Evolution of MATLAB for Diesel Engine System Performance Development

Brian J. Ouellette

Technical Manager, System Performance Integration
Off-Highway Engine Business

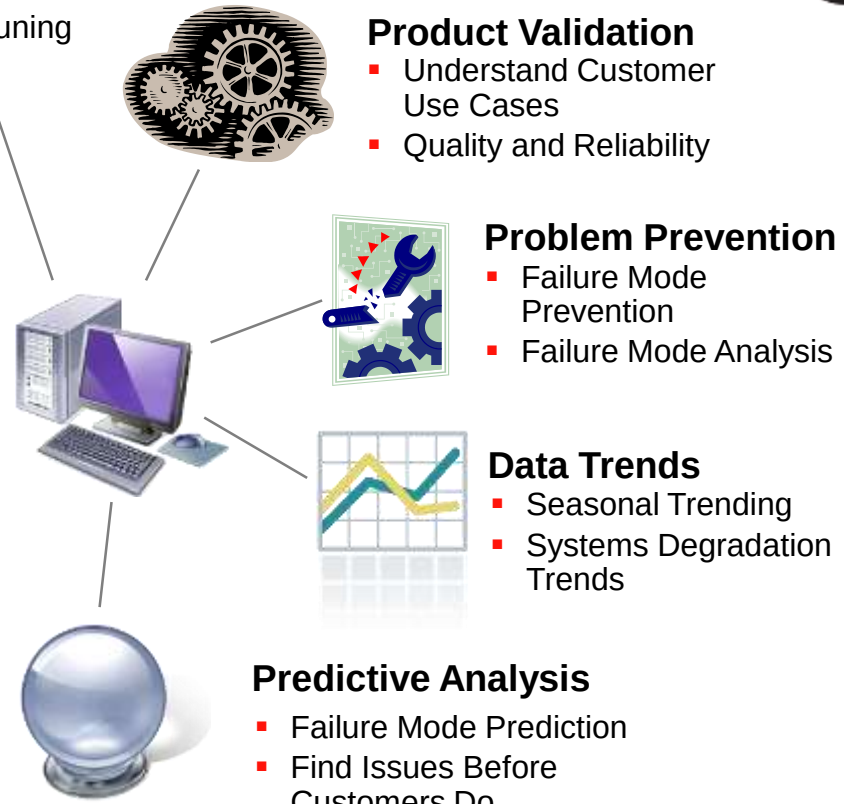
Cummins Inc.

May 12, 2016

2016 MathWorks Automotive Conference
Plymouth, Michigan

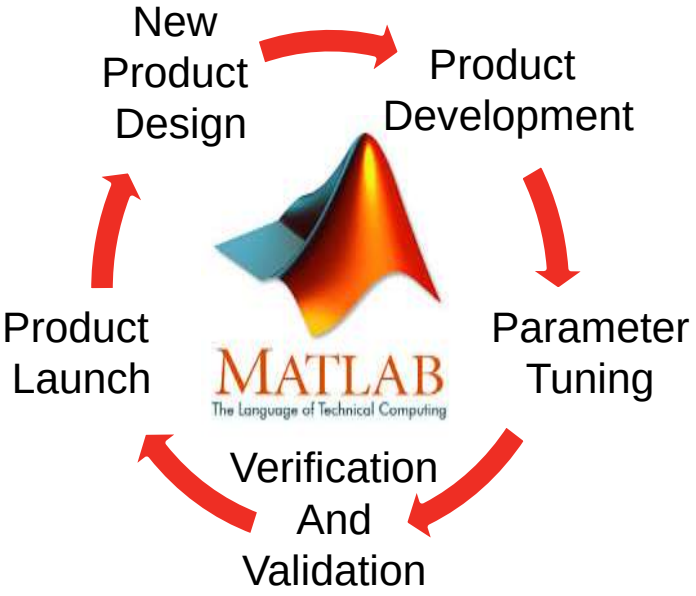
Introduction

- Technology within the diesel engine industry has evolved over the past twenty years
- Progression in these technologies has resulted in system complexity and developing awareness of <u>Total System Performance</u>
- MATLAB provides a variety of tools and applications that engineers can utilize in managing system complexity, from platform concept up to and beyond product launch



