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Demonstrating Fuel Consumption and Emissions Reductions with Next Generation Model-Based Diesel Engine Control

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Presentation Outline

- The state of the art in engine control today
- Requirements for engine control in the future
- Our approach to model-based engine control
- The implementation of model-based control and its results
- Accomplishments to date and conclusions

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Control System Complexity – today and in the future

Independent Control Parameters or Orthogonal Variables	Cumulative Number of Control Variables	Date Implemented (actual or projected)
Injection Timing	1	1990s
Injection Pressure Control	2	2002
EGR	3	2002
VGT	4	2007
Aftertreatment Control - DPF	5	2007
Aftertreatment Control - SCR	6	2010
In-cylinder Combustion Feedback	7	2012
Multiple Injection Strategies	8-10	2012
Multiple Combustion Regimes (LTC)	10-12	2014
Waste Heat Recovery	12-14	2017
Hybridization/ Auxiliary Electrification/ Energy Recovery	14-16	2017
Fuel Tolerance/ Advanced Biofuel Capable	16-18	2020
Fully Independent Valve Actuation	18-20	2025
Individual Cylinder Control	20-22	2025
Cycle-by-cycle Control	22-25	2025

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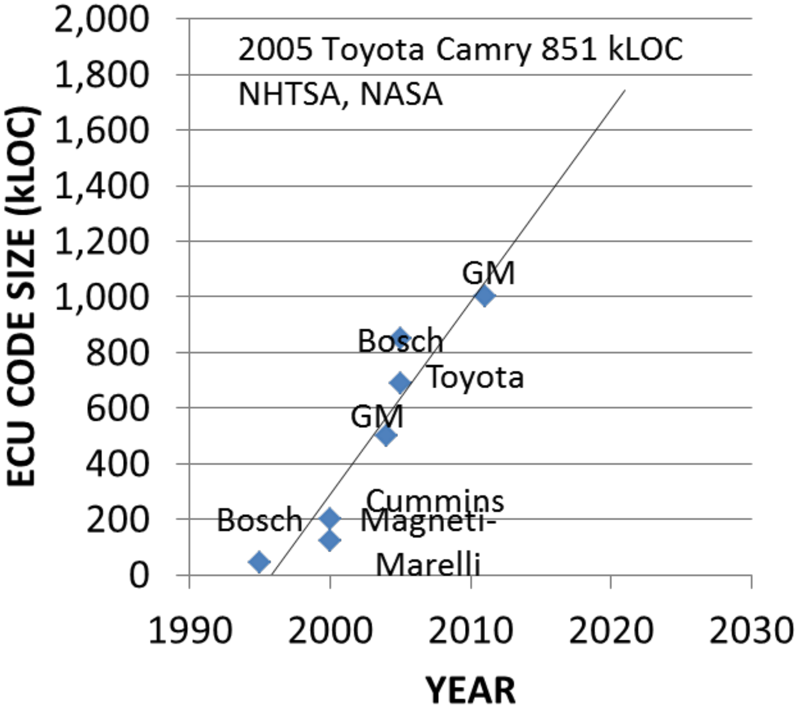
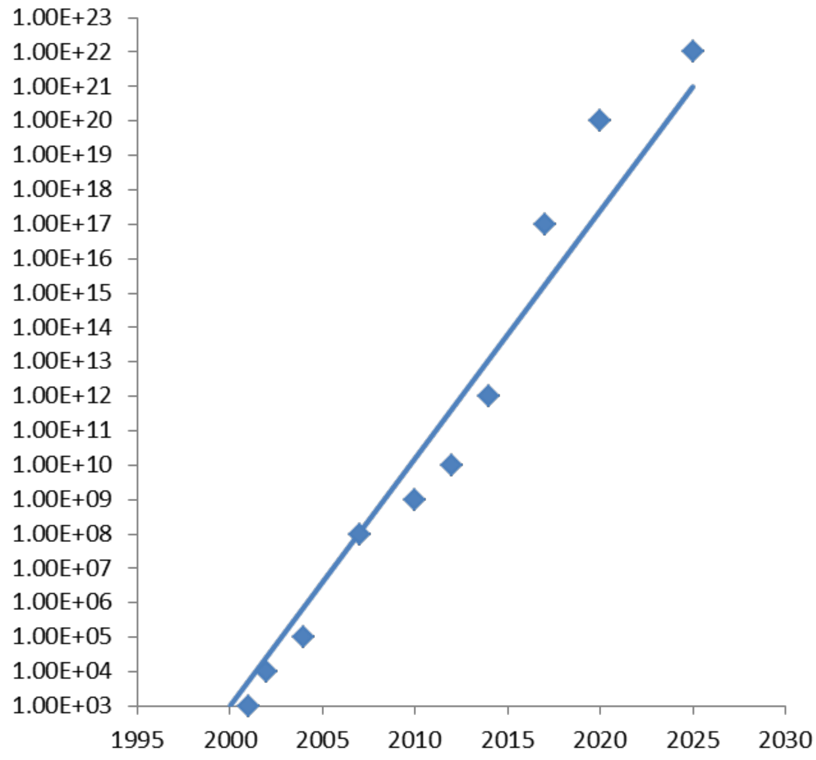
Engine Control Software – Complexity Increase





Software Lines of Code (LOC)

Full Factorial Calibration Space
(for 10 level variation in each parameter)

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The Future of Engine Control

- To date, HDD engine control has been focused on and based around emissions reduction on an integrated, cycle-based basis.
- Emphasis moving from emissions reduction to real-time fuel consumption or energy usage minimization.
- We are now at about one-quarter the number of independent control parameters that we will see implemented before 2025.
  - adding roughly one independent control parameter every 1-2 years.
- Each additional independent control parameter – to first order – increases the calibration space by a factor of 10x.

