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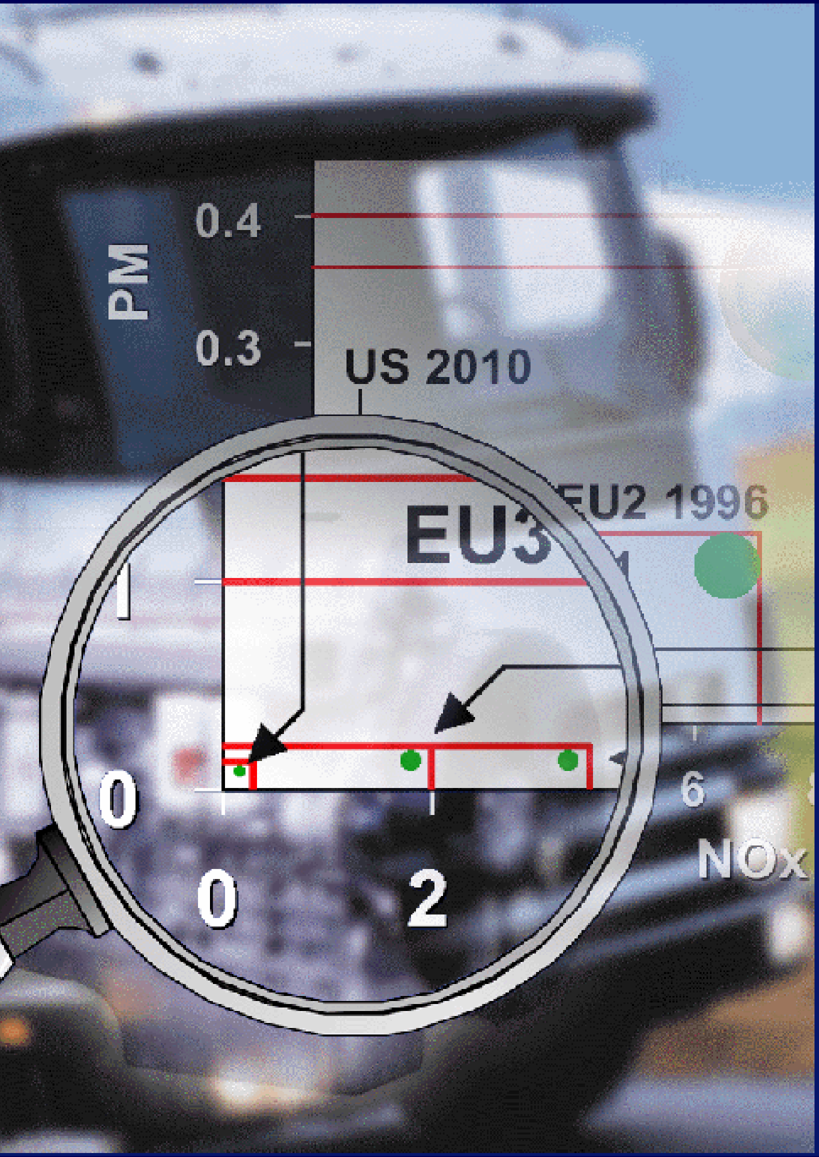

Lowest Engine-Out Emissions as the Key to the Future of the Heavy Duty Diesel Engine - New Development Results

Franz X. Moser

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AVL LIST GmbH, Austria

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

Content

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

- Introduction
- **Engine-Out Emissions Required for Various Emission Standards**
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Future Exhaust Emission Standards and Required Raw Emissions

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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]
PM	0.03	30 *)	0.04
NOx	3.5	70 (SCR)	9.0

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

Two Routes for Realising Various Low Emission Scenarios

- **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

- 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**
- Requirements on EGR Rate Control
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Concepts for NOx = 4 - 5 g/kWh Raw Emission and (assumed) Legal Limit 1.0 g/kWh

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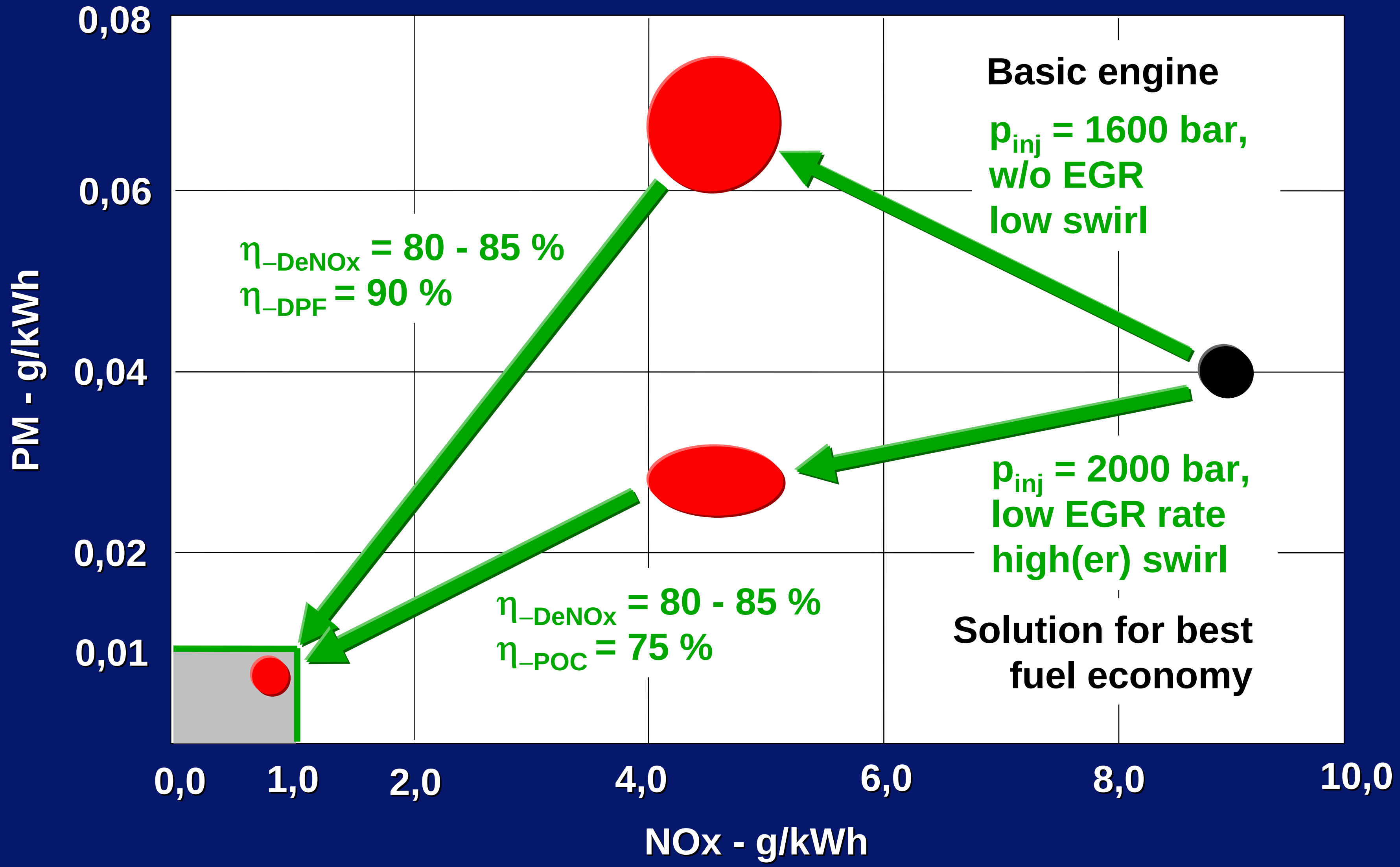

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- Introduction
- Engine-Out Emissions Required for Various Emission Standards
- **Concept for 1 - 2 g/kWh NOx Raw Emissions**
- Requirements on EGR Rate Control
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Relationship between EGR Rate, Injection Pressure and NOx / Soot Emissions

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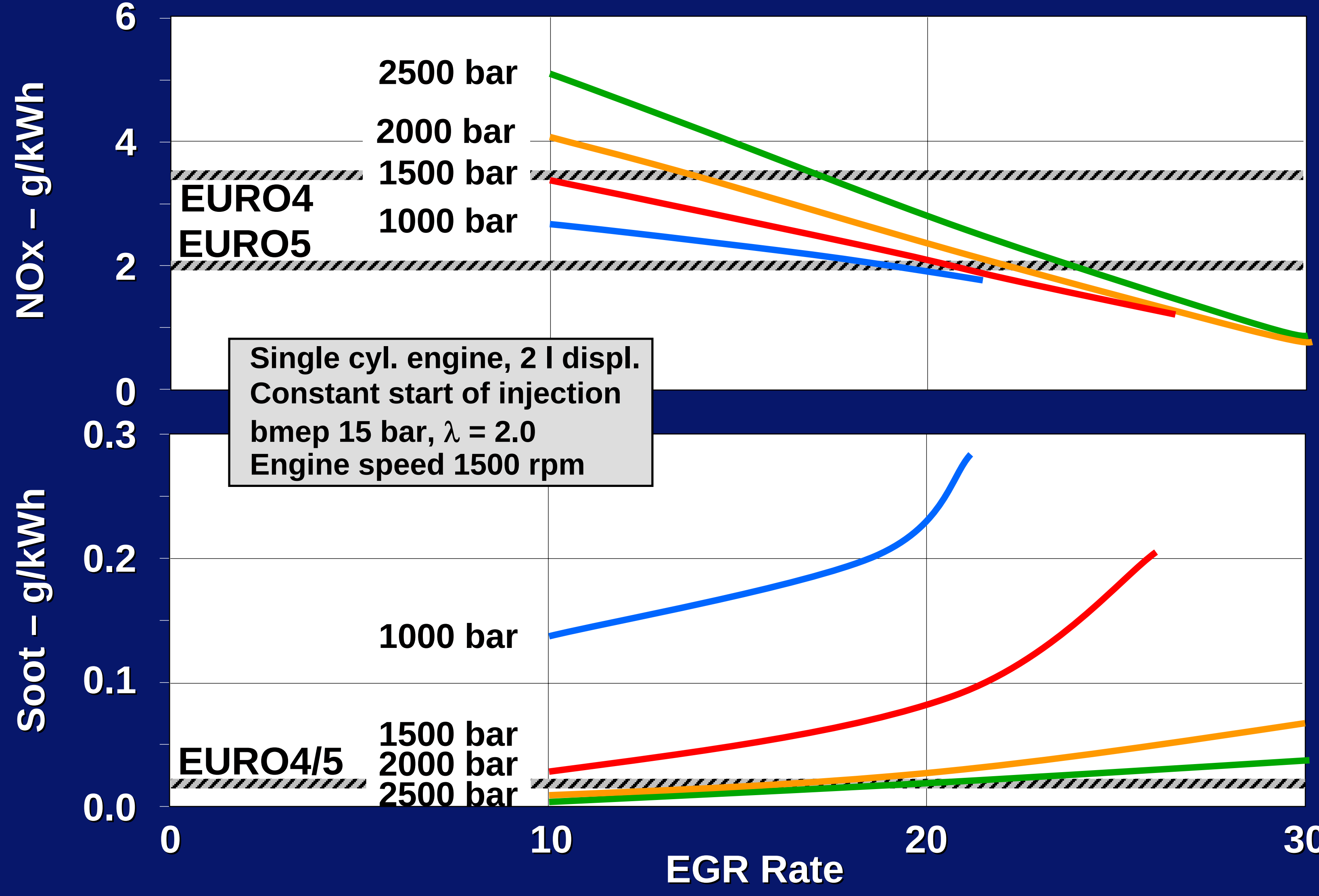

Latest Development Results for Lowest Soot and NOx Engine-Out Emissions

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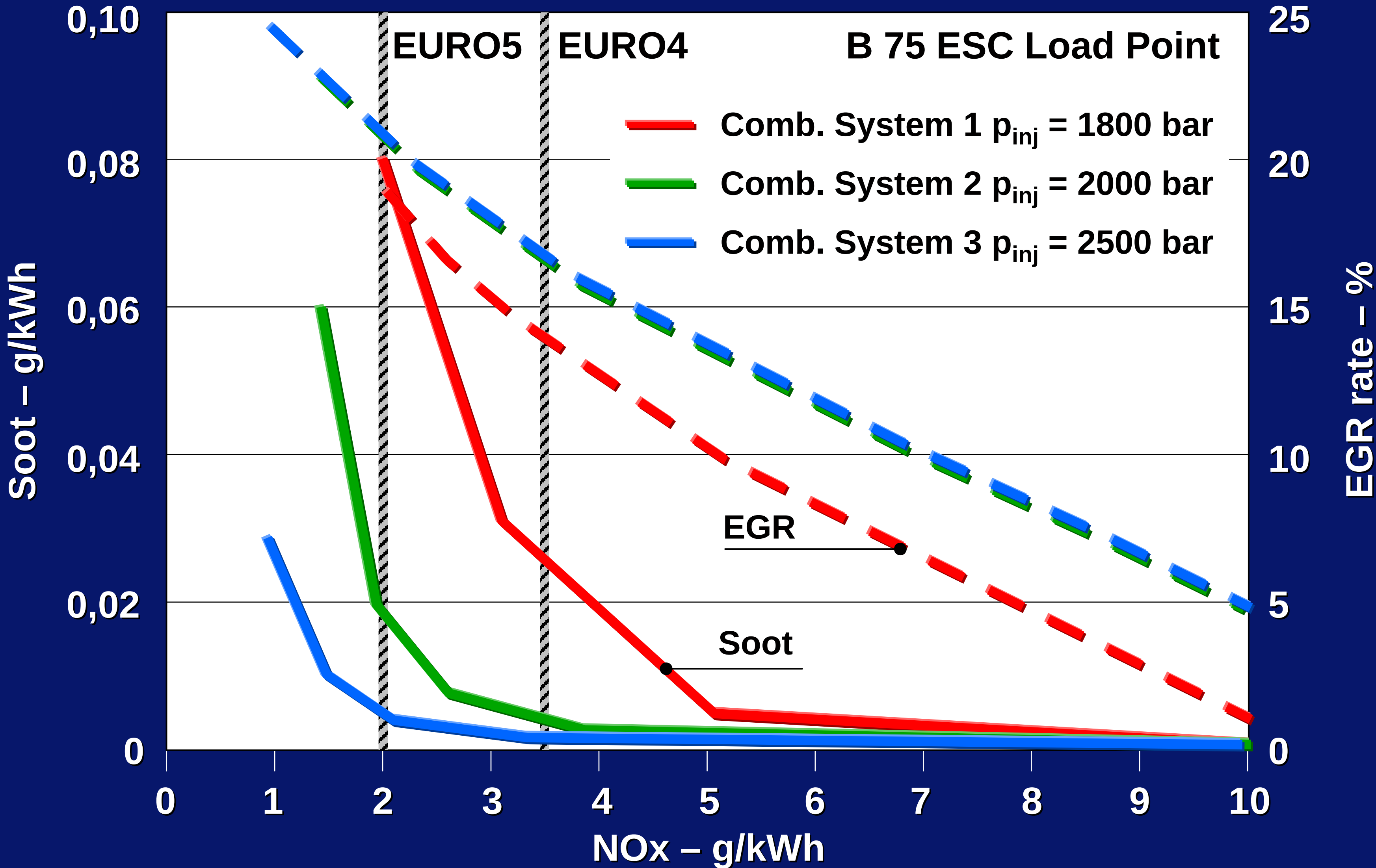