Topics for Discussion Today

- Challenges of Complex Systems
- MATLAB Tools of the Trade
- Future Use Cases
- Summing It All Up



Growth In System Complexity

- Driving factors to complexity within the diesel engine industry

Performance
Total Cost of Operation
Maintenance
Resale Value

Total System Integration

Advancing Technology

Customer Requirements

Fluid Efficiency

Encompasses both Diesel Fuel burned and Diesel Exhaust Fluid (DEF) consumed

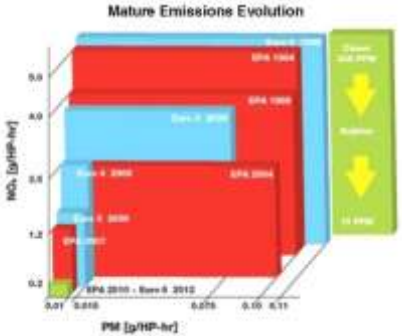
Emissions

Reliability

US EPA and Euro regulations towards near zero exhaust emission constituents and reduction in CO2

1991 – 6 Engine Sensors and 7 Engine Actuators
(no Aftertreatment)
2013 – 34 Sensors and 18 Actuators
(Engine and Aftertreatment)

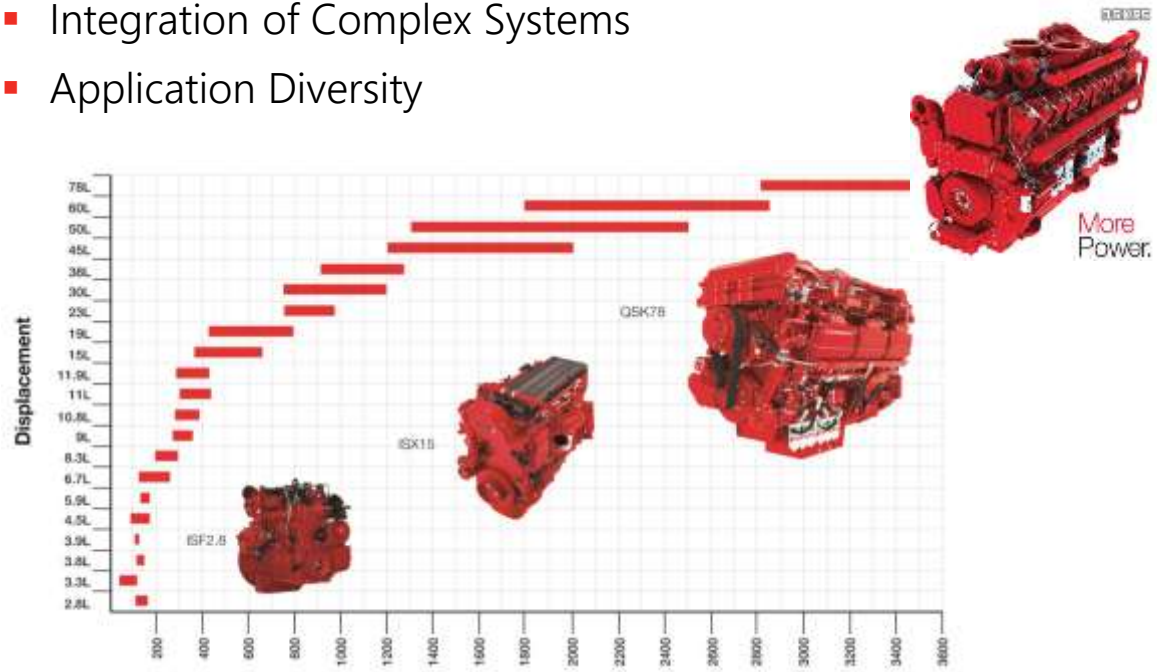
90% Reduction in emissions over this time period

