL
2. BLACK SMOKE FROM EXCESSIVE RICHNESS
   - *OVER FUELING*
   - *POOR COMBUSTION*
   - *TRANSIENTS*
3. WHITE SMOKE
   - *COLD START*
   - *MISFIRE*
4. OTHER HYDROCARBON ORIGINS
   - *NOZZLE DRIBBLE*
   - *SECONDARY INJECTIONS*
   - *AFTER INJECTIONS*
5. FUEL QUALITY
   - *SULFUR CONTENT*
   - *AROMATIC CONTENT*
   - *CETANE NUMBER*

Technical Options

(For In-Cylinder Control)

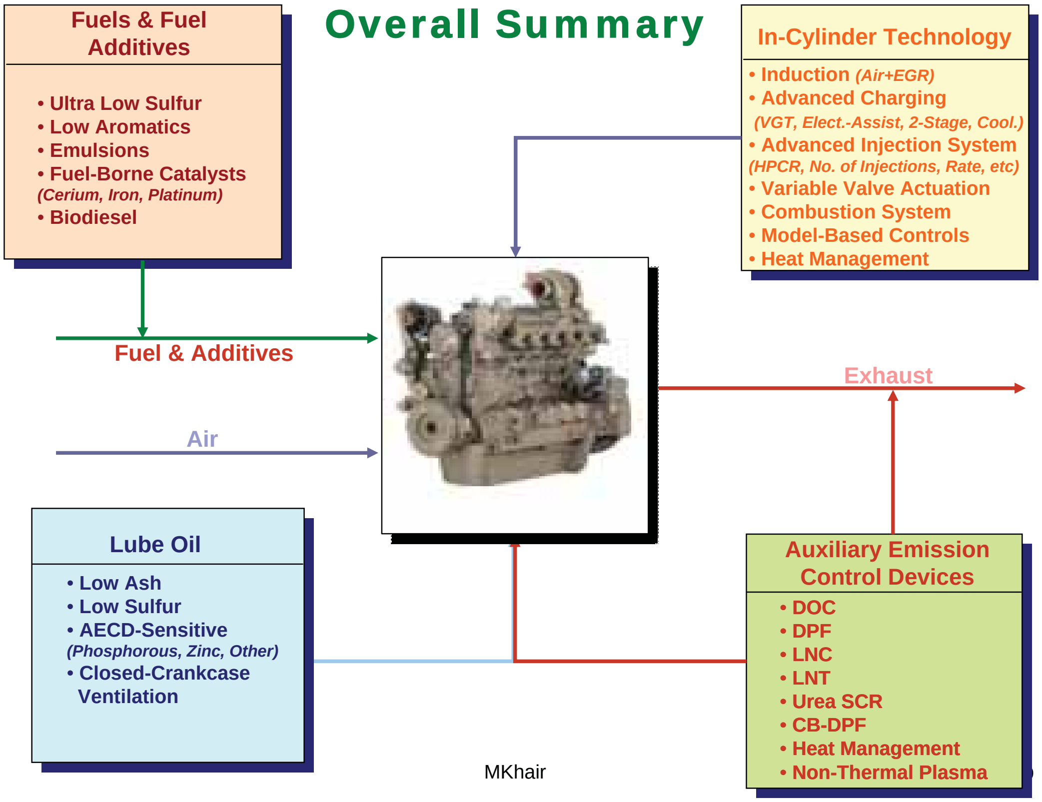
Generalized / Simplified Solutions

For NO_x Reduction — Lower Combustion Temperature

For PM Reduction — Better Mixing

The balance of this presentation will address these generalized/simplified solutions

Overall Summary

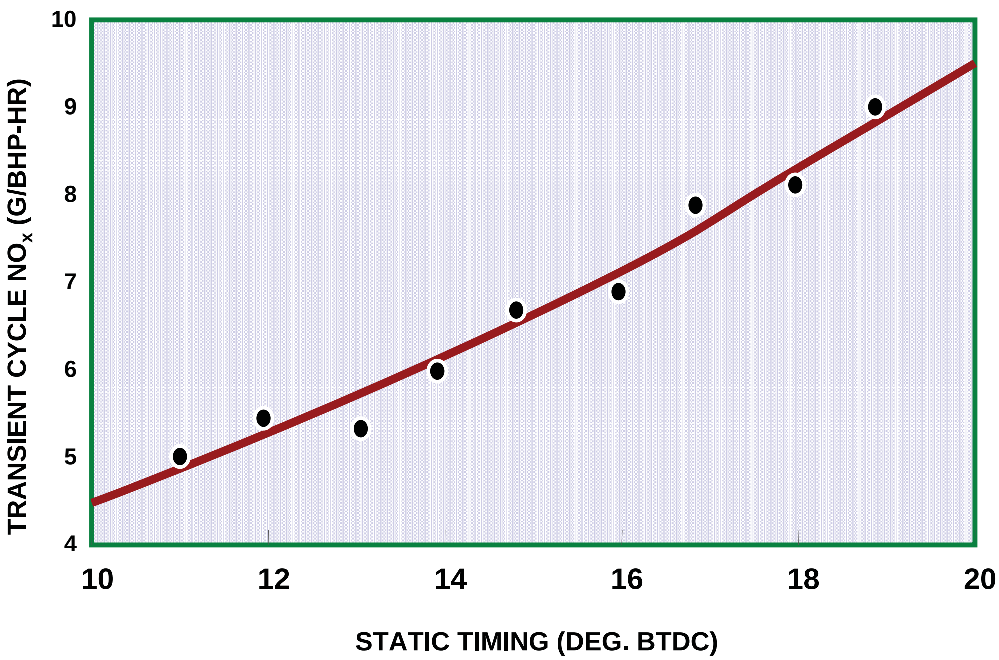


Developments in In-Cylinder Technologies

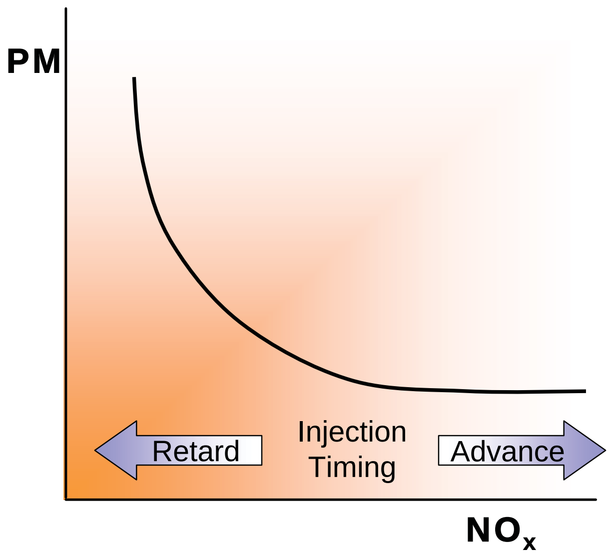
- Fuel Injection System
- Combustion System
- Induction, EGR , and Charging Systems
- Valve Train

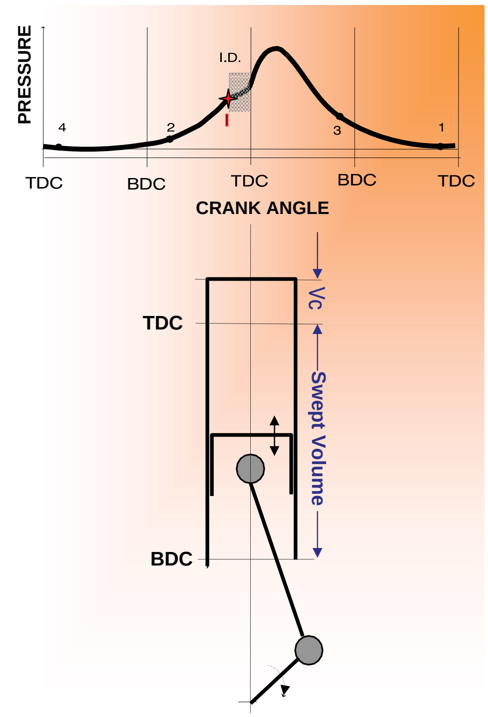
Fuel Injection System Developments

Effect of Injection Timing Retard



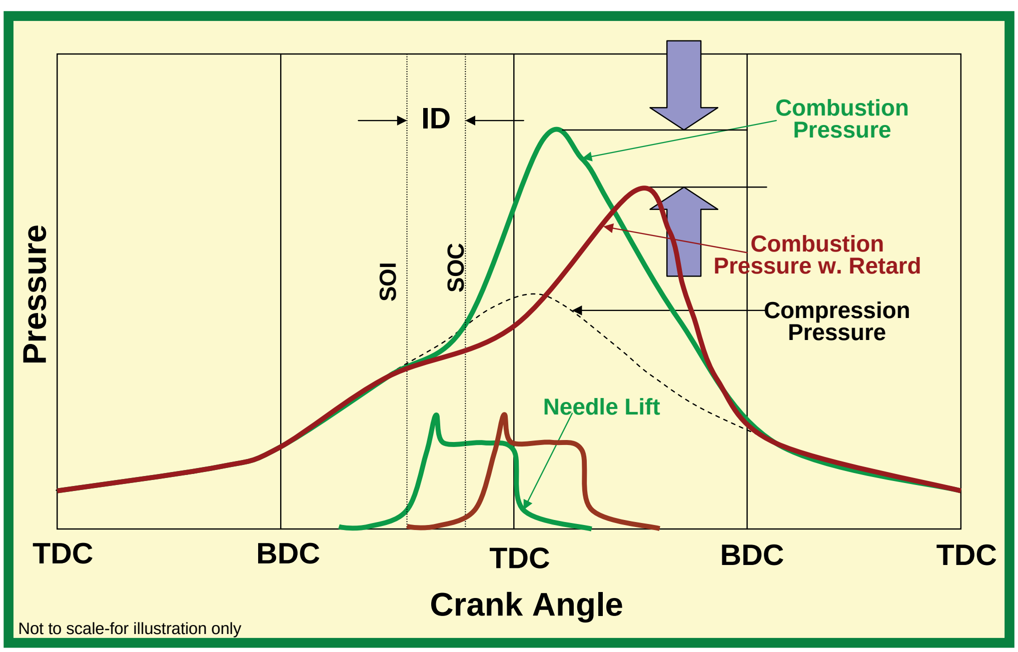
NO_x-PM Tradeoff - Review



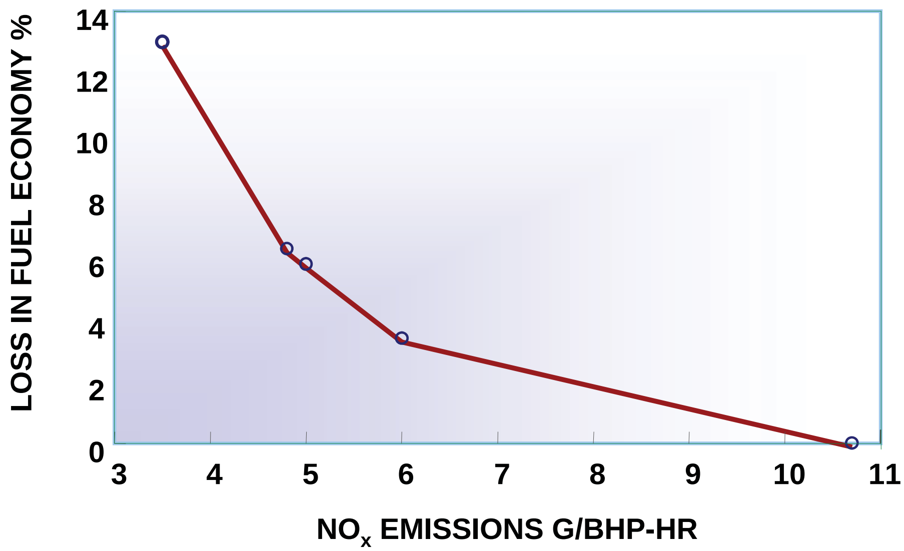


MKhair

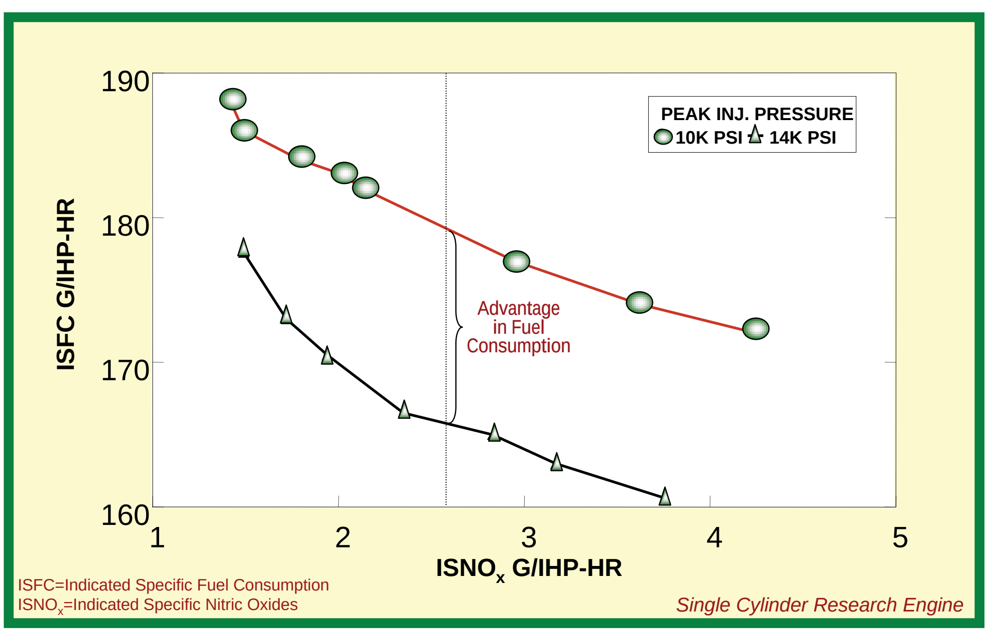
Mechanism for Reduced NO_x



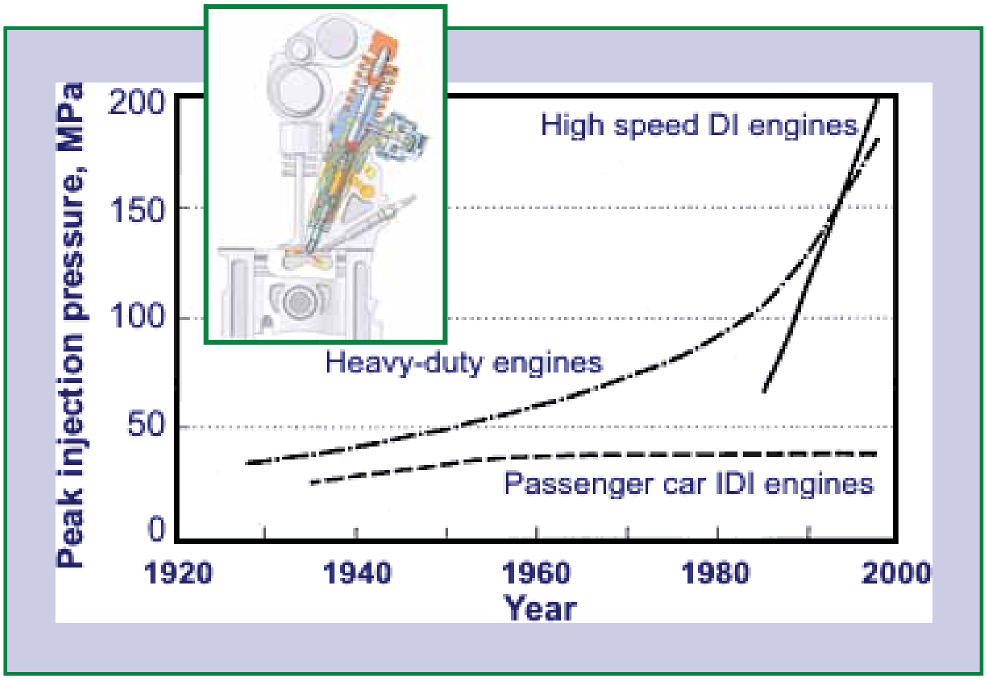
Effect of Injection Timing Retard on Fuel Economy



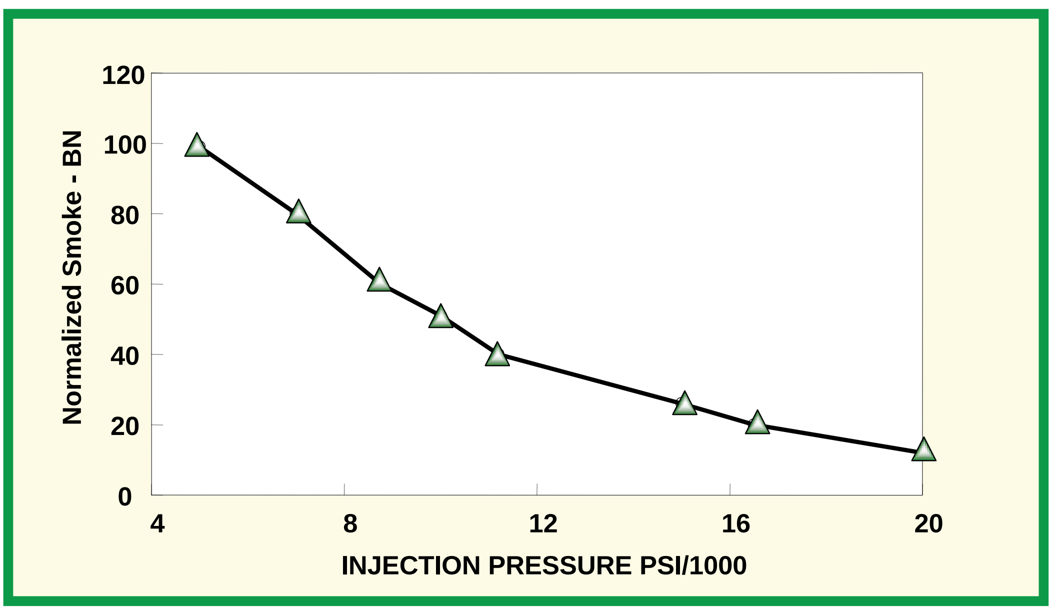
Effect of Injection Pressure on Fuel Consumption



