DETROIT DIESEL CORPORATION

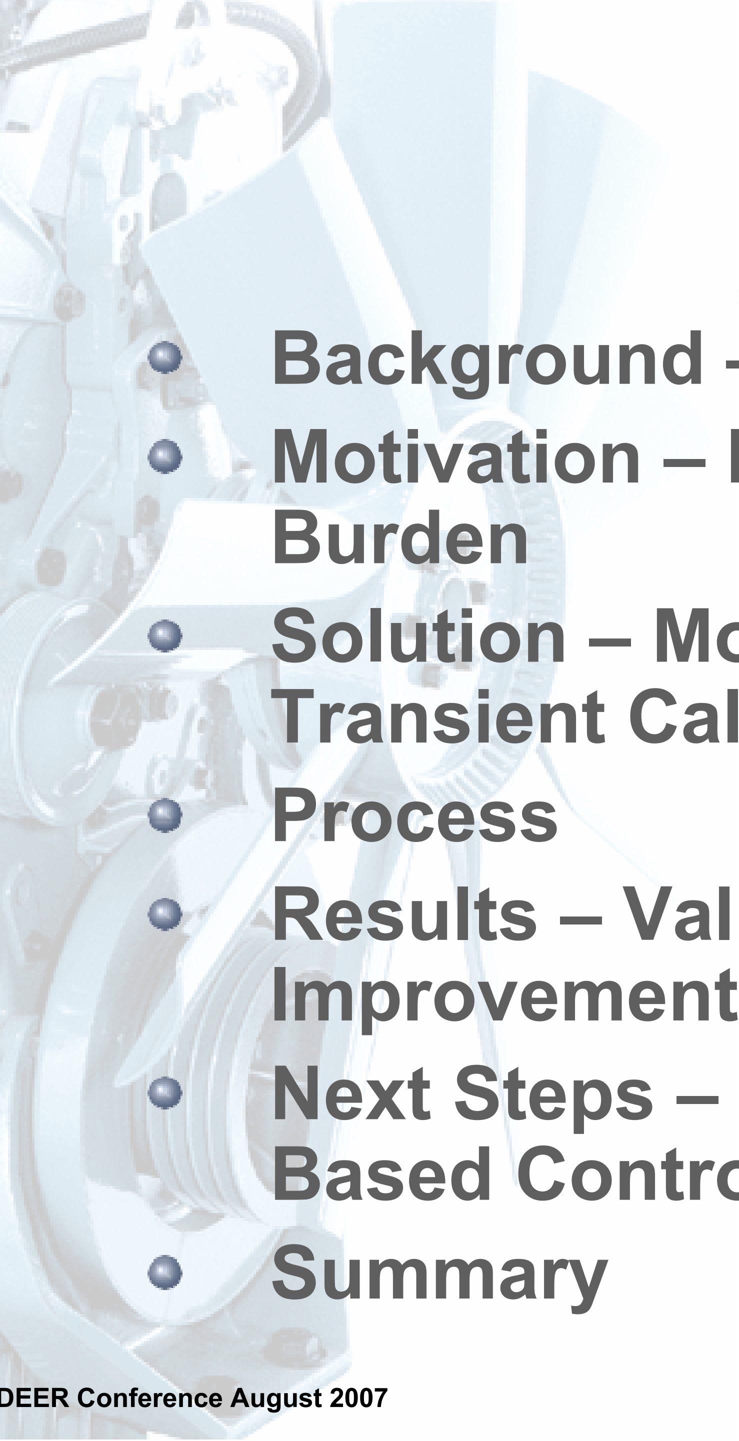
Atkinson LLC

Fuel Efficiency and Emissions Optimization of Heavy-Duty Diesel Engines using Model-Based Transient Calibration

Chris Atkinson
Atkinson LLC
&
Marc Allain, Houshun Zhang, Yury Kalish & Craig [illegible]vonen
Detroit Diesel Corporation

U.S. DEPARTMENT OF ENERGY

DETROIT MICHIGAN 2007 DIESEL ENGINE-EFFICIENCY & EMISSIONS RESEARCH CONFERENCE



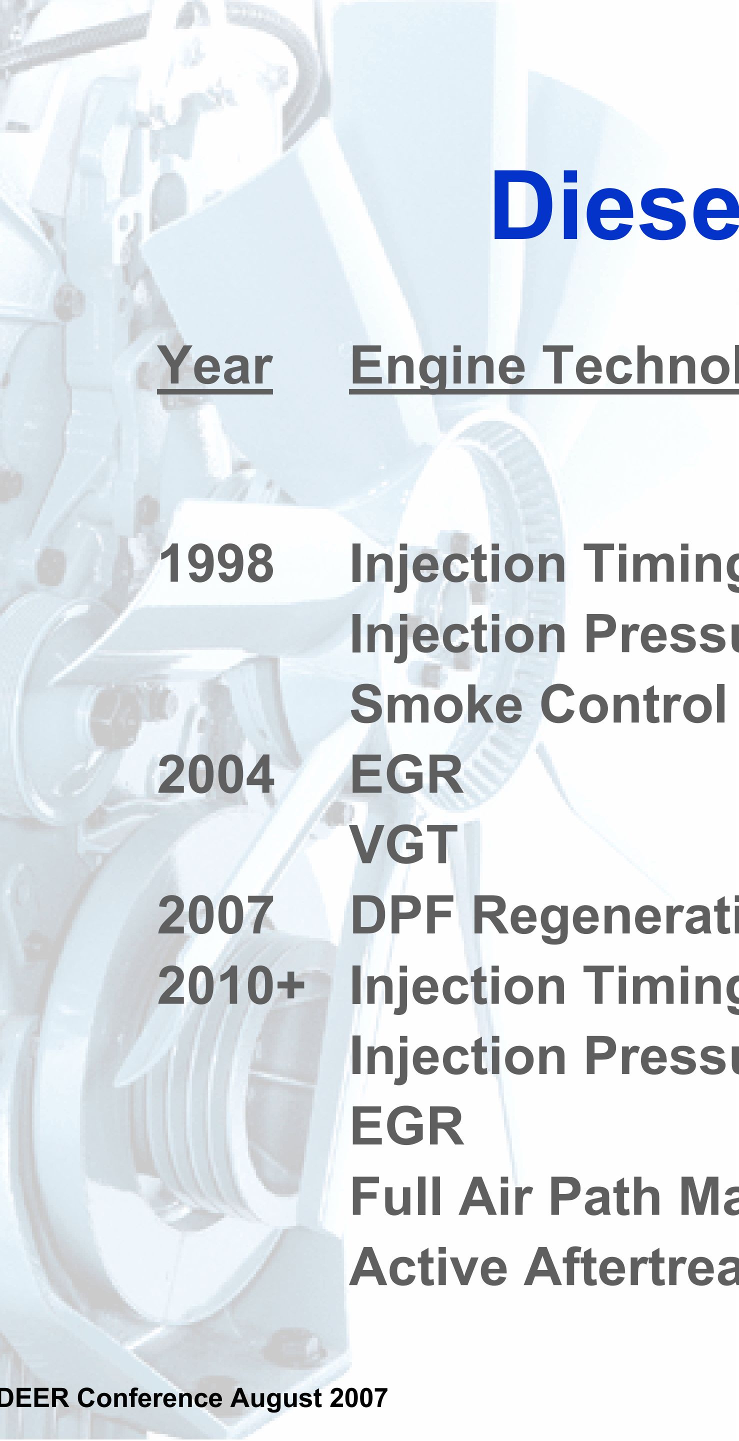
Presentation Topics

- Background – Diesel Engine Industry Trends
- Motivation – Increasing Control and Calibration Burden
- Solution – Model-Based Calibration and Rapid Transient Calibration Optimization
- Process
- Results – Validation of Fuel Efficiency Improvements and Emissions Compliance
- Next Steps – Further Improvements using Model-Based Control and Diagnostics
- Summary

Background – Industry Trends

- Ever Decreasing Emissions Levels
- Increasing Demands for Fuel Efficiency
- Rapidly Increasing Complexity of Engine Control
- Close Integration of Aftertreatment Systems
- New Combustion Regimes under Investigation
- Emissions Regulations – FTP, In-Use, NTE
- HD OBD Requirements

⇒ All Of These Lead To A **Significantly Increased** Calibration and Optimization Burden.



Diesel Engine Control Complexity

Year	Engine Technologies	Number of Calibrateable Control Parameters
1998	Injection Timing	3
	Injection Pressure	
	Smoke Control	
2004	EGR	4 - 5
	VGT	
2007	DPF Regeneration	6 - 7
2010+	Injection Timing (multiple)	11 - 15+
	Injection Pressure or Rate Shaping	
	EGR	
	Full Air Path Management	
	Active Aftertreatment Control	

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, Turbocharger Control	1,000,000
2007	Speed, Load, Injection Timing, Injection Pressure, EGR, Turbocharger Control, Particulate Filter Regeneration	10,000,000
2010	Speed, Load, Multiple Injection Timing, Injection Pressure, EGR, Turbocharger Control, Aftertreatment Controls	10,000,000,000

The Challenge for Calibration

- The Curse of Dimensionality – a 2007 specification diesel engine has 10^7 test points if tested in a full factorial experiment
- Calibration requirements will increase by 2-3 orders of magnitude by 2010-2014 due to new engine technologies
- Design of Experiments can reduce the overall engine steady-state mapping burden significantly (perhaps by a factor of 100), but this still results in huge experimental matrices
- Most importantly, steady state engine mapping not well suited to TRANSIENT emissions regulations, fuel consumption reduction, performance and aftertreatment regeneration.

Motivation – The Engine Development Dilemma

- How can engine calibration be performed quicker, better and cheaper?
- How do we improve real-world fuel efficiency while maintaining very low regulated exhaust emissions?
- How do we maximize the brake thermal efficiency of any given engine and aftertreatment hardware set?
- How can we further increase fuel efficiency through smart calibration and control?
- How can we do all of this without further overloading transient engine test facilities and without incurring significant extra expense?