  "The Curse of Dimensionality"
- Currently at about 1,000,000 lines of code in engine controllers.
- Engine control today is a calibration-intensive set of hundreds of algorithms & thousands (or tens of thousands of calibration parameters).
- The trajectory of conventional engine control is an unsustainable increase in cost and effort required to control and calibrate engines.

Transforming Engine Control

- Engine control needs to be transformed.
- To date engine control has been dedicated to emissions reduction and compliance.
- But it is transitioning to fuel consumption or CO_2 reduction and energy minimization with tremendous complexity to come.
- Engine control must become more integrated with overall vehicle control.
- Current control and calibration targets will transition to
  - fuel consumption or energy use minimization
  - with power/ energy blending
  - and exhaust conditions amenable to near-zero tail-pipe out emissions levels for emissions compliance.

An Alternative to Conventional Engine Control

- Model-based engine control
  - Removes the requirement for the exhaustive development of algorithms and strategies.
  - Reduces the calibration requirement significantly.
  - Front-loads the engine testing effort.
  - Shifts the majority of the engineering effort to computational environment and out of the high cost engine test cell.

- Why data-driven models specifically?
  - Are able to determine the nonlinearities between engine cycle demand inputs, engine operating parameters, and outputs (emissions, fuel consumption and performance).
  - Able to make associations automatically and capable of learning.
  - Reduce data and testing requirements to a minimum.
  - Utilize immediate operating history of engine for fully dynamic, transient prediction.

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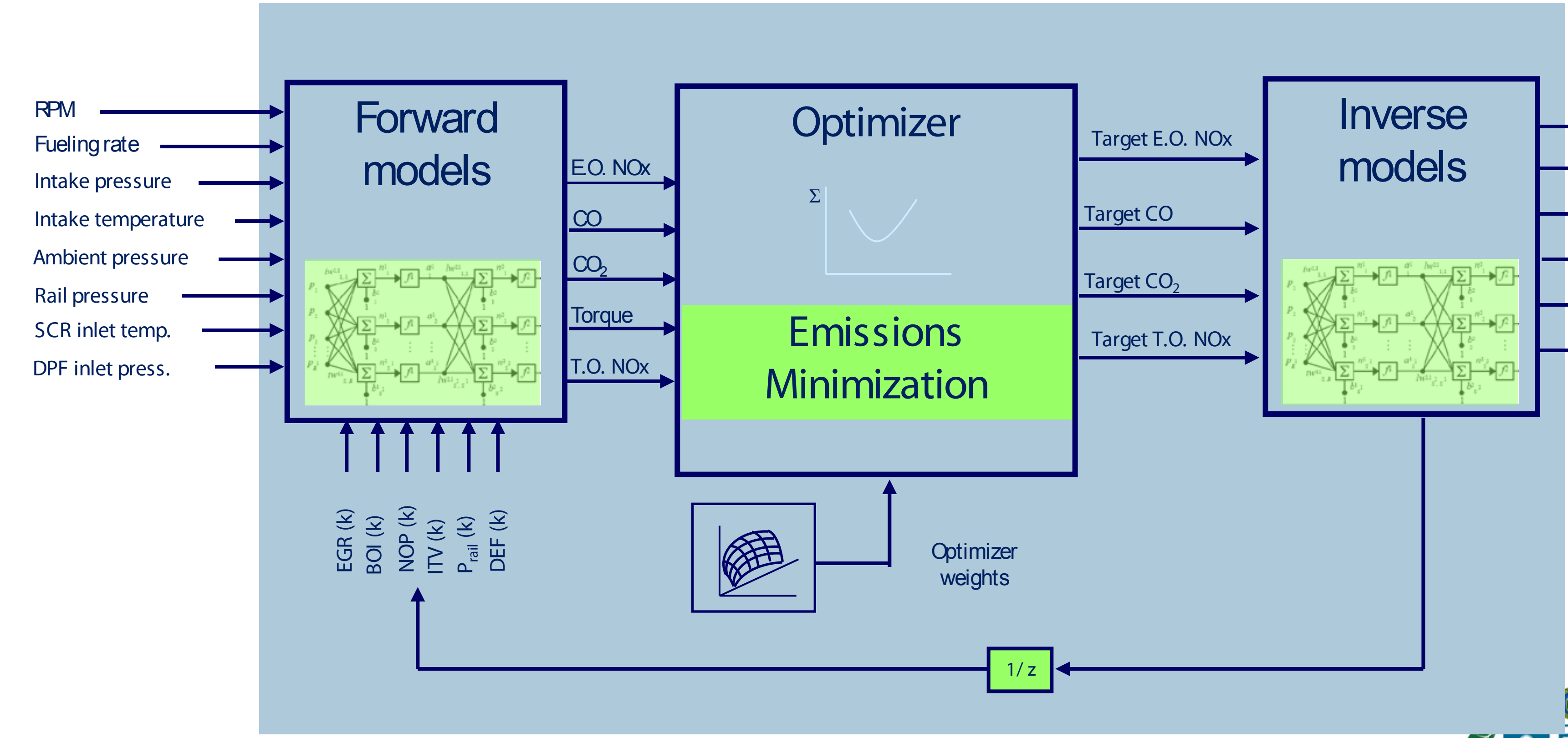
Predictive Model-Based Engine Controller

