



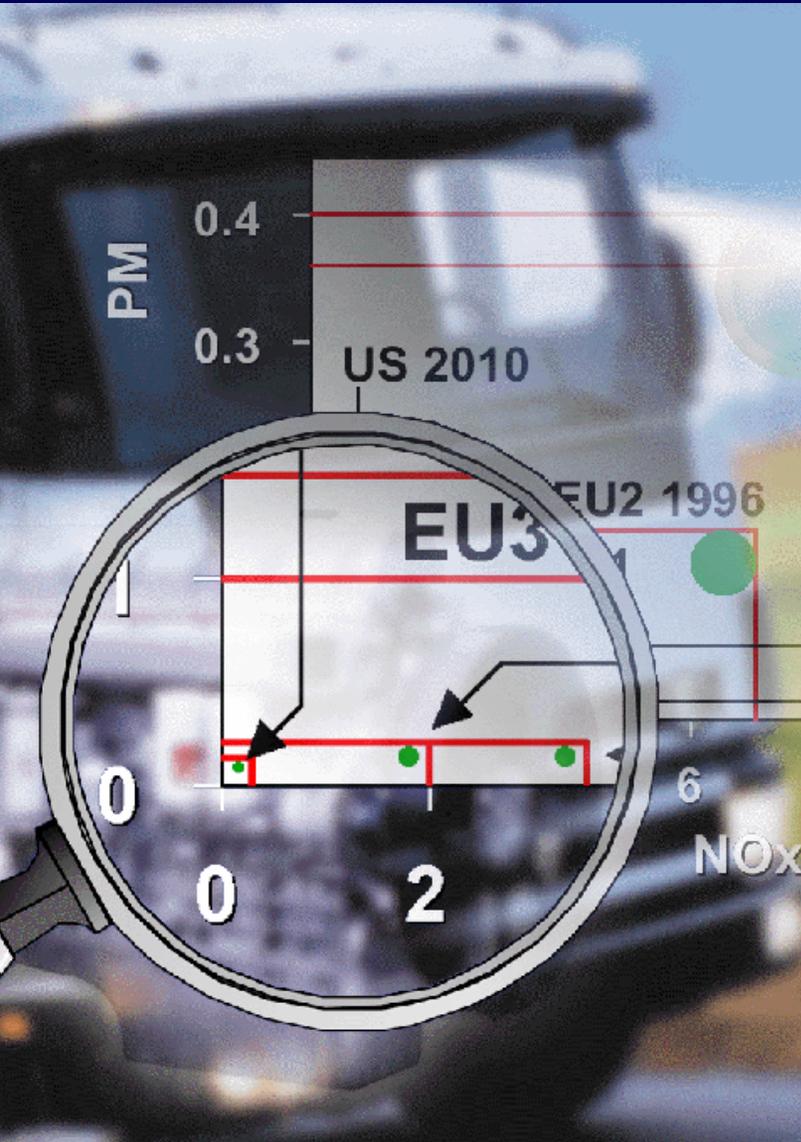
# Lowest Engine-Out Emissions as the Key to the Future of the Heavy Duty Diesel Engine - New Development Results

**Franz X. Moser**

Theodor Sams, Rolf Dreisbach

AVL LIST GmbH, Austria

10<sup>th</sup> Diesel Engine Emission Reduction Conference  
Aug. 30 – Sept. 2, 2004, San Diego



- **Introduction**
- **Engine-Out Emissions Required for Various Emission Standards**
- **Engine Concepts**
- **Requirements on EGR Rate Control**
- **Summary and Conclusions**

- Introduction
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# Future Exhaust Emission Standards and Required Raw Emissions



Commercial Powertrain Systems

USA 2010, USHDTC, ESC

Japan 2008, JTC, under discussion

Component	Emission limit [g/kWh]	Efficiency of aftertreatment system [%]	Max. raw emission [g/kWh]
PM USA	0.013	90	0.1
PM Japan	0.01	90	0.08
NOx (USA & J)	0.27	80	1.0
NOx (USA & J)	0.27	90	2.0

Europe 2012, ESC, ETC, assumption for EURO6

Component	Emission limit [g/kWh]	Efficiency of aftertreatment system [%]	Max. raw emission [g/kWh]
PM	0.01	75	0.03
PM	0.01	90	0.08
NOx	1.0	80	4.0

# EURO 4 – Emission Limits and Appertaining Raw Emissions



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## Europe ETC, 2005 ( EURO4 )

Component	Legal limit [g/kWh]	Efficiency of aftertreatment system [%]	Engine raw emission [g/kWh]
<b>PM</b>	0.03	30 *)	<b>0.04</b>
<b>NOx</b>	3.5	70 (SCR)	<b>9.0</b>

\*) Resulting from reduction of organic soluble particulate components by oxidative action of aftertreatment system

# Two Routes for Realising Various Low Emission Scenarios



*Commercial Powertrain Systems*

- **4 - 5 g/kWh NOx Raw Emission with NOx-Aftertreatment and Particulate Filter**
- **1 - 2 g/kWh NOx Raw Emission with Exhaust Gas Recirculation, NOx-Aftertreatment and Particulate Filter**

# Engine Concepts: Engine Components Evaluated

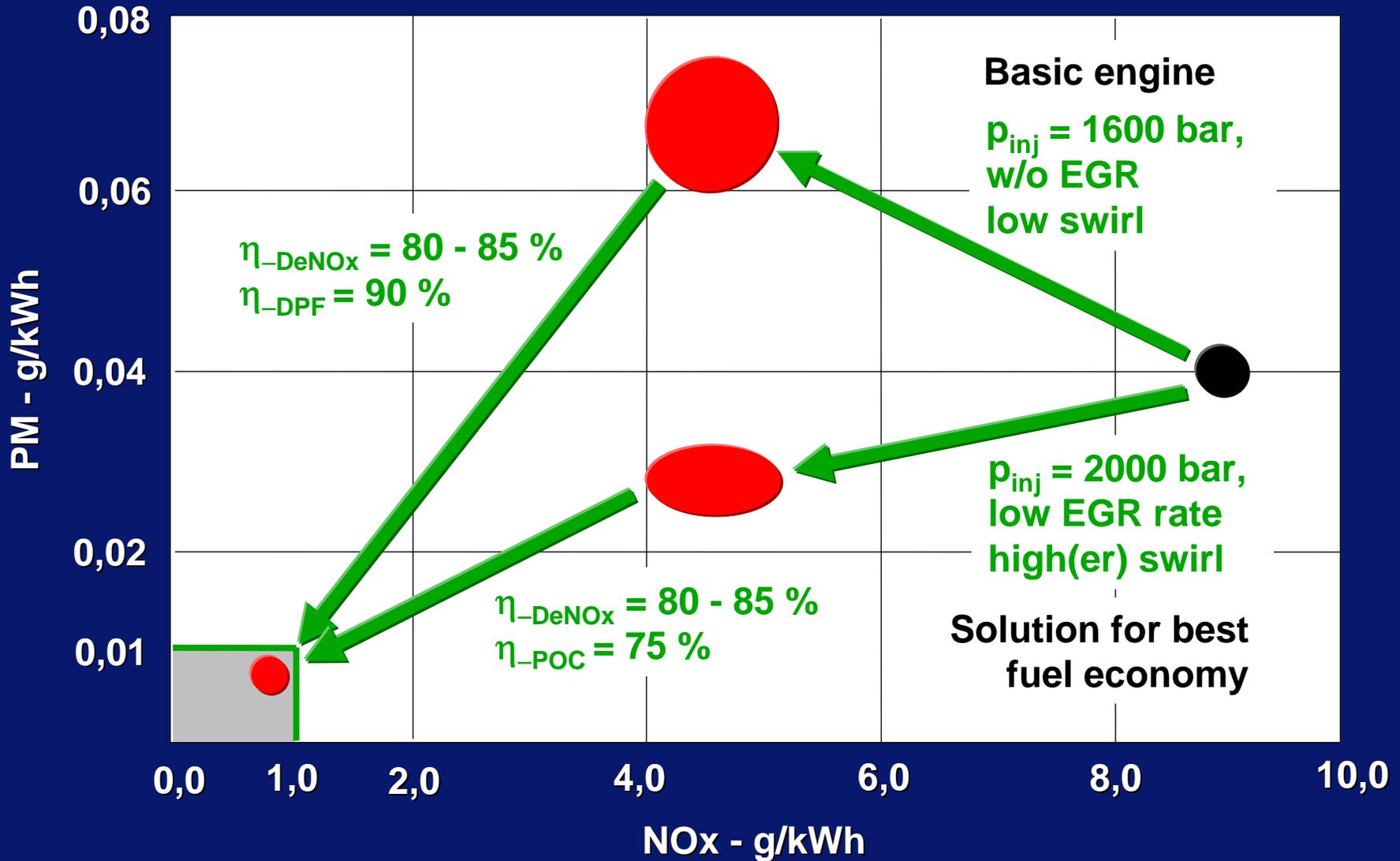


*Commercial Powertrain Systems*

- **Fuel Injection System**
- **Exhaust Gas Recirculation**
- **Turbocharging**
- **Cooling System**
- **Control System**

- Introduction
- Engine-Out Emissions Required for Various Emission Standards
- **Concept  
for 4 - 5 g/kWh NOx Raw Emissions**
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# Concepts for NOx = 4 - 5 g/kWh Raw Emission and (assumed) Legal Limit 1,0 g/kWh

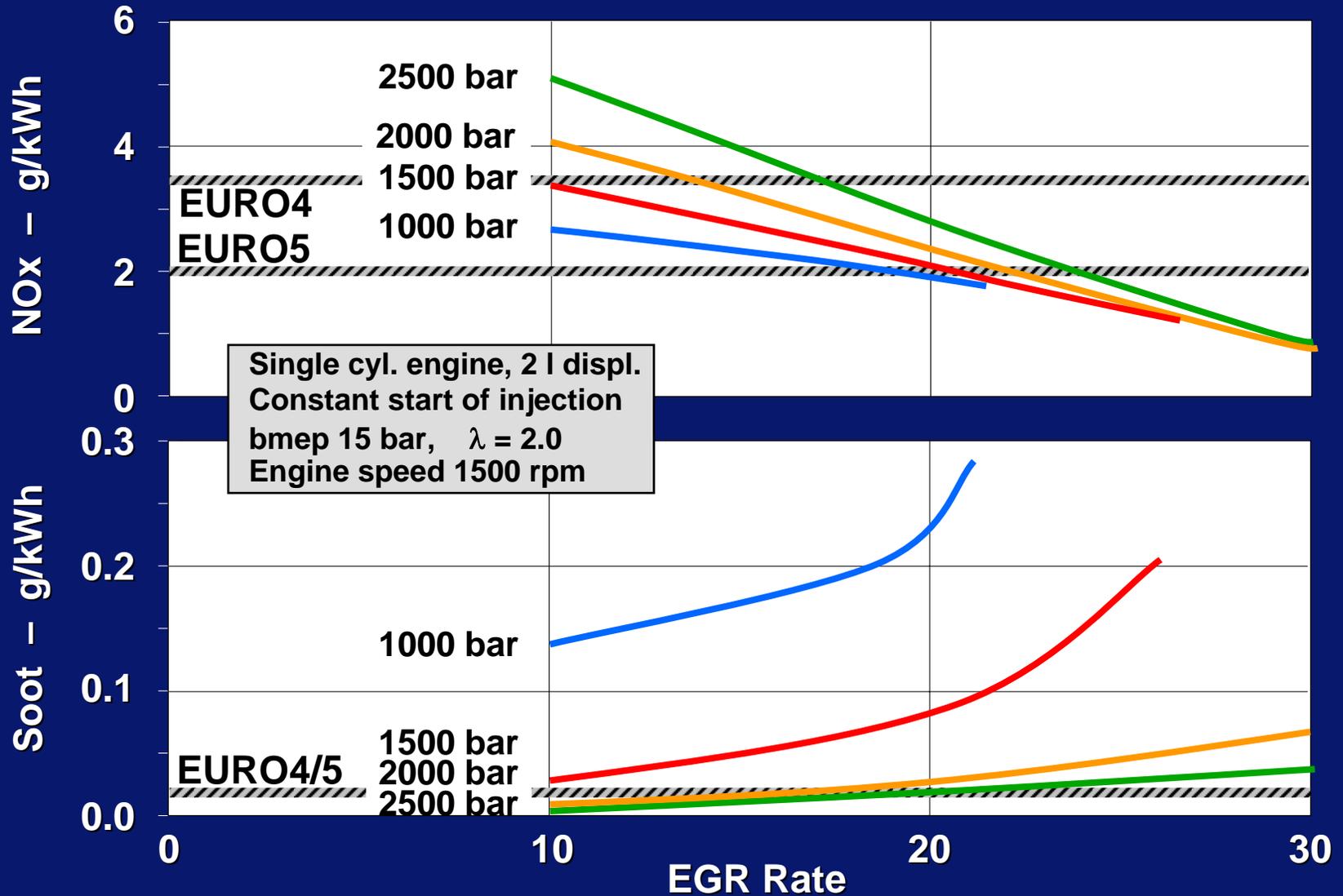


- Introduction
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- **Concept for 1 - 2 g/kWh NO<sub>x</sub> Raw Emissions**
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# Relationship between EGR Rate, Injection Pressure and NOx / Soot Emissions



