The MathWorks

MATLAB® & SIMULINK®

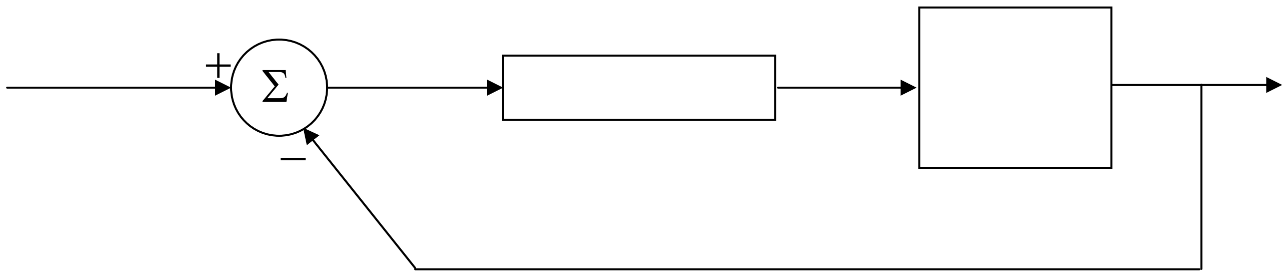
2007 SAE Commercial Vehicle Engineering Congress – MathWorks Hosted Panel on Analytical Calibration

Analytical Calibration Panel
Introductory remarks

SAE Commercial Vehicle Conference, Rosemont, IL, October 31st 2007

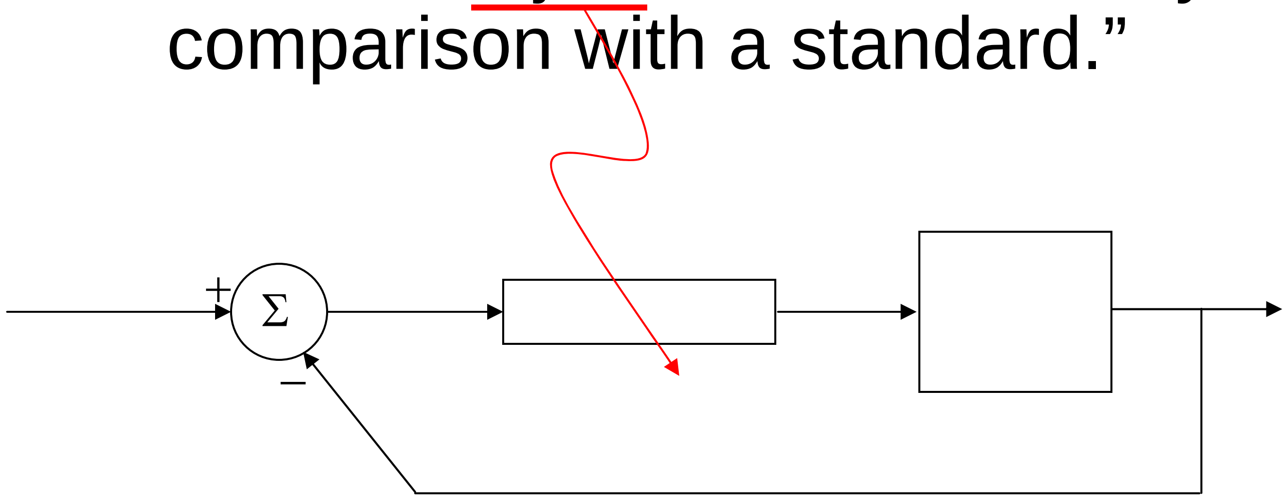
Giorgio Rizzoni
Director
The Ohio State University Center for Automotive Research

"To check, adjust, or determine by comparison with a standard."



Calibrate

"To check, adjust, or determine by comparison with a standard."



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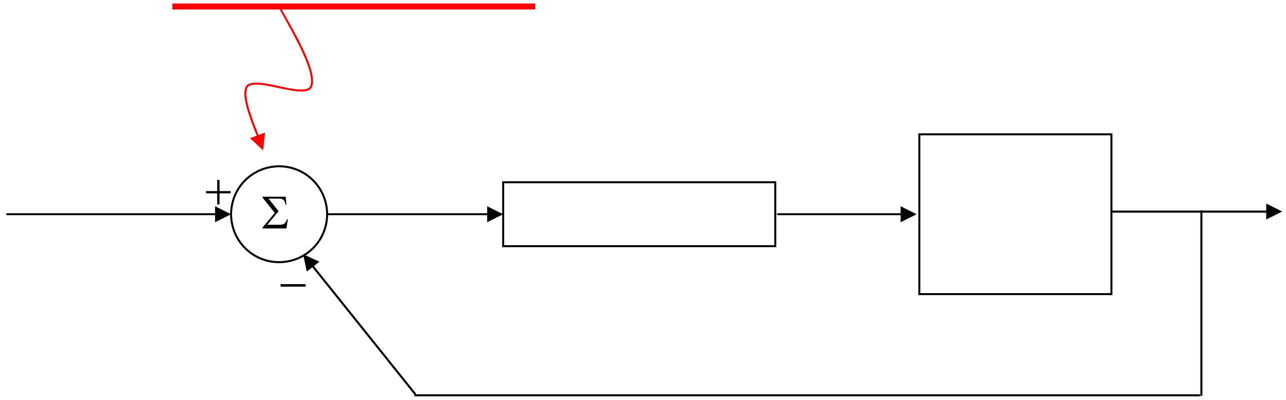

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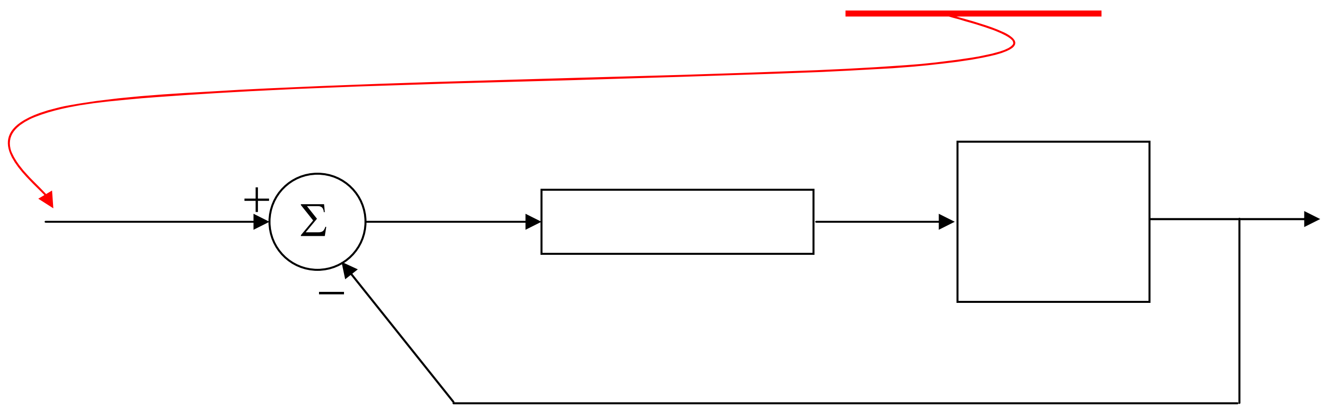

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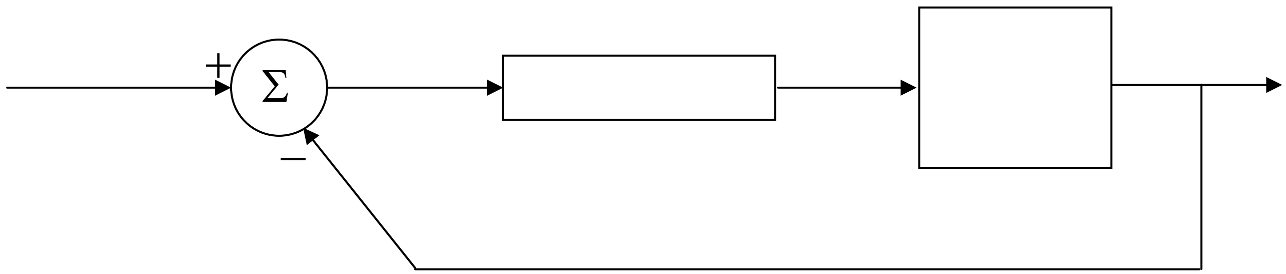
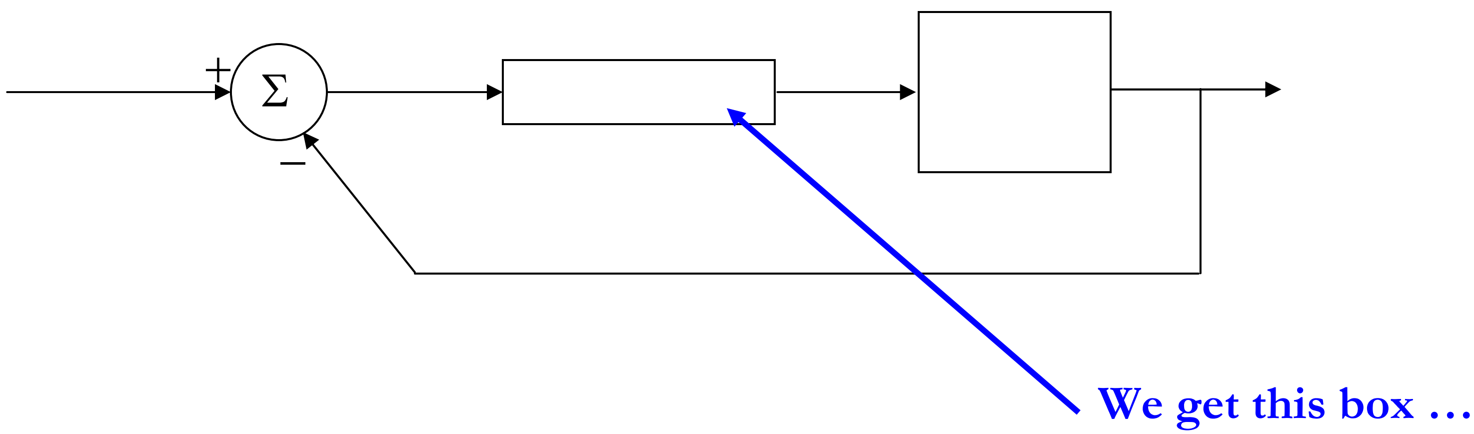


So ...
Does Control = Calibration?
Do we need Calibrators?

“To check, adjust, or determine by comparison with a standard.”

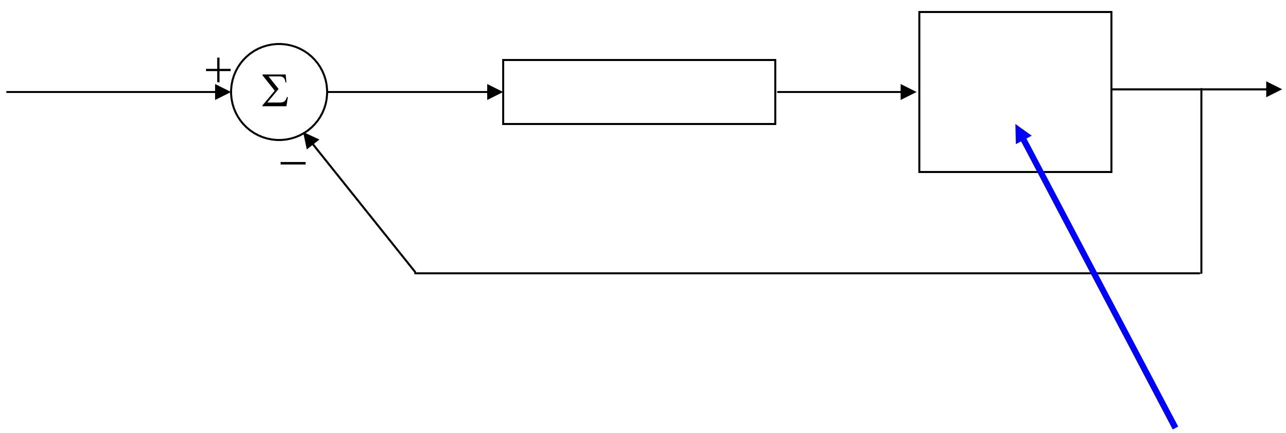


So …

Does Control = Calibration? No!

Do we need Calibrators?

"To check, adjust, or determine by comparison with a standard."



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Do we need Calibrators?

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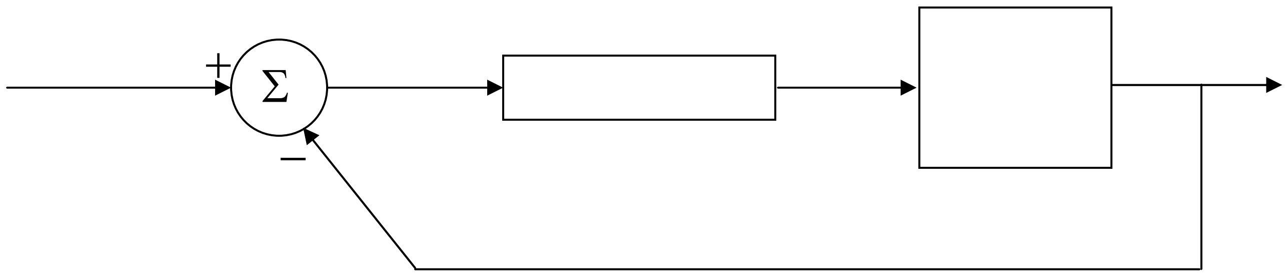
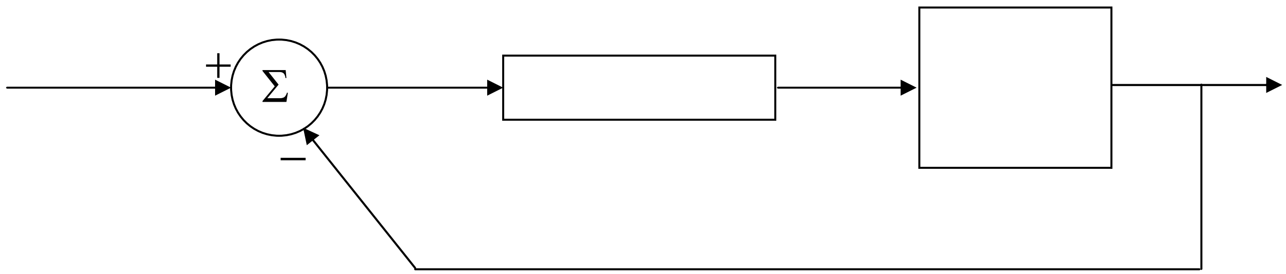


So ...

Does Control = Calibration? No!

Do we need Calibrators? Yes!

"To check, adjust, or determine by comparison with a standard."



So ...

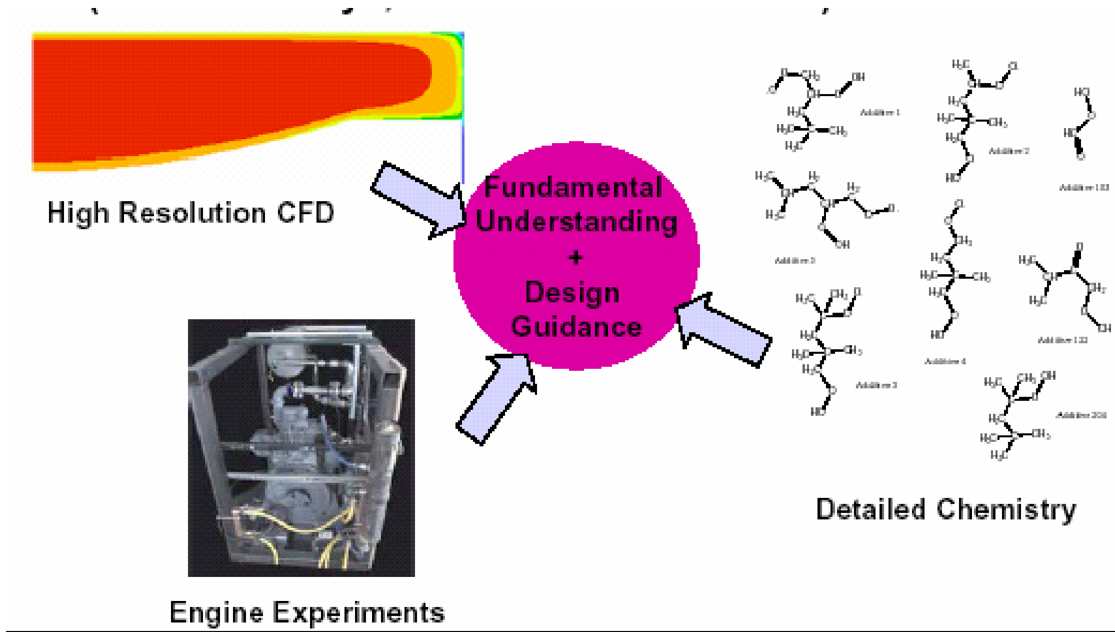
Does Control = Calibration? No!

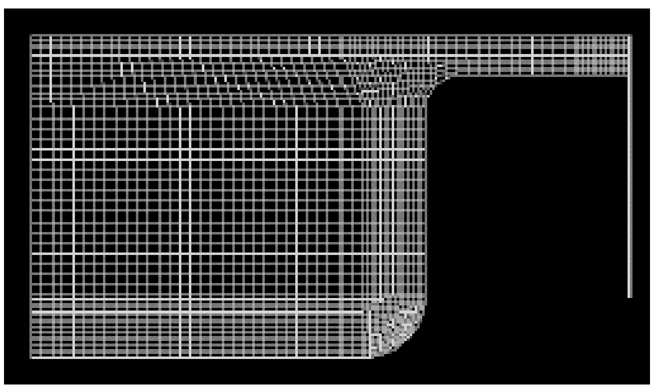
Do we need Calibrators? Yes!

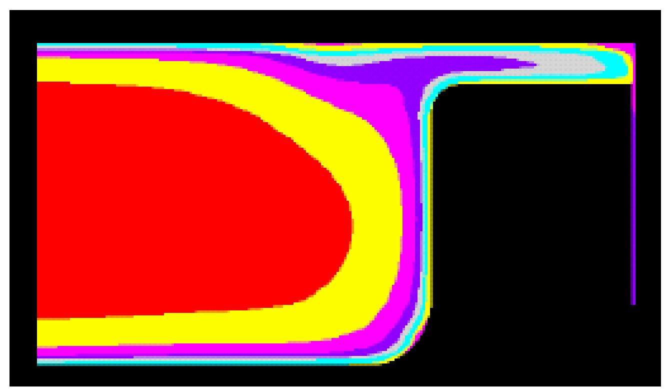
Typically, Calibrators are the plant experts!

Modeling → Control → Calibration

How do we go from this...

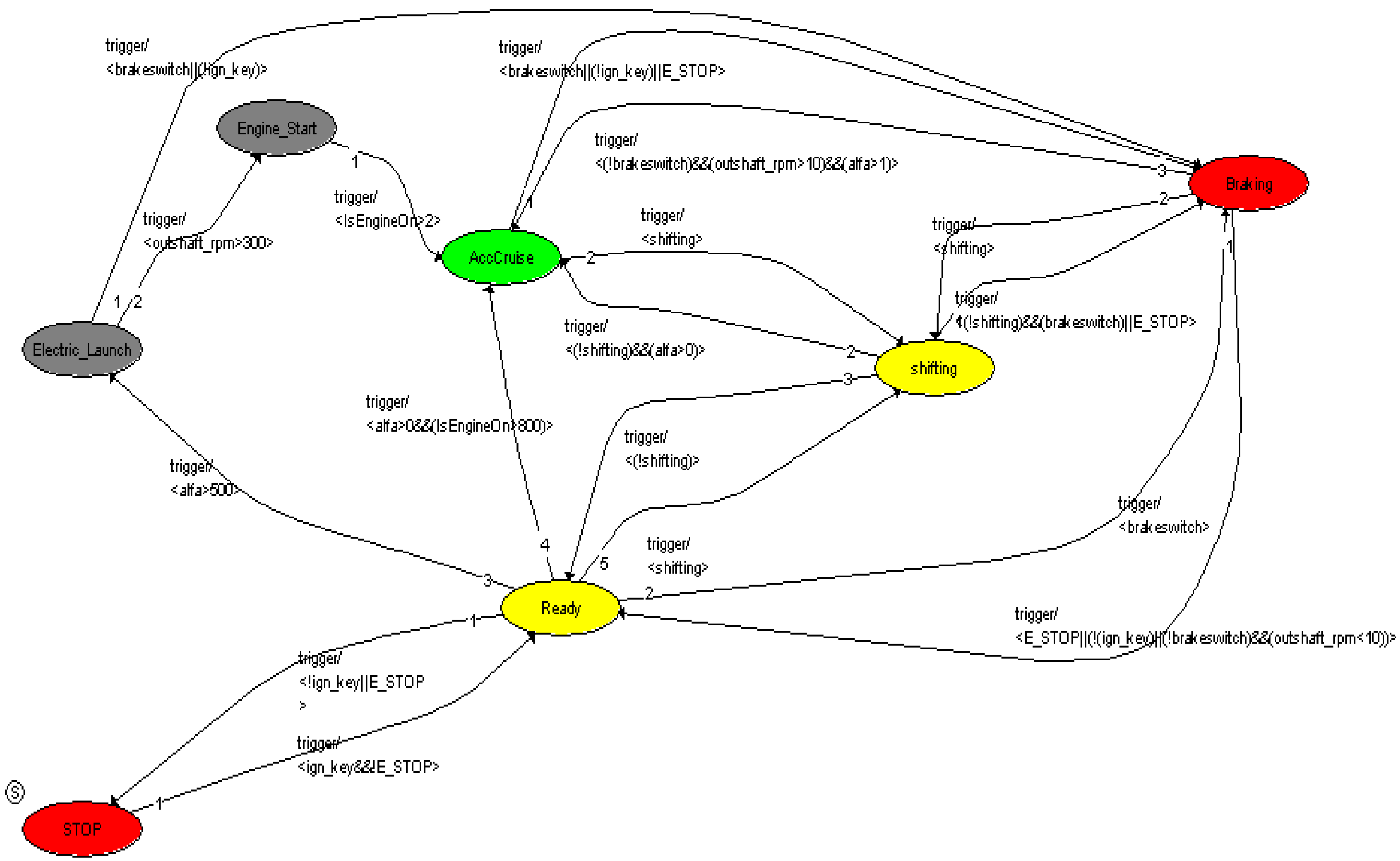






Modeling → Control → Calibration

To this?



… and do it with a <u>short development cycle</u>, keeping in mind <u>dimensionality</u>, <u>modularity</u>, <u>adaptability</u>, <u>scalability</u>, all the while admitting a <u>rigorous calibration process</u>?

An Obvious Answer: Good Modeling

All models are lies (some are better than others)

(Box)

> Granted that every equation and every measurement is approximate, the question then arises as to what confidence we can have in the predictions of the associated theory. This is a problem in stability theory. We must ask ourselves, "Is it true that the answer derived from an approximate formulation is a reasonable approximation to the answers given by more exact formulations?"
>
> Clearly, this question is one of the basic problems of science, and it is equally clear that it can never be answered completely. What we will have over time in a hierarchy of theories of greater and greater sophistication yielding more and more accurate answers to more and more questions. But there will never be an ultimate theory that is "exact." To some people, this fact may be disappointing; to others like myself it is exciting and challenging to see how far we can get.
>
> From *Some Vistas of Modern Mathematics* by Richard Bellman,
> University of Kentucky Press, 1968

The "real" answer goes beyond simply "modeling"

Define the problem

Understand the plant

Pick a control theory

Control-Oriented model

Calculate a control law

Make it work

Manager
(with help)

Define the problem
(the “real” problem)

Understand the plant

Pick a control theory

Control-Oriented model

Calculate a control law

Make it work

Define the problem

Understand the plant

Pick a control theory

Control-Oriented model

Calculate a control law

Make it work

"Modeler"

- *Physics*
- *Matlab simulation*
- *some data*

Define the problem

Understand the plant

Pick a control theory

How many academicians start here ….

Control-Oriented model

Calculate a control law

Make it work

Control Theorist

Define the problem

Understand the plant

Pick a control theory

Control-Oriented model

Calculate a control law

Make it work

Calibrator and control practitioner

Define the problem

Understand the plant

Pick a control theory

How many academicians start here ….

Control-Oriented model

Calculate a control law

Make it work

Define the problem

Understand the plant

Pick a control theory

How many academicians start here ….

Control-Oriented model

Calculate a control law

… and finish here?