Solution – Model-Based Calibration

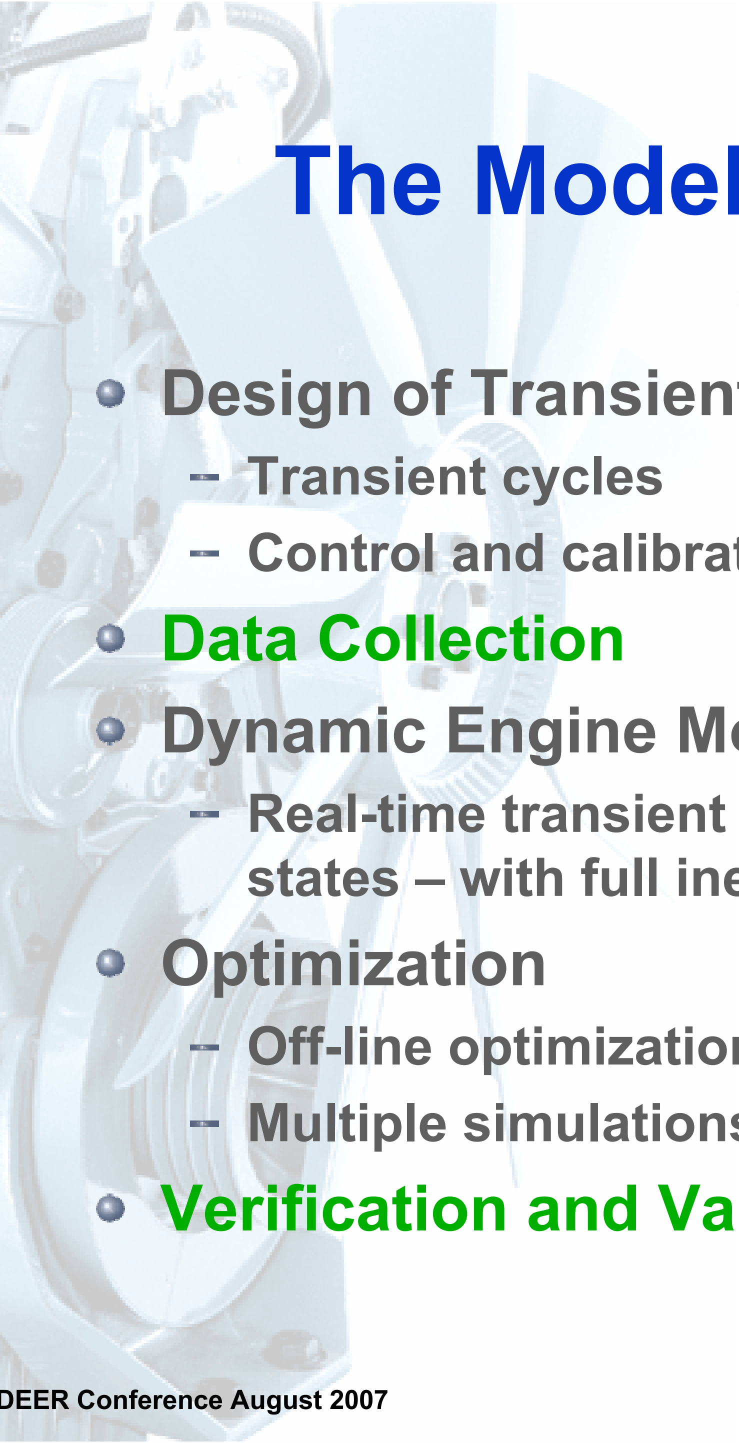
The Problem:

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

The Solution:

Transfer the majority of the calibration effort out of the transient test cell and onto the engineer’s desktop, using a systematic MODEL-BASED Rapid Transient Calibration approach.

The Model-Based Calibration Process

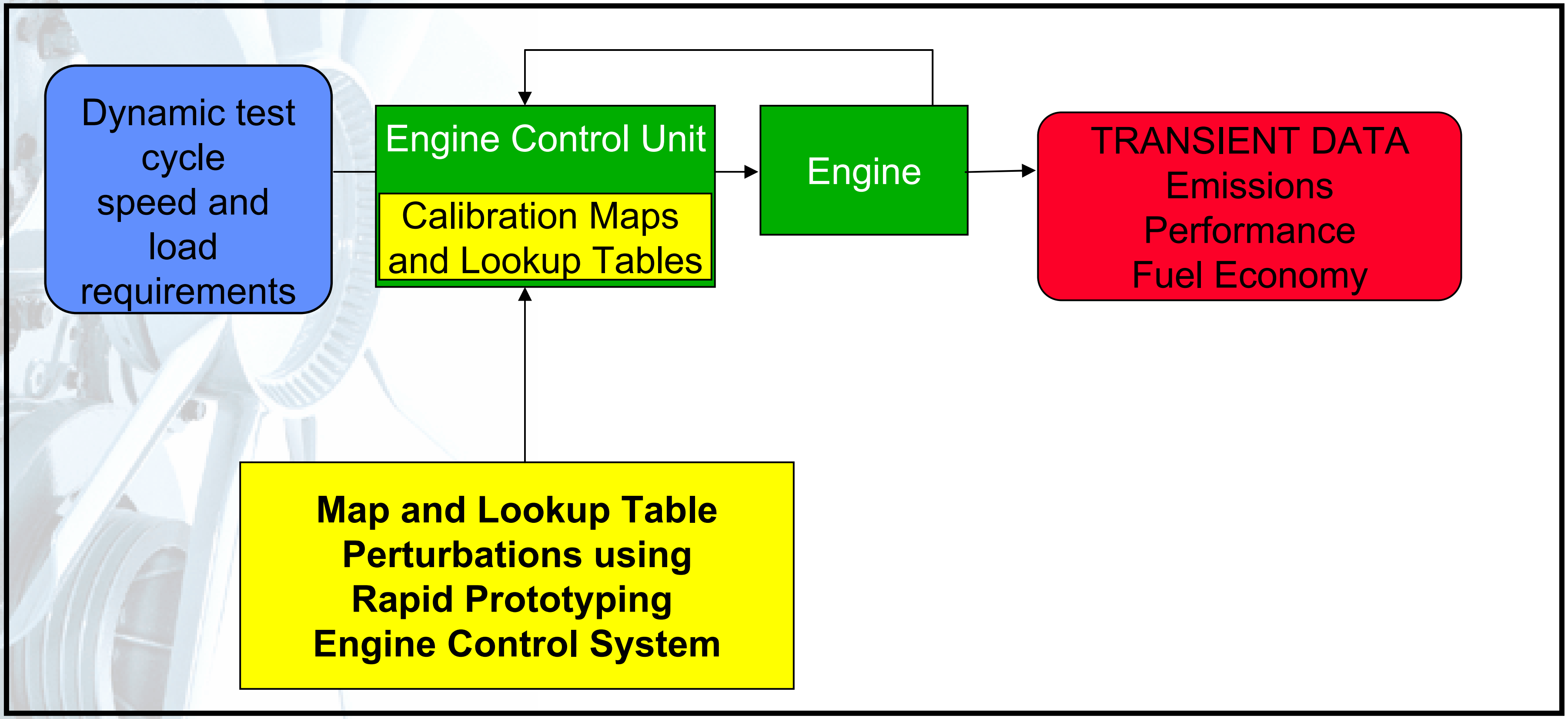


- Design of Transient Experiments
  - Transient cycles
  - Control and calibration perturbations
- Data Collection
- Dynamic Engine Modeling
  - Real-time transient engine performance, emissions and operating states – with full inertial, thermal, EGR and air path dynamics included
- Optimization
  - Off-line optimization of engine calibration
  - Multiple simulations with varying optimization weights
- Verification and Validation of Calibration Data Sets

First Application of this Technology

- Utilized a 2007-specification DDC Series 60 engine with EGR, VGT and DPF.
- 15 custom transient cycles developed and implemented (~10 dynamometer days).
- Dynamic engine models developed off-line.
- Calibration optimization performed off-line.
- Simulated engine performance performed off-line.
- Re-visited transient engine test cell for validation and verification (~10 dynamometer days).

