Clean & Efficient Diesel Engines - Designing for the Customer

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“… so much has been written and said about the Diesel engine in recent months that it is hardly possible to say anything new”

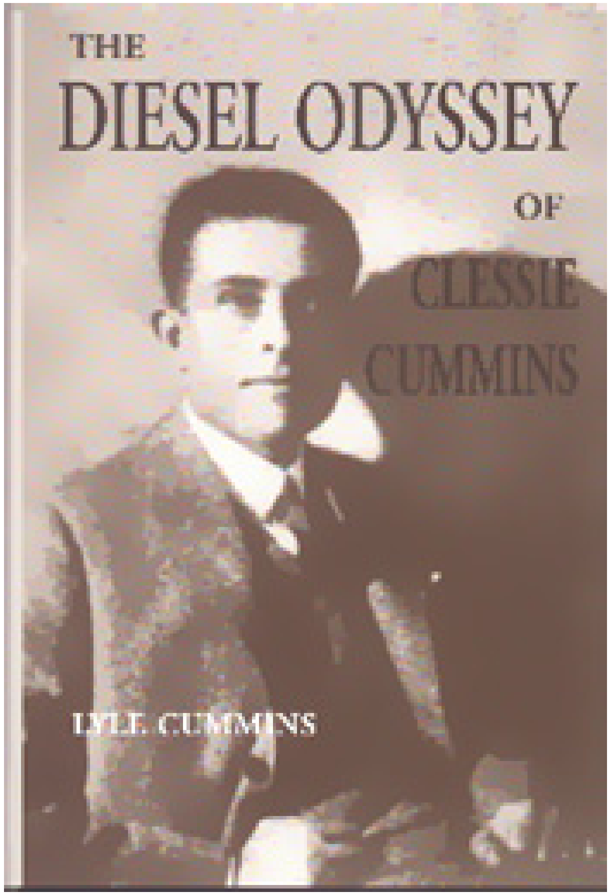
Diesel’s patent filed 1894

First successful operation 1897

Rudolf Diesel, c. 1910

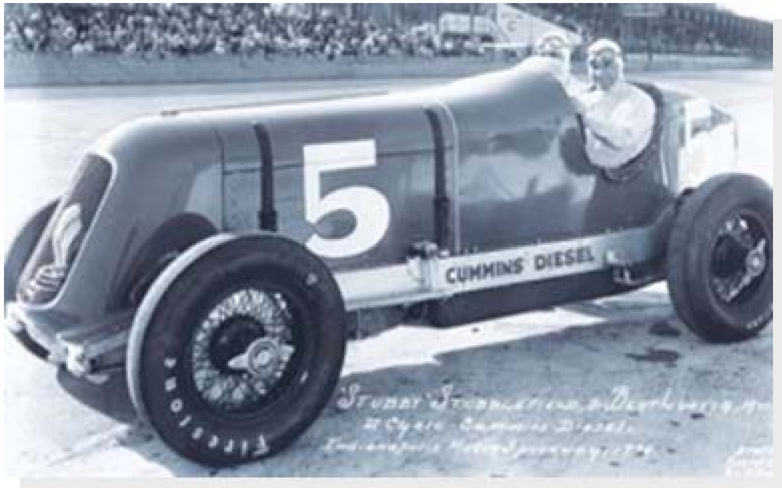
Cummins founded 1919

Diesel Race Cars
– A Short (& Incomplete) History

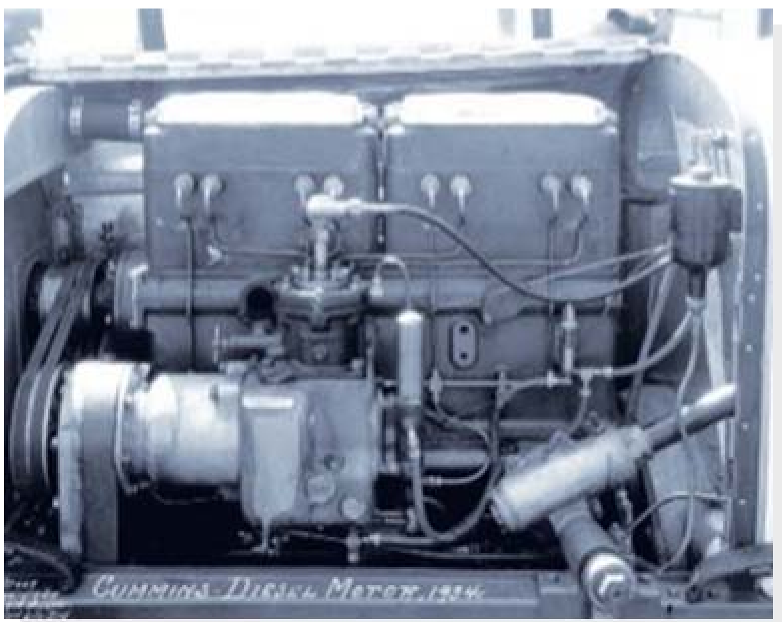


1931	Cummins Diesel, Indy 500
1934	Cummins Diesel, Indy 500
1950	Cummins Diesel, Indy 500
1952	Cummins Diesel, Indy 500
2006	Audi Diesel, Le Mans
2007	Audi Diesel, Le Mans
2008	Audi & Peugeot Diesels, Le Mans