Historical Progression of Injection Pressure

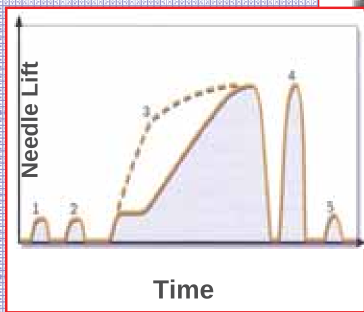


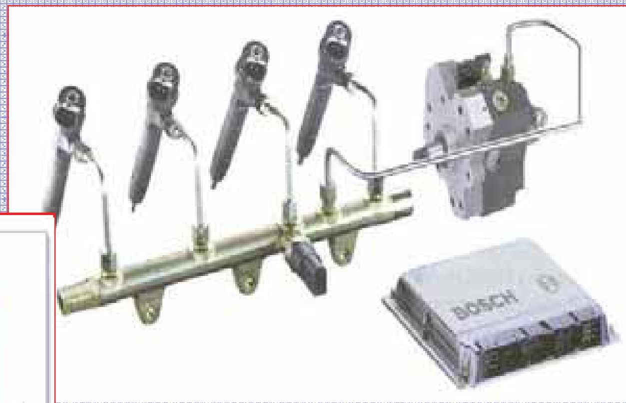
Effect of Injection Pressure on Smoke



Adding Control Flexibility to Injection Systems

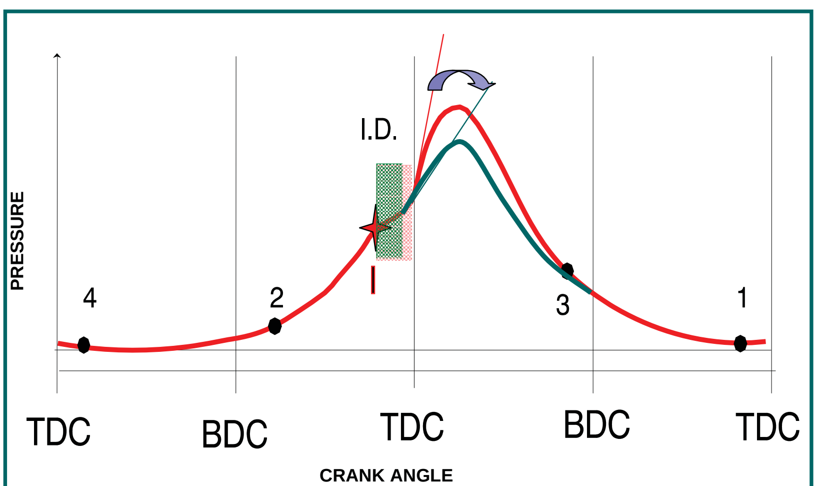
- Multiple Injections
- Rate Shaping
- High Pressure
- Smoke Control



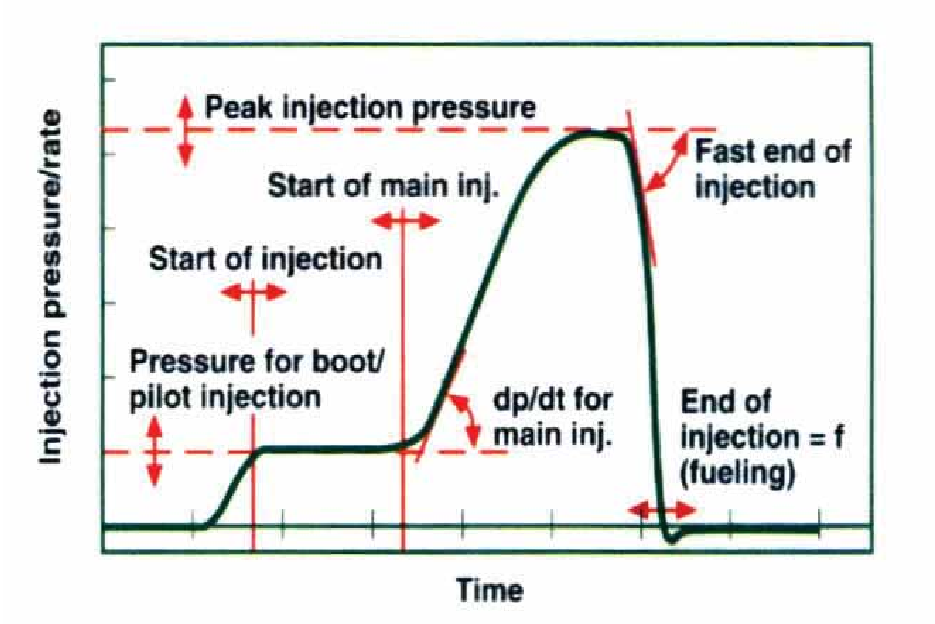


Common-Rail System

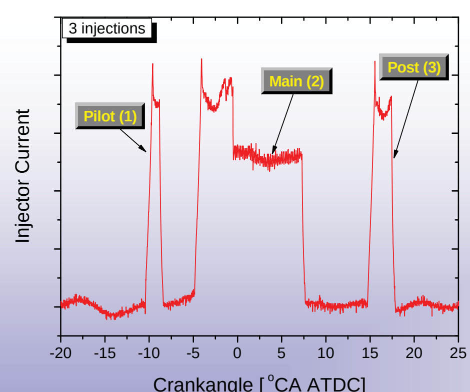
Effect of Reduced Ignition Delay

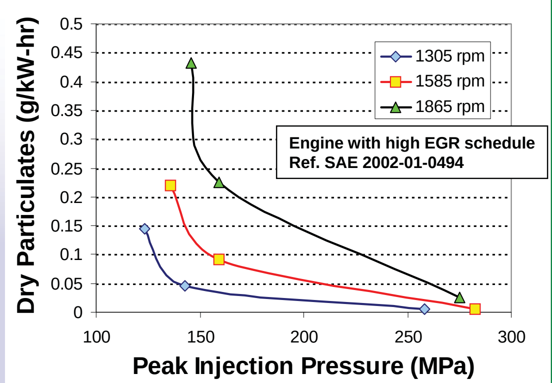


Reducing Fueling During Ignition Delay



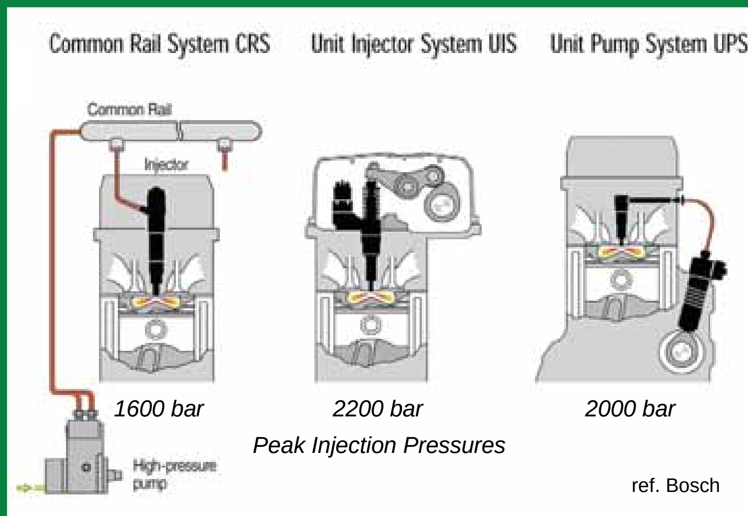
Adding Control Flexibility through Multiple Injections/Combustion Cycle





- Multi-injection fuel injection systems *(3-5 pulses per cycle)* are important for alternation combustion modes
- in-cylinder reductant injection for DPF, LNT, Lean NO_x catalysts
- Fuel-air mixing can still be improved by higher injection pressure (> 200 MPa) and smaller injector hole sizes

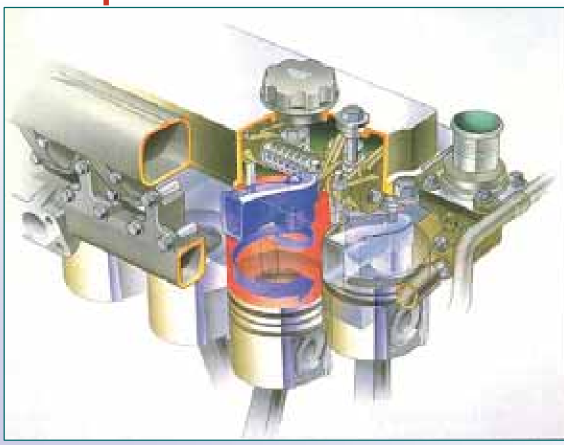
Most Likely Injection Systems for Future Diesels



Combustion System Developments

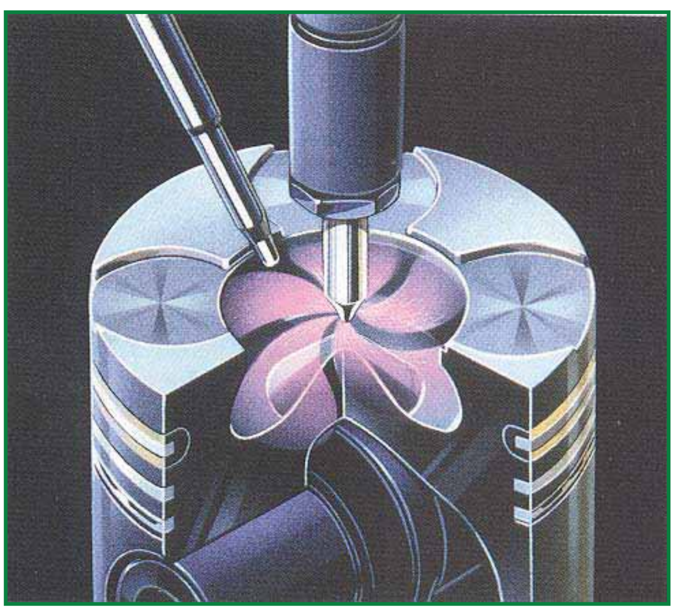
Improved Mixing through Port & Bowl Design

Optimized Swirl Ports

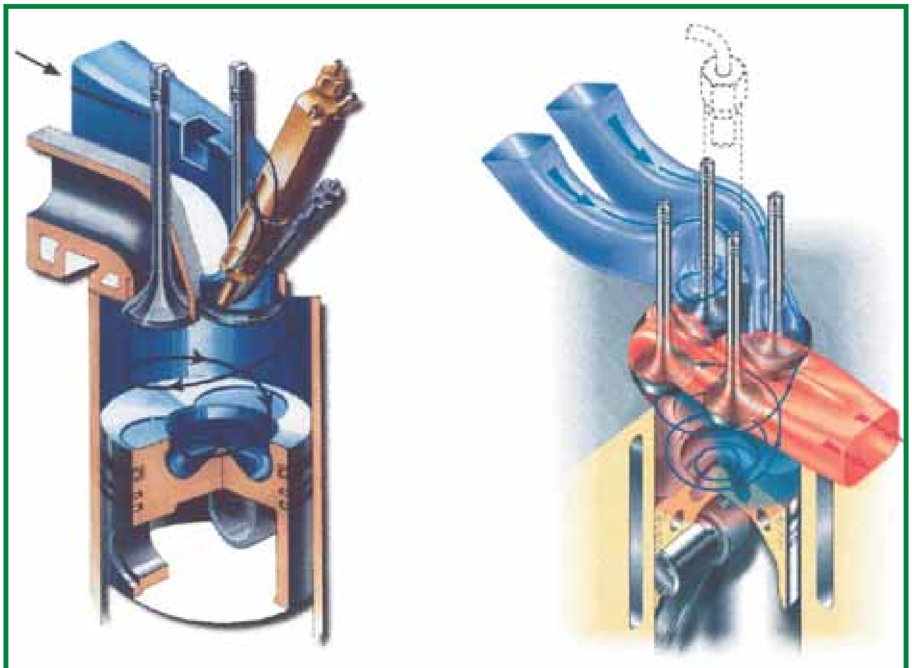


Matching Combustion Bowls

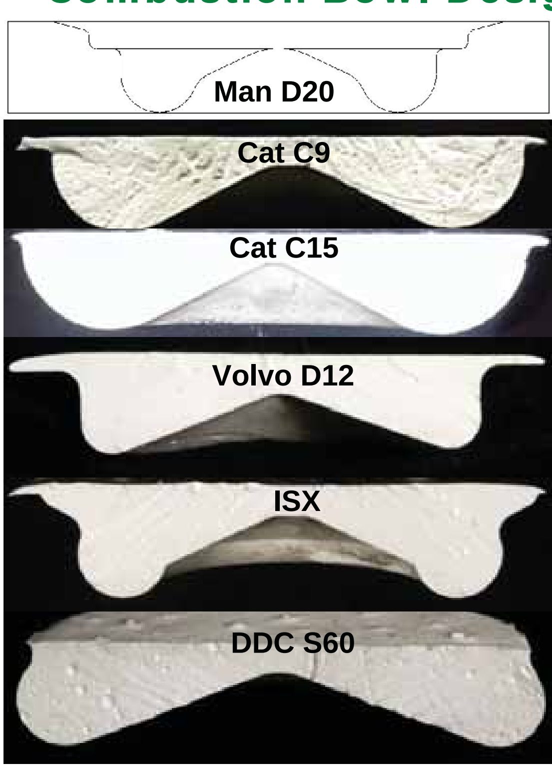
Improved Mixing through Injector Positioning



Better Breathing with Multiple Intake Valves

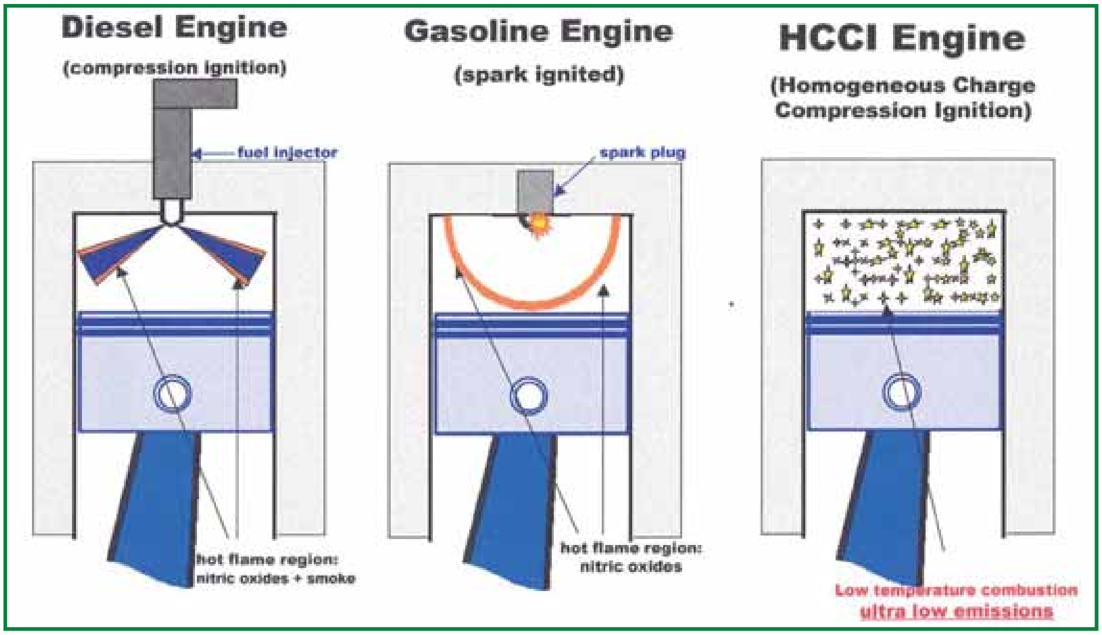


Combustion Bowl Designs for Better Mixing

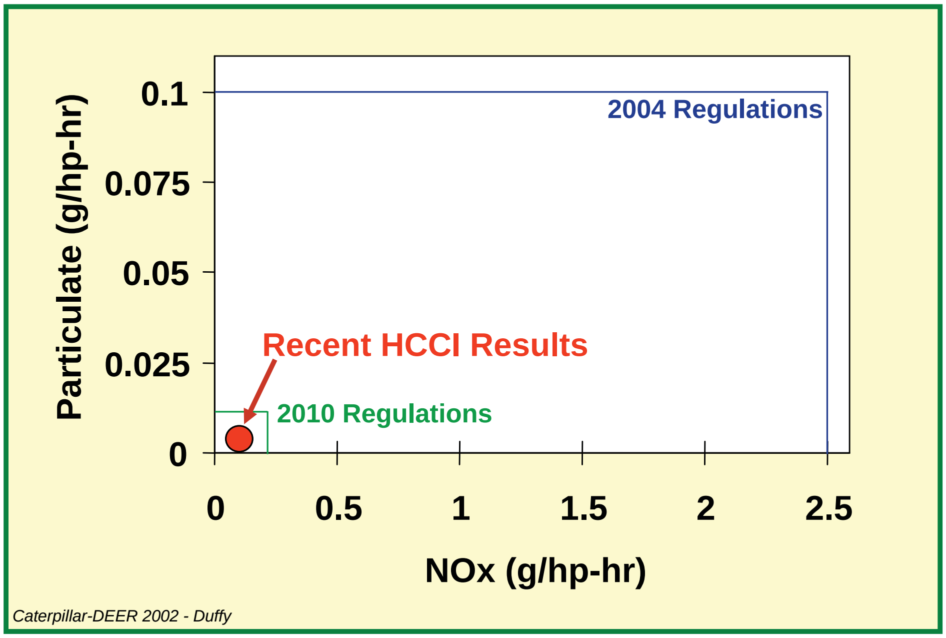


- Spray-wall interactions are unavoidable
  - Avoid liquid impingement
  - Take advantage of jet break-up and wall-jet opportunities
- Pilot and Post injections change the bowl shape and spray angle requirements
  - CAT uses pilot at almost all conditions
    - Spray angle narrower

Adopting Alternate Combustion Modes

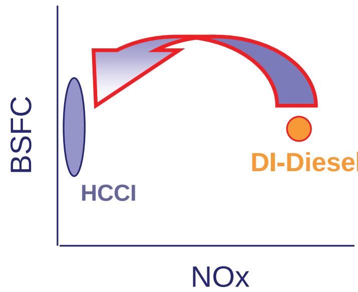


The Main Promise of HCCI for Diesel Engines



Additional Aspects of HCCI Combustion

- Ultra-low NO_x and potentially PM emissions
- Can achieve similar efficiency
- High HC and CO emissions
- Recent research focuses on in-cylinder injection
- Vaporization difficult with port injection