Data Collection



Dynamic test cycle speed and load requirements

Engine Control Unit

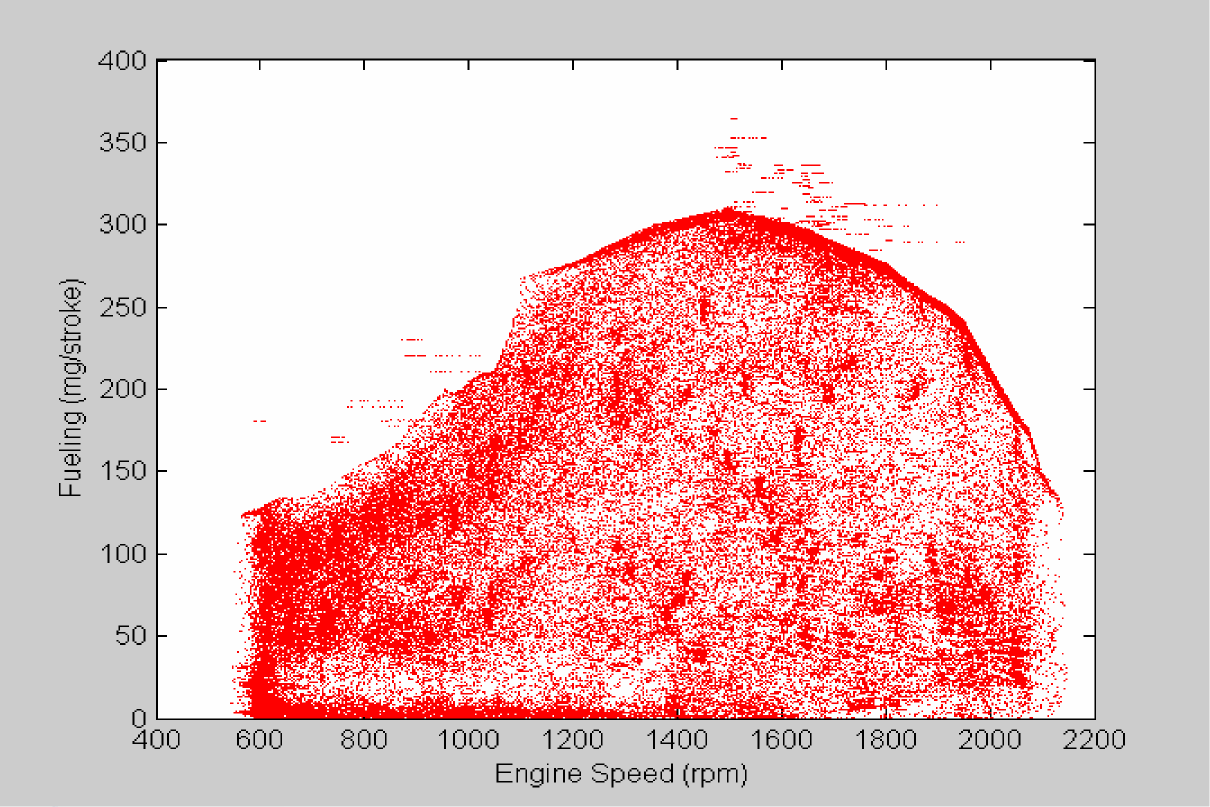
Calibration Maps and Lookup Tables

Engine

TRANSIENT DATA
Emissions
Performance
Fuel Economy

Map and Lookup Table Perturbations using Rapid Prototyping Engine Control System

Transient Engine Data Coverage



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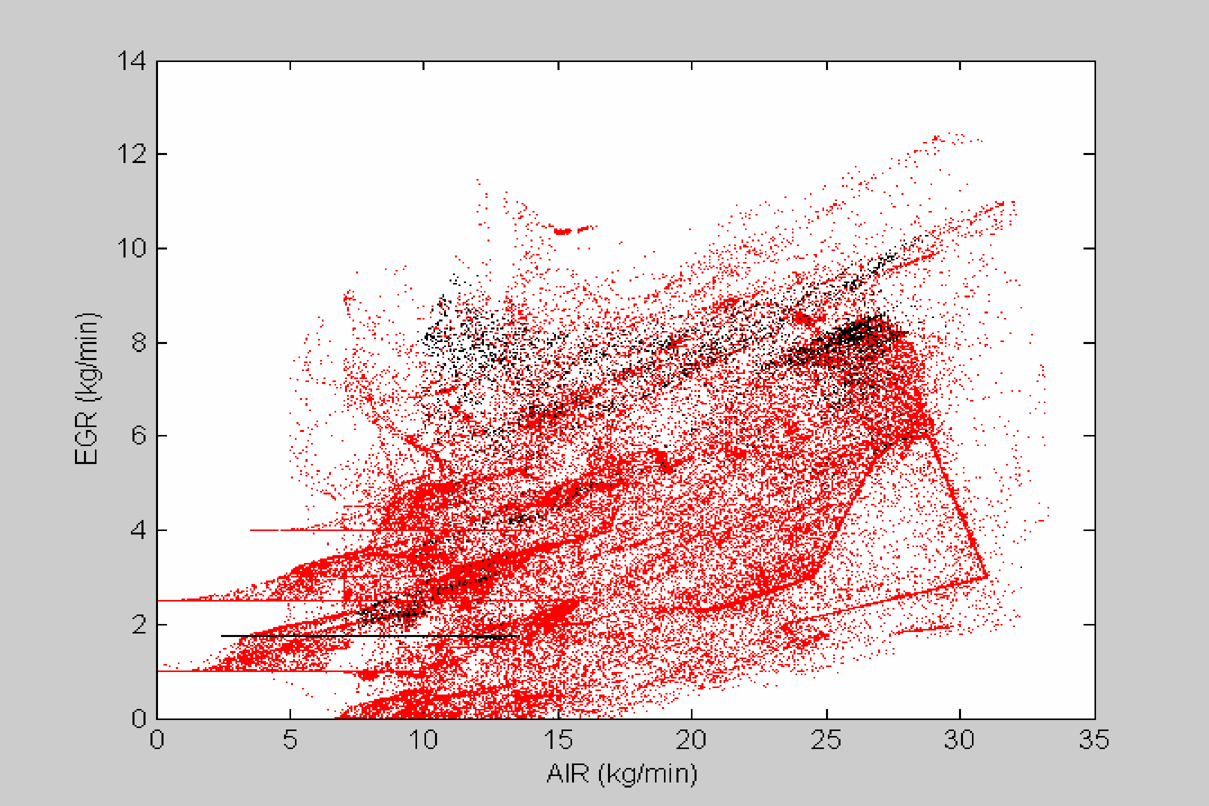
Air-EGR Perturbations (all cycles)



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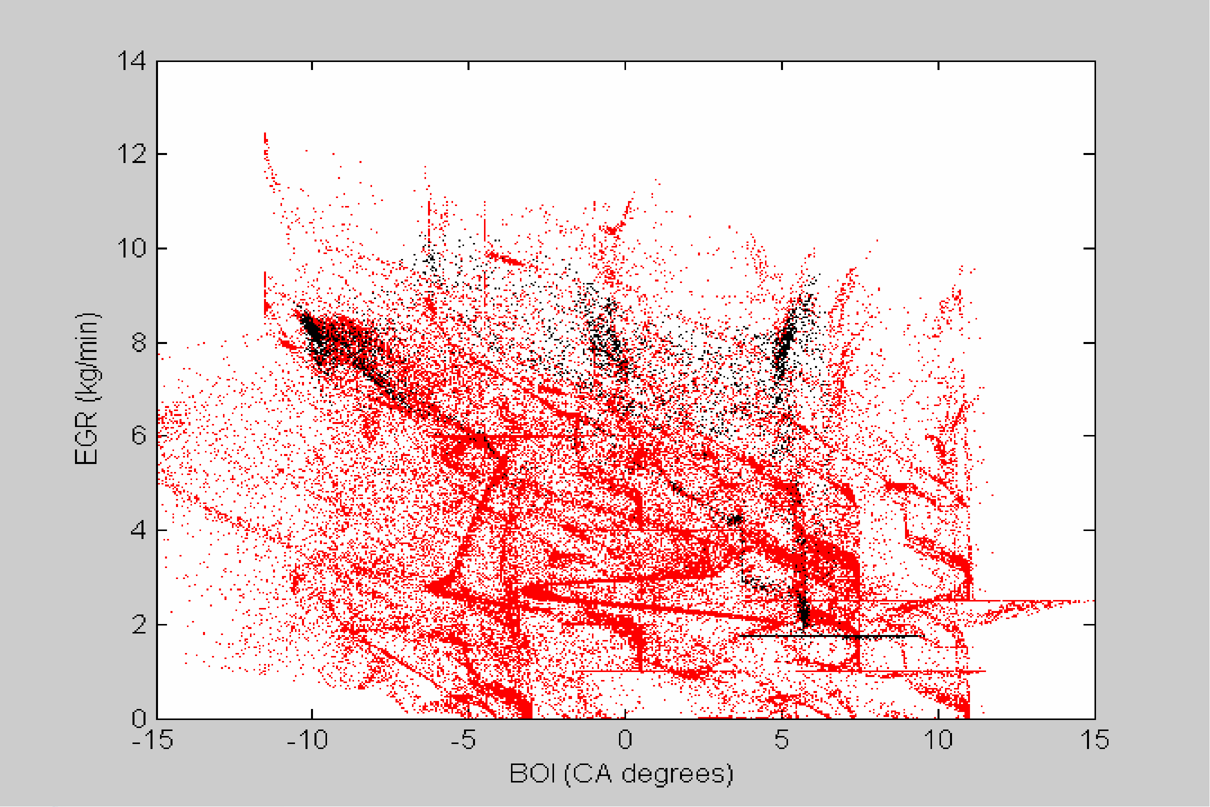
EGR-Injection Timing Perturbations



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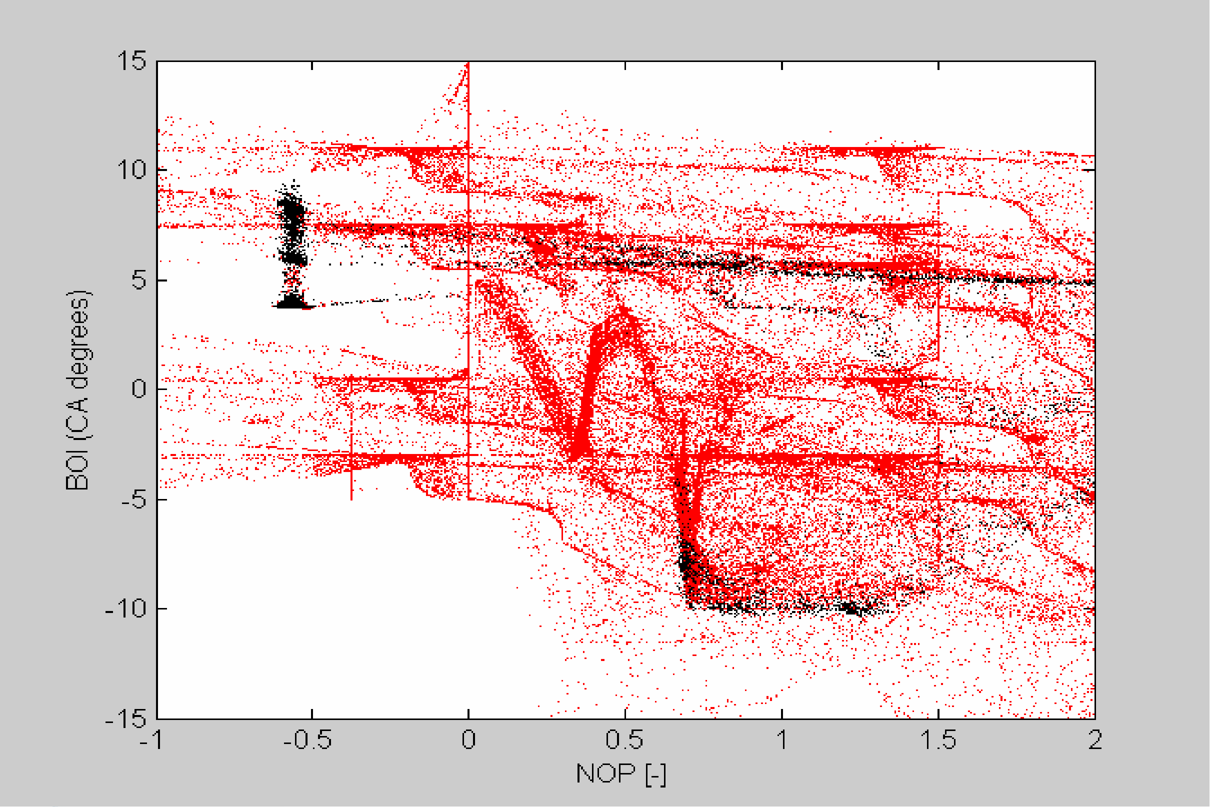
Injection Pressure-Timing Perturbations



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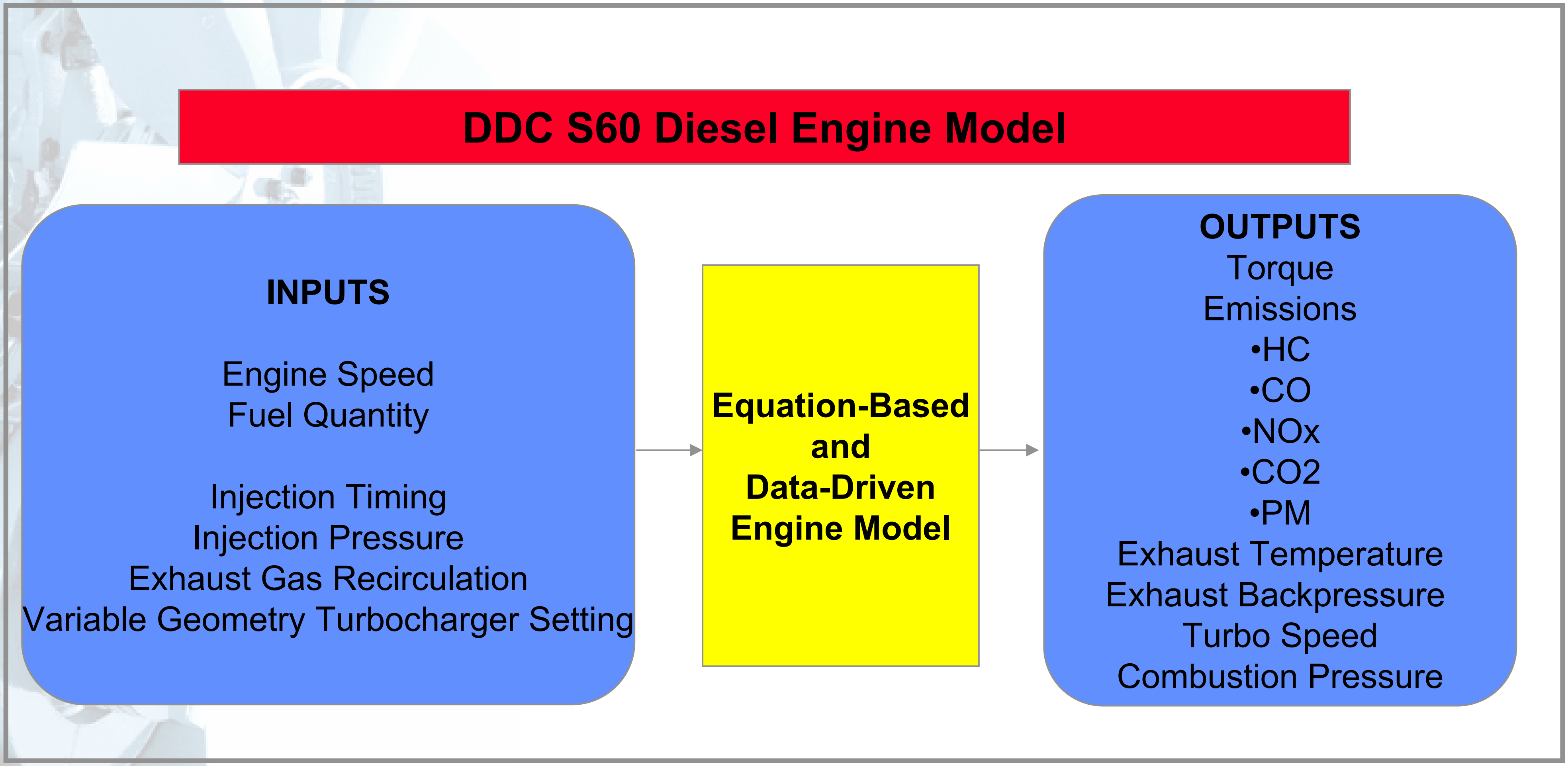
Dynamic Engine Modeling Approach

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).

