System Simulation for Robust Calibration & Diagnostics

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Agenda

- Product Development Challenges
- Investment for System Simulation
- Process Integration of System Simulation
- Pure Simulation
- Approach to System Simulation
- Model Accuracy Assessment
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- Data Analysis
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- Acknowledgements
Cummins Inc., a global power leader, is a corporation of complementary business segments that design, manufacture, distribute and service a broad portfolio of power solutions.
Dynamic Systems & Controls (DS&C) Engine Integration

- Under Corporate Technical function, DS&C is the centralized controls group providing software for world wide Cummins products

- Component software such as aftertreatment and fuel system is integrated with engine and machine controls in order to be validated at system level before delivering to the application teams for calibration

- Within DS&C, Engine Integration group covers air handling and combustion controls software development and calibration for diesel and spark ignited products
Product Development Challenges

System performance calibration development is customer field test centric

30%

of product development cost is spent for calibration iteration with feedback from customer field test

Opportunity for Robust Cal & Diagnostics development considering noise factors and aging

Target to reduce product development cost by 10% utilizing simulation
Product Development Challenges

Evaluate all noise factor categories early in the development

43% of calibration related quality issues are because customer field test didn’t cover all noise factor categories.

Compared to customer field test, better opportunity to evaluate piece to piece variation and aged system* performance utilizing simulation.

*Still challenging to understand how aged system performs and how to create physical part or model
Benefits of Simulation

- Develop, verify and validate calibrations more efficiently
- Faster problem resolution
- Cost-effectively verify calibrations by complementing real-world testing
- Efficiently evaluate system robustness to noise factors: Environmental, duty-cycle, part-to-part variability and system aging
- Improved customer satisfaction
Investment for System Simulation

System Simulation

Plant Modeling

- Capability to introduce noise factors and failed parts for performance features and over 300 diagnostics
- Empirical transient models for engine out NOx and PM
- Aftertreatment outlet NOx estimation
- Fast running plant models for close to real time execution rate

Sensors Model  Actuators Model

Controls Model

Computing Power/Execution Time

Model Complexity/Model Fidelity
Process Integration of System Simulation

- Simulation Leads are assigned to global major development programs to provide system simulation capability
- Processes and measures are updated
- Benefits to product development efficiency and product quality are being evaluated
  - 6-10% reduction in system performance & OBD product development cost is estimated per program
Pure Simulation

Pure Simulation Benefits

- Allows concurrent execution of multiple test cases
  - Even at Real-Time execution rates running multiple instances in parallel means that the effective number of test hours versus real-time is increased

**Pure Simulation opportunity drives for a strategic approach to simulation for robustness assessment**

- Parallel Processing
  - Case 1
  - Case 2
  - Case 3
  - Case 4
  - ...
  - Case 60

12 hours Stimulus Cycle @ RT

12 hours Wall-Clock Time

720 hours of Test Data!
Approach to System Simulation

Approach to System Simulation to deliver technical efficiency & effectiveness

1. **Operating Conditions** *(Duty cycle, rating, GCVW…):* $u(t)$
2. **Initial Conditions** *(Cold start, ash loading…):* $x_0$
3. **Noise Factors** *(Ambient temp/press, sensor variation, aging…):* $d$
4. **Outputs of Interest** *(Fluid consumption, Diagnostics…):* $y(t)$
5. **Requirements on Outputs** *(Tech Profile, Fault Codes…):* $y_{REF}$
6. **Test Bed** *(Pure Simulation, HIL…):* $P$
Model Accuracy Assessment

- Probability/Cumulative Density Function
- Time Series Overlay
- Correlation, $R^2$
- Error w.r.t. reference
- Error vs Time
- Statistics Summary
- Rate of Change
- Cumulative Error
Clustering is an approach for grouping data using K-Means algorithm

Long term customer data can be processed for various purposes
(identify representative duty cycles or challenge maneuvers for specific failure modes)

Engine Speed & Load traces from clustering analysis are used as input to the System Simulation

SAE Paper # 2017-01-0204
Data Analysis

System Simulation

Plant Modeling

- Engine
- Aftertreatment
- Vehicle

- Sensors Model
- Actuators Model
- Controls Model

MATLAB SIMULINK

Virtual Field Test

Automated Tech Profile Assessment
Requirements written as scripts for data analysis

Graphical User Interface for performance analysis plots

OBD Capability Data Plotter

Diagnostics

- Vehicle
- Error Thd
- Capability, Ppk

Fleet

Vehicle

Trend Plot

Day File

Day Plot
Virtual OBD Experience

- Successful correlation of simulated failure modes to real-world failure modes
  - Benefits → Reduce iterations to find Worst Performing Acceptable / Best Performing Unacceptable failed parts

- Identified emissions shift associated with failure levels
  - Benefits → Reduce iterations to find threshold failed part

- Identified system-level risks due to component level failures
  - Benefits → Catastrophic failure avoidance in test cell
Virtual OBD Failed Part Testing

Emissions Threshold Monitors

- AVL BOOST Catalyst Model Updates
- Sensor Shift in Controls Model
- Not Capable
- Capability Demonstrated

Fuel System Feedback is not Modeled

GT Power Engine Model Updates

- Fuel System
- SCR Catalyst
d- DOC Catalyst
- DPF Catalyst
- EGR
- Boost
- NOx Sensors
- Pressure Control
- Pressure Control Low
- Pressure Sensor Rat’ High
- Pressure Sensor Rat’ Low
- Single Injector Overfuel
- Single Injector Underfuel
- All Injectors Overfuel
- All Injectors Underfuel

- EGR High
- EGR Low
- EGR Slow
- EGR Coolant

- Boost High
- Boost Low
- Boost Slow
- CAC Coolant
Closing Comments

Remaining Challenges

- Missing simulatable components in Controls Model and modifications required to run System Simulation
- Engine Control Module hardware performance not matching Controls Model performance
- Long duration from Controls Model release to functional System Simulation

Next Steps

- Evaluation of Controls Model development processes to improve completeness and efficiency
- Develop plant modeling requirements for system simulation
- Assignment of Simulation Leads to more development programs
- Monitor product development efficiency and product quality benefits of system simulation
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