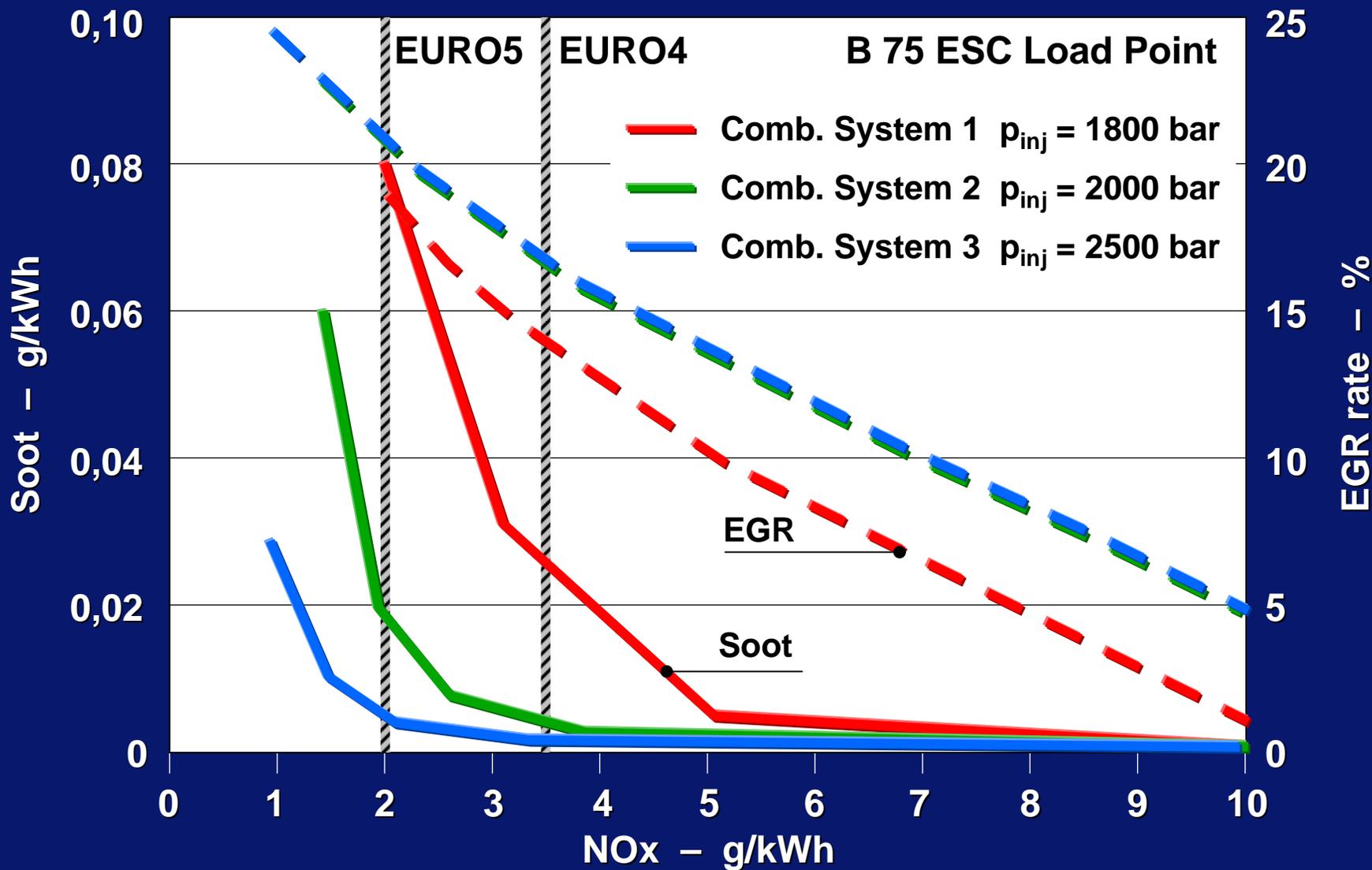
Commercial Powertrain Systems



# Latest Development Results for Lowest Soot and NOx Engine-Out Emissions



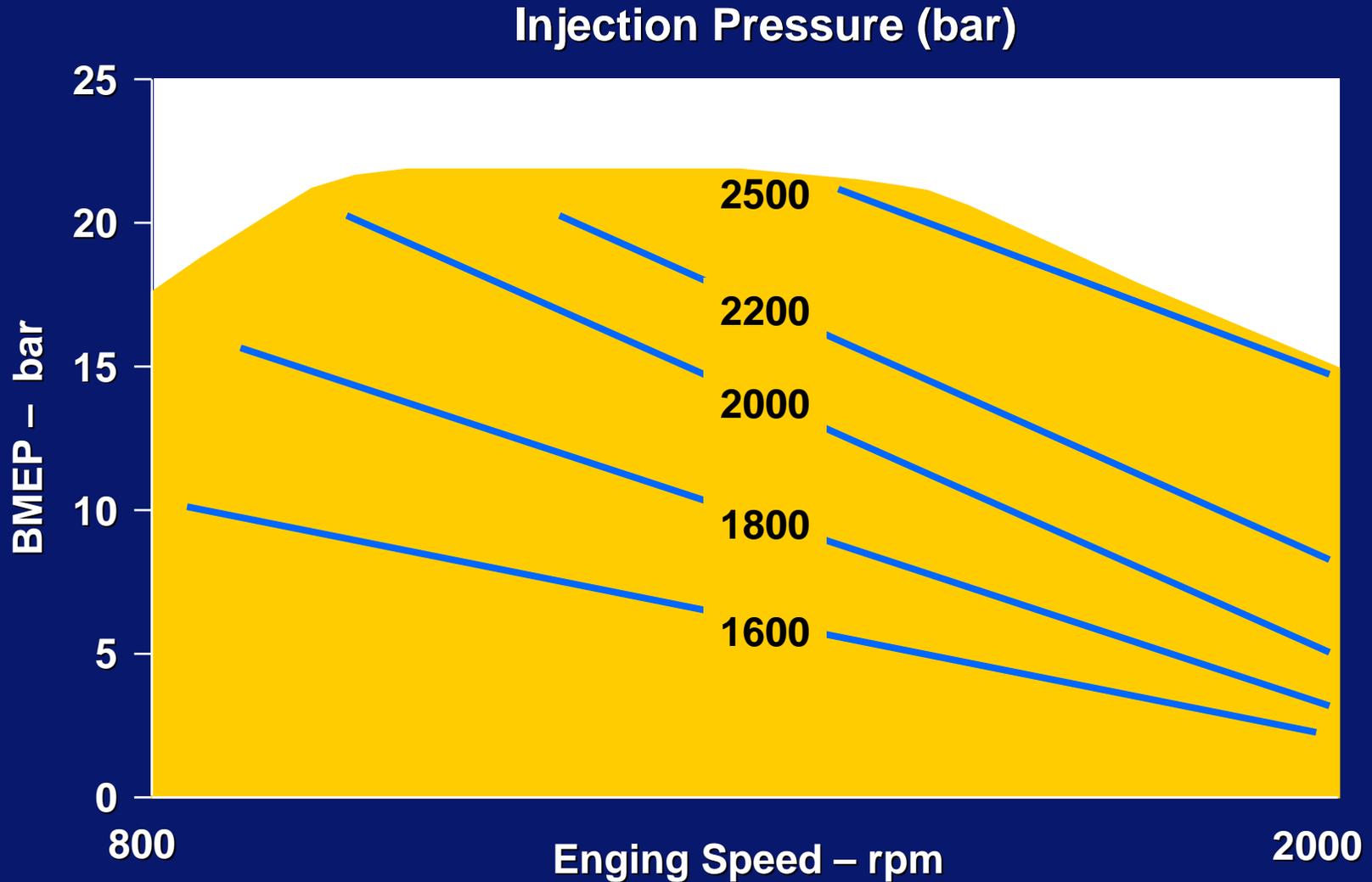
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# Injection Pressure Demand for 1,0 g/kWh NOx and Min. Soot (engine-out)



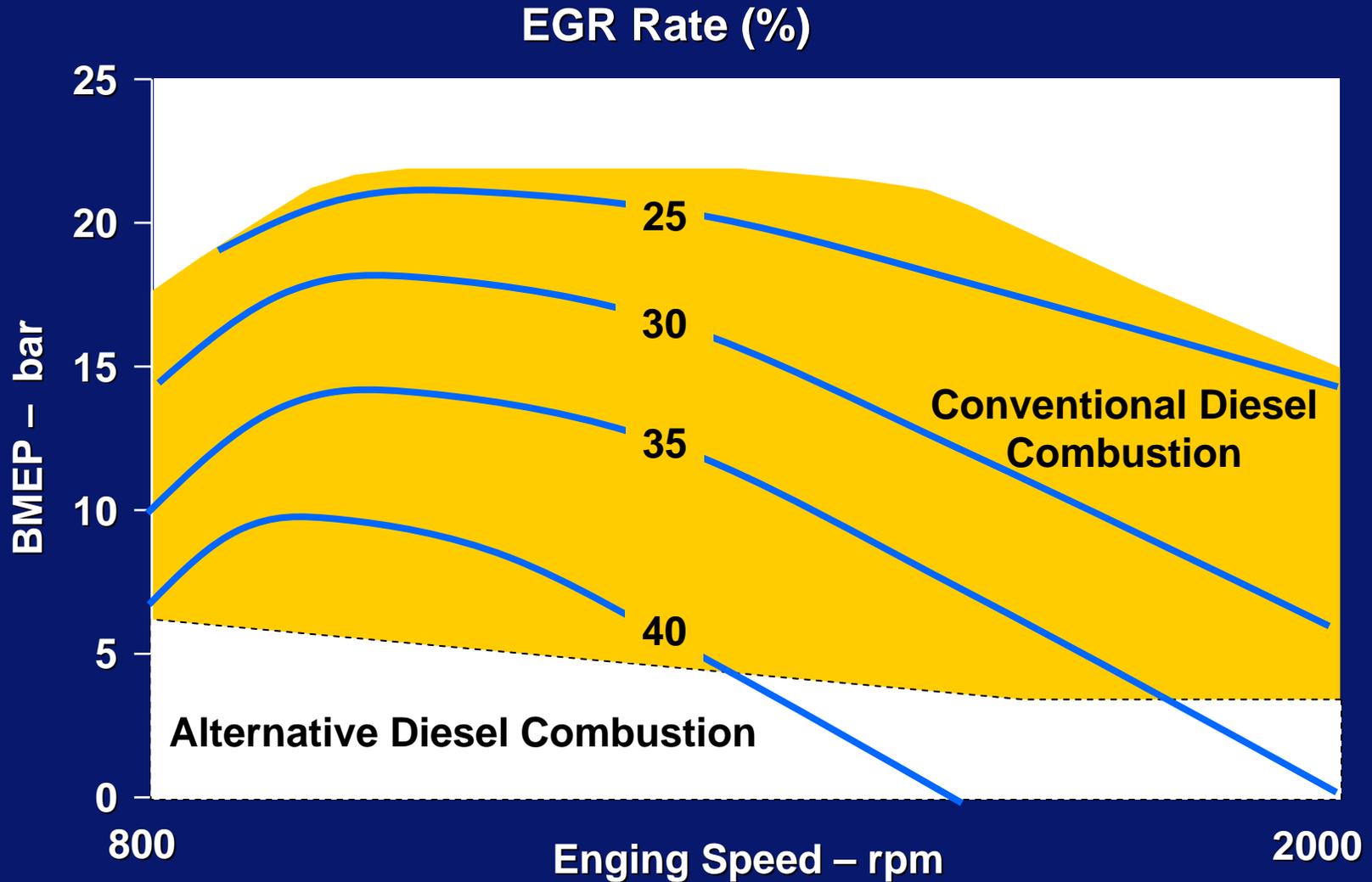
Commercial Powertrain Systems



# EGR-Rate Demand for 1,0 g/kWh NOx and Min. Soot (engine-out)



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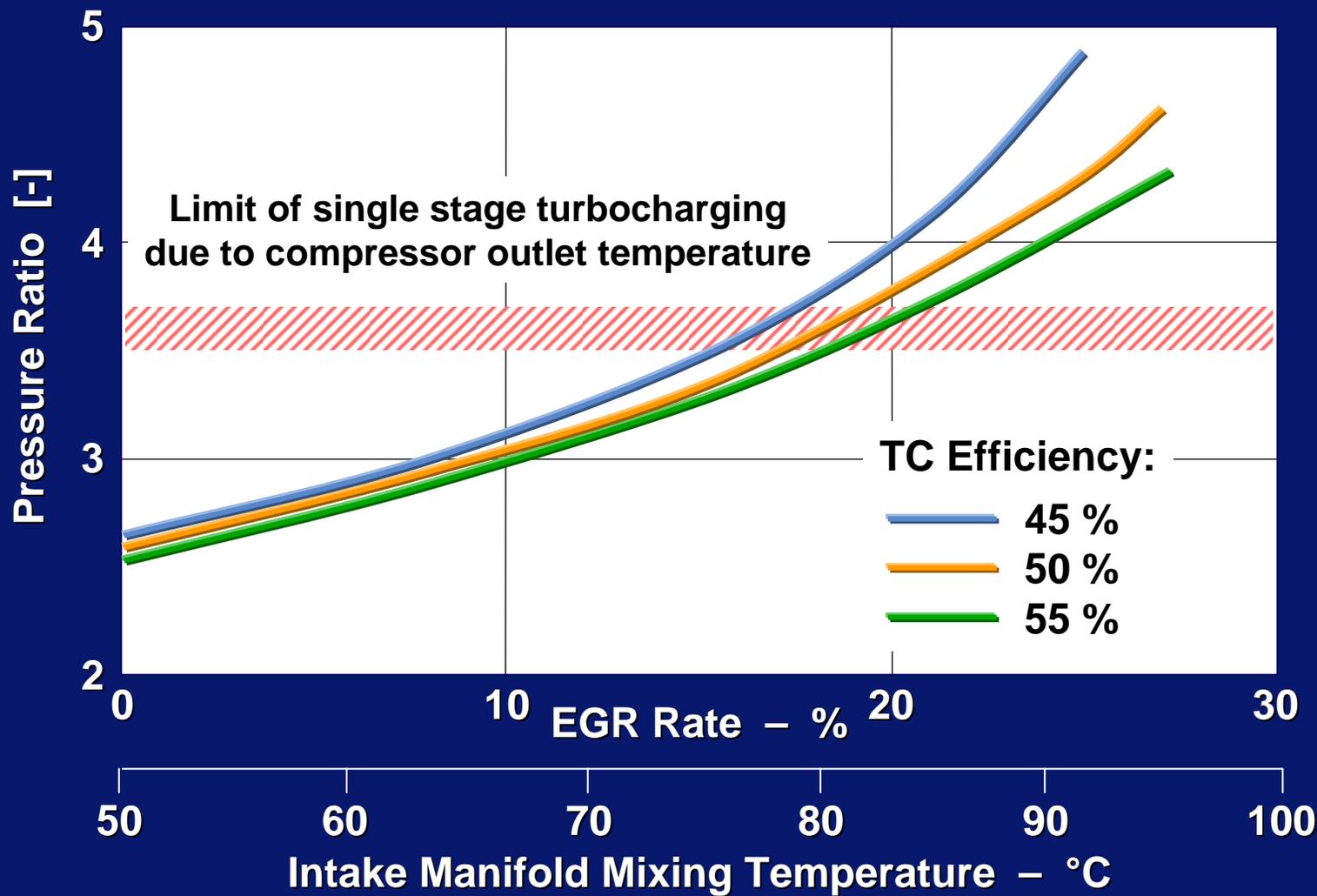


# Boost Pressure Demand Depending on EGR Rate and Turbocharger Efficiency

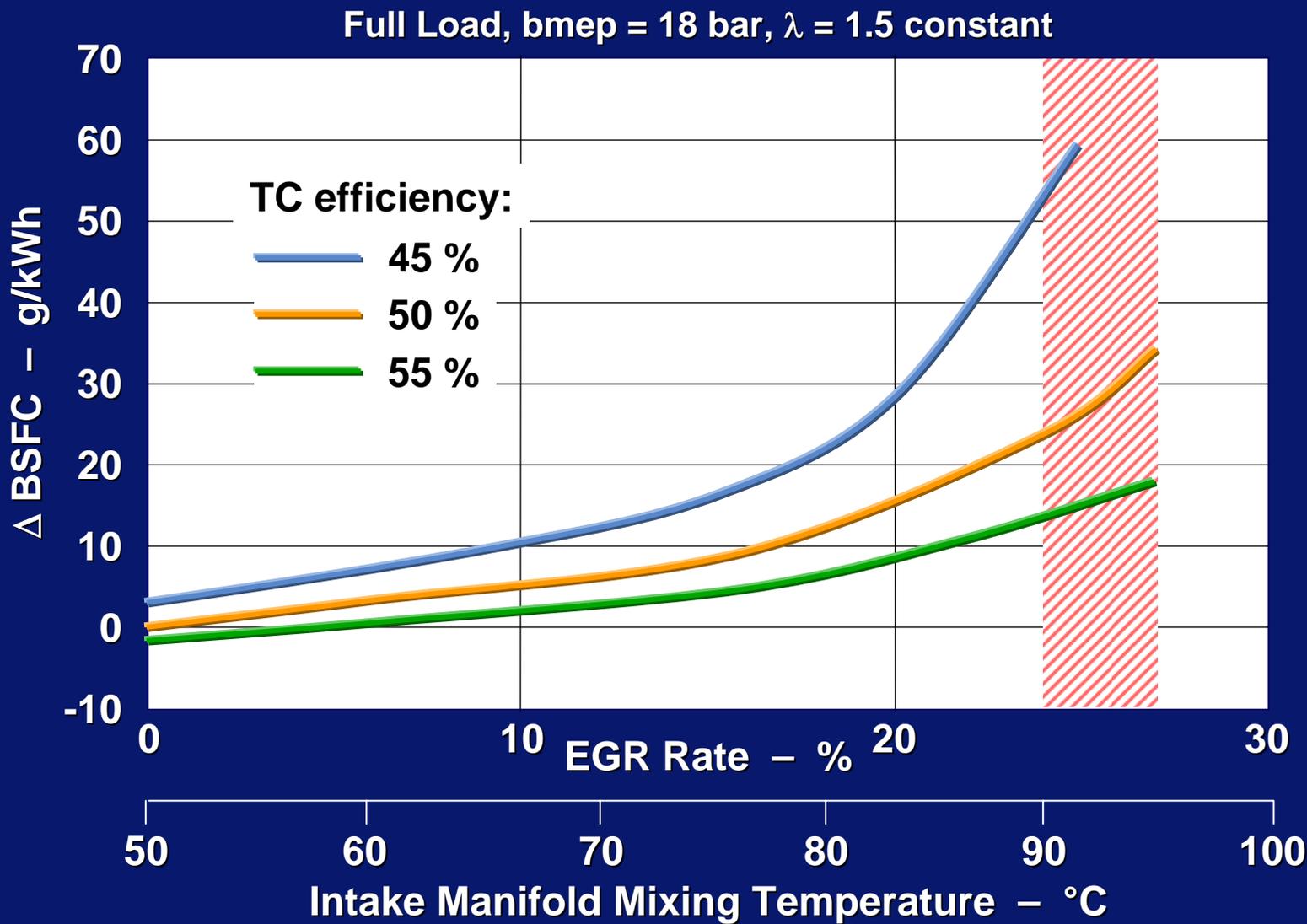


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Full Load, bmep = 18 bar,  $\lambda = 1.5$  constant