Diesel Engine Modeling



DDC S60 Diesel Engine Model

INPUTS

Engine Speed
Fuel 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 Backpressure
Turbo Speed
Combustion Pressure

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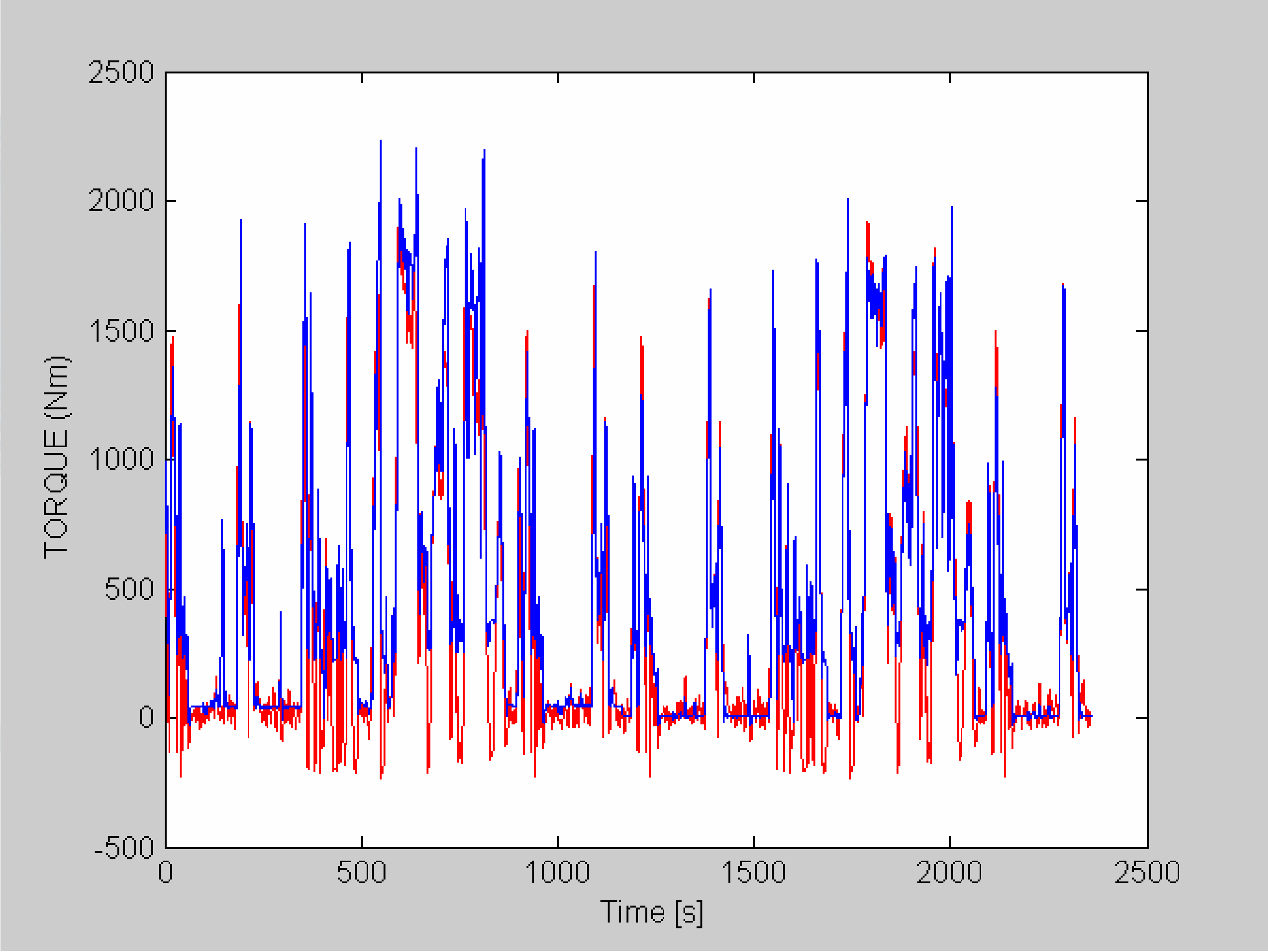
Transient Engine Modeling Results - Torque



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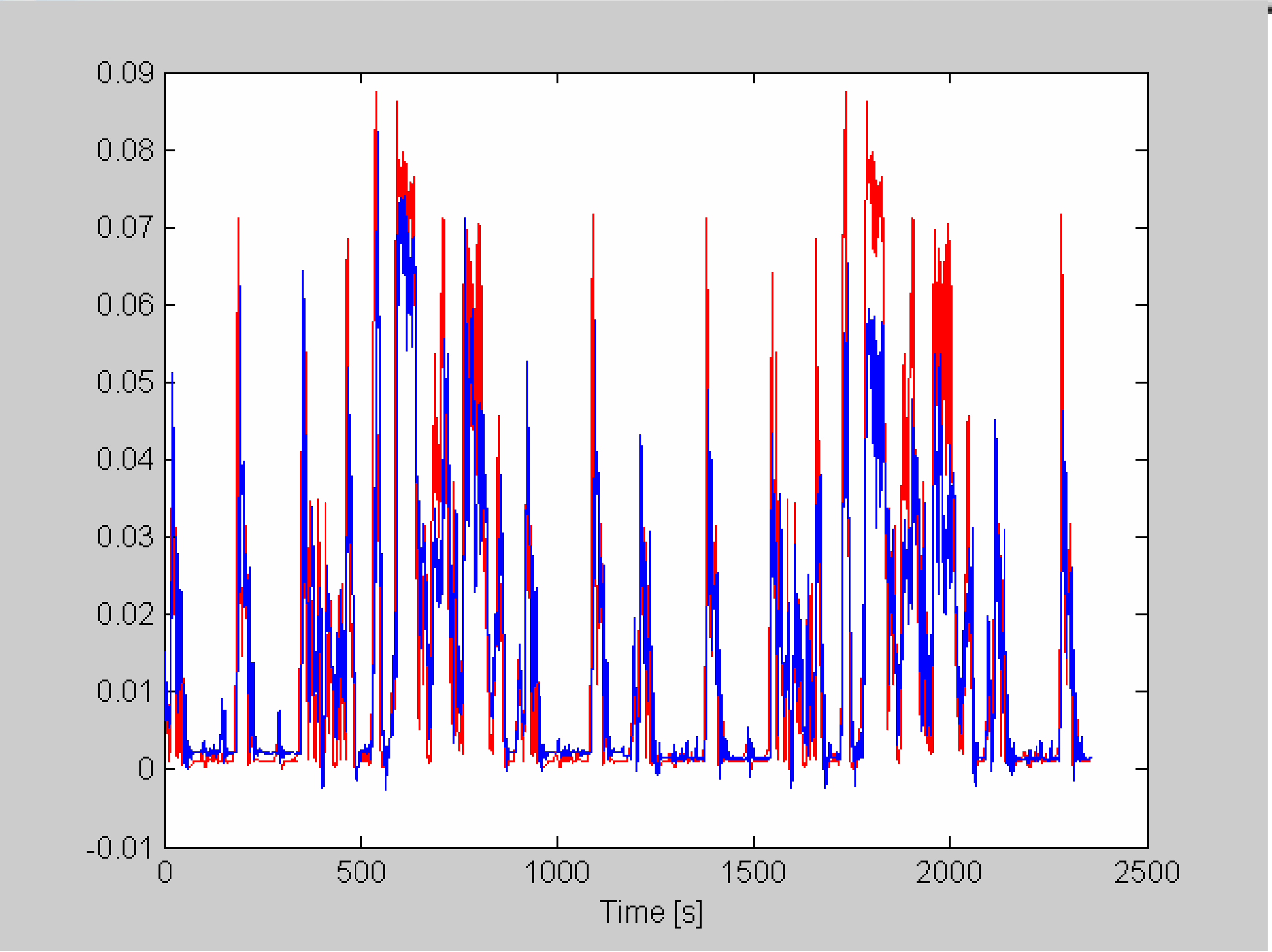
Transient Engine Modeling Results - NOx



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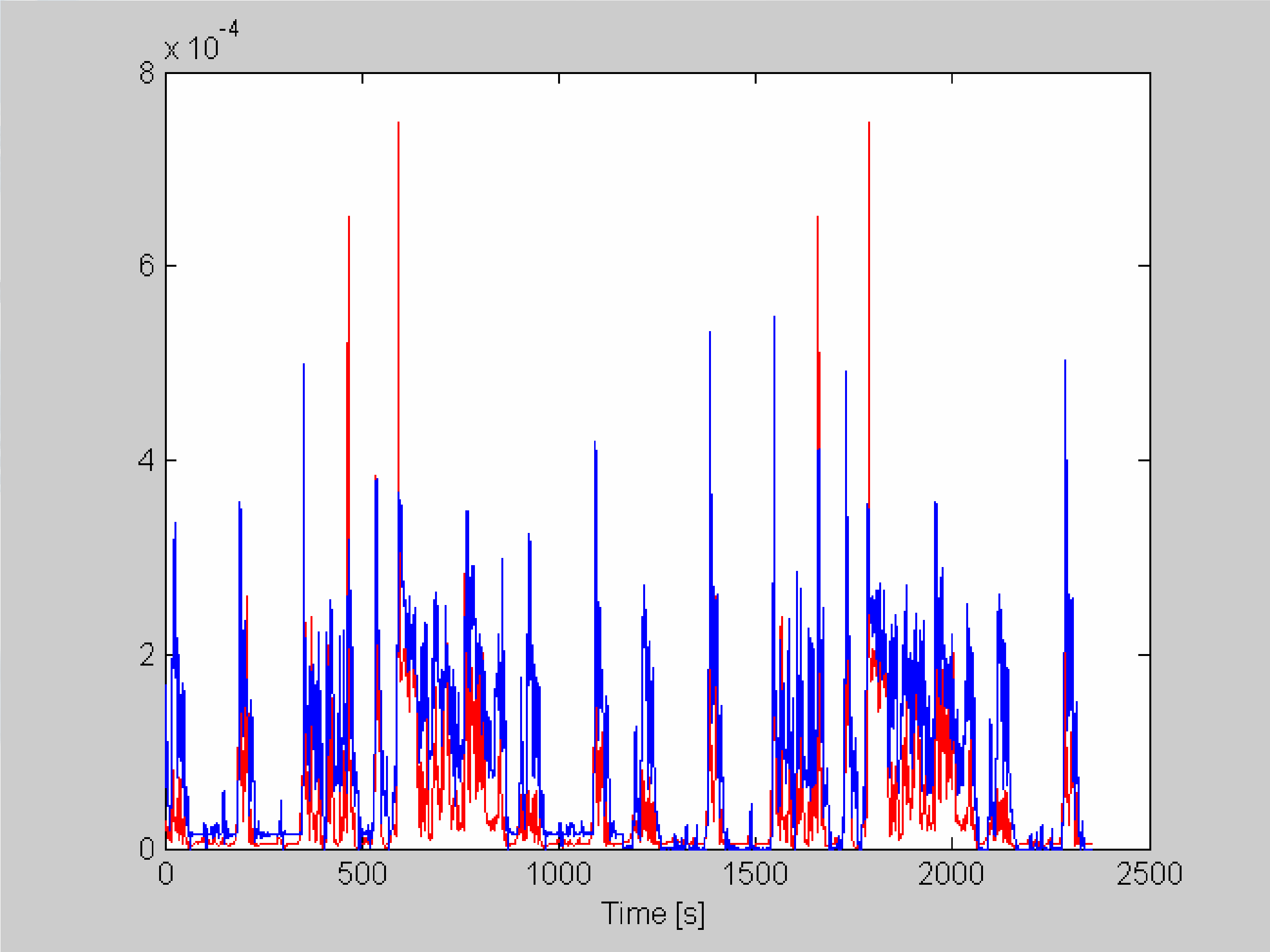
Transient Engine Modeling Results - PM