EGR-Rate Demand for 1,0 g/kWh NOx and Min. Soot (engine-out)

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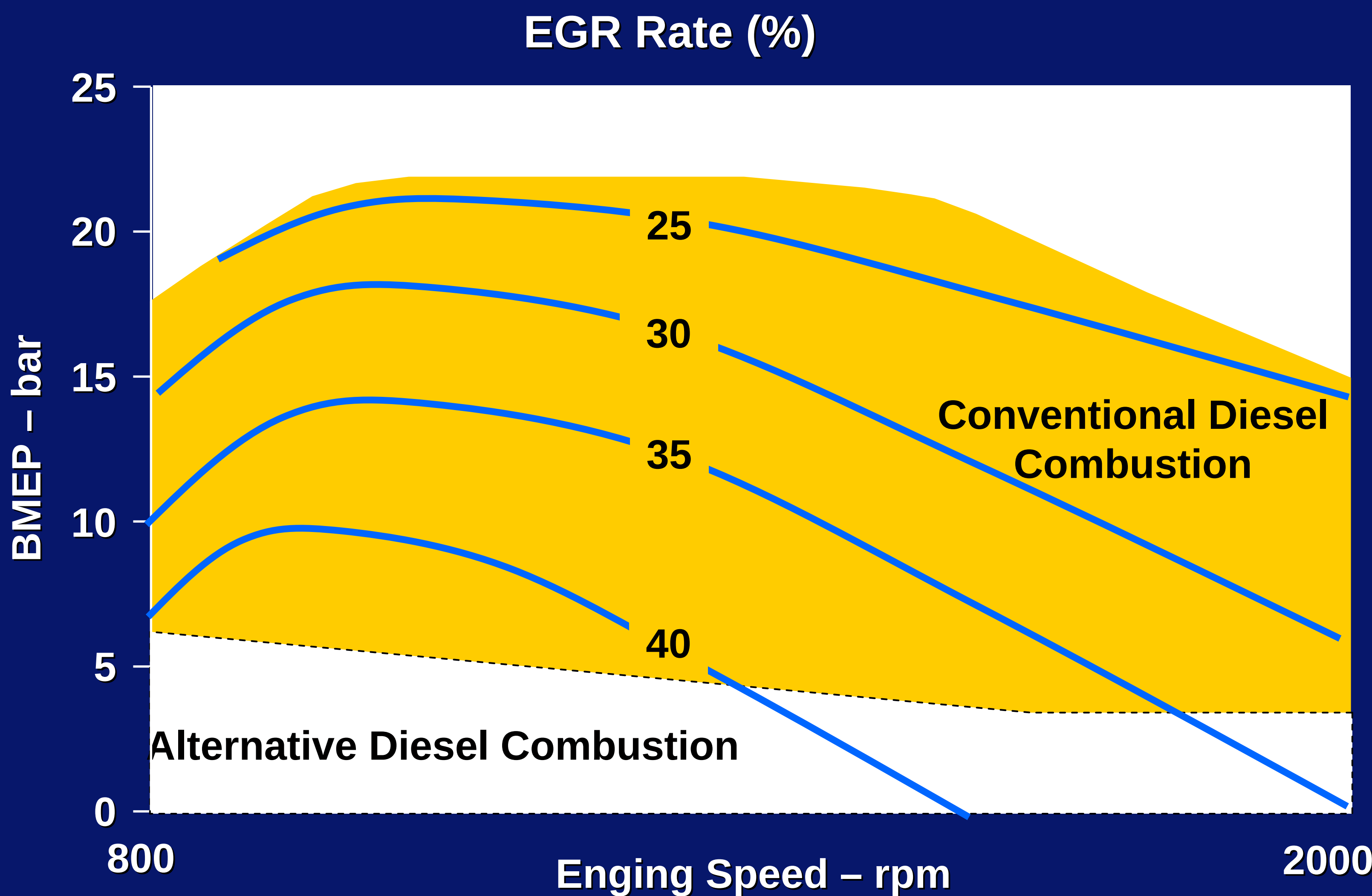

Boost Pressure Demand Depending on EGR Rate and Turbocharger Efficiency

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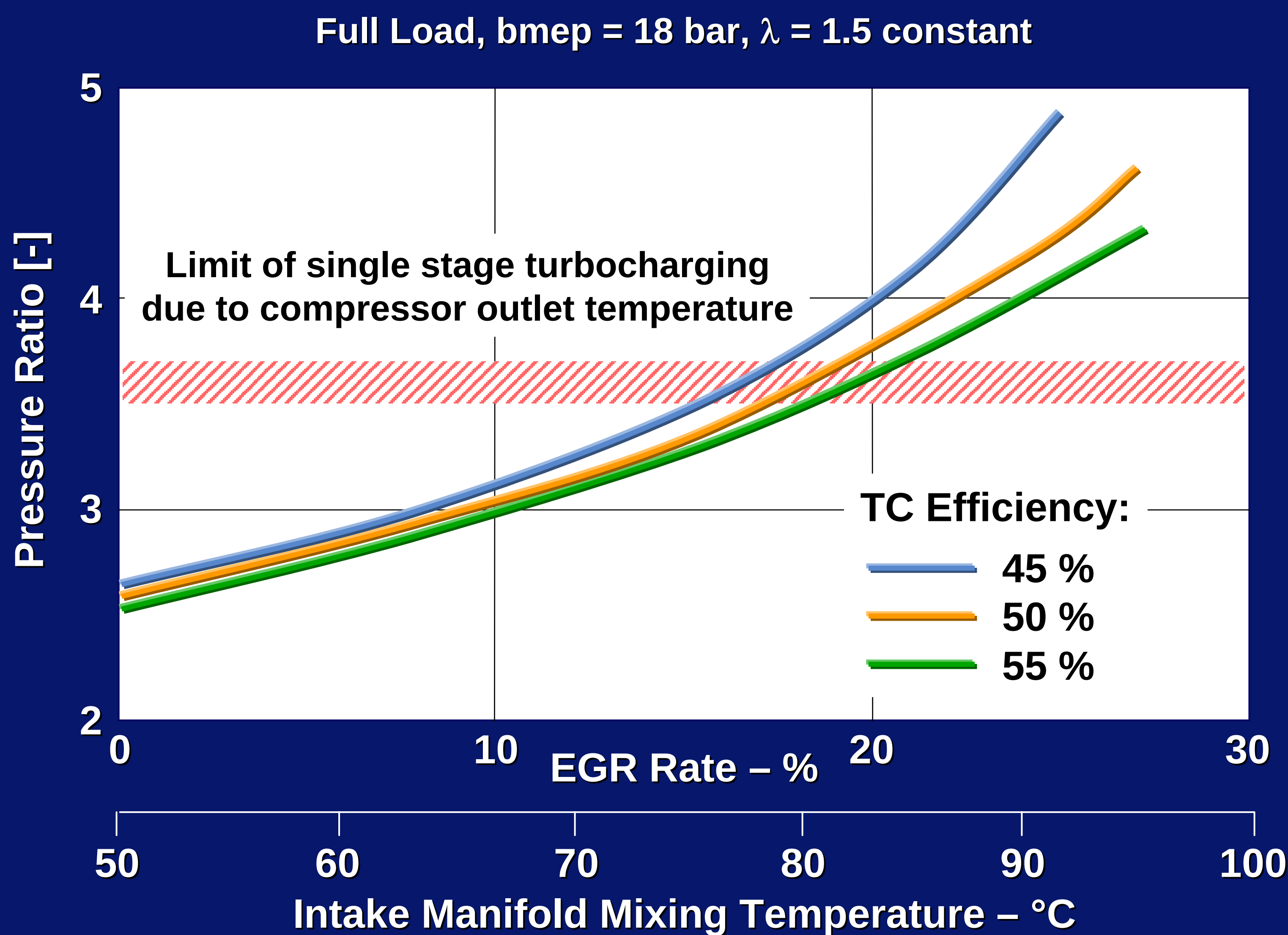
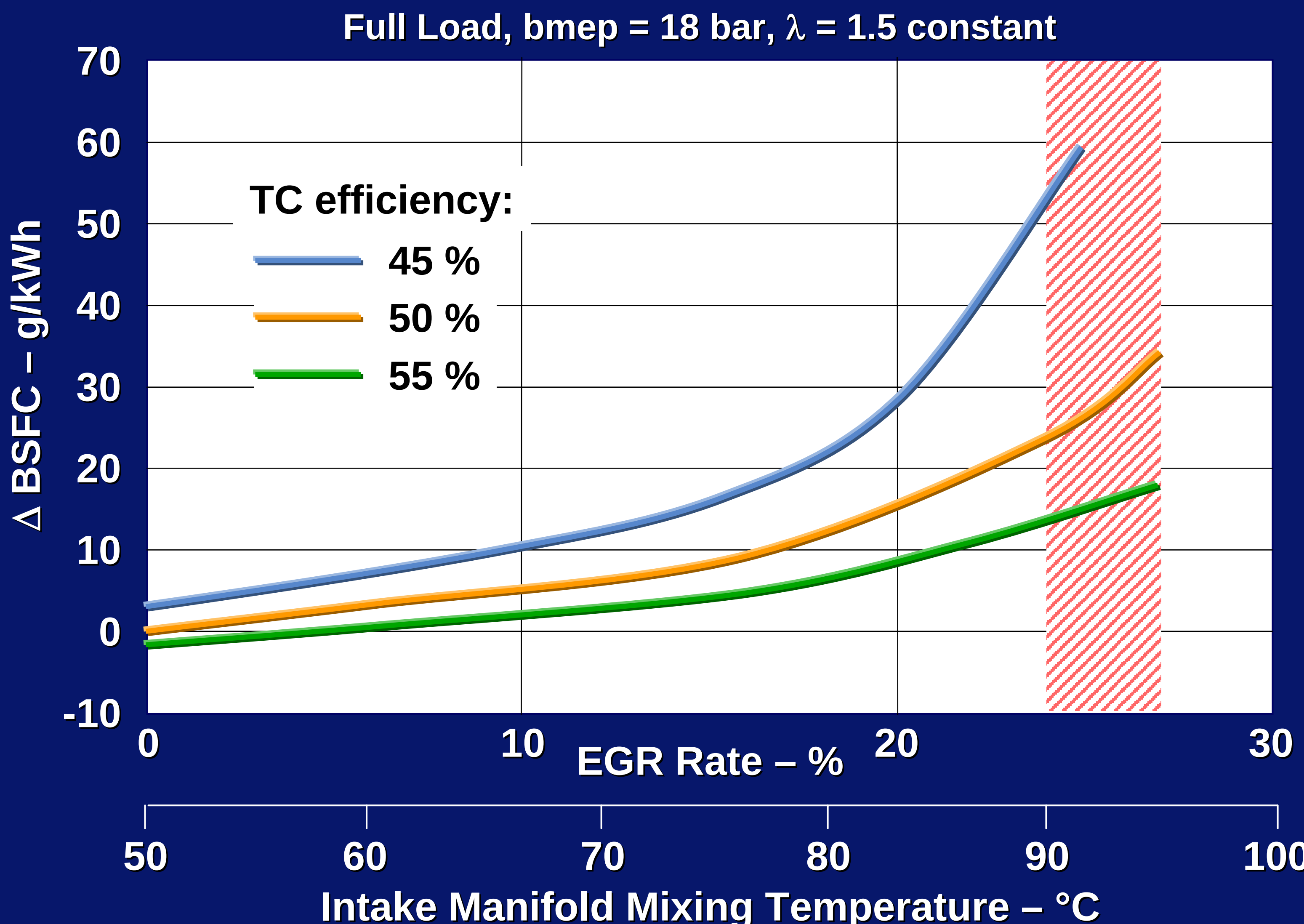