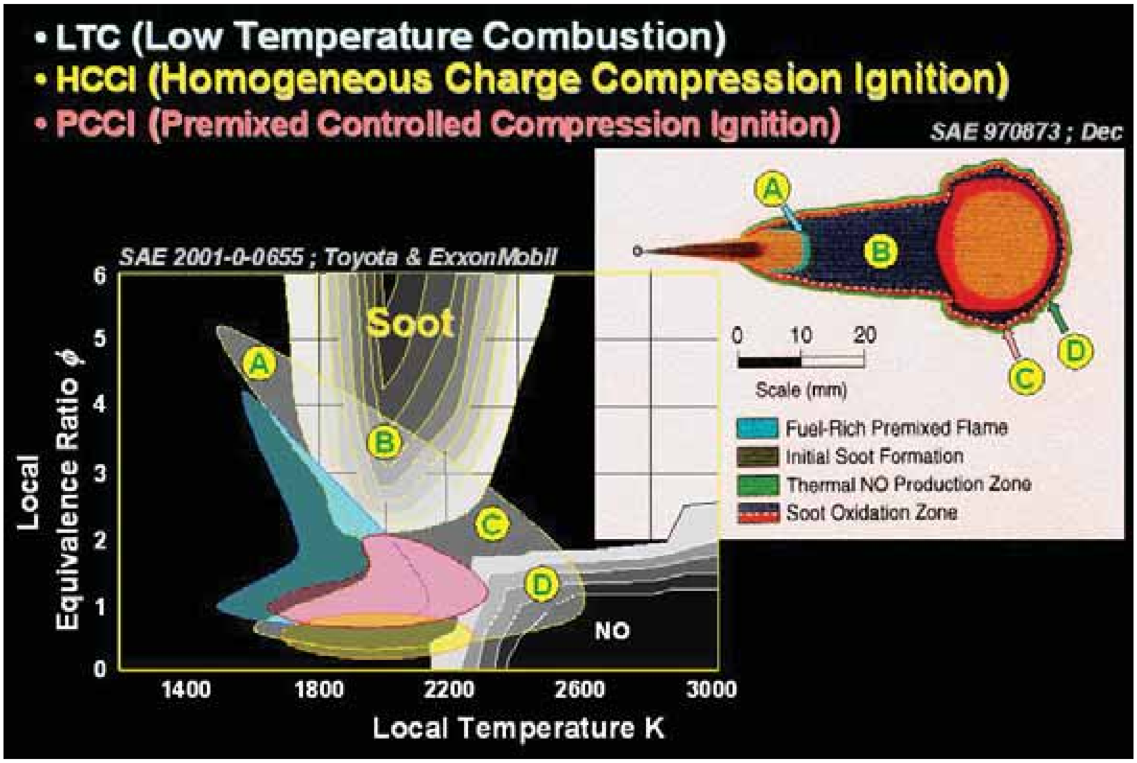


Issues Associated with HCCI Combustion

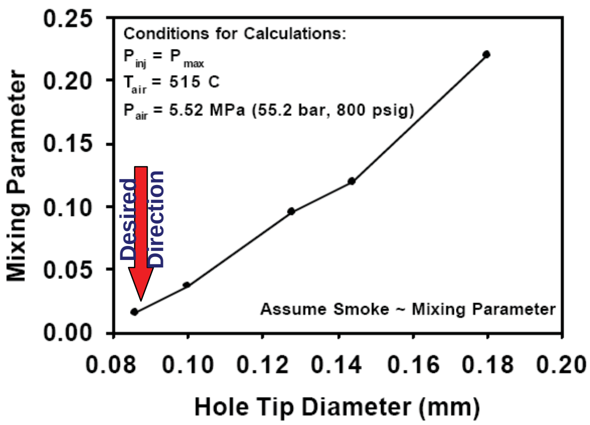
Adapted From Caterpillar-DEER 2002 - Duffy

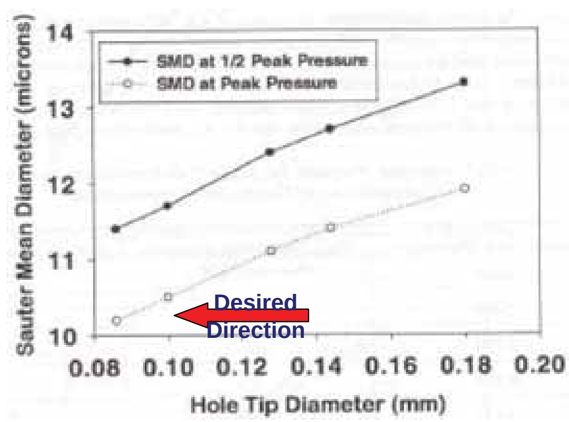
- Combustion Phasing and Control
- Proper Air / Fuel Mixing
- Limited Load Range
- Fuel Characteristics
- Cold Start

Adopting Principles of Low Temperature Combustion



Small Nozzle Holes for Better Mixing



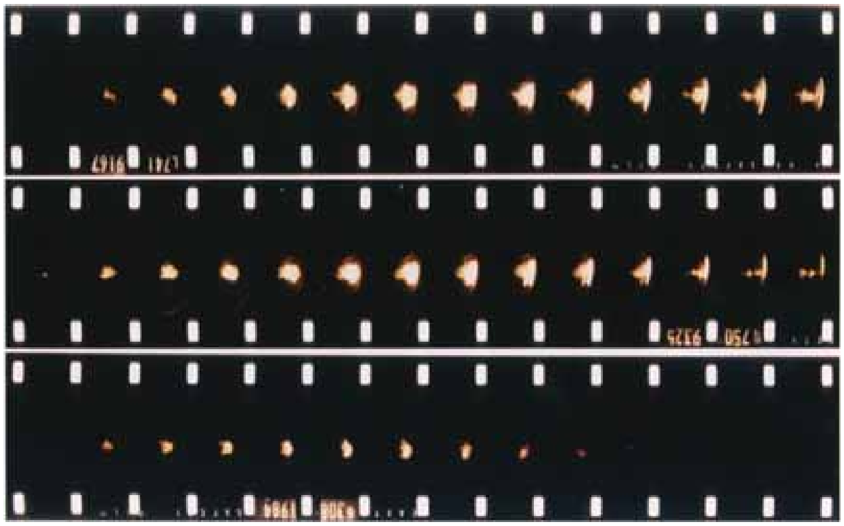


1. Mixing Rates Quantified in Terms of SwRI Defined Mixing Parameter

2. How much fuel survives longer than 0.6 ms during injection at phi>1(rich)?

3. Rich Regions Mean More Soot

Effect of Ultra High Injection Pressure & Nozzle Hole Size



0.144 mm

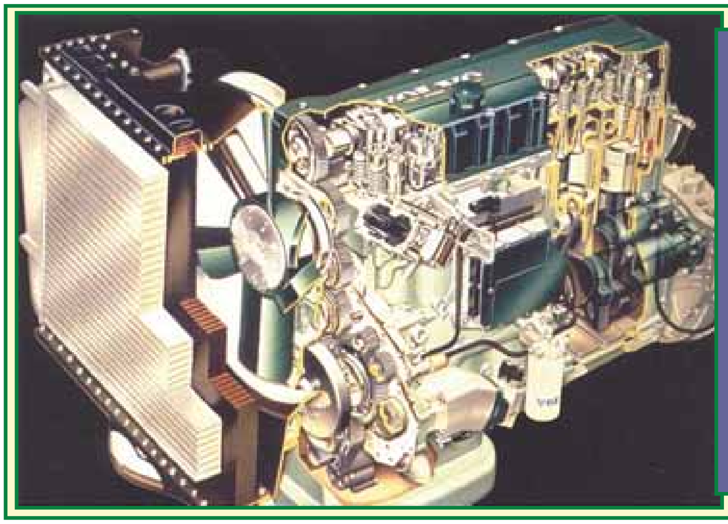
0.128 mm

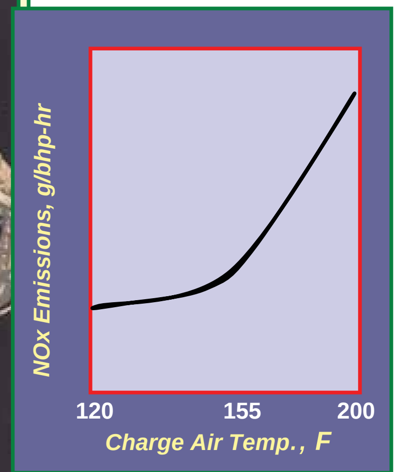
0.086 mm

- Small Holes Produce High Pressure, Small SMD, High Mixing Rates and Low Soot Formation Rates

Induction, EGR, & Air Charging System Developments

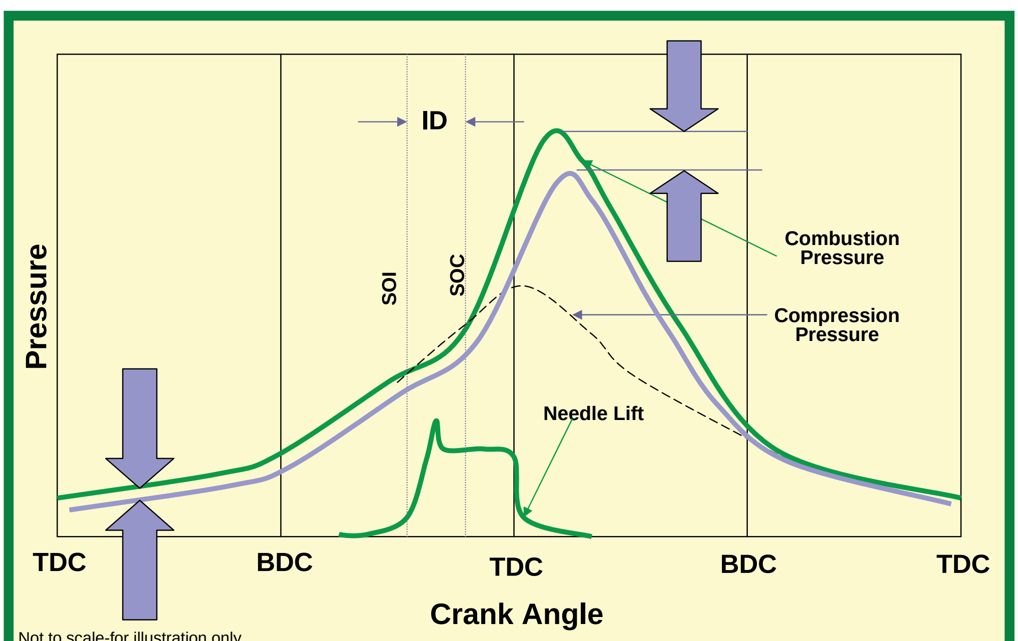
Charge Air Cooling for Lower NO_x & Better Fuel Economy



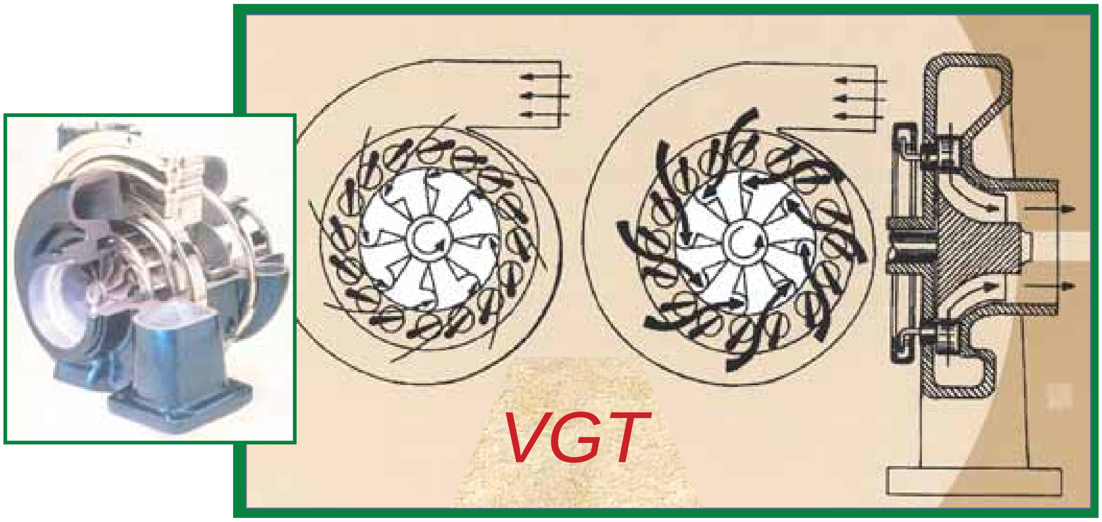


Air-to-Air Intercooling For Better Fuel Economy and Lower NO_x Emissions

Effect of Intake Manifold Temperature on Peak Combustion Pressure

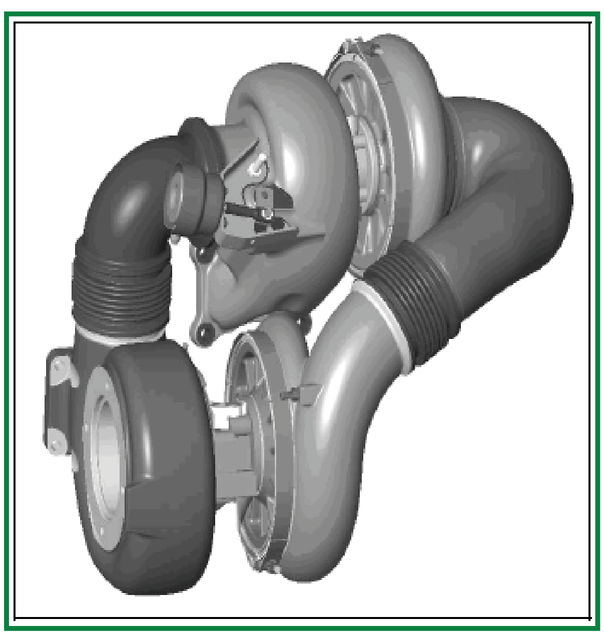


Added Charge Air Control through VGT

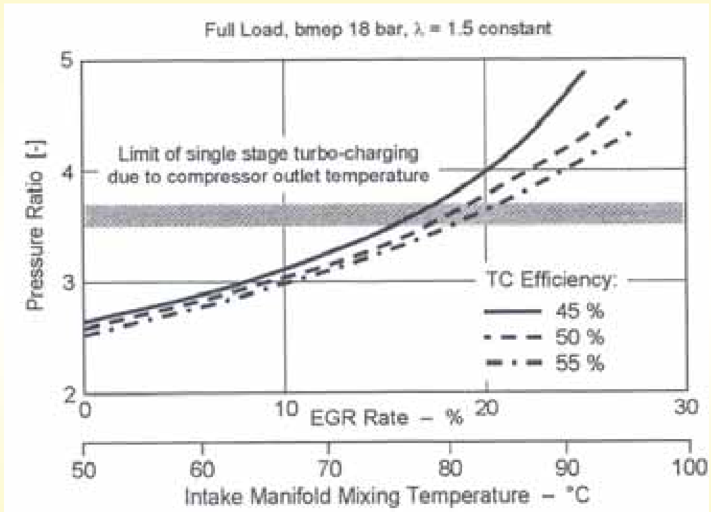


Variable Geometry Turbo For Better
Charging Throughout Engine Operating Modes
to Control Smoke and Particulate Emissions

Higher Boost through In-Series Turbocharging



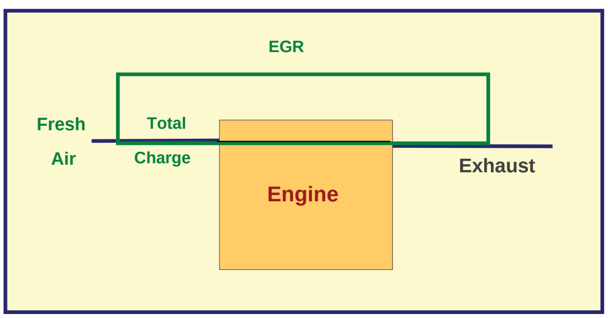
Advantage of High pressure Ratio Charging



Moser, Sams, Dreisbach, AVL 2004

The Higher the Pressure Ratio, the Greater the EGR rate & the Lower NO_x

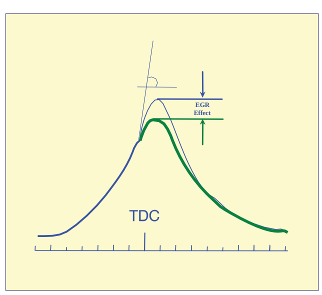
Definition of Exhaust Gas Recirculation



EGR Calculation

$$\frac{\text{Exh. gas recirculated}}{\text{Total Charge}} \times 100$$

$$\frac{\text{Exh. gas recirculated}}{\text{Fresh air + EGR}} \times 100$$

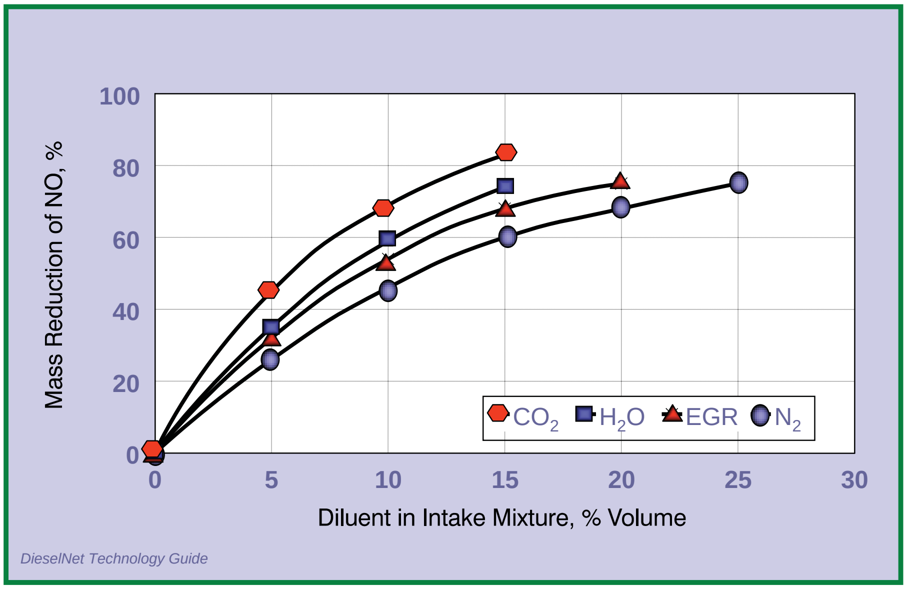


EGR Effect

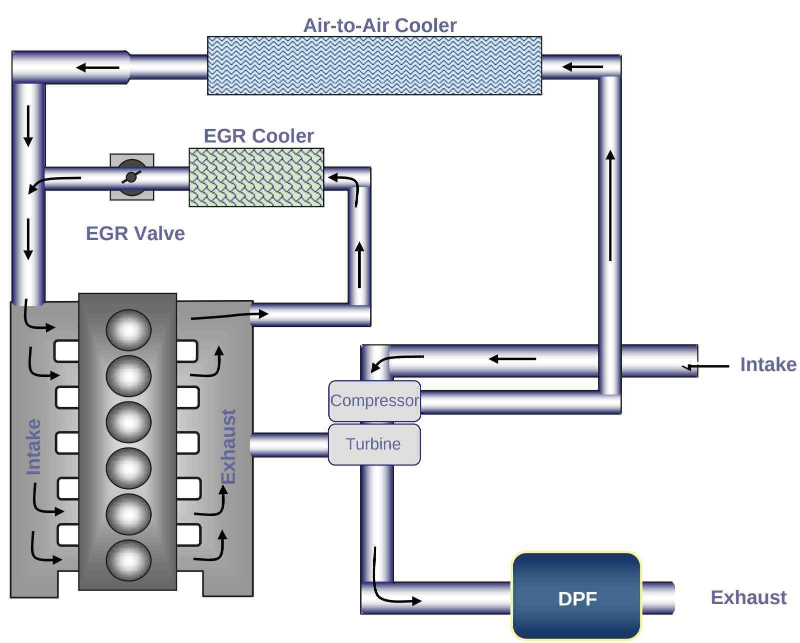
1) $Q' = m' \times c_p \times (T_{comb.} - T_{EGR})$