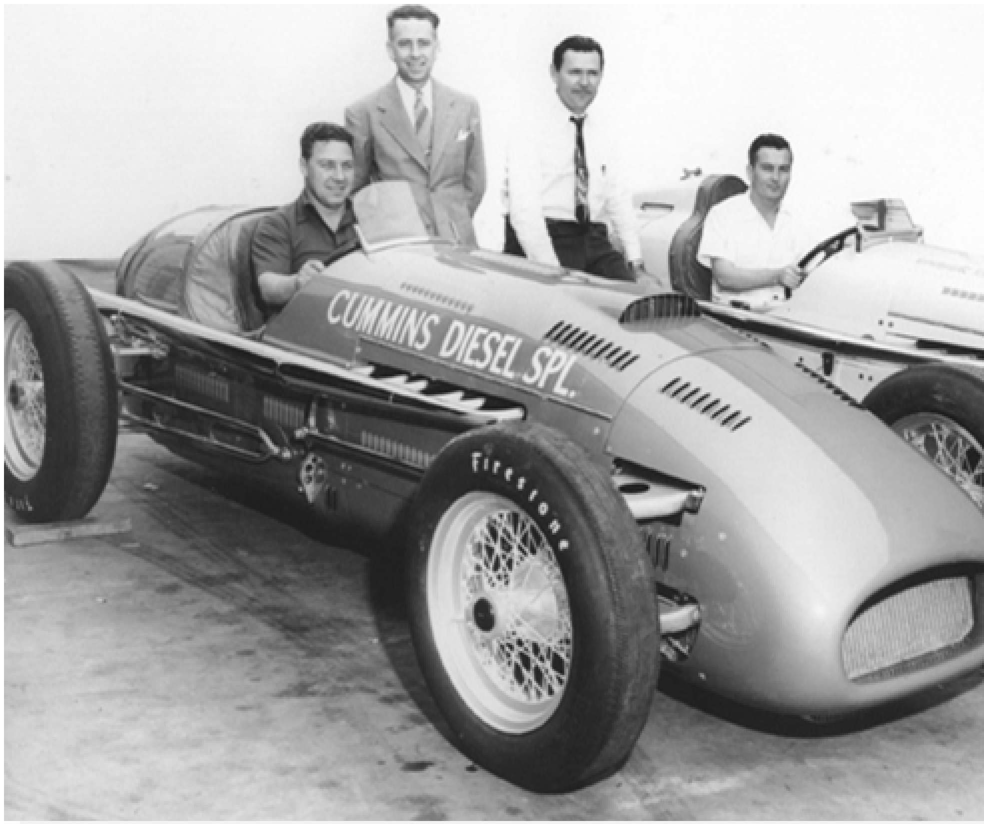
1931 Indy 500 Cummins Diesel, Driver Dave Evans
Deusenberg Chassis, No Pit Stops ! 97 MPH
Place 13th, Prize Money $450



1934 Indy 500 Cummins Diesel,
Two-Stroke !
Driver Stubby Stubblefield
Car Deusenberg,
105.9 MPH, 200 Laps
Place 12th, Prize Money $880



1950 Indy 500 Winner, Driver Johnnie Parsons
Car Kurtis-Kraft Offenhauser, 132 MPH



1950 Indy 500 Cummins Diesel, Driver Jim
Car Kurtis-Kraft, Laps 52 of 138 / Supercha
129.2 MPH
Place 29th, Prize Money $1939

Spun	**Magneto**
Stalled	**Piston**
Vibration	**Crankshaft**
Rod	**Overheating**
Rod	**Ignition**
Accident	**Magneto**
Crankshaft	**Oil line**
Drive gears	**Rear axle**
Clutch	**Oil tank**
Axle	**Drive shaft**
Clutch shaft	**Piston**
Caught fire	**Fuel tank**
	Drive shaft

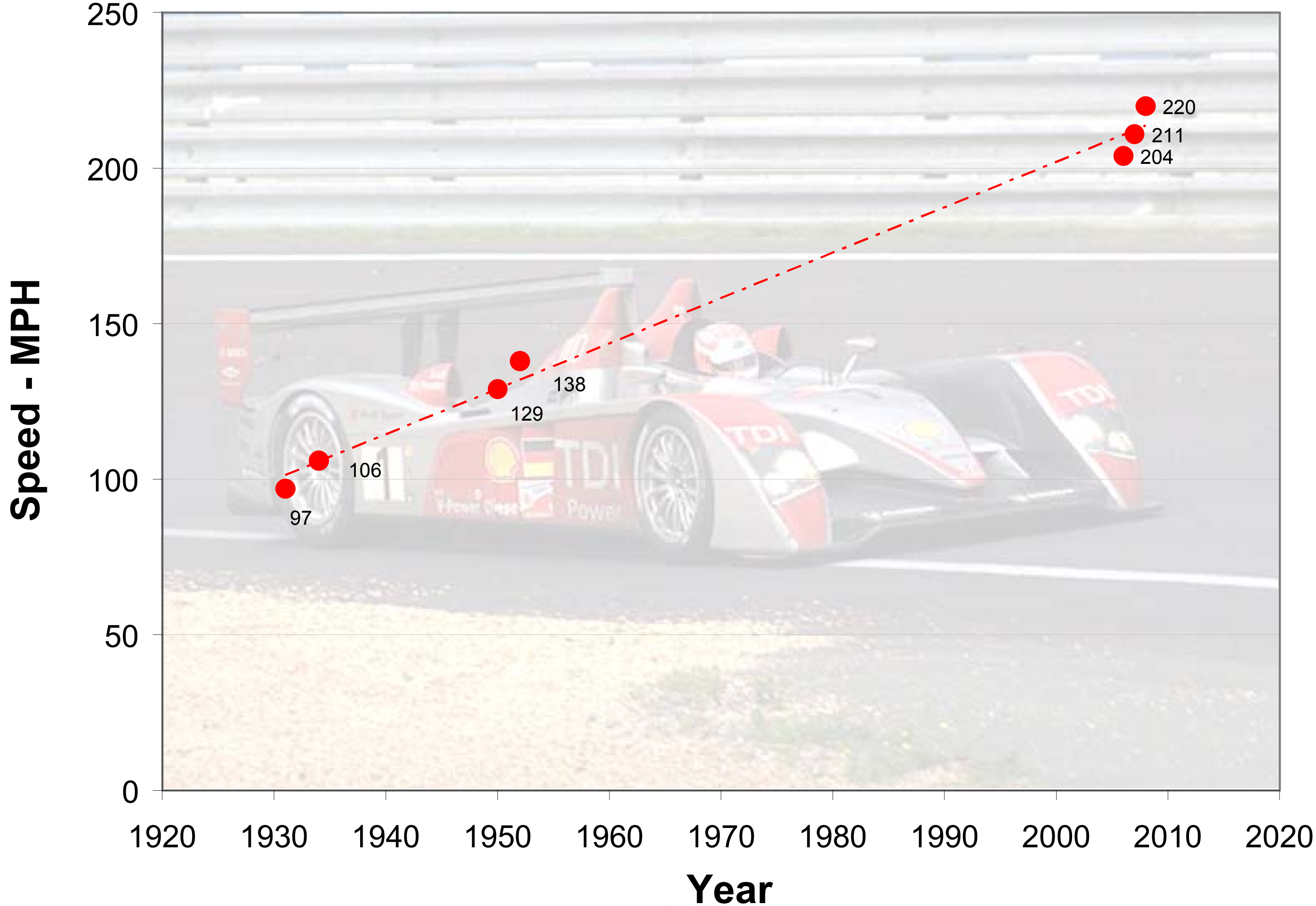
1952 Indianapolis 500 Pole
Cummins Diesel Special
Driver Freddie Agabashian, 138 MPH
Retired / Turbocharger, 71 Laps
Place 27th, Prize Money $2653