Make it work

Define the problem

Understand the plant

Pick a control theory

How many academicians start here ….

Control-Oriented model

Calculate a control law

… and finish here?

Make it work

How many practitioners start here ….

Define the problem

Understand the plant

Pick a control theory

How many academicians start here ….

Control-Oriented model

Calculate a control law

… and finish here?

Make it work

How many practitioners start here ….

… and finish here?

Define the problem

Understand the plant

How many practitioners start here ….

Pick a control theory

How many academicians start here ….

Control-Oriented model

… and finish here?

Calculate a control law

… and finish here?

Make it work

Usually, one person cannot play all these roles …

A Preview of the Panel

- Emissions legislation has significantly increased the **complexity** of the calibration problem, and extended this problem to heavy-duty and off-highway applications
- Complex combustion and exhaust aftertreatment behavior coupled with insufficient sensor information make the task of achieving **open loop calibration** for new emissions standard very challenging.
- **Model-based approaches** and computer-aided calibration tools can assist in this process, however the current state of models
- For example, the problem of transient system response is still a very challenging one: models of **engine transient behavior**, especially vis-à-vis emissions, are still inadequate.

Growth in complexity -1990-2005

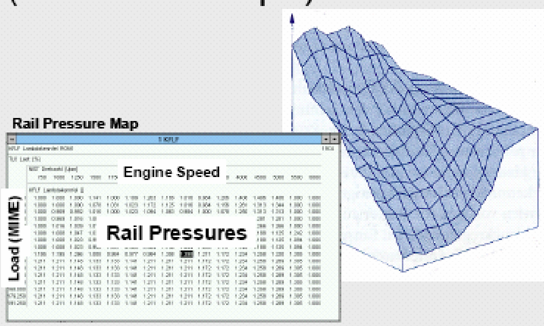
- Processor: 8-bit → 32-bit
- Performance (MIPS): <1 → 300
- Transistors: < 1M → 25M
- Memory: 33 kB → 4,000 kB
- Application parameters: 500 → 8,000
  - Expected number in 2007: 20,000
- Connector pins: 50 → 150
- ECU manual ~5,000 pages!!

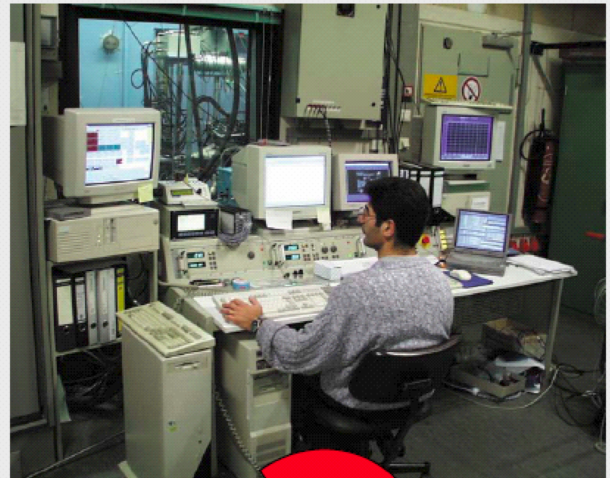
Courtesy: Bosch, FKFS

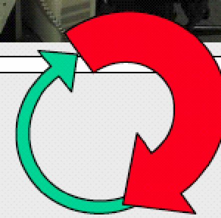
ECU mapping process

TEST BENCH

Steady State Calibration
(i.e. basic maps)

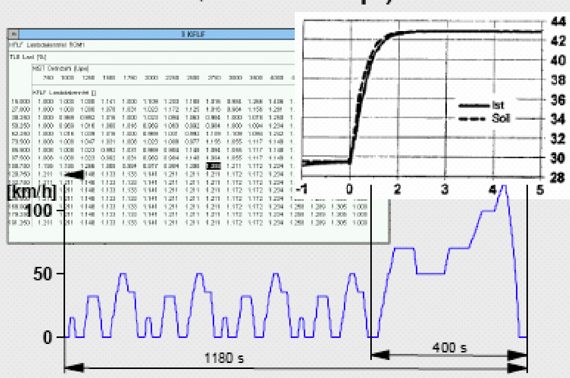


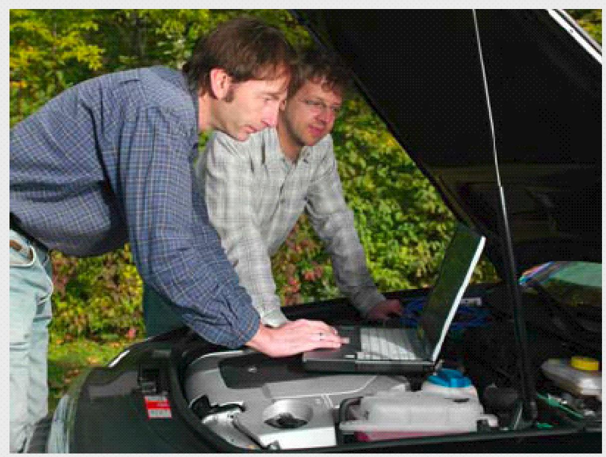




IN-CAR

Transient / Driveability Calibration
(i.e. acceleration,
cold start, warm up)



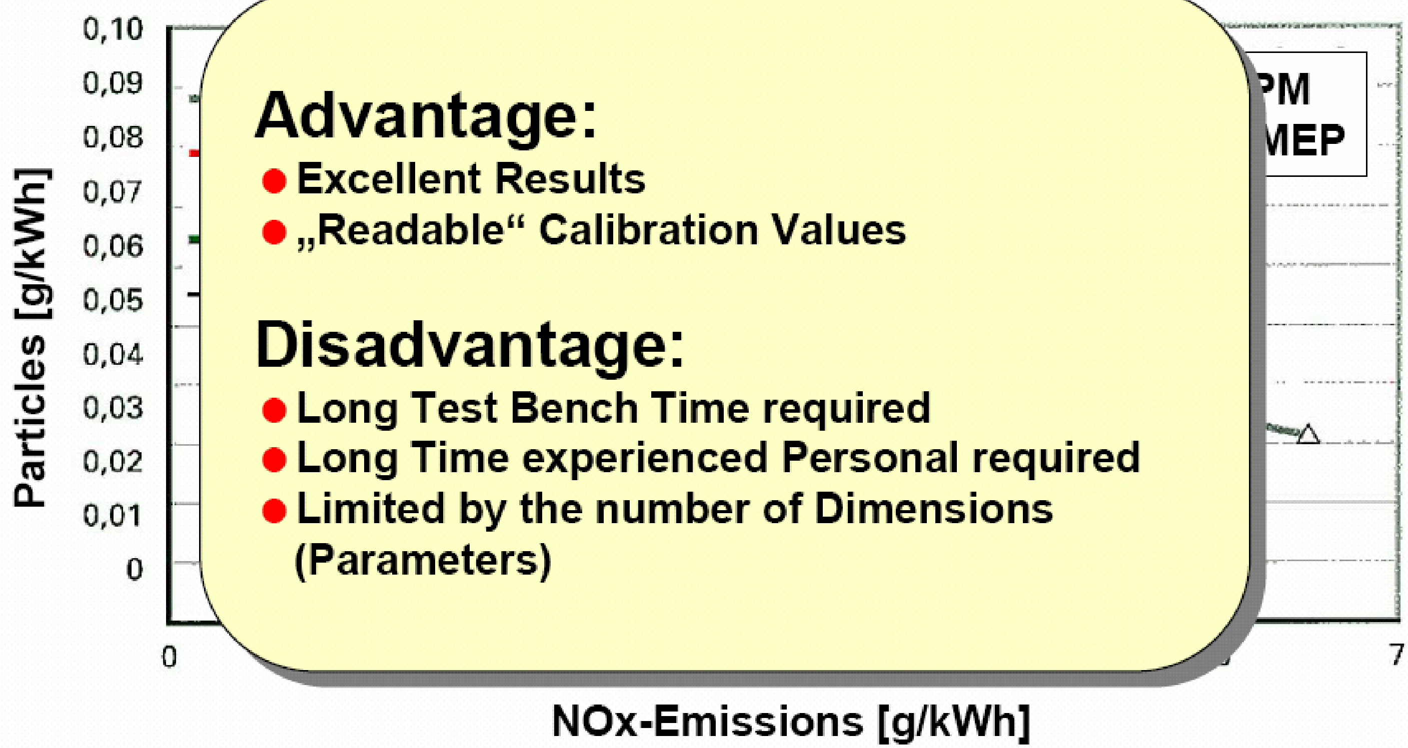


Courtesy: Bosch, FKFS

Manual mapping process

TEST BENCH
„Manual" Calibration Strategy

- Starting with the „biggest" Influence
- Ending with the „smallest" Influence



Advantage:

- Excellent Results
- „Readable" Calibration Values

Disadvantage:

- Long Test Bench Time required
- Long Time experienced Personal required
- Limited by the number of Dimensions (Parameters)

Courtesy: Bosch, FKFS

ECU Mapping Process

TEST BENCH
„Automated“ Calibration Strategy

U

Advantage:
- „Global“ Optimization possible (Emission Test Results can be evaluated on the Test Bench)
- Different „Target“-Functions can be defined and optimized w/o new Measurements
- Saves Test Bench Time
- „Less“ experienced Test Personal required for the Test Bench Work (not true for the Test Plan Definition)

Disadvantage:
- Extremely high Measurement Accuracy required (Measurement Errors are difficult to detect)
- Not usable with Engines with unknown Operating Limits
- ECU Calibration Settings are usually not „readable“ making In-Car Calibration extremely difficult

Courtesy: Bosch, FKFS

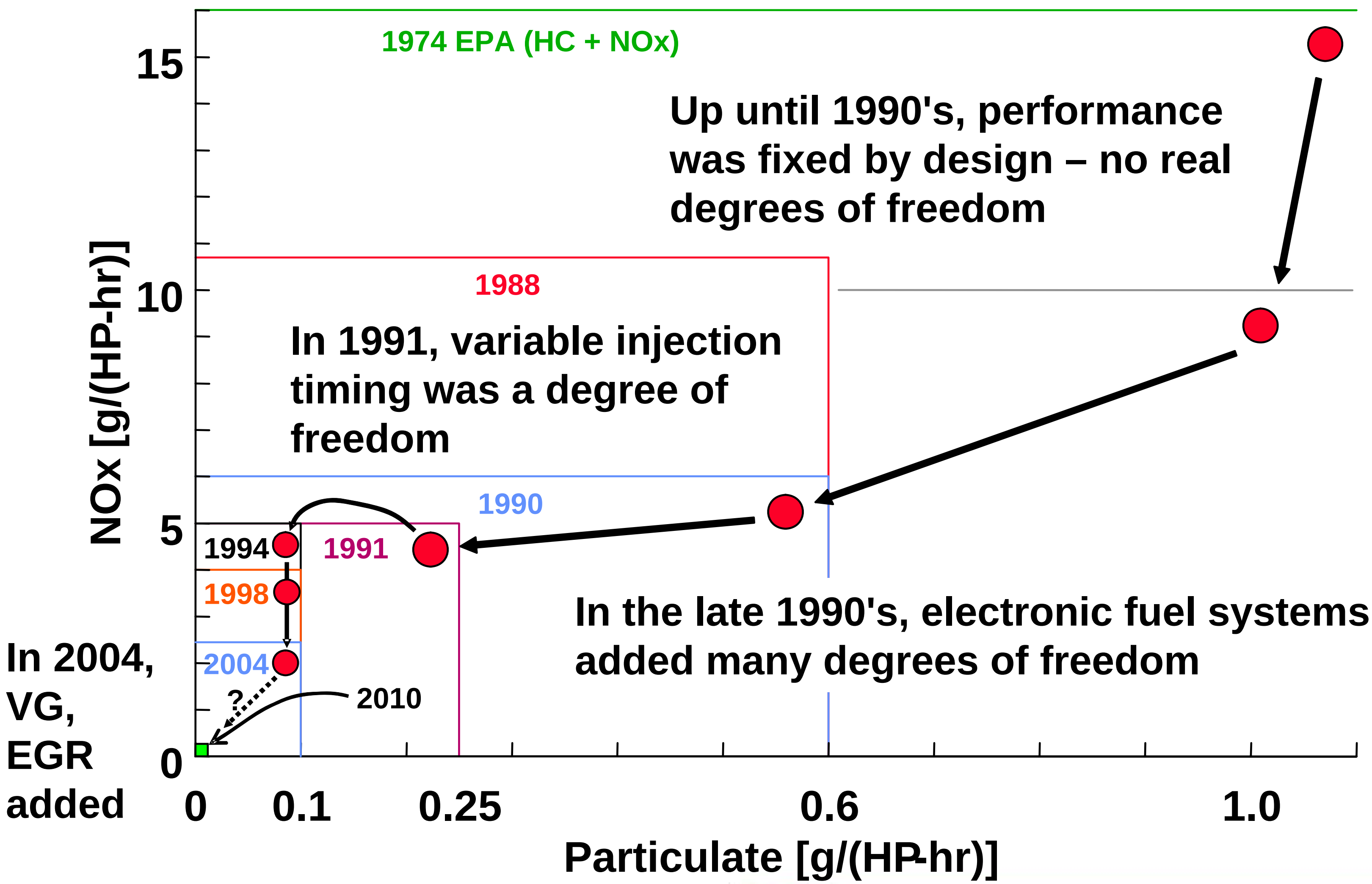
Acknowledgments

- **Steve Yurkovich**,
  - Professor of Electrical and Computer Engineering, Center for Automotive Research, CAR, The Ohio State University.
- **Yann Guezennec**,
  - Professor of Mechanical Engineering, Center for Automotive Research, CAR, The Ohio State University.
- **Michael Bargende**,
  - Professor of Mechanical Engineering, Center for Automotive Research Institute of Automotive Engineering and Vehicle Engines, FKFS, Universität Stuttgart

Analytical Calibration for Diesel Engines

Lisa Farrell, PhD
Cummins Inc

Evolution of Complexity for HD Diesel Engine Calibration



Evolution of Complexity for HD Diesel Engine Calibration

In 2007, robust particulate filter after-treatment was introduced for HD US on-highway engines

What is coming for 2010?

- May introduce new degrees of freedom
- May introduce new after-treatment challenges

Increasing complexity of Diesel engine systems requires the application of analytical calibration methods

Analytical Calibration Benefits – The Cummins Inc Perspective

Design of experiments has led to reduced data collection times

Key benefit is constant development cycles with increasing system complexity

A means to optimize engine systems with many degrees of freedom outside the test cell environment

Rigorous problem definition

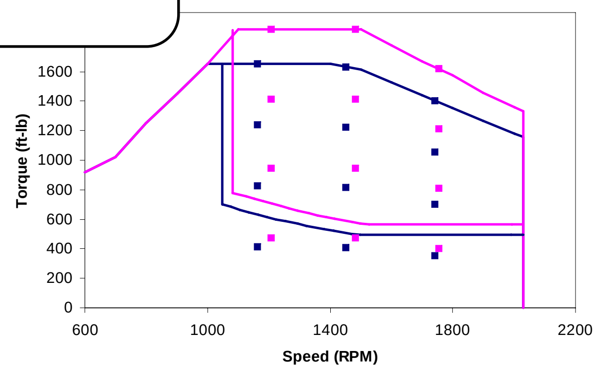
- Constraints – mechanical/emissions
- Objective function – emissions/fuel consumption

Analytical Calibration Development
Steady-state Performance

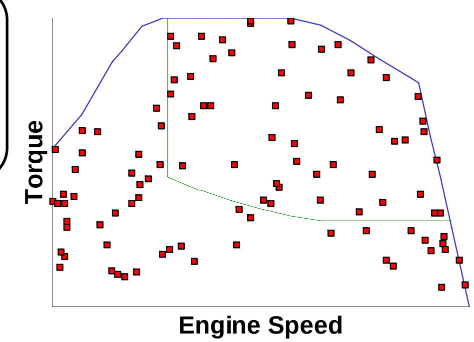
Iteration

Calibration Planning

Engine Family Torque Curves

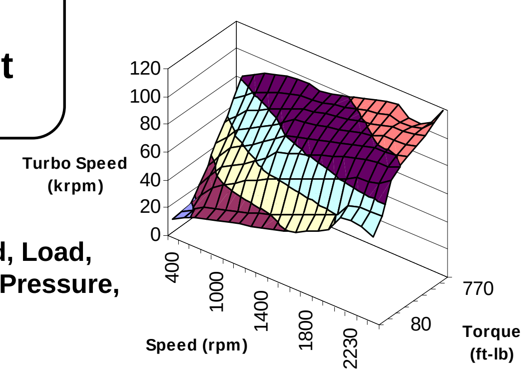


DOE Data Collection



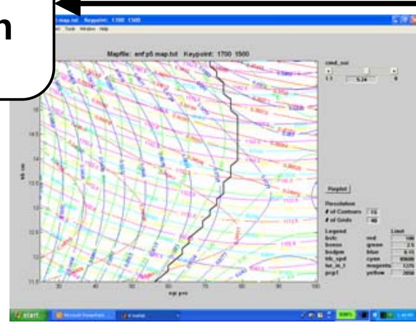
Variation in
Speed, Load, Timing
VG, EGR, Rail Pressure
Pilot, Post, etc.

Model Development

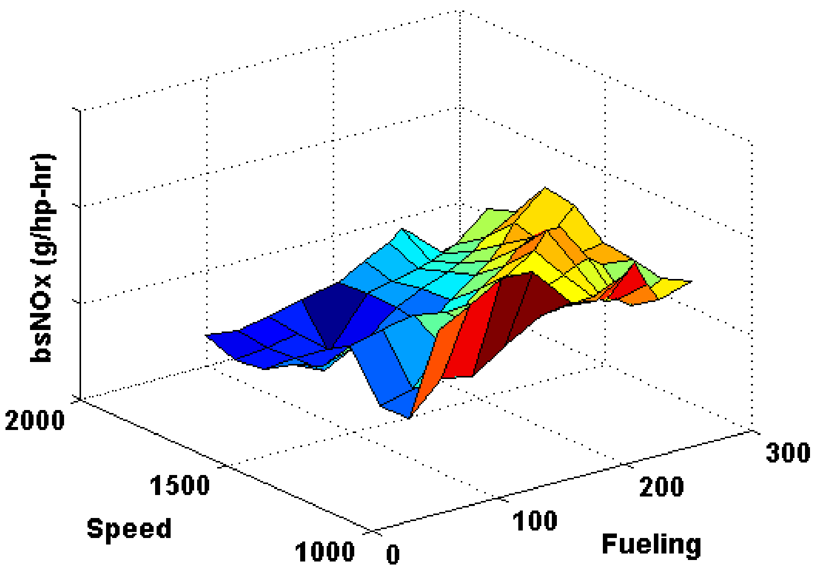


Global Model
Turbo Speed = f(Speed, Load, Timing, VG, EGR, Rail Pressure, Pilot, Post, etc.)

Optimization and Validation

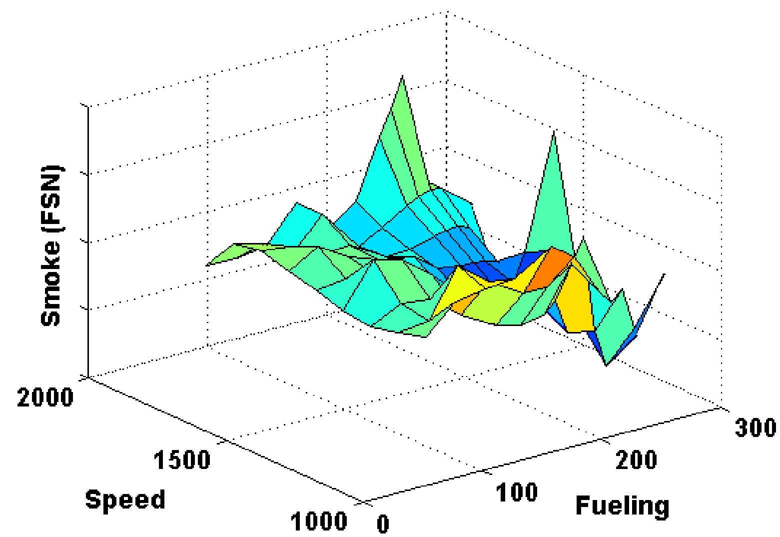


Benefits of Analytical Calibration



Fuel Consumption is optimized over a cycle while constraining cycle bsNOx and surface smoke targets.

Optimal set of control surfaces are determined.



Excellent benefit and capability for steady-state performance.

Transient Calibration Development

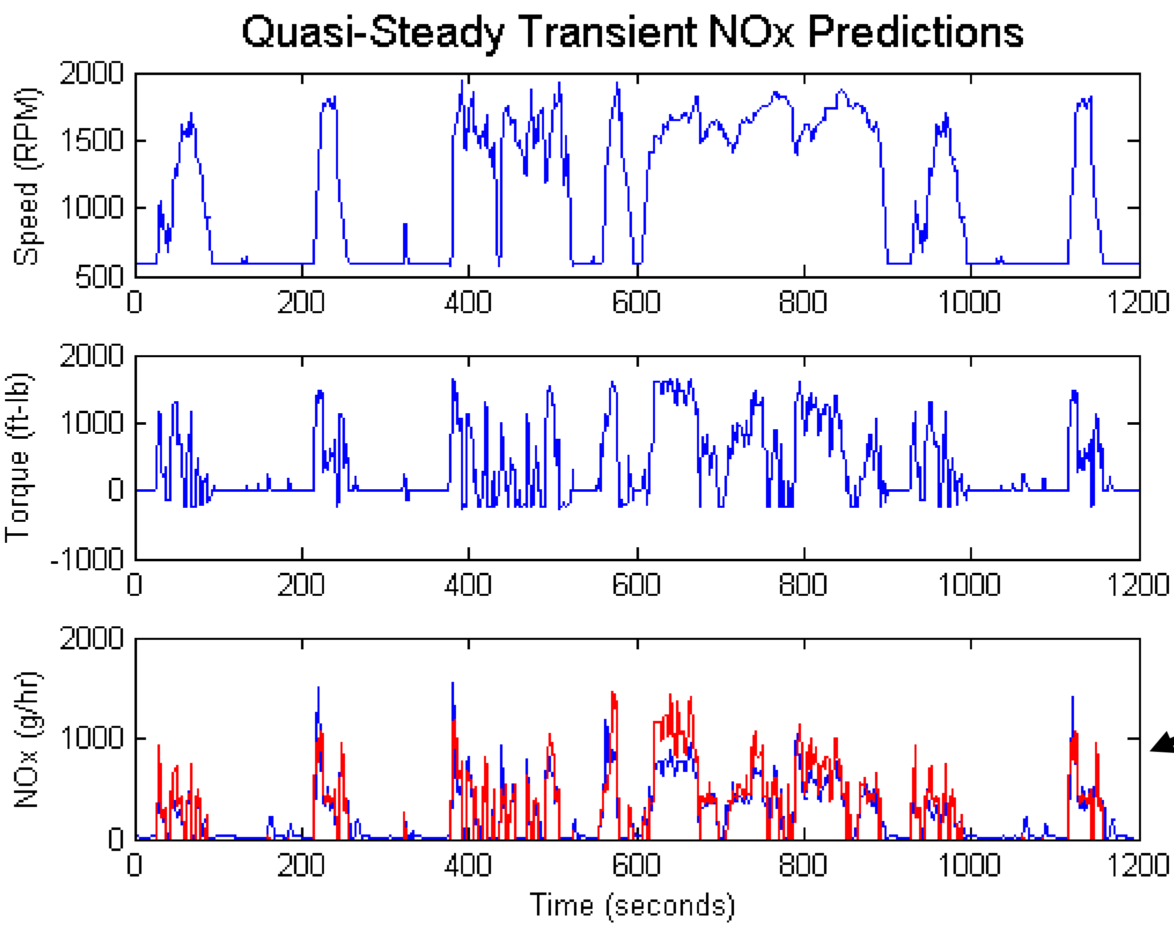
The traditional approach for transient tuning has been centered on transient testing

Current analytical calibration methods for transient tuning are limited, if available at all

Approach for Cummins Inc is a quasi-steady cycle optimization

- Captures transient NOx trends reasonably
- Does not capture transient PM trends

Transient Results



Comparison of measured dilution tunnel NOx emissions vs. quasi-steady predicted NOx emissions

What is Needed for Dynamic Calibration of Diesel Engines?