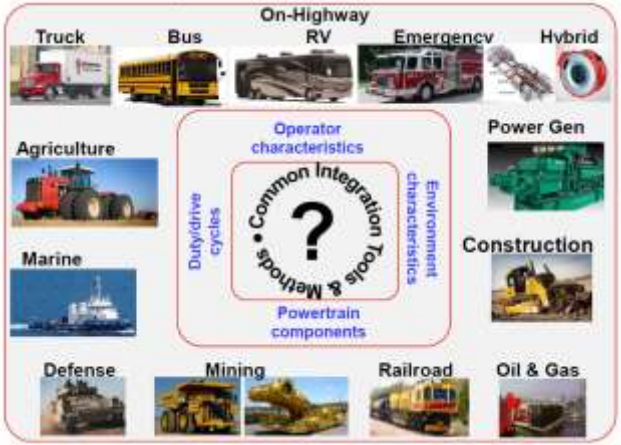


- Growth in system complexity drives many challenges in system performance analysis
  - ❑ Gather the right data
  - ❑ Define the questions to answer in analysis
  - ❑ Apply proper techniques for analysis
  - ❑ Present the data so it makes sense

Cummins Complex System Challenge

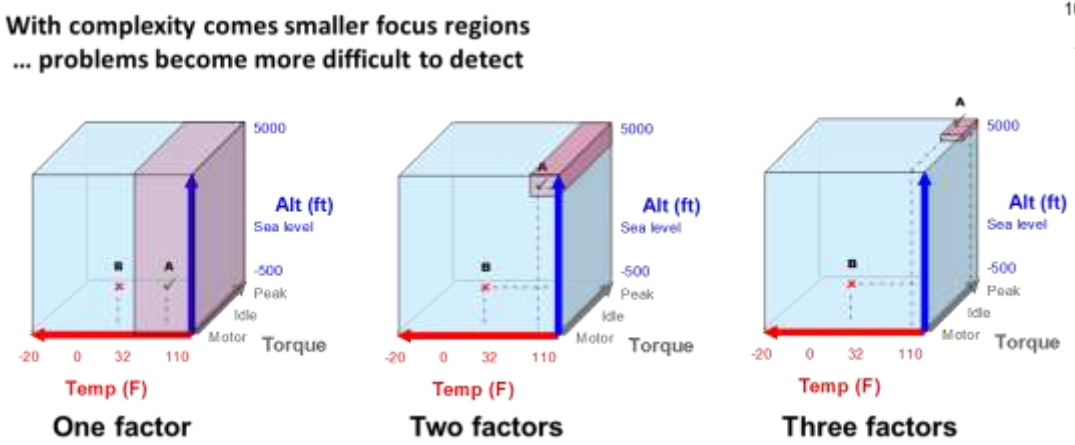
- Cummins Broad Global Product Range
- Integration of Complex Systems
- Application Diversity

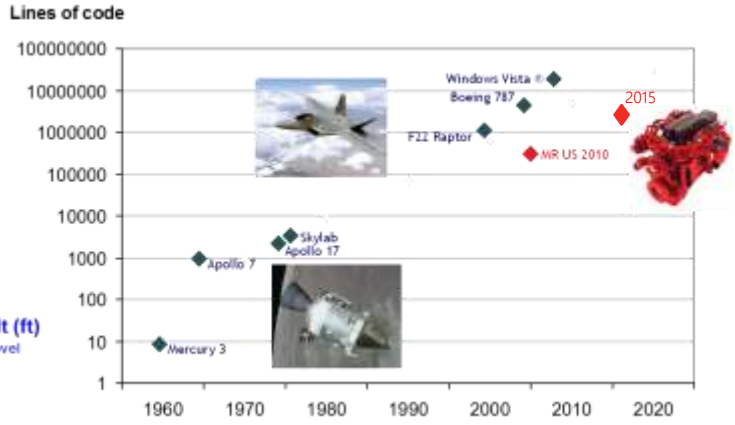




Challenges of Complex Systems

- Increasing complexity narrows the region of investigation, making it more difficult to determine where the issues lie
- Complex systems tend to "disguise" themselves to the benefit of the consumer





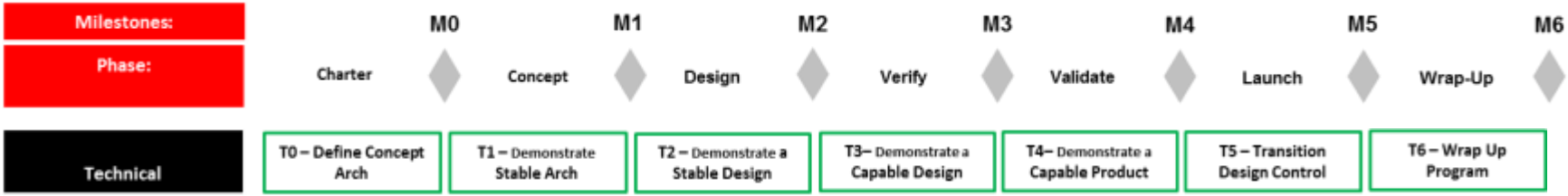
Role of the System Performance Integrator