Calculates torque & emissions at every time step

Calculates "best" NOx/ CO/ CO_2 combination based on optimization weights

Calculates actuator outputs based on "best" emissions



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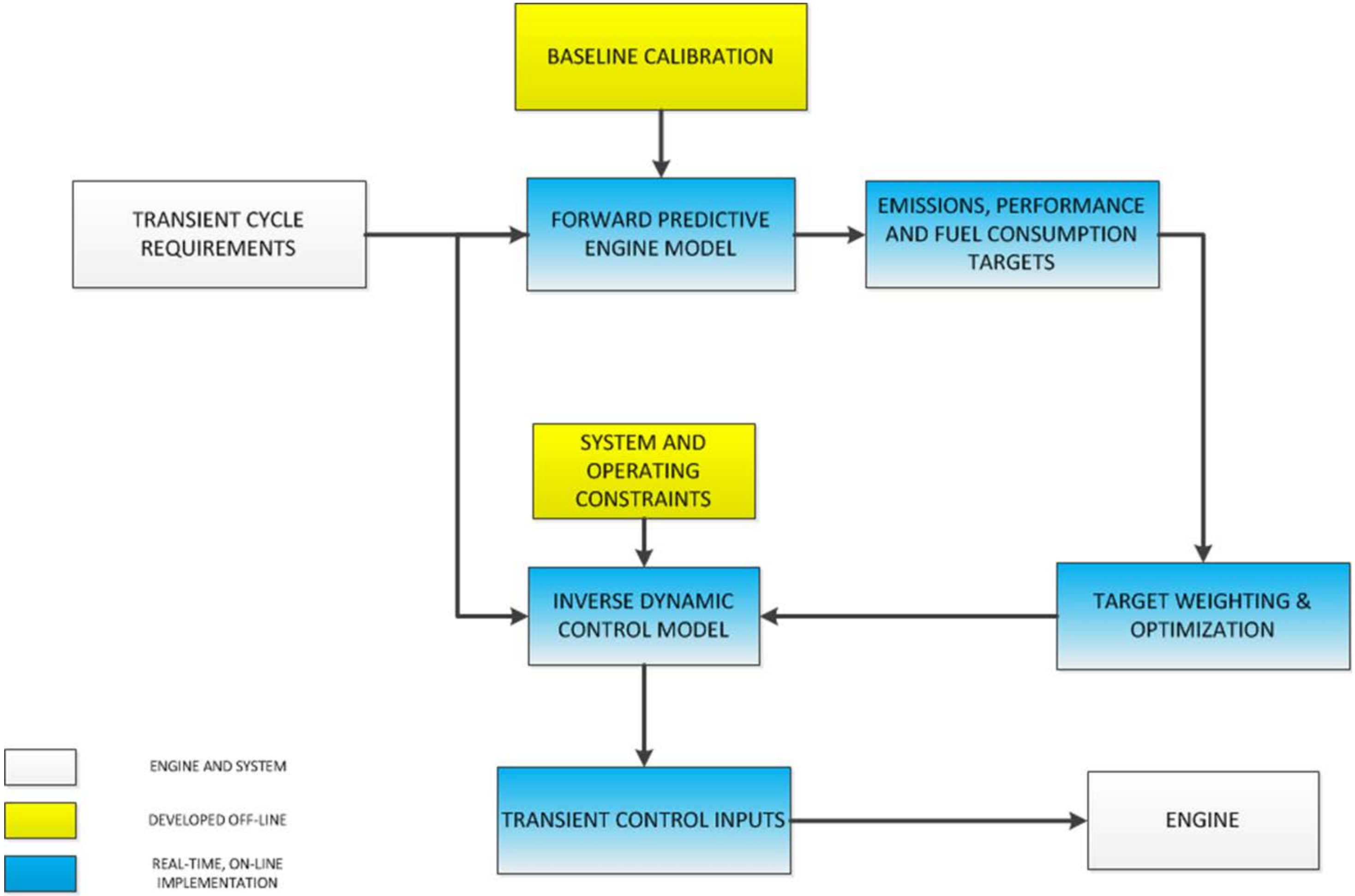
Model-Based Control System

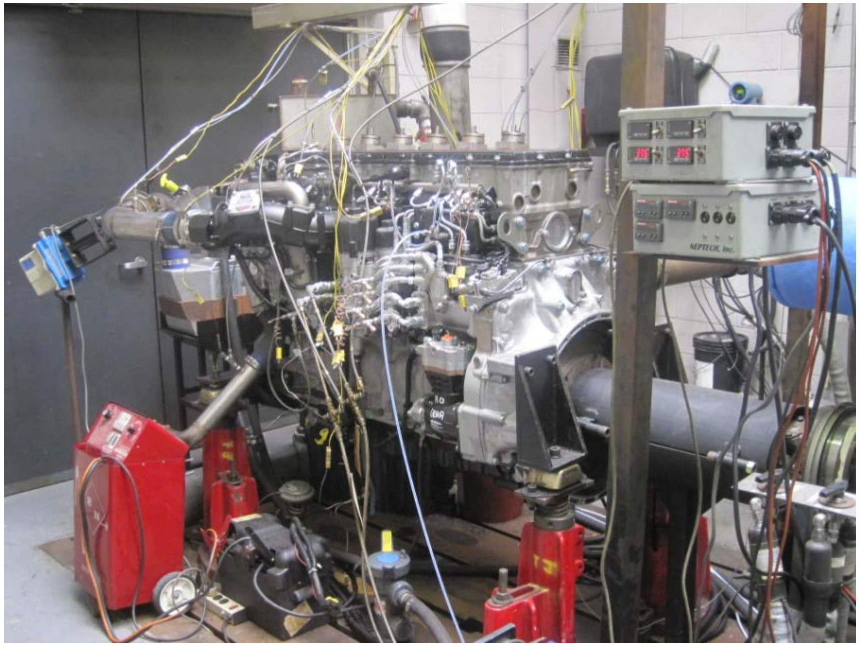


MODEL-BASED CONTROL SYSTEM

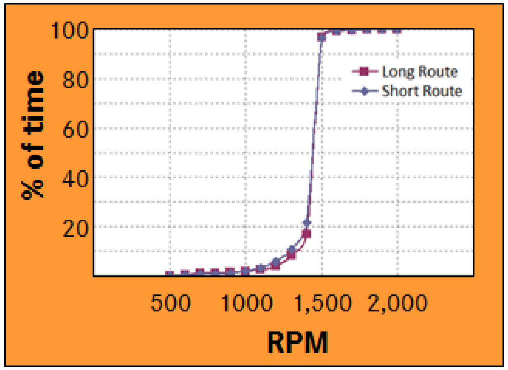
Application of the Model-Based Engine Controller