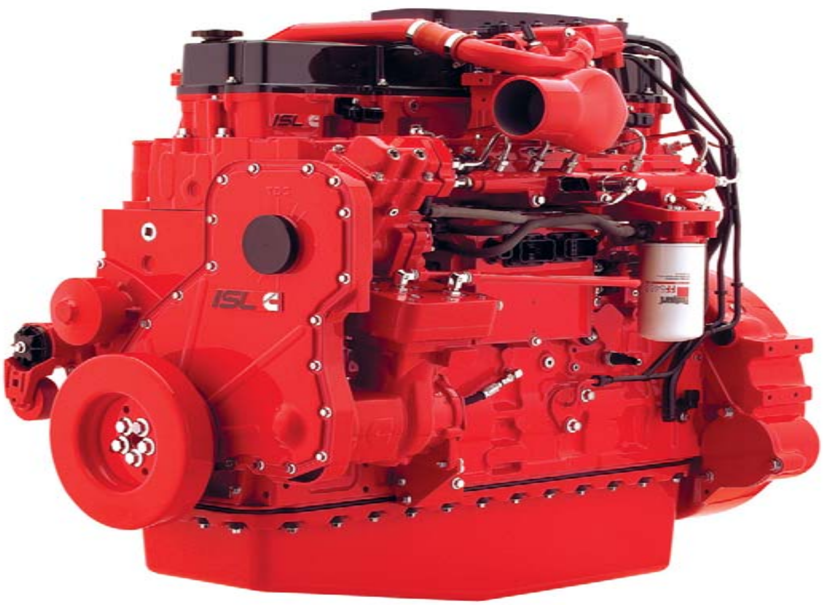
Can dynamic models for key performance parameters be incorporated into analytical techniques?

What statistical or physical models are appropriate for transient response?

What is the optimization method for transient response tuning parameters?

What is the Future of Diesel Engines?

Engine + After-treatment (TBD)



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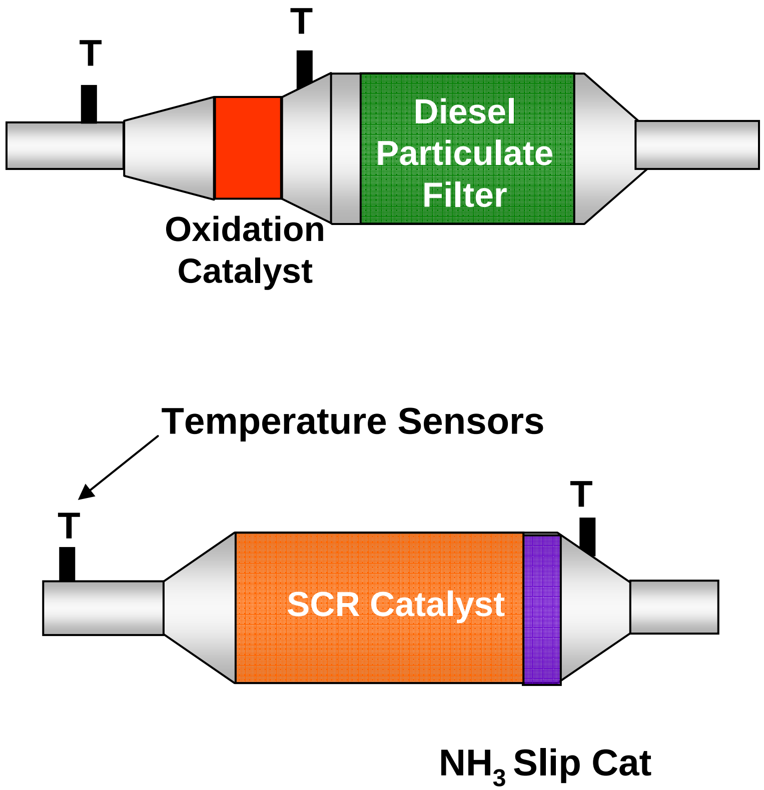
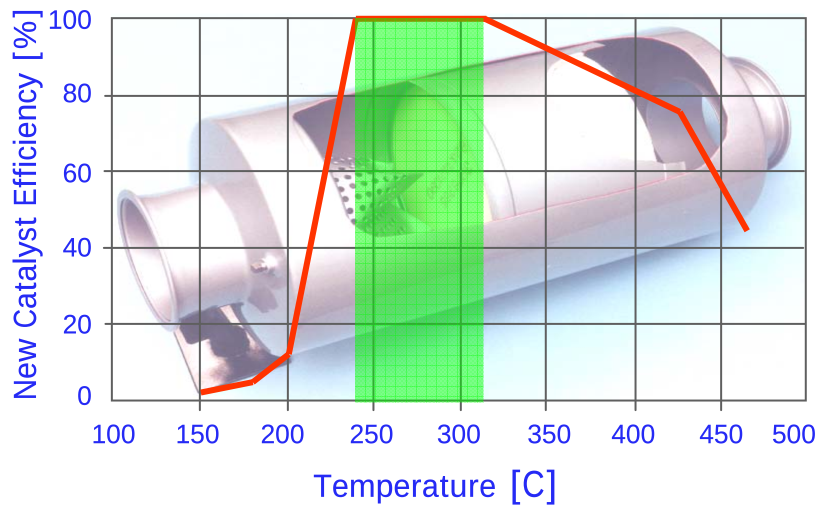
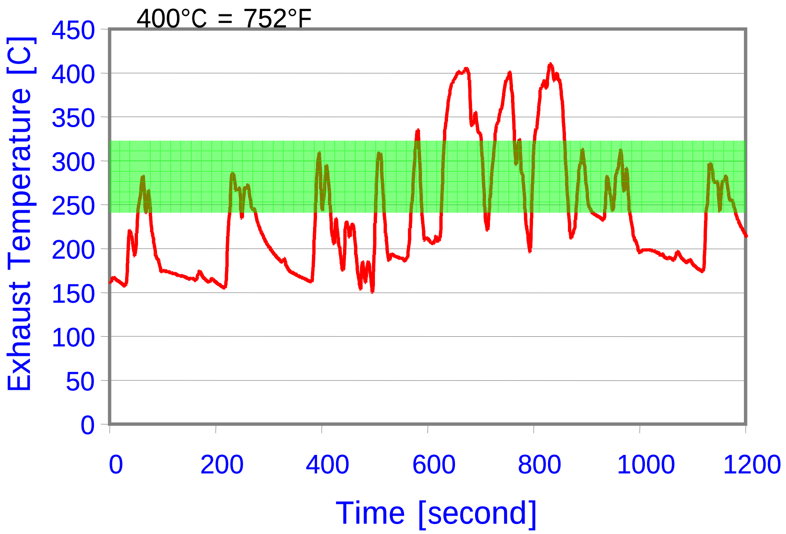
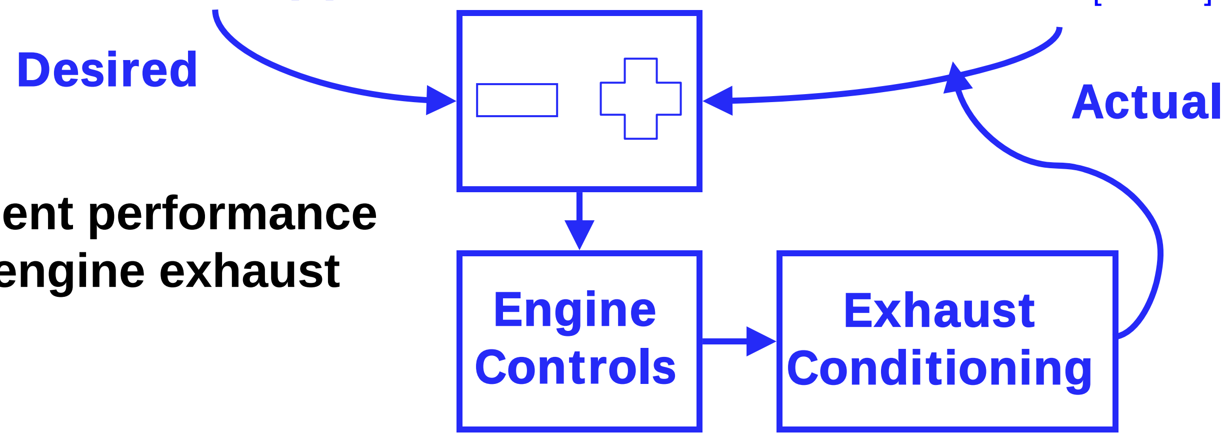


How Can Dynamic After-Treatment Performance Be Included?







After-treatment performance is linked to engine exhaust conditions

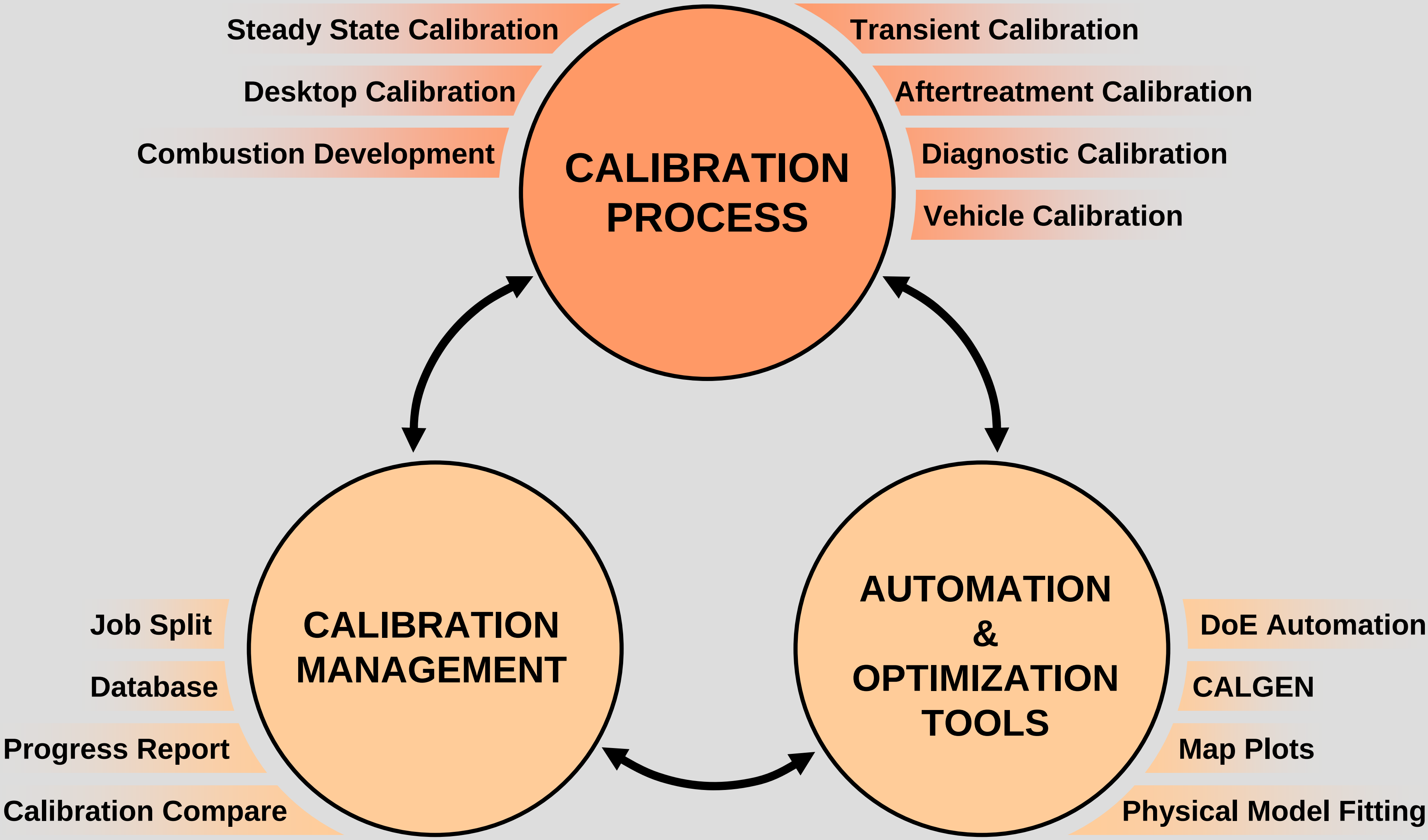
Summary

- Analytical calibration methods have been very successful when applied to steady-state performance
- Dynamic tuning capability needs further development of analytical methods
- Inclusion of after-treatment modeling techniques would enhance analytical calibration methods for diesel engines in the future

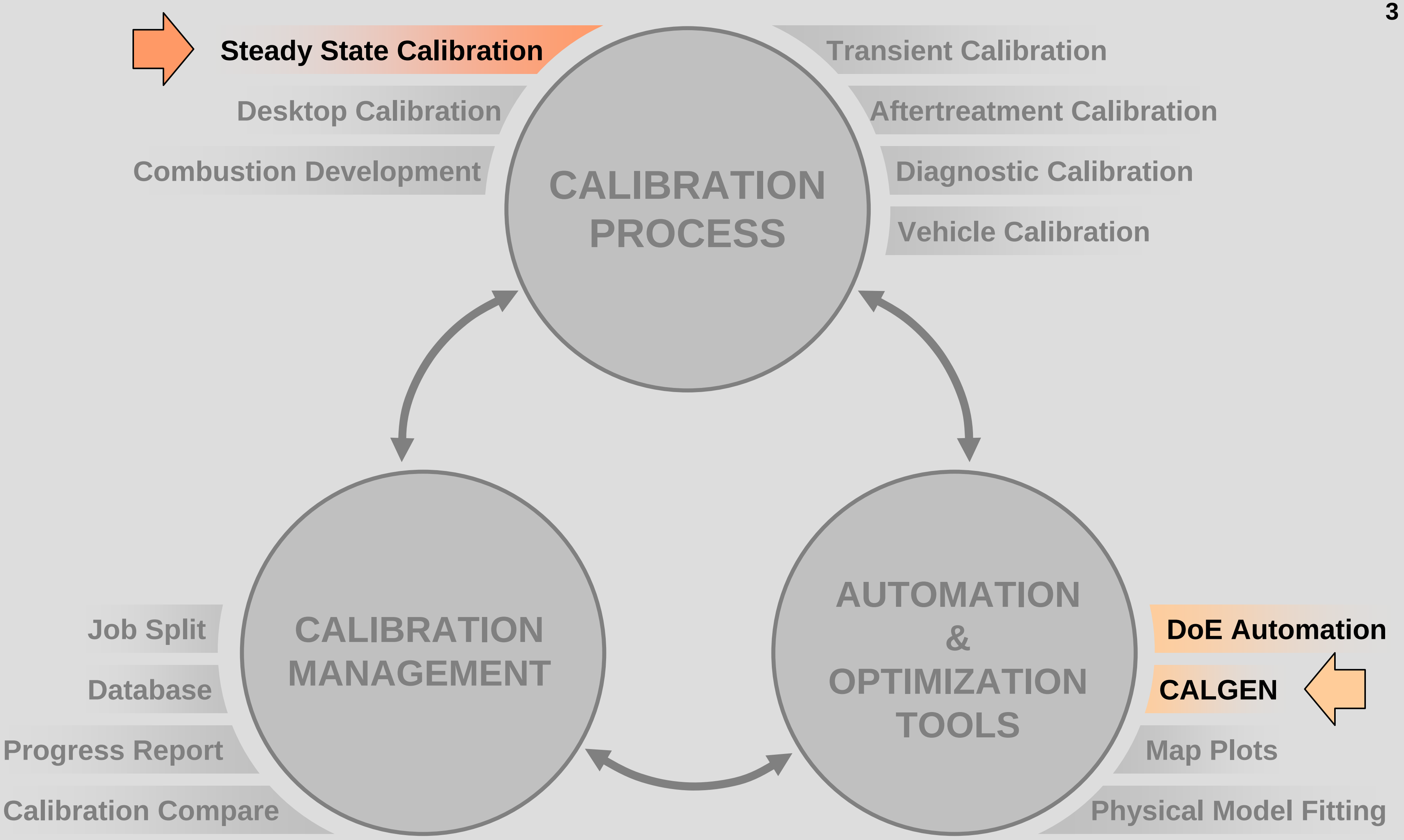
Analytical Calibration at International Truck and Engine Corporation

2007 SAE Commercial Vehicle Congress
Eduardo Nigro

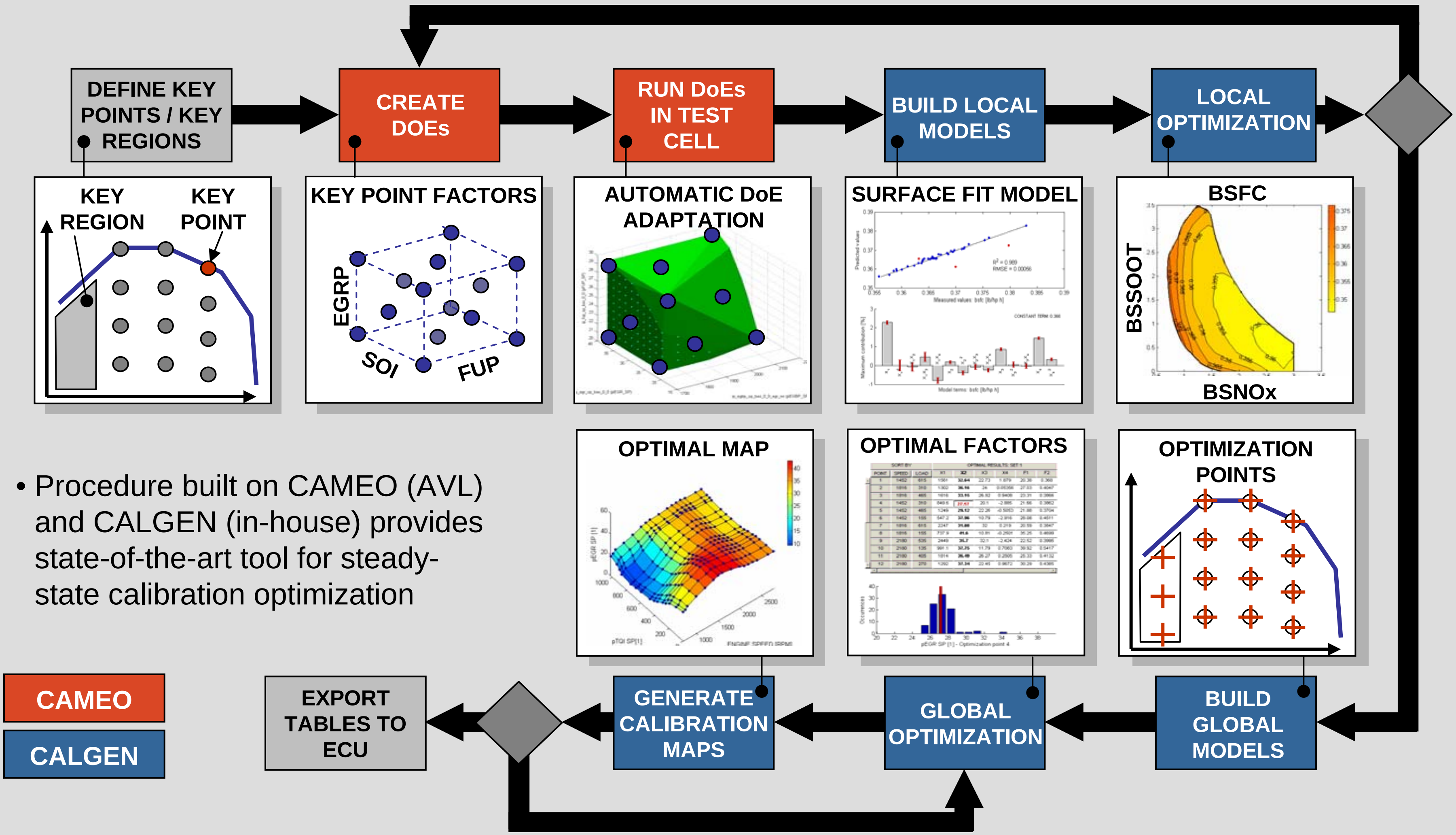
Calibration Process Overview



Calibration Process Overview



Steady State Optimization Process



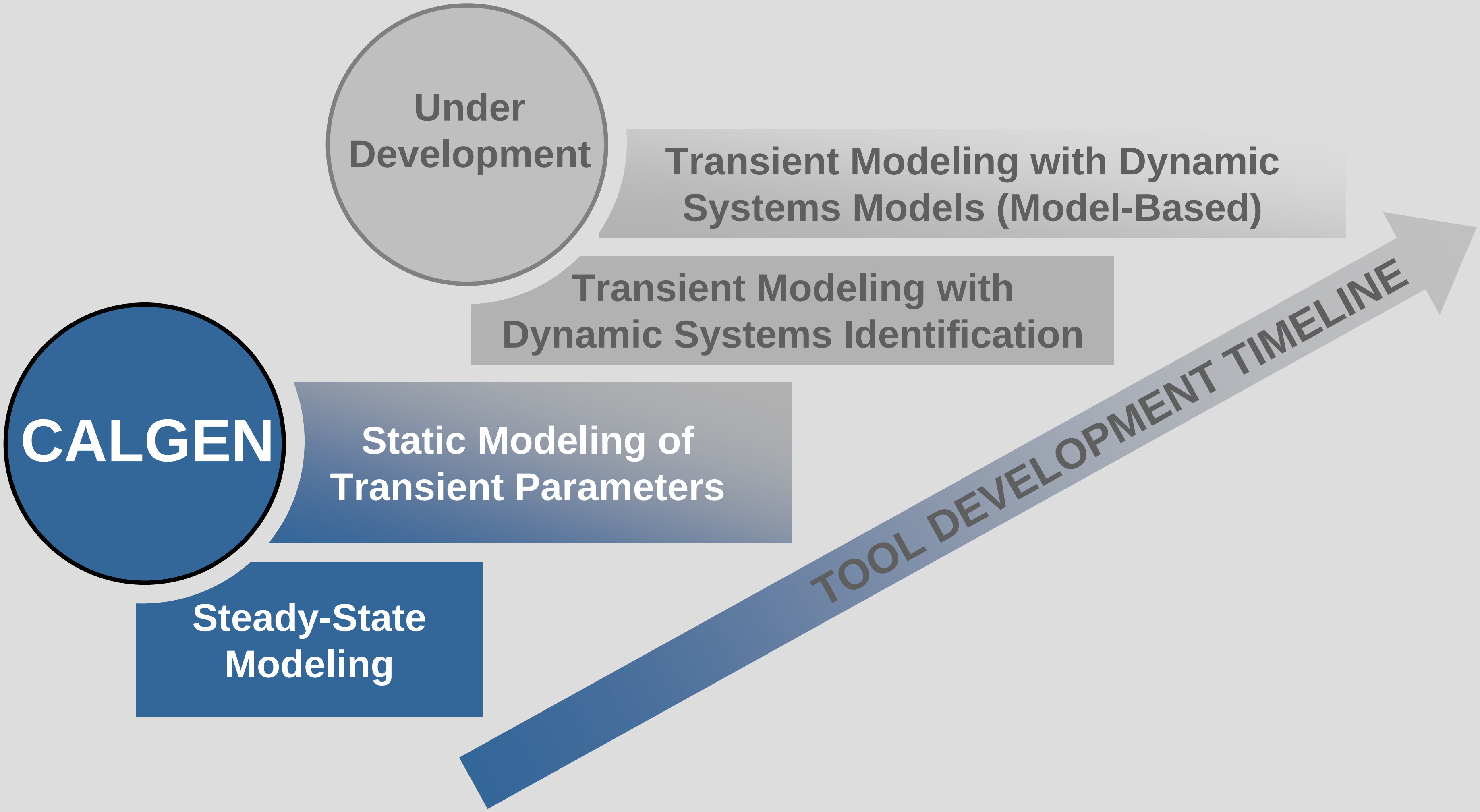
- Procedure built on CAMEO (AVL) and CALGEN (in-house) provides state-of-the-art tool for steady-state calibration optimization

Analytical Tools

- Analytical tools must be **end-user-oriented**
- **CALGEN** is used by engine calibrators