Audi R10 – Turbo Diesel with GTL Diesel Fuel

Winner Sebring 12hr race 2006, 2007,

Le Mans 2006 / 204 MPH Max, 2007 211 MPH Max & 2008 220 MPH Max

Diesel Race Car Speeds 1931-2008



Outline

- Macro Trends, Sustainability
- Clean & Efficient Diesel Engine Technology
  - 2007 Report Card
  - Customer Expectations
  - Looking ahead to 2010
- Beyond 2010 …
  - Regulatory Drivers
  - Leading Technologies for Heavy-Duty

SAE 2007-01-4170

Meeting the US 2007 Heavy-Duty Diesel Emission Standards - Designing for the Customer

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ABSTRACT

The paper covers the design and development of Heavy-Duty (HD) Diesel engines that meet the 2007 HD US EPA emission standards. These standards are the most stringent standards in the world for on-highway HD diesel engines, and have driven the application of new technologies, which includes: particulate aftertreatment, crankcase ventilation systems, and second generation cooled EGR.

The paper emphasizes the importance of designing the product to meet the tough expectations of the trucking industry – for lowest total cost of ownership, lowest operating costs, high uptime, ease of maintenance, high performance and durability. A key objective was that these new low emission engines should meet or exceed the performance, reliability and fuel economy standards set by the products they replace. Additionally, these engines were designed to be fully compatible and emissions compliant with bio-diesel B20 blends that meet the ASTM and EMA fuel standards.

To meet these exacting requirements, extensive use was made of Analysis-Led Design, which allows components, sub-systems and the entire engine, aftertreatment and vehicle system to be modeled before designs are taken to prototype hardware. This enables a level of system and sub-system optimization not previously available.

The paper will present results from the development of Cummins 2007 HD engine and aftertreatment systems, including:

- Engine and Aftertreatment Integration for Optimum Performance
- NO_x control using Cooled EGR
- Crankcase Gas Filtration for HD Engines
- Application of Analysis-Led Design Tools

INTRODUCTION

The modern HD diesel engine is used around the world to power applications as varied as heavy-duty trucks, electrical power generators, ships, locomotives, agricultural and industrial equipment. The success of the HD diesel engine results from its unique combination of fuel economy, durability, reliability and affordability – which drive the lowest total cost of ownership.

The exhaust emission standards introduced in the U.S. in 2007 have required the development and introduction of the *Clean Diesel* [**Error! Reference source not found.**], which achieves near-zero emissions of Oxides of Nitrogen (NO_x) and particulate (PM), while retaining the customer values outlined above. The progress toward near-zero emissions has involved the development of:

- Advanced engines using new technologies
- Advanced aftertreatment systems
- Availability of ultra-low sulfur diesel fuels