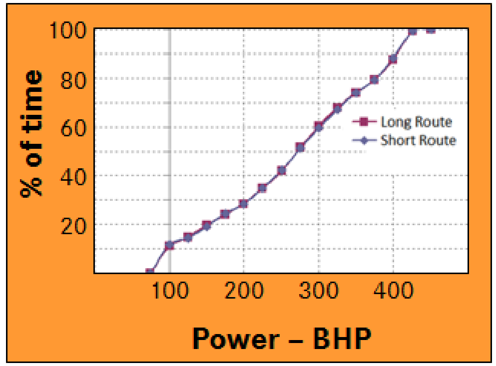
12.8 liter Detroit Diesel DD13 Engine

- 5 independent control parameters (in addition to speed and fueling)
    - Injection timing
    - Injection pressure
    - EGR
    - Wastegate actuation
    - Rail pressure
- Target values include
    - Instantaneous NOx, CO and CO_2
    - Real-time TQ
- Required ~10 hours of high fidelity dynamometer data to develop



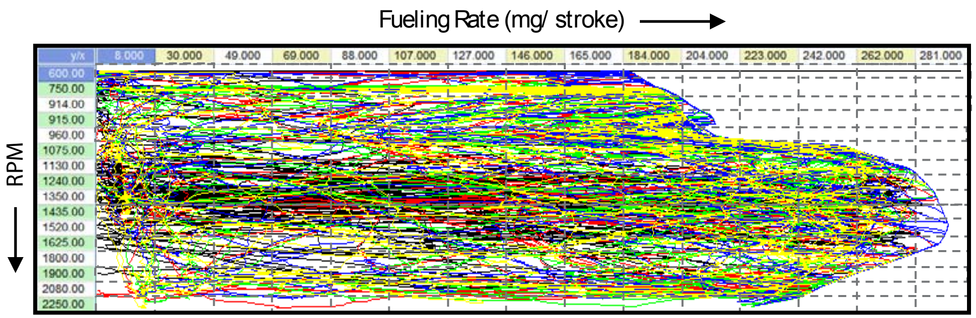
Controller Development – Data Collection





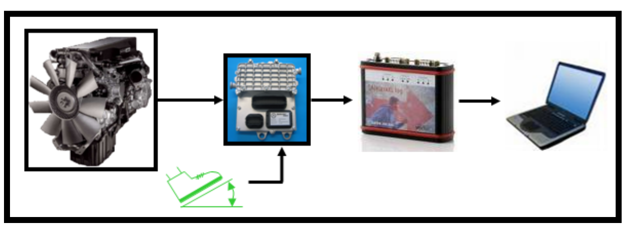
Step 1

- Generate 20-40 minute dynamometer cycles representative of SuperTruck RPM/ load profiles