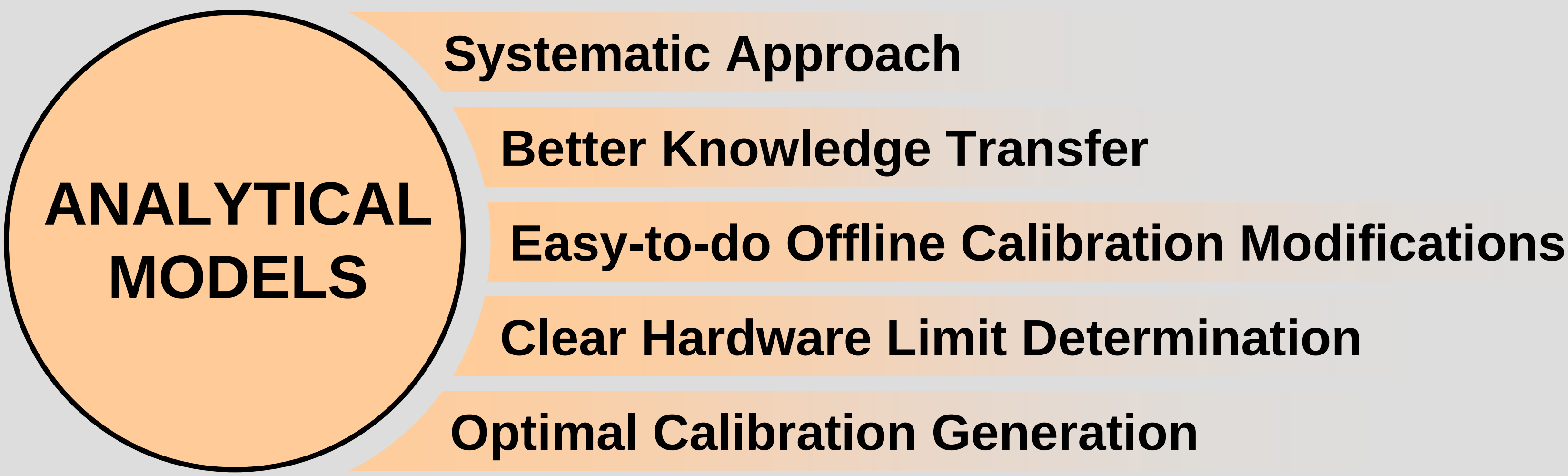
LOW COST + PROCESS ORIENTED + EASY TO USE + FAST

Vision for Tool Development



Analytical Models

- Analytical models strengthen the calibration process
- Benefits in process flow, data quality and development time



Math-based Control Development and Analytical Calibration

Yongsheng He
General Motors Research and Development

October 31, 2007

Outline

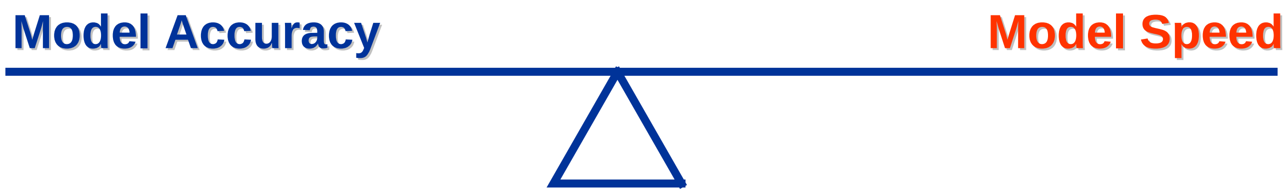
- **Introduction**
  - Math-based control development
  - Analytical calibration
- **Math-based control development**
  - Detailed 1D engine model
  - Mean value engine model
- **Results and Discussion**
  - Step transients
  - FTP cycle
- **Summary**
  - Current capabilities
  - Future outlook

Introduction

- **Math-based control development in automotive industry**
  - Much of control design and development process could be done off-line using computer simulations
  - Dramatically reduce development time and risk
- **Integrated engine and control system model valuable**
  - Accurately evaluate control algorithms
  - Explore different control strategies & study parameter sensitivity
    - Before experiments conducted
    - Before hardware selected and built
- **Analytic calibration critical to develop modern embedded powertrain controllers (complexity, speed-to-market, etc.)**
  - Physical dyno and/or vehicle testing to be minimized
  - Computer simulations also to be reduced

Model Accuracy vs Model Speed

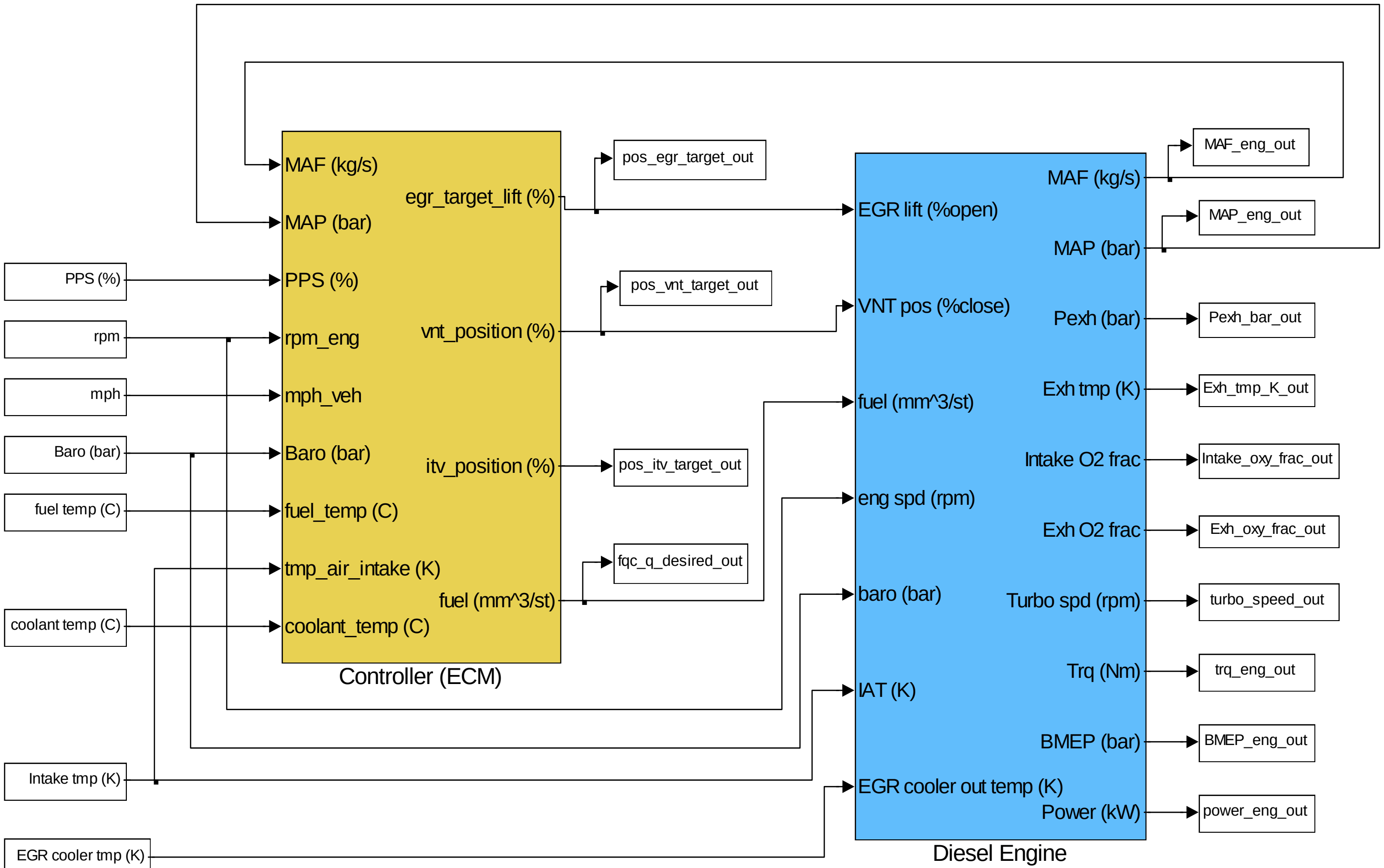
- **Fast-running engine model with sufficient accuracy**
  - Efficient evaluation of control algorithms and control strategies
  - Exploration of the classical trade-off in the modeling process



- **Detailed 1D engine model**
  - Predict gas dynamics and engine performance within 3-5%
  - Run speed on the order of 100~1000 times slower than real time

- **Mean value engine model**
  - Capture dynamics over one or more engine cycles
  - Run speed close to or faster than real time

Integrated Engine & Control System Simulation

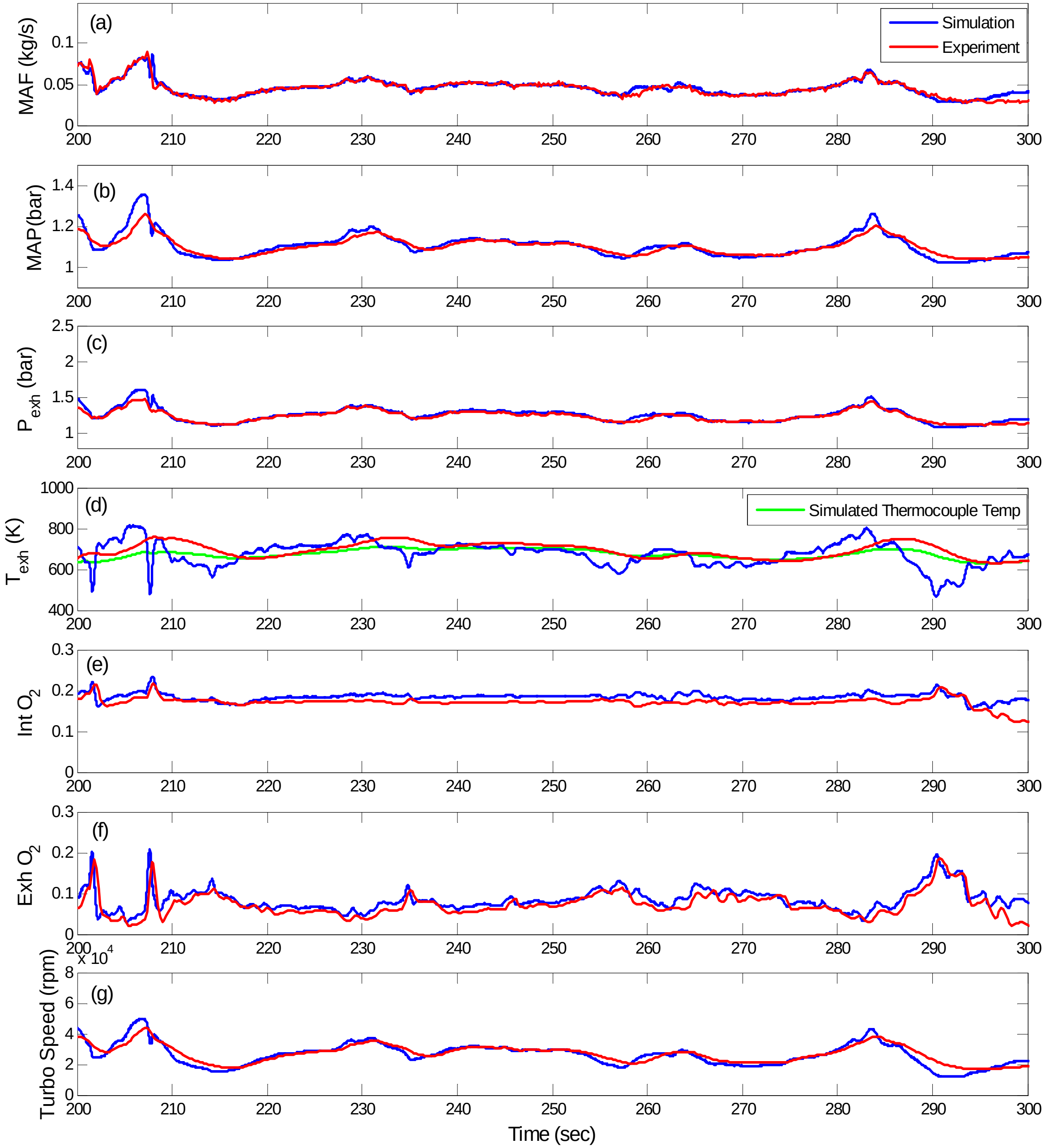


(SAE Paper 2006-01-0439)

FTP Cycle: Simulation Results

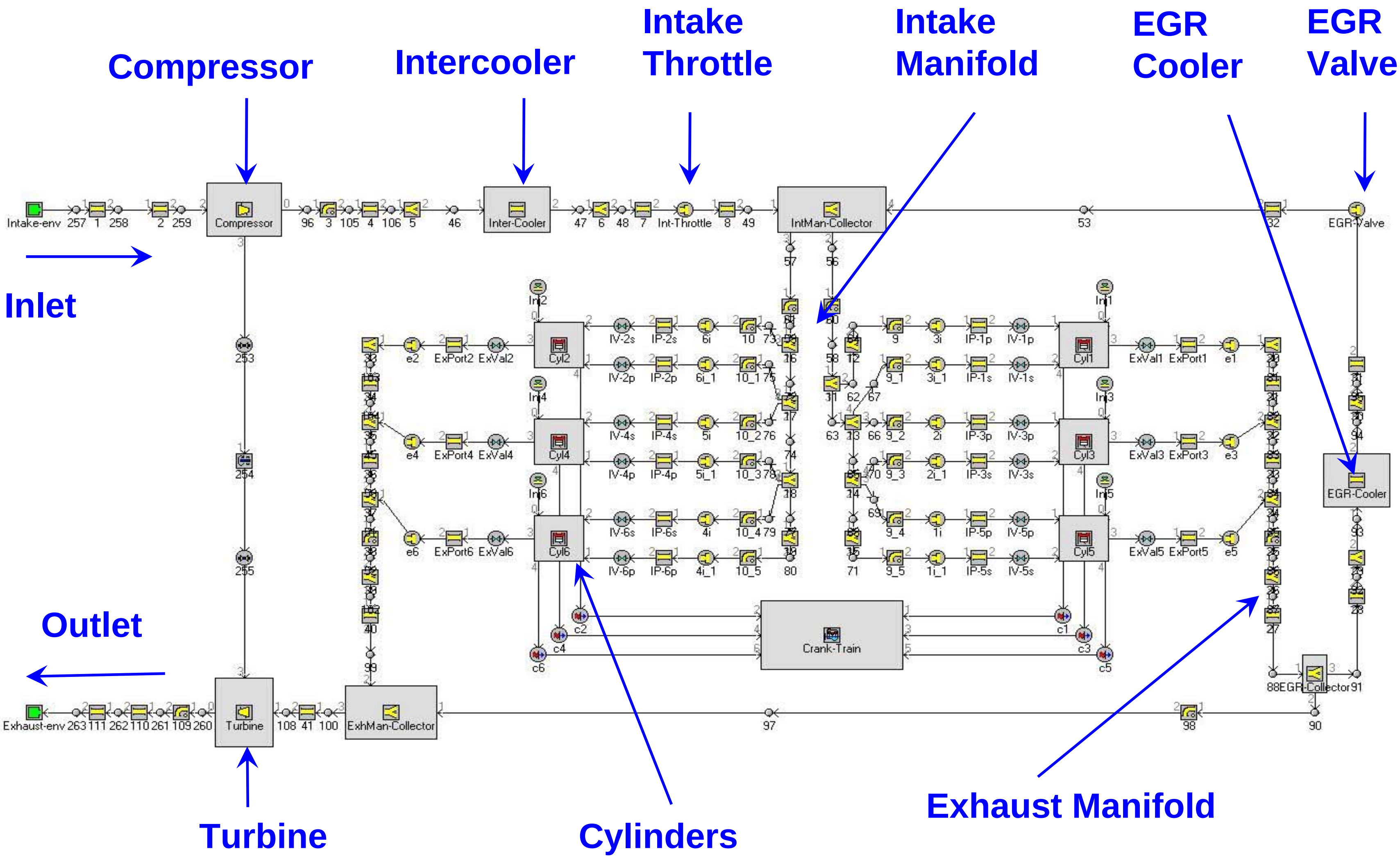
- **Blow-up of the FTP results to compare simulations and experiments (200-300 s)**

  .... Experiment
  —— Simulation



(SAE Paper 2006-01-0439)

Detailed 1D Engine Model

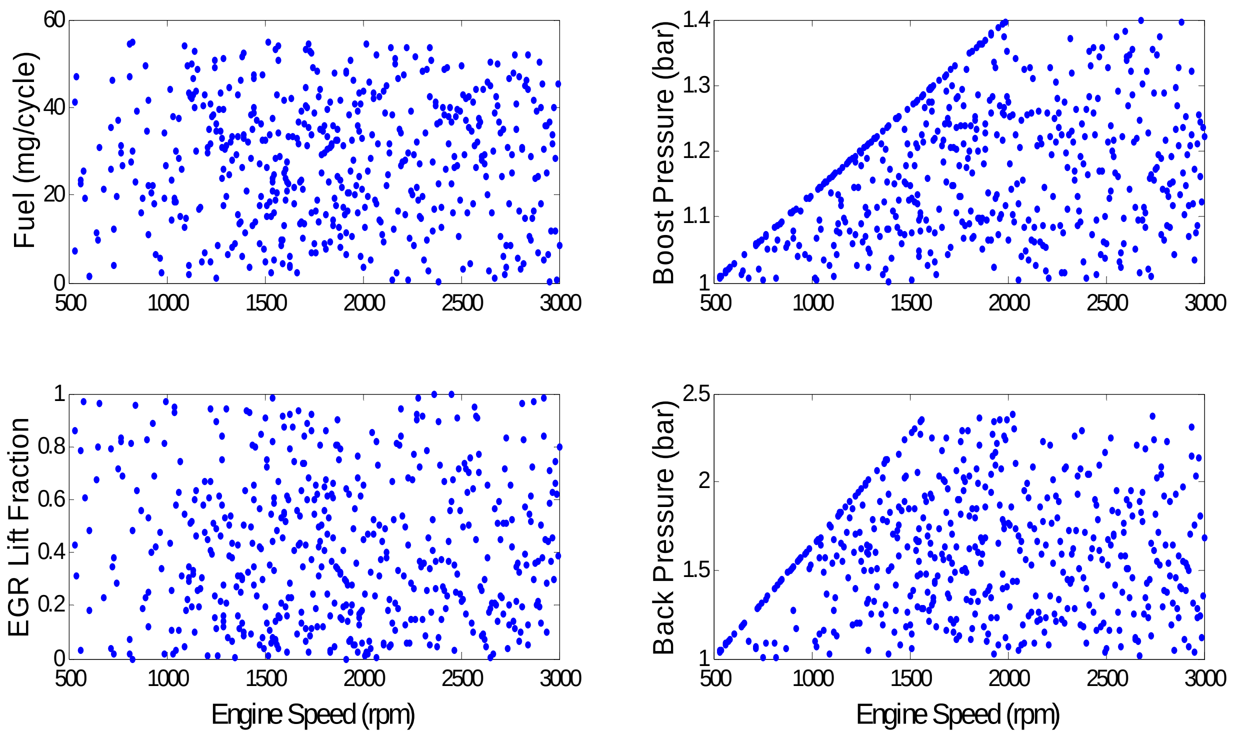


(SAE Paper 2007-01-1304)

Input Variables and DOE

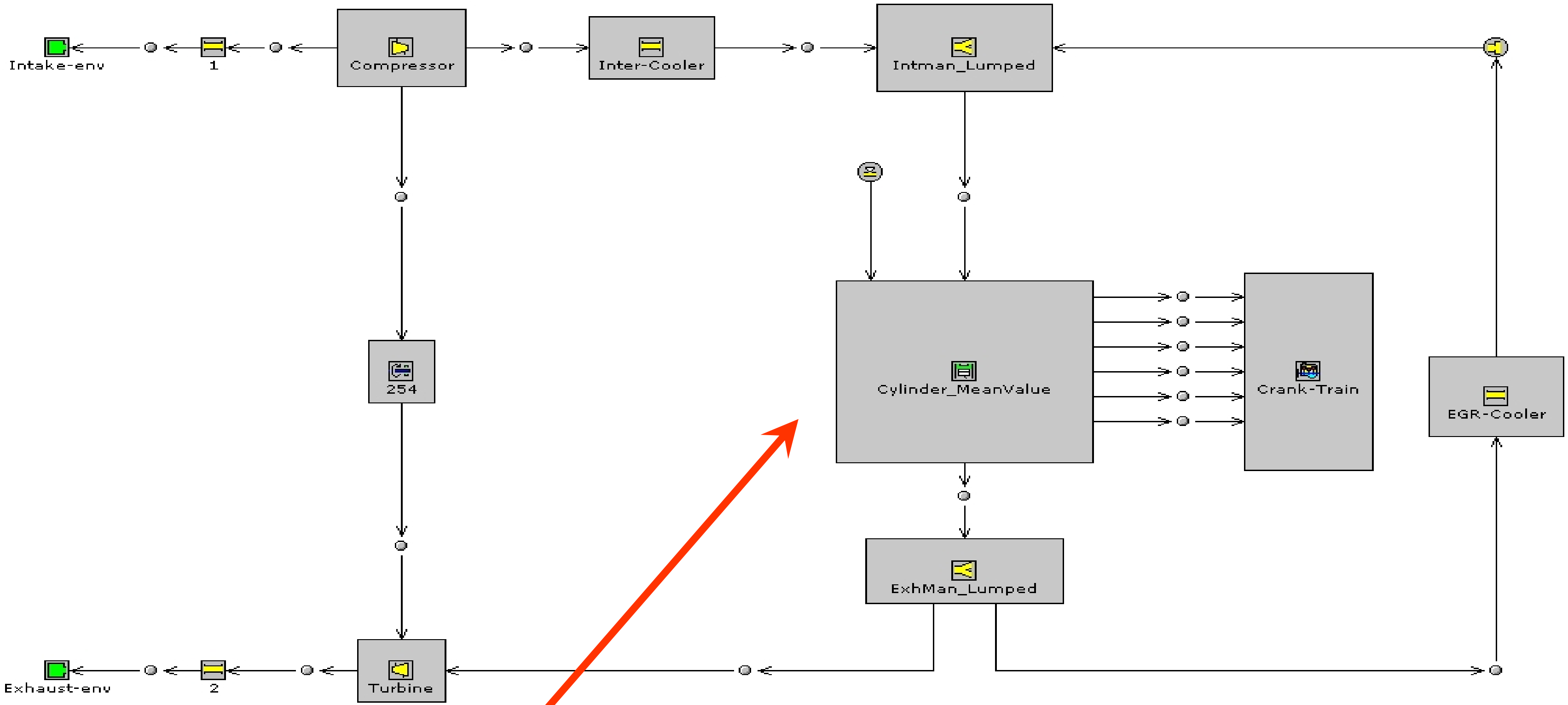
- **Turbocharged V6 diesel engine with external EGR**
- **Focus on the control of fueling, EGR, and VNT**
- **DOE: Constrained Latin Hypercube**
  - Consider the physical constraints of engine operations

Engine Speed (rpm)	[530 3000]
Total Fueling (mg/cycle)	[0 55]
EGR Valve Lift Fraction	[0 1]
Boost Pressure (bar)	[1 1.4]
Back Pressure (bar)	[1 2.4]



(SAE Paper 2007-01-1304)

Mean Value Engine Modeling – Final Model

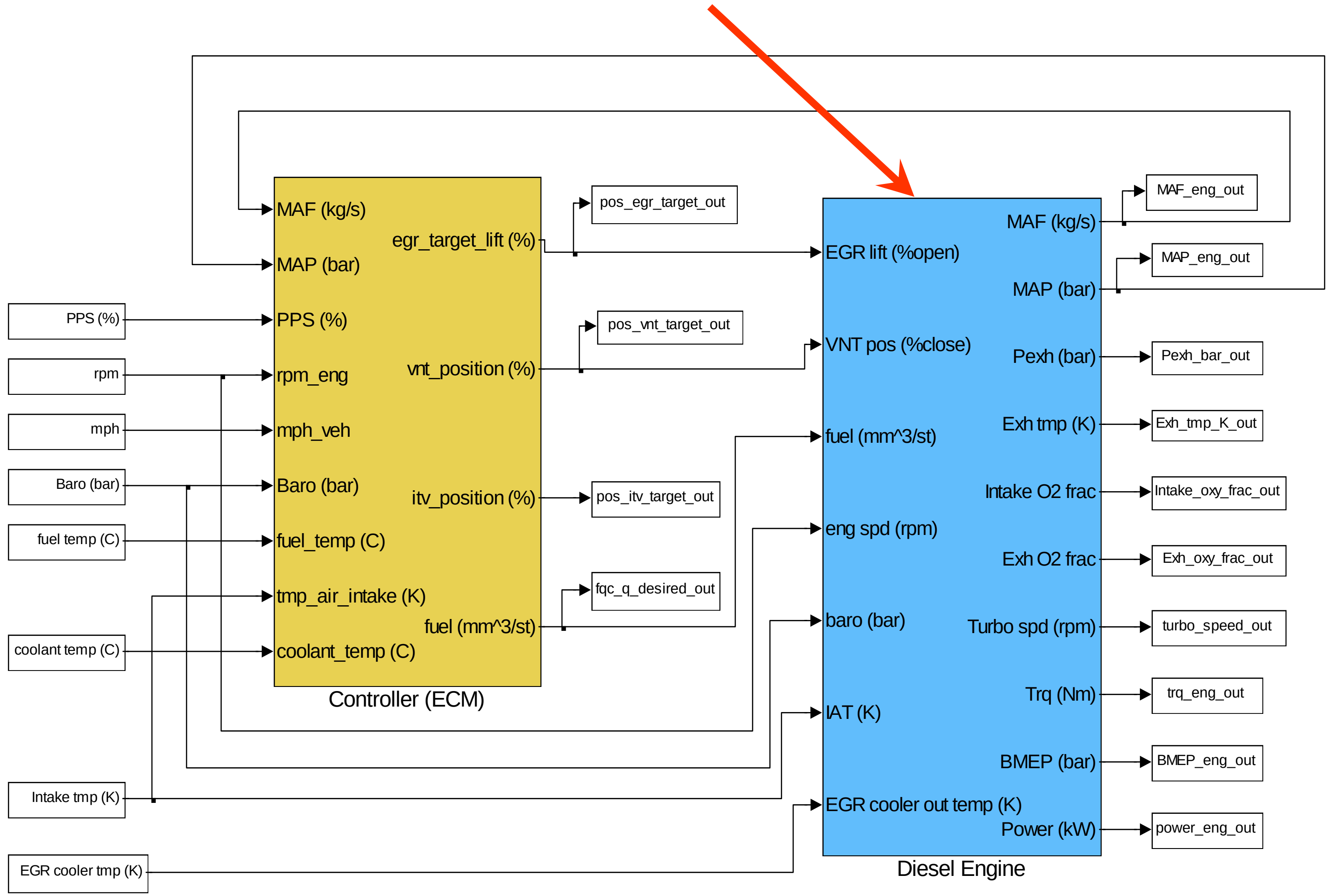


- Hybrid RBF (Model-Based Calibration Toolbox, MATLAB) to approximate cylinder quantities for better accuracy