Effect of EGR Rate and Turbocharger Efficiency on Fuel Consumption



Effect of EGR Rate on Heat Rejection

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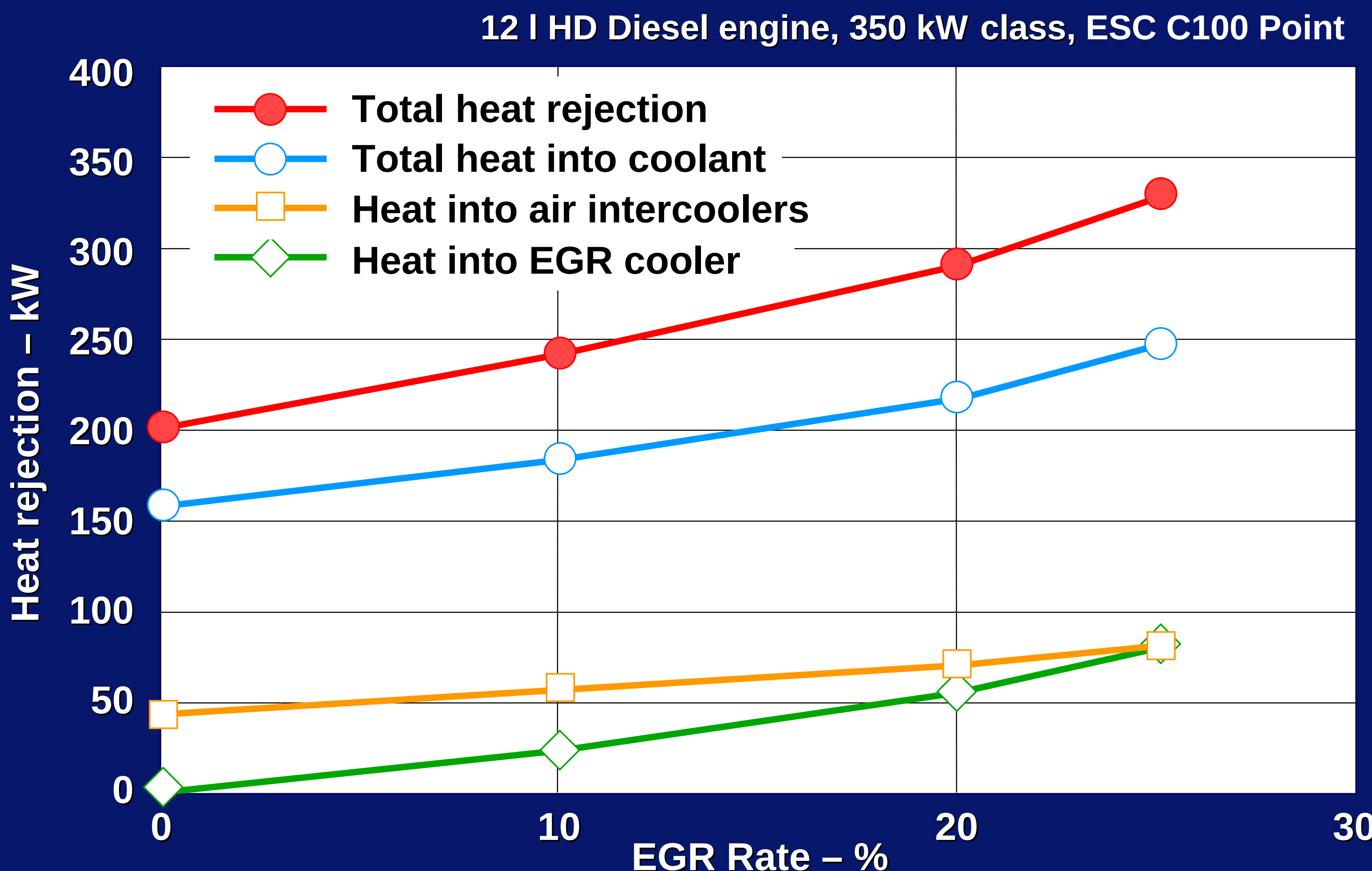

Concepts for NOx = 1- 2 g/kWh Raw Emission and Legal Limit 0.27 g/kWh

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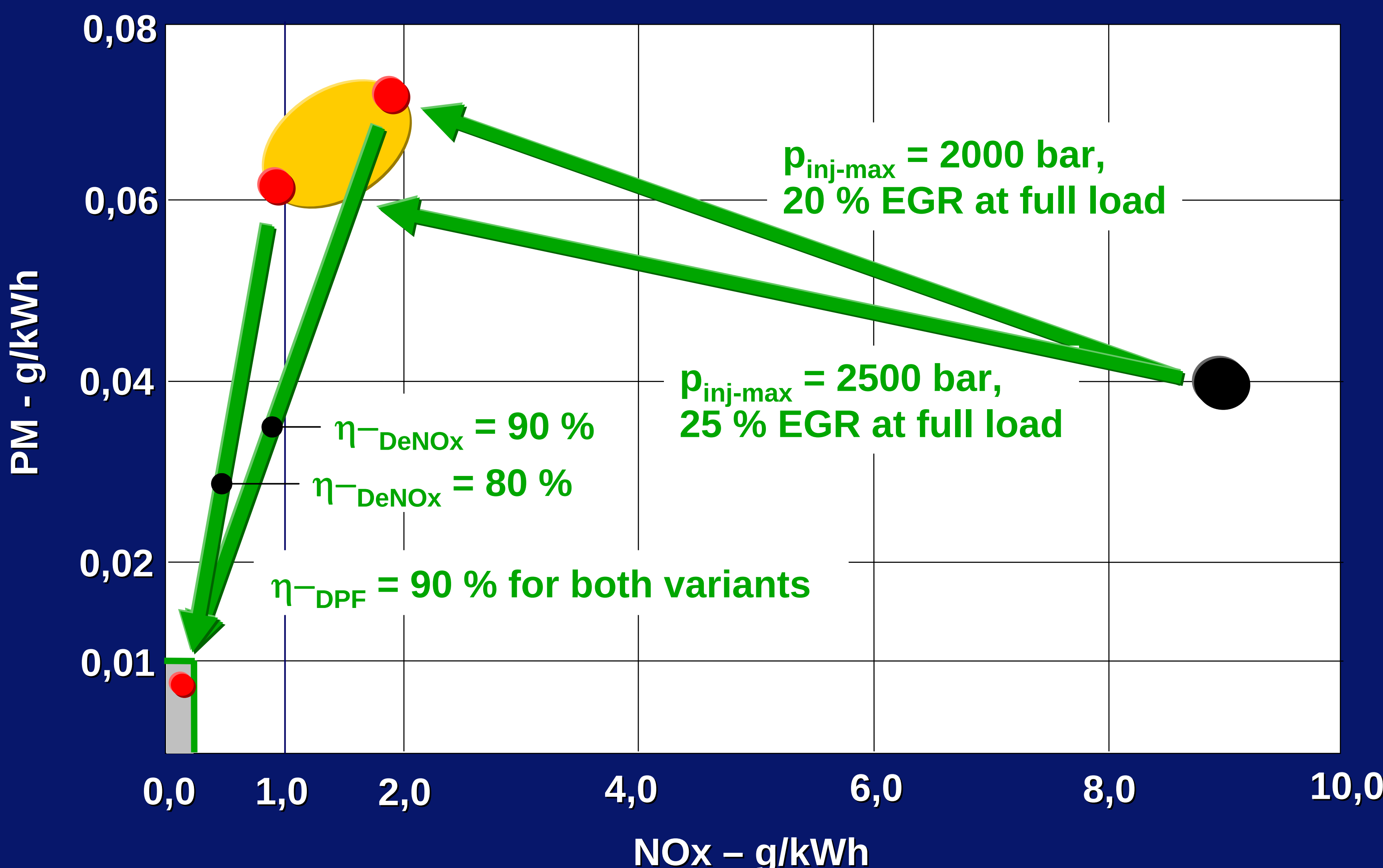

Requirements on EGR Rate Control

- Introduction
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Absolute and Relative Effect of EGR Rate on NOx Emissions

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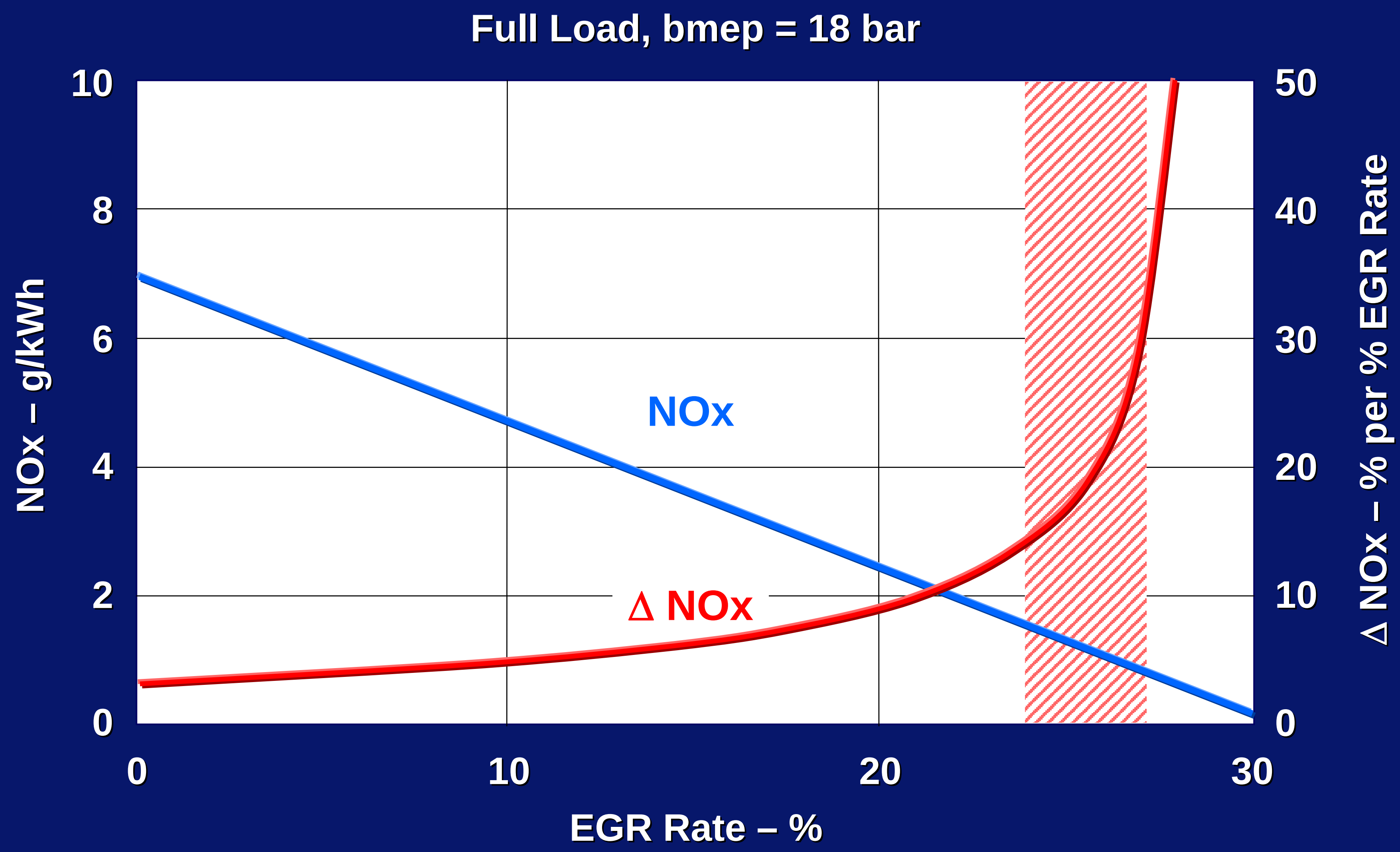

EGR Rate Control Areas within Engine Map of PassCar and HD Diesel Engines

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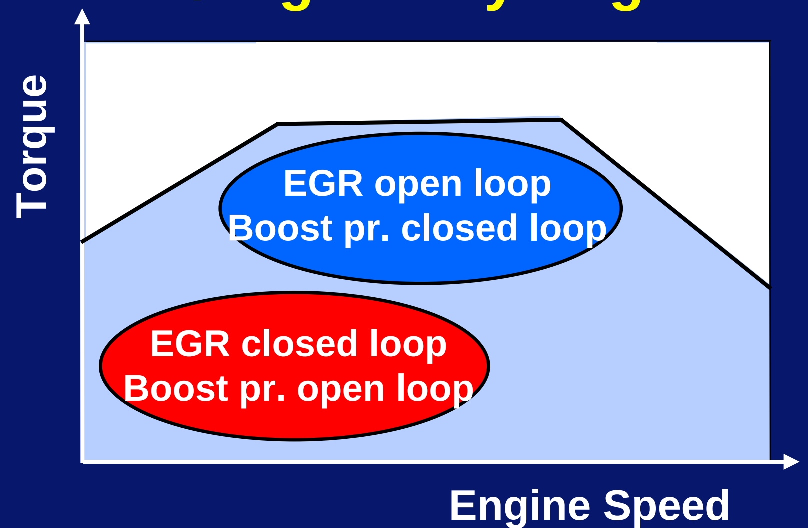
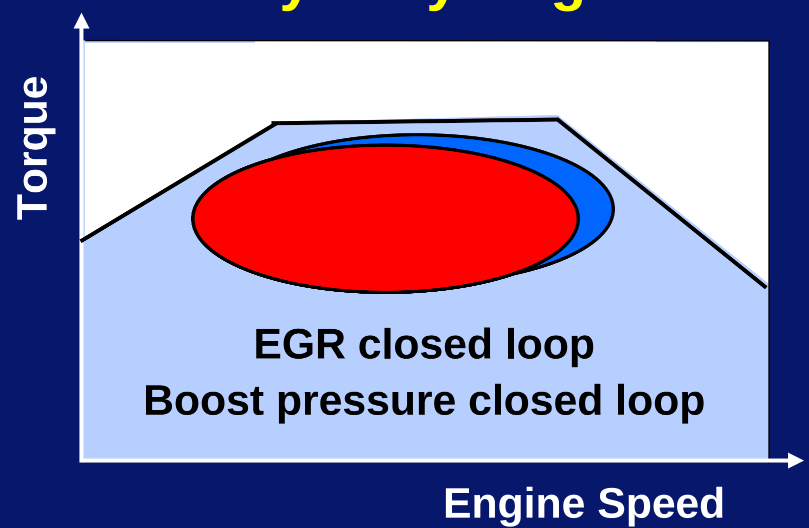
PC / Light Duty Engine