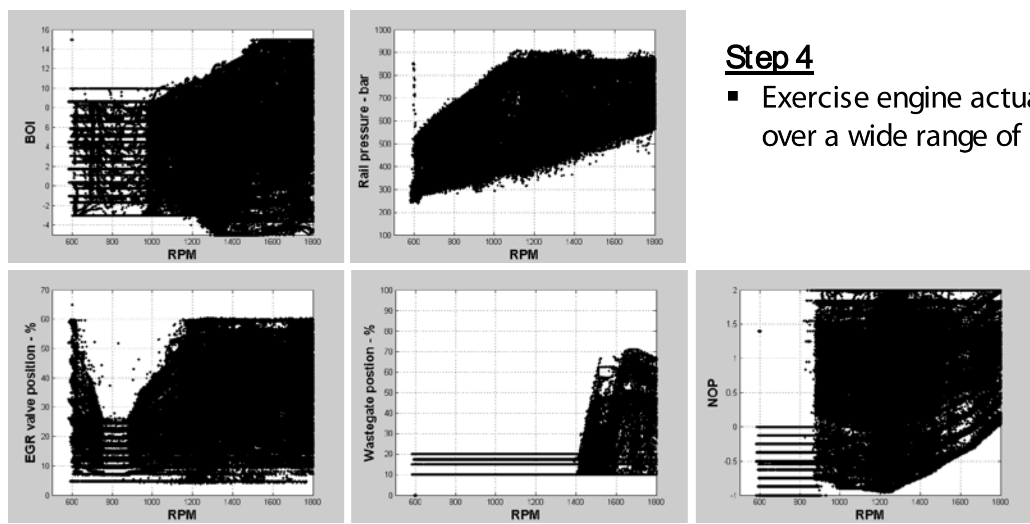
Step 2

- Generate additional cycles that cover a wide range of transient excursions



Step 3

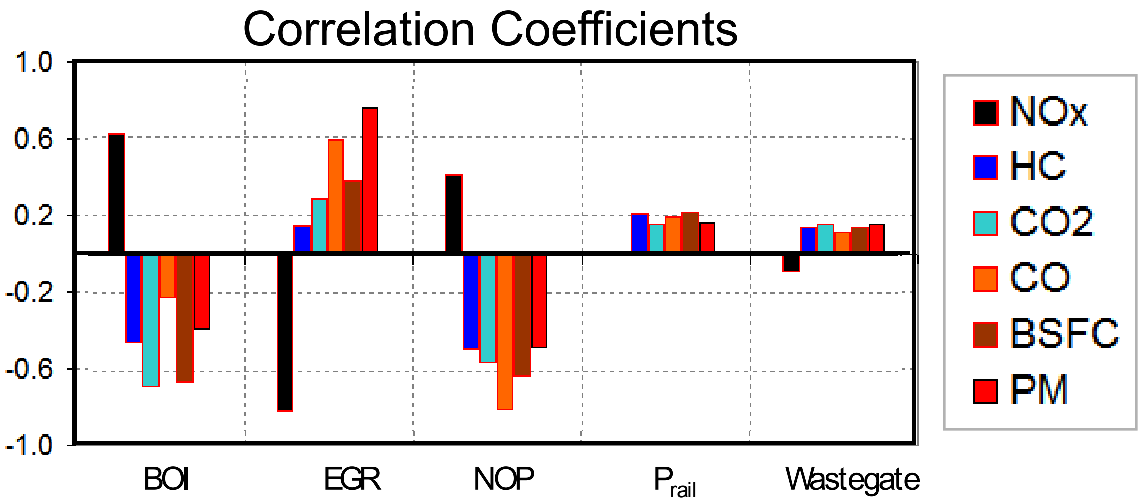
- Enable production ECM bypass



Step 4

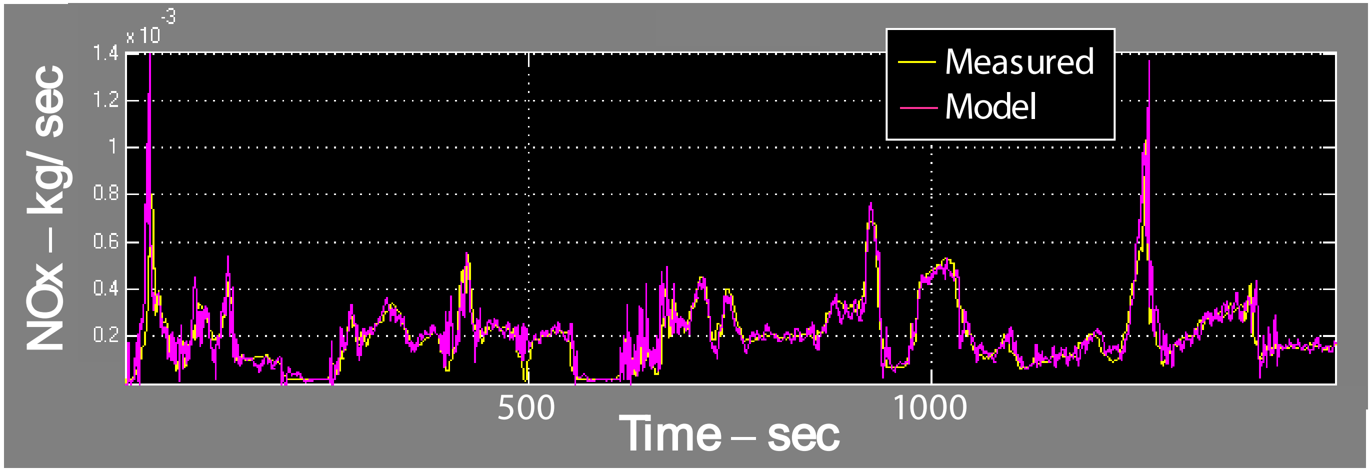
- Exercise engine actuators over a wide range of settings

Controller Development – Neural Network Models



Step 5

- Establish correlation between individual performance parameters and engine control variables
- Define predictive model inputs



Step 6

- Train models
- Verify model's correlation to measured data

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Model-Based Engine Controller Implementation

- Forward Predictive Models.
- Inverse Control Models.
- Real-Time Optimizer with emissions and fuel efficiency cost function to 'steer' real-time emissions and fuel consumption levels.

Parameter Description

k – current time period, $k-1$ – previous time period, etc.

Engine operating trajectory of speed and fueling

$u(k)$ – actual engine control inputs at current time step

$u(k-1)$ – actual engine control inputs at previous time period (history)

$y(k+1)$ – actual, unmeasured, engine outputs (emissions, fuel consumption, performance) at future time step

$Y(k+1)$ – predicted engine outputs (emissions, fuel consumption, performance) at future time step

$U_i(k+1)$ – predicted control inputs, subject to variable emissions, fuel consumption and performance targets (denoted i)

B_i – modeled forward weights and biases (fixed)

D_i – modeled inverse weights and biases (fixed)

C_i – output emissions, fuel consumption and emissions targets (variable)

Predicted Outputs (calculated using Forward Predictive Models)

$$Y(k+1) = B_1 \cdot u(k) + B_2 \cdot u(k-1) + B_3 \cdot u(k-2)$$

Predicted Controller Parameters (calculated using Inverse Models for single step look ahead)

$$U_i(k+1) = C_i \cdot [D_1 \cdot Y(k+1) + D_2 \cdot Y(k) + D_3 \cdot Y(k-1)]$$

Controller Parameter Option Selection

$$\hat{U}_i(k+1) = \text{optimum}\{U_i(k+1)\}$$

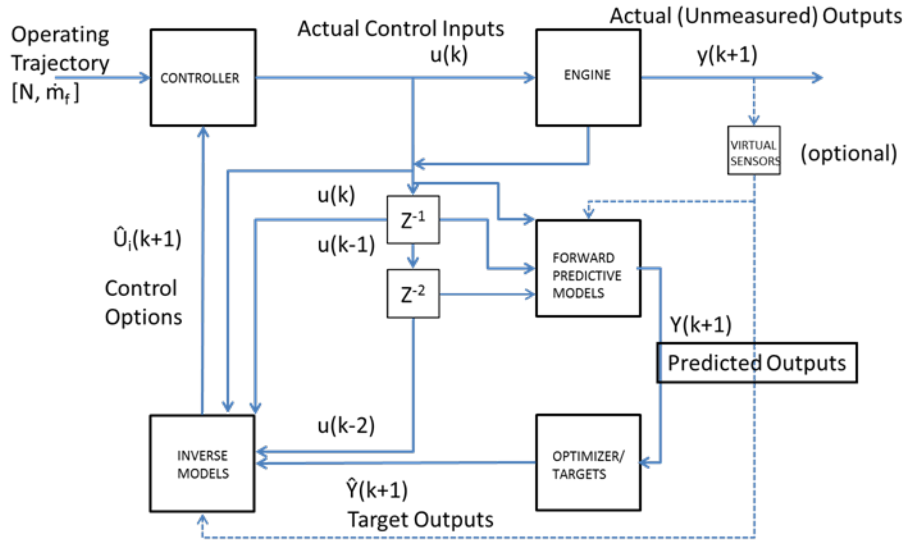
Subject to the constraints:

$U(k) \in \{u_{min} ; u_{max}\}$

$|U(k+1) - U(k)| < \Delta U_{max\ slew}$

$|Y_i(k+1) - Y_i(k)| < \Delta Y_{i\ max\ slew}$ (primarily torque)

$Y_i(k+1) < Y_{i\ max}$ (emissions constraints)



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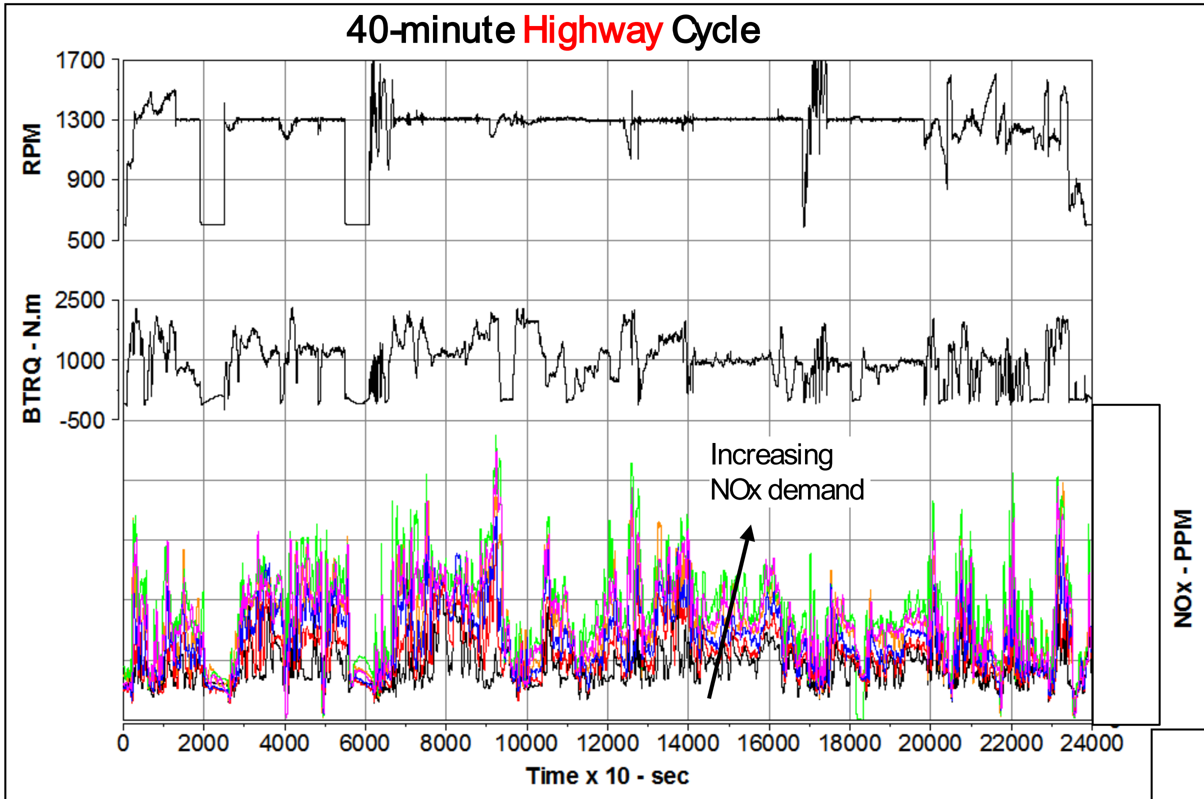
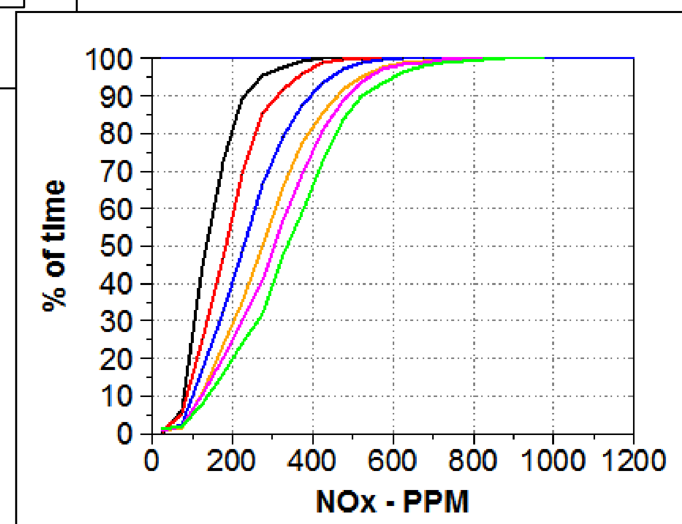
Directions in Engine-Efficiency and Emissions Research Conference