R^2	Hybrid RBF
Volumetric Efficiency	0.999
Indicated Efficiency	0.967
Exhaust Energy Fraction	0.979

(SAE Paper 2007-01-1304)

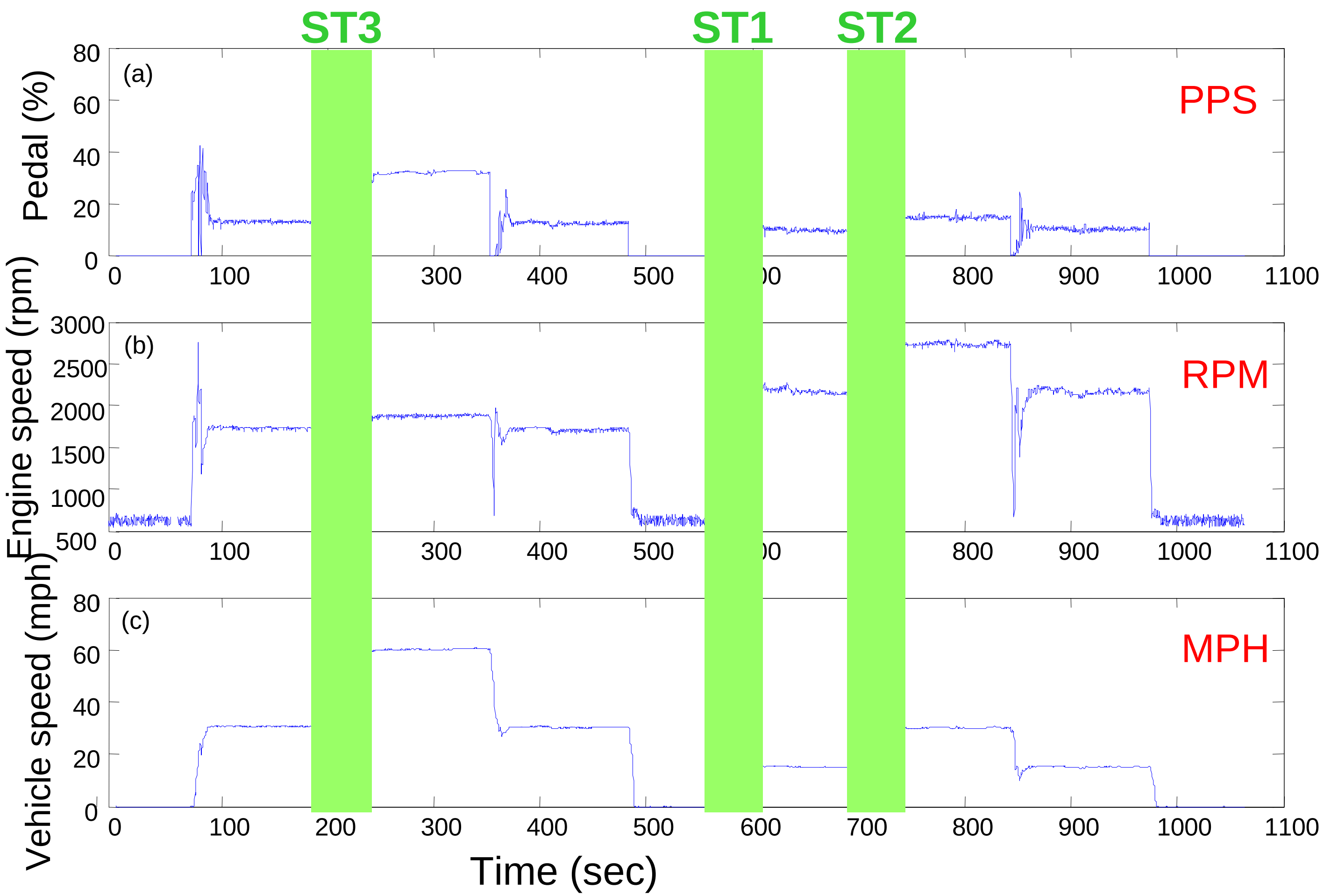
Integrated Engine & Controller Model – Updated with Mean Value Model



(SAE Paper 2007-01-1304)

Model Validation: Vehicle Testing

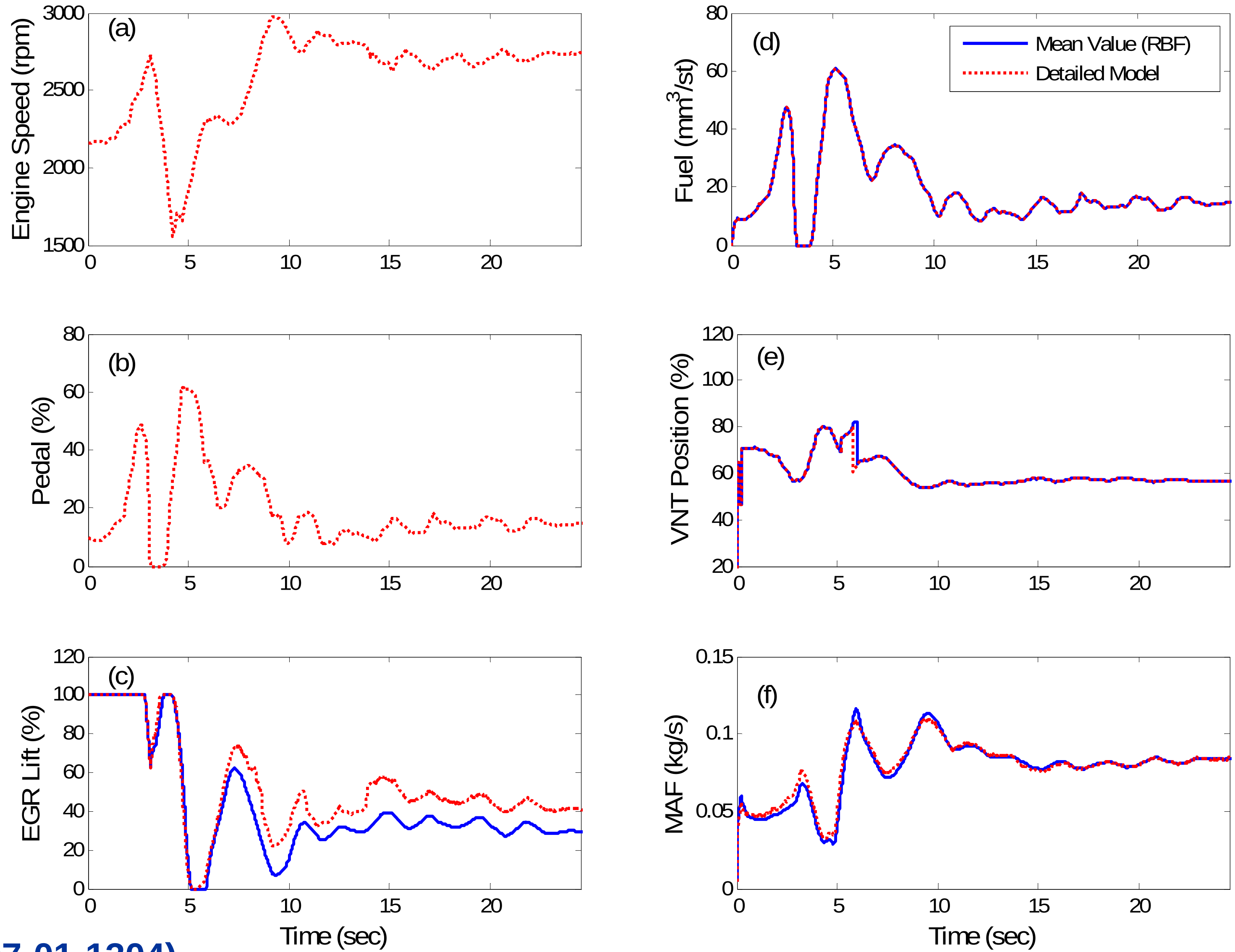
- **Series of different cruising and acceleration conditions**
  - Selected for validation: 3 step transients (**ST**)



(SAE Paper 2007-01-1304)

Step Transient: Simulation Results (1/3)

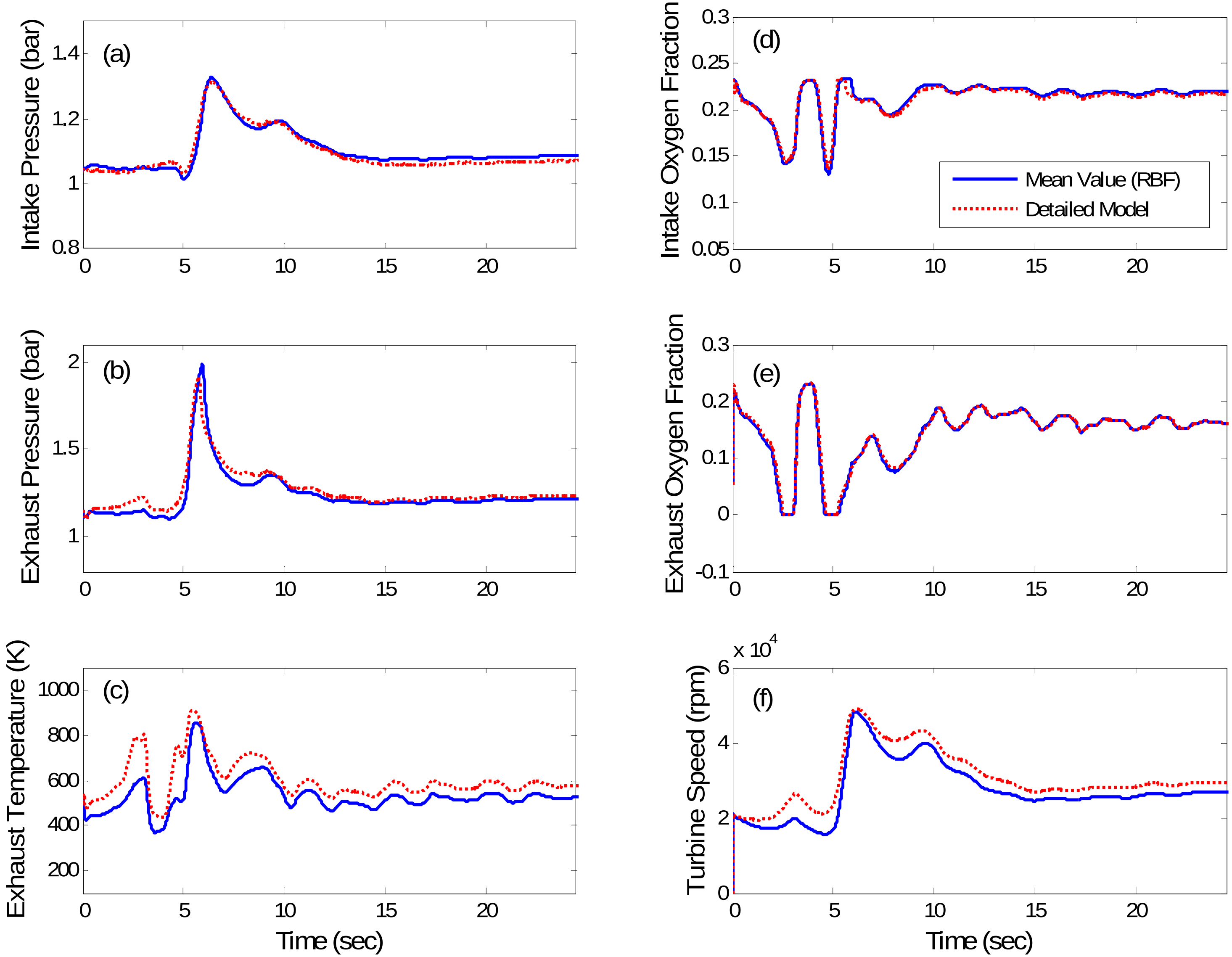
ST2



(SAE Paper 2007-01-1304)

Step Transient: Simulation Results (2/3)

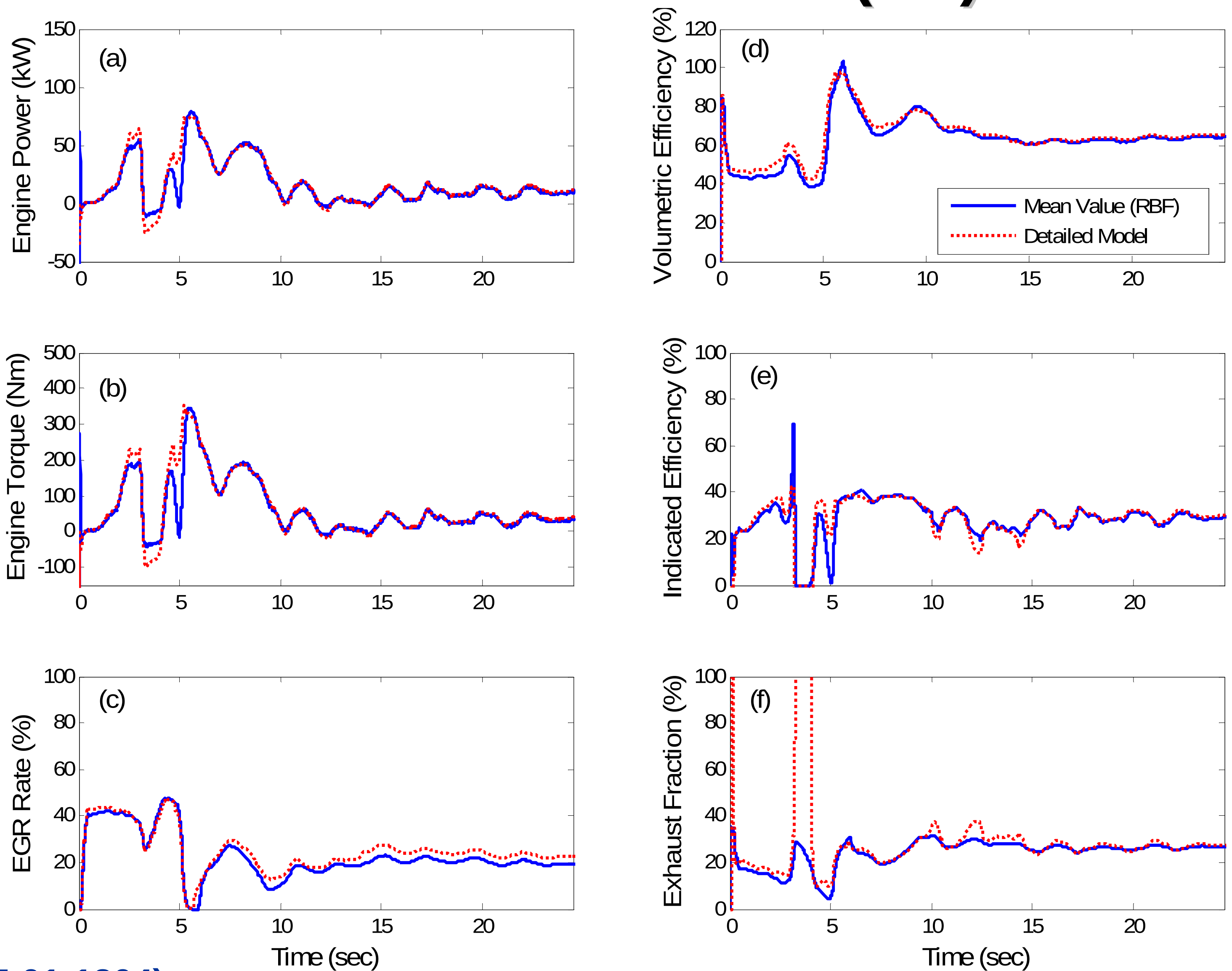
ST2



(SAE Paper 2007-01-1304)

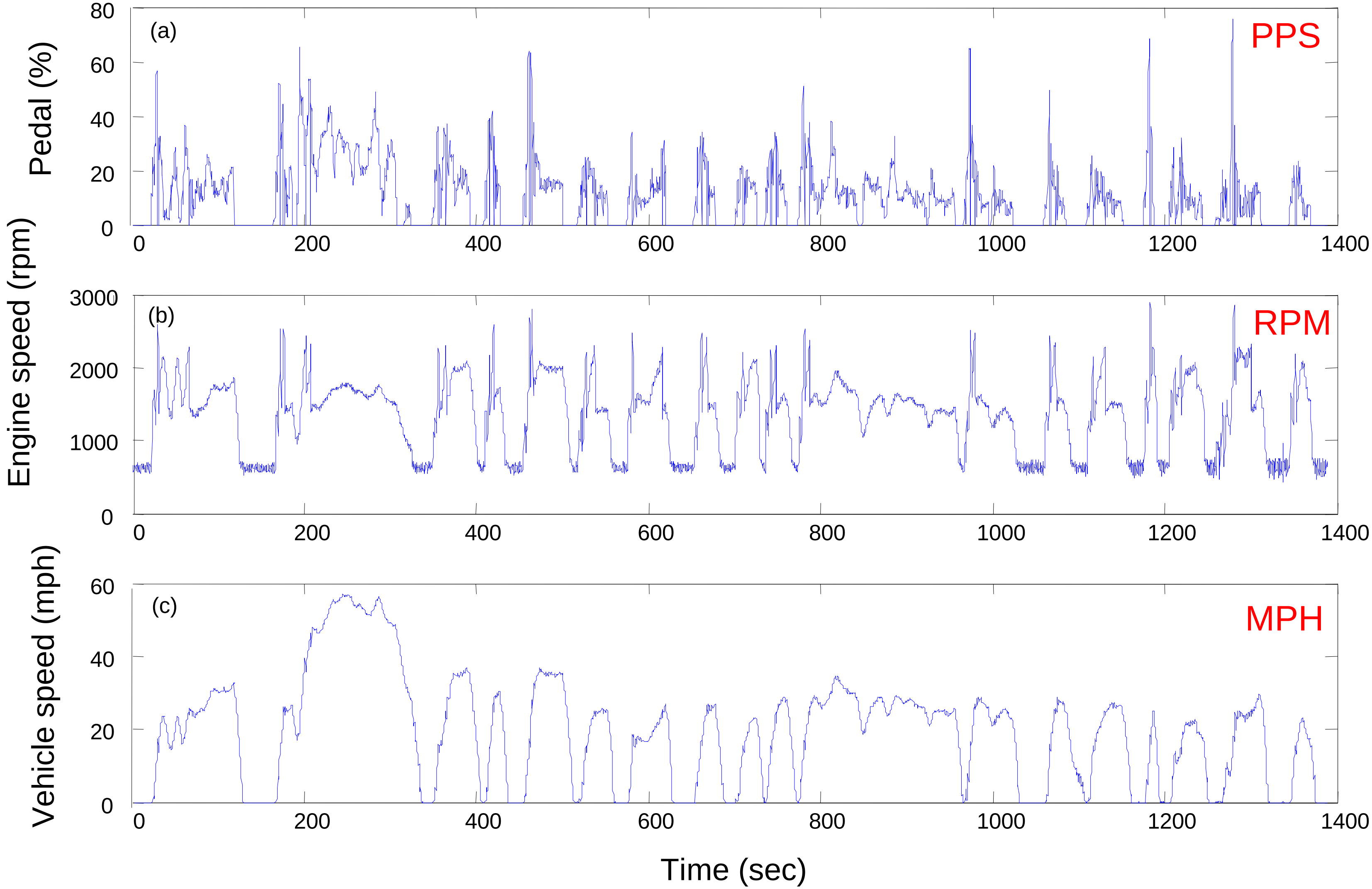
Step Transient: Simulation Results (3/3)

ST2



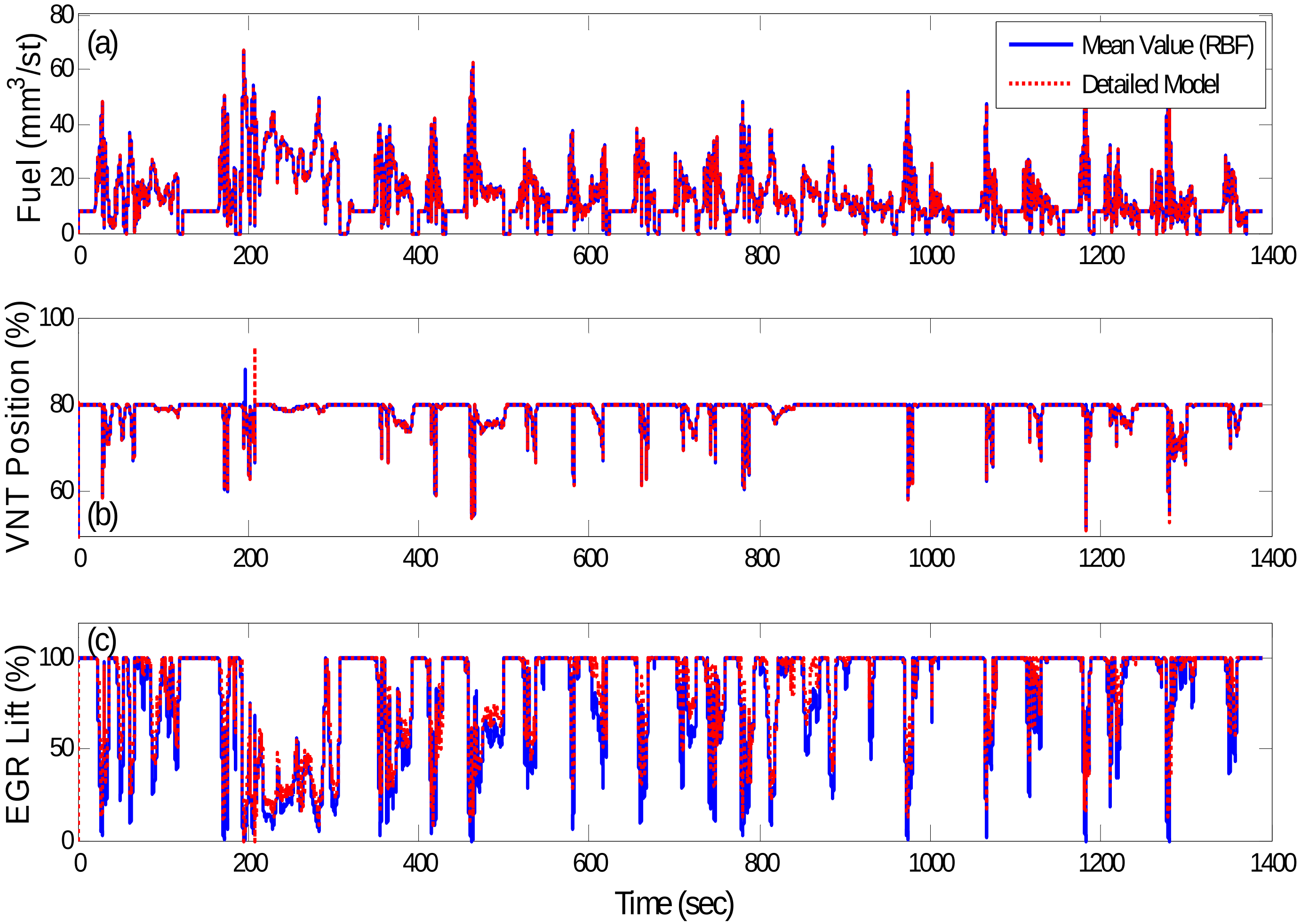
(SAE Paper 2007-01-1304)