- To support continual growth in system complexity, Cummins adopted the role of System Performance Integrator to support new and derivative engine platform development programs
- The role of the System Performance Integrator includes (but is not limited to) responsibility for all aspects of engine system performance
  - Base Engine Performance: Torque, Power, Fuel Efficiency, Reliability
  - Engine Emissions: NOx, Hydrocarbon, Particulate Matter, CO2
  - Engine Systems: Fuel System, Turbo System, EGR, Power Cylinder
  - Aftertreatment Systems: DOC, Diesel Particulate Filter, SCR
  - OEMs / Applications: Duty Cycles, Environment, Utilization, Operation Envelop

How Does MATLAB Fit?

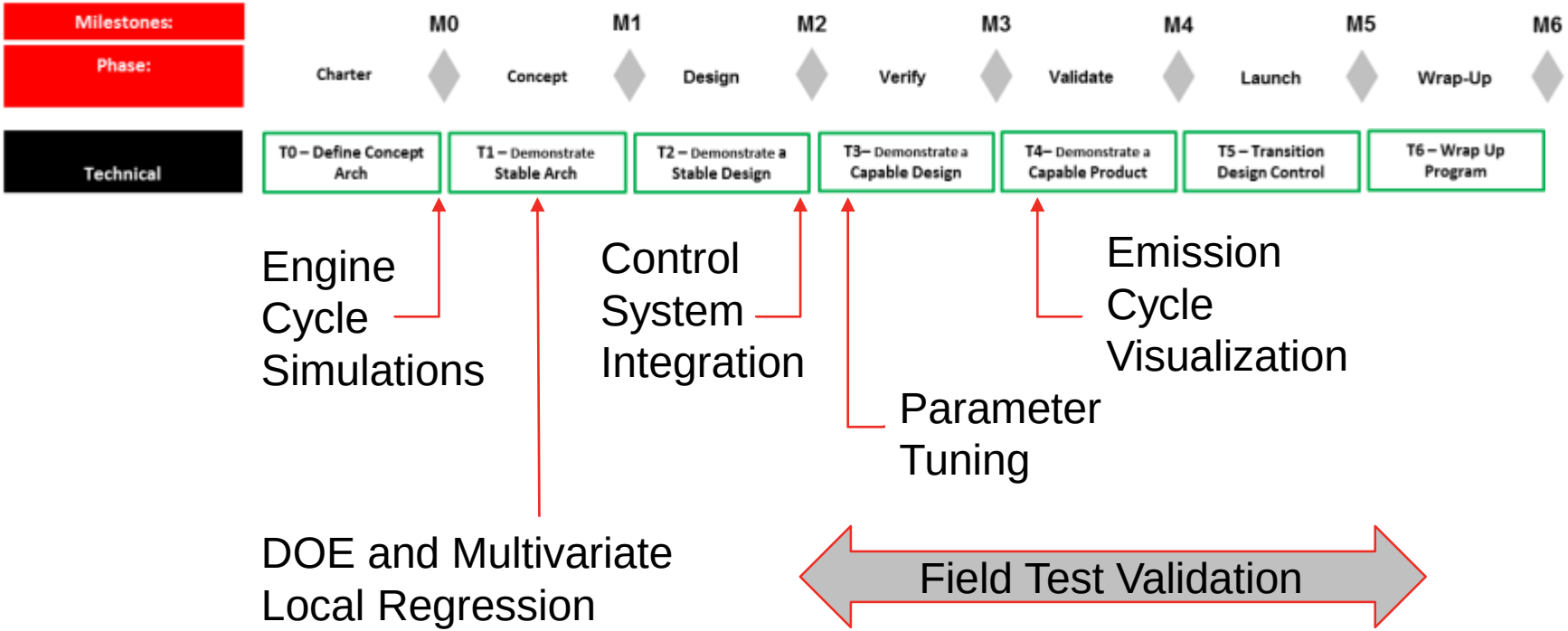
- MATLAB provides engineers the ability and tools access to quickly analyze and visualize large data sets over the course of their development activities, for concept to development to production
- MATLAB 2015a (current version utilized by Cummins) offers several new and enhanced features for engineers to apply towards large sets of data
  - Ease of Importing Excel Data into MATLAB
  - Statistical Analysis and Machine Learning Toolboxes
  - Apply and Utilize Table structures
  - Numerous methods of Data Visualization
  - Auto Code Generation for Plots and Data Import
  - Utilize shared community applications (APPS)