2) EGR displaces fresh O_2

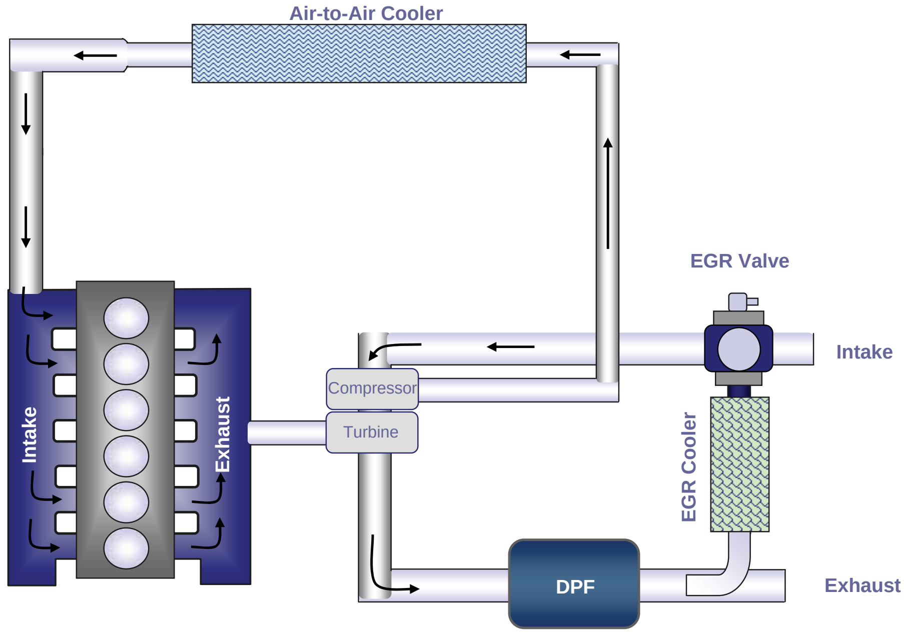
Why EGR and Not Another Diluent?



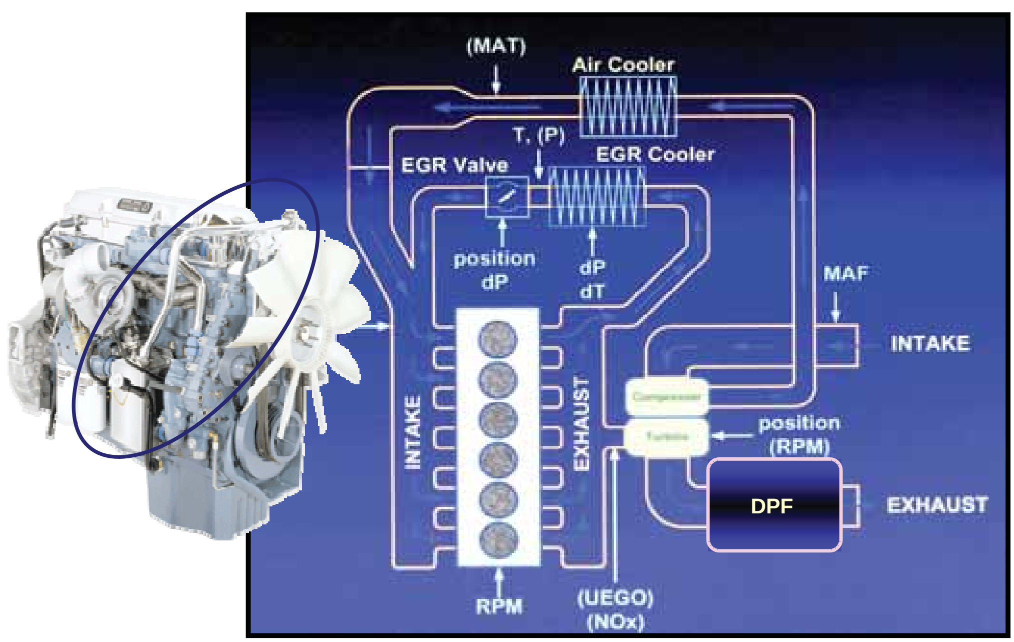
High Pressure Loop EGR System – Short Route



Low Pressure Loop EGR System – Long Route

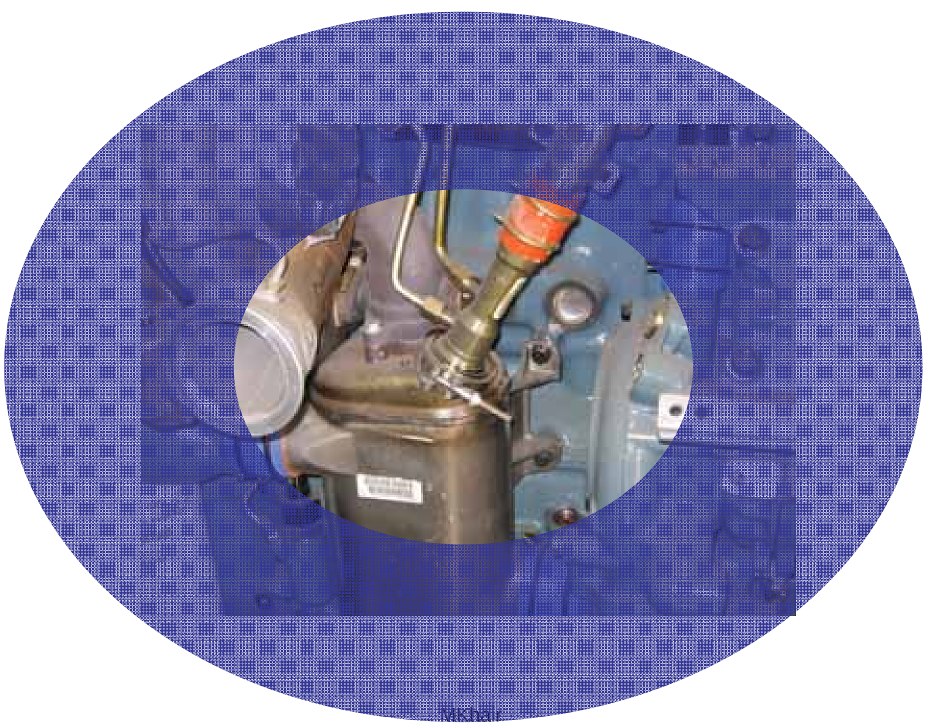


Cooled HPL Exhaust Gas Recirculation for Lower NO_x

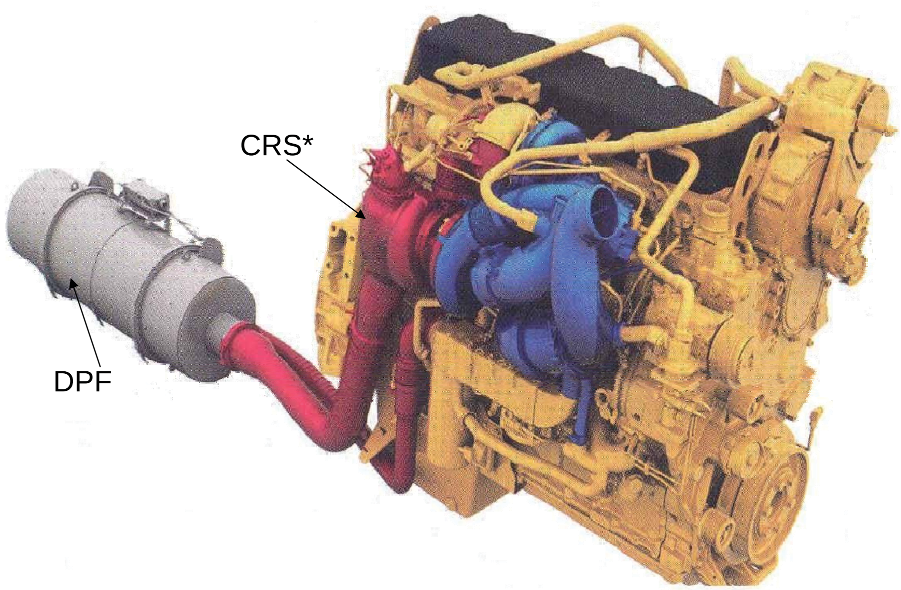


Monitoring EGR Flow Rate

Close Up of EGR Cooler & EGR Flow Venturi



Cooled LPL Exhaust Gas Recirculation for Lower NO_x



** Caterpillar Regeneration System*

EGR Advantages / Disadvantages

Advantages

- **Good NO_x Reduction**
- **No Major Engine Redesign**
- **Reasonable Fuel Penalty**
  - ***(Relative to Other Technologies)***
- **Very Effective at Light Load Conditions**

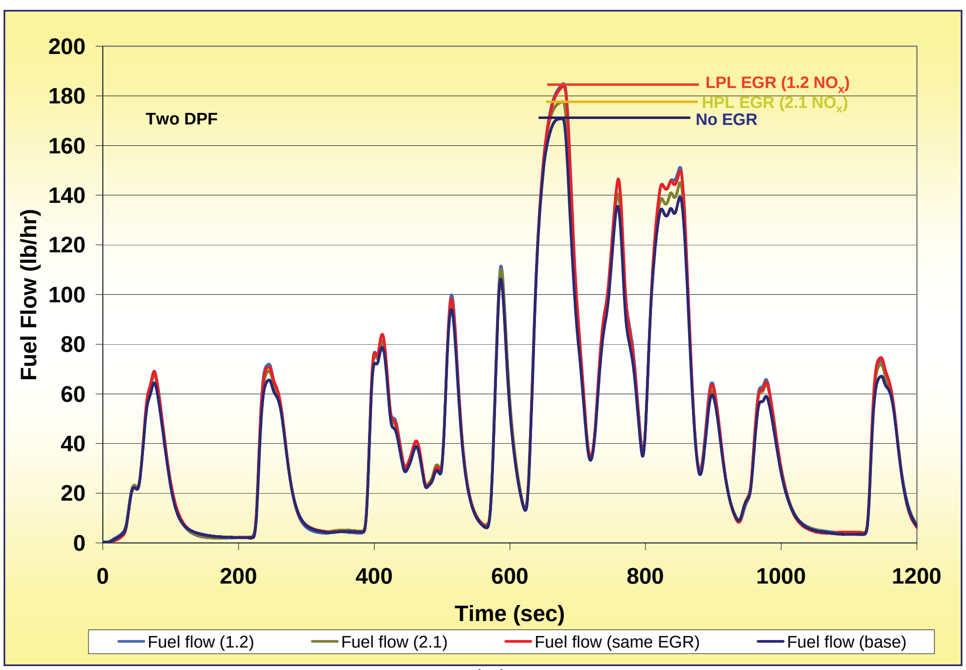
Disadvantages

- **Increased Cooling Load**
- **Increased Particulate Matter**
- **Increased Fuel Consumption**
- **Adverse Impact on Durability**
- **Degrades Lube Oil Quality**

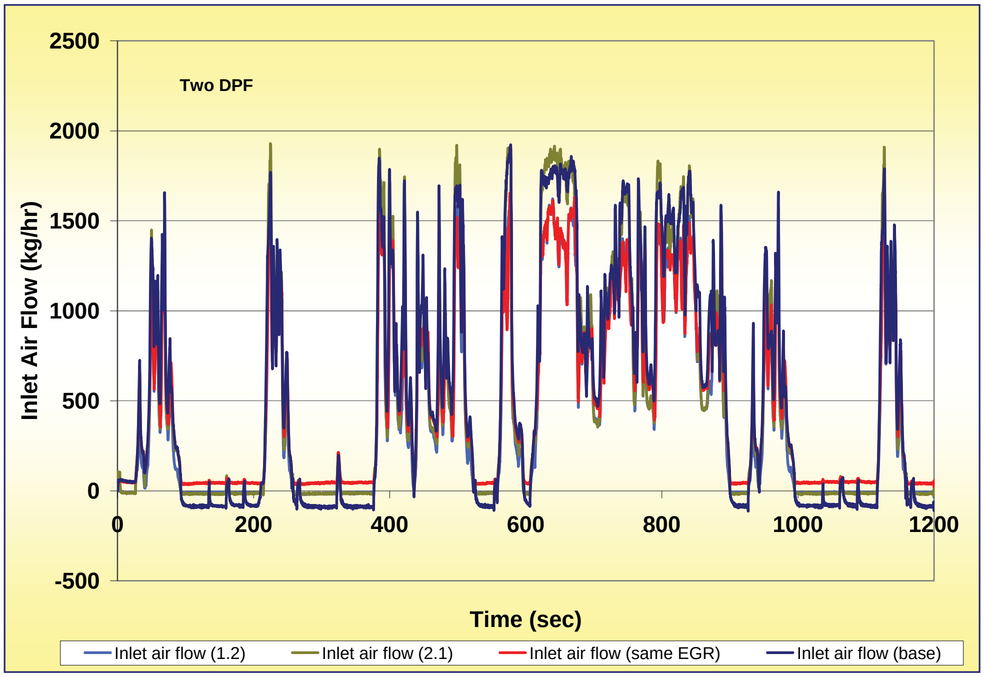
Other Issues with EGR

- EGR Cooler Fouling/Effectiveness
- Cylinder-To-Cylinder Distribution
- Limitation at High Load Conditions
- Transient Control/Smoke Problems