Model Validation: FTP Cycle



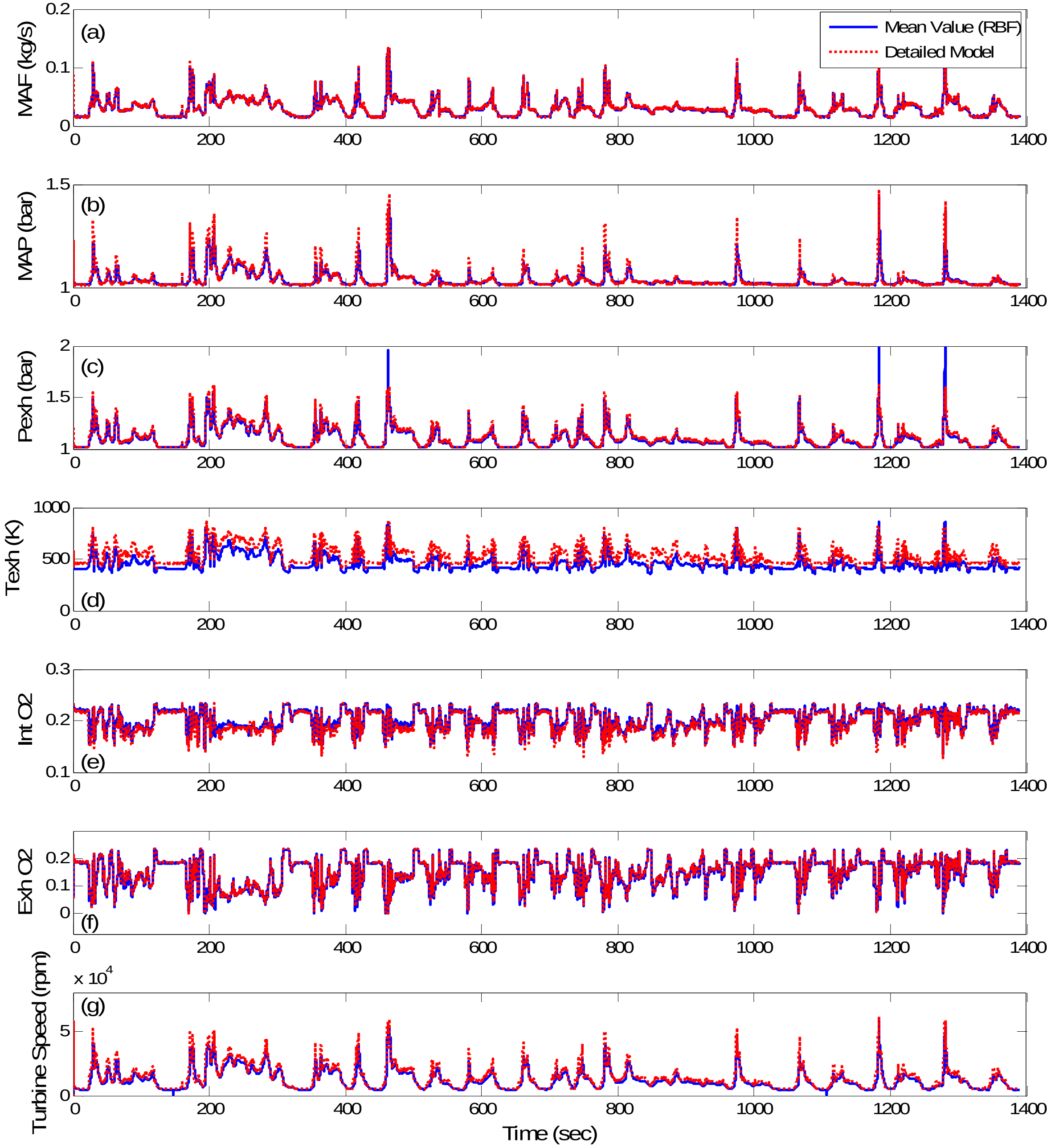
(SAE Paper 2007-01-1304)

FTP Cycle: Simulation Results (1/2)



(SAE Paper 2007-01-1304)

FTP Cycle: Simulation Results (2/2)

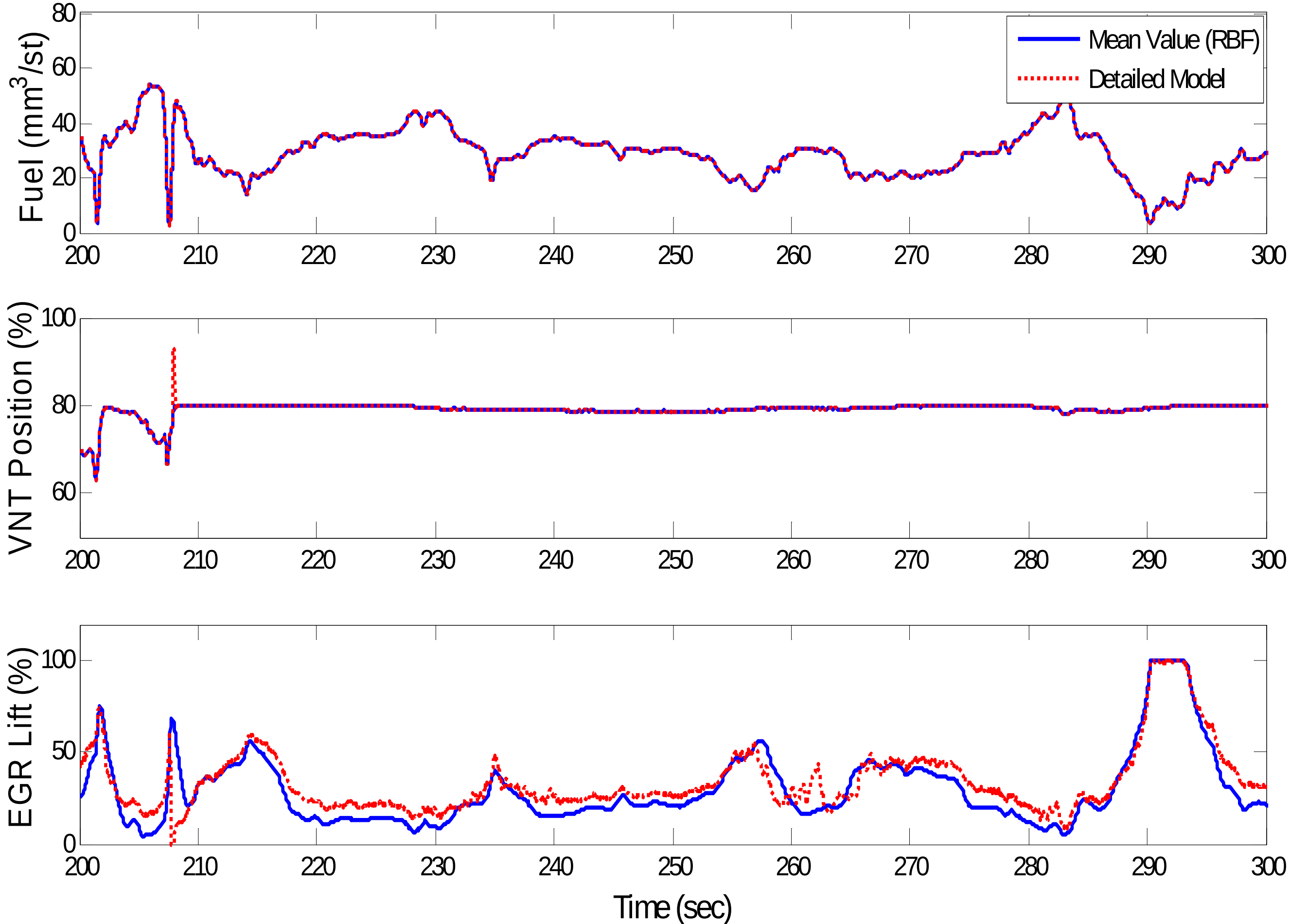


(SAE Paper 2007-01-1304)

FTP Cycle: Simulation Results Blow-up (1/2)

- **Blow-up of the FTP results for comparison (200-300 s)**

Detailed
Mean Value

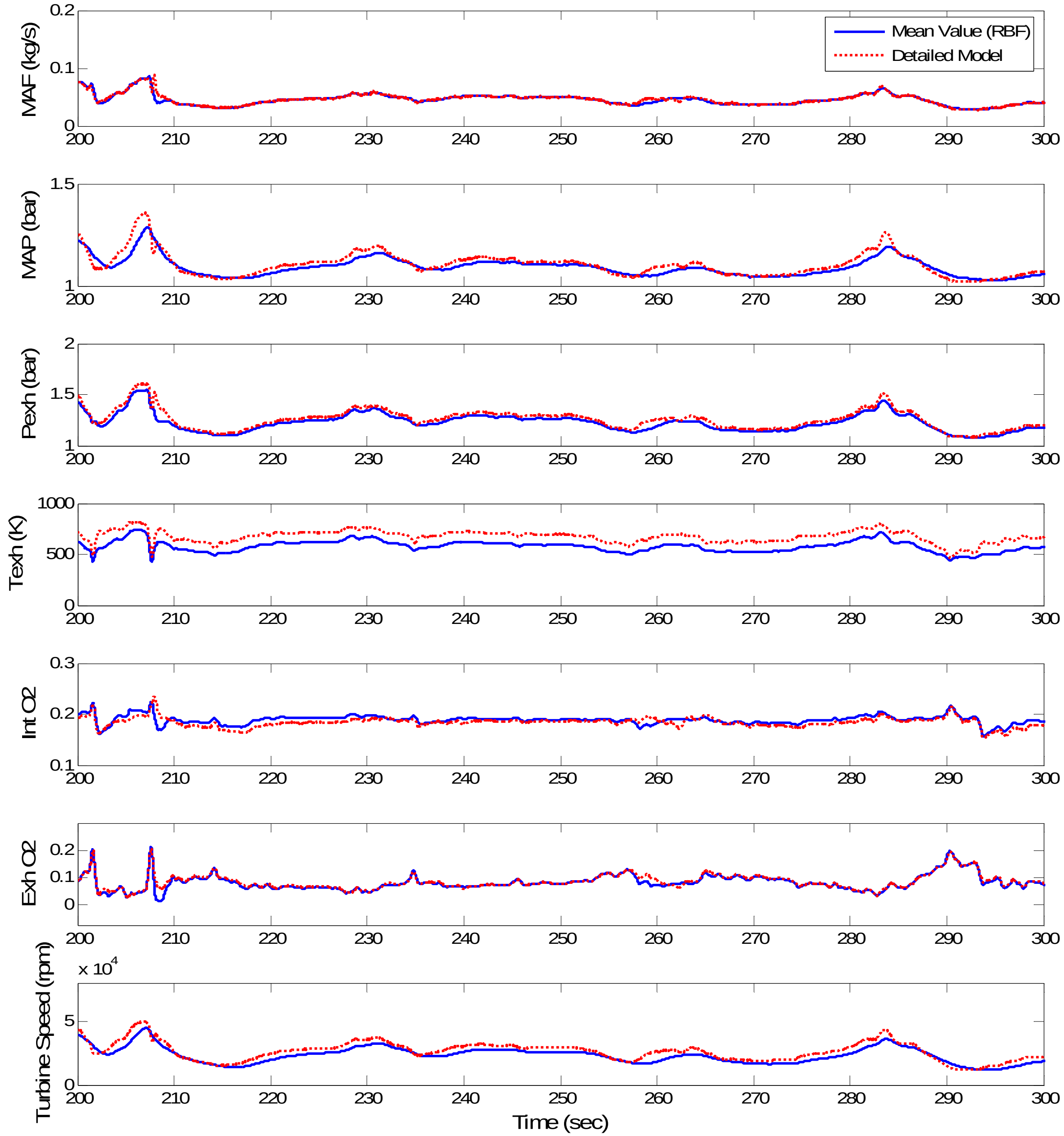


(SAE Paper 2007-01-1304)

FTP Cycle: Simulation Results Blow-up (2/2)

- **Blow-up of the FTP results for comparison (200-300 s)**

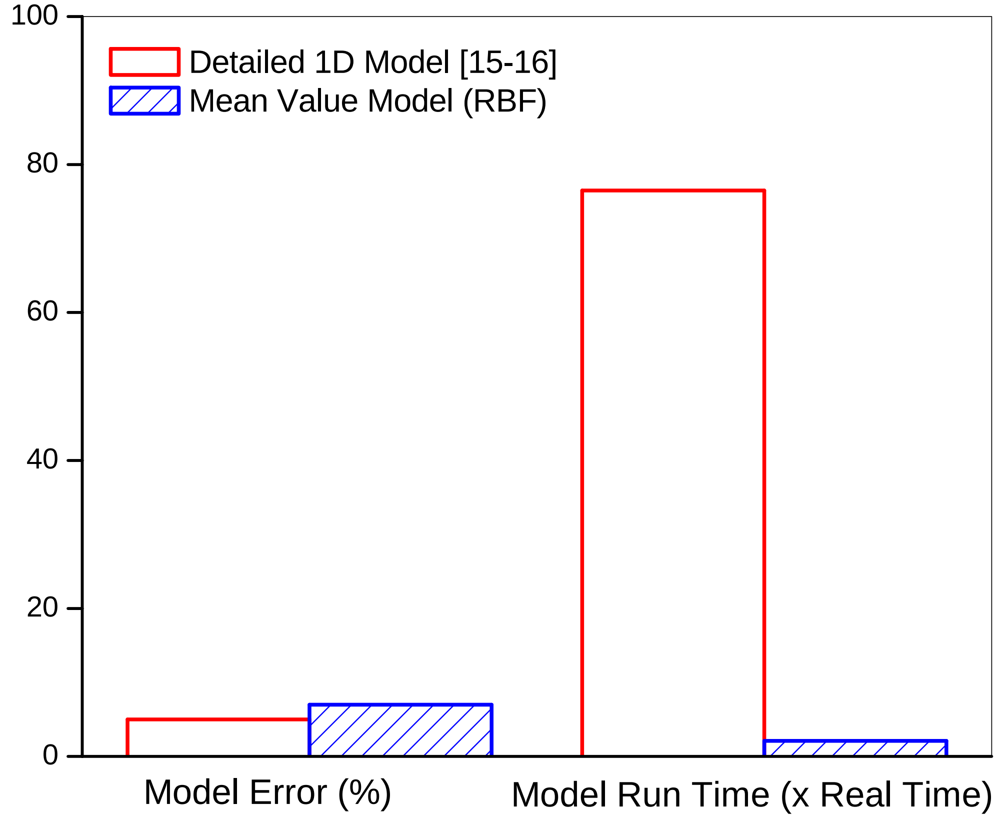
Detailed
Mean Value



(SAE Paper 2007-01-1304)

Model Accuracy vs Model Speed (Summary)

- **Mean value engine model developed in this study**
  - Accuracy slightly compromised (cylinder quantities)
  - About 40 times faster than the detailed model



(SAE Paper 2007-01-1304)

Summary

- **A fast-running mean value engine model with sufficient accuracy developed for control applications**
  - Reduced from a detailed engine model in GT-Power
    - Constrained Latin Hypercube to consider physical constraints
    - Hybrid RBF to approximate cylinder quantities for better accuracy
    - Completely simplified (cylinders, intake & exhaust system)
  - Model development time & model throughput minimized

- **The developed mean value model integrated with a comprehensive controller model for control analysis**
  - The integrated engine and control system model extensively validated with satisfactory accuracy achieved
    - 1 Step change, 3 Step transients, 1 FTP cycle
  - Control strategies development & preliminary calibrations before hardware availability and testing

Summary

- **Current Capabilities:**
  - Provide fast-running models for control development
  - Explore control strategies and study control parameter sensitivities
  - Generate preliminary calibrations before hardware availability and testing
  - Use for air-EGR system calibrations
  - Allow easy adaptation to hardware changes
  - …

- **Future Outlook:**
  - Analytic calibration → critical and integral part of modern embedded powertrain controllers development process, but more important in the early development phase
  - Physical dyno and/or vehicle testing → still needed, but to be minimized
  - Computer simulations → more accurate, powerful and standardized, but model development time, model throughput, and model runs to be reduced

JOHN DEERE

John Deere Power Systems
Analytical Engine Calibration at John Deere

Jason Schneider

Engine Engineering

Motivation

- **Performance Optimization**
- **Off-Road Market**
  - Number of applications – Over 1000 internal and external
- **Application Variation**
  - Different Usage Profiles
  - Different Optimization Objective
- **Complexity**
  - HPCR
  - Cooled EGR
  - VTG and EGR Valve

Worldwide Engine Customers

Internal Applications

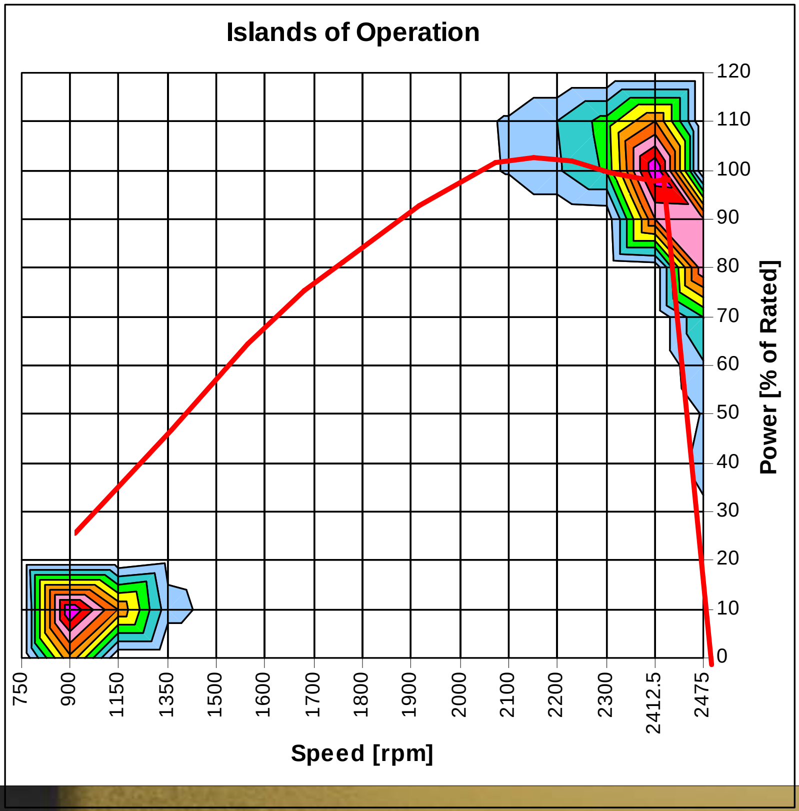
≅ 50% Engine Volume
Ag, C&F, CC&E Division Applications

External Applications

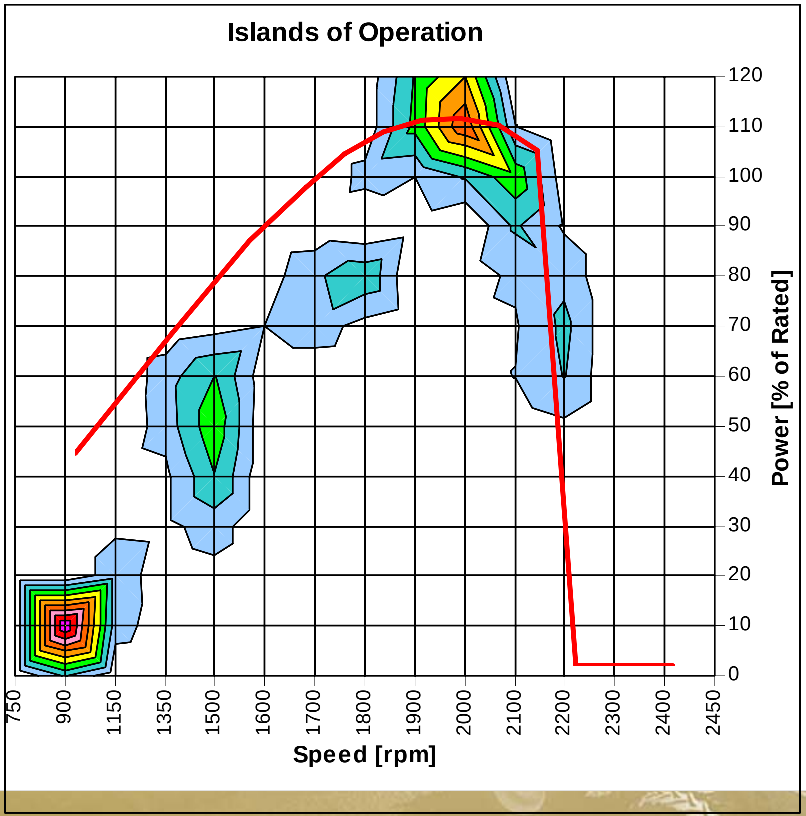
≅ 50% Engine Volume
Industrial, Power Generation and Marine Applications