Process Flow for New Product Development



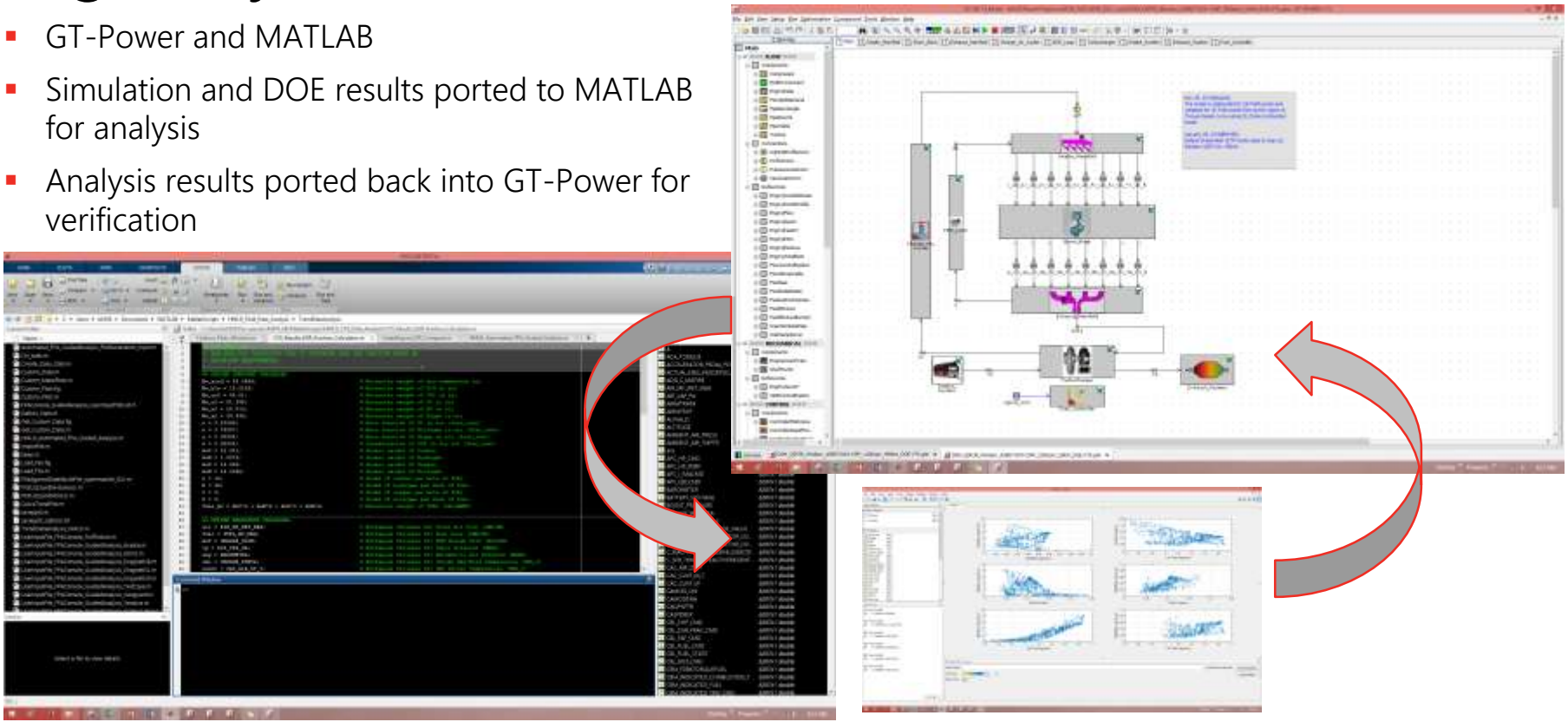
- Standard development process flow for new product introduction
- At each Milestone, progress reviews held to determine readiness to proceed to next Phase
- System Performance (Technical flow) engaged at each Milestone and deliverable Phase
- MATLAB utilized as one of many tools by System Performance teams