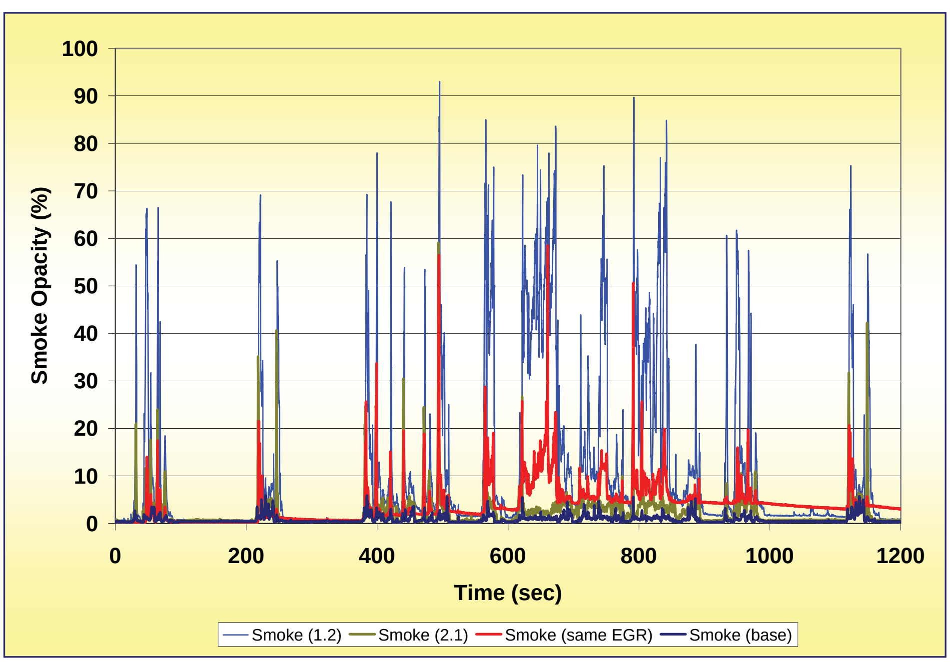
Fuel Consumption Increase with EGR



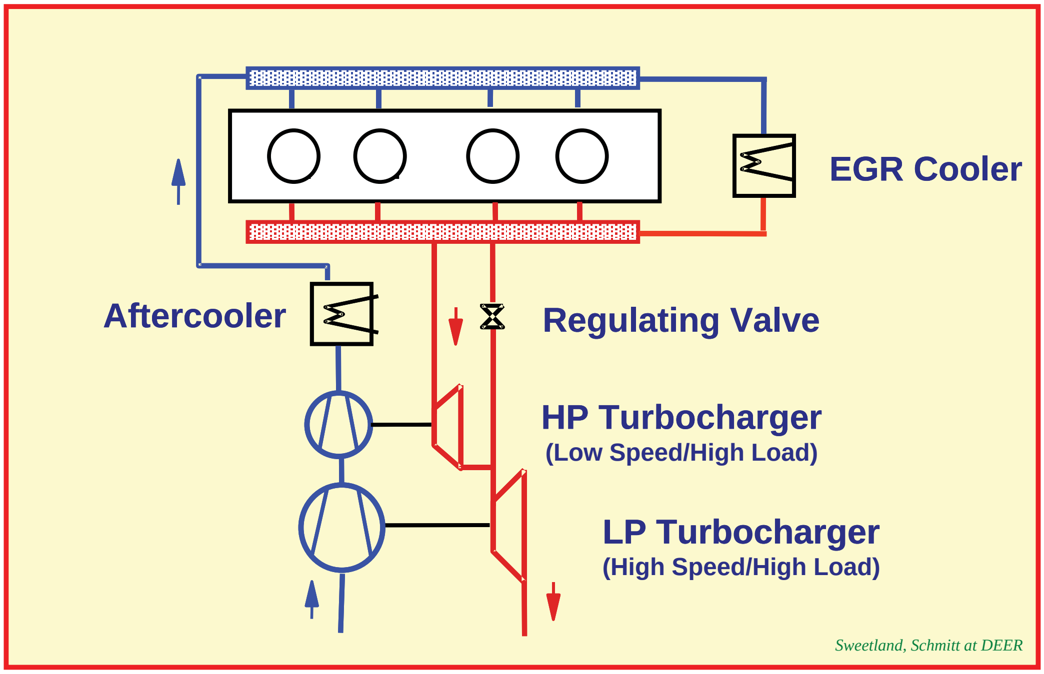
EGR Effect on Air Flow



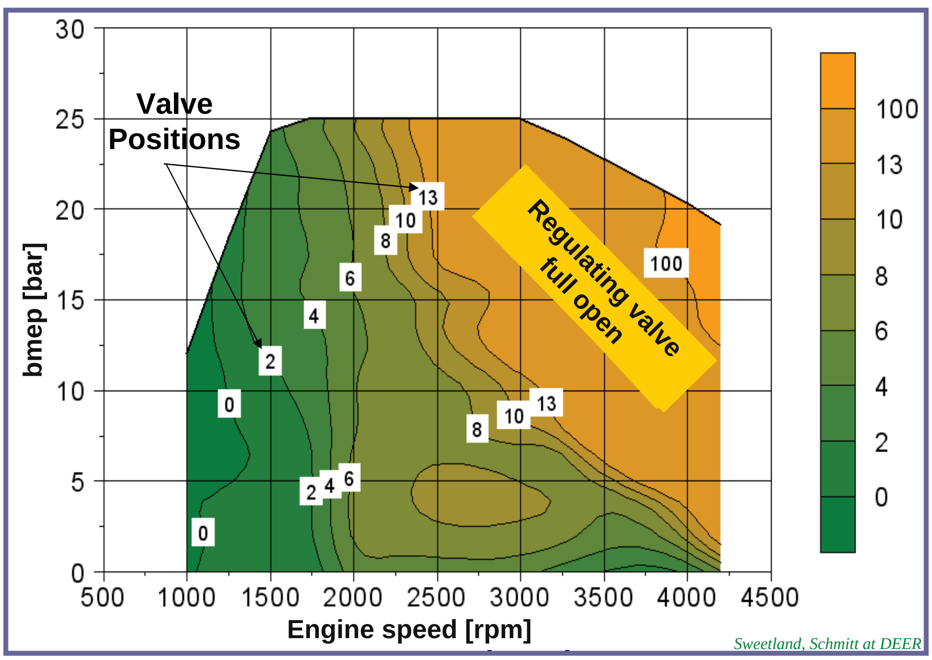
EGR Effect on Smoke



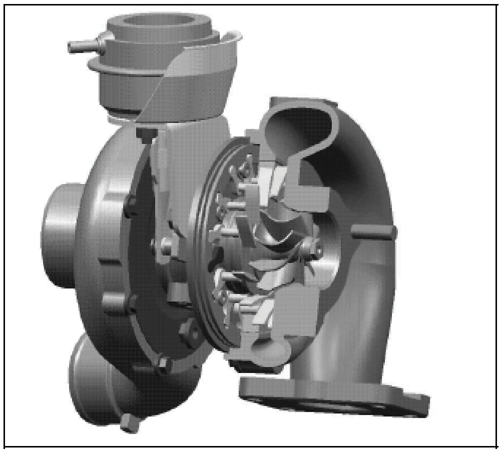
Using Multiple Turbochargers for Better Air Control

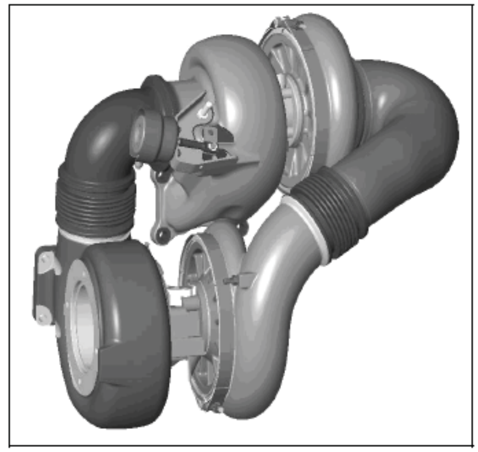


Added Valves to Better Control Air Flow

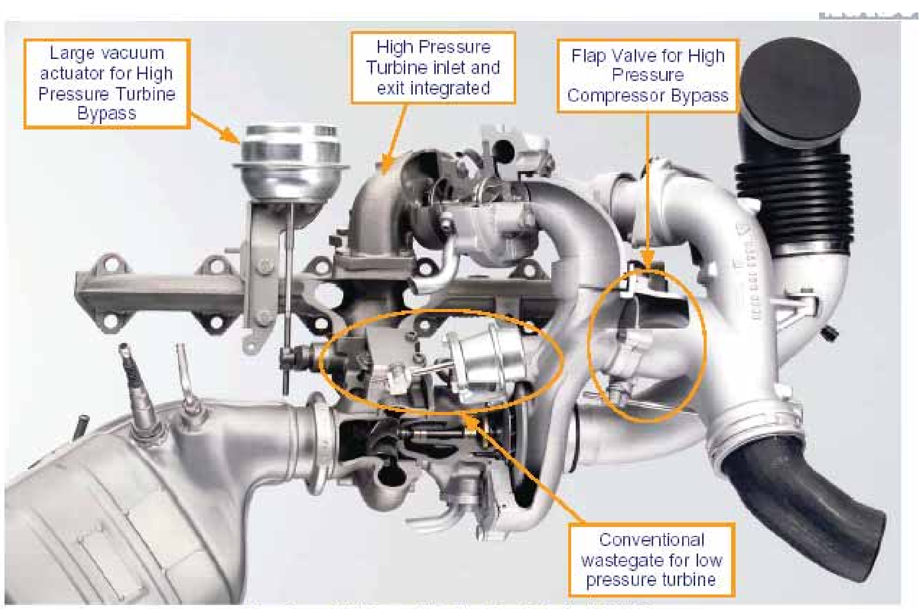


Technical Advances in Turbocharging



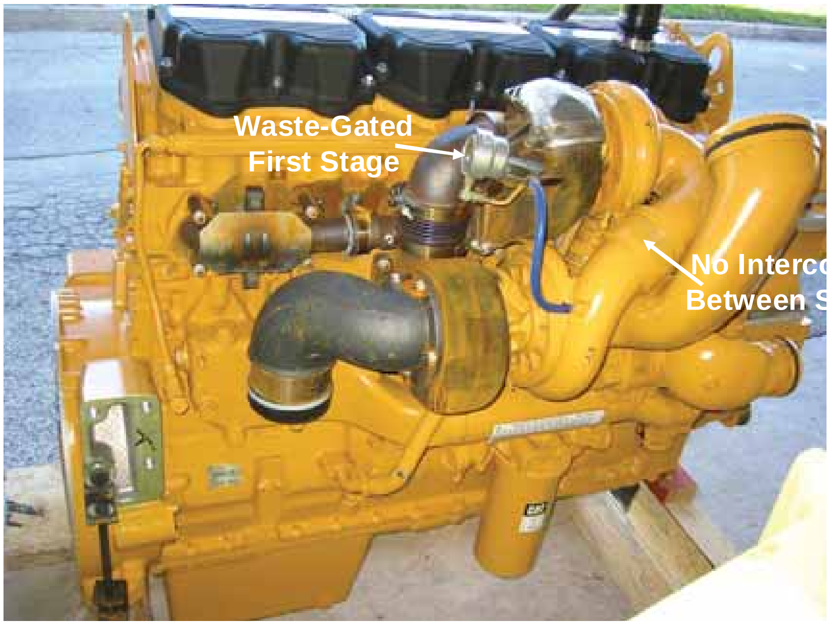


Modern LD Production Turbocharging System



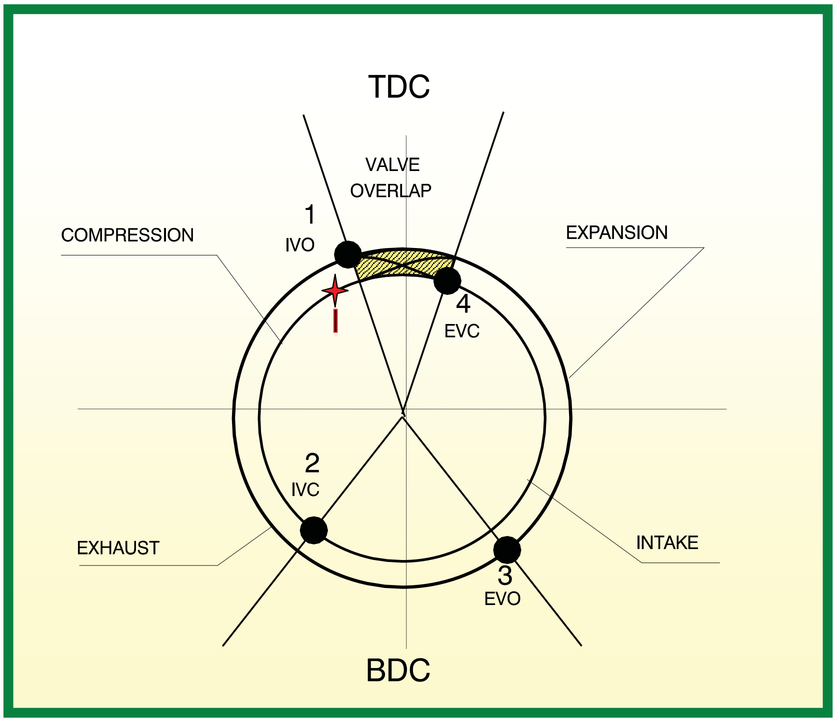
Picture Source: BMW Geneva Motor Show Press Pack, March 2004, 43pp

Modern HD Production Turbocharging System



Valve Train System Developments

Description of Valve Overlap



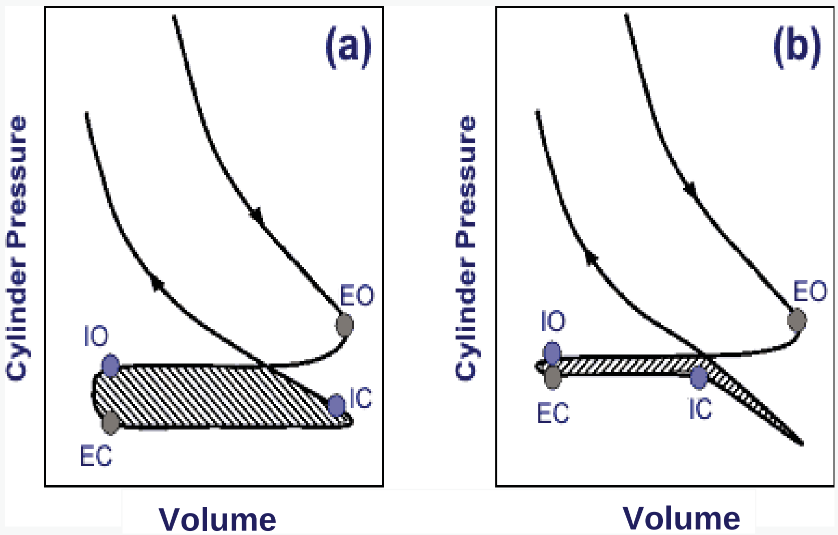
Flexible Valve Control System

Variable Valve Actuation

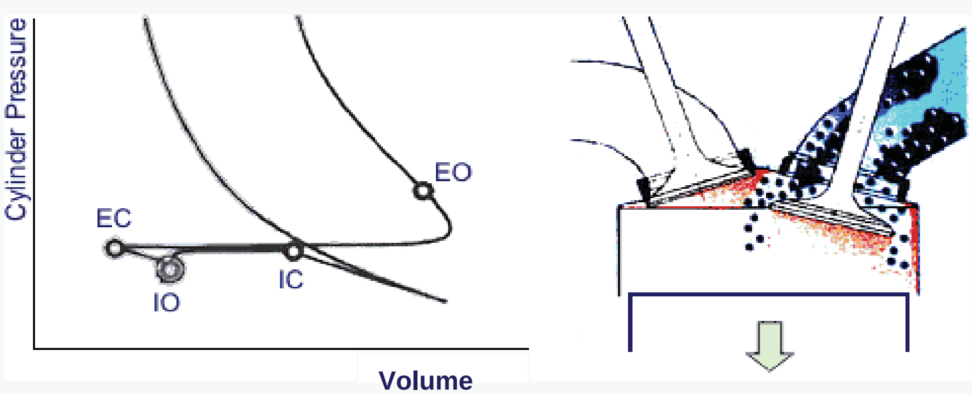
Electro-Magnetic System

Camless Engine Design

Benefits of Early Valve Closing



Valve Actuation for Emission Control

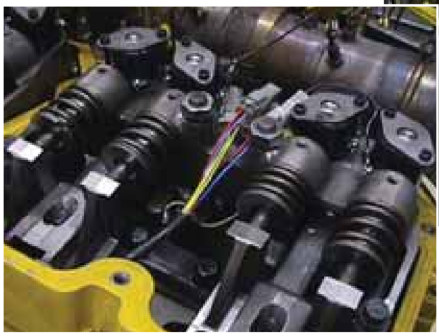


Potential benefits of Valve Actuation

- Fuel Economy
  - Valve Overlap
  - Volumetric Efficiency
  - Cylinder Cutout
- Emissions
  - Fuel Economy Strategies + EGR Control
  - Variable Swirl, Tumble
- Startability
  - Higher Cranking Speeds through Cylinder Cutout
  - Increased Effective Compression Ratio
- Warm-Up
  - Internal EGR for Intake Charge Heat
- Transient Response
  - Early EVO for Reduced Turbo Lag
- Increased Low Speed Torque
  - 2+4 Stroke
  - Flush Cyl Charge at TDC
- Power Density
  - Turbo Response with Delayed Fuel Injection
- Engine Braking

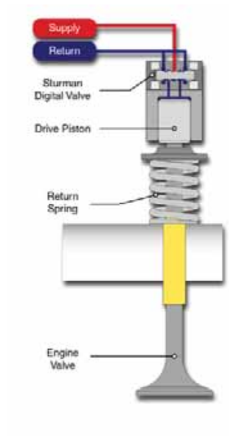
Example of a Variable Valve Actuation System

- Jacobs Vehicle Systems Lost Motion VVA System



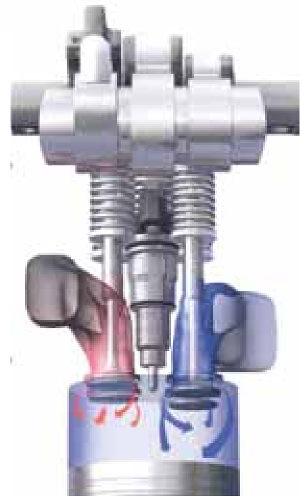
- Full 6-cylinder VVA

Other Engines with Internal EGR



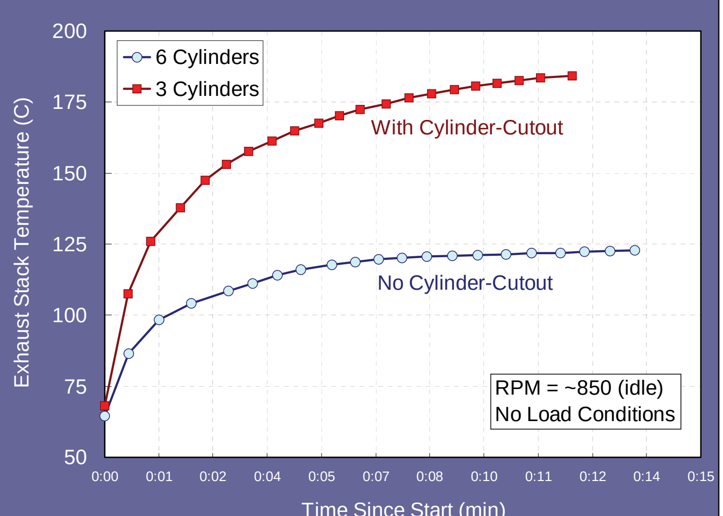
Ref. Sturman Industries

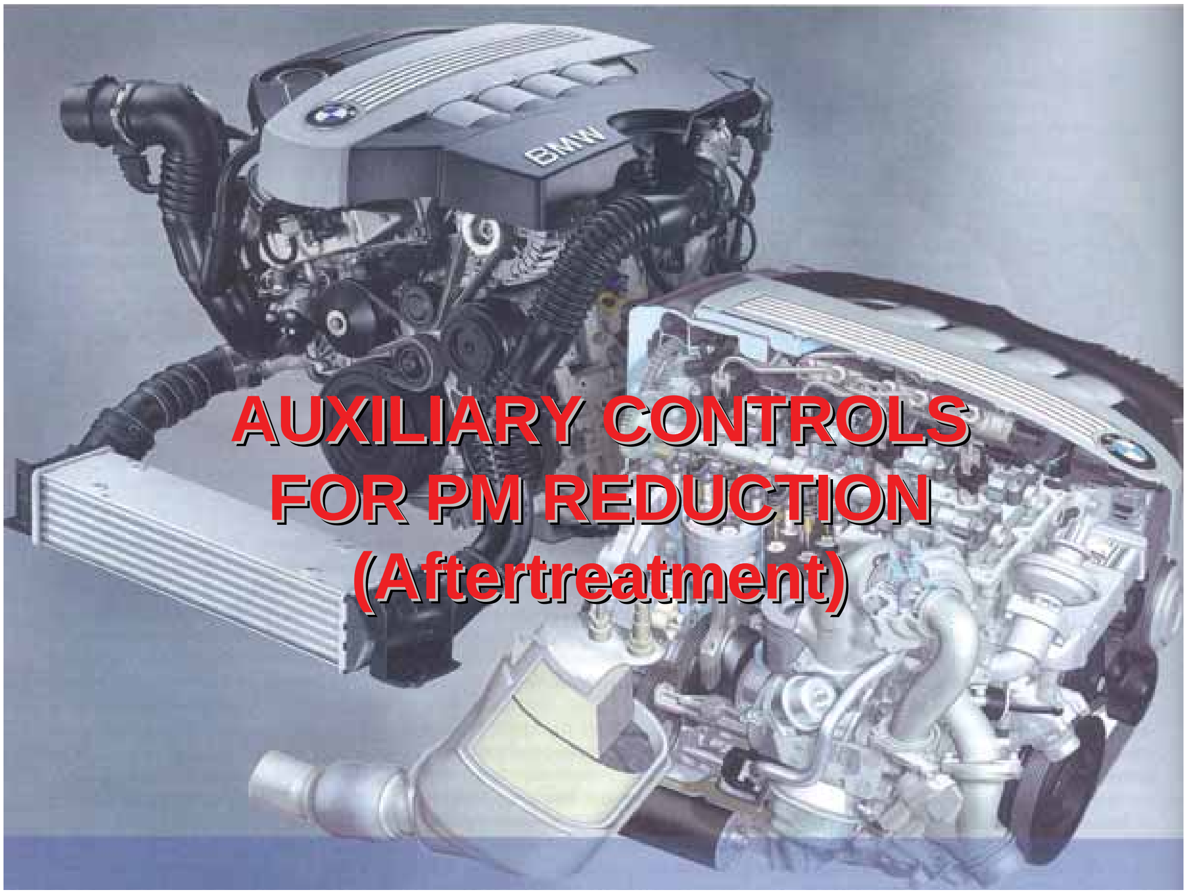
- Internal EGR systems are in production (Mack, CAT, Volvo)
  - May be sufficient for 19-56 kW engines to achieve 4.7g NO_x+ NMHC target