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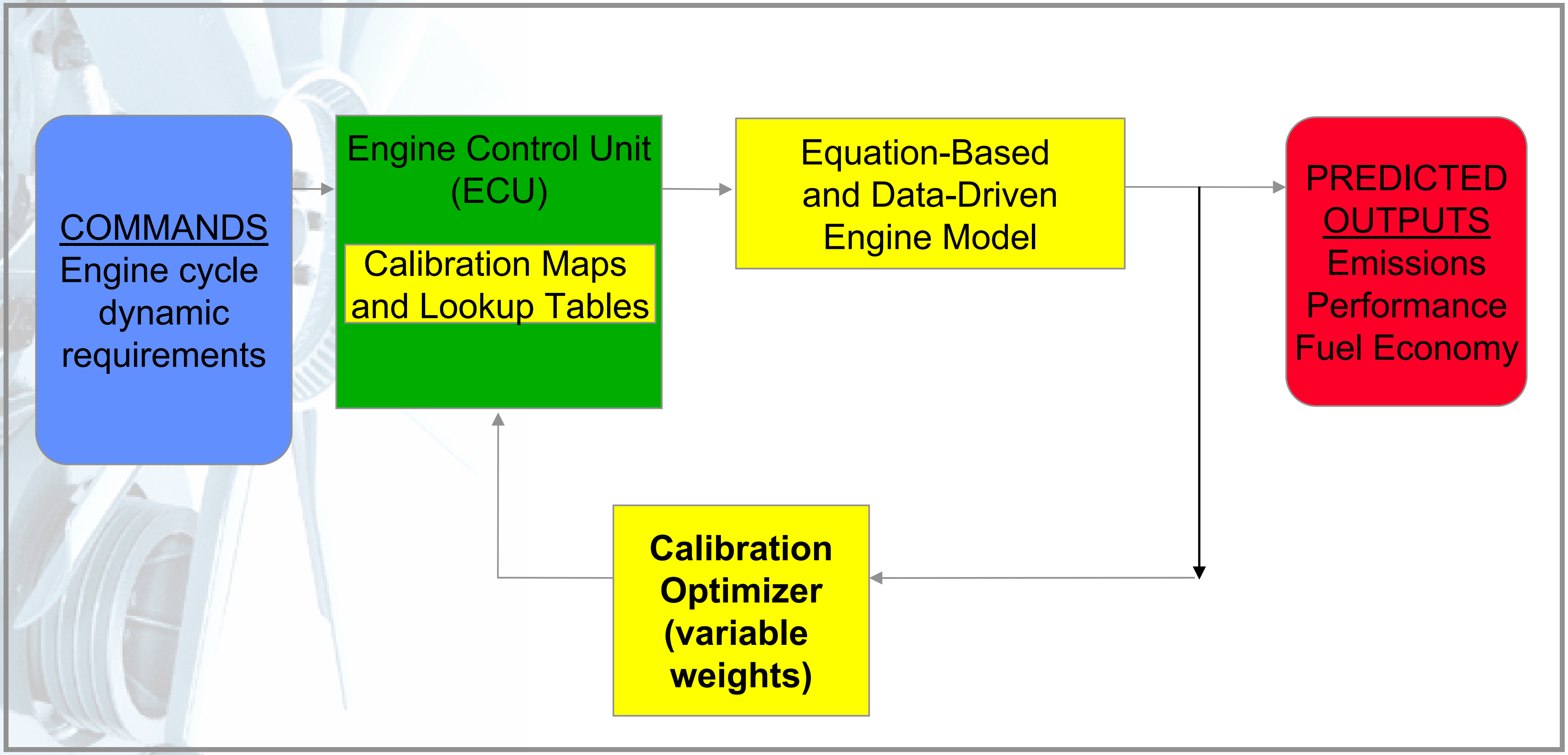
Rapid Transient Calibration Optimization



COMMANDS
Engine cycle dynamic requirements

Engine Control Unit (ECU)

Calibration Maps and Lookup Tables

Equation-Based and Data-Driven Engine Model

PREDICTED OUTPUTS
Emissions
Performance
Fuel Economy

Calibration Optimizer (variable weights)

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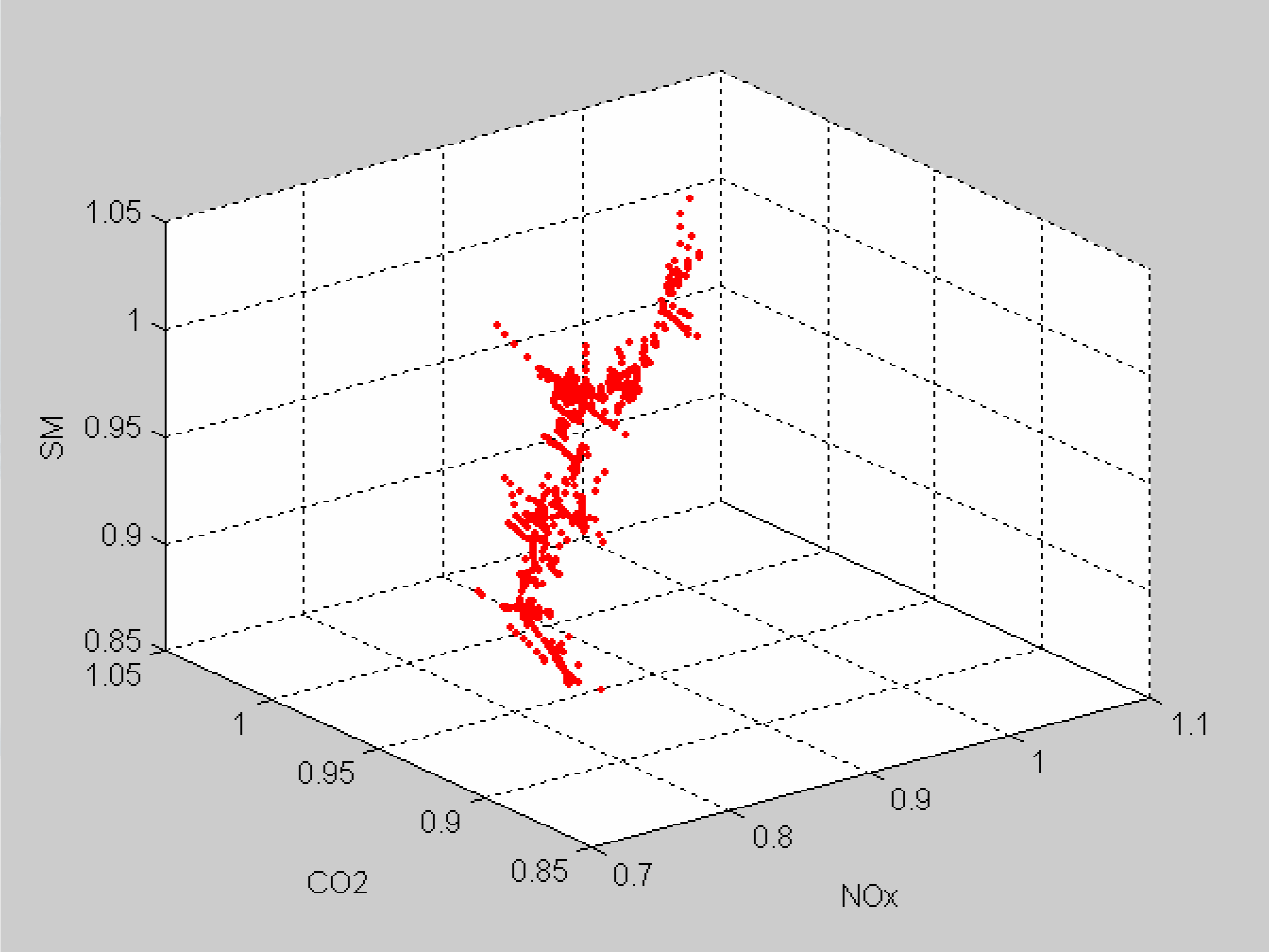
Calibration Optimization Functions

- 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, exhaust temperature and peak injection pressure,
- While also meeting NTE and steady-state exhaust emissions levels.

Typical Calibration Optimization Progress – cell by cell



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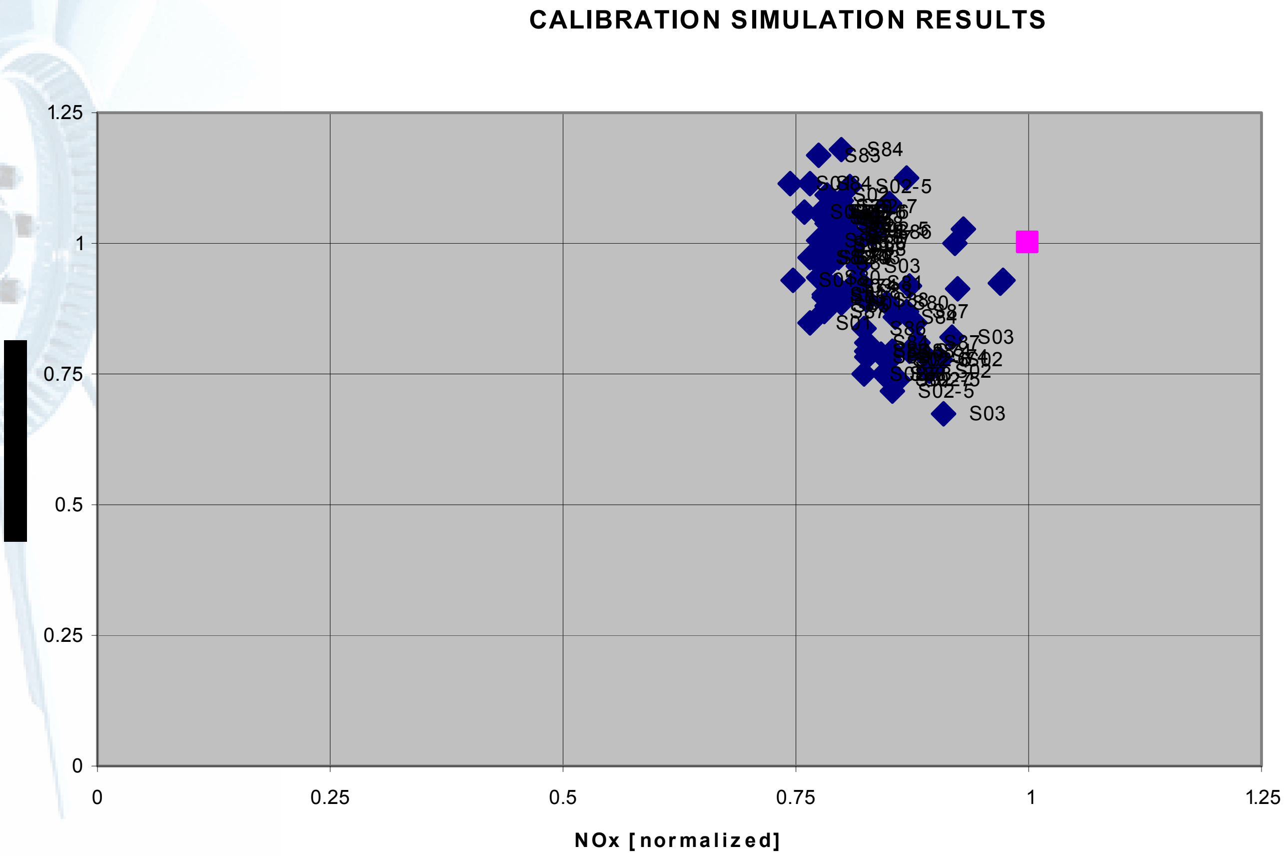
Simulated Emissions Results – I