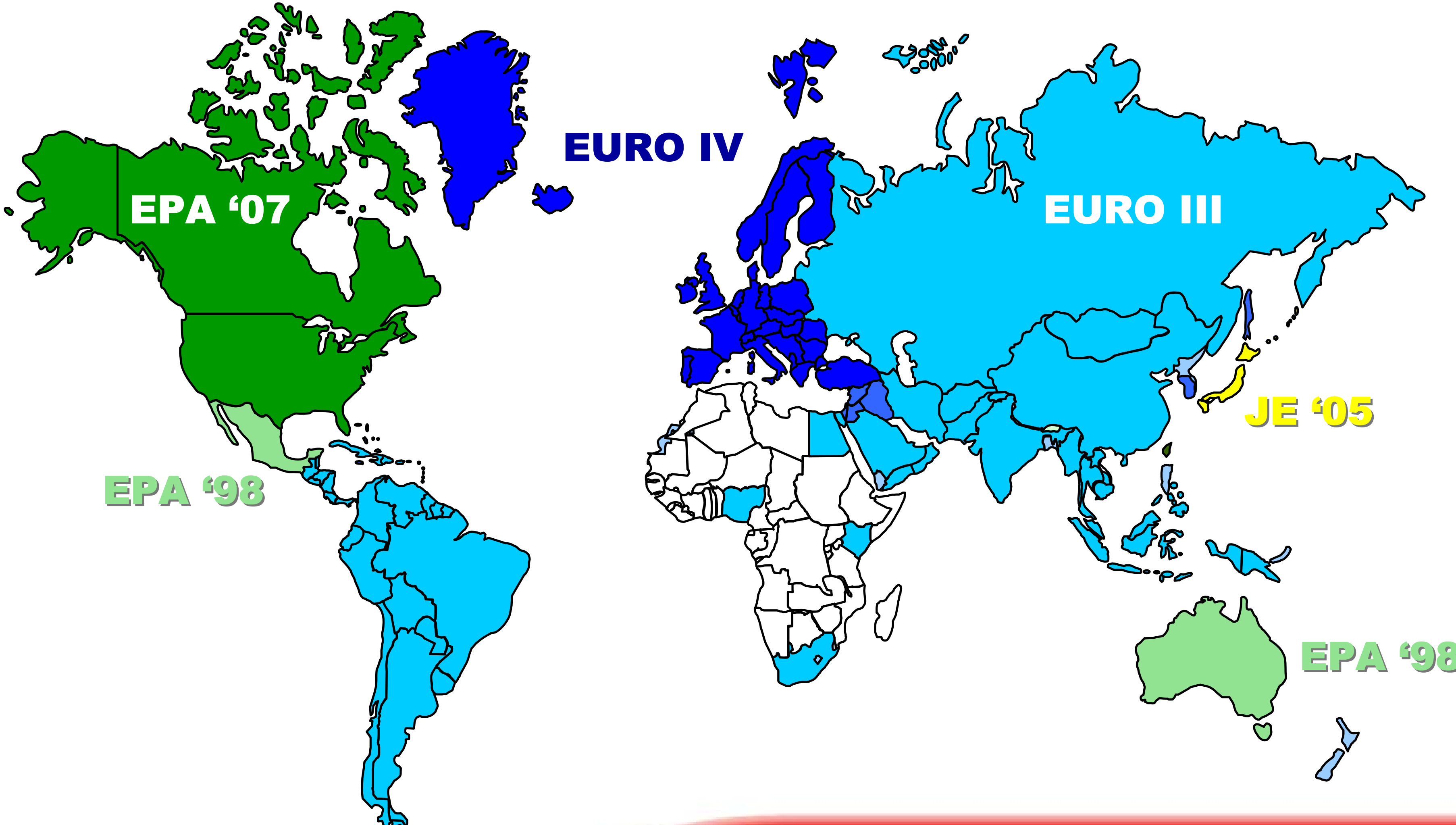
The paper documents the design and development of 11 liter and 15 liter HD engine systems. The smaller engine is used in a wide range of applications from 280 to 500HP, which include: RV, fire truck, urban bus, mixers and class 8 regional-haul trucks. The larger engine is

Cummins acknowledges the support of the US Department of Energy in the development of the technologies included in this presentations

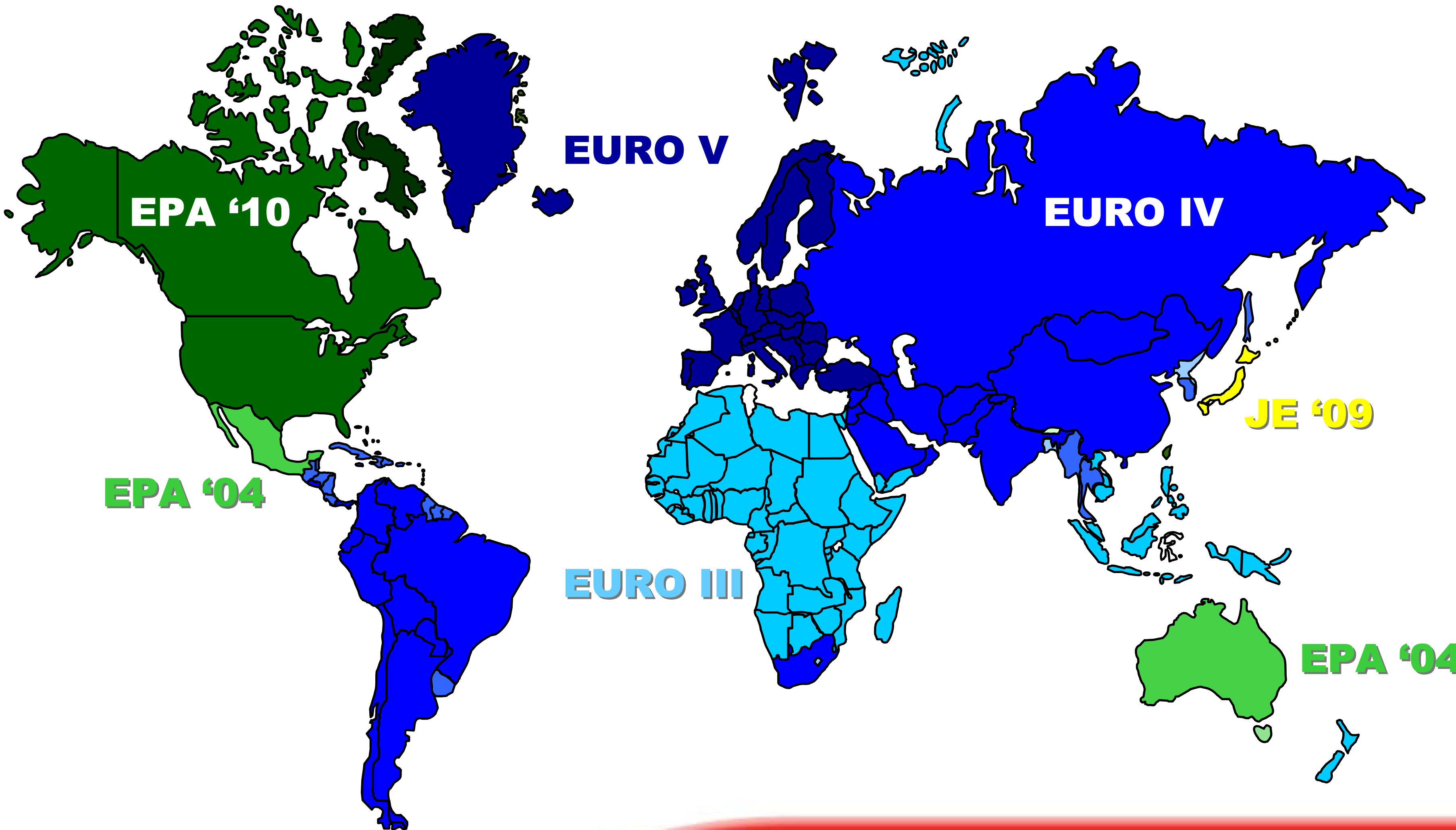
Macro Trends

- $5 Diesel Fuel in the US, $10-12 in Europe
- … Increased Emphasis on Fuel Economy
- Climate Change / Greenhouse Gas Emissions / CO_2
- Energy Independence / Renewable Energy Sources
- Increased Urgency for Sustainable Development
- Congestion, Truck Weight Limits (97,000lbs ?)
- Product Complexity, Vehicle Integration
- Commodity Prices – Precious Metals, Steel, Nickel …
- Globalization – Brazil, Russia, India, China …
- Global Emissions Evolution