Usage Profile Examples

Application 1

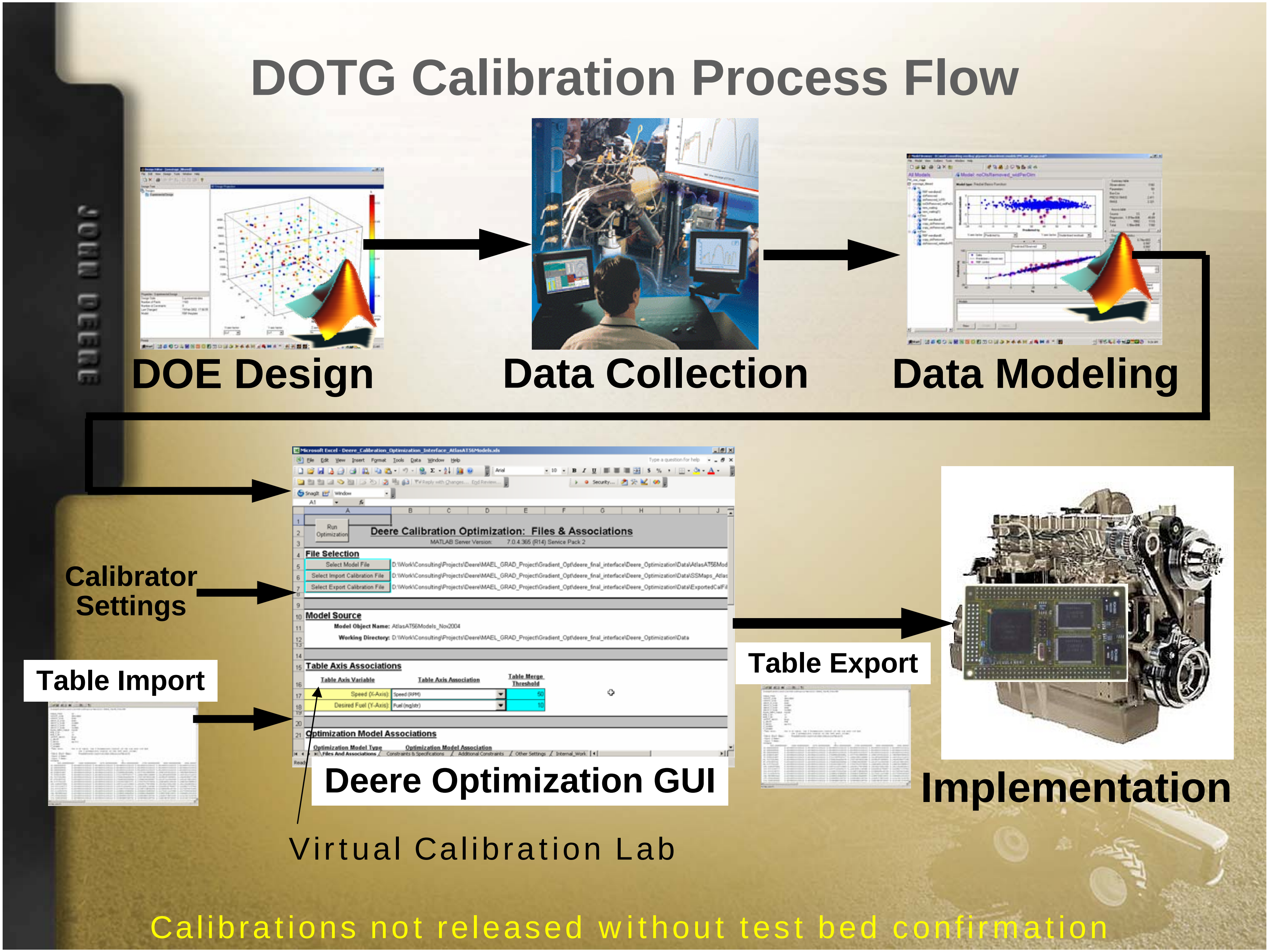


Application 2

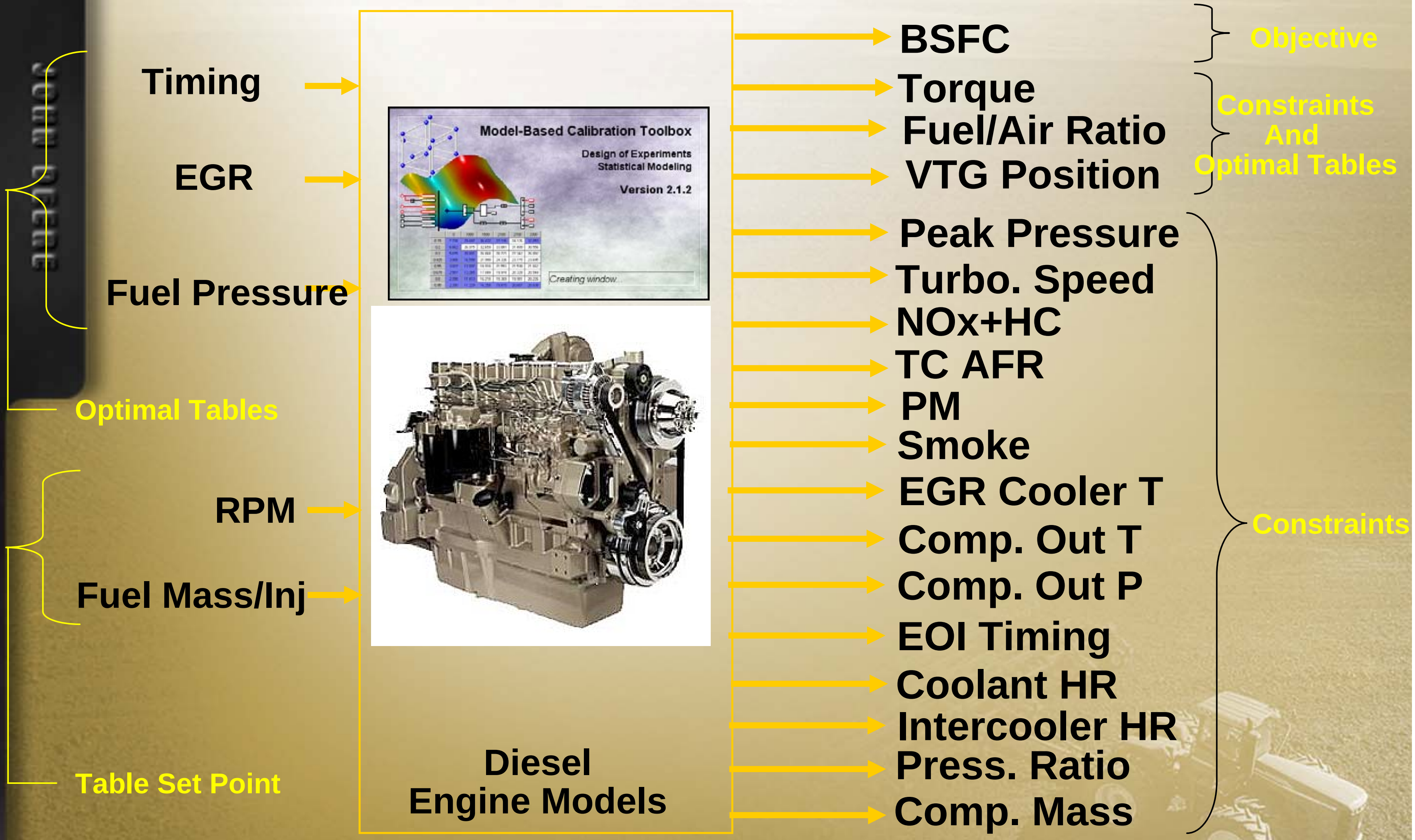


Analytical Calibration Objective

- **Generate calibration tables off line from test bed**
  - Comply with emission legislation
  - Minimize BSFC, subject to application, base engine and calibration constraints
- **Deere developed empirical engine models are used**
  - DOE – Matlab MBC Toolbox
  - Matlab (MBC Toolbox), Statistica, Table Curve 3D
- **Deere Optimized Table Generator (DOTG) interface is used to enter calibration optimizer settings**
  - Excel driven Matlab optimization
- **Final results are calibration set point tables**


DOTG Calibration Process Flow
JOHN DEERE
DOE Design
Data Collection
Data Modeling
Calibrator Settings
Table Import
Deere Calibration Optimization: Files & Associations
File Selection
Select Model File
Select Import Calibration File
Select Export Calibration File
Model Source
Table Axis Associations
Optimization Model Associations
Deere Optimization GUI
Table Export
Implementation
Virtual Calibration Lab
Calibrations not released without test bed confirmation

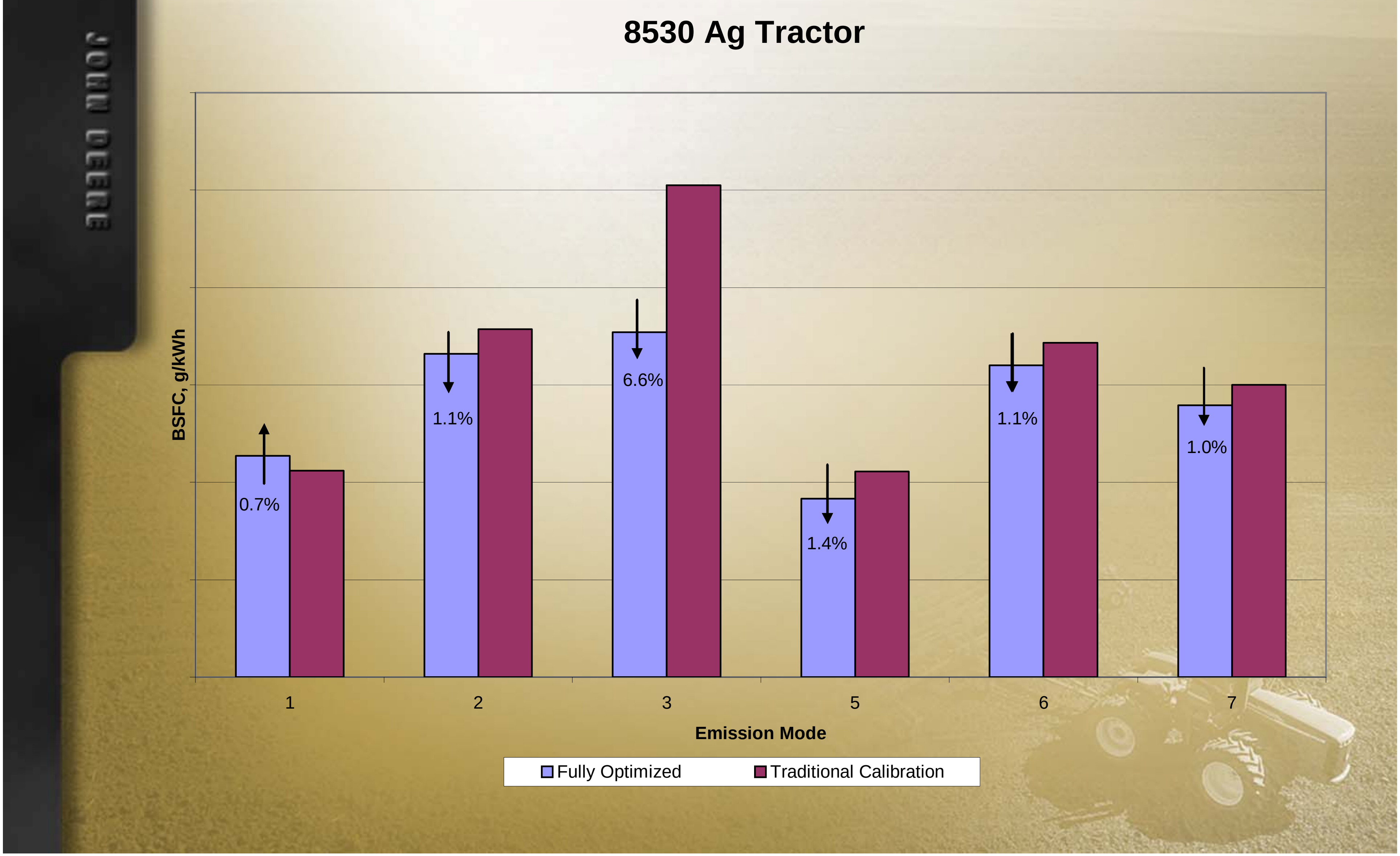
Input and Output Scheme



Benefits

- **Performance optimization given application constraints**
  - 1-3% improvement in application specific fuel consumption compared to conventional techniques
- **Reduction of needed testing and associated expense**
  - Measured in hundreds of thousands of dollars compared to conventional techniques
- **Control of constraint usage to minimize errors**
  - Example – peak firing pressure or exhaust temperature
  - Consistent reliability performance across applications
- **Calibration methodology is controlled**
  - NTE compliance
  - Similar performance output of engine across applications

Optimization Potential –



Industry Record, Nebraska Test 2005: Most Fuel Efficient Row-Crop Tractor

- **8430 Series Tractor / 9.0L PowerTech Plus**
  - 8.8% more fuel efficient with 40% less emissions
  - Engine optimization
  - Vehicle efficiency improvement

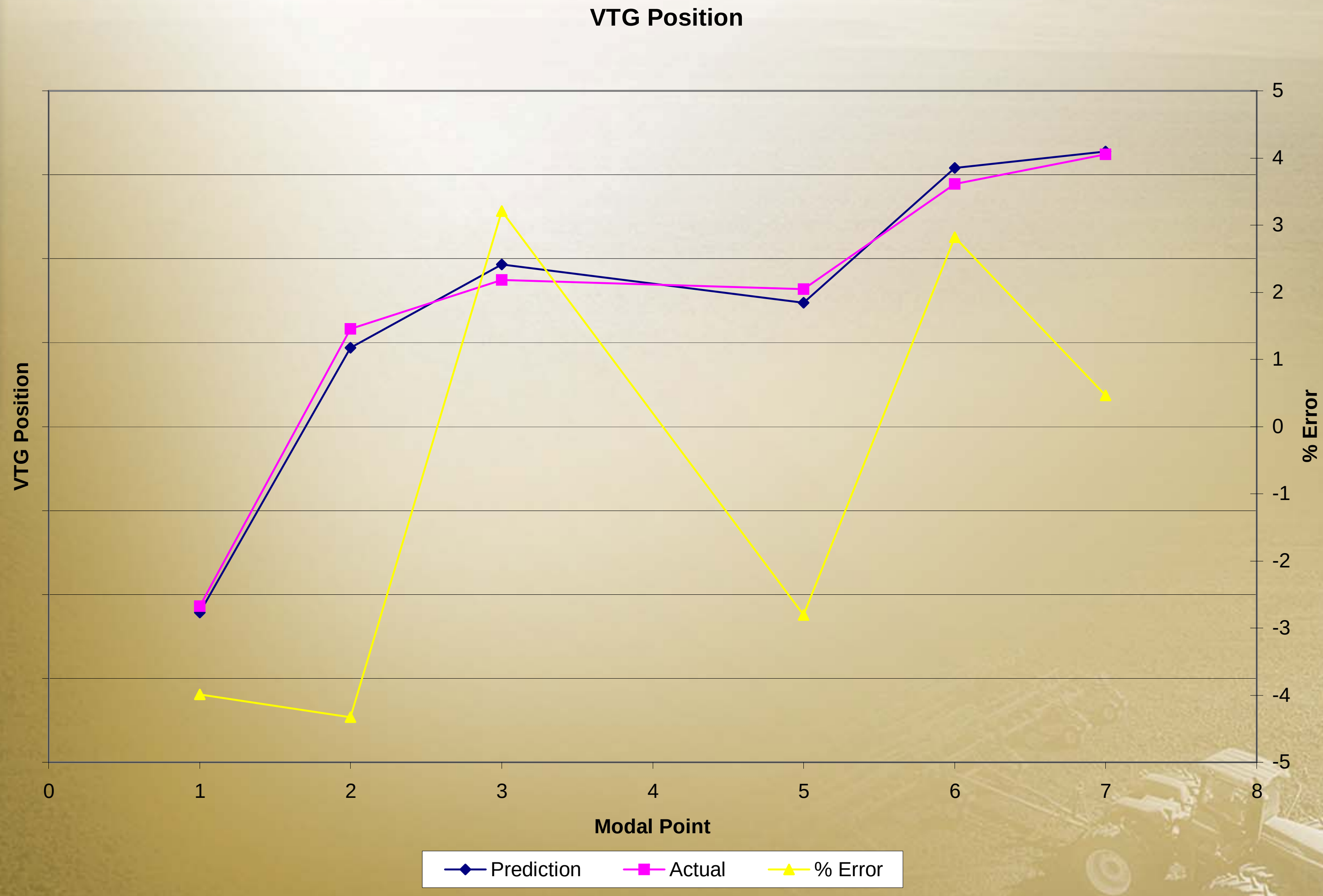
Accuracy

Example Results – OEM Rating

Example Results – OEM Rating

Example Results – OEM Rating

Example Results – OEM Rating



Transient Certification Tests

- **NRTC in effect for Interim Tier 4**
  - New problem statement for Deere
- **Methods heavily depended on emissions technology chosen**
  - Number of independent variables
    - EGR vs Non-EGR
    - After-treatment and interaction

Transient Certification Tests

- **Perturbation of calibration tables for sequence of transient test runs**
  - Select value for calibration tables that minimizes emission tradeoff point by point
  - Fuel Pressure, Injection Timing, EGR rate, etc.
- **Steady state points weighted to for correlation to transient test**
  - Calibration process as outlined can be used to reach targets
  - System control tuning for refinement of NOx and PM tradeoff for cooled EGR engine
- **Transiently accurate emission models**
  - Most elegant

Future

First Steps

- **Elimination of confirmation runs for steady state**
  - Allows further release of expensive calibration resources to earlier stages of product development

- **Accurate transient emission models for transient optimization**
  - Fits well with need for embedded models for systems with AT to predict state of system

Future

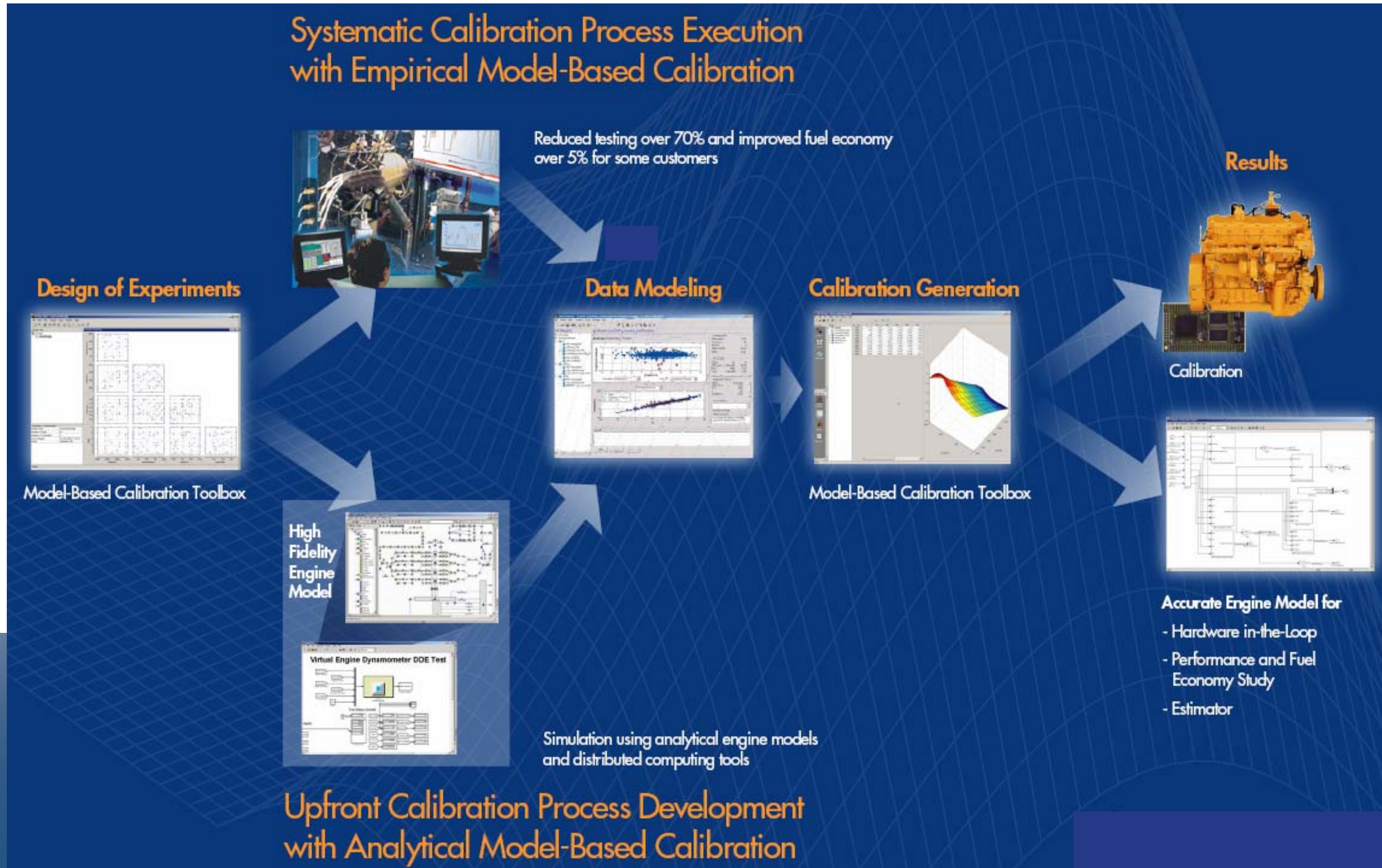
Needs

- **Better integration of calibration process with ECU software development process**
  - Collective mind set
  - Comprehensive tool set
    - Controller Models → Engine Models → Calibration

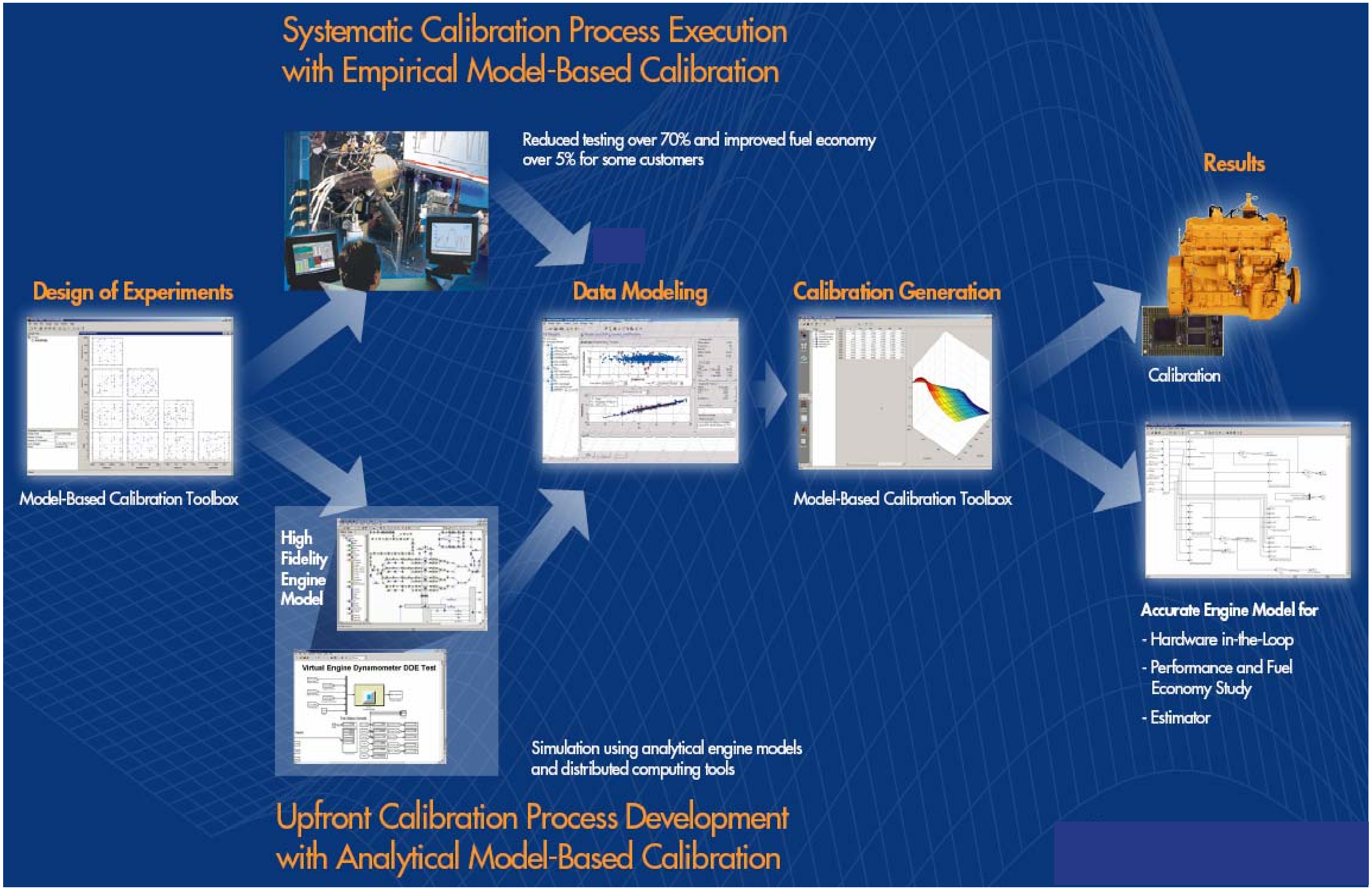
- **Predictive emission models that are accurate to drive process further upstream**
  - Engine cycle simulation environment

