DETROIT DIESEL CORPORATION

Model-Based Transient Calibration Optimization for Next Generation Diesel Engines

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Presentation Topics

- Diesel Engine Technology Trends
- Calibration Requirements
- Model-Based Calibration
- Transient Engine Model Development
- Rapid Transient Calibration Optimization
- Results
- Model-Based Control and Diagnostics
- Summary

Diesel Engine Technology Trends

- Ever Decreasing Emissions Requirements
- Ever Increasing Fuel Economy Demands
- Increasing Mechanical and Electronic Complexity of Engines
- Cost Reduction Demands
- Reduced Product Engineering Development Cycles
- Increasing Demands on Transient Test Facilities

Technical Challenges

- Rapidly Increasing Complexity of Engine Control
- Integration of Aftertreatment Control
- New Low Temperature Combustion Regimes
- Emissions Testing – FTP, In-Use, NTE
- 435,000 Mile Useful Life Requirements
- HD OBD Requirements

All Of These Lead To A Significantly Increased Calibration Burden.

Diesel Engine Complexity

Year	Engine Technologies	Number of Calibrateable Parameters
1998	Injection Timing Injection Pressure	3
2004	Injection Timing Injection Pressure EGR Turbocharging Control	4 - 5
2007+	Injection Timing (multiple) Injection Pressure EGR Turbocharging Control Aftertreatment Control	11 - 15+

Increasing Calibration Complexity

YEAR	Actuators	Sensors	Control Outputs
1998	2	8	3
2002	4	10	3
2004	8	15	5
2007	10	19	11
2010	12	22	15

Full Factorial Calibration Space

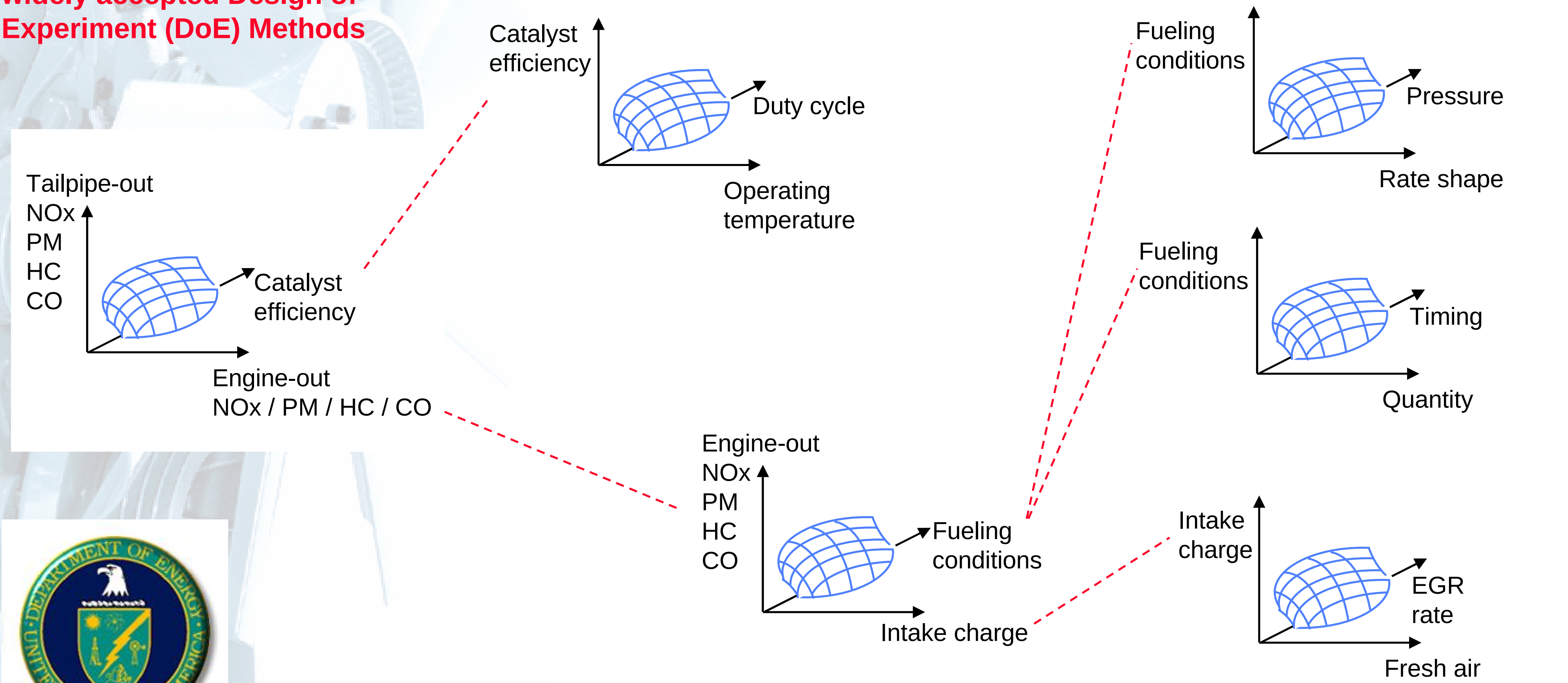
Year	Engine Control Parameters	Number of Discrete Test Setpoints
1998	Speed, Load, Injection Timing & Pressure	10,000
2002	Speed, Load, Injection Timing & Pressure, EGR	100,000
2004	Speed, Load, Injection Timing & Pressure, EGR, Turbocharging Control	1,000,000
2007	Speed, Load, Multiple Injection Timing, Injection Pressure, EGR, Turbocharging Control, Particulate Filter Regeneration	1,000,000,000
2010	Speed, Load, Multiple Injection Timing, Injection Pressure, EGR, Turbocharging Control, Aftertreatment Controls	10,000,000,000

The Challenge for Calibration

- The Curse of Dimensionality – a 2007 specification diesel engine might have 10^9 test points if tested in a full factorial experiment
- Calibration requirements may increase by 2-3 orders of magnitude by 2010-2014 due to new engine technologies
- Design of Experiments can reduce the overall engine mapping burden significantly (perhaps by a factor of 100), but this still results in huge experimental matrices
- And, steady state engine mapping not well suited to TRANSIENT emissions regulations, fuel economy reduction, driveability and aftertreatment regeneration.