Global On-Highway Emissions - 2007

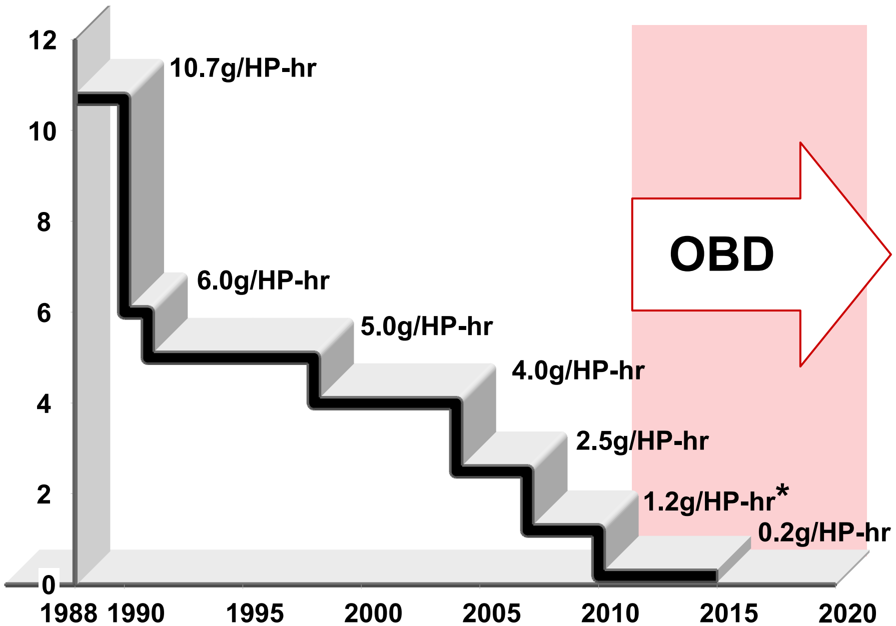


Global On-Highway Emissions - 2010

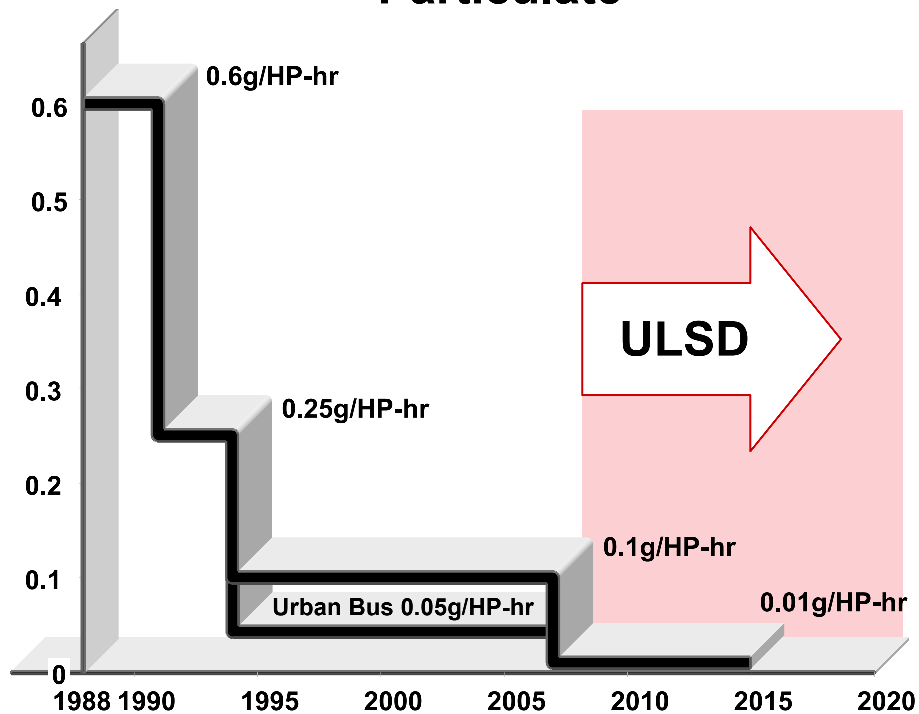


Evolution of US HD On-Highway Emission NOx & PM Standards

NOx / NOx+HC



Particulate



>98% Reduction of NOx & PM

* Phase-In Average

Sustainability

- Sustainable Development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs

- A Sustainable Lifestyle consumes only renewable resources, without causing damage to the environment

Steps Toward Sustainability

- **Fuels derived from biomass** – that do not impact world food supplies, such as ethanol from sugar cane, or cellulosic ethanol,
- **Clean & Efficient diesel engines**
- **Nuclear energy** – with sustainable processing of waste,
- **Clean coal technology**
- **Renewable energy** – wind, solar, hydro, tidal …
- **More Efficiency use of energy**

Expectations - HD Market

- Low operating costs
- High uptime
- Low maintenance
- High residual value

Lowest Cost of Ownership

- High performance
- Safe operation
- Ease of operation
- Driver satisfaction
- Information systems
- Sociability
- Emissions compliance

Cummins 2007 HD Report Card

- Delivered 2007 product on-time
  - 60,000 Cummins 07 HD Engines in service
  - Estimated 4 billion miles
- Fuel economy equal or better than 2004 product - including DPF regeneration & ULSD
- Good Reliability – Engine & DPF
- Strong performance & braking (VGT)
- Service intervals same as 2004
  - Ash interval is greater than 200k miles
  - Crankcase breather interval 120-150k
- Meeting Emissions Goals