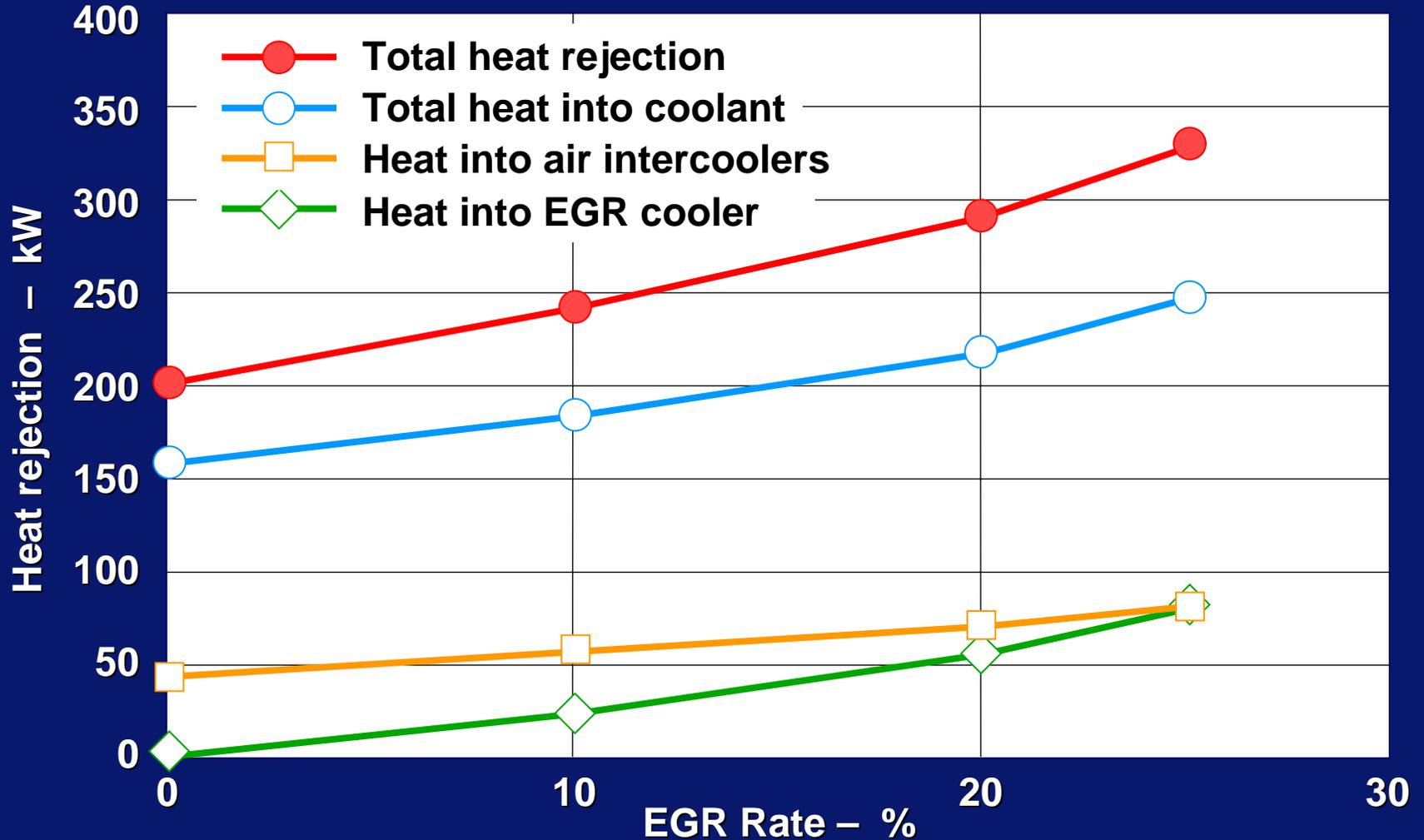


# Effect of EGR Rate and Turbocharger Efficiency on Fuel Consumption

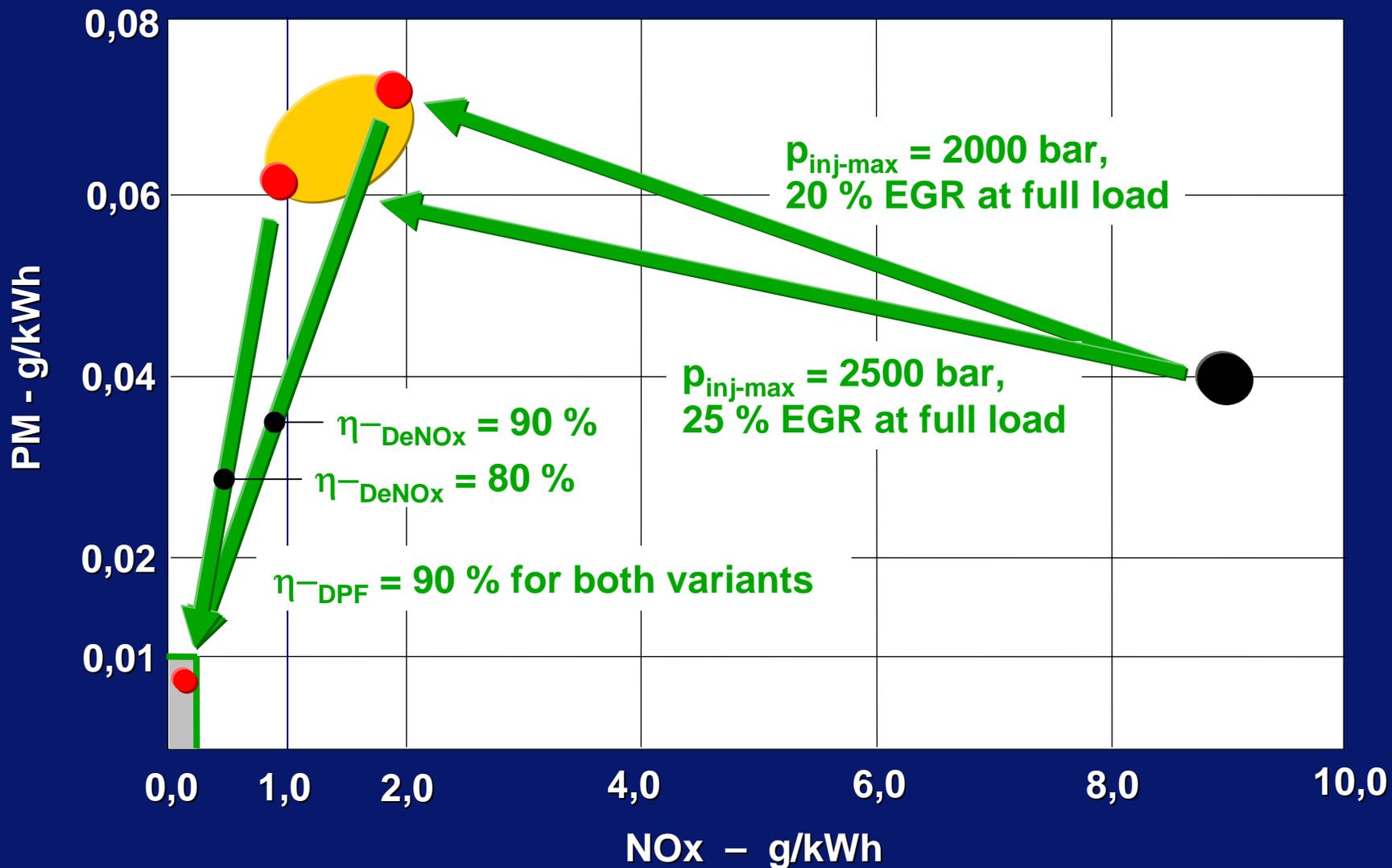


# Effect of EGR Rate on Heat Rejection

12 l HD Diesel engine, 350 kW class, ESC C100 Point



# Concepts for NOx = 1 - 2 g/kWh Raw Emission and Legal Limit 0,27 g/kWh



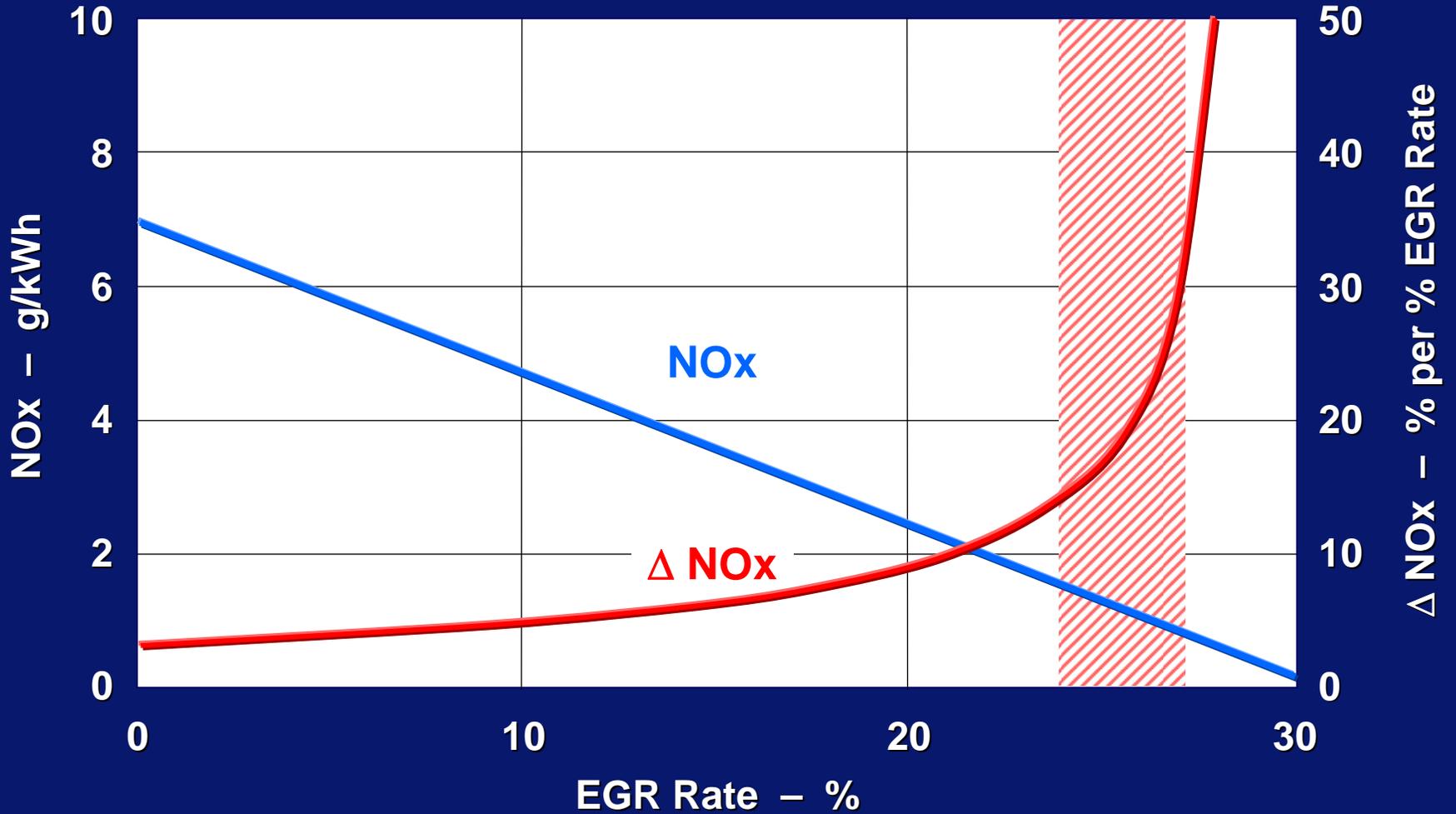
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# Absolute and Relative Effect of EGR Rate on NOx Emissions



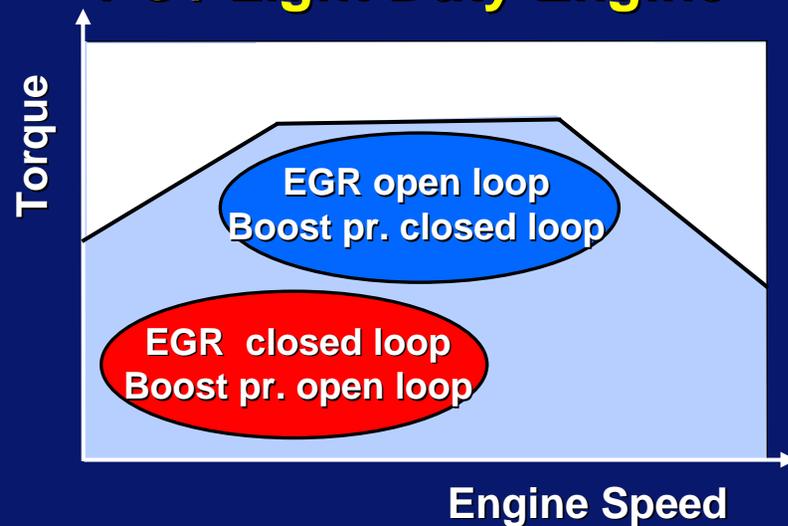
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Full Load, bmep = 18 bar



# EGR Rate Control Areas within Engine Map of PassCar and HD Diesel Engines

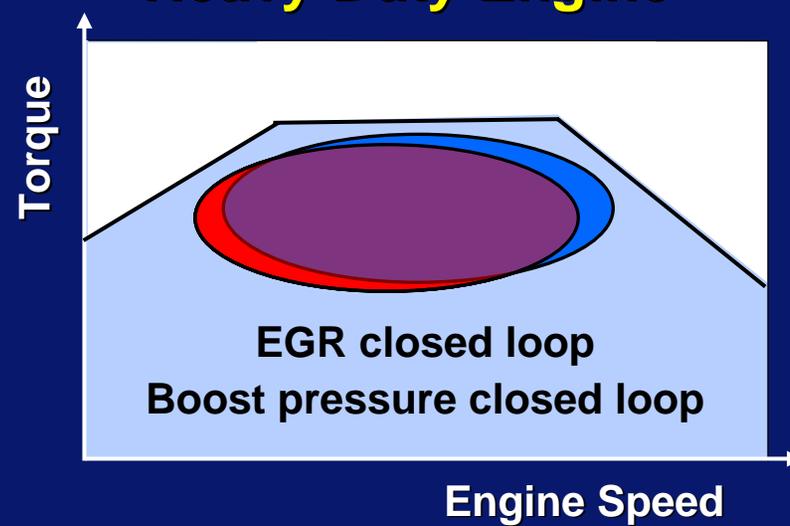
## PC / Light Duty Engine



### Operating Area:

- EGR and boost pressure control demand in different map areas

## Heavy Duty Engine



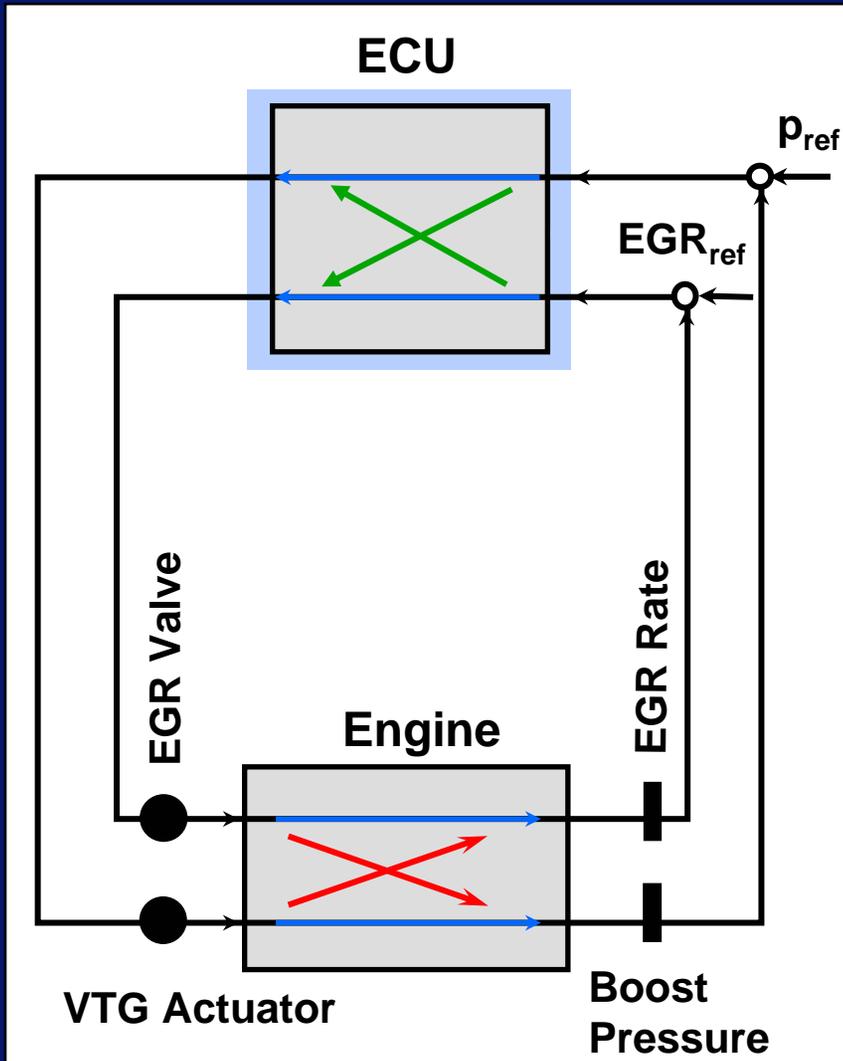
### Operating Area:

- EGR and boost pressure control demand in the same map area

### Challenge:

- Necessity of simultaneous control of EGR rate and boost pressure

# Concept of Model Based Controller for EGR and VTG



- A **single** model based controller for EGR rate and boost pressure
- Reciprocal influence of EGR rate and boost pressure being taken into account in real engine operation

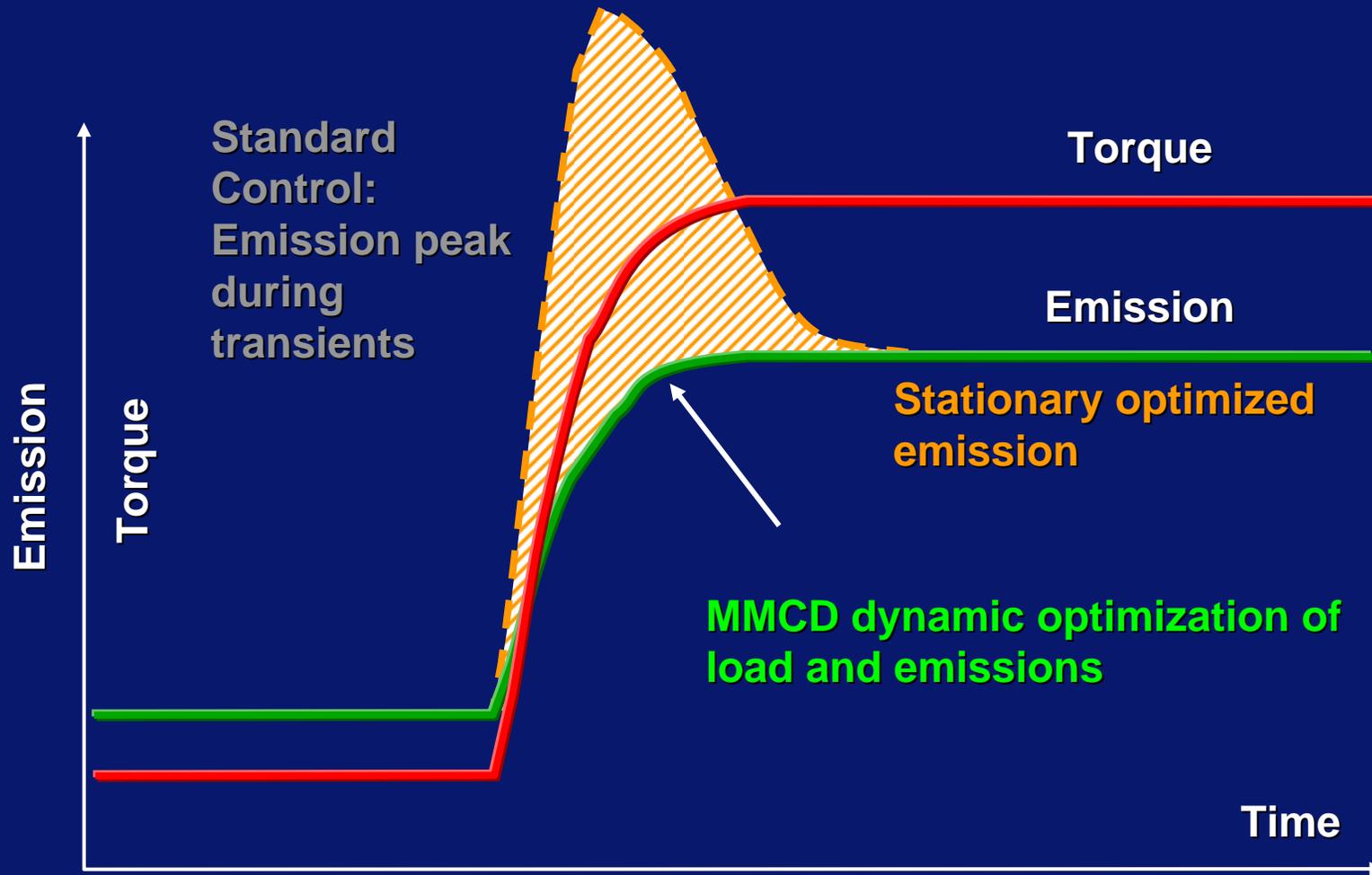
## Result:

- Better dynamic engine response
- Control of EGR rate and boost pressure decoupled to a high extent
- Reduced ECU storage demand and application effort
- Emission reduction
- Fuel consumption improvement

# Emission Improvement by Model Based Controller during Transients



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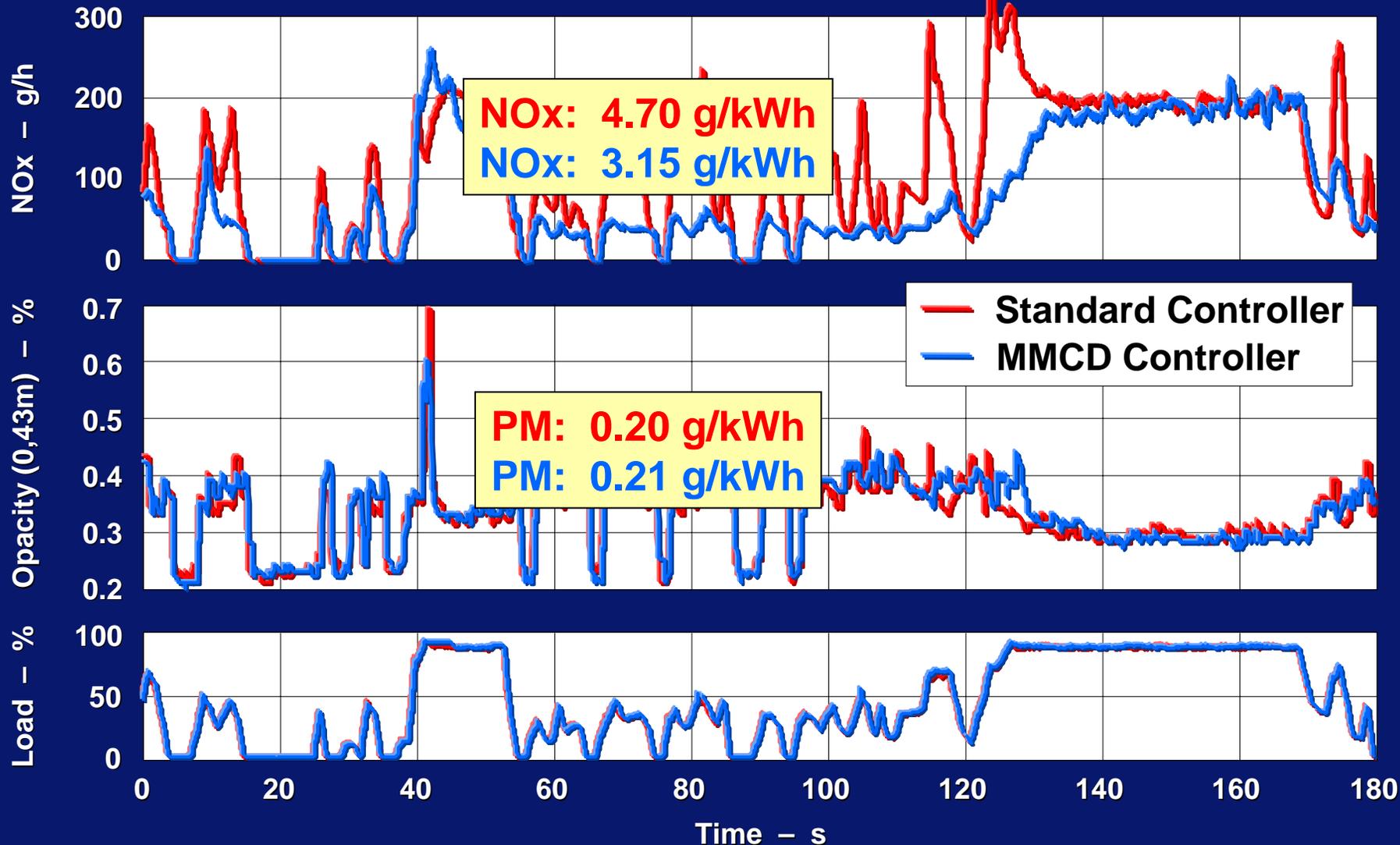
MMCD: Model-Based Multivariable Controller Design

# Transient Emission Reduction by AVL MMCD Controller



Commercial Powertrain Systems

## ETC Test Results:



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# Emission Scenarios, Engine Technologies and Consequences



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Emission Standard NOx / PM	Raw emission NOx / PM	EGR rate [%]	Exh. after-treatment	Boost press. ratio [-]	PFP [bar]	Bsfc ETC [g/kWh]	Road fuel cons. (incl. urea* & fan)
<b>3.5 / 0.03</b>	<b>9.0 / 0.04</b>	–	SCR	2.6	200	200	100 %
<b>1.0 / 0.01</b>	<b>5.0 / 0.08</b>	–	SCR + DPF	2.7	180	215	107 %
	<b>5.0 / 0.03</b>	10	SCR + POC	3.1	200	208	105 %
<b>0.27 / 0.01</b>	<b>1.0 / 0.06</b>	25	SCR + DPF	4.3	200	228	115 %
	<b>2.0 / 0.07</b>	20	Ads.Cat? + DPF	4.0	200	218	111 %

\* urea consumption calculated with 50% of diesel price

- All emission scenarios for and beyond 2010, being promulgated or discussed, require further intensive development of exhaust aftertreatment systems and utmost reduction of engine-out emissions.
- To meet already promulgated US/EPA 2010 emission standards requires PM filtration and DeNOx efficiencies of at least 90% in order to keep efforts needed for the basic engine and fuel consumption deterioration within acceptable limits.
- Emission standards discussed in Japan`s PNLTR are considered extremely critical with the introduction date 2008 !
- For EURO 6, still to be discussed, the right balance between further emission reduction and fuel economy / CO2-emissions has to be found. Taking over US 2010 limits would lead to an unacceptable fuel consumption deterioration and CO2-increase.

- **By 2010, fuel injection system manufacturers have to be prepared to volume supply of fully flexible injection systems with 2500 bar pressure capability.**
- **Precise control of VTG and EGR rate requires a new approach, e.g. by means of model-based solutions.**
- **Turbocharger manufacturers are highly challenged to develop turbochargers with total efficiencies of at least 55 %.**
- **For cooling systems new approaches regarding enhanced efficiencies and compactness have to be found.**
- **New quality control processes enabling the extreme narrowing of emission relevant production tolerances of the total system engine plus aftertreatment have to be developed and verified.**

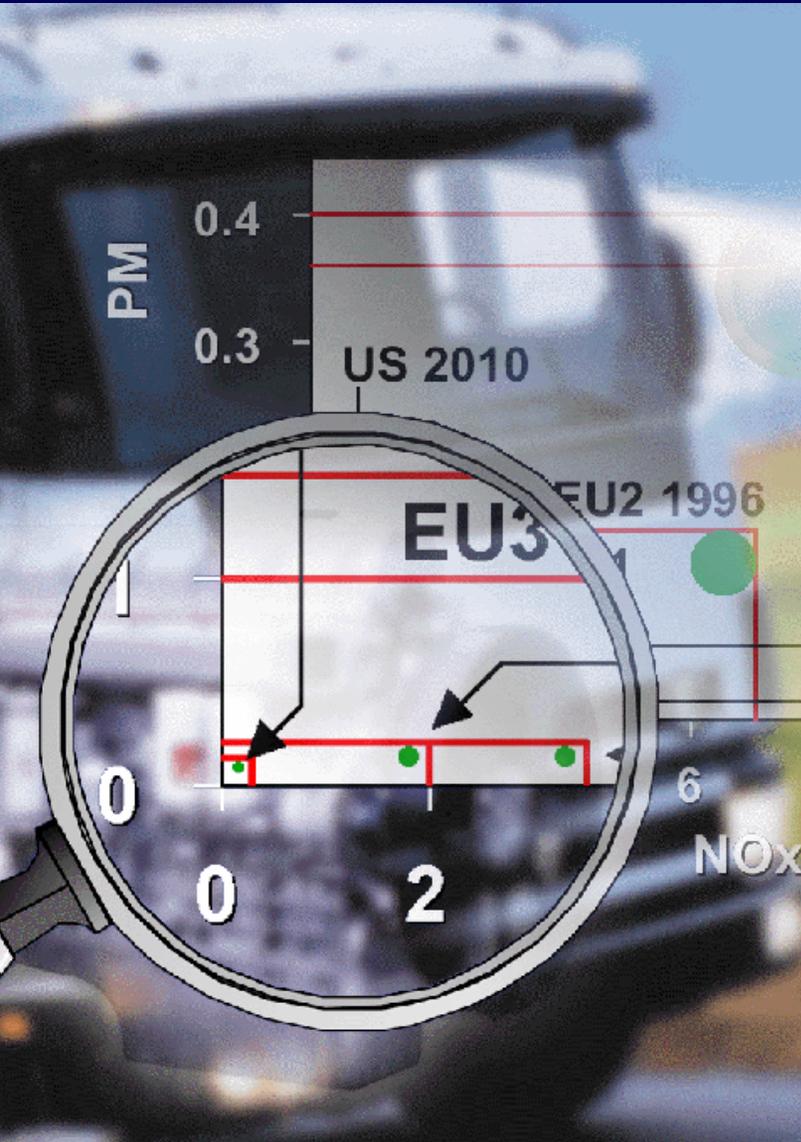
# Lowest Engine-Out Emissions as the Key to the Future of the Heavy Duty Diesel Engine - New Development Results