Effect of Cylinder Cut-Out on Exhaust Temperature

- **Tests conducted**
  - Traditional cold start vs. cold start with 3 cylinders cut-out
  - Results show large increase in exhaust temperature



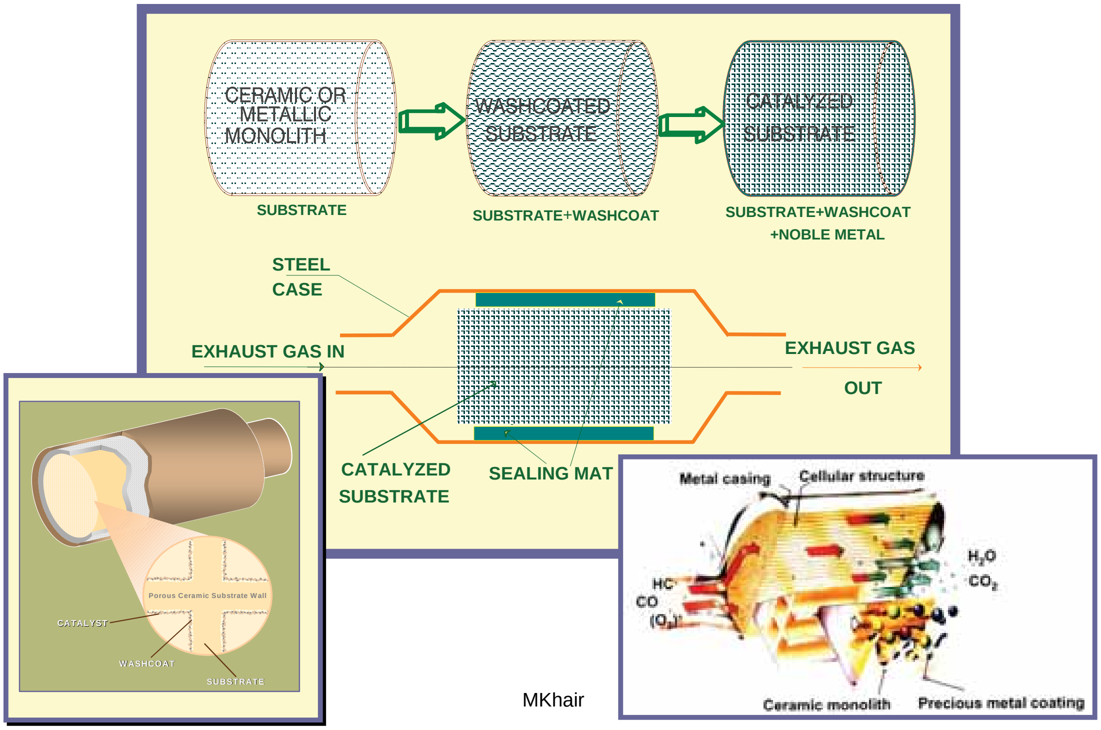


Developments in Exhaust Aftertreatment

- Systems for PM Control
  - Diesel Oxidation Catalyst (DOC)
  - Diesel Particulate Filter (DPF)

- Systems for NO_x Control
  - Lean NOx Catalyst (LNC)
  - Lean NOx Trap (LNT)
  - Urea Selective Catalytic Reduction (SCR)

Anatomy of a Diesel Oxidation Catalyst



MKhair

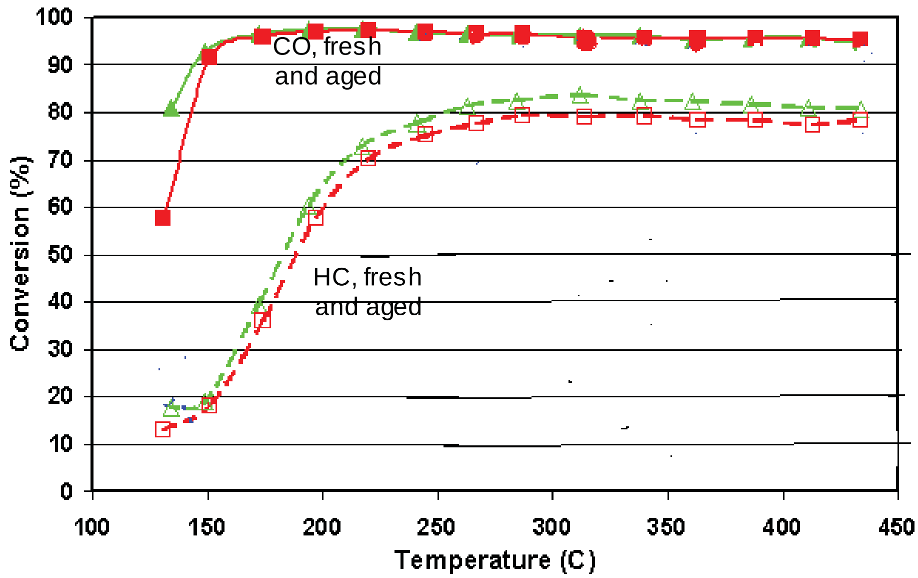
Proliferation of Diesel Oxidation Catalysts

- Underground Mining – Over 250,000
- On Road & Off Road – Over 750,000

Example Installation of a Diesel Oxidation Catalyst

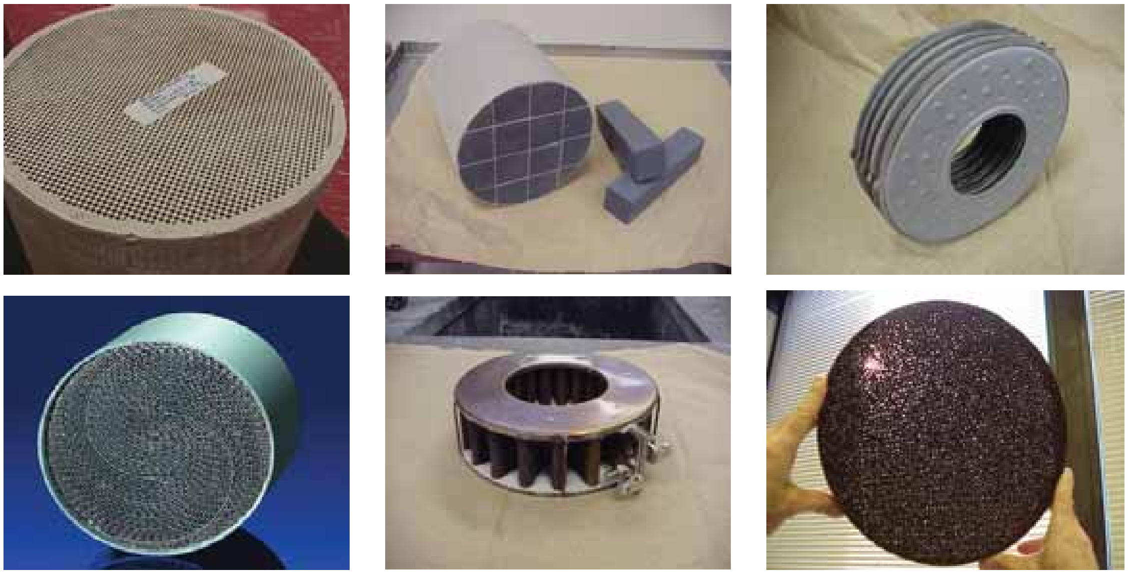
- From 20 to 50% Total PM Reduction in Applications Using <500 ppm Sulfur Fuel
- From 60 to 90% HC Reduction (Including HC Species Considered Toxic)
- From 50 to 70% Reduction in CO
- Diesel Odor Reduction
- Passive device

Improved Durability of Modern DOCs

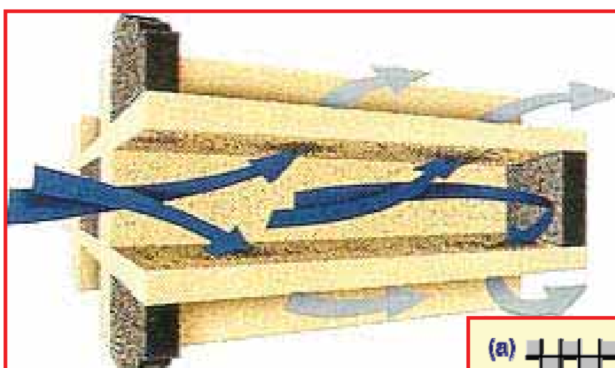


Aged 80,000 km in 50 ppm sulfur fue. NO_2 performance dropped only 10%, vs. 40% for previous formulations

Collection of Diesel particulate Filters

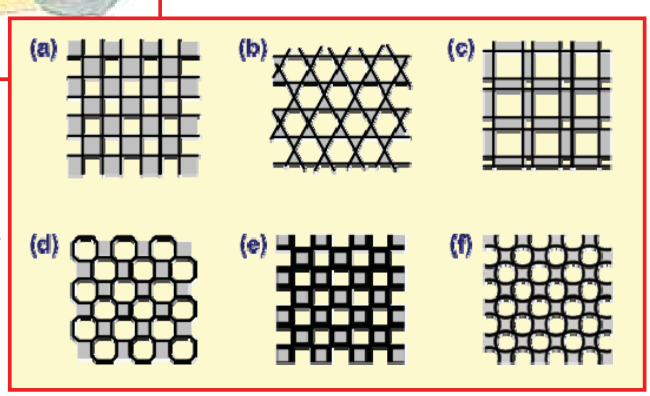


Principle of Operation of the Wallflow Design

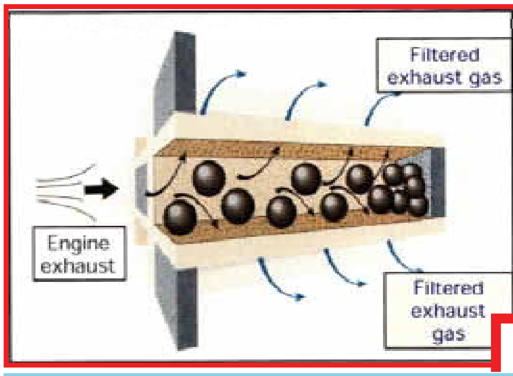


Wallflow Construction

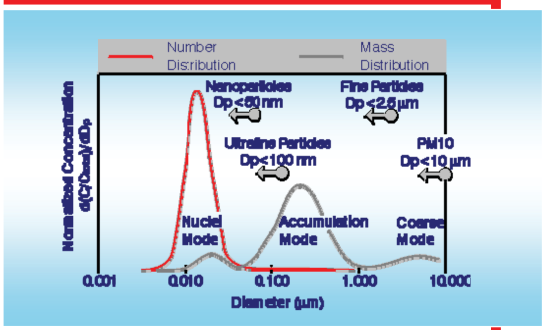
Asymmetric Designs



Limitations of the Wallflow DPF Design

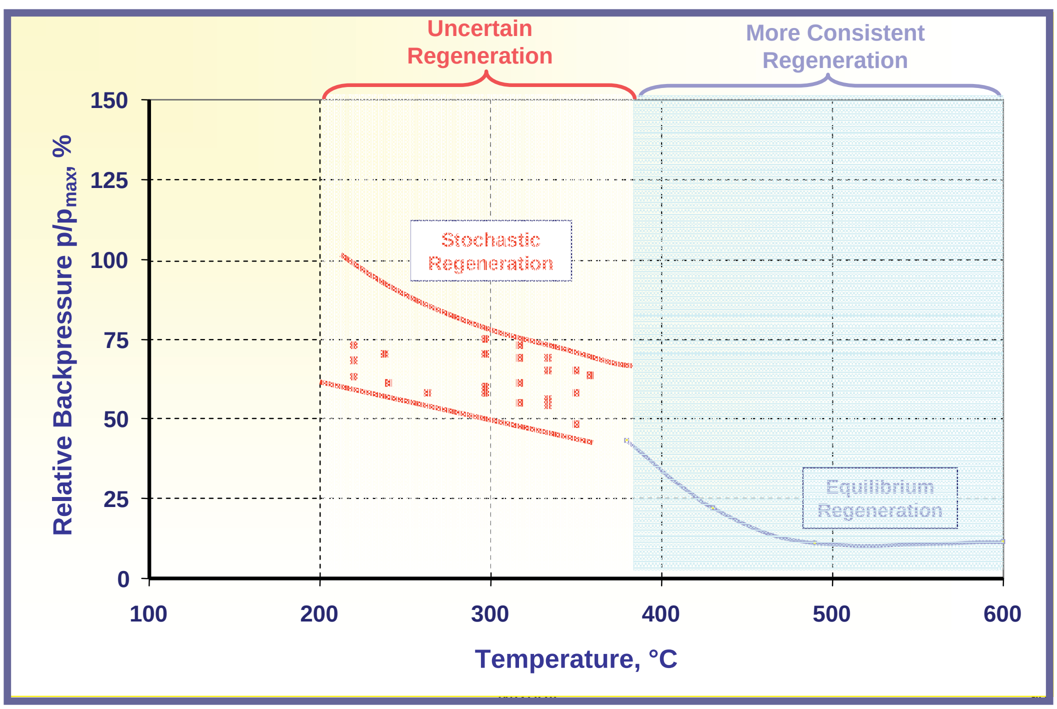


Diffusion Filtration



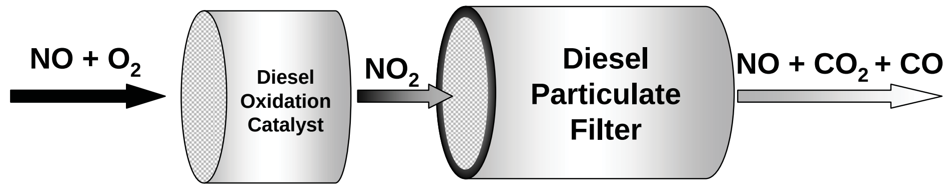
- **Particulate Collection**
  (Filtration Efficiencies of ~ 90%+)
- **Particulate Disposal**
  (Through the Regeneration Process)

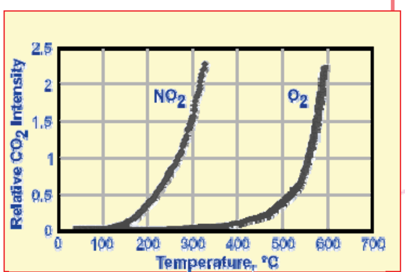
Using Fuel-Borne Catalyst to Enhance Regeneration



Swiss Agency for the Environment , Berne 2000

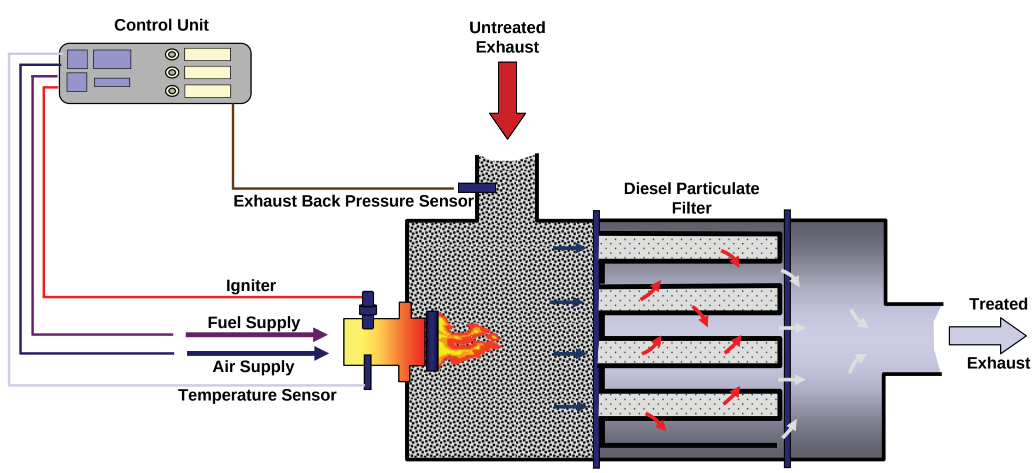
Regeneration through the CRT Effect or NO_2 Regen