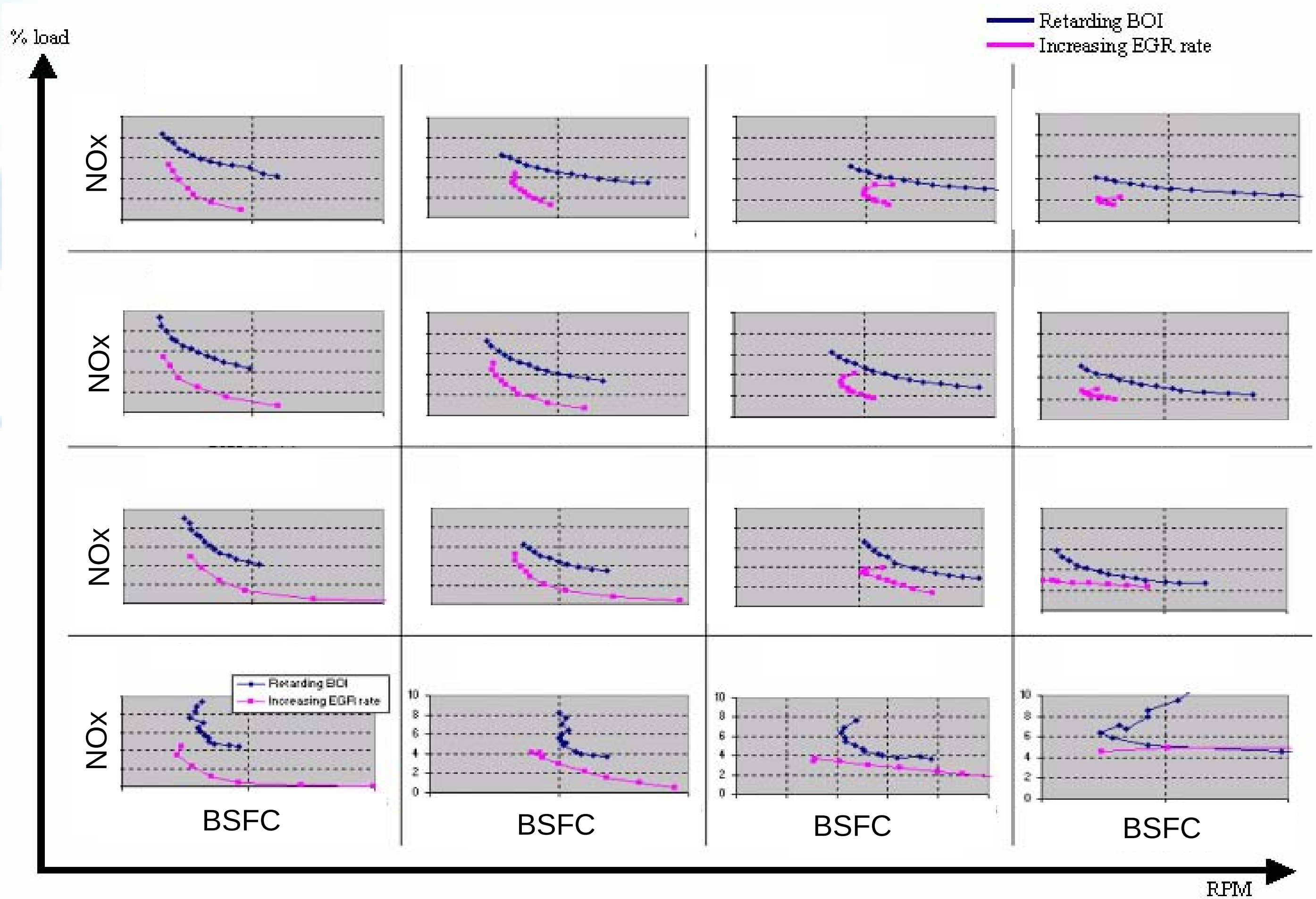
Steady-State Degrees of Freedom

Steady-State Calibration Is handled adequately through widely accepted Design of Experiment (DoE) Methods



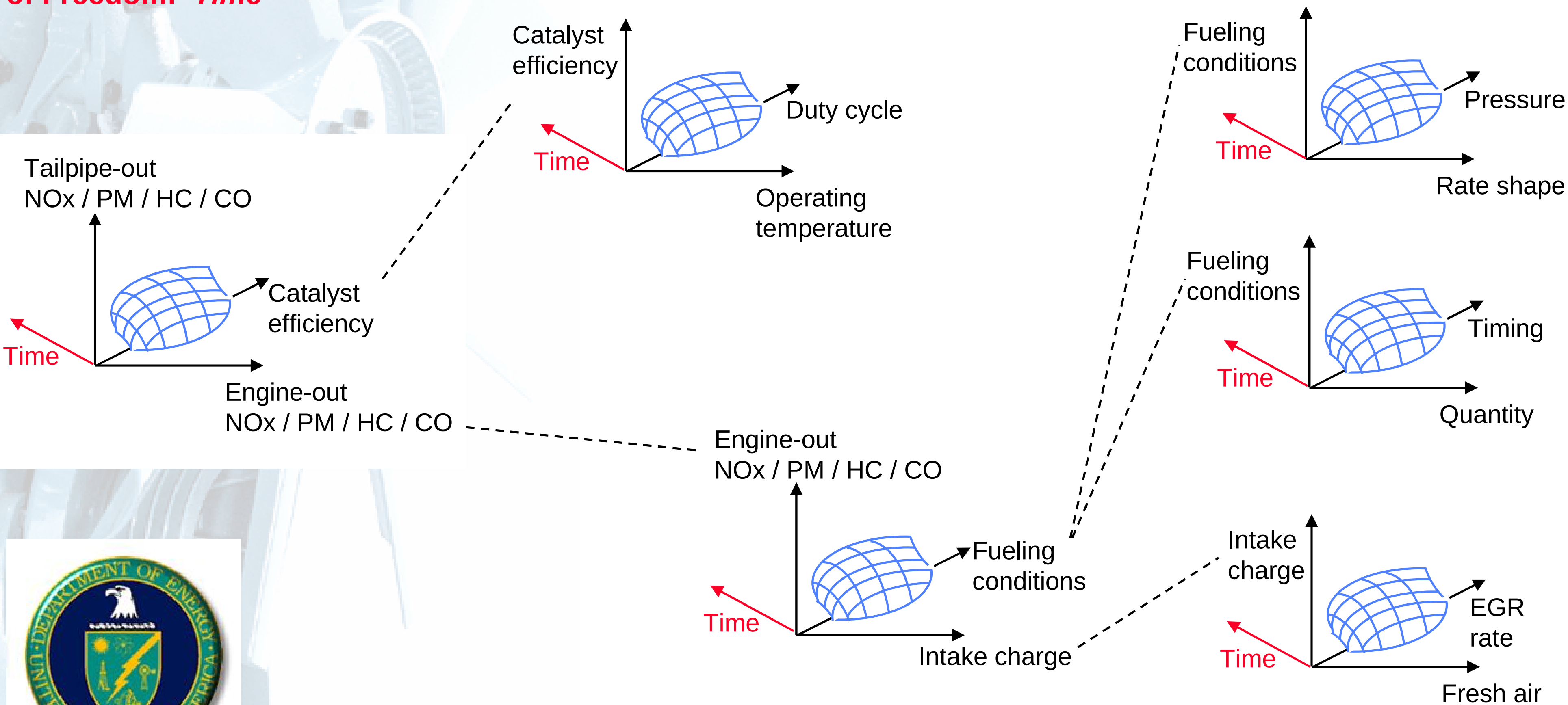
Steady-State Performance Mapping

- For Steady-State Calibration, Static Engine Performance Mapping Is Sufficient
- Time-Consuming Process
- Results Not Directly Applicable to Transient Calibration