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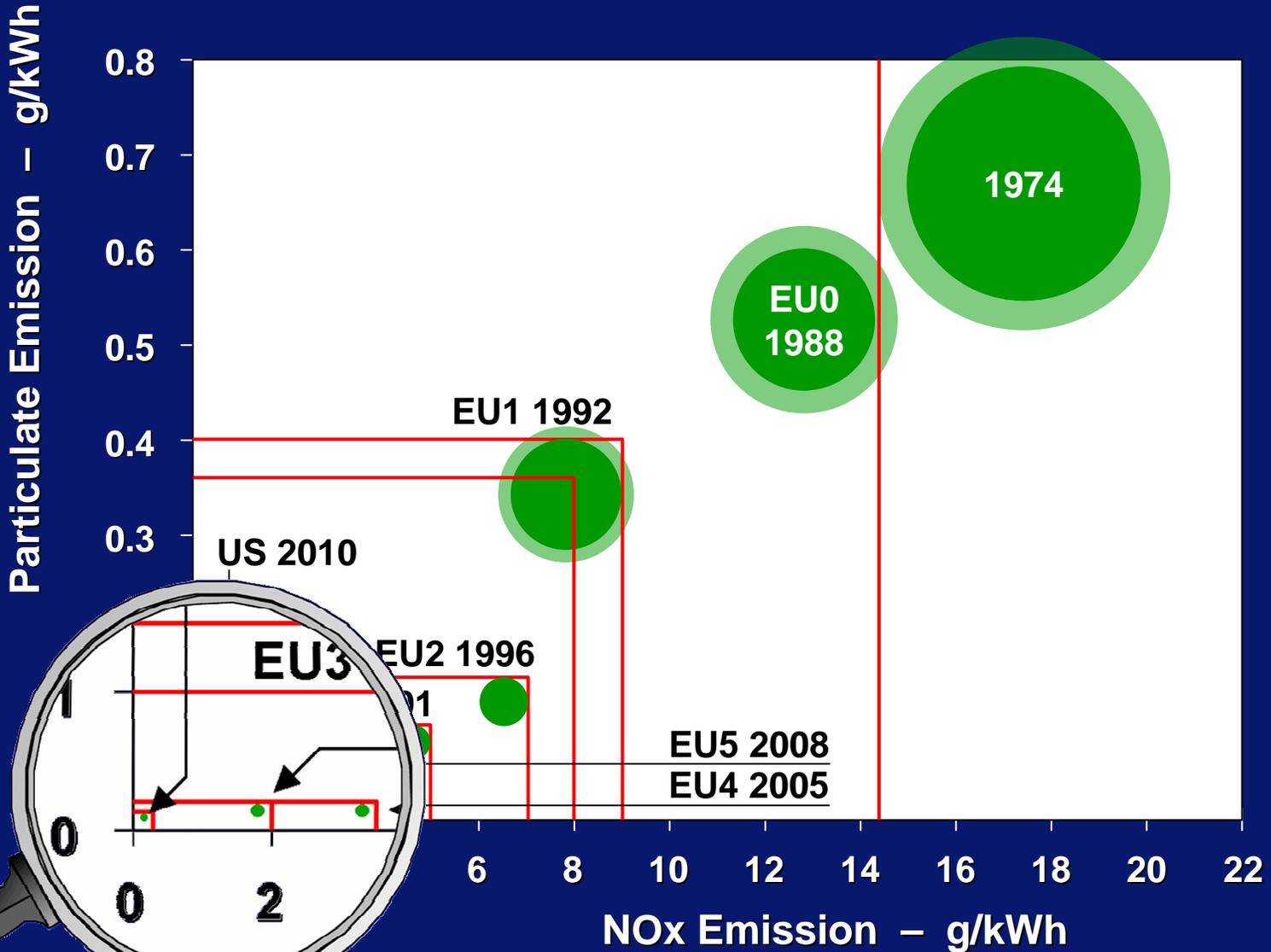
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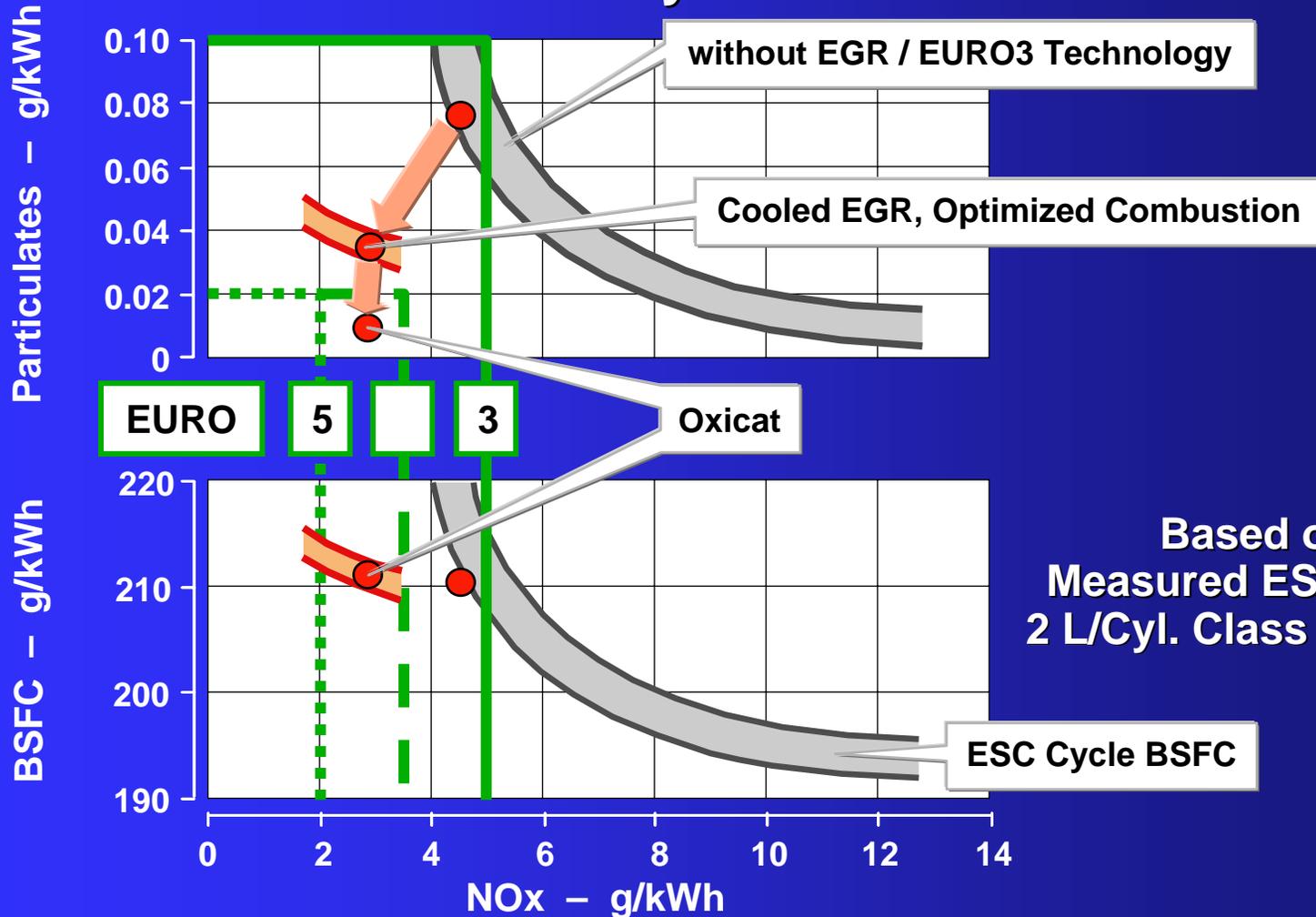


# HD Diesel Engine NOx and PM Emission Development



# Emission Reduction Strategies

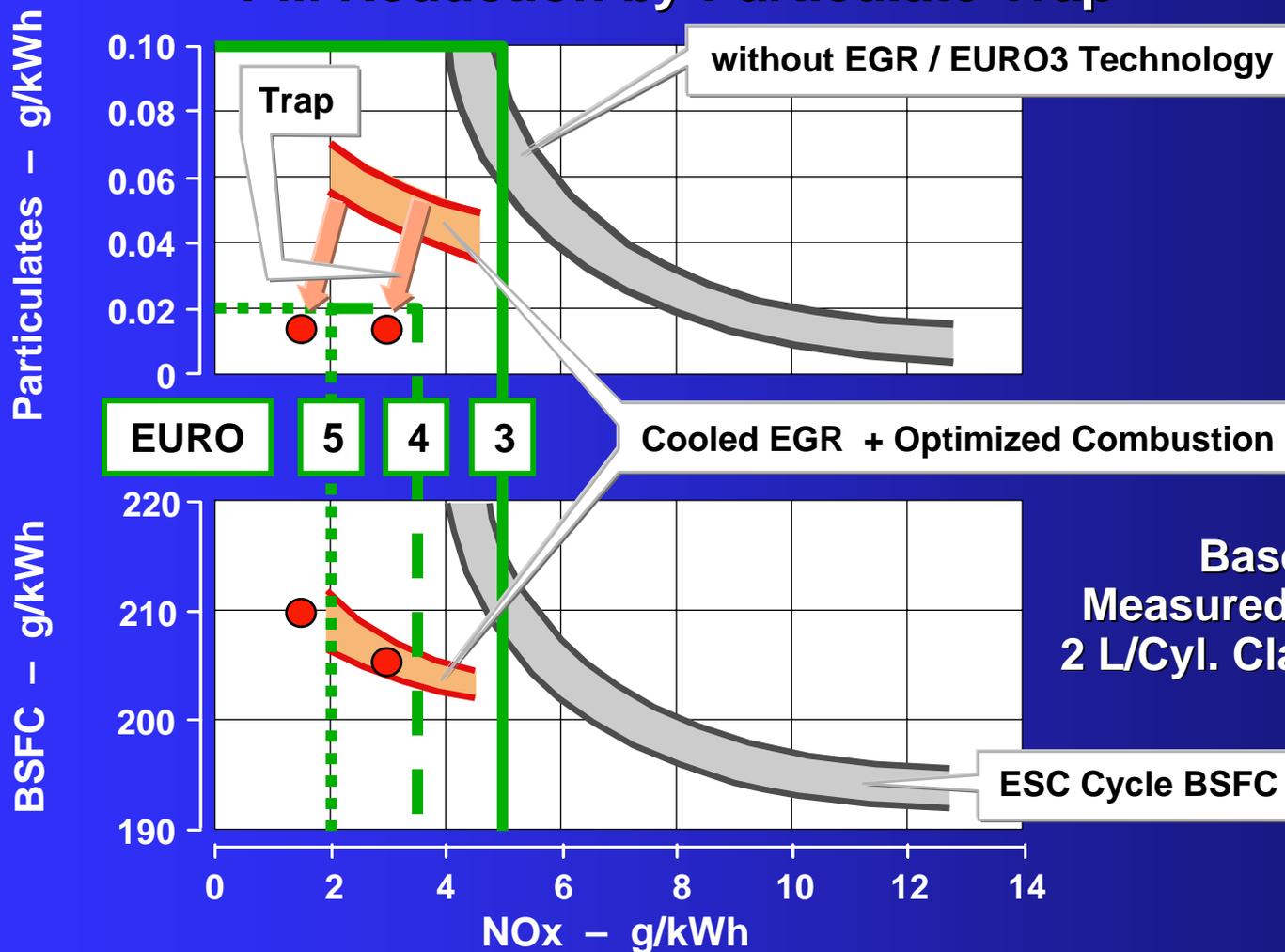
**Strategy 1: - PM Reduction by Engine Int. Measures & Oxicat  
- NOx Reduction by Cooled EGR**



Based on  
Measured ESC Data,  
2 L/Cyl. Class Engines

# Emission Reduction Strategies

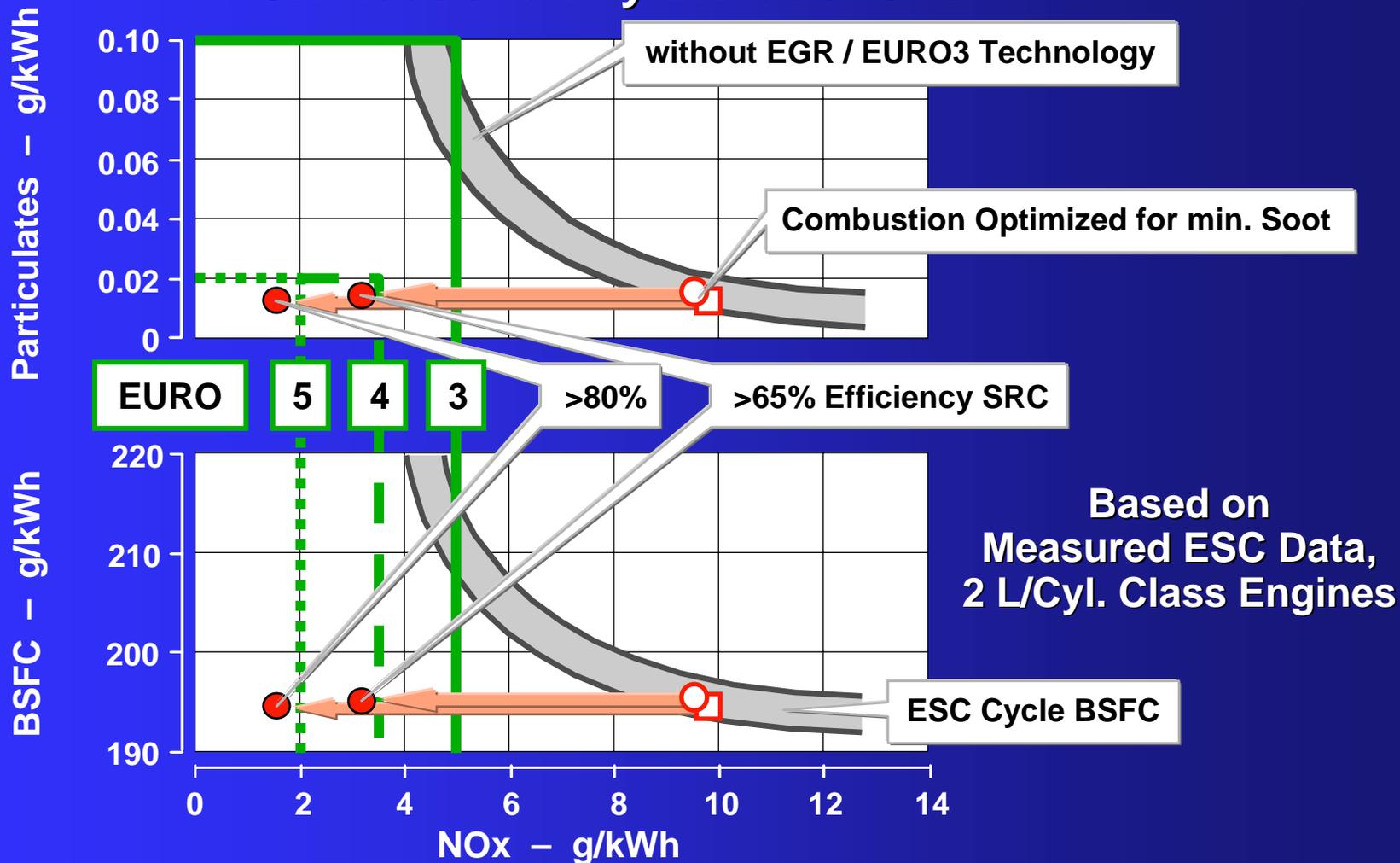
## Strategy 2: - NOx Reduction by Exhaust Gas Recirculation - PM Reduction by Particulate Trap