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

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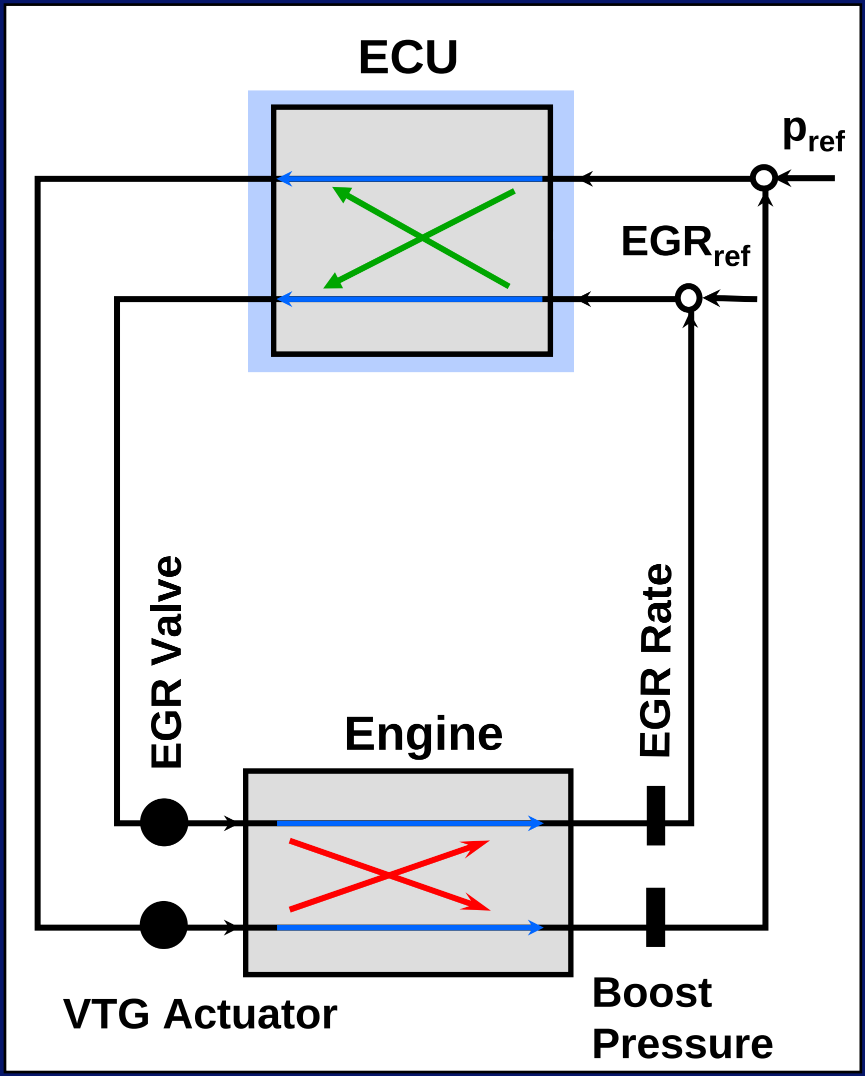
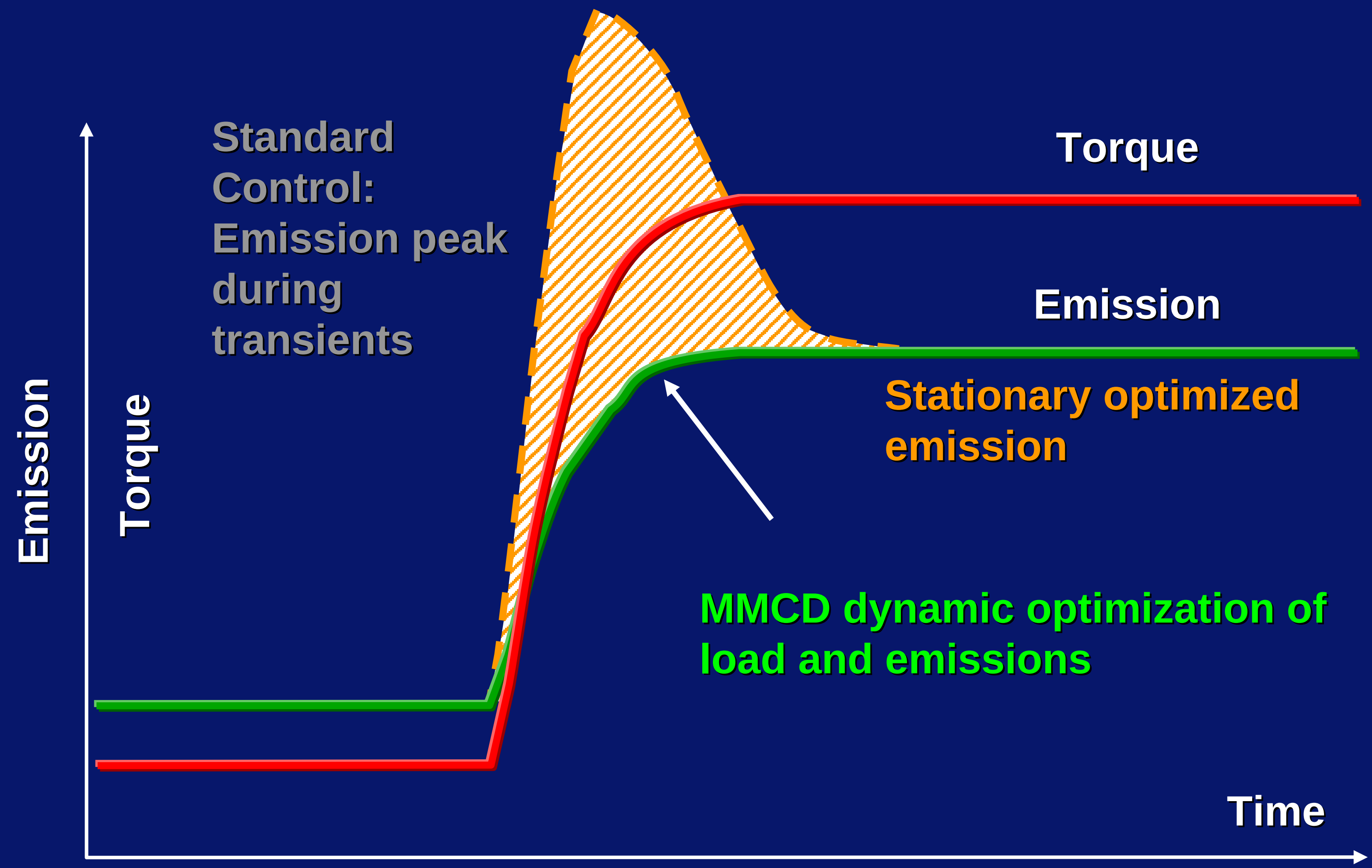


- A <u>single</u> model based controller for EGR rate and boost pressure
- Reciprocal influence of EGR rate and boost pressure being taken into account in real engine operation

<u>Result:</u>

- 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



MMCD: Model-Based Multivariable Controller Design

Transien Emission Reduction by AVL MMCD Controller

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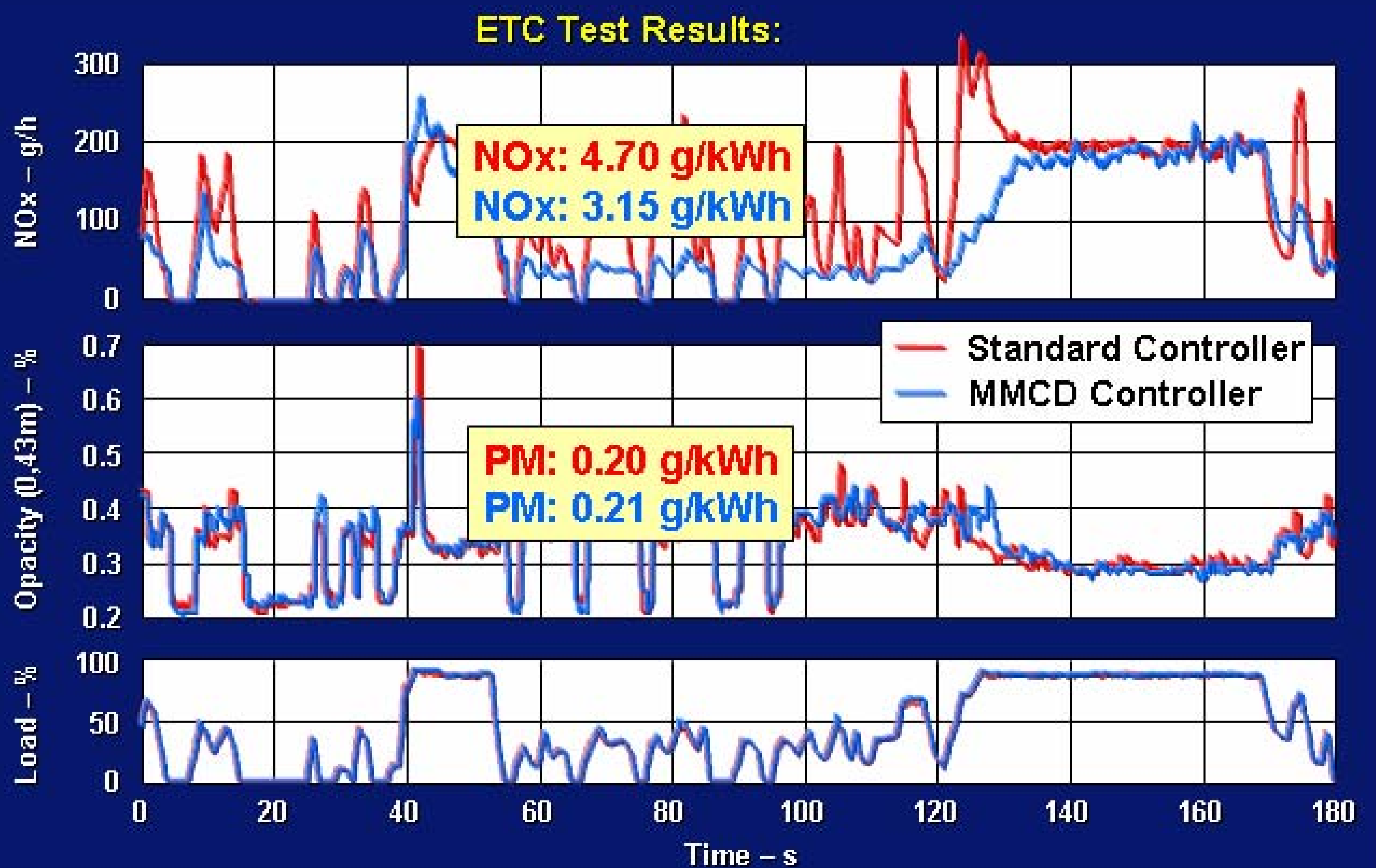

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Emission Scenarios, Engine Technologies and Consequences

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

* urea consumption calculated with 50% of diesel price

Conclusions & Recommendations

- 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 / CO_2-emissions has to be found. Taking over US 2010 limits would lead to an unacceptable fuel consumption deterioration and CO_2-increase.

Conclusions & Recommendations (cont.)

- 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.

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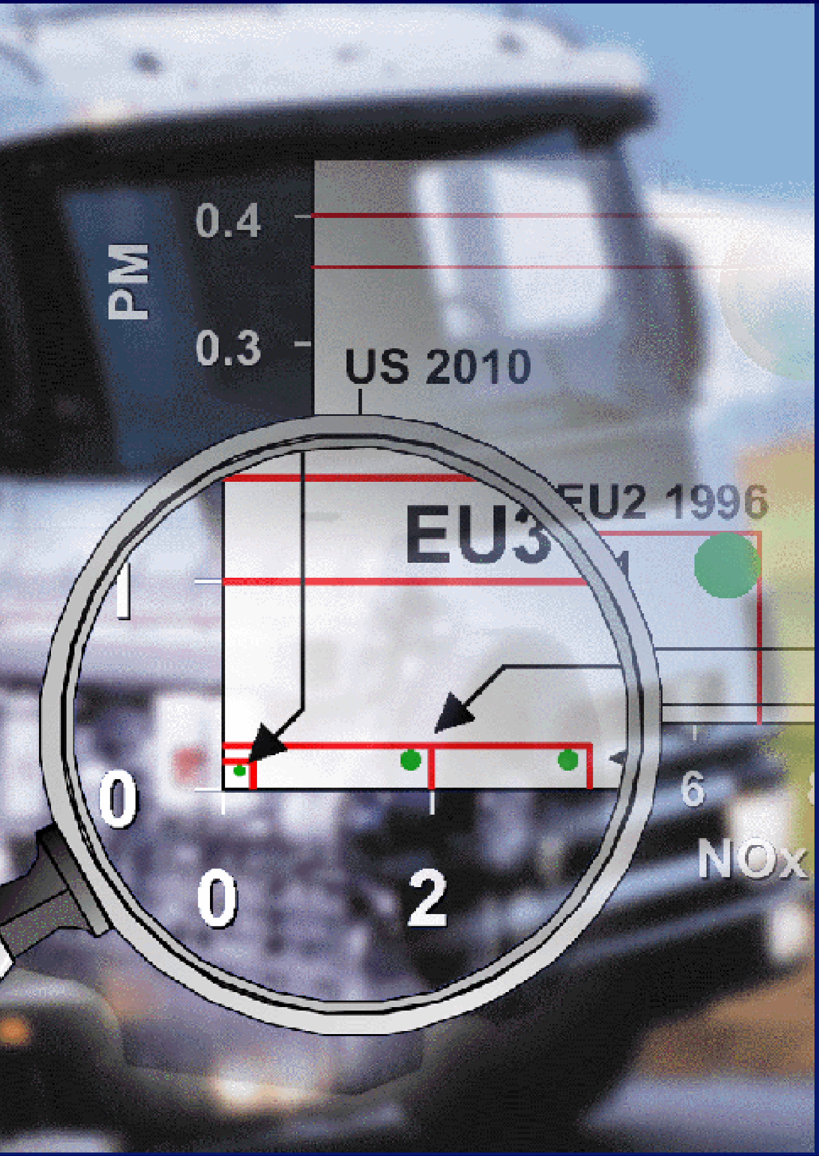

Lowest Engine-Out Emissions as the Key to the Future of the Heavy-Duty Diesel Engine: New Development Results

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HD Diesel Engine NOx and PM Emission Development