Evaluation of Model-Based Controller Performance

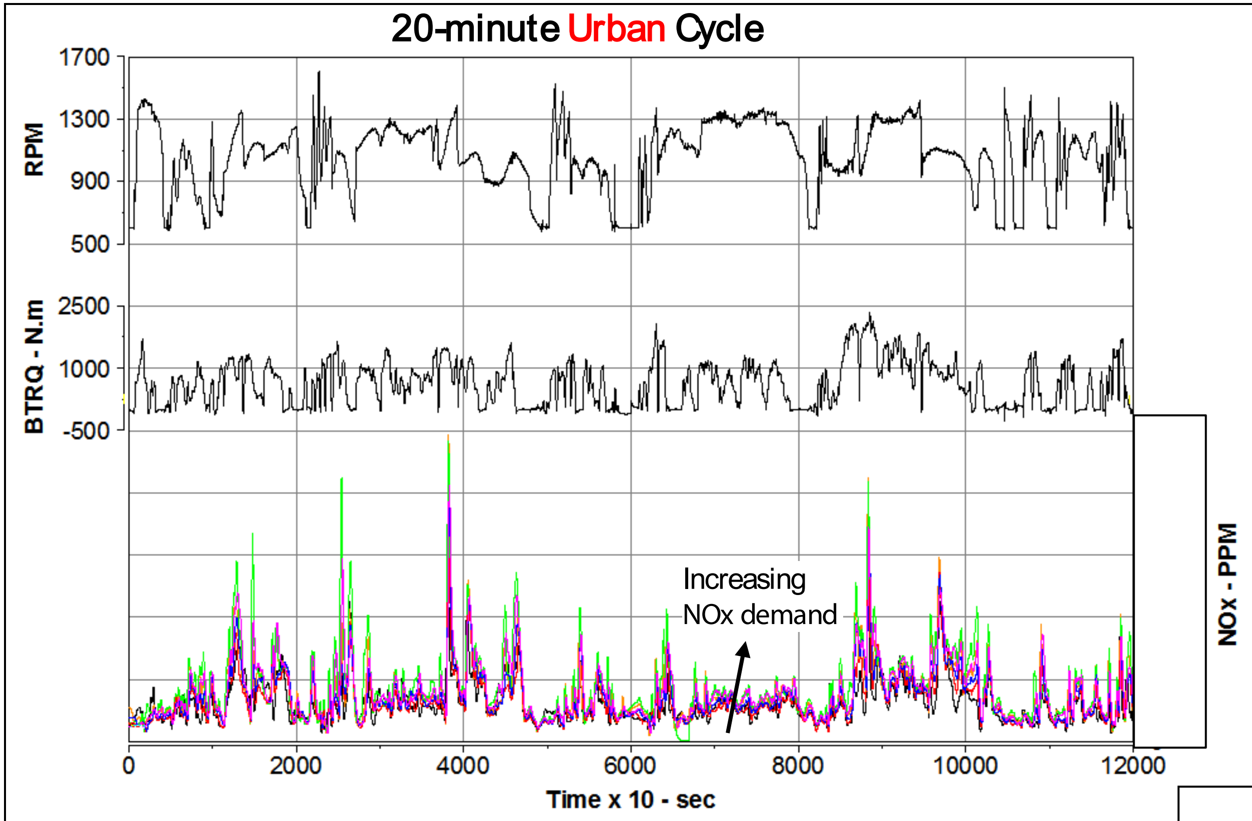


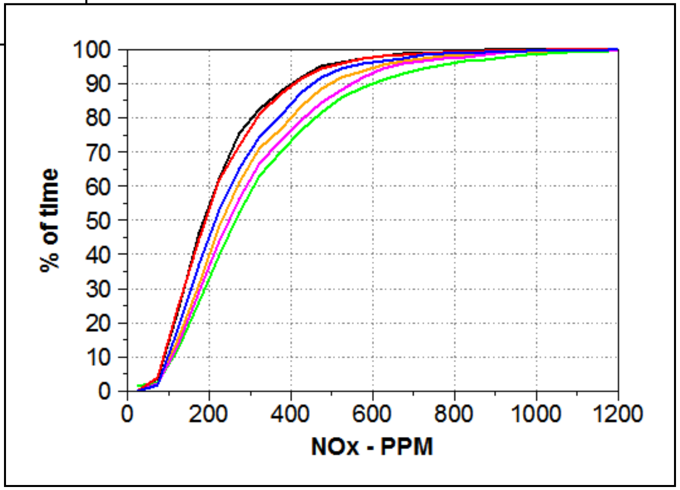
- A single input (NOx gain) is needed to drive the controller to higher/ lower NOx levels
- Controller response is predictable and repeatable
- NOx levels are scaled across the spectrum
- In general fuel efficiency increases with increasing NOx levels



- 6 discrete cycles with 6 different levels of NOx emissions output requested
- Controller is able to 'steer' emissions levels in real-time

DD13 Transient Cycle Results





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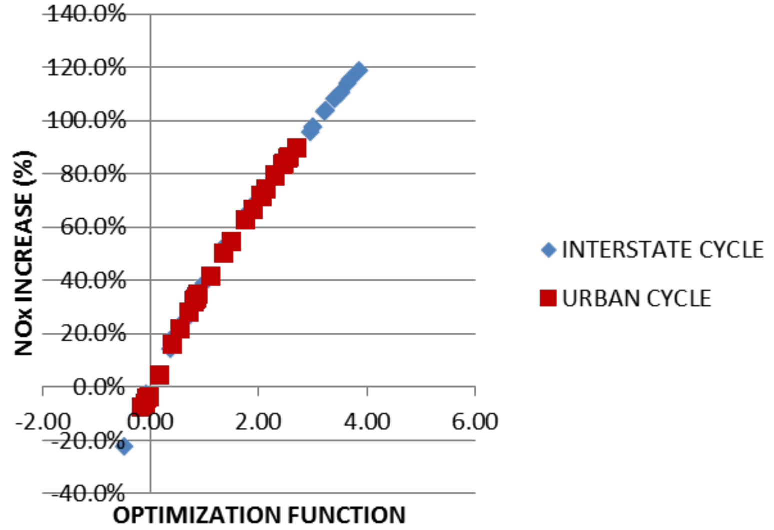
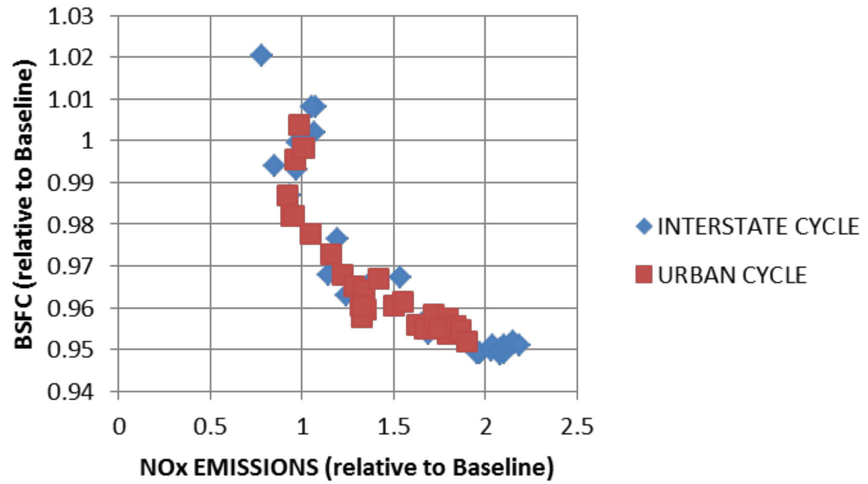
Real-Time Control Optimization