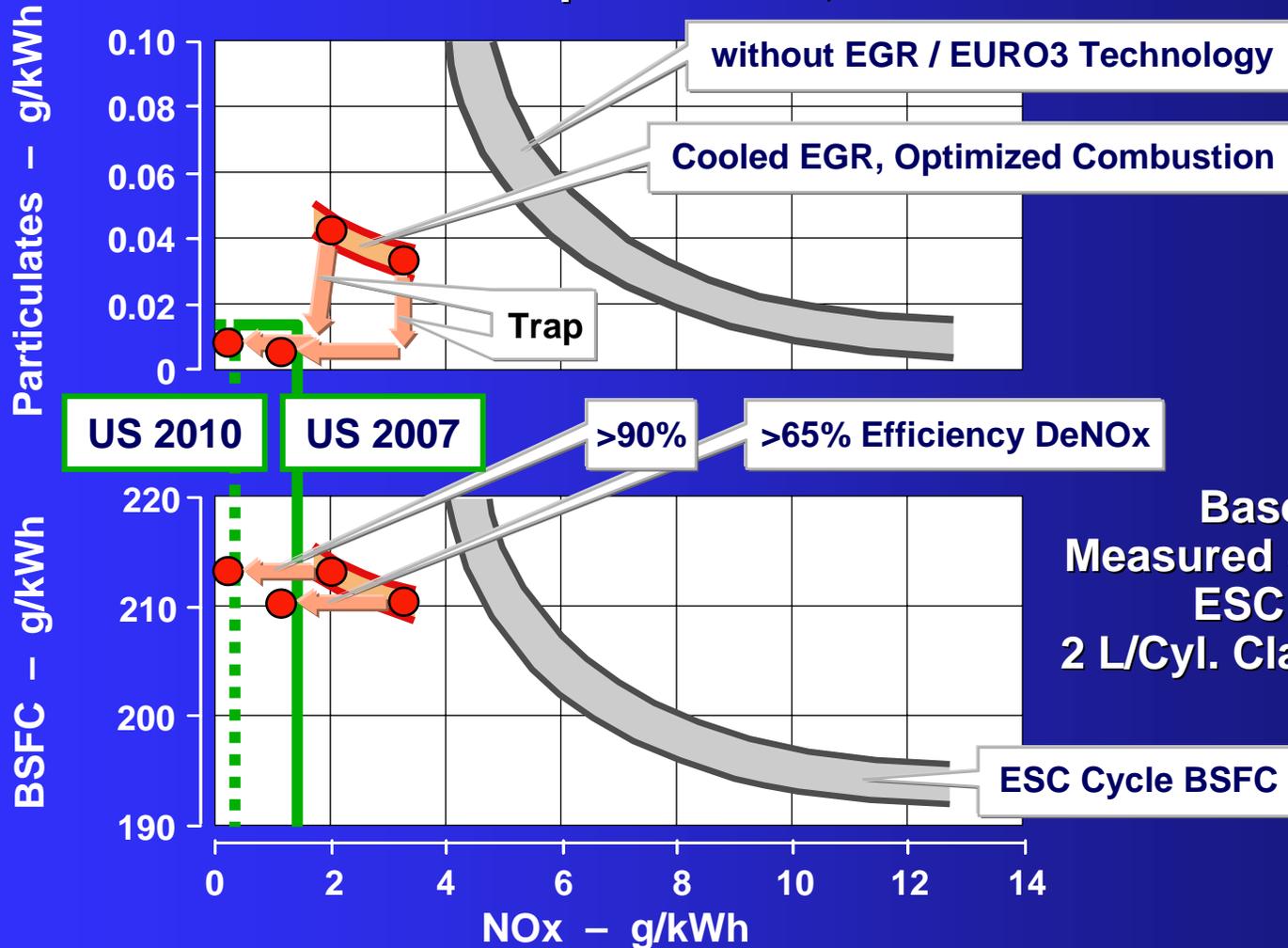
Based on Measured ESC Data, 2 L/Cyl. Class Engines

# Emission Reduction Strategies

## Strategie 3: - PM Reduction by Engine Internal Measures - NOx Reduction by Exhaust Gas Aftertreatment

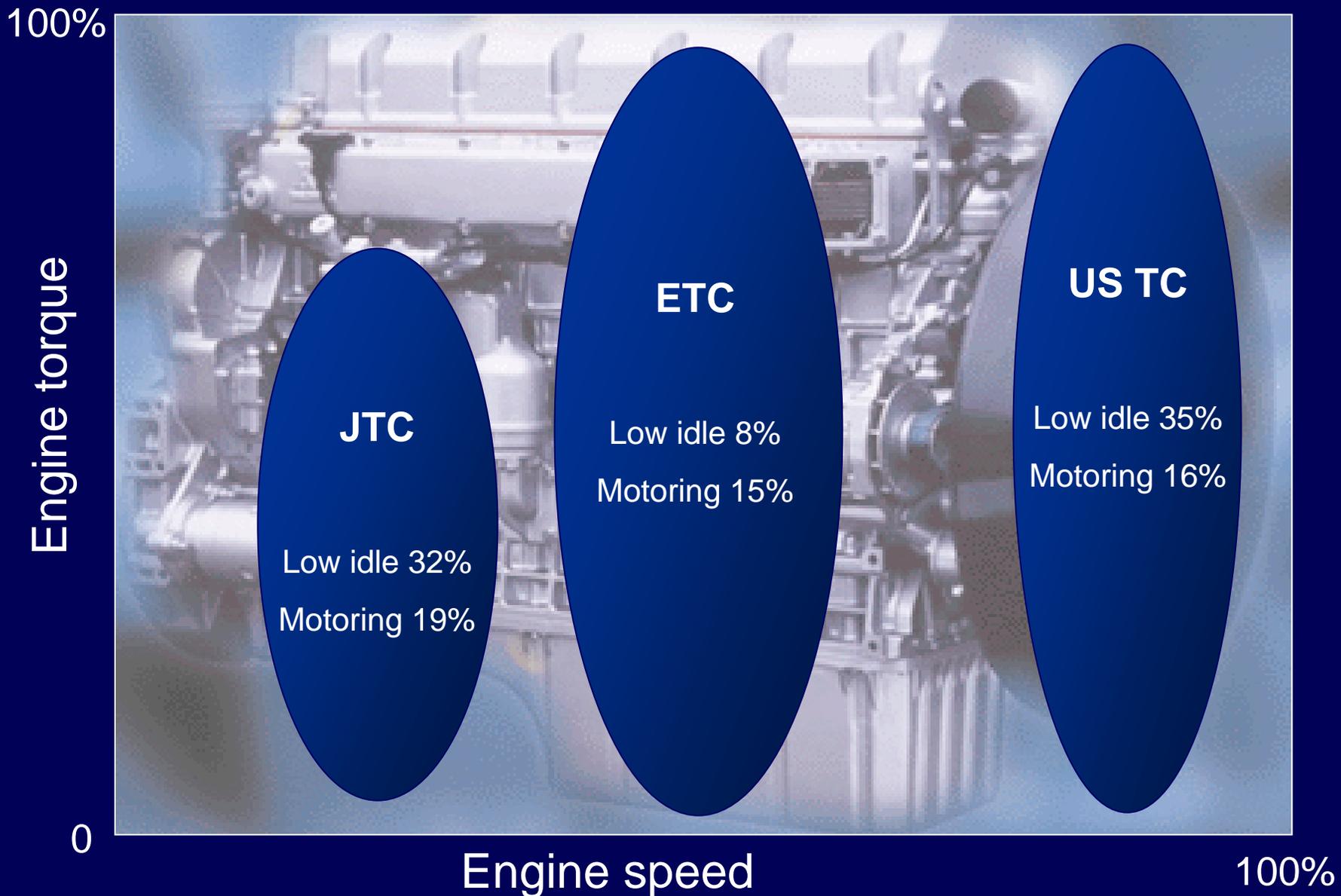


## Strategy 4: - Combination of all Technologies, i.e. Combustion Optimization, DeNOx & PM Aftertreatment



Based on Measured & Projected ESC Data, 2 L/Cyl. Class Engines

# Main Operating Areas in Emission - Cycles USA, Europe, Japan



# **Development Strategies**

**for**

**US 2007 / 2010**

2004

## Boundary Conditions:

- Mechanically sound engine
- Lube oil consumption < 0,1g/kWh
- High performance EGR-system
- Improved cooling system
- 2-stage turbocharging for spec. power > 25-26 kW / ltr
- PfP - potential > 200 bar
- Fully flexible FIS with pressure potential > 2400bar

+

## Combustion system

- high EGR tolerance
- comb. bowl for low soot in oil
- alternative combustion (part load)
- temperature management for EAS

+

Diesel particulate filter



2007

2007

US 2007  
development

+

De-NOx system  
development  
and  
integration

2010

# HDDE Development Strategies for US 2007



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Route 1

2004

Route 2

## Boundary Conditions:

- Mechanically sound Engine
- Lube oil consumption < 0,1g/KWh
- High performance EGR-system
- Improved cooling system
- 2-stage turbocharging > 25-27 kW/l
- PfP - potential > 200 bar
- Fully flexible FIS, press. potential > 2000bar

## Boundary Conditions:

- Mechanically restricted engine design
- lube oil consumption > 0,1g/kWh
- PfP - potential < 170 bar
- Limited FIS , press. potential < 1600bar

+

+

- Highly EGR-tolerant comb. system
- Comb. bowl for low soot in oil
- Alternative combustion (part load)
- Temperature management for EAS

- Combustion system with **no (or low) EGR tolerance**
- Comb. bowl for low soot in oil
- **Alternative combustion (part load)**
- **Temperature management for EAS**

+

+

Diesel particulate filter

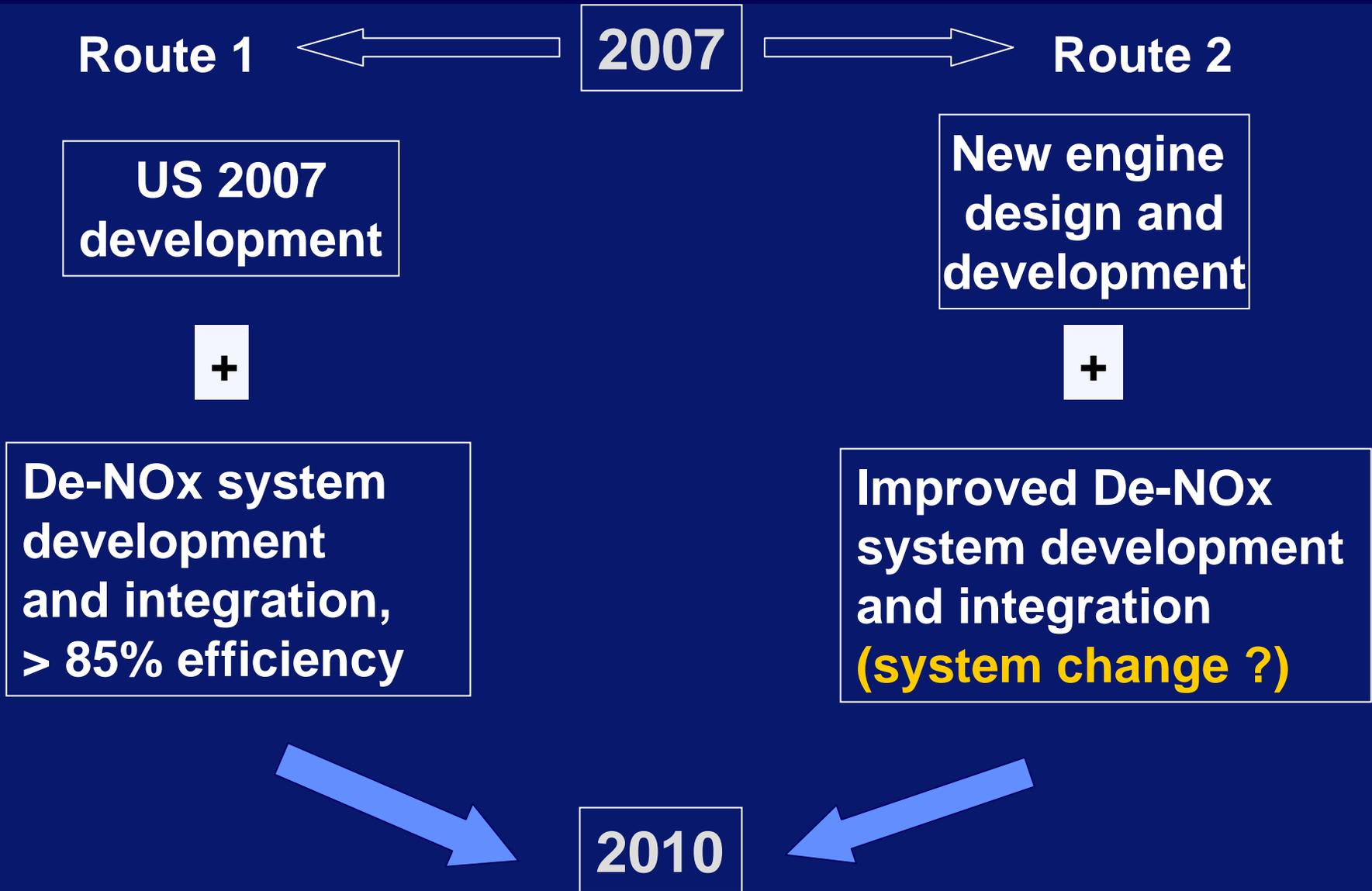
2007

**De-NOx system** and **Diesel particulate filter**

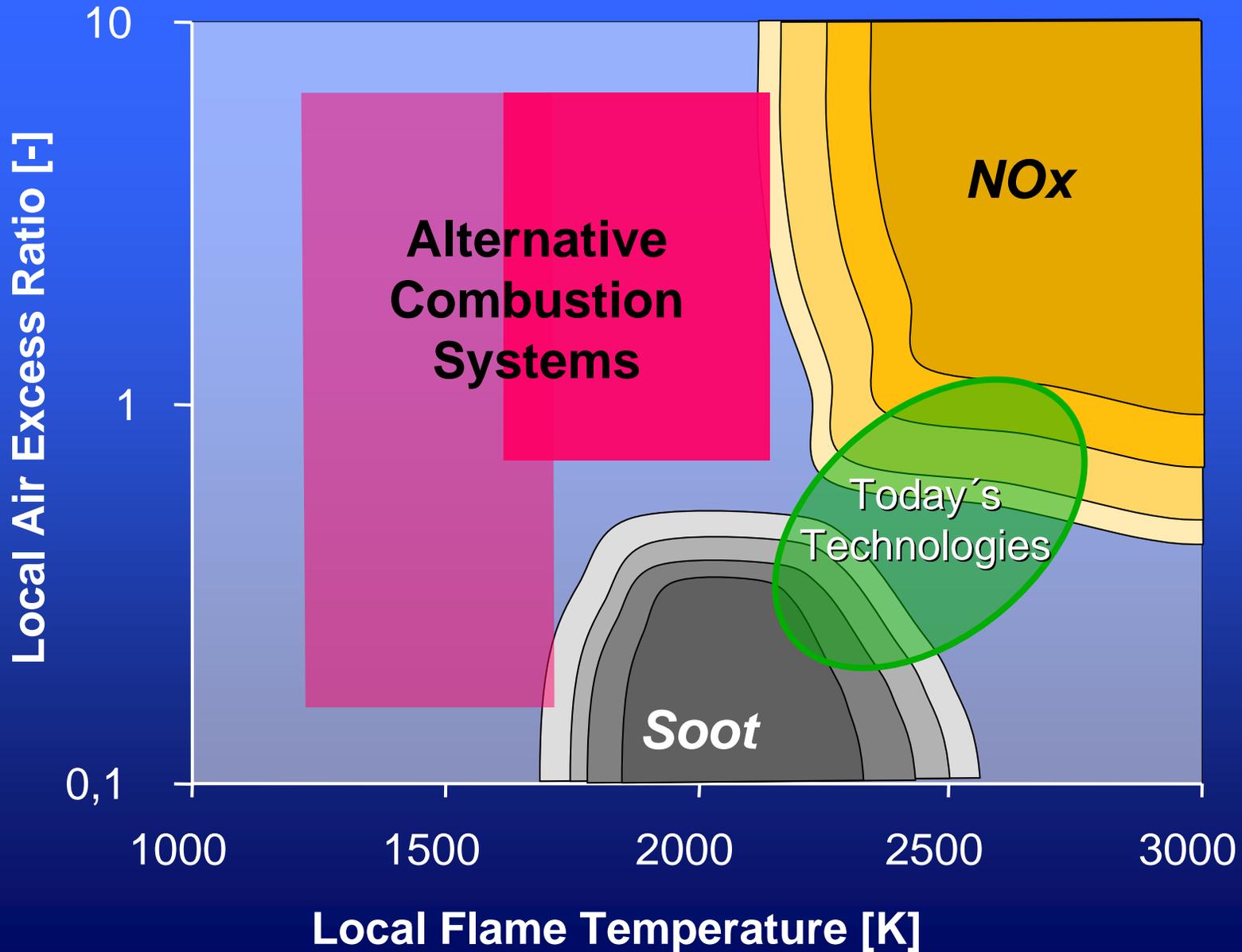
# Development Strategies for US 2010



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# Diesel Combustion Systems for Low NOx / Soot Emission