Thank You

Analytical Calibration and What it Means



Analytical Calibration Process

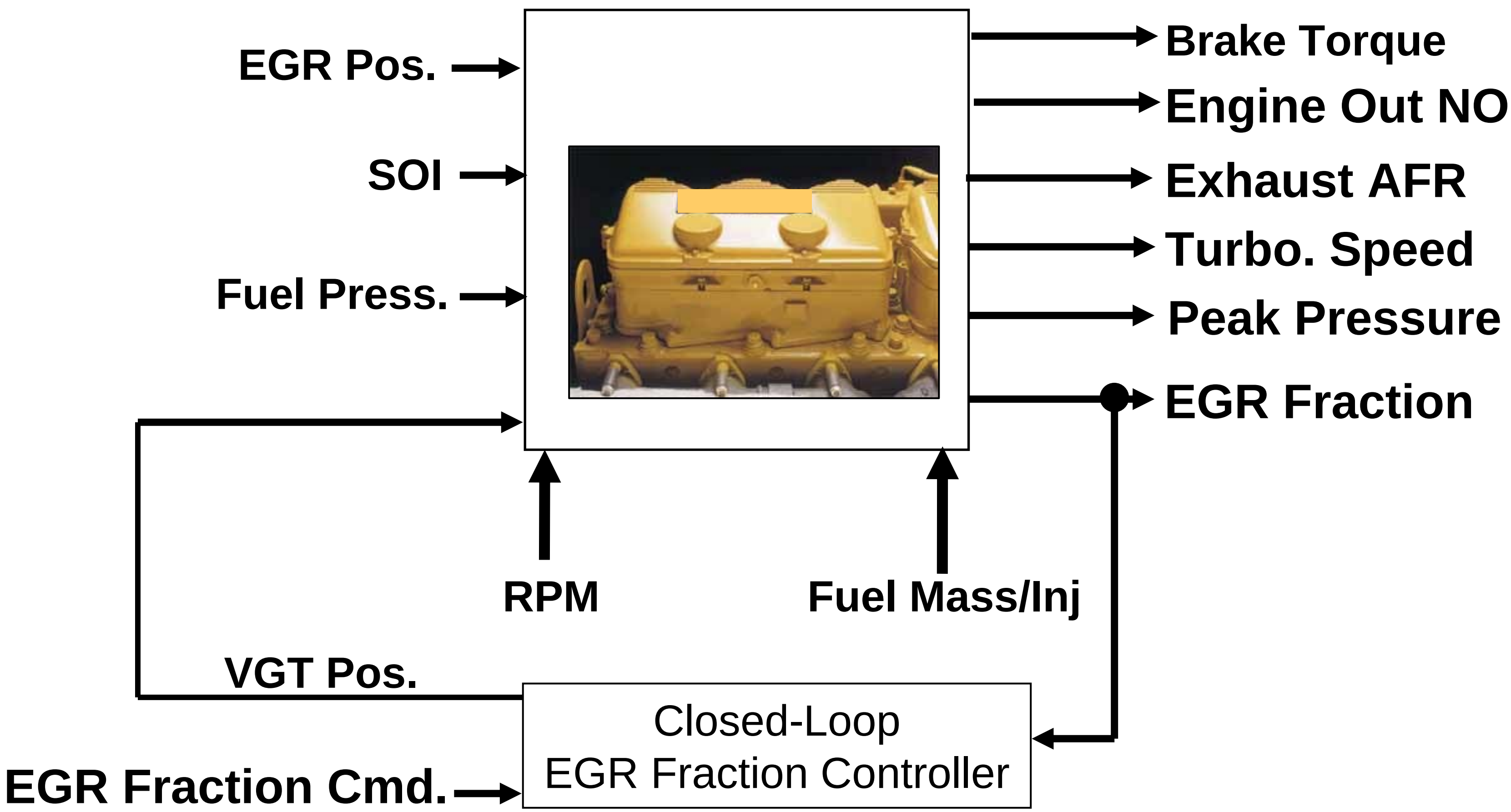


Current Benefits of Analytical Calibration

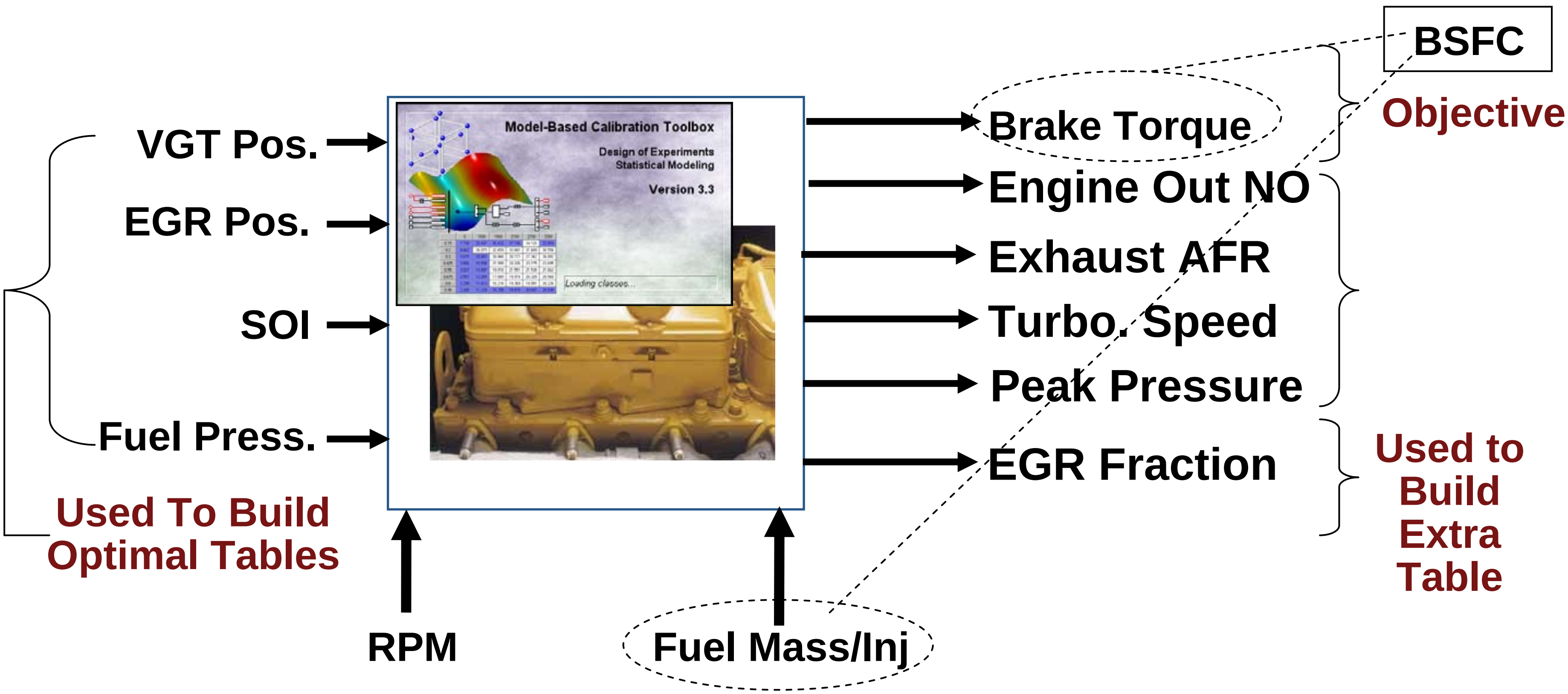
- Enables calibration process prototyping before hardware availability
- Provides diagnostic data for later hardware testing
- Provides fast-running statistical engine model for control development
- Can be used for calibrations related to engine-breathing (e.g., EGR, VE)
- Provides a non-hardware training environment for new calibrations
- Acts as an executable specification of company calibration processes
- Provides a means of determining minimum DoE testing requirements

Analytical Calibration Workflow Example

Identify Future Physical Test Setup

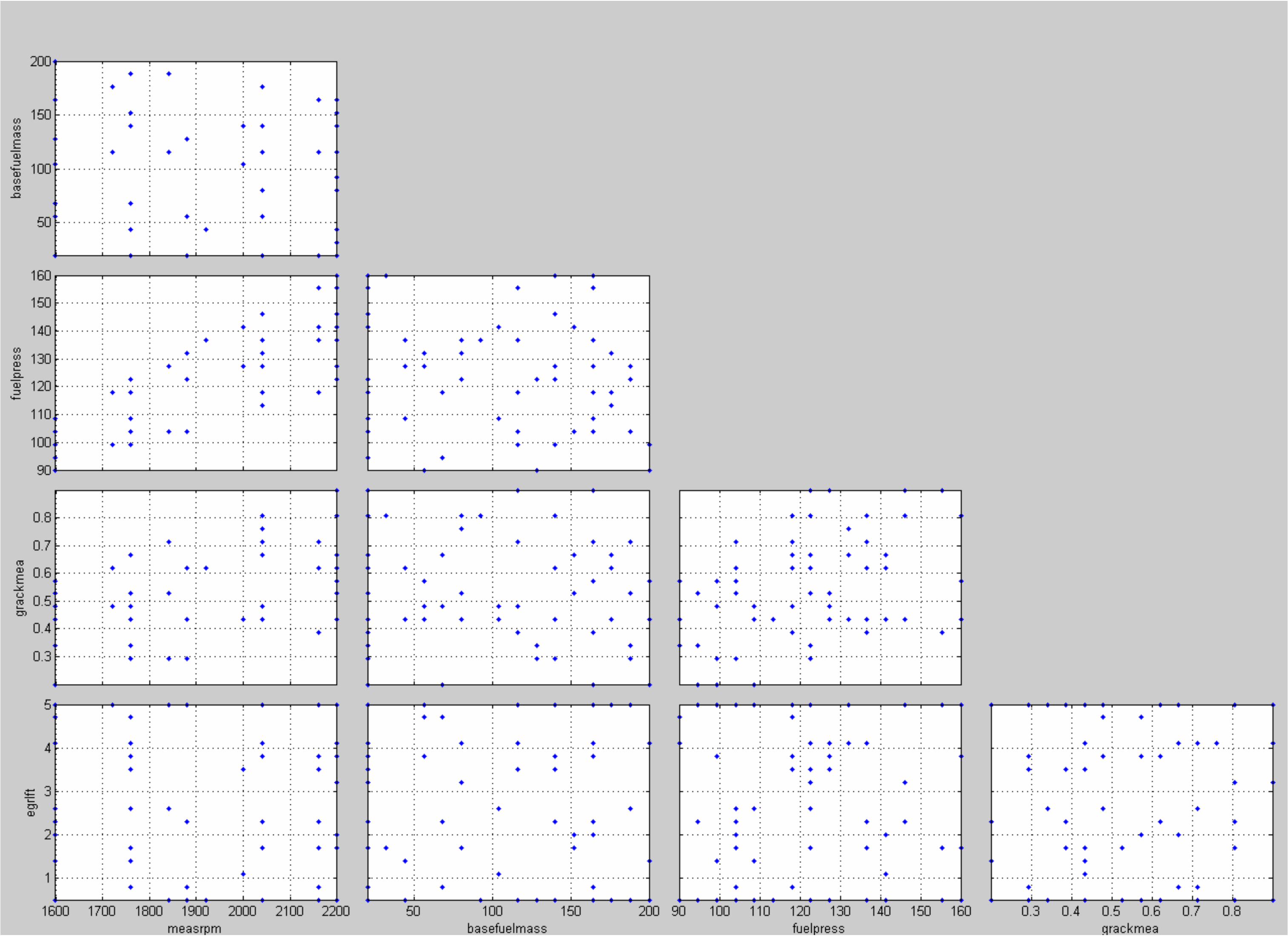


Define Optimization Model Setup

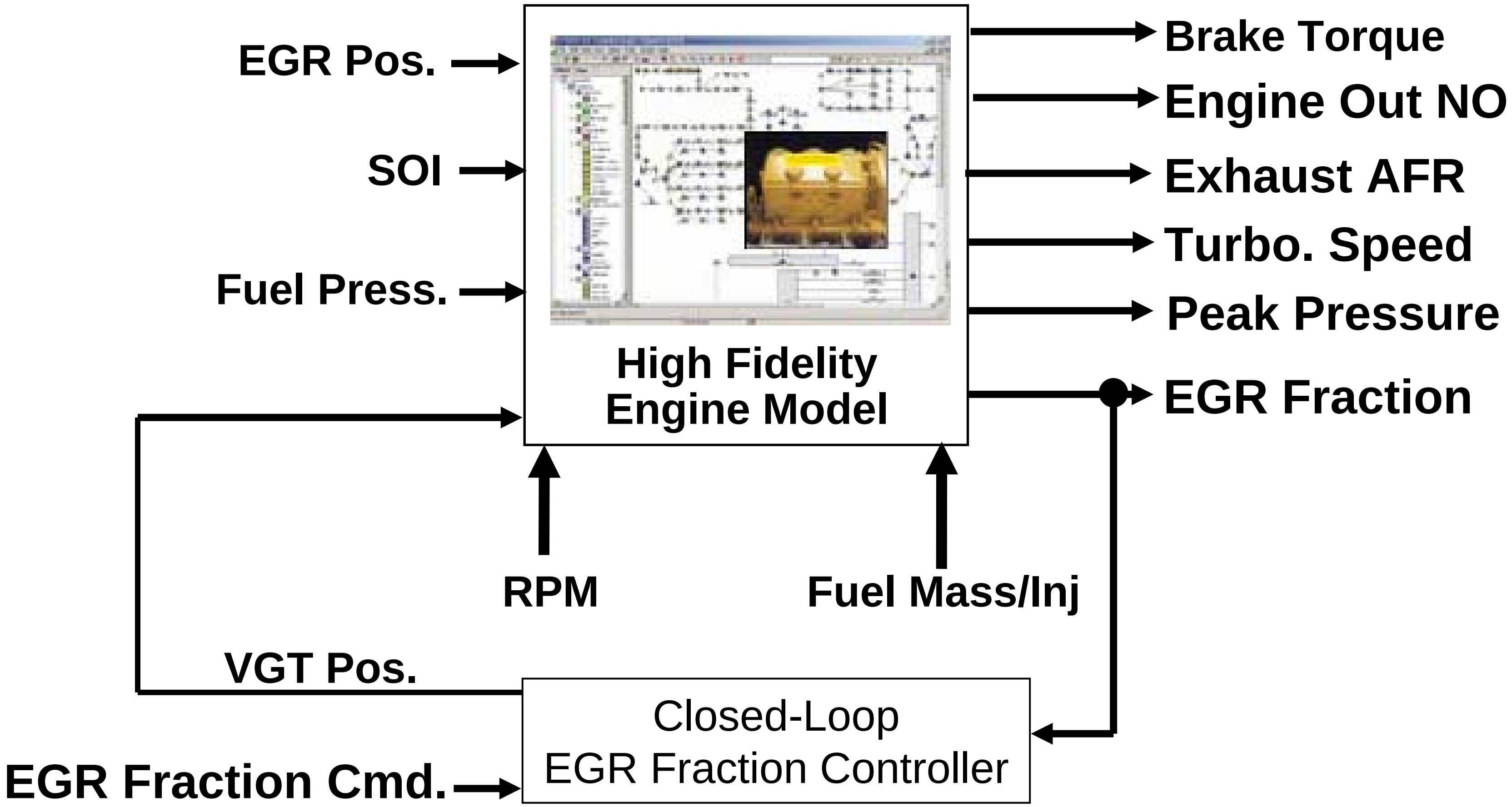


Minimize mode-weighted brake specific fuel consumption, subject to multiple mode-based output constraints

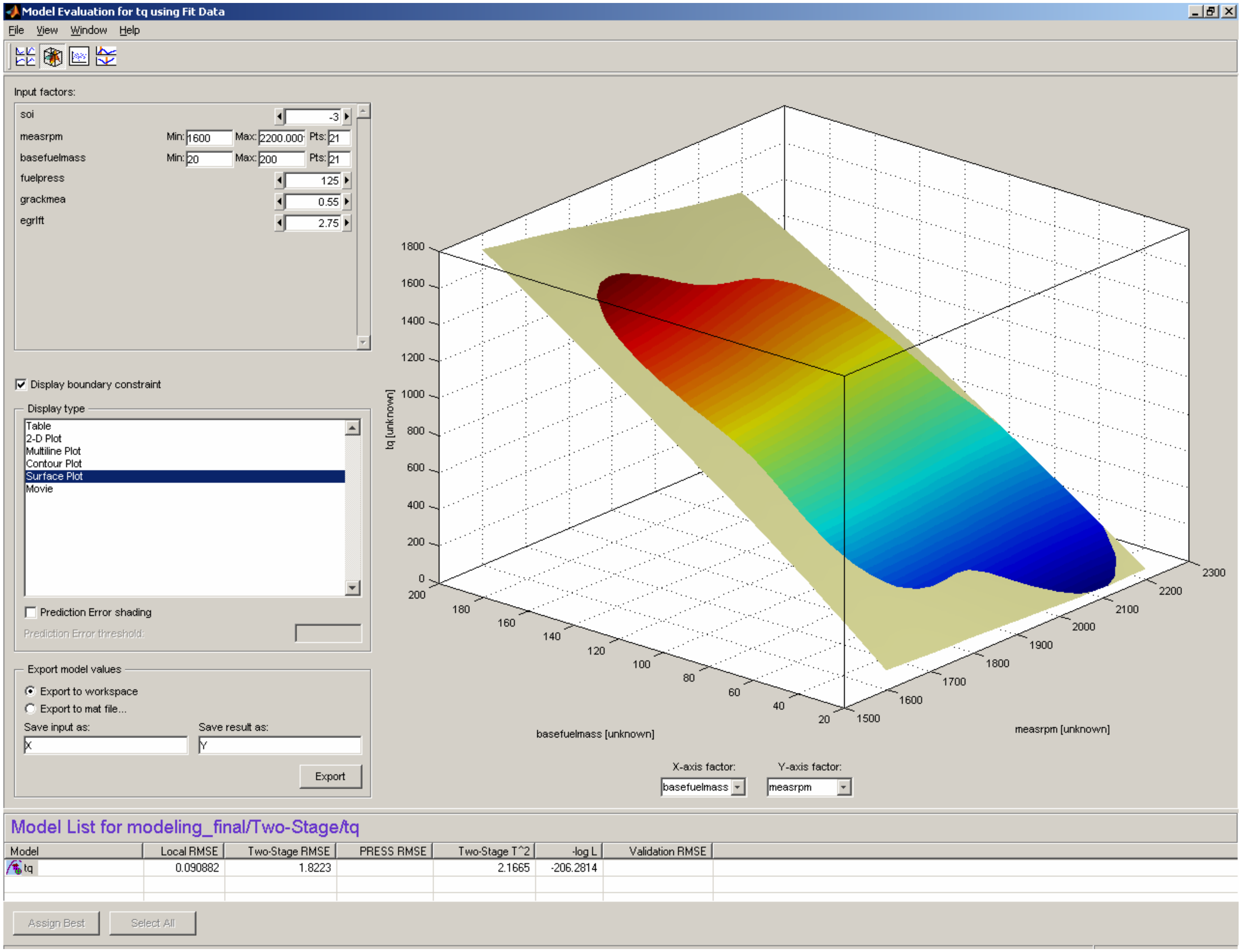
Design Experiment



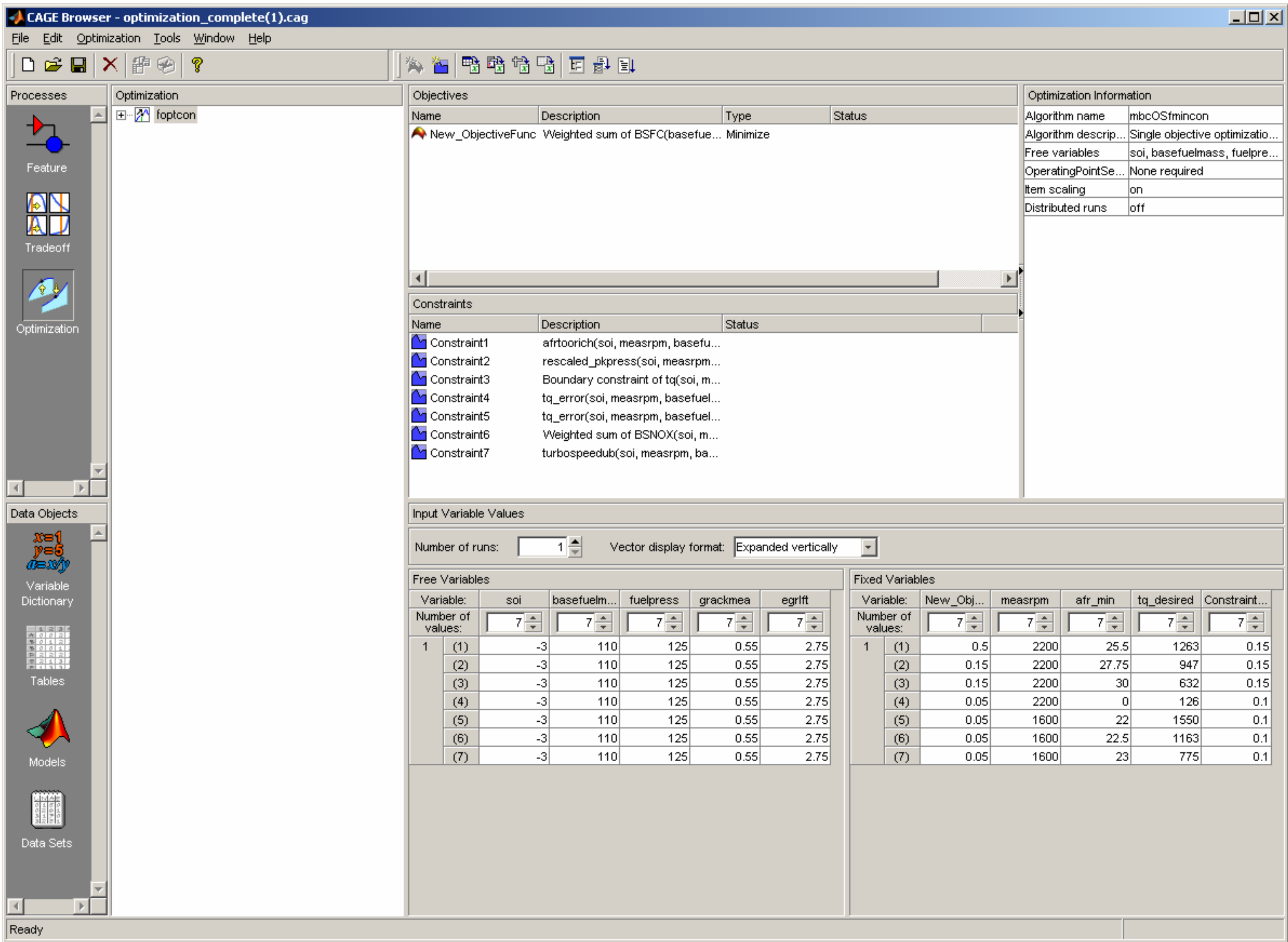
Execute Virtual Testing with Distributed Computing



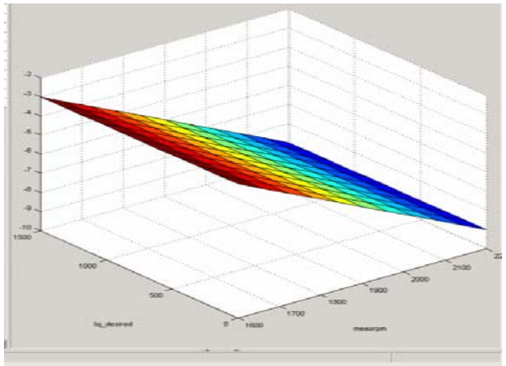
Statistically Model Engine Responses



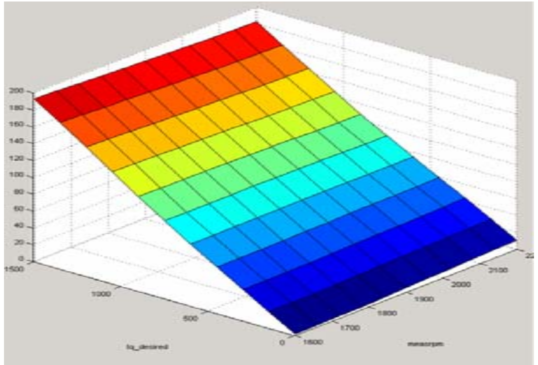
Set Up Optimizations With Constraints



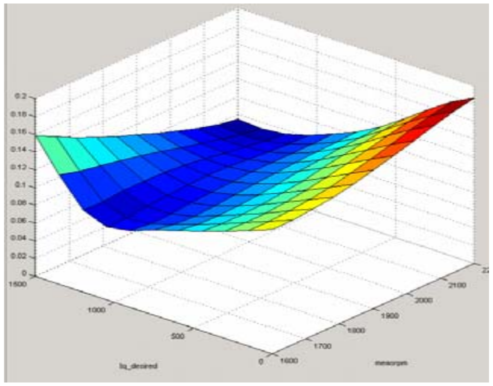
Generate Optimal Calibration Tables



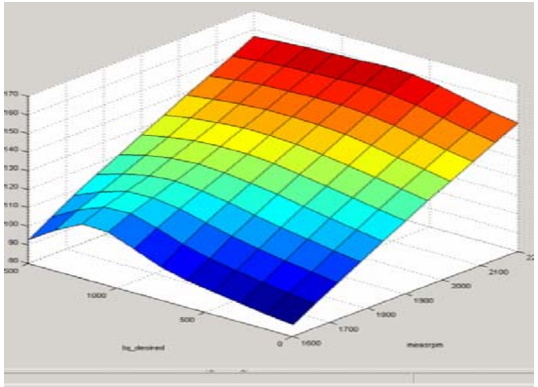
SOI Table



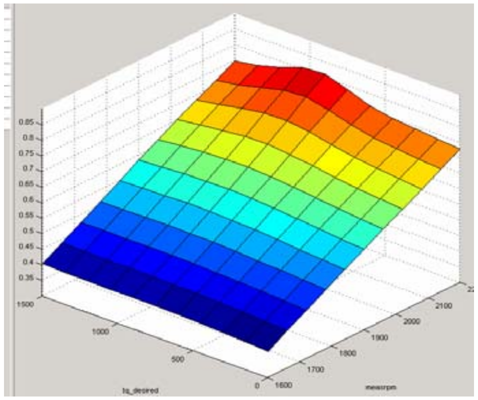
Fuel Mass Table



EGR Mass Fraction Table



Fuel Pressure Table



VGT Rack Position Table

Future Benefits of Analytical Calibration

- Inexpensive calibration adaptation to late program hardware changes
- Tighter feedback between engine hardware design and control design using model sharing
- Improvement of predictive quality of CAE engine models resulting from calibrator feedback