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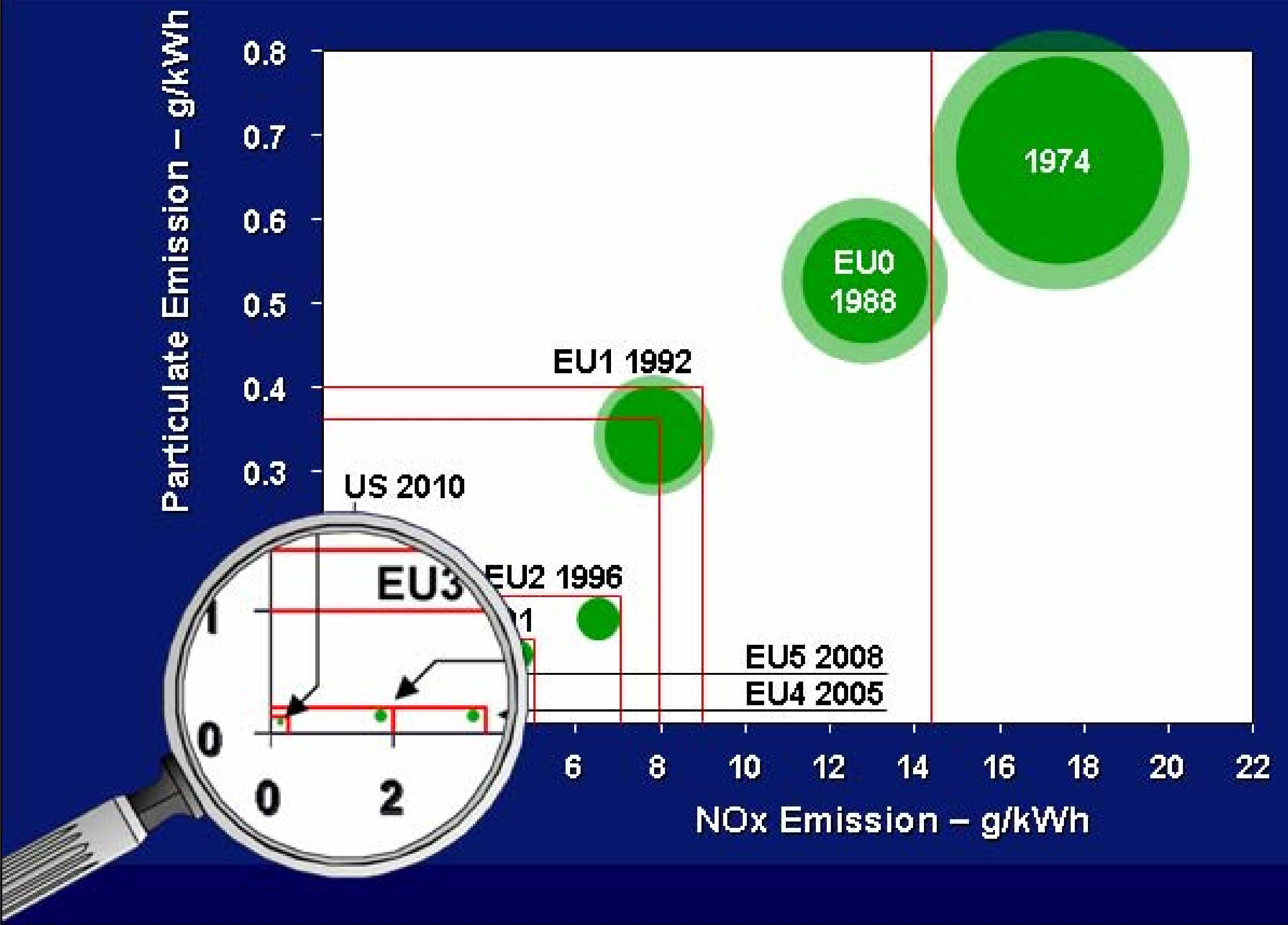
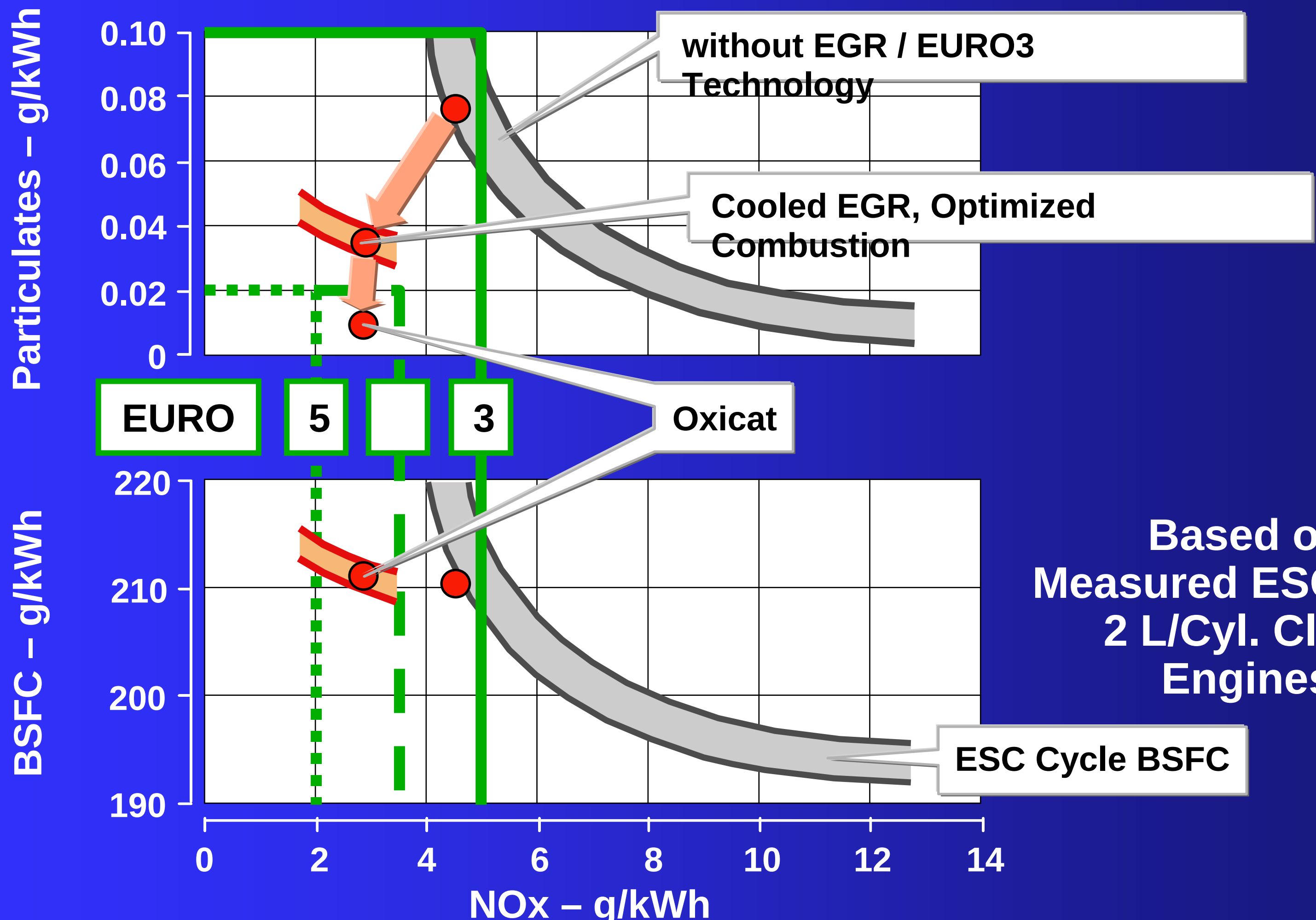


Emission Reduction Strategies

Commercial Powertrain Systems

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



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

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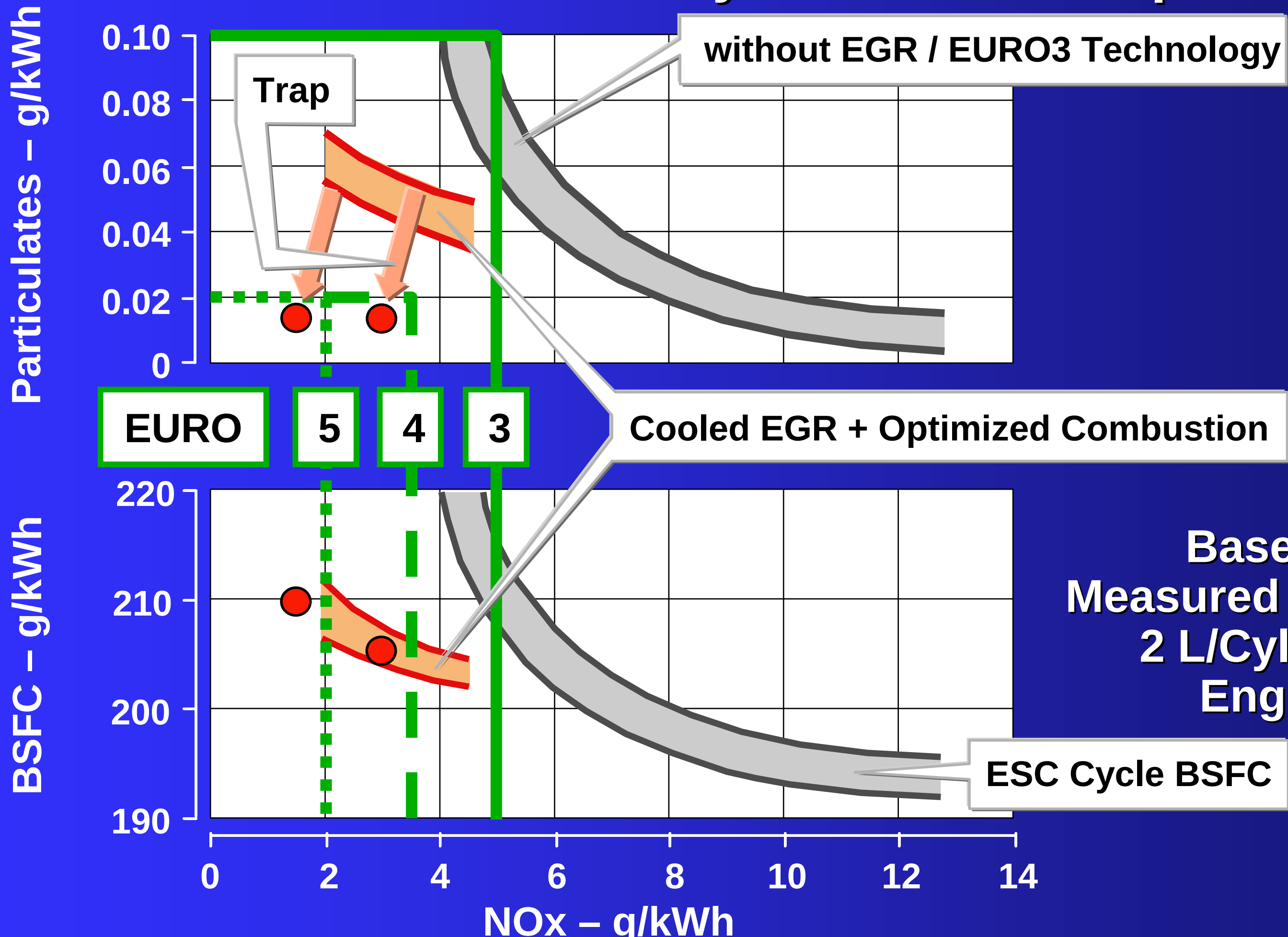
Strategy 2: - NOx Reduction by Exhaust Gas Recirculation - PM Reduction by Particulate Trap