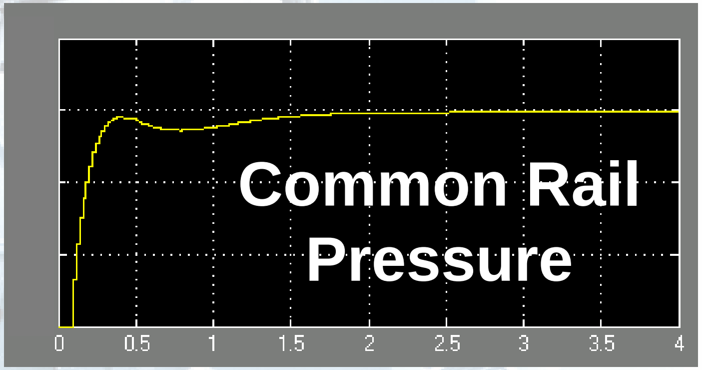


Transient Degrees of Freedom

Transient Engine Calibration must account for an additional Degree of Freedom: *Time*



Competing & Overlapping Time Scales



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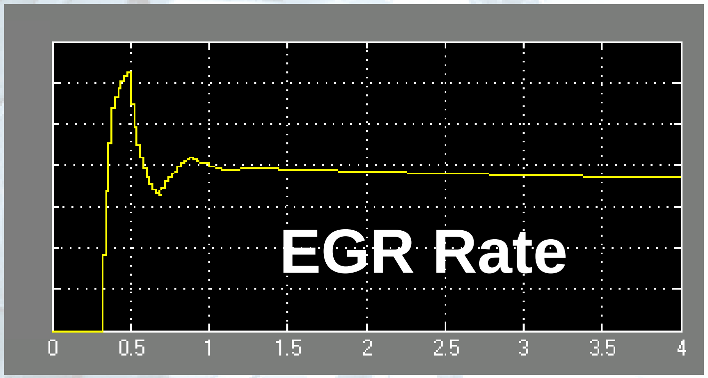

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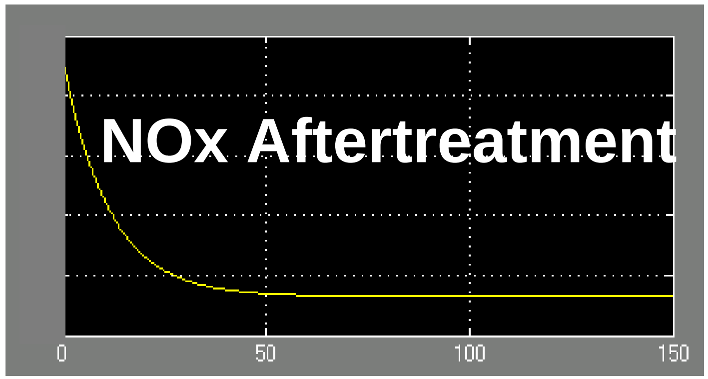

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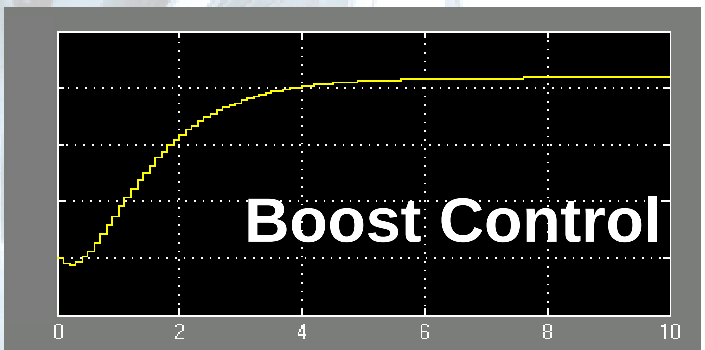

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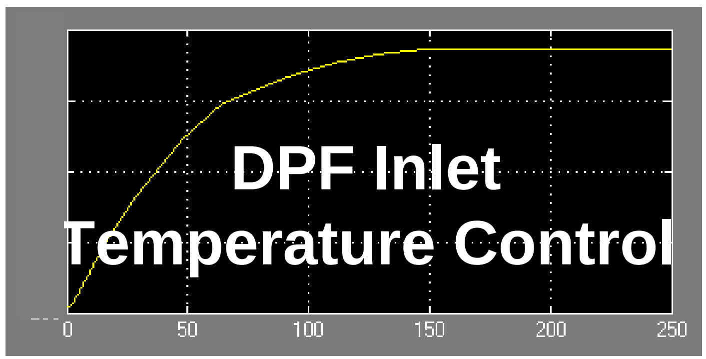


Time - sec

- **Step Response Of Individual Engine Systems**
- **Orders of Magnitude Difference in Transient Response**
- **Including *Time* as an integral part of the Setpoint Definition Process enables optimum Transient Calibration**
- **Transient Engine Performance Mapping corresponds to a Transient Design Of Experiment**

Engine Operating Modes

Calibration Requirements are increased further due to Multiple Engine Operating Modes including

- Steady-state
- Transient
- Cold
- Altitude
- Smoke Control
- Aftertreatment Regeneration

(predominantly transient or dynamic phenomena) and varying ambient or exhaust conditions

Model-Based Calibration

Problem: How can engine calibration be performed quicker, better and cheaper?

Solution: Transfer the majority of the calibration burden out of the Engine Test Cell and onto the engineer's desktop, using MODEL-BASED Rapid Transient Calibration Methods.

Model-Based Methods

A definition of model-based methods, relevant to engine calibration, is

"a combination of first principles, equation-based modeling and data-based techniques used to develop high fidelity, real-time dynamic models, suitable for predicting engine emissions, performance and operating states over highly transient operating cycles".