Process Flow for New Product Development

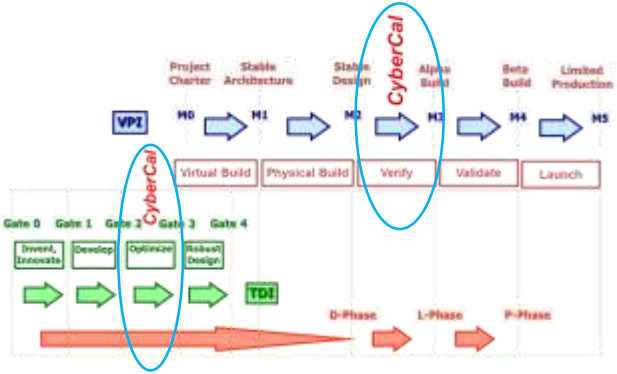


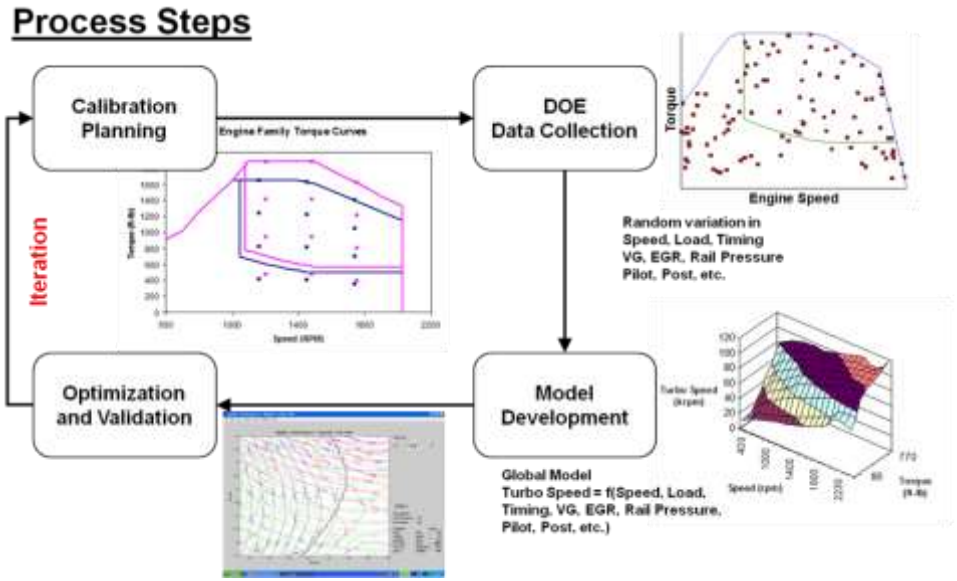
Engine Cycle Simulations

- GT-Power and MATLAB
- Simulation and DOE results ported to MATLAB for analysis
- Analysis results ported back into GT-Power for verification



DOE and Multivariate Local Regression

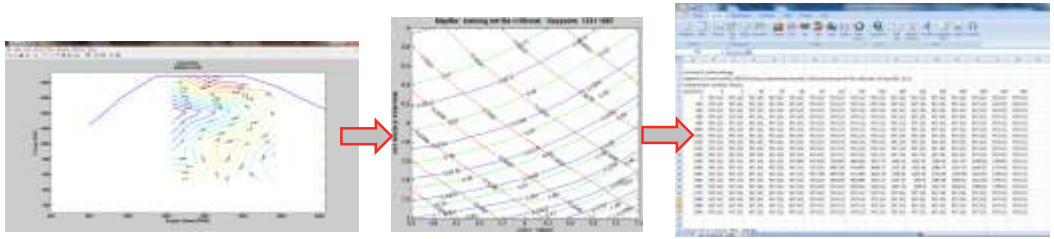