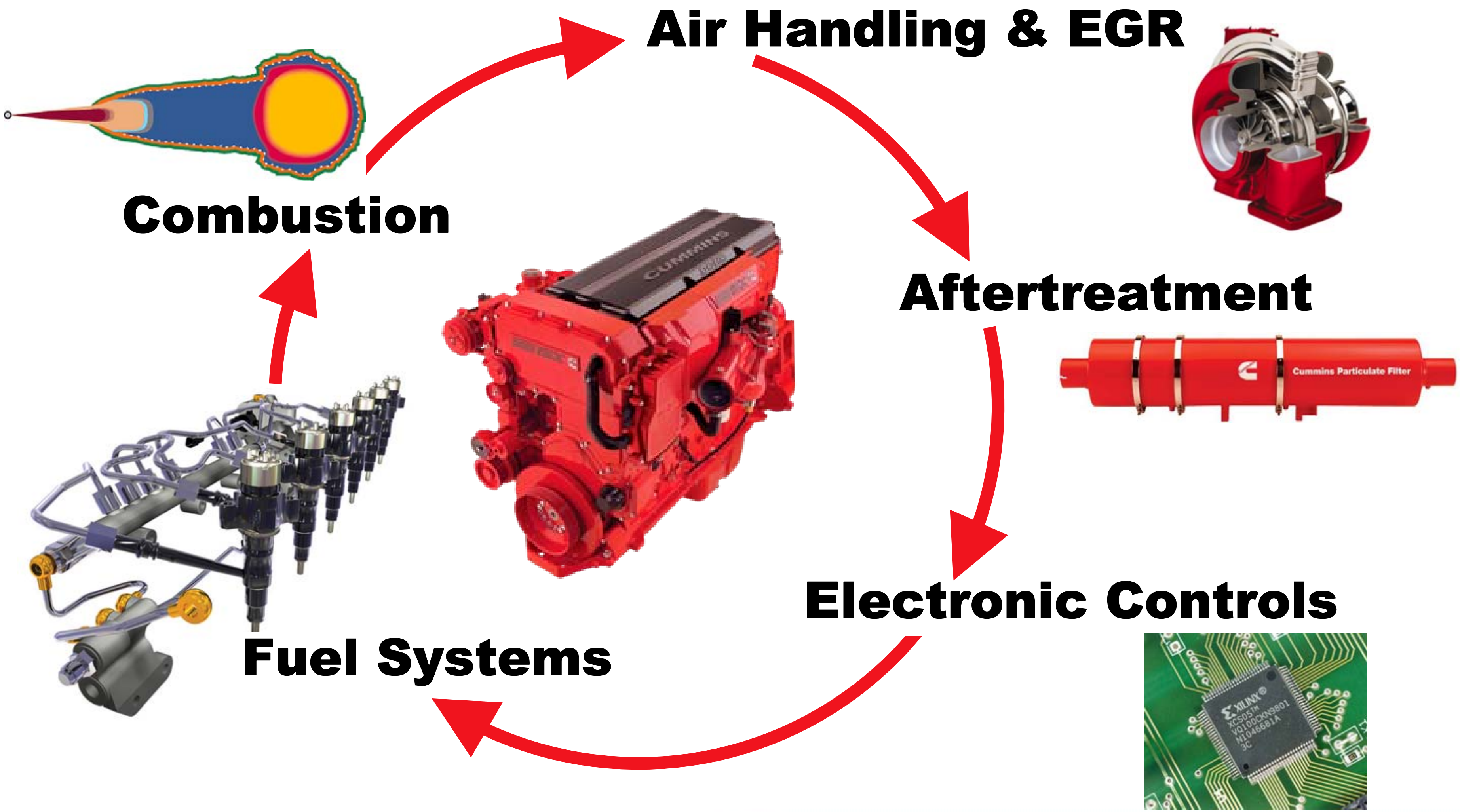
2007 Light-Duty Pick-Up

Dodge Ram Turbo-Diesel, 6.7L

- Cooled EGR + NOx Adsorber + DPF
- Met the 2010 standards 3 years ahead of time
- Fuel Efficient, Clean, Quiet and Powerful

Ultra-Low Emission HD Diesels

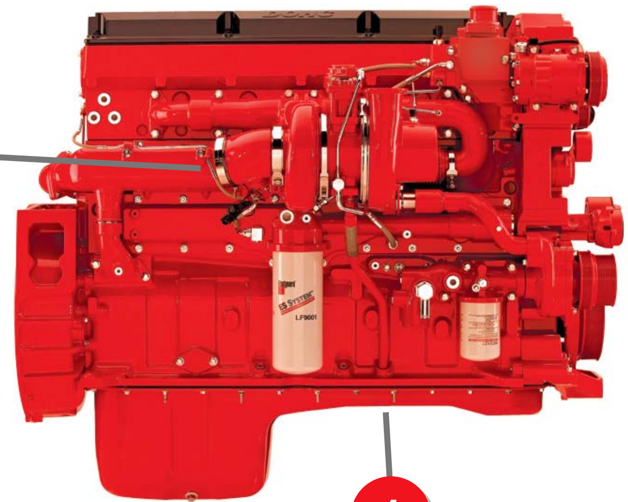
Integration of Cummins Component Technologies



2007 Particulate Filter

Low Temperature Active Regeneration
- Dosing Injector
- DOC

2



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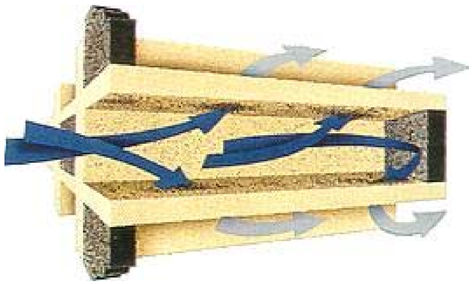
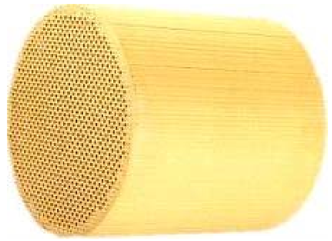
Wall-Flow Filter
- Catalyzed
- High Efficiency Soot Filter
- Ash Capacity
- Soot Capacity
- Durability / Fatigue Life