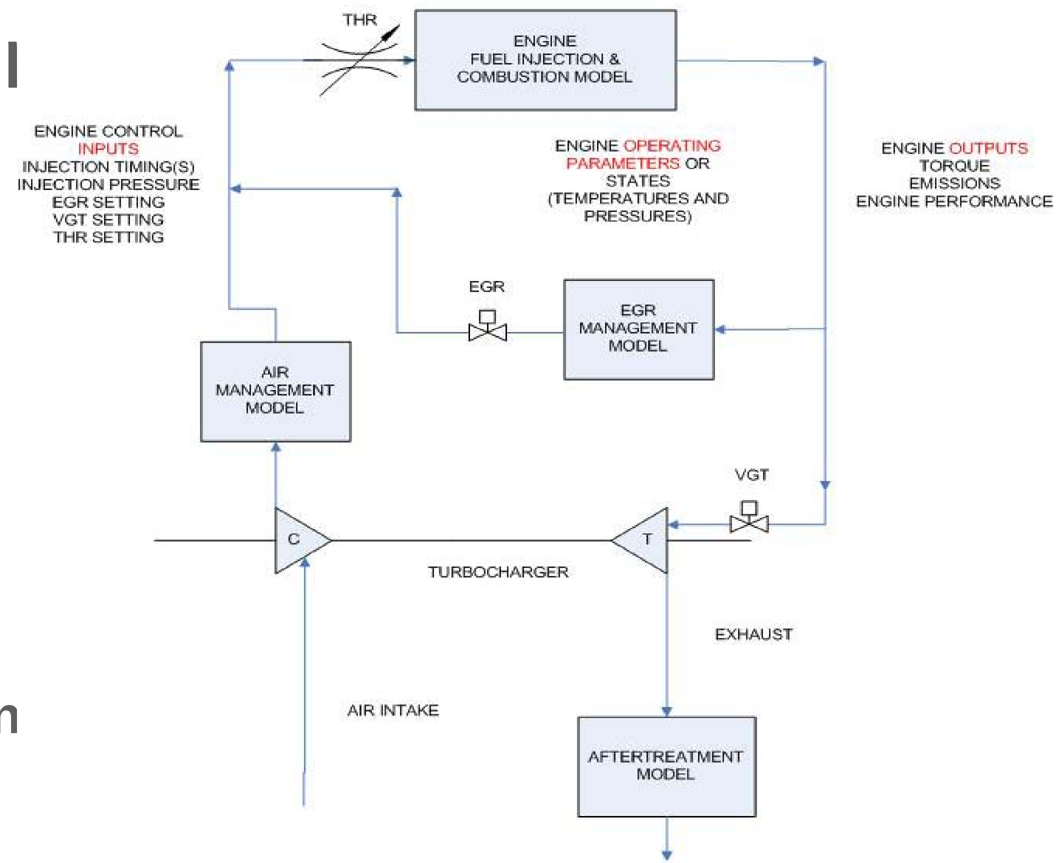
Modeling Approach

Dynamic (transient) models use a combination of

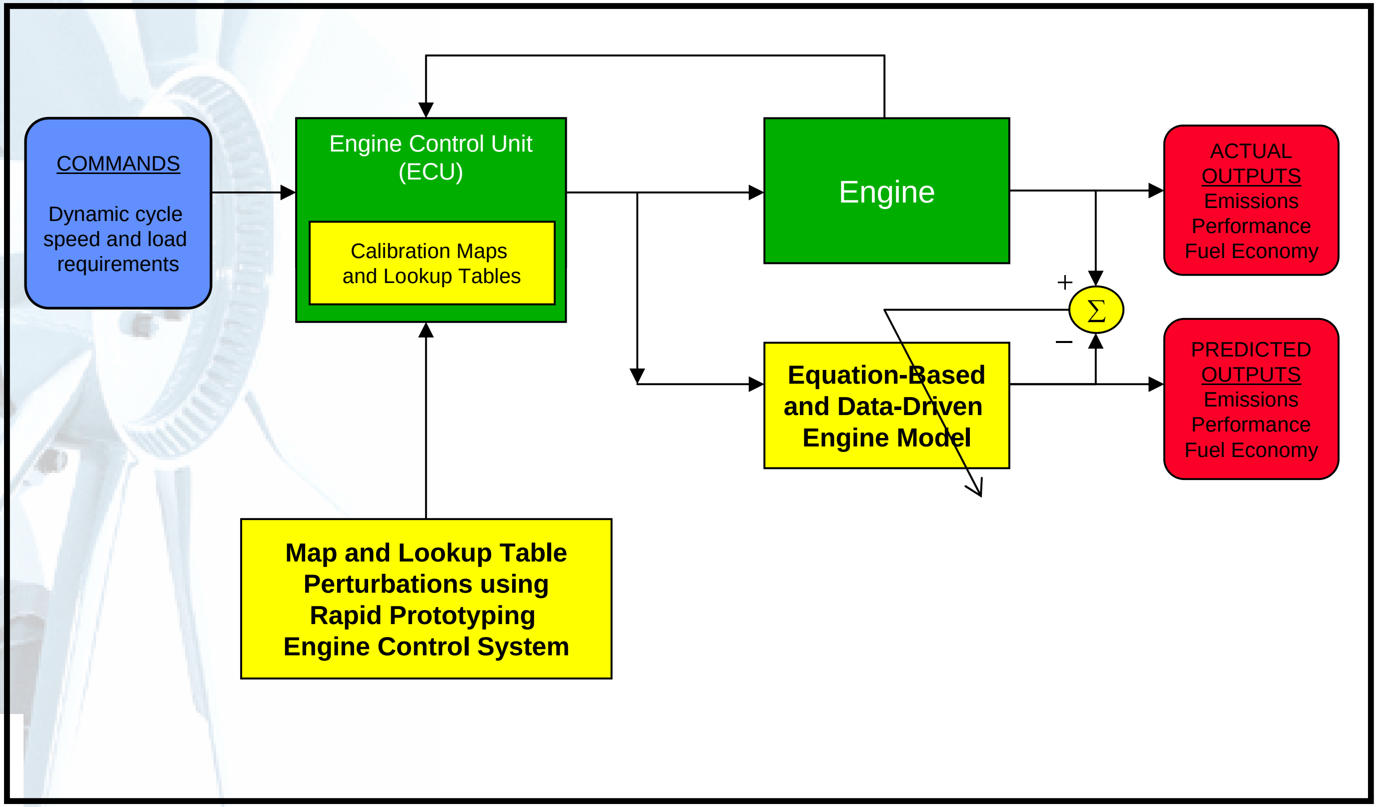
- **Physical Modeling**
  - First principles
  - Equation-based
  - Phenomenological
- **Heuristic Modeling**
  - Data-driven
  - Learning
  - Data from actual engine operation (real time emissions, performance, fuel consumption and operating states).

Example of a Transient Engine Model

- Composite Model made up of Interacting Sub-models:
  - Air Flow Model
    - Volumetric Efficiency
  - EGR Flow Model
    - Charge Estimation
  - Fuel Injection and Combustion Model
    - Air-Fuel Ratio Estimation
    - Thermal Effects
    - NOx and PM Formation Sub-models



Transient Model Development



Diesel Engine Modeling

Direct Injection Diesel Engine

INPUTS

Engine Speed
Fuel Injection Quantity
Injection Timing
Injection Pressure
Exhaust Gas Recirculation
Variable Geometry Turbocharger Setting