(~100 FTPs with different calibration optimization weights)



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Simulated Emissions Results – II

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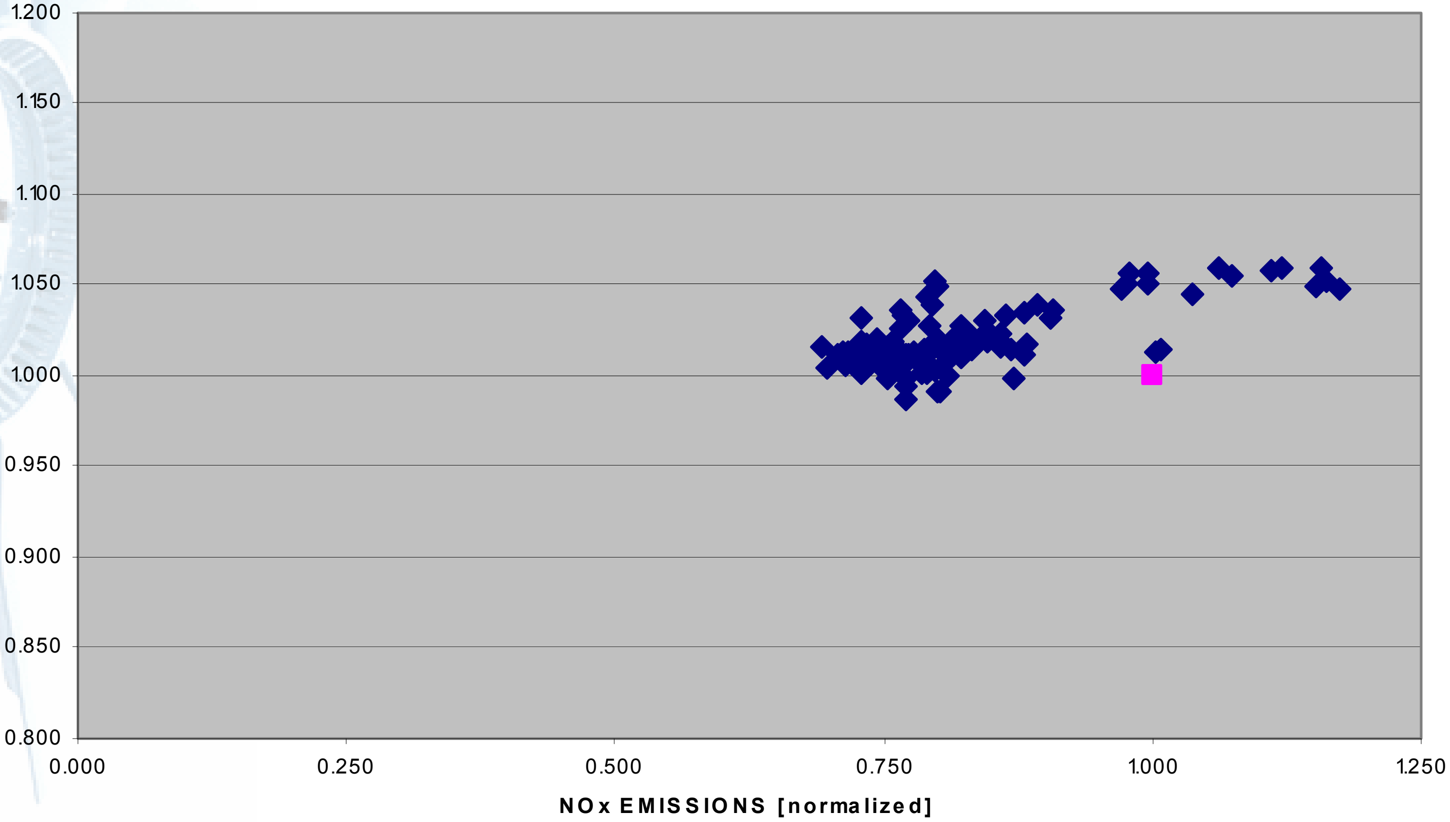

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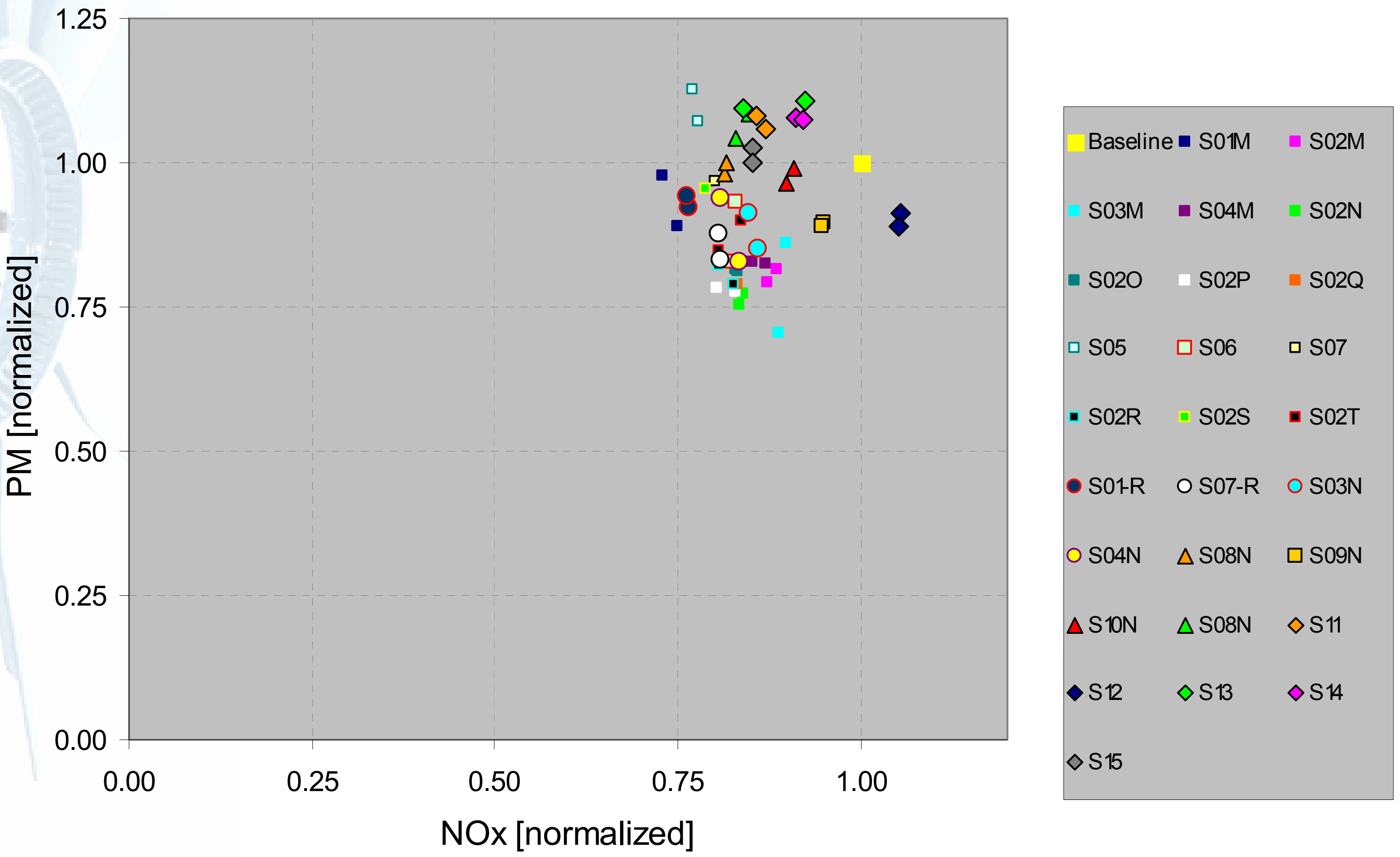
Validation and Verification – Actual FTP Emissions Results - I



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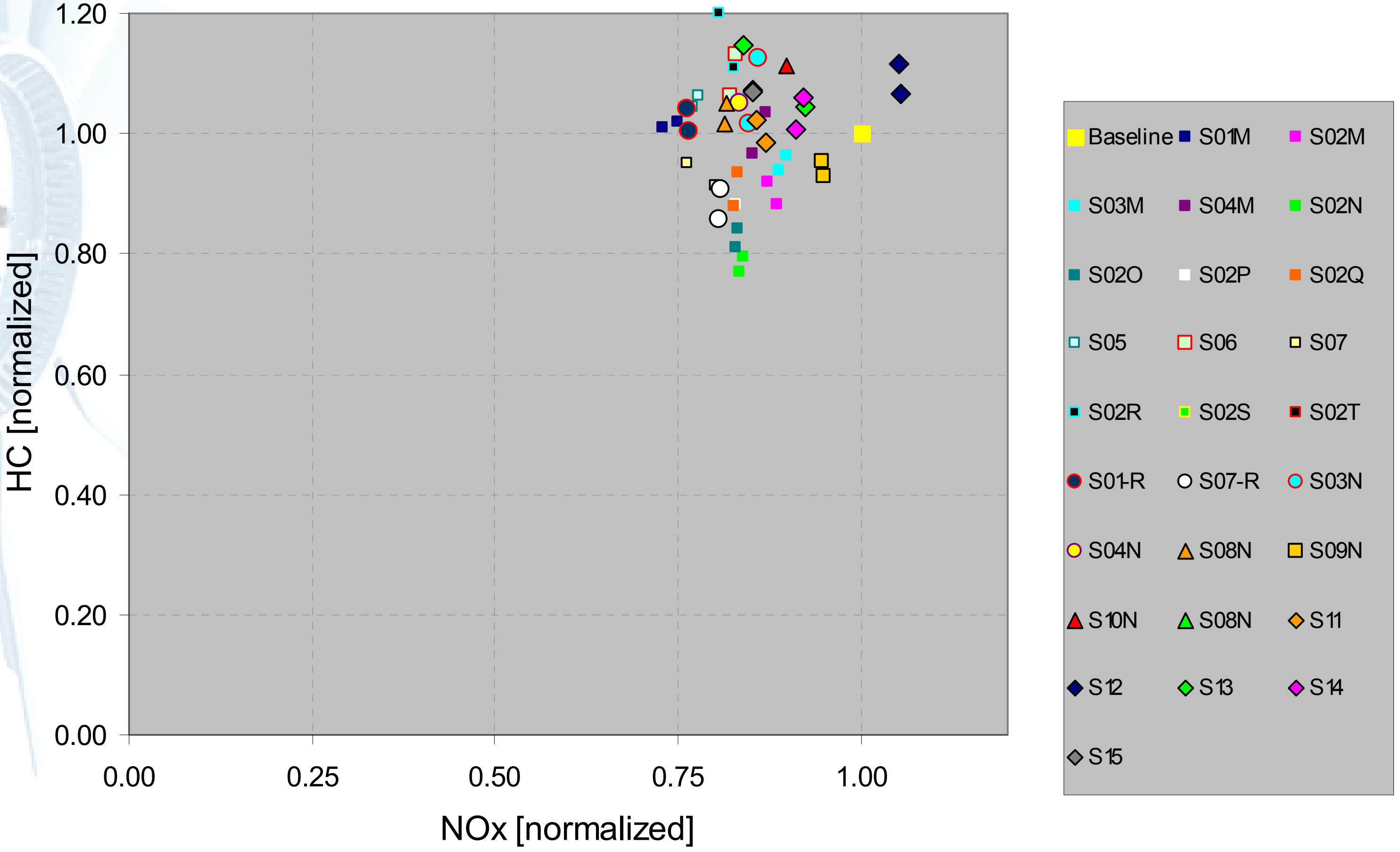
Validation and Verification – Actual FTP Emissions Results - II