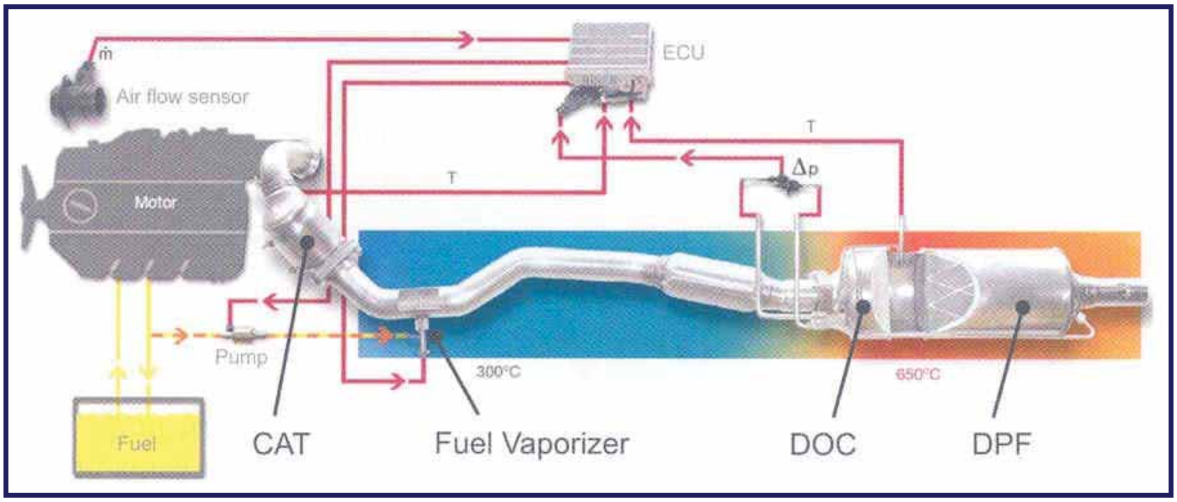


- Balance Point Temperature 270ºC for CRT
- Balance Point Temperature 250ºC for CCRT
- Requires <50 ppm Sulfur Fuel
- Requires NO_x/C Ratio of 8:1 Min.-20:1 Preferred
- Requires 40% Duty Cycle Above BPT

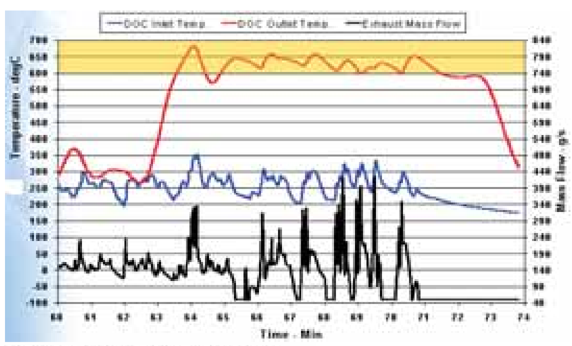
Using a Burner to Regenerate the DPF

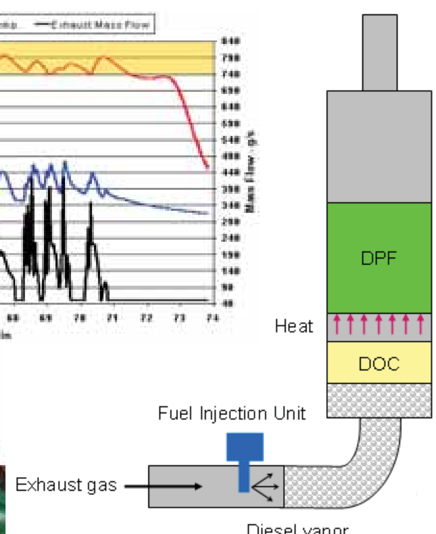


Example of an Integrated System for PM Reduction

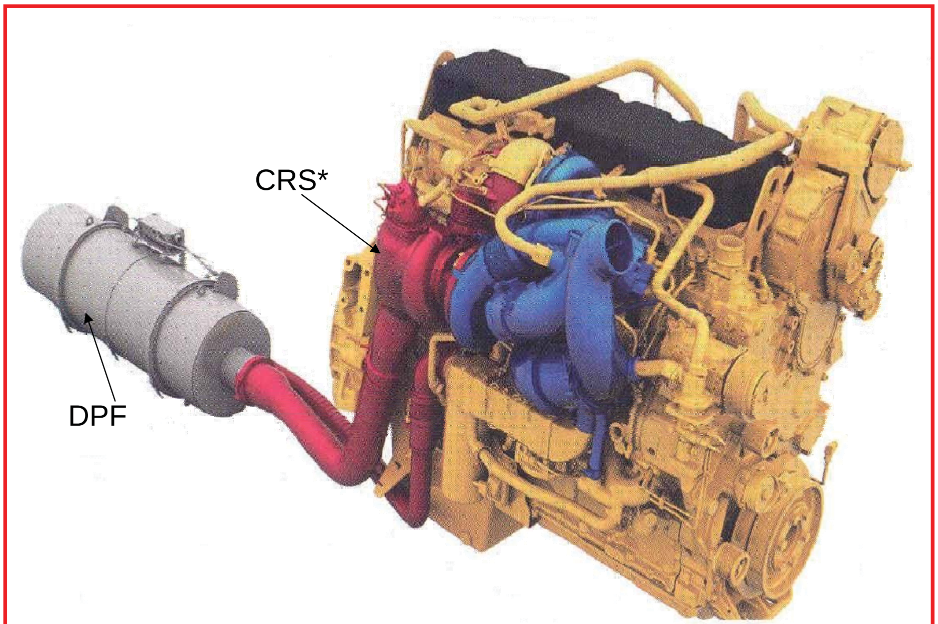


Example of a Retrofit System for PM Reduction



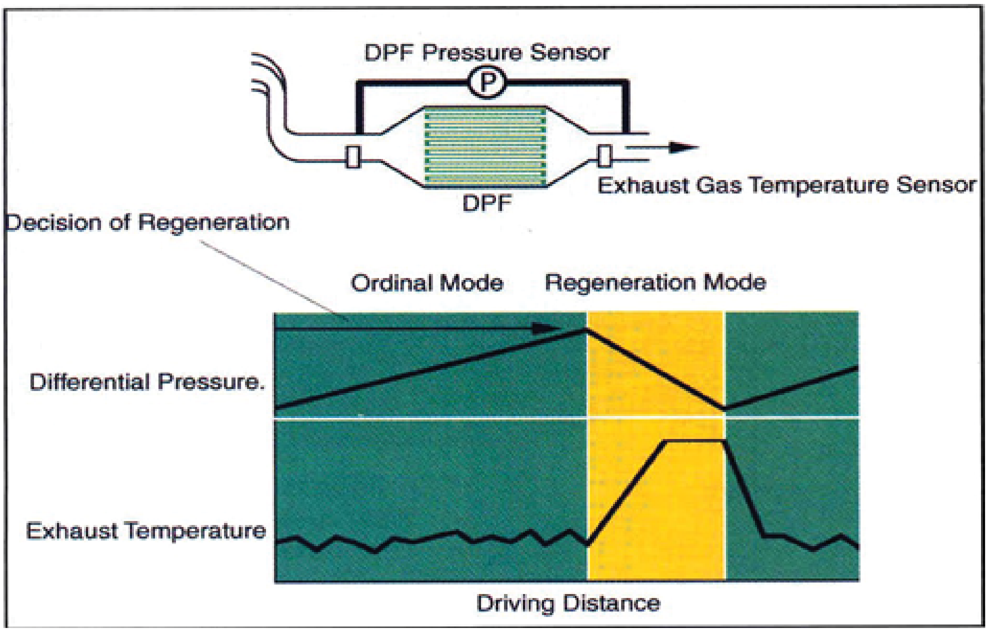


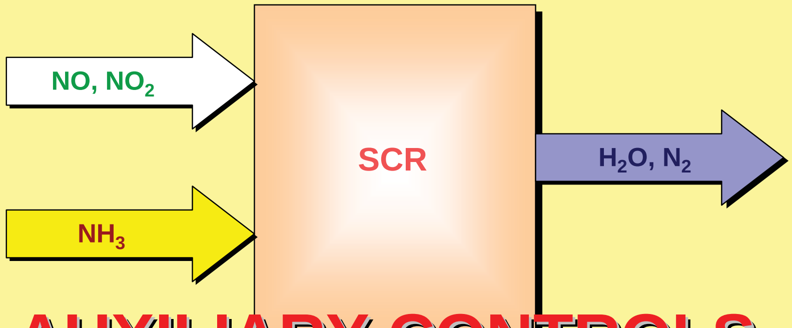
The Caterpillar Clean Gas Induction (CGI) System



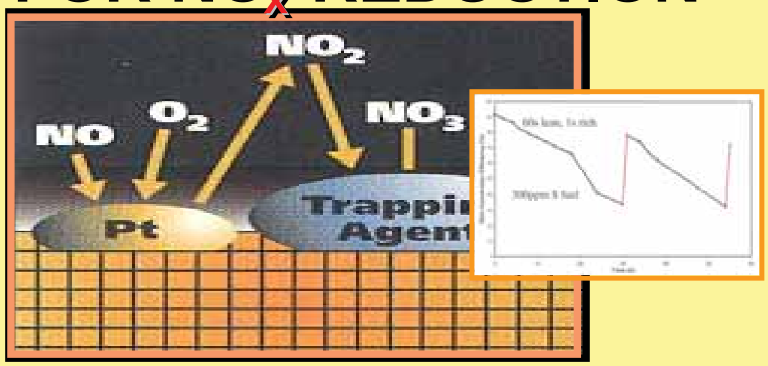
** Caterpillar Regeneration System*

Principle in DPF Regeneration Control

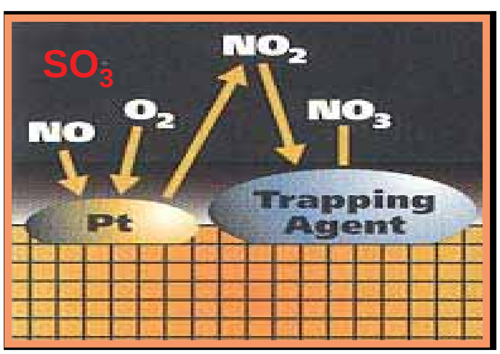


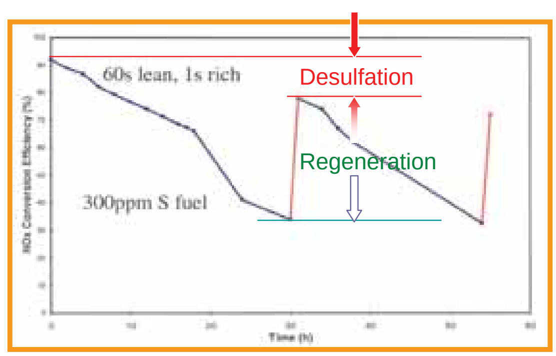


AUXILIARY CONTROLS FOR NO_x REDUCTION



The Lean NOx Trap (NO_x Adsorber or NO_x Storage Catalyst)





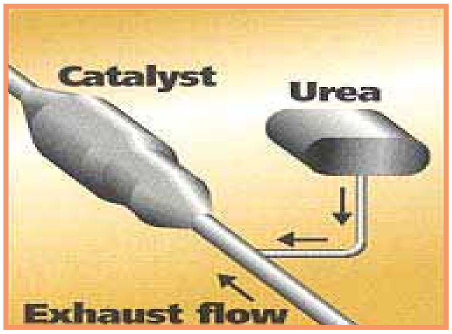
Advantages

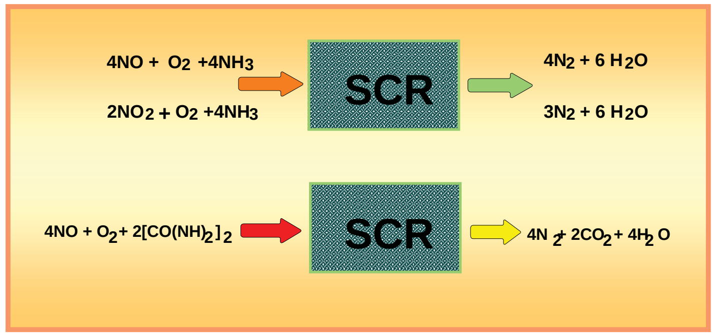
- Uses Same onboard HC (Fuel) as the Reductant
- Can Achieve Very High NO_X Conversion (>90%)
- Active temp. Range 250-450^{o}C

Disadvantages

- Extremely Sensitive to Sulfur
- Complex Regeneration Control
- Complex/Critical Desulfation Control
- Uncertain Durability
- High Fuel Consumption Penalty (1.50-10.0%@95% Conversion)
- High Precious Metal Content

Urea Selective Catalytic Reduction–*Brief Description*





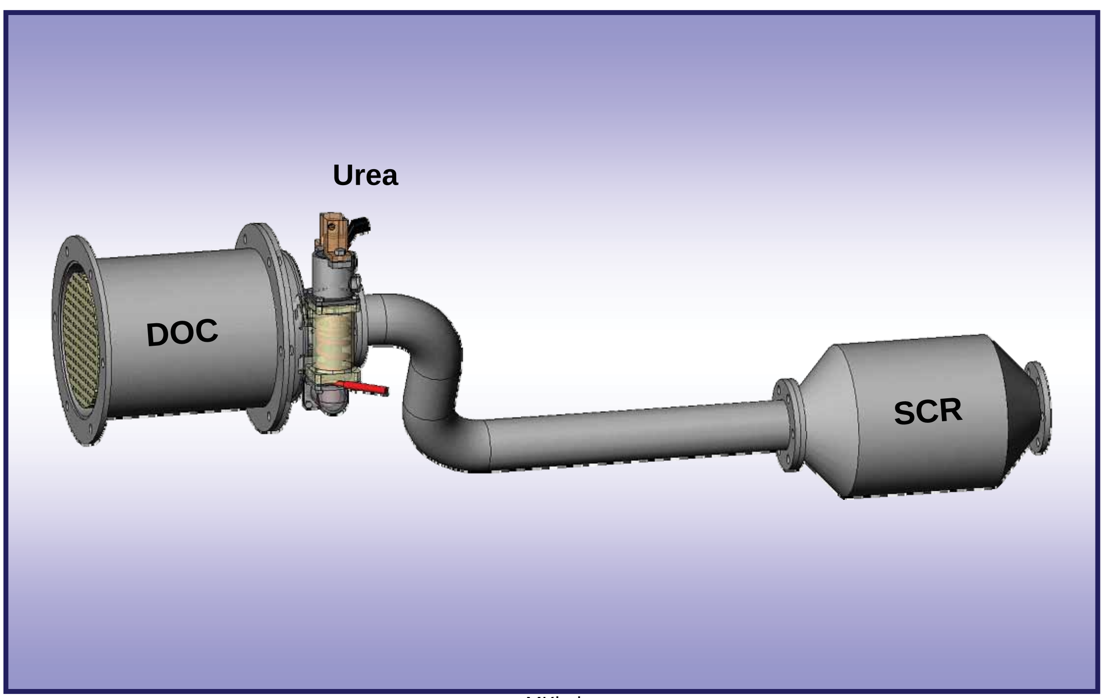
Advantages

- High NO_X Conversion (90%+)
- Excellent Sulfur Tolerance
- Active temp. Range 250-550°C
- Proven Durability
- Allows For Engine performance Optimization Flexibility

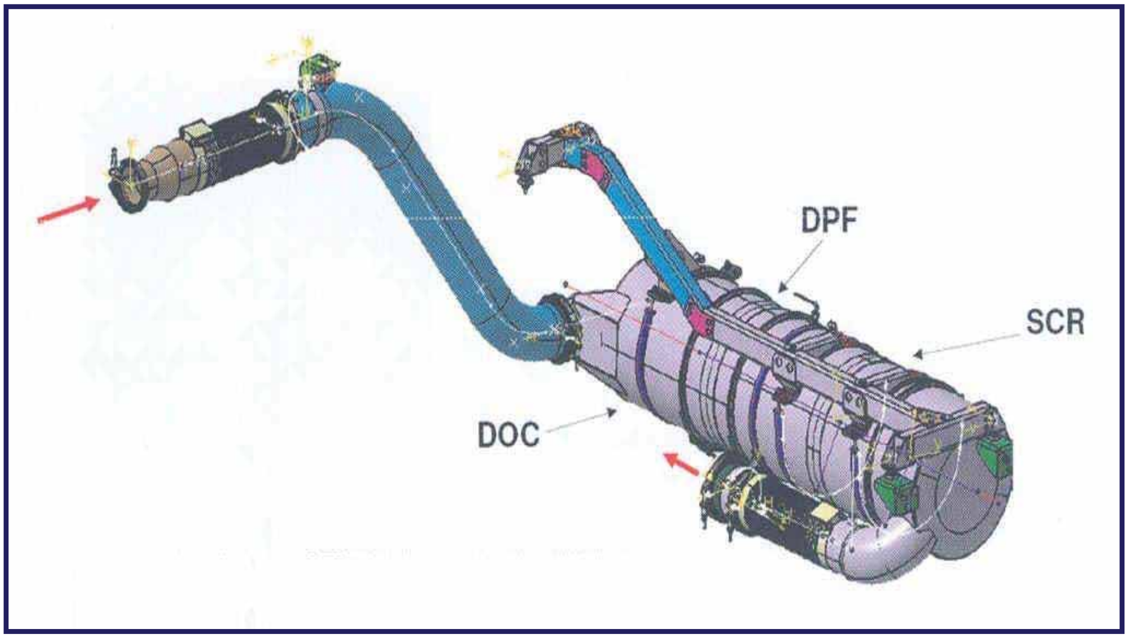
Disadvantages

- Requires Additional Fluid on Vehicle
- Infrastructure Issues
- Potential Ammonia Slip
- Size & Packaging
- Regulatory Enforcement Concerns