→

Equation-Based and Data-Driven Engine Model

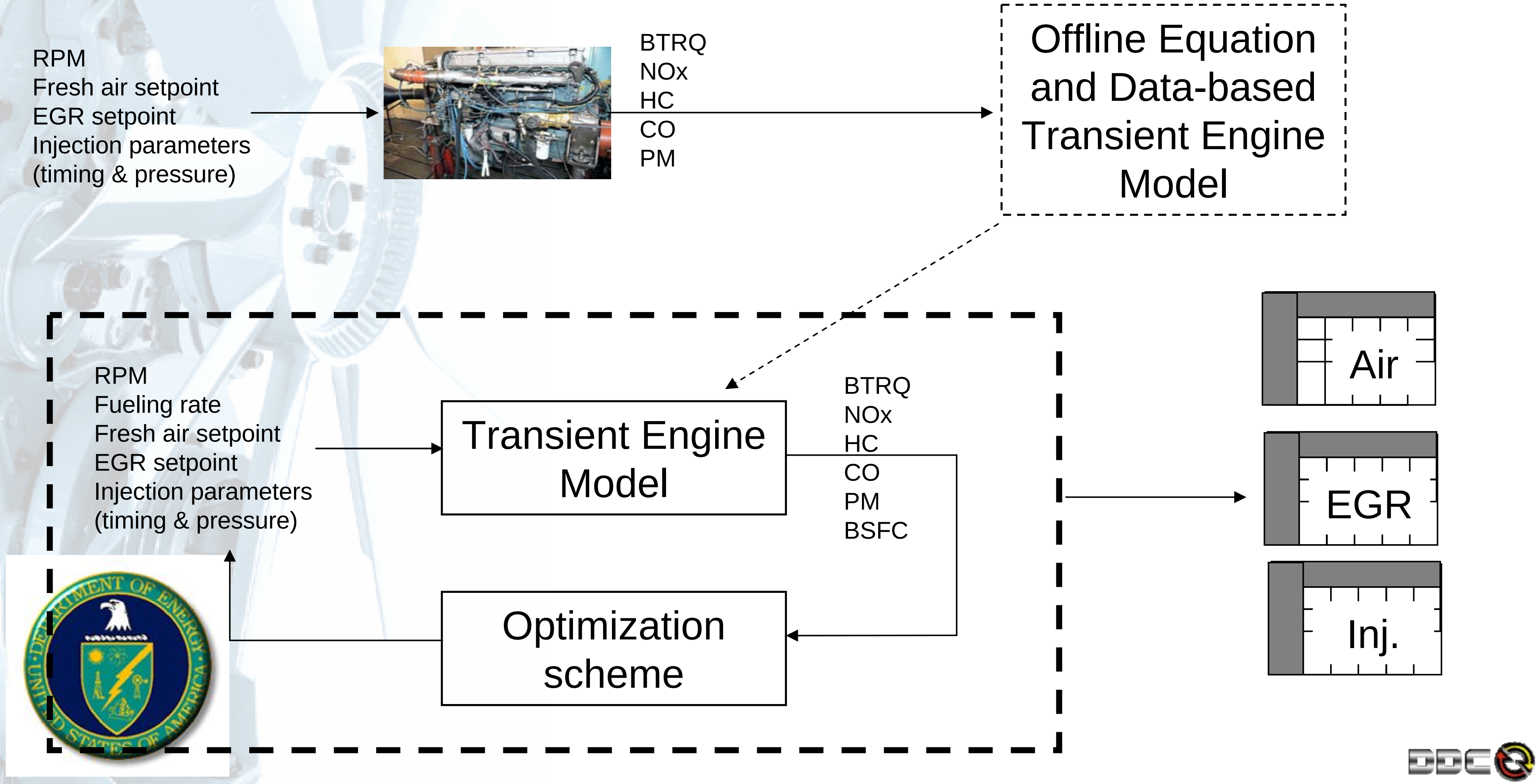
→

OUTPUTS

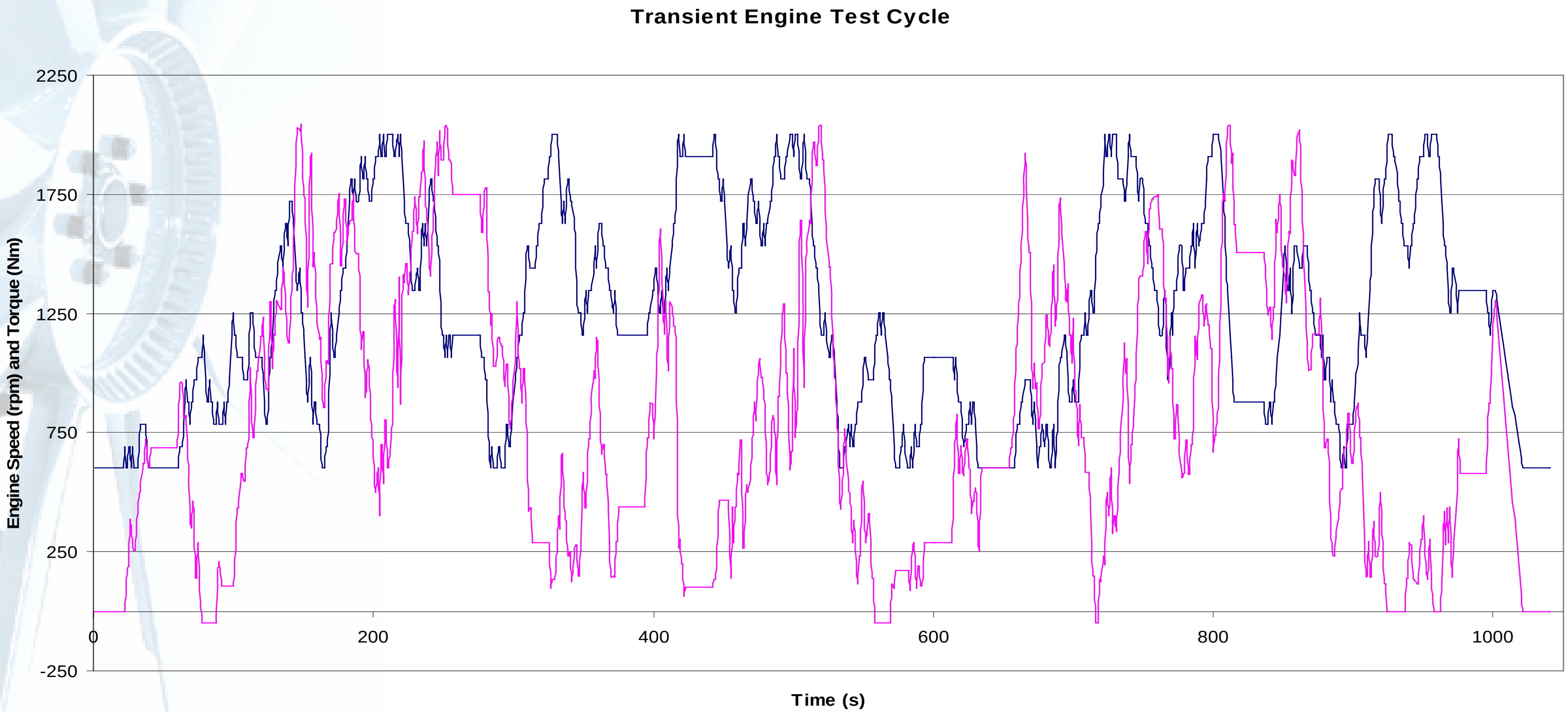
Torque
Emissions
- HC
- CO
- NOx
- CO2
- PM