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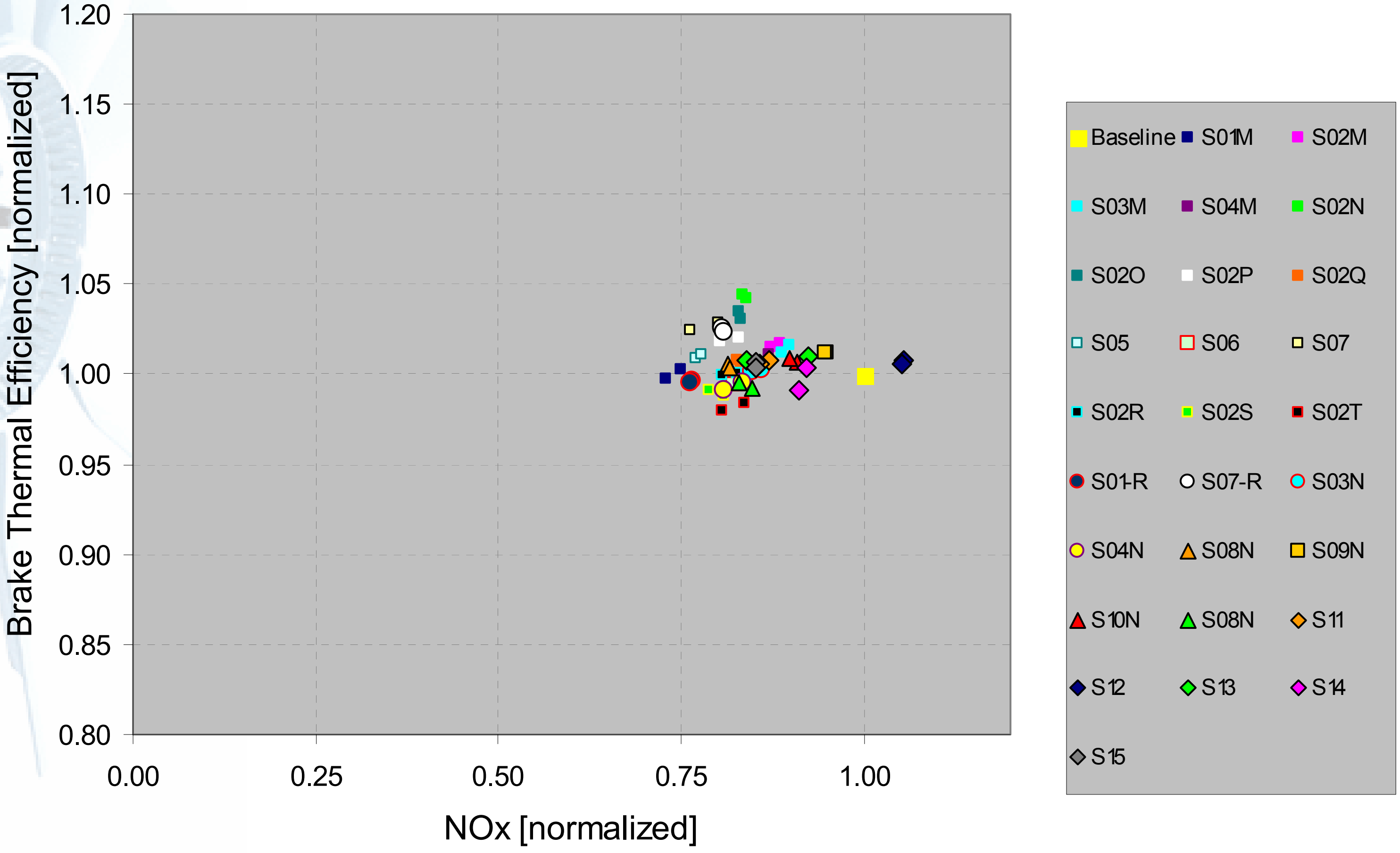
Validation and Verification – Actual FTP Emissions Results - III



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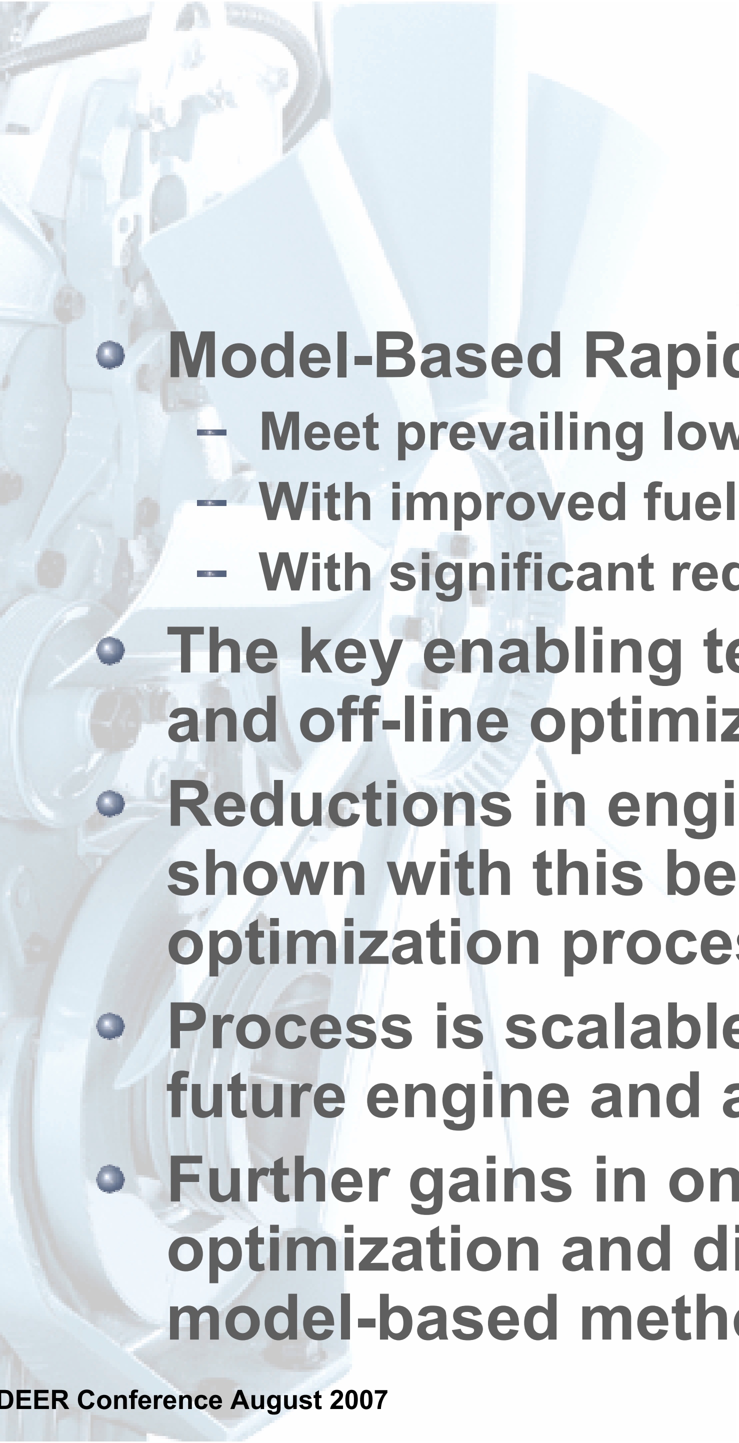
Project Results

- Rapid Transient Calibration process requires two periods of about 10 dynamometer days each in the transient test cell
  - Data collection – 15 custom transient cycles
  - Verification and validation
- 4 calendar months beginning to end
- Improved real-world fuel efficiency (~5%) across the FTP while meeting the same regulated emissions levels, with the same levels of engine performance and protection.
- Shifted a significant portion of the calibration burden out of the high cost, high demand transient test cell.
- Process is scalable – adding an extra control or calibration variable (such as urea dosing for SCR) will add effort, but not in a geometric fashion.

Future Applications

- Control Strategy Development
  - Using Point-by-Point calibration optimization (determining the optimum set of control parameters on a time-based basis, rather than on a table-based basis) gives insight into transient control strategies.
- Model-Based Control System Development
  - Utilize dynamic engine modeling techniques for real-time on-line, on-engine application, rather than off-line use.
- Model-Based Diagnostics
  - Dynamic modeling for real-time Virtual Sensing.