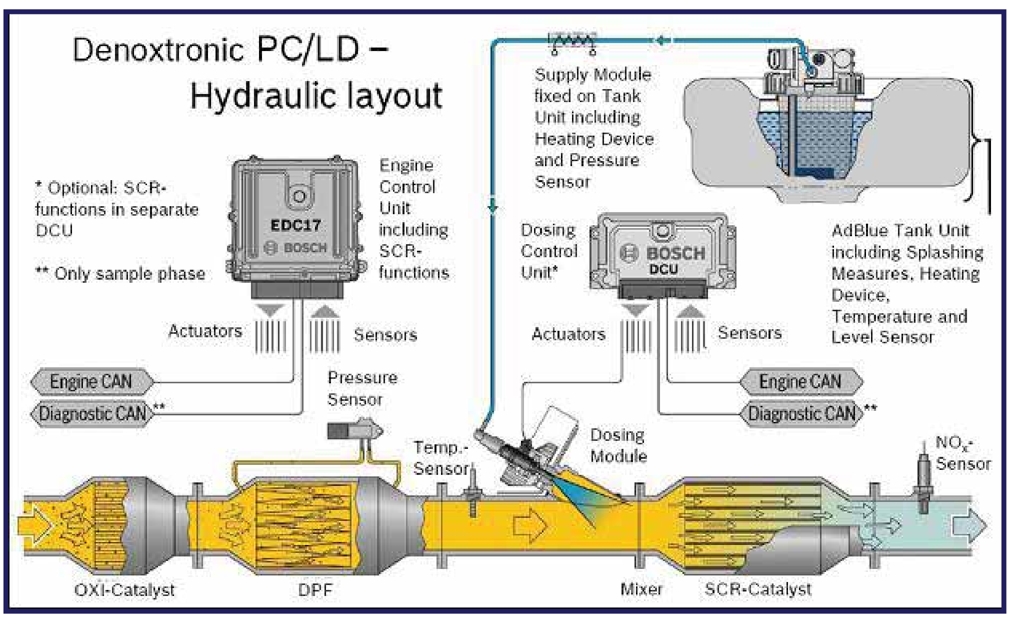
Example Urea SCR NO_x Reduction System



NOx / PM Integrated System - Production

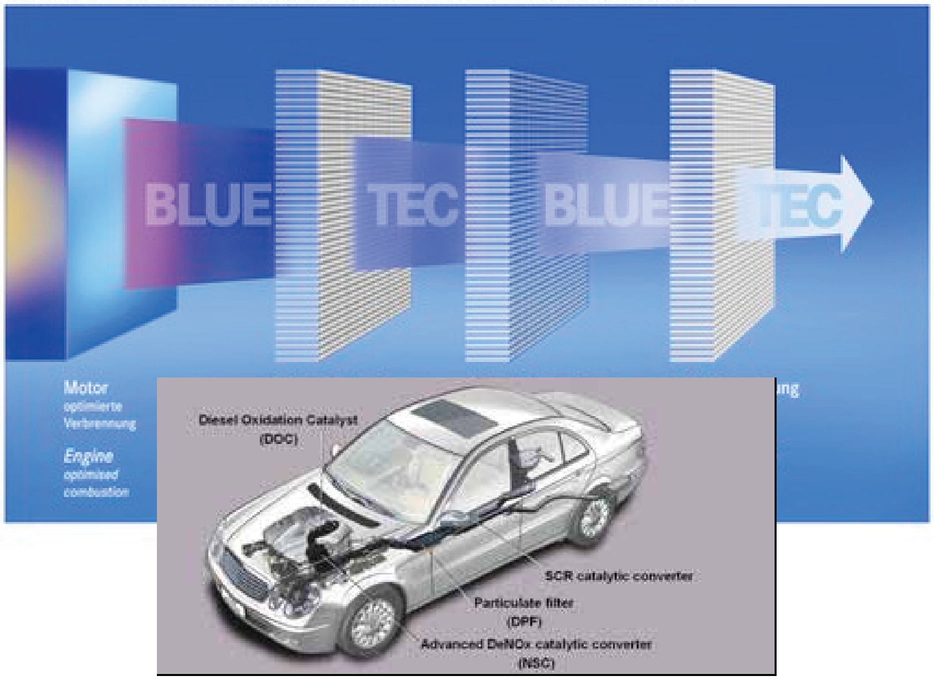


Another Example of a NO_x / PM Integrated System

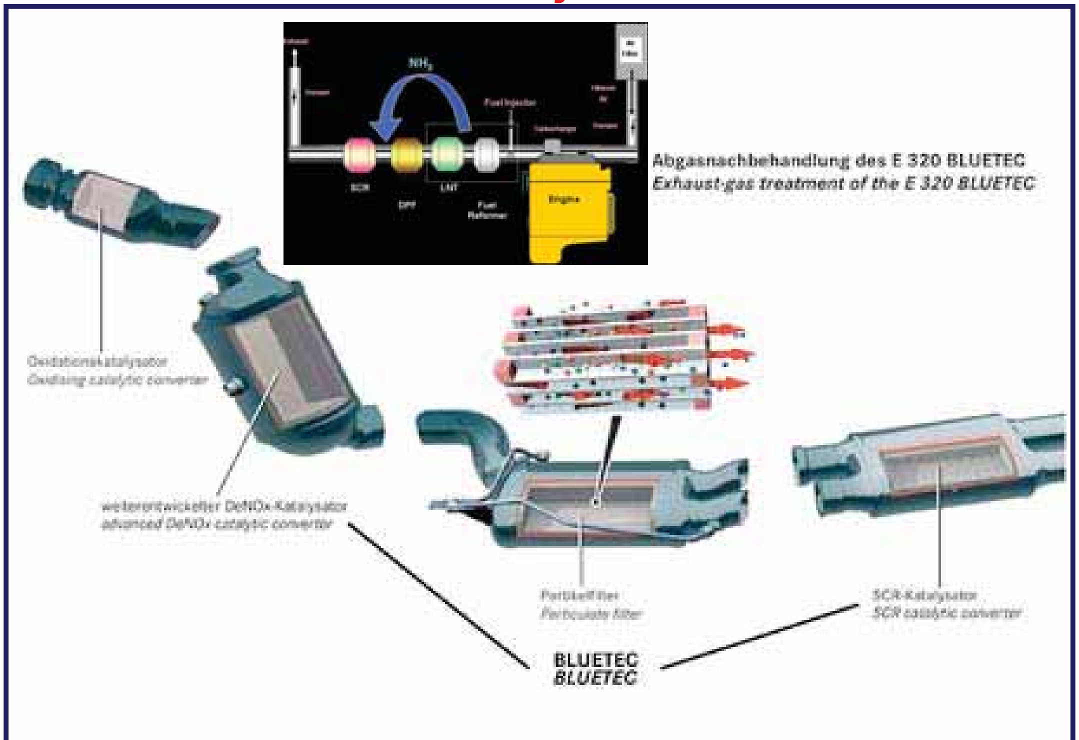


A Derivative SCR System

BLUETEC – die Technologie für die saubersten Diesel der Welt
BLUETEC – the technology for the cleanest diesels in the world



Ammonia SCR System Details

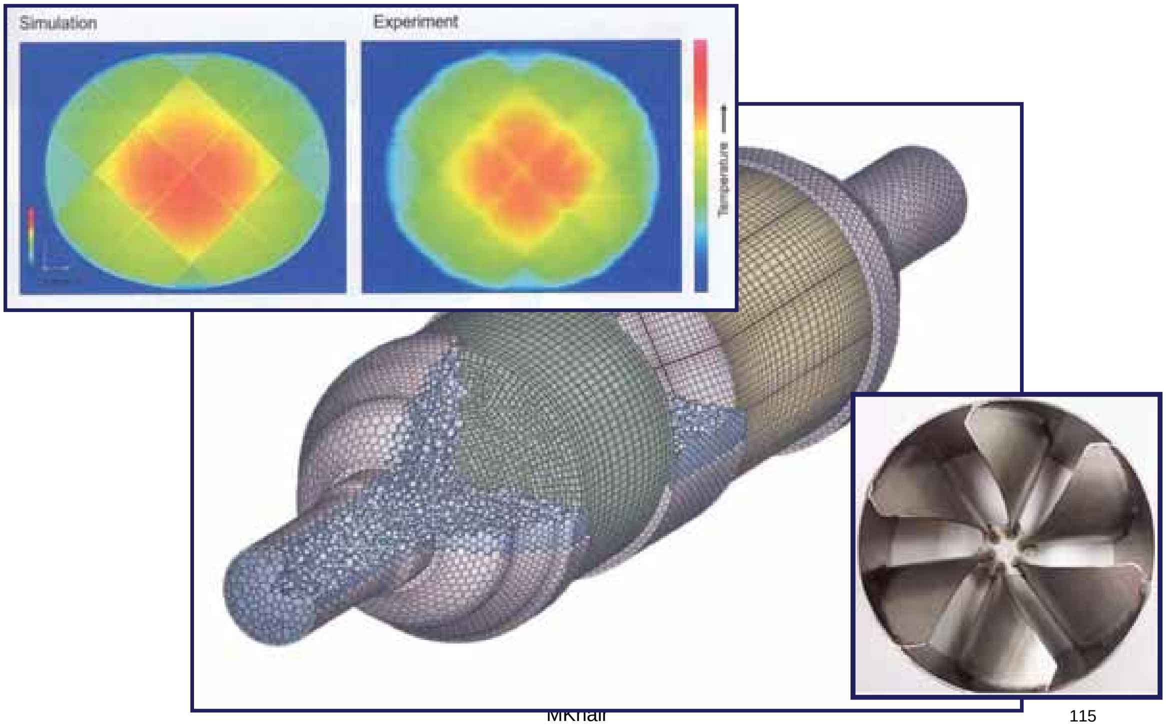


Various Components of the System

Tradeoffs of Various Aftertreatment Architectures

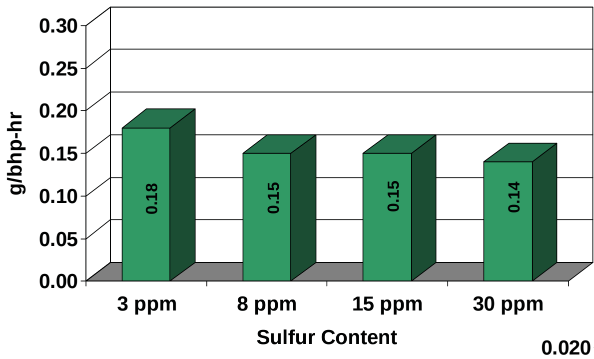
	Reductions-Potential PM	Reductions-Potential NO_x	Costs	HC	CO_2	Risks
Diesel Particulate Filter System (DOC – DPF)	+ +	0	– –	0	–	Ash deposits Oil dilution Emission impact due to regeneration
NO_x-Storage-System (NSC – DPF)	+ +	+ +	– – –	–	– –	HC inrease Aging behaviour
SCR Urea-System (DOC – DPF – SCR)	+ +	+ + +	– – –	0	–	Urea infrastructure Urea consumption Packaging urea tank Freezing protection

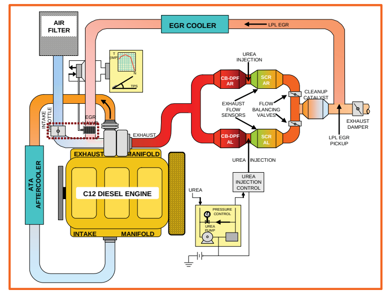
Improving Conversion through Better Flow Distribution

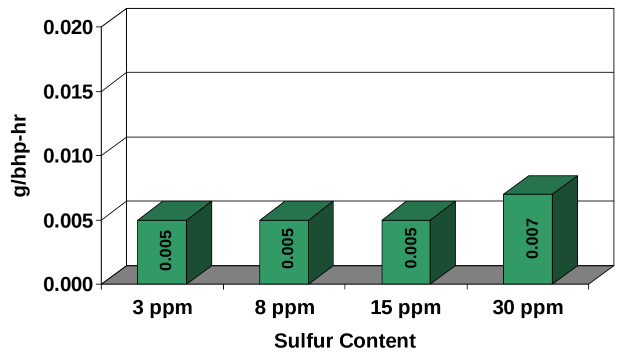


Accomplishments

An Integrated System for NO_x / PM Reduction - SCR

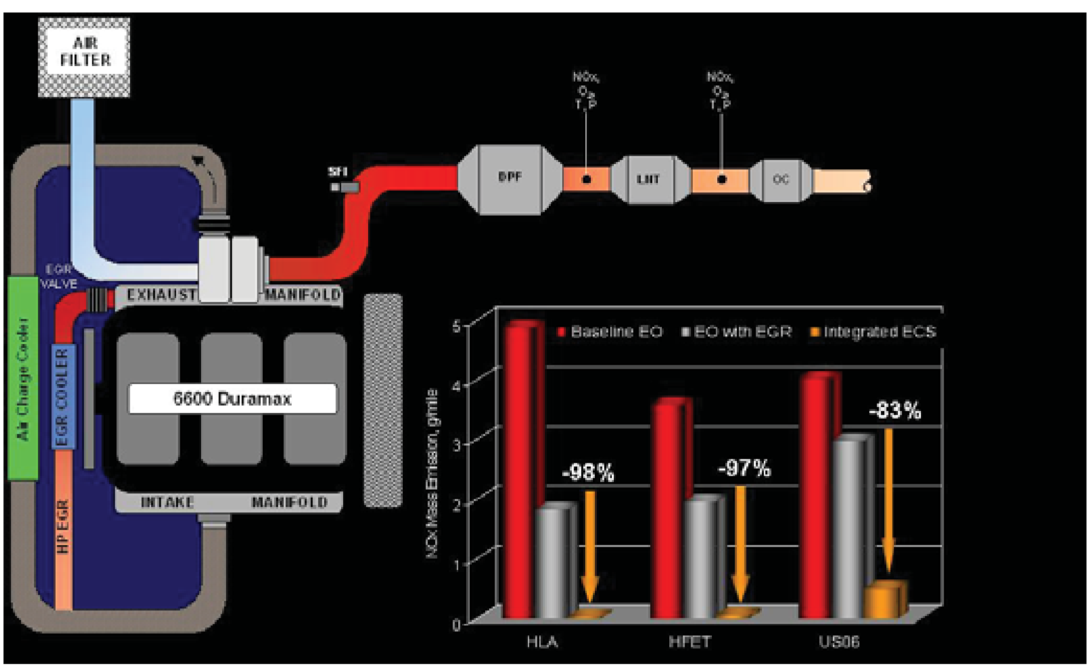




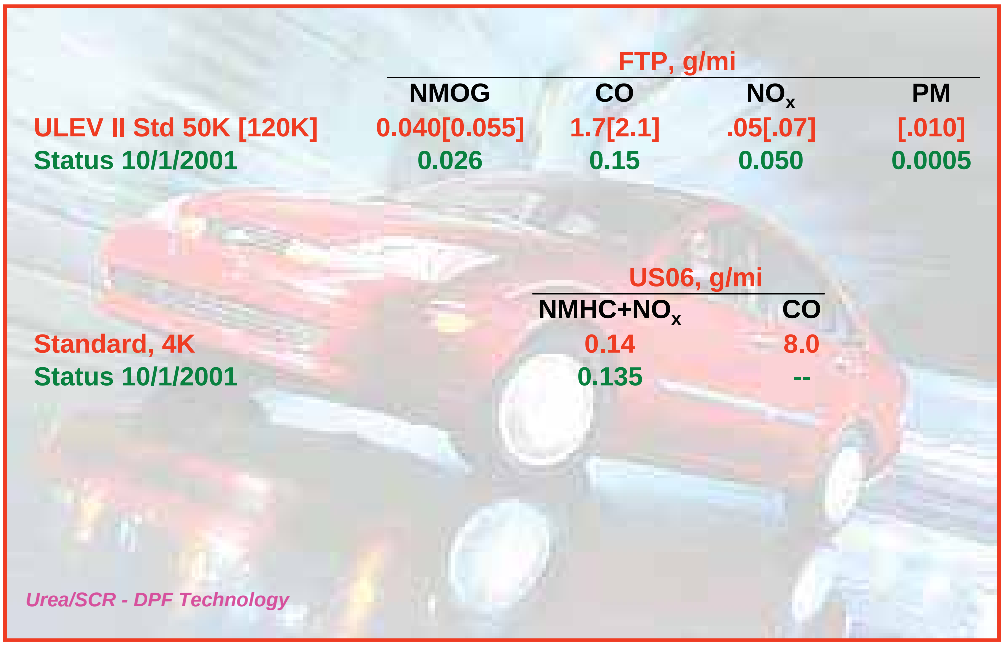


APBF-DEC Heavy-Duty SCR Project

An Integrated System for NO_x / PM Reduction - LNT



A Demonstration By Ford Motor Company

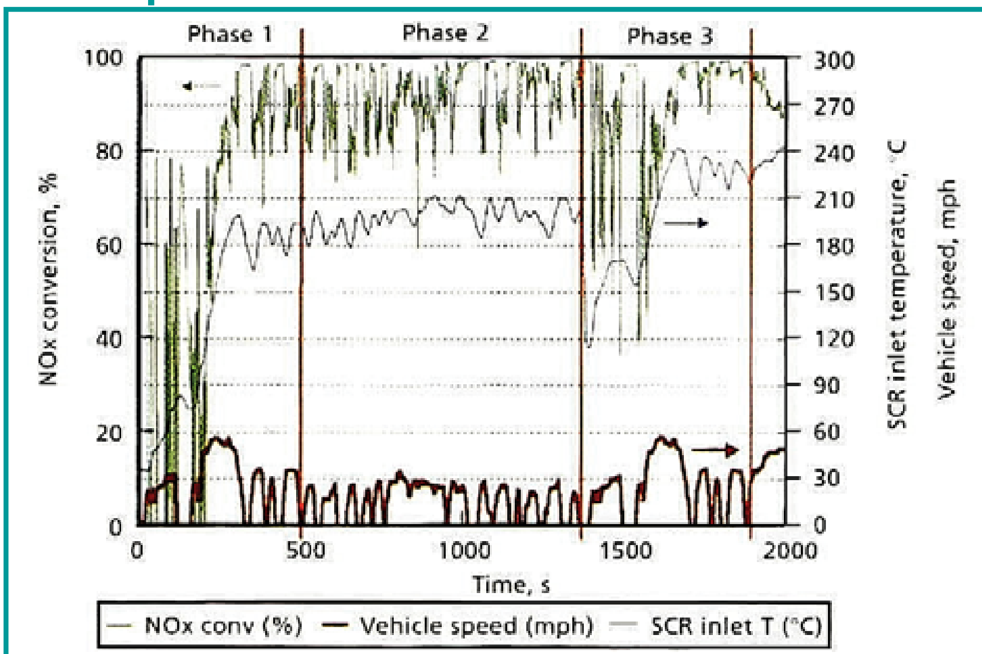


	FTP, g/mi			
	NMOG	CO	NO_x	PM
ULEV II Std 50K [120K]	0.040[0.055]	1.7[2.1]	.05[.07]	[.010]
Status 10/1/2001	0.026	0.15	0.050	0.0005

	US06, g/mi	
	NMHC+NO_x	CO
Standard, 4K	0.14	8.0
Status 10/1/2001	0.135	--

Urea/SCR - DPF Technology

Example for NOx Reduction Via SCR in LDV



Thank You for your Attention

For More Information Please Contact

Magdi Khair at: mkhair@swri.org
Telephone: (210) 522-5311
Cell: (210) 381-3060