Exhaust Temperature
Exhaust Pressure
Turbo Speed
Combustion Pressure

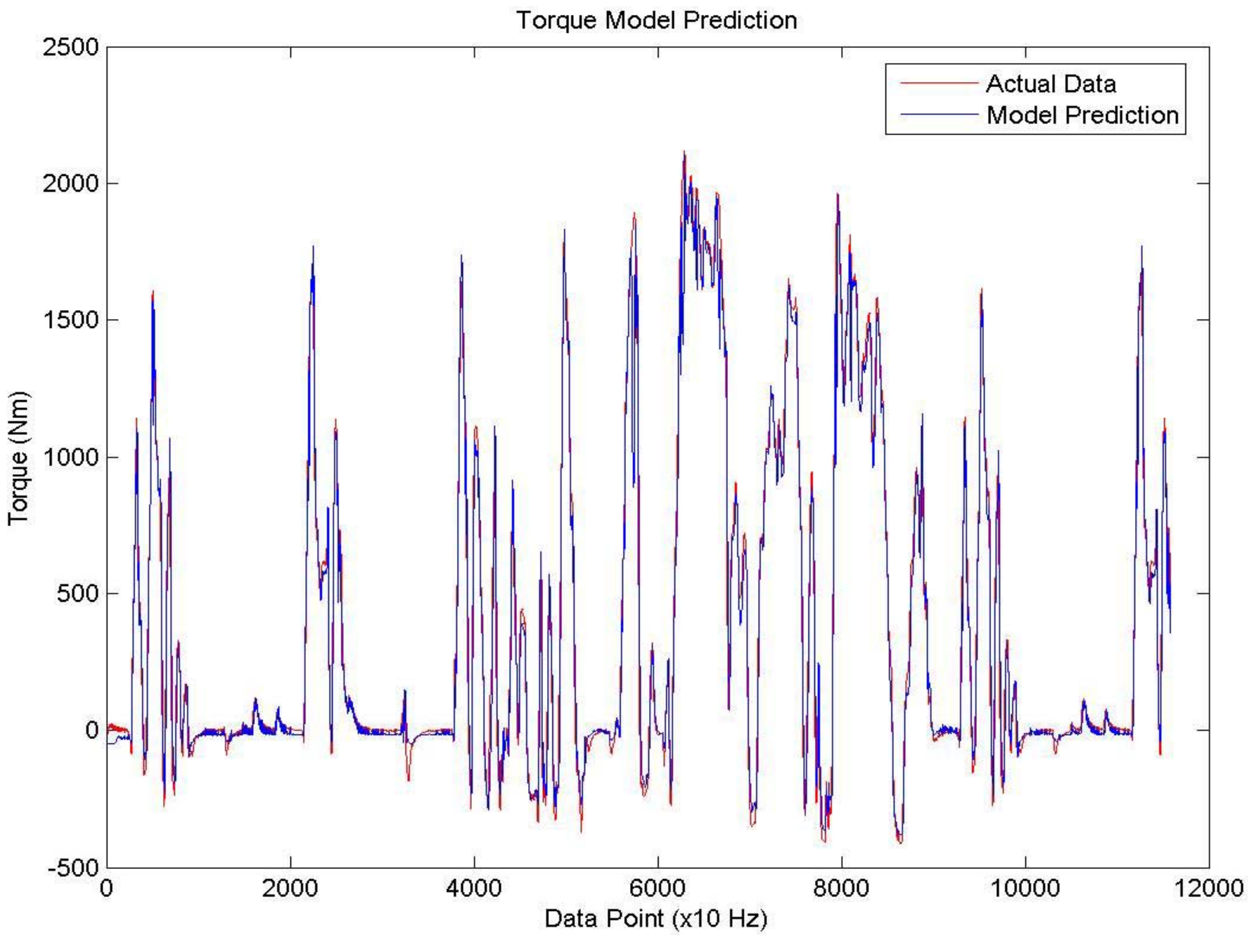
Transient Design Of Experiment



Transient Engine Test Cycles

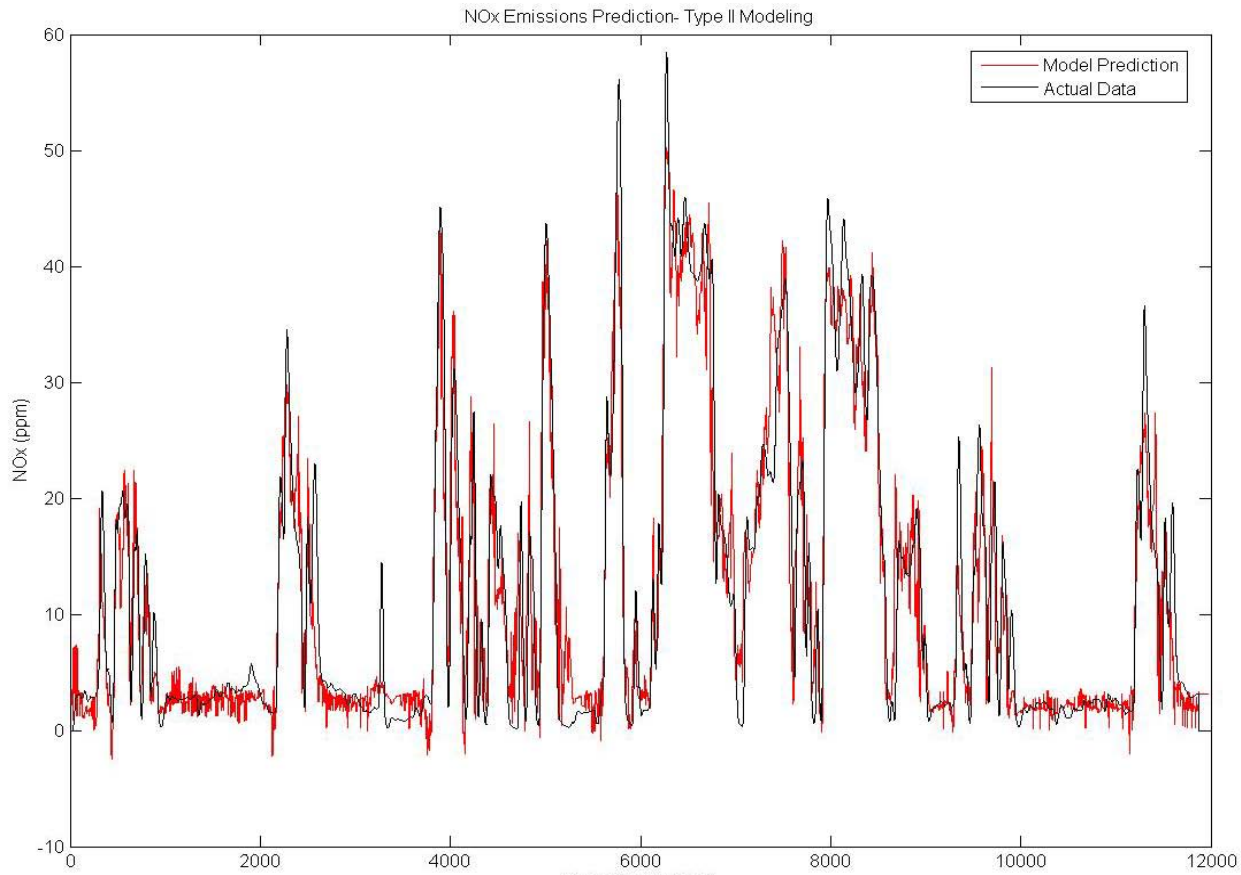


Transient Engine Modeling Results - Torque



Transient Engine Modeling Results - NOx