# NEDC Simulation with Alternative Combustion



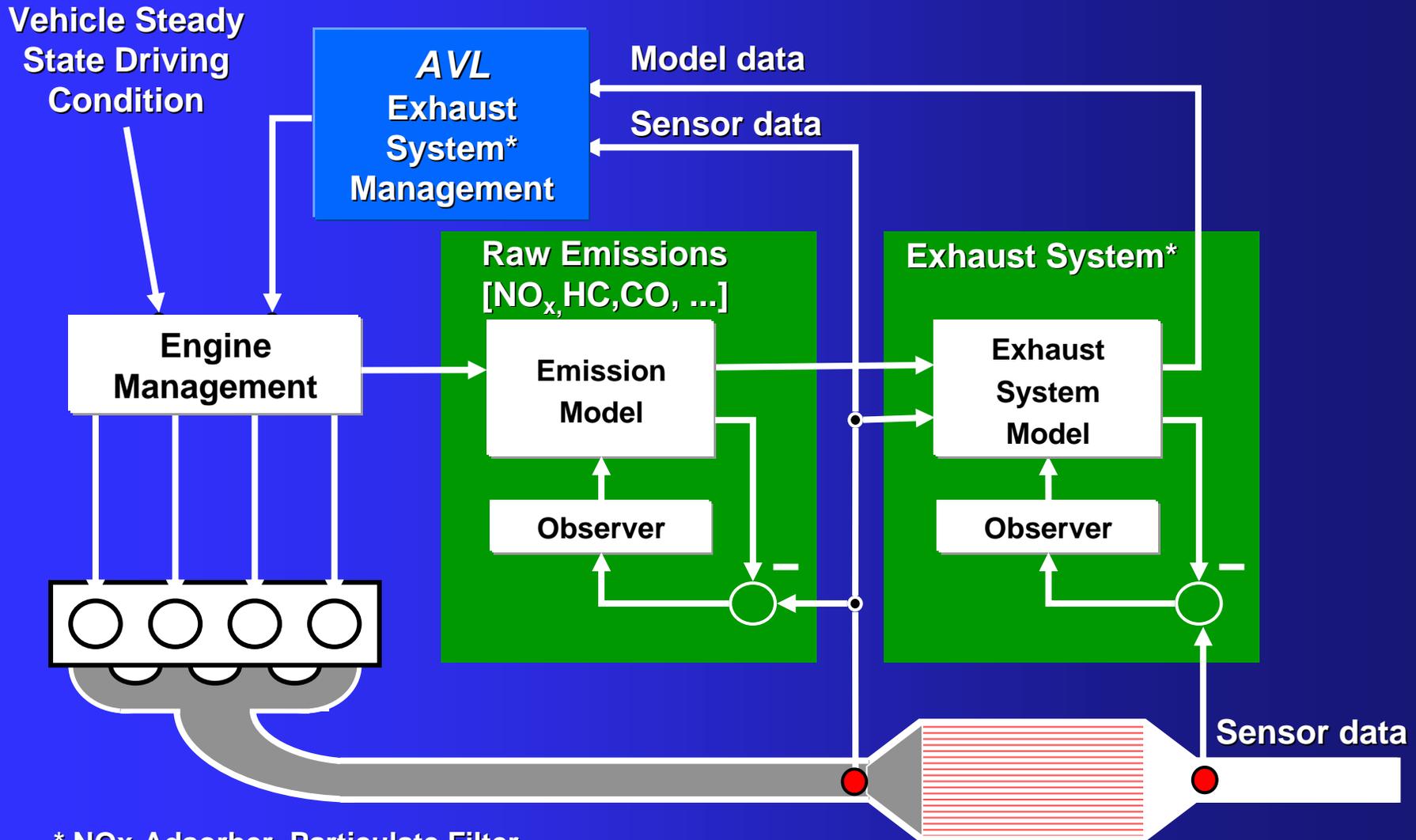
Commercial Powertrain Systems

NEDC Simulation - 2,2 L HSDI Diesel Engine in 1590 kg ITW Vehicle.

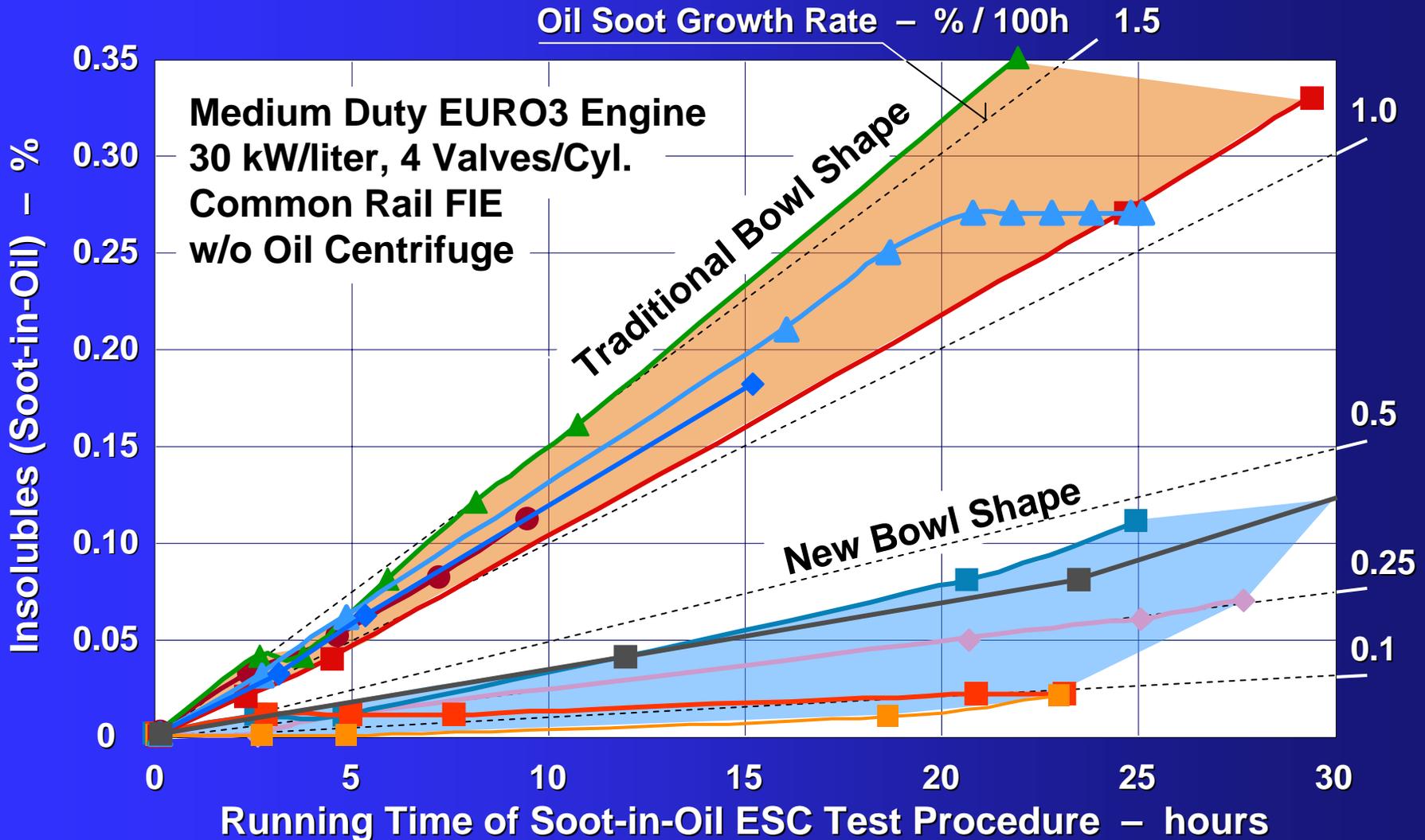
	NOx Reduction		Soot Reduction	
	g/km	%	g/km	%
Standard Combustion	0,230	-	0,020	-
<b>Combined Standard &amp; Alternative Combustion</b>	<b>0,093</b>	<b>60</b>	<b>0,006</b>	<b>70</b>