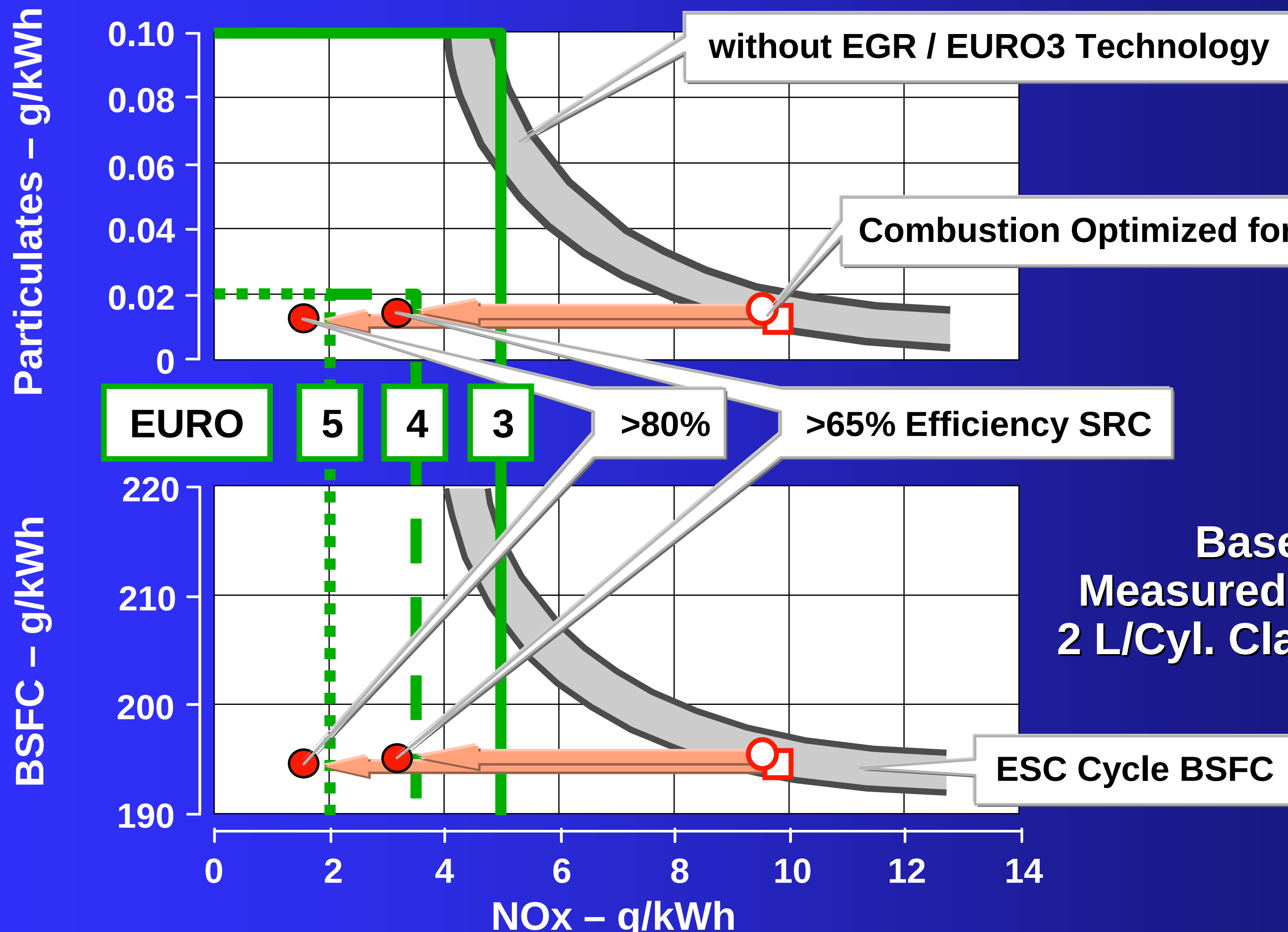


Based on Measured ESC Data, 2 L/Cyl. Class Engines

Emission Reduction Strategies

Commercial Powertrain Systems

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



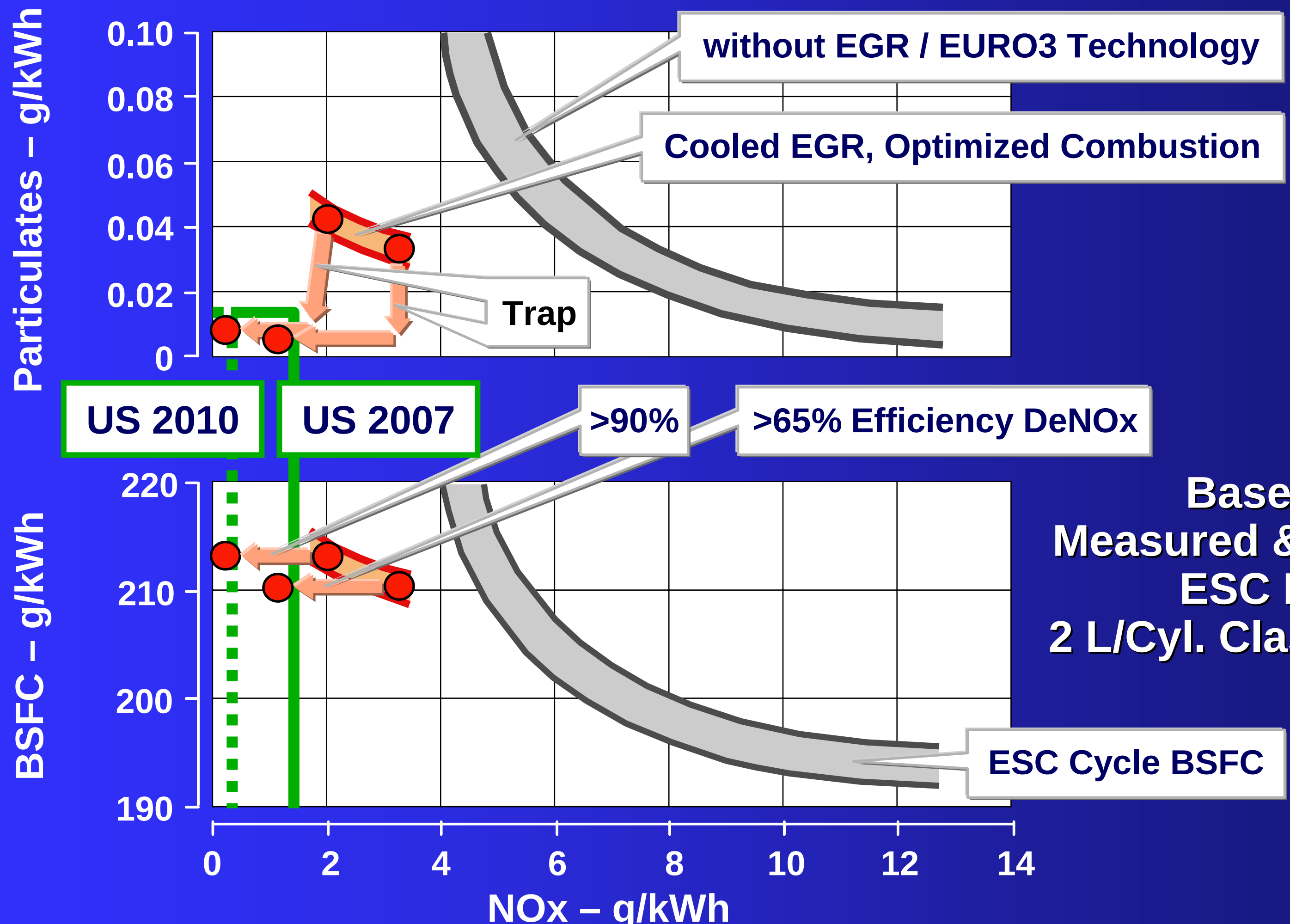
Based on
Measured ESC Data,
2 L/Cyl. Class Engines

202010-11

Emission Reduction Strategies

Commercial Powertrain Systems

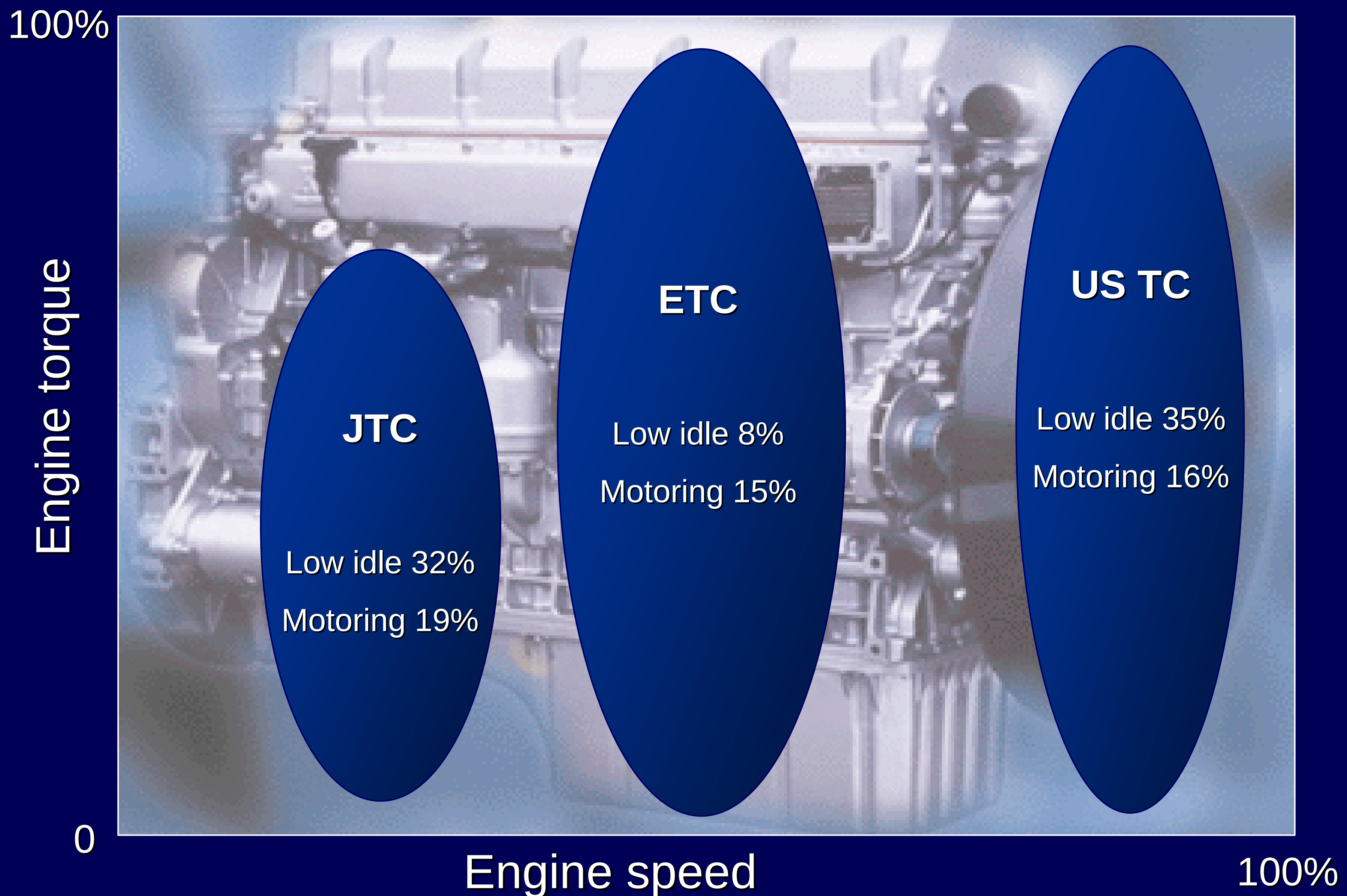
Strategy 4: - Combination of all Technologies, i.e. Combustion Optimization, DeNOx & PM Aftertreatment



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

202010-13

Main Operating Areas in Emission Cycles USA, Europe, Japan



Development Strategies

for

US 2007 / 2010

HDDE Development Strategies for US 2007

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**

HDDE Development Strategies for US 2010

2007

US 2007 development

+

De-NOx system development and integration

2010

HDDE Development Strategies for US 2007

2004

Route 1

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

+

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

+

Diesel particulate filter

Route 2

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

+

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

+

De-NOx system and Diesel particulate filter

2007

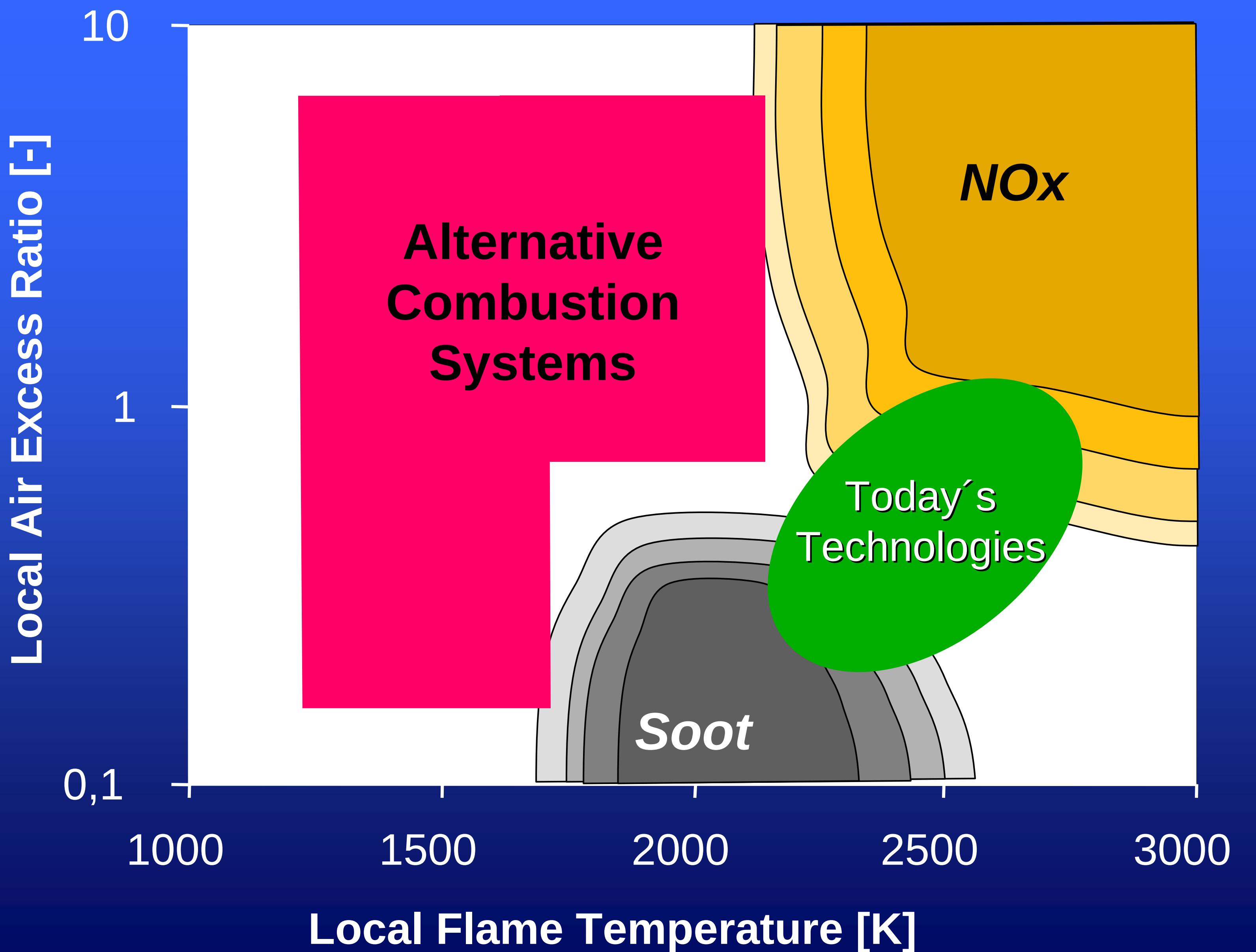
Development Strategies for US 2010

2007

Route 1	Route 2
US 2007 development	New engine design and development
+	+
De-NOx system development and integration, > 85% efficiency	Improved De-NOx system development and integration (system change ?)