3

Oxidation Catalyst
- Passive Regeneration
- HC Low Temperature Oxidation

Active Engine
- Thermal Management
- Flexible Air & Fuel Systems
- Exhaust Temperature Control
- Exhaust Mass Flow Control





Future Needs – Exhaust Aftertreatment

- Higher NOx conversion Efficiencies
  - NAC, SCR, NAC/SCR Hybrid Catalysts
  - Application of catalysts – durability, controllability
  - Requires a more complete understanding of the catalysis
- Reduced fuel (& urea) penalty
  - DeNOx, DeSOx, DeSoot …
  - Substrates for reduced backpressure
- OBD
  - Emission Sensors … & Emission Surrogates
- Other unknowns …
  - PM Count, NH_3, CAFÉ, GHG legislation …

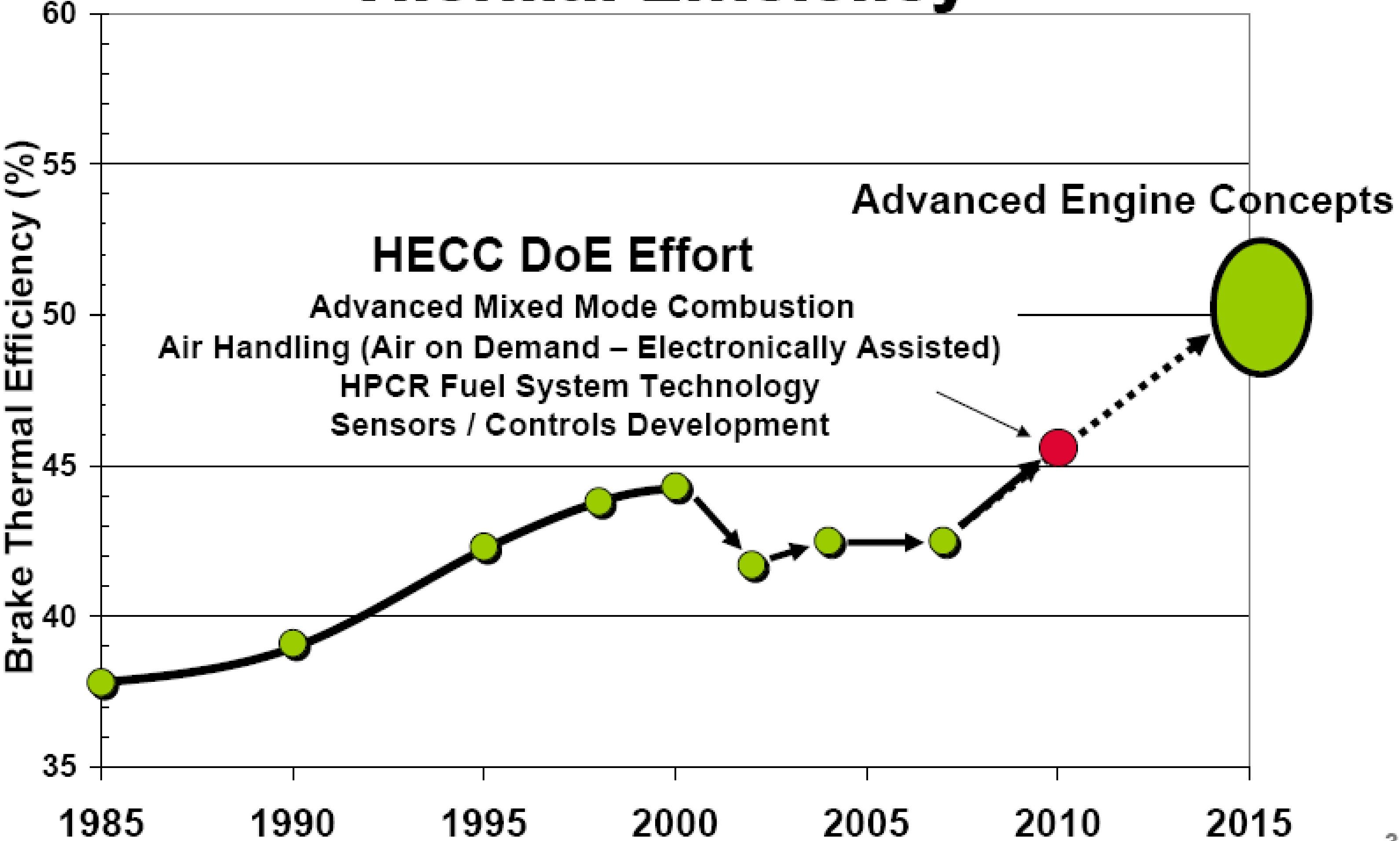
- Improved Analytical Tools – Models, Simulation