NOx

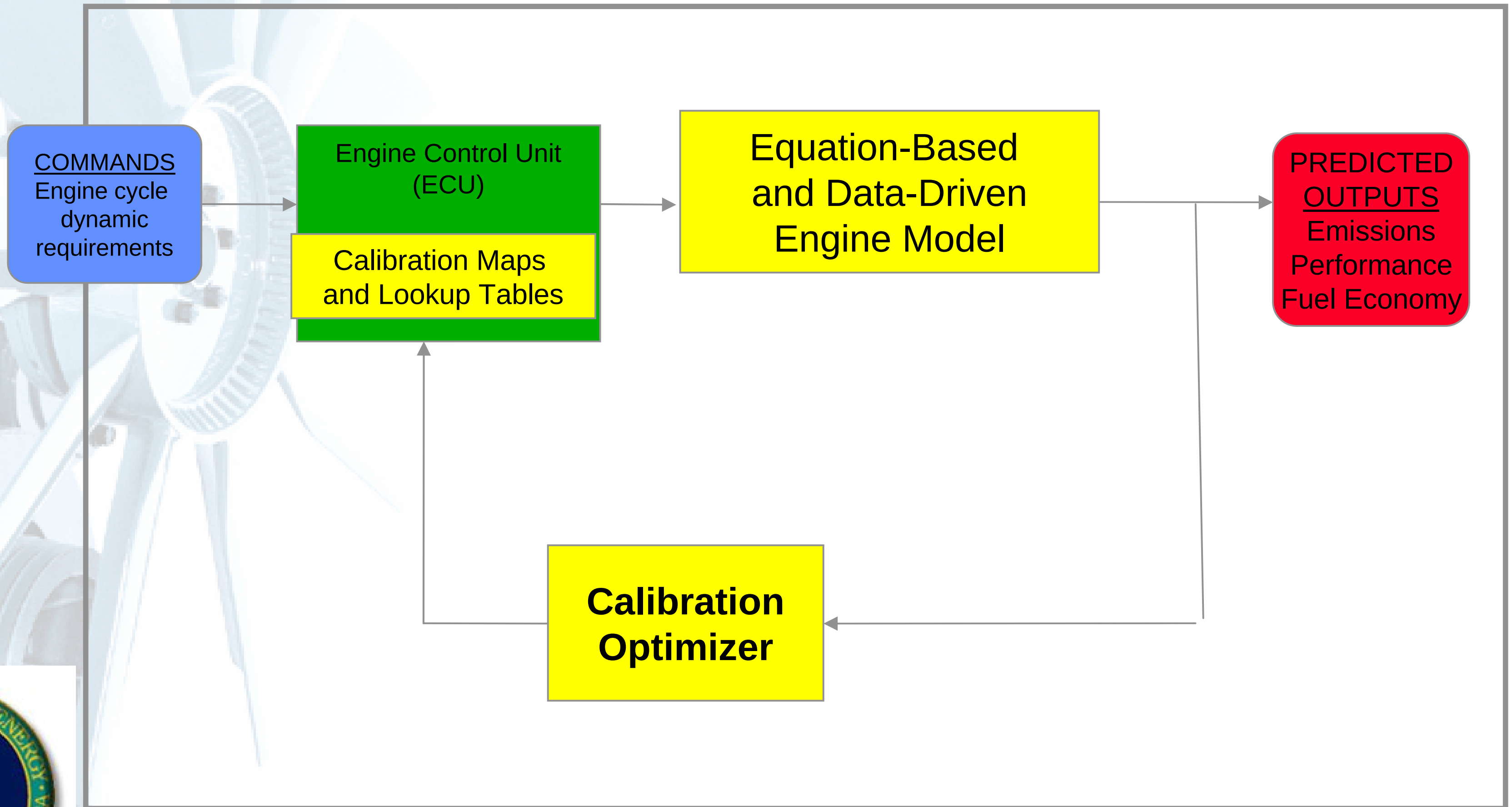


Time

Typical Model Emissions Prediction Accuracy

NOx, CO_2 (instantaneous)	2-5%
CO, HC (instantaneous)	5-10%
PM (instantaneous)	5-10%
NOx, CO_2 (integrated)	2-3%
CO, HC (integrated)	3-5%
PM (integrated)	5-6%
Fuel consumption	1-3%

