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

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• 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
# Control System Complexity – today and in the future

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<th>Independent Control Parameters or Orthogonal Variables</th>
<th>Cumulative Number of Control Variables</th>
<th>Date Implemented (actual or projected)</th>
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<td>Injection Timing</td>
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<td>Cycle-by-cycle Control</td>
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<td>2025</td>
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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)
• 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.
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.
Predictive Model-Based Engine Controller

Calculates torque & emissions at every time step

Calculates “best” NOx/CO/CO₂ combination based on optimization weights

Calculates actuator outputs based on “best” emissions

Forward models

- RPM
- Fueling rate
- Intake pressure
- Intake temperature
- Ambient pressure
- Rail pressure
- SCR inlet temp.
- DPF inlet press.

E.O. NOx

CO

CO₂

Torque

T.O. NOx

Target E.O. NOx

Target CO

Target CO₂

Target T.O. NOx

Inverse models

- BOI (k+1)
- EGR (k+1)
- NOP (k+1)
- ITV (k+1)
- P_rail (k+1)
- DEF (k+1)

Optimizer

- Optimizer weights

Emissions Minimization

Calculates torque & emissions at every time step

Calculates “best” NOx/CO/CO₂ combination based on optimization weights

Calculates actuator outputs based on “best” emissions
Model-Based Control System

- Baseline Calibration
- Forward Predictive Engine Model
- Emissions, Performance and Fuel Consumption Targets
- Transient Cycle Requirements
- System and Operating Constraints
- Inverse Dynamic Control Model
- Target Weighting & Optimization
- Transient Control Inputs
- Engine

Model-Based Control System
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 CO₂
  - 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
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
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

\[ Y(k+1) = \text{predicted engine outputs (emissions, fuel consumption, performance) at future time step} \]

\[ U(k+1) = \text{predicted control inputs, subject to variable emissions, fuel consumption and performance targets (denoted i)} \]

\[ B_i = \text{modeled forward weights and biases (fixed)} \]
\[ D_i = \text{modeled inverse weights and biases (fixed)} \]
\[ C_i = \text{output emissions, fuel consumption and emissions targets (variable)} \]

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)

\[ U(k+1) = C_1 \cdot [D_1 \cdot Y(k+1) + D_2 \cdot Y(k) + D_3 \cdot Y(k-1)] \]

Controller Parameter Option Selection

\[ \hat{U}(k+1) = \text{optimum}[U(k+1)] \]

Subject to the constraints:

\[ U(k) \in [u_{min} ; u_{max}] \]
\[ |U(k+1) - U(k)| < \Delta u_{max \text{ slew}} \]
\[ |Y(k+1) - Y(k)| < \Delta Y_{\text{max \text{ slew}}} \text{ (primarily torque)} \]
\[ Y_i(k+1) < Y_i \text{ \text{max} \text{ (emissions constraints)}} \]
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

40-minute Highway Cycle

![Graph showing RPM, DTRQ, and NOx over time](graph)

- Time x 10 - sec

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% of time vs NOx - PPM
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
Model-Based Control reduces Algorithm and Calibration requirements

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
• 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.
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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