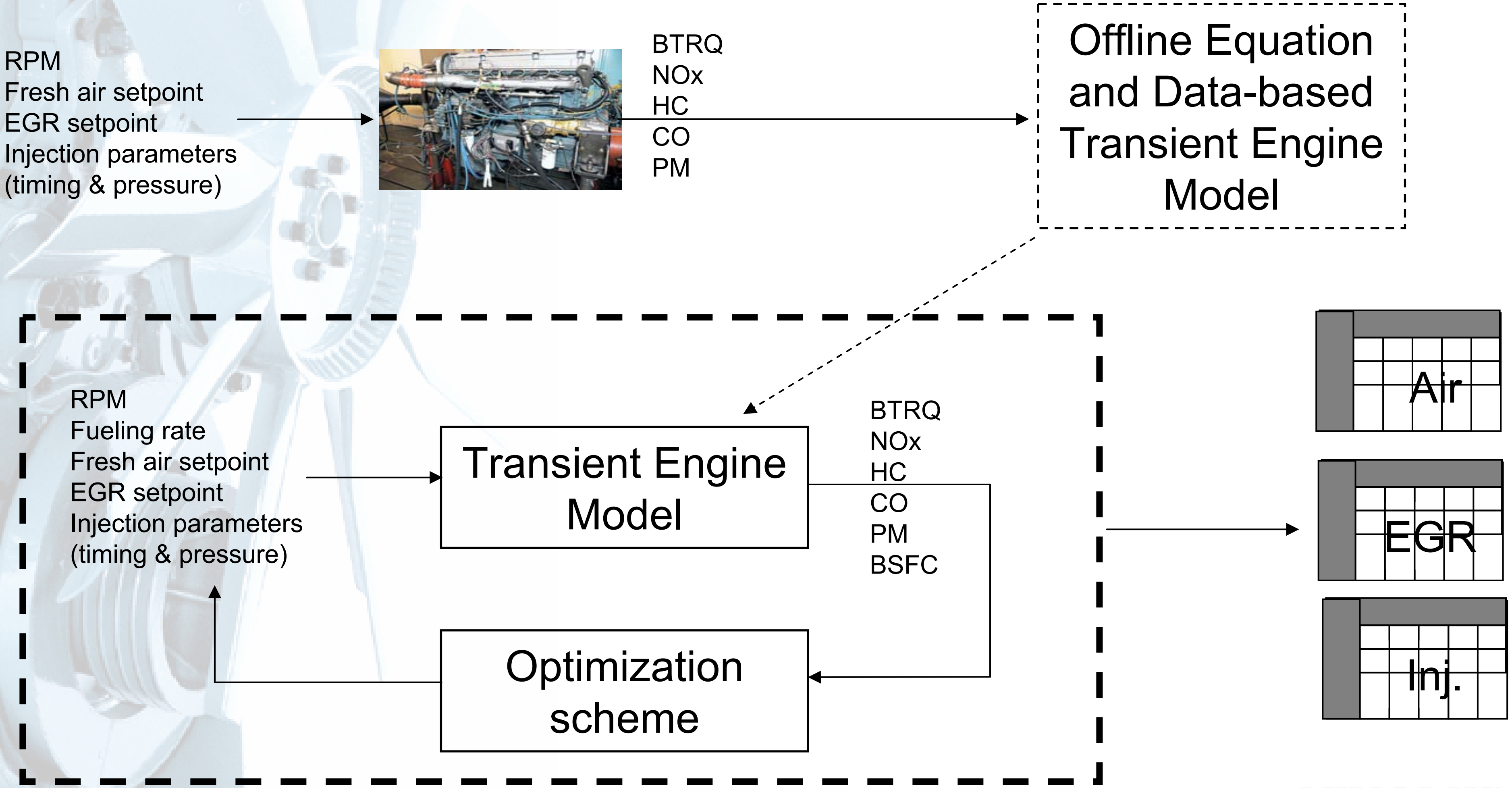
Summary

- Model-Based Rapid Transient Calibration is able to
  - Meet prevailing low emissions standards
  - With improved fuel economy
  - With significant reductions in the time and effort required to calibrate.
- The key enabling technologies are dynamic engine modeling and off-line optimization.
- Reductions in engineering time, cost and effort have been shown with this beginning-to-end model-based calibration optimization process.
- Process is scalable – encouraging for even more complex future engine and aftertreatment systems.
- Further gains in on-line engine control, calibration, optimization and diagnostics are possible using the same model-based methods.

Acknowledgements

- **U.S. Department of Energy**
  - Gurpreet Singh
  - Roland Gravel
- **National Energy Technology Laboratory**
  - Carl Maronde
  - Jeffrey Kooser
- **Atkinson LLC**
  - Gregory Mott

Design of Transient Experiments



RPM
Fresh air setpoint
EGR setpoint
Injection parameters
(timing & pressure)

BTRQ
NOx
HC
CO
PM

Offline Equation and Data-based Transient Engine Model

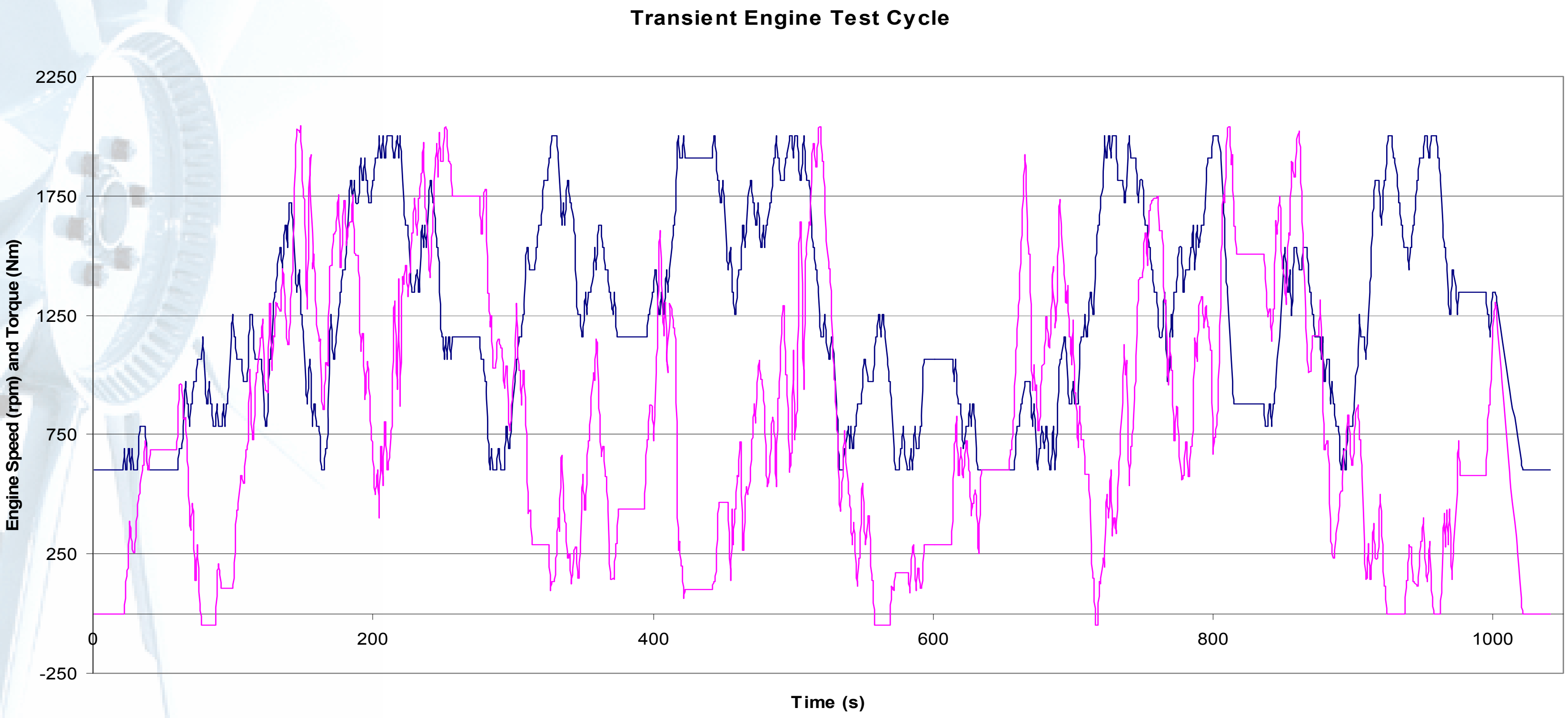
RPM
Fueling rate
Fresh air setpoint
EGR setpoint
Injection parameters
(timing & pressure)

Transient Engine Model

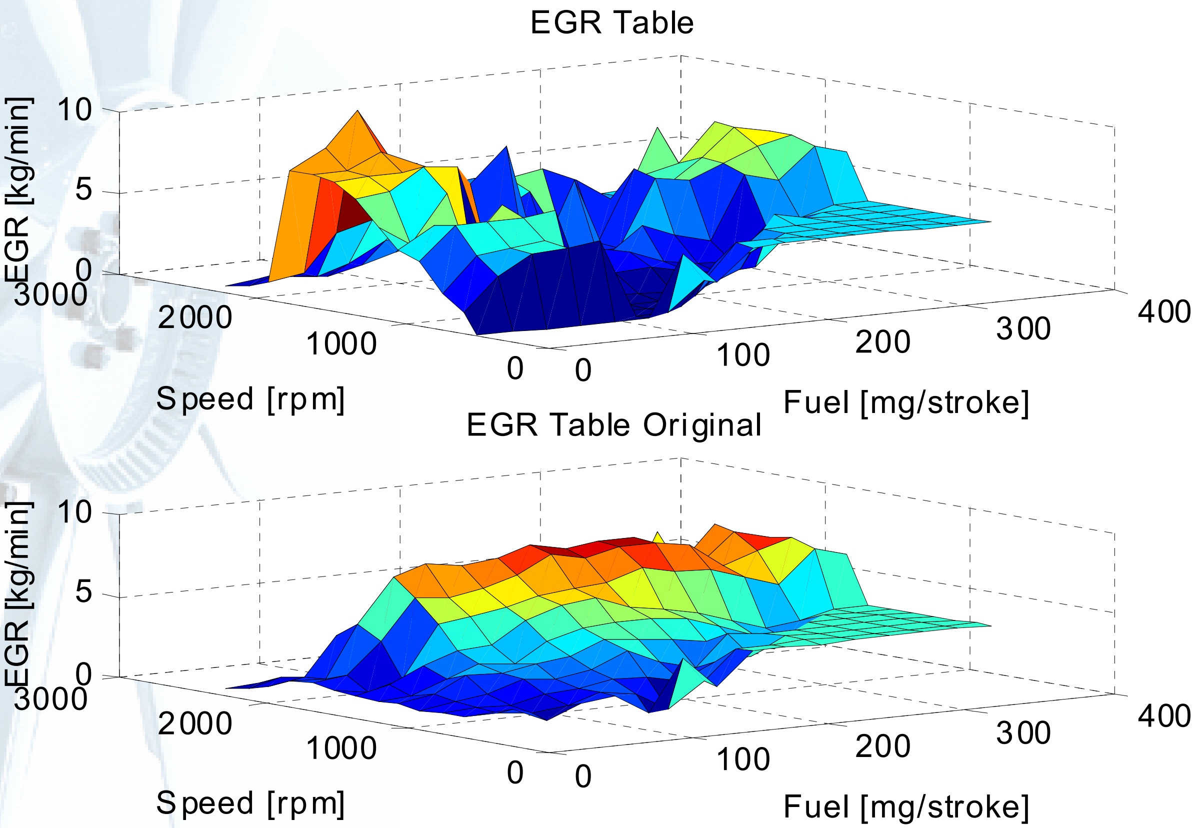
BTRQ
NOx
HC
CO
PM
BSFC

Optimization scheme

Transient Engine Test Cycle



Typical Table-Based Output



Simulated Emissions Results – III

(Integrated FTP emissions as a function of optimization weights)

	NOx_Weight	CO_Weight	PM_Weight	CO2_Weight	NOx	CO	PM	CO2
EMISSIONS								
NOx	**-0.62**	0.31	0.26	-0.06	1			
CO	0.43	**-0.61**	-0.36	-0.05	**-0.67**	1		
PM	0.36	-0.36	**-0.58**	0.19	**-0.51**	**0.81**	1	
CO2	-0.05	0.09	0.07	**-0.37**	0.05	0.00	0.07	1

- Increasing NOx, CO, PM or CO2 weights in the optimization function results in a reduction in those emissions
- NOx and PM emissions are anti-correlated, as expected, while CO and PM are co-correlated.

Background – Industry Trends

- Ever Decreasing Emissions Requirements
- Ever Increasing Fuel Economy and Brake Thermal Efficiency Demands
- Increasing Mechanical and Electronic Complexity of Engines and Aftertreatment Systems
- Cost Reduction Demands for Engine Development
- Reduced Product Engineering Development Cycles
- Increasing Demands on Transient Engine and Emissions Test Facilities