2010

Diesel Combustion Systems for Low NOx/Soot Emission



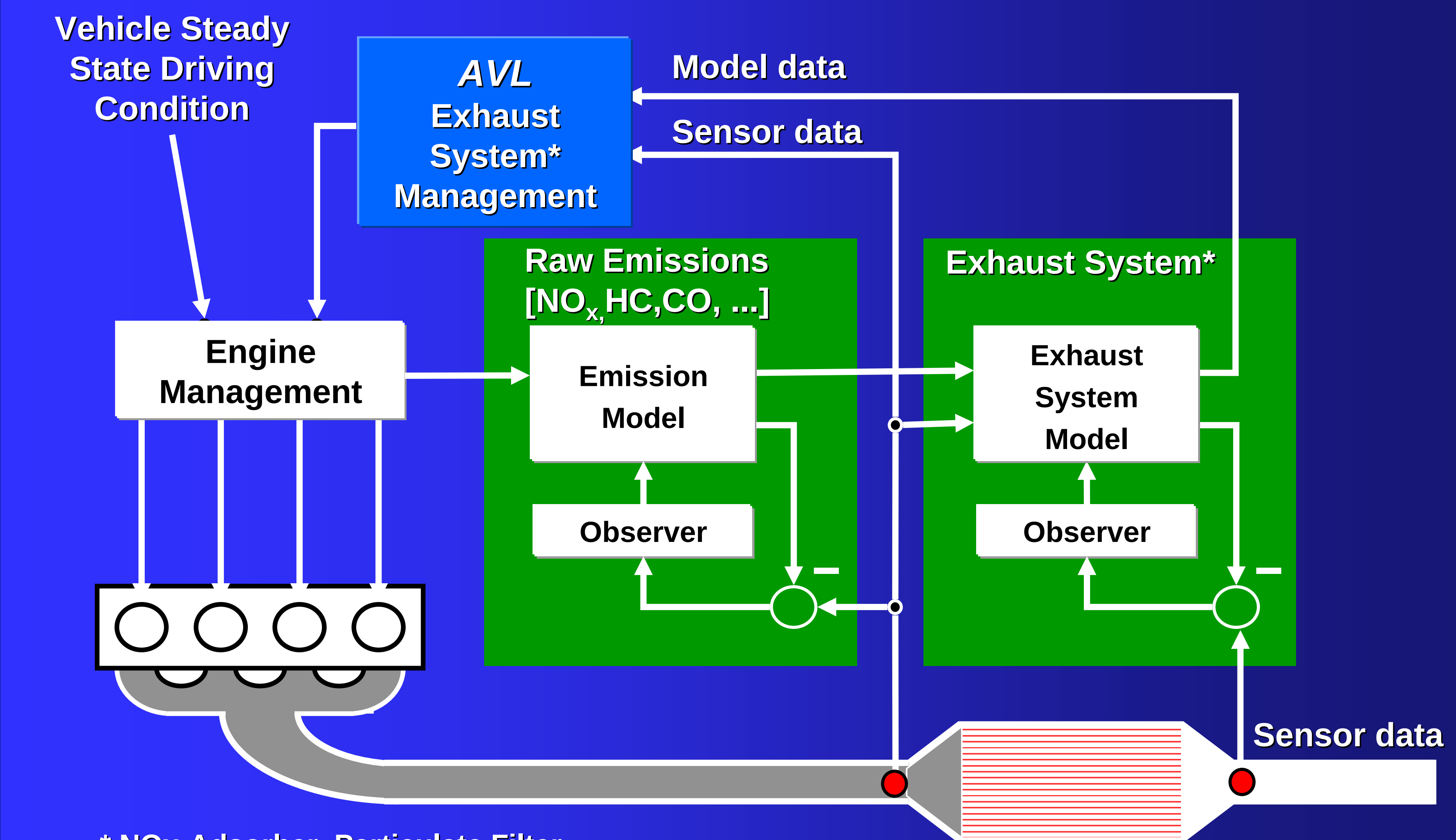
NEDC Simulation with Alternative Combustion

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	-
Combined Standard & Alternative Combustion	0,093	60	0,006	70

Simulation based on Single Cylinder Test Results

Model-based Exhaust Emission Control



* NOx-Adsorber, Particulate Filter, ...

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

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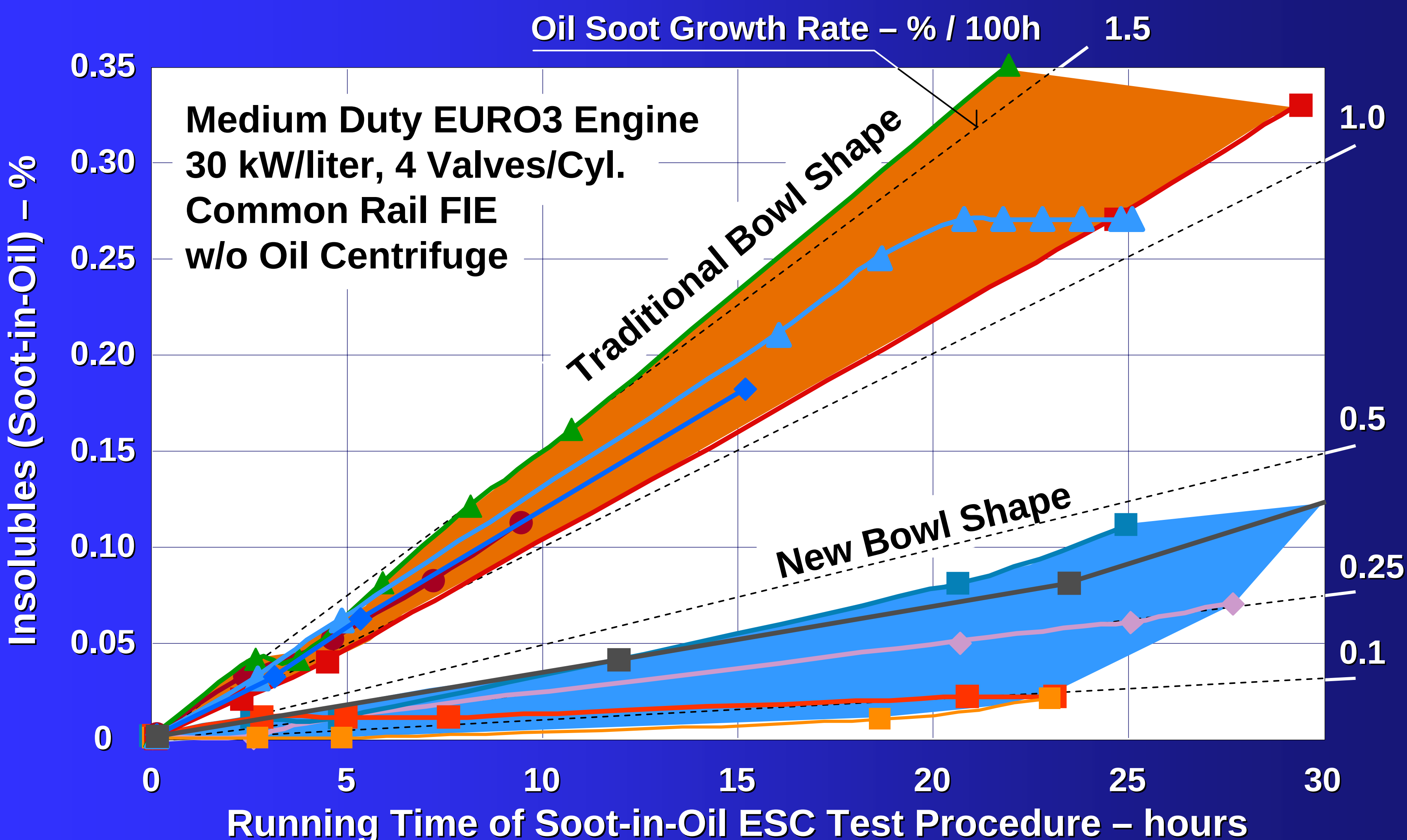

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Exhhaust Temperatures in Test Cycles and Aftertreatment Dependencies

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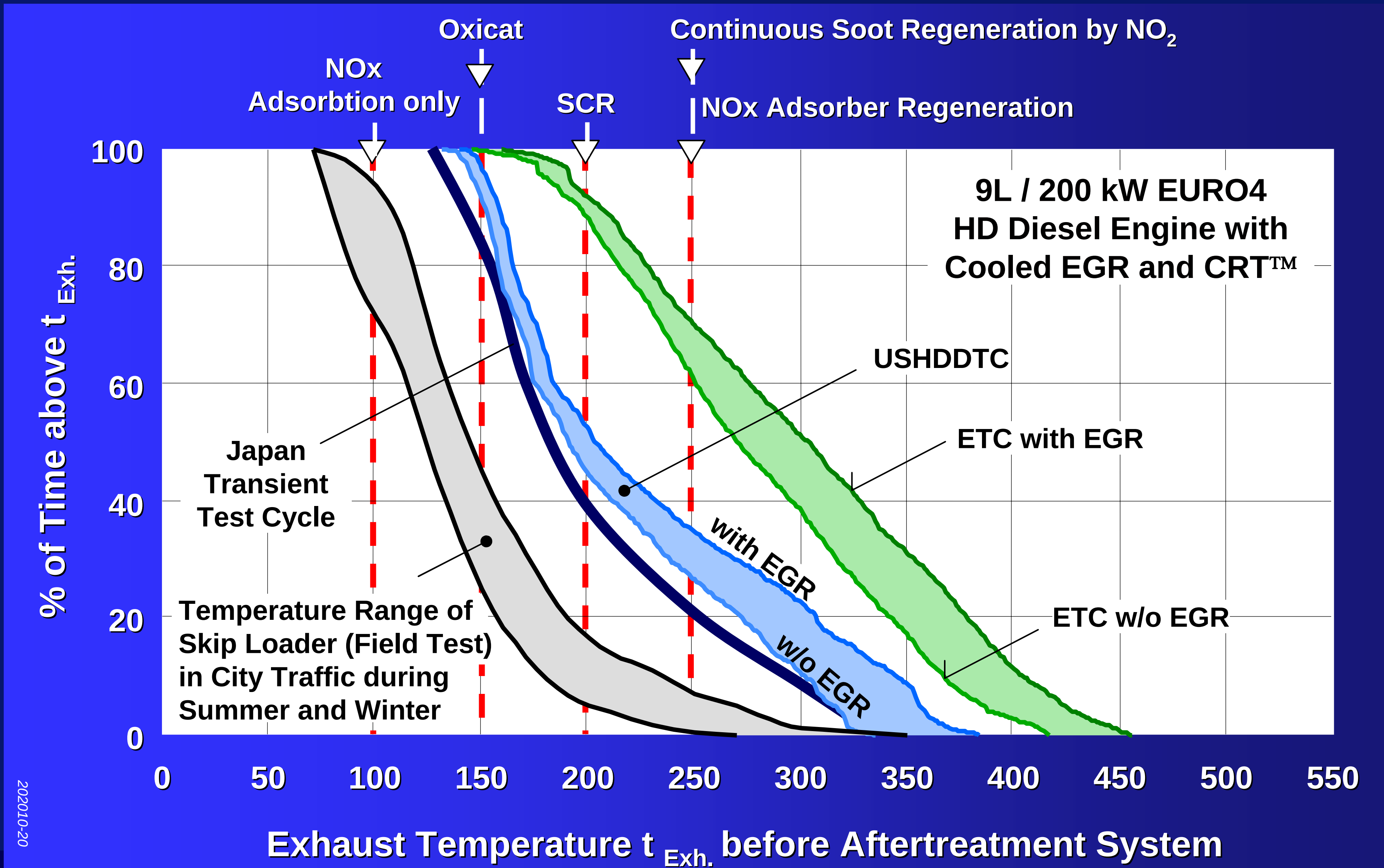

HD Diesel Technologies 1974 – 2010
Truck Fuel Consumption and Speed

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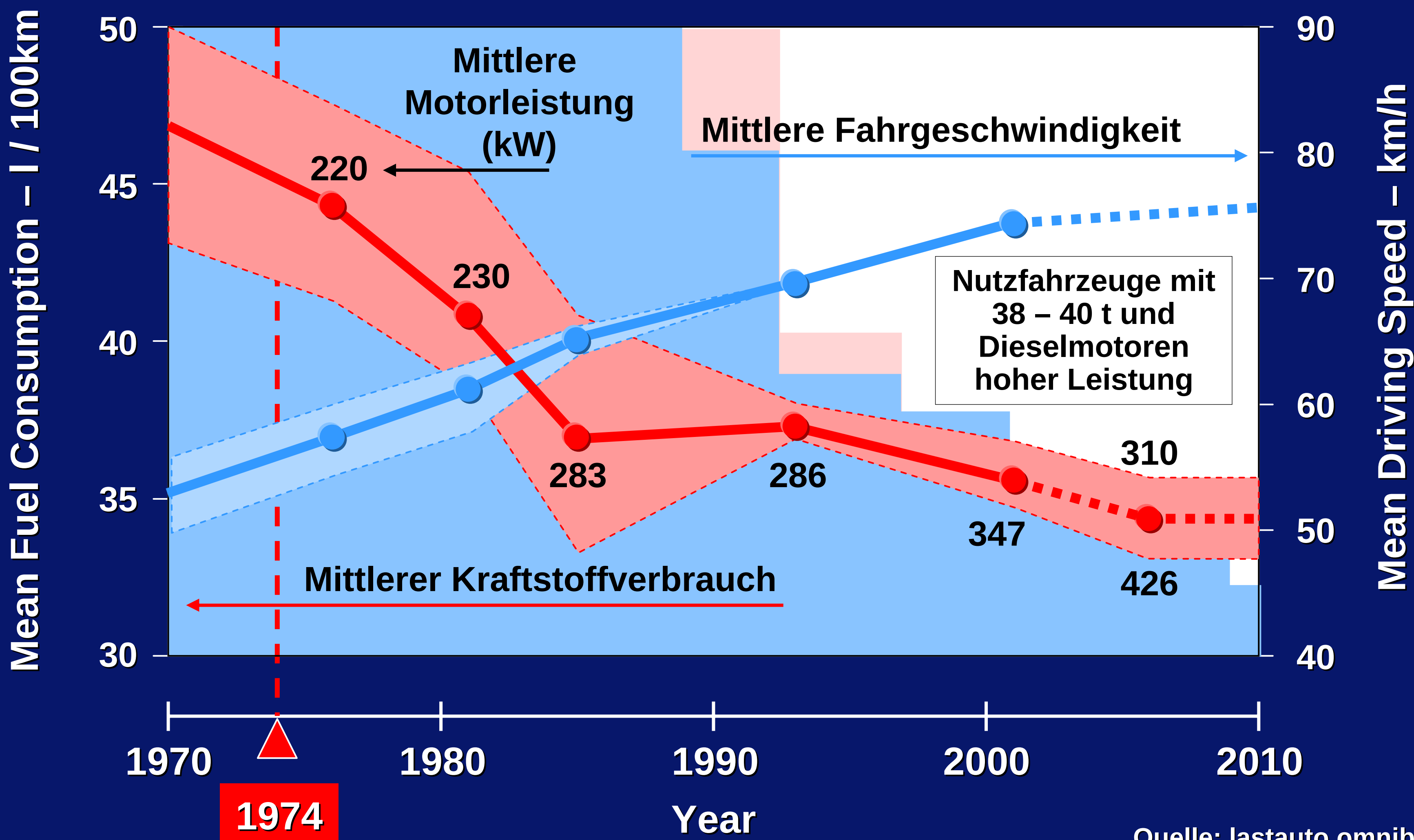