*Simulation based on Single Cylinder Test Results*

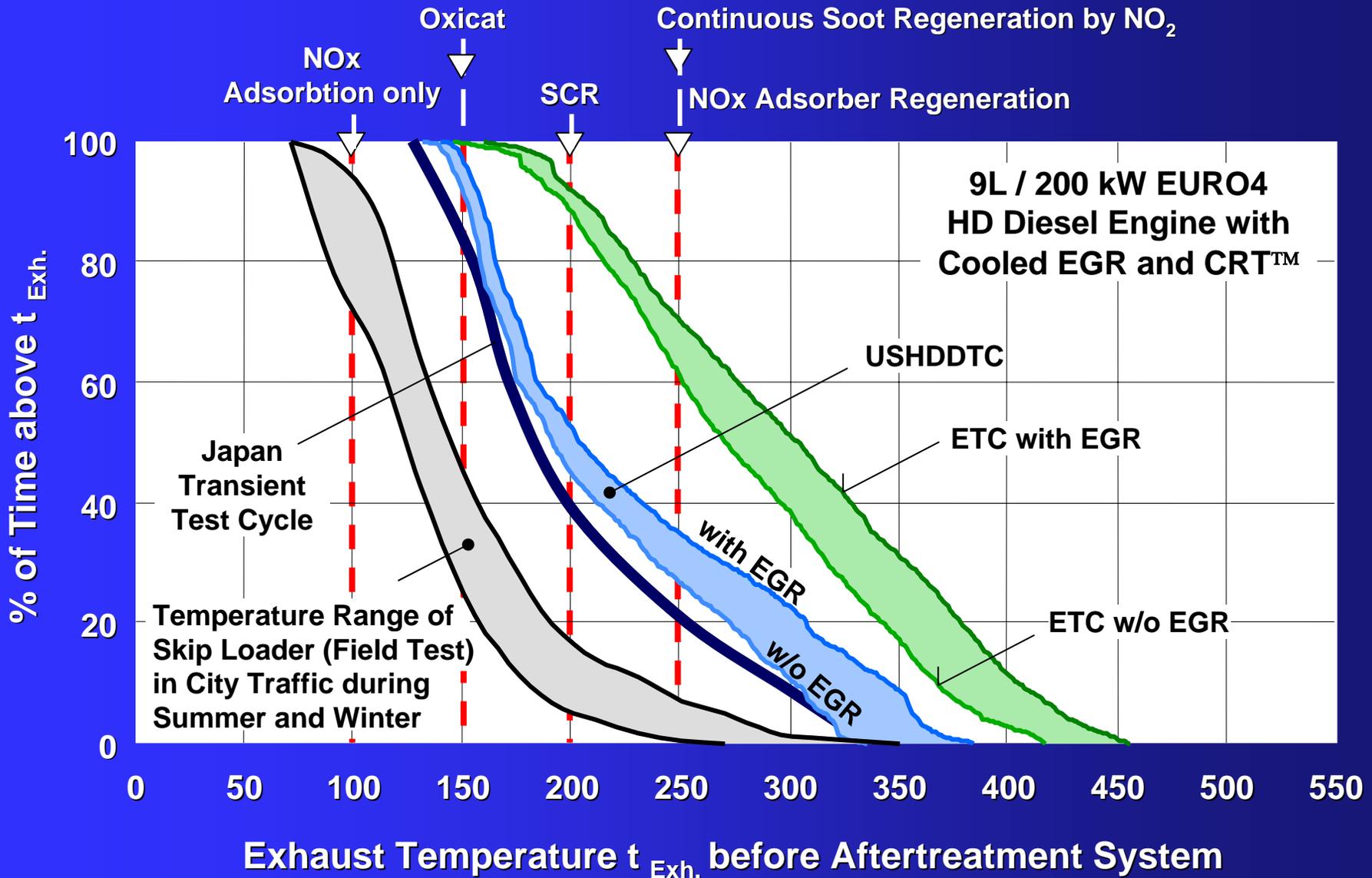
# Model-based Exhaust Emission Control



# Solving the Soot-In-Oil Problem: Effect of Combustion Bowl Shape

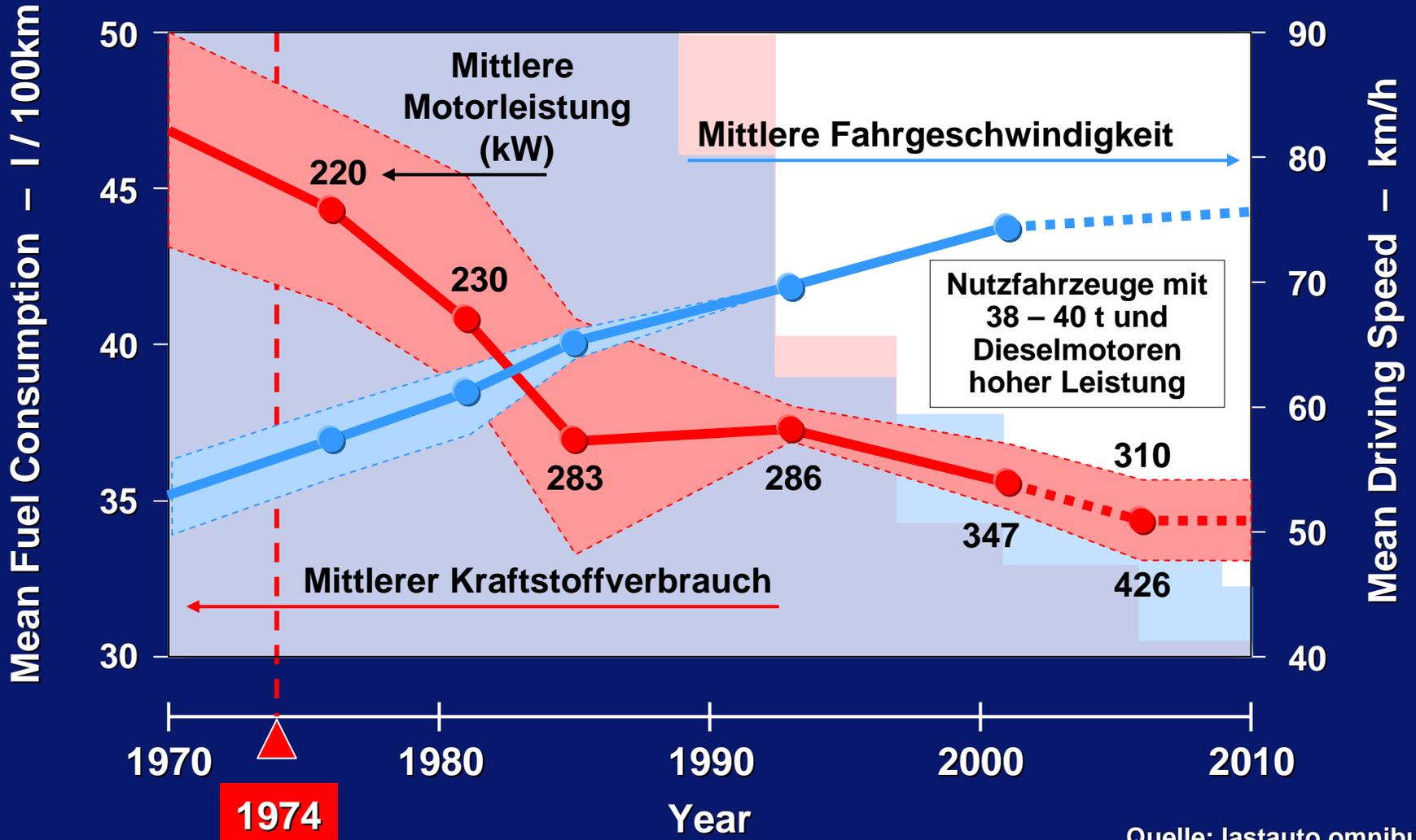


# Exh. Temperatures in Test Cycles and Aftertreatment Dependencies



# HD Diesel Technologies 1974 – 2010

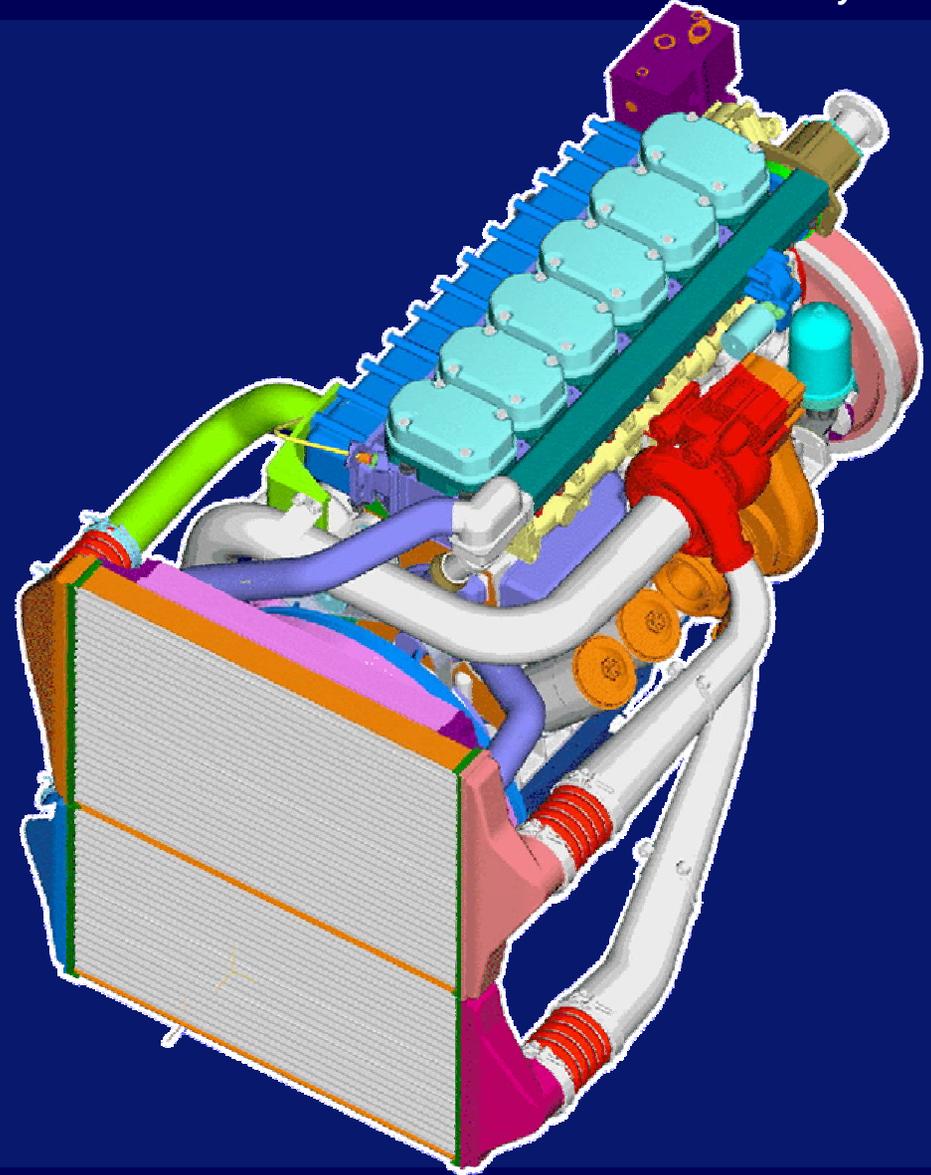
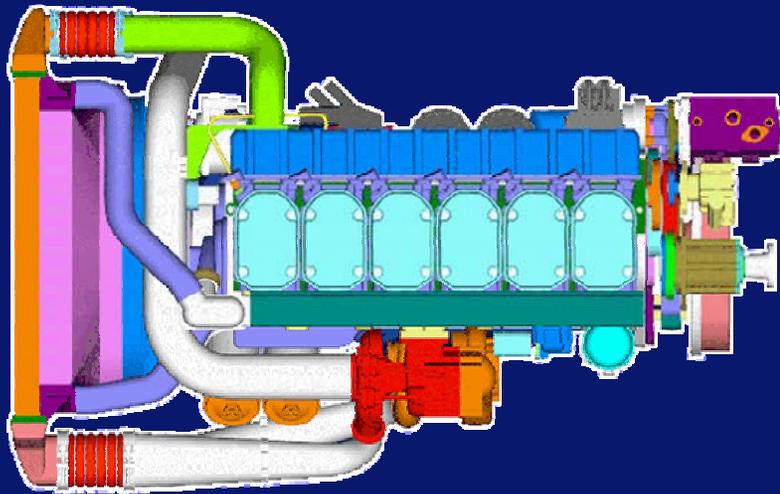
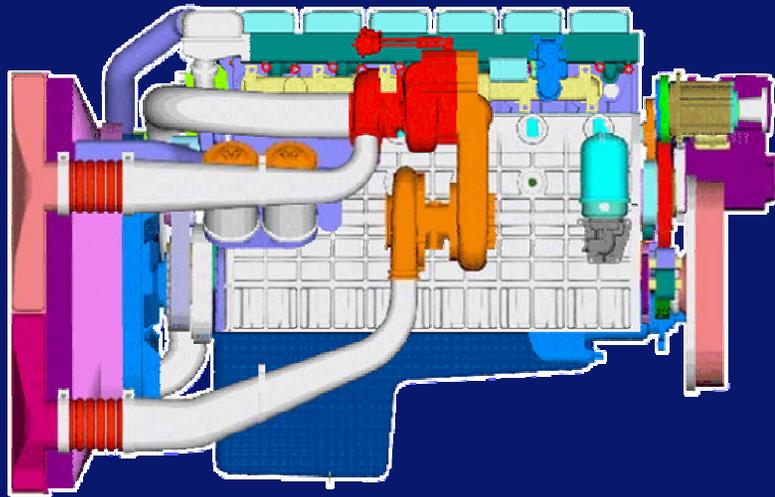
## Truck Fuel Consumption and Speed



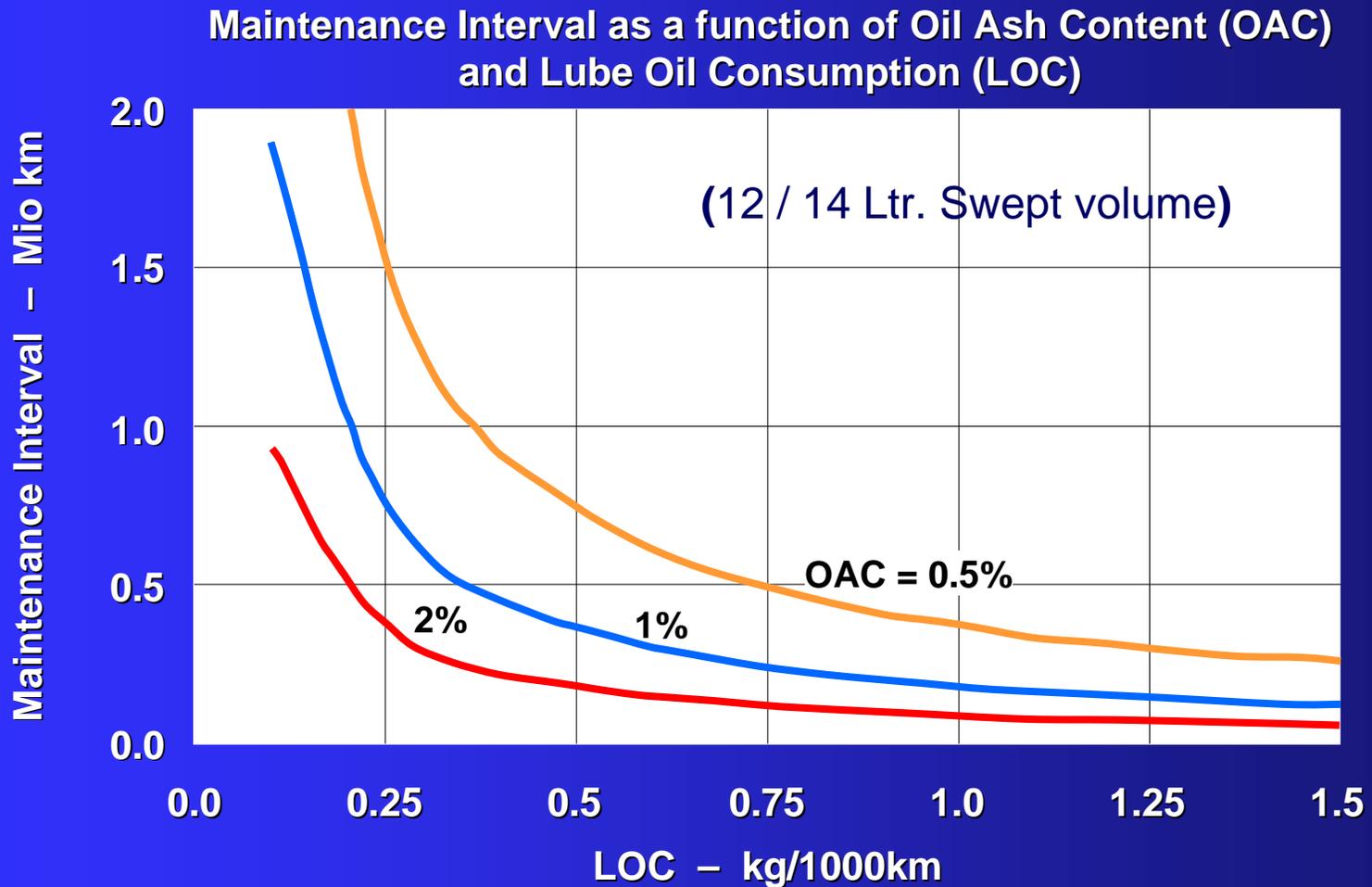
# „Future Truck Diesel Engine“ 2-Stage Turbocharging Design

**AVL**

Commercial Powertrain Systems



# Lube-Oil Ash Deposits and DPF Maintenance Intervals



Filter Volume 25 Liter; Max. Acceptable Ash Content 75g / Liter Filter Volume

# Flow Through Non-Blocking PM-Catalyst

Test A

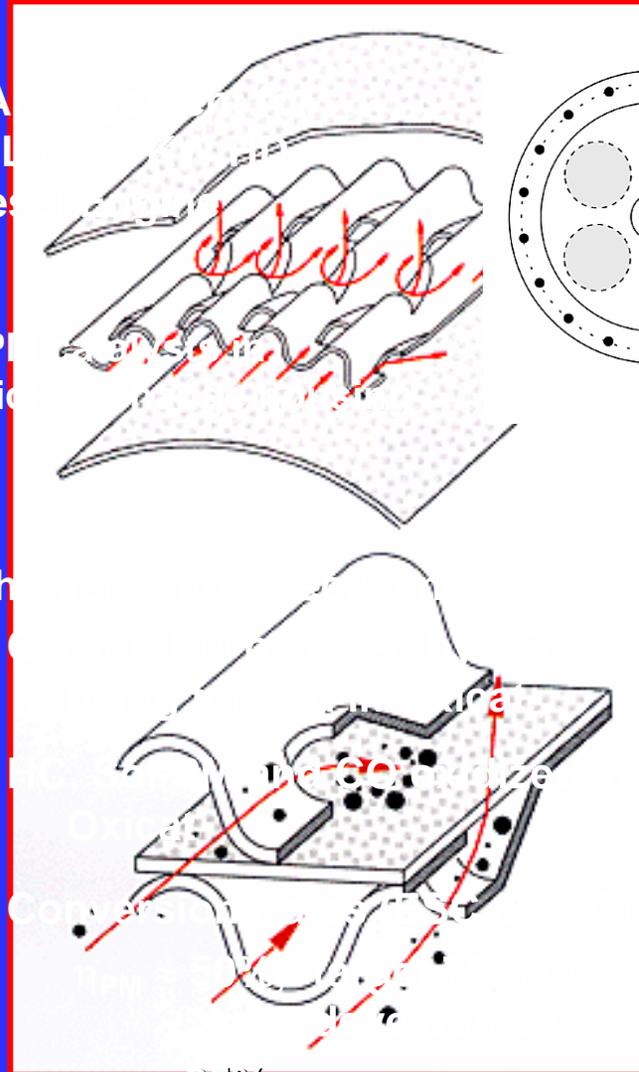
6.6L

Dies

5 P

quic

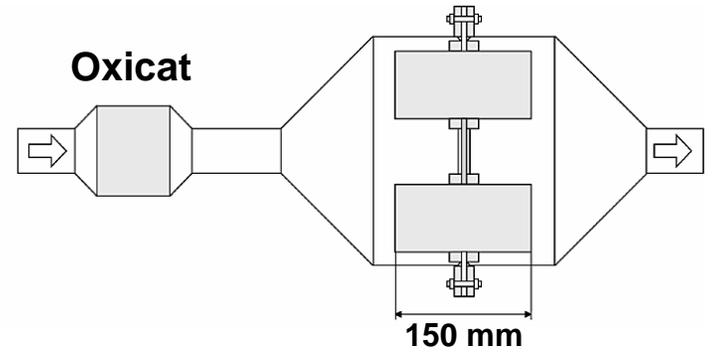
Mech



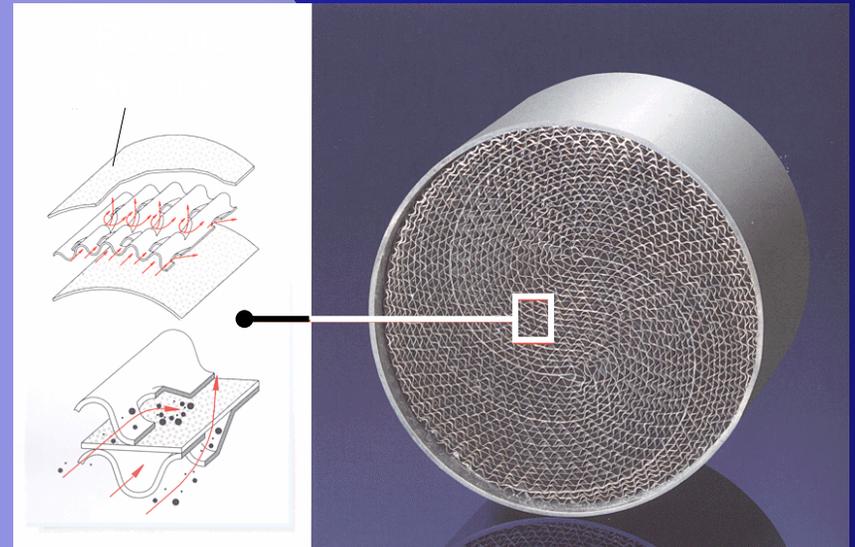
$\eta_{HC} \approx 85\%$

$\eta_{CO} \approx 90\%$

Oxicat



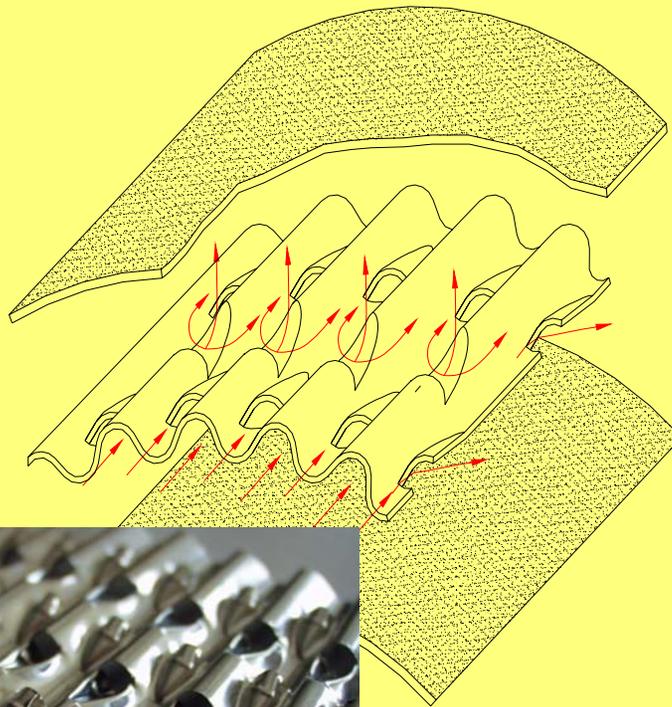
- Principle of Particle Deposition in Porous Smooth Section of Mixing Section



Source: Emitec GmbH & MAN Nutzfahrzeuge AG

# Principle of Particle Depositing in a Porous Flat Foil of the Mixing Section

## Structure with porous flat foils



## Trapping of particles passing the porous foil