Actual Integrated Cycle Results

- BS NOx varies as demanded by the Optimization Function
- Optimization Function weights can be constant across a cycle (as here) or varied on a point-by-point basis
- BSFC varies with BS NOx
  - 2% reduction at the same NOx level
  - 4% reduction at 30% higher NOx
- Model-based controller demonstrates lower emissions with better fuel economy





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DIRECTIONS IN ENGINE-EFFICIENCY AND EMISSIONS RESEARCH CONFERENCE

Model-Based Control reduces Algorithm and Calibration requirements

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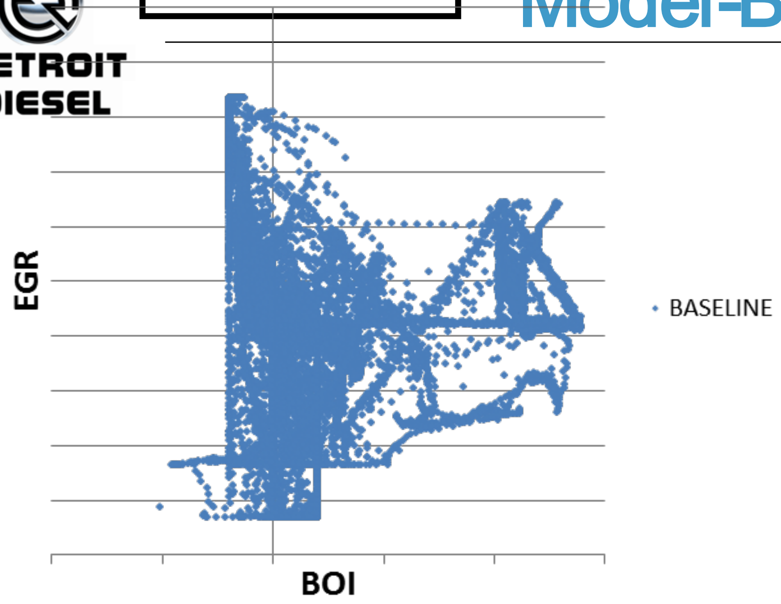
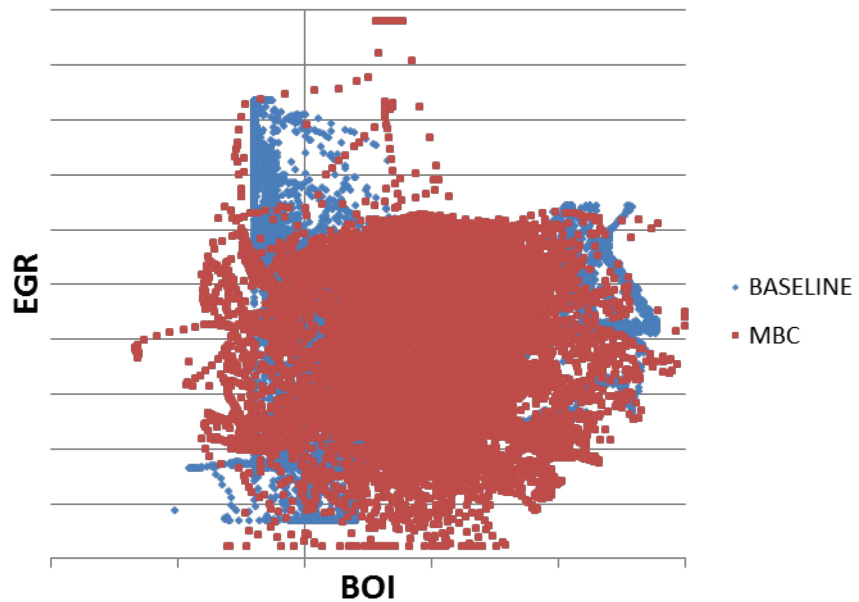


Conventional Engine Controller

- Algorithm intensive
- Calibration intensive



Model-based Controller

- Requires no a priori algorithm development – algorithms replaced by fully predictive models
- Calibration replaced by real-time optimization

Accomplishments

- Model-based control has been demonstrated and validated on 3 different engine displacements to date.
- Able to accommodate a range of engine technologies.
- Applicable to a wide range of engine operation and driving cycles.
- Two in-vehicle proof-of-concept tests successfully completed.
- Lower emissions and lower fuel consumption has been demonstrated in a much reduced time frame (and hence at much lower cost).
- Scalable to accommodate future control parameter requirements.

The Future of Engine Control

- With model-based control, the calibration task is transformed into one of setting real-time emissions and performance targets.
- Majority of the experimental test cell work is performed upfront in data collection, and not after the fact in calibration.
- Validation and verification in the engine test cell are still required.
- Shifts the emphasis from the high cost physical test environment, while reducing effort required to manageable levels,
- Compatible with virtual sensing, OBD and model-based calibration efforts.
- Model-based engine control allows interaction with vehicle control to allow look-ahead capability and the continuous optimization of fuel consumption (SuperTruck Program).

Control becomes predictive rather than reactive, with substantial emissions, fuel efficiency and cost benefits.

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