Quelle: lastauto omnibus

Future Truck Diesel Engine
2-Stage Turbocharging Design

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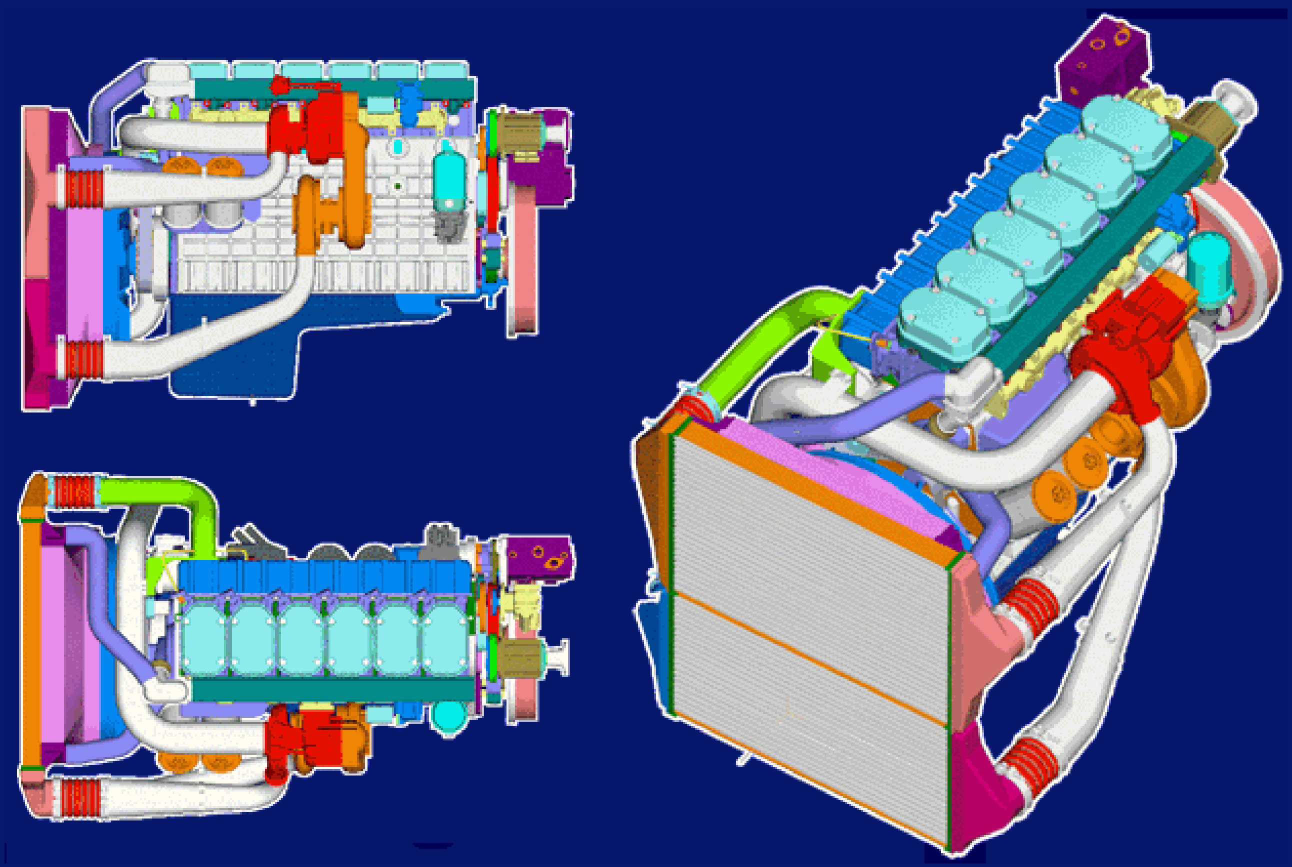
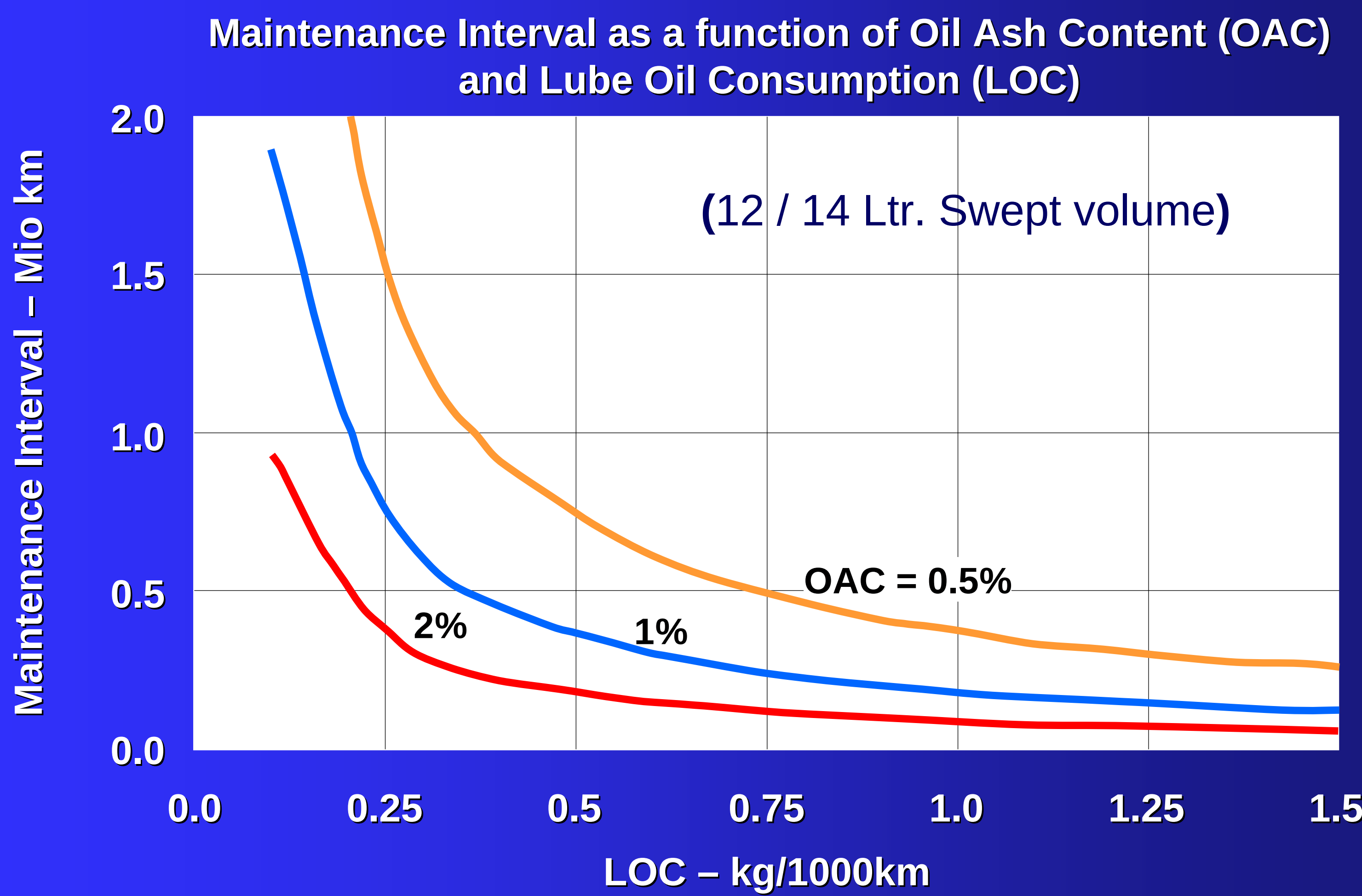


Lube-Oil Ash Deposits and DPF Maintenance Intervals



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

Flow Through Non-Blocking PM Catalyst

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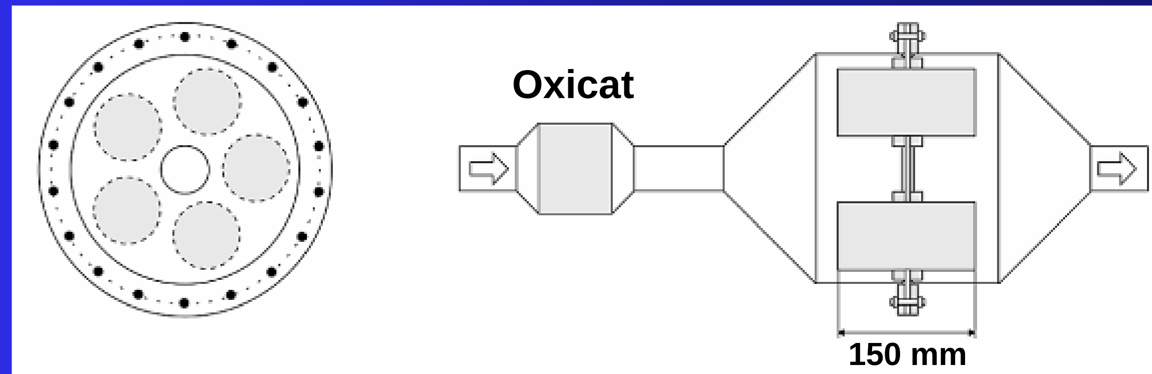
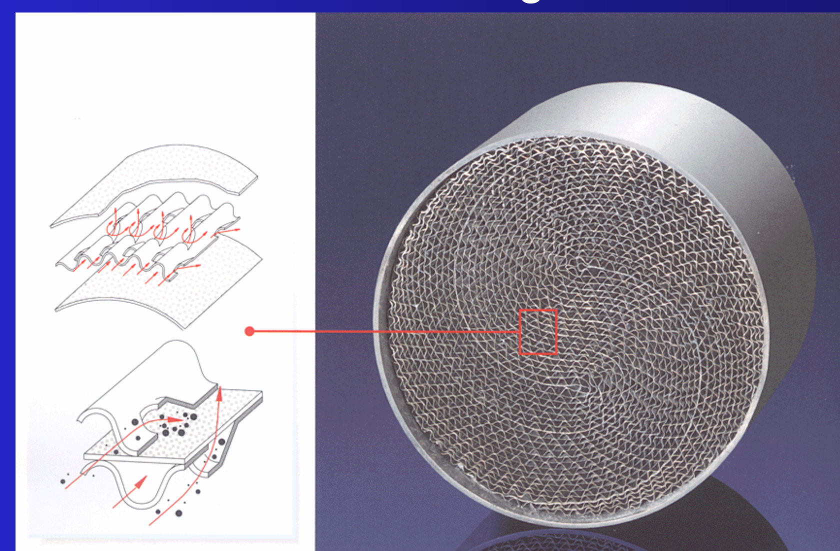
Test Arrangement for 6.6L / 228 KW HD Diesel Engine

5 PM catalysts in quick-exchange housing



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



Source: Emitec GmbH & MAN Nutzfahrzeuge AG

Mechanism and Effectiveness:

Carbon-PM oxidized by NO_2 being formed in Oxicat

HC, Sol-PM and CO oxidized in Oxicat

Conversion Rates (ESC & ETC):

$\eta_{PM} \approx 50\%$, target 70% by further development

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

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

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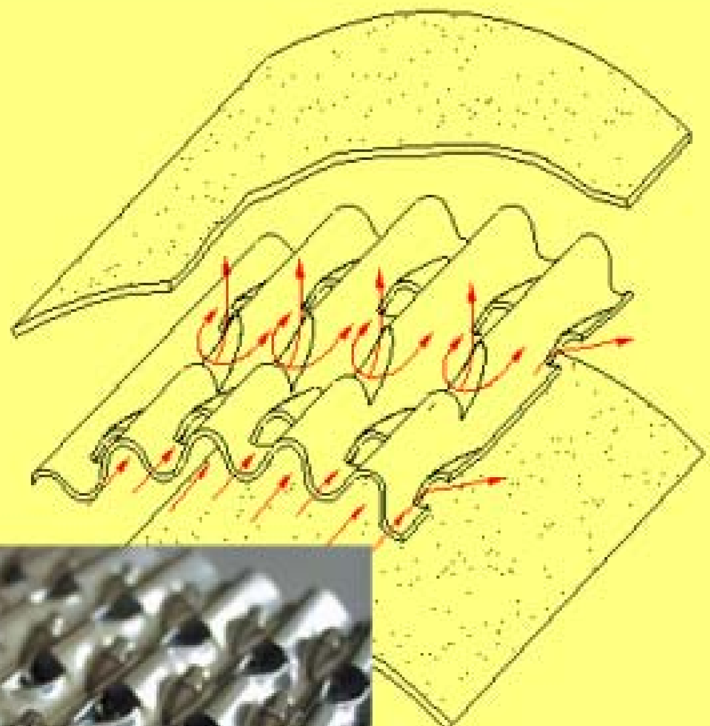
Principle of Particle Depositing in a Porous Flat Foil of the Mixing Section

Structure with porous flat foils



Trapping of particles passing the porous foil