Future Needs – Engine Efficiency

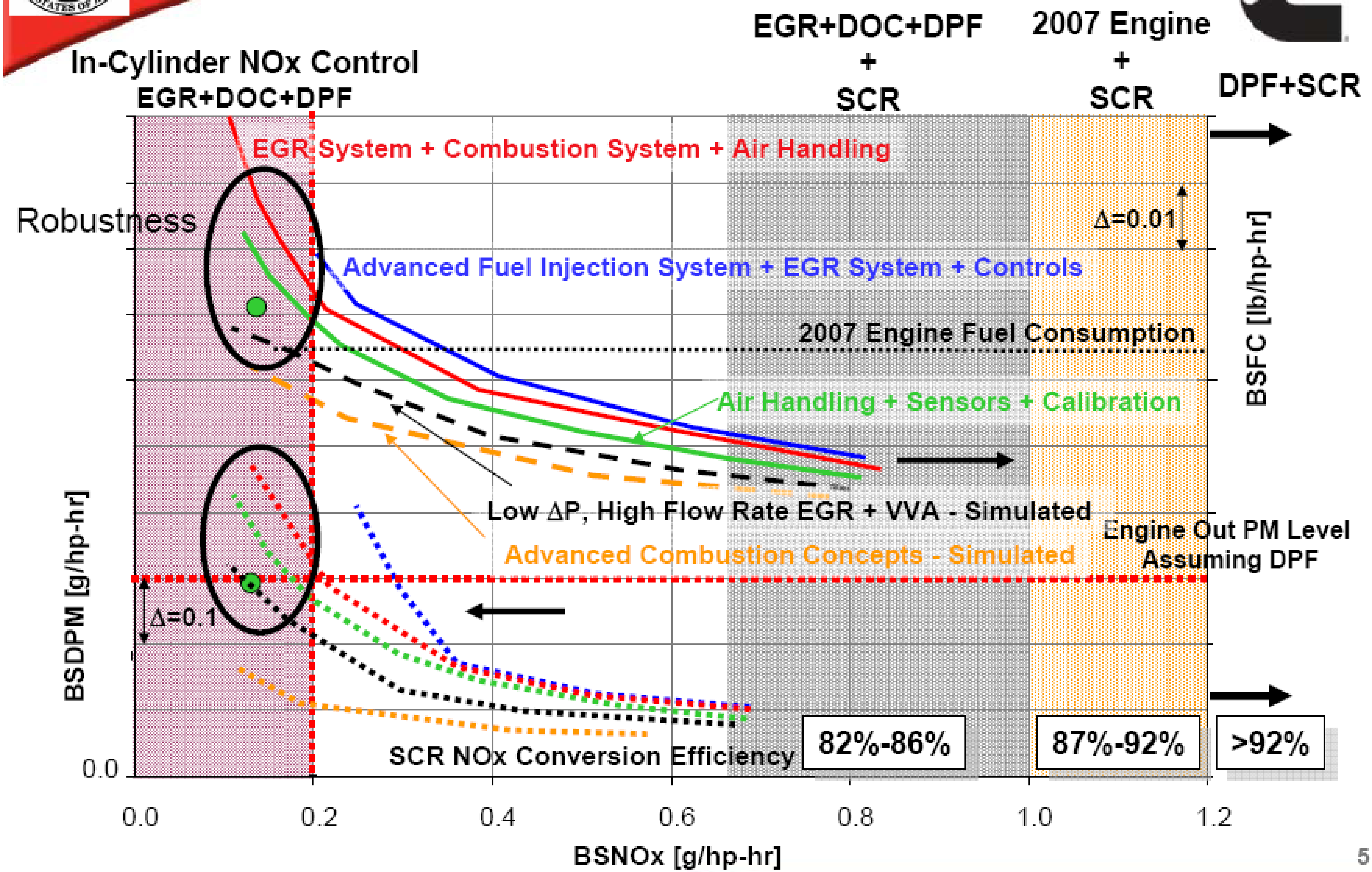
- More efficient combustion systems / fuels
- Reduced engine parasitic losses / lubricants
  - Smart accessories – variable delivery options
  - Electrically driven accessories
- Waste Heat Recovery & Bottoming Cycles
- Hybrid Power Trains – LD, MD & HD
- Auxiliary Power Units / Anti-Idling Technologies
- Engine weight reduction – lightweight materials

- Improved Analytical Tools – Models, Simulation

Historical Perspective of HD Brake Thermal Efficiency

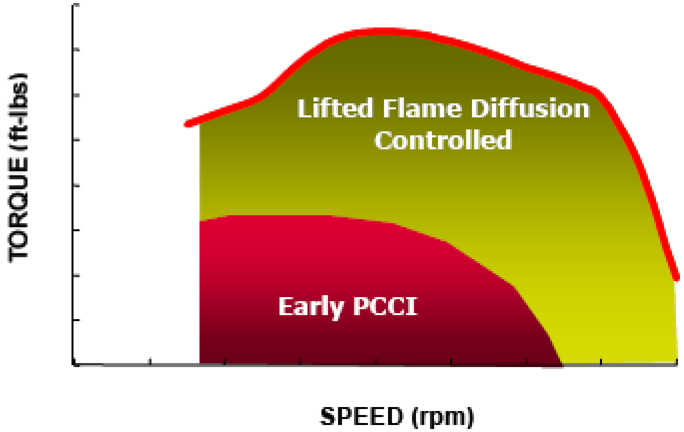


Achieving a Wide Range of Engine Out NOx Capability



Challenges for Lifted Flame Combustion

- Creating desired intake valve closing conditions
  - A/F, EGR, IMT
- Fuel injection system technology
  - Injection pressure
  - Nozzle configuration
- Fuel injection plume to plume interaction
- Combustion surfaces
  - Difficult to scale to smaller bore engines
- Controls development for transient operation



US - Beyond 2010

- NOx and PM standards – Near Zero
- Customer pressure on Fuel Economy
- Regulatory pressure on CO_2
- Continued emphasis on OBD and In-Use Testing
- Increasing <u>customer expectations</u>:
  - Operating Cost Improvements despite rising fuel prices
  - Extended Service Intervals
  - Higher Uptime & Reliability
  - Integrated Remote Information Systems (Telematics)
  - Higher Gross Vehicle Weights?
  - 1M Mile Durability, High Residual Value

Summary, Closing Remarks

- Clean & Efficient Diesel Engines will play a key role in achieving climate & energy goals
- Diesel engines are the most fuel-efficient power source available – BUT further improvement must be made …
  - 50+% BTE by 2015 ?
  - Advanced Mixed Mode Combustion
  - Waste Heat Recovery / Bottoming Cycles
  - HD Hybrid ?
  - Anti-Idling Technologies

Thank You !