Rapid Transient Calibration Optimization



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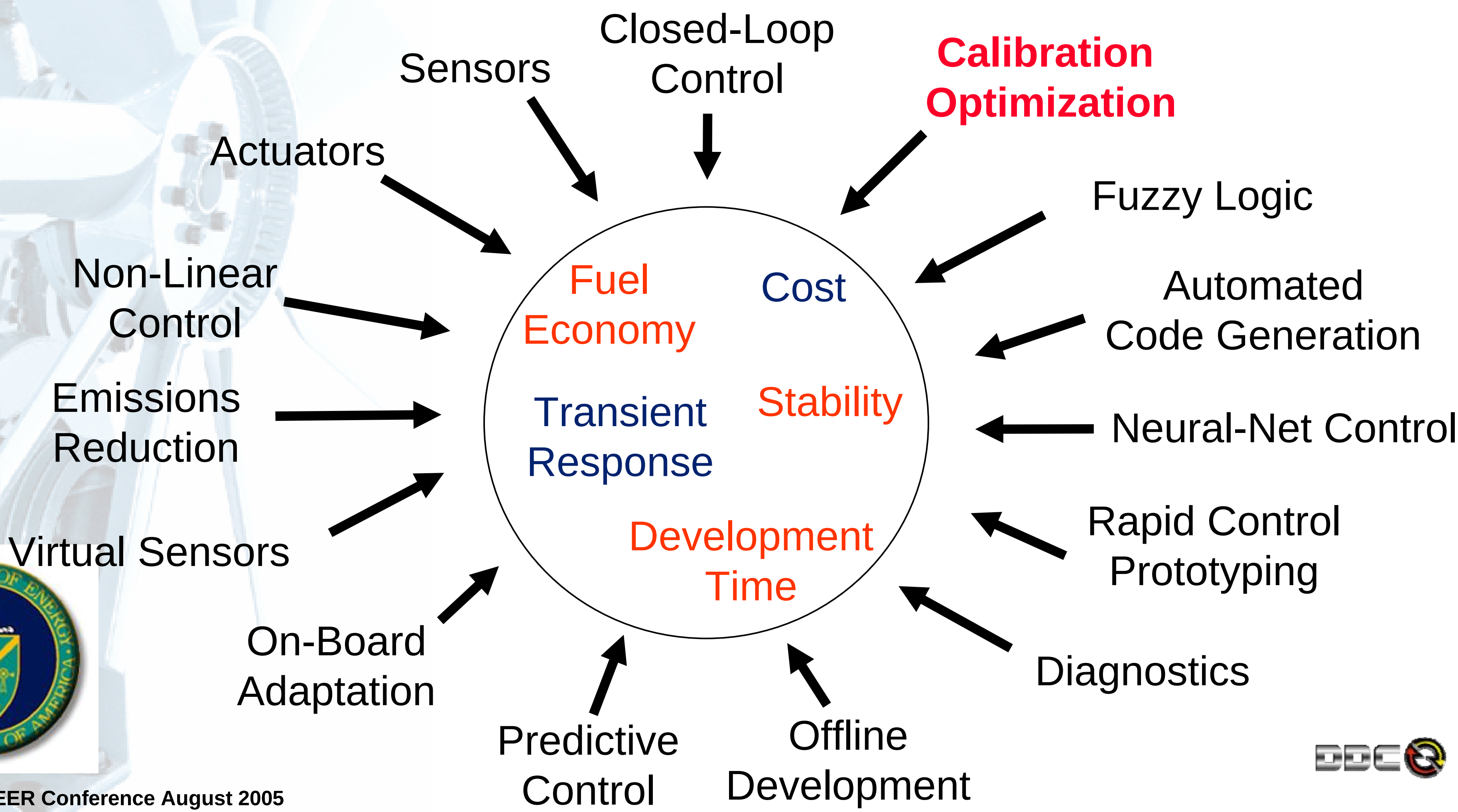
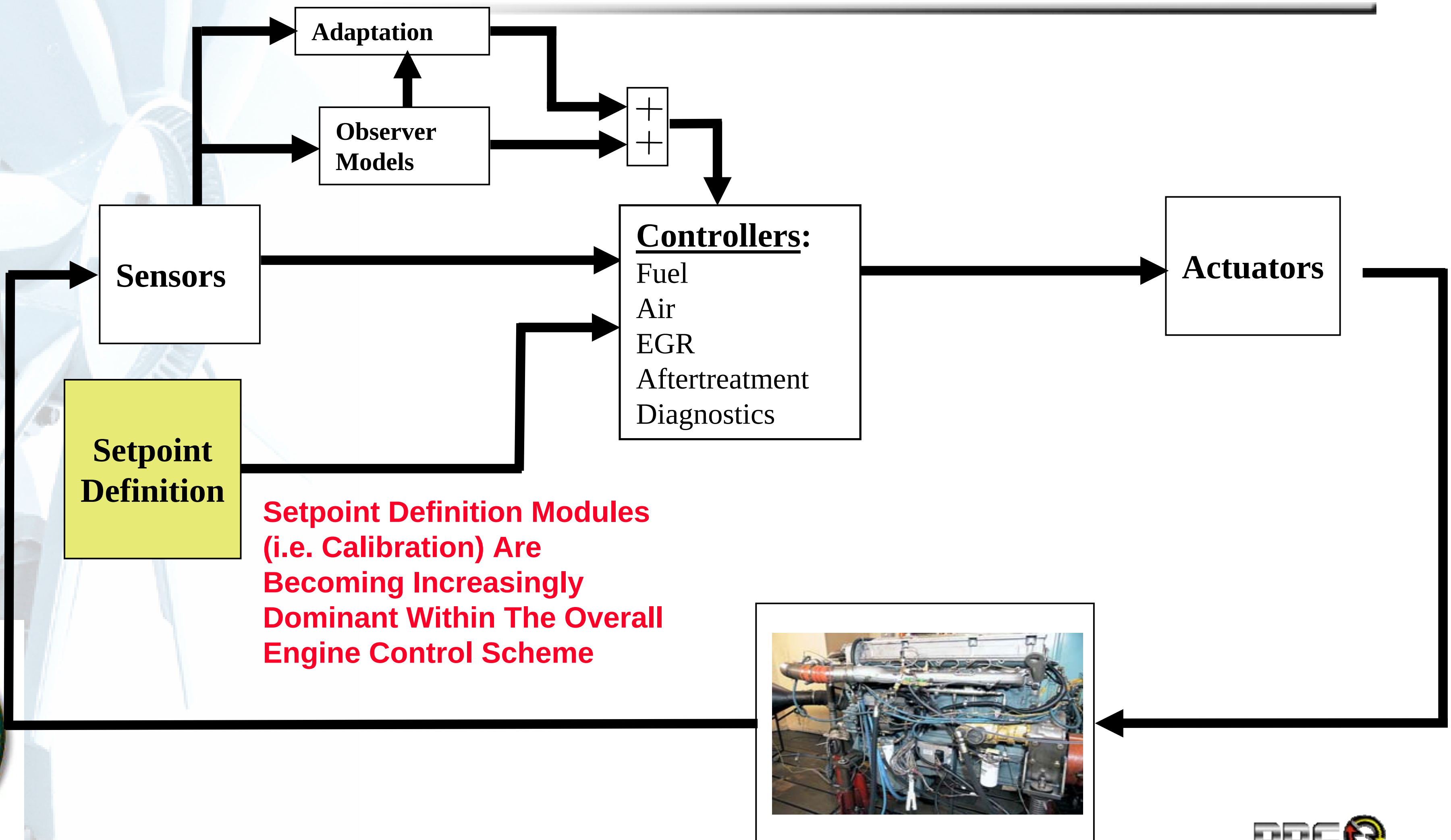
Transient Calibration Optimization Functions

- **Cost function –** minimize **fuel consumption,**
- **Subject to the** constraint **of meeting NOx and PM emissions integrated across a transient cycle,**
- **While** not exceeding **certain engine operating state parameter levels, such as turbocharger speed, peak cylinder pressure and peak injection pressure,**
- **While also** meeting **NTE emissions levels.**

Model-Based Technologies under Development



Model-Based Control Components



Setpoint Definition Modules (i.e. Calibration) Are Becoming Increasingly Dominant Within The Overall Engine Control Scheme

Summary

- Model-based methods can transfer a significant portion of the engine calibration burden from the test cell to the desktop
- Transient engine models are the technology required to meet the transient emissions regulations and operating requirements
- A combined equation-based and data-driven engine modeling approach offers high model fidelity and predictive capability
- Calibration optimization is well suited to the computational environment
- As engine mechanical and electronic complexity increases, so these methods will become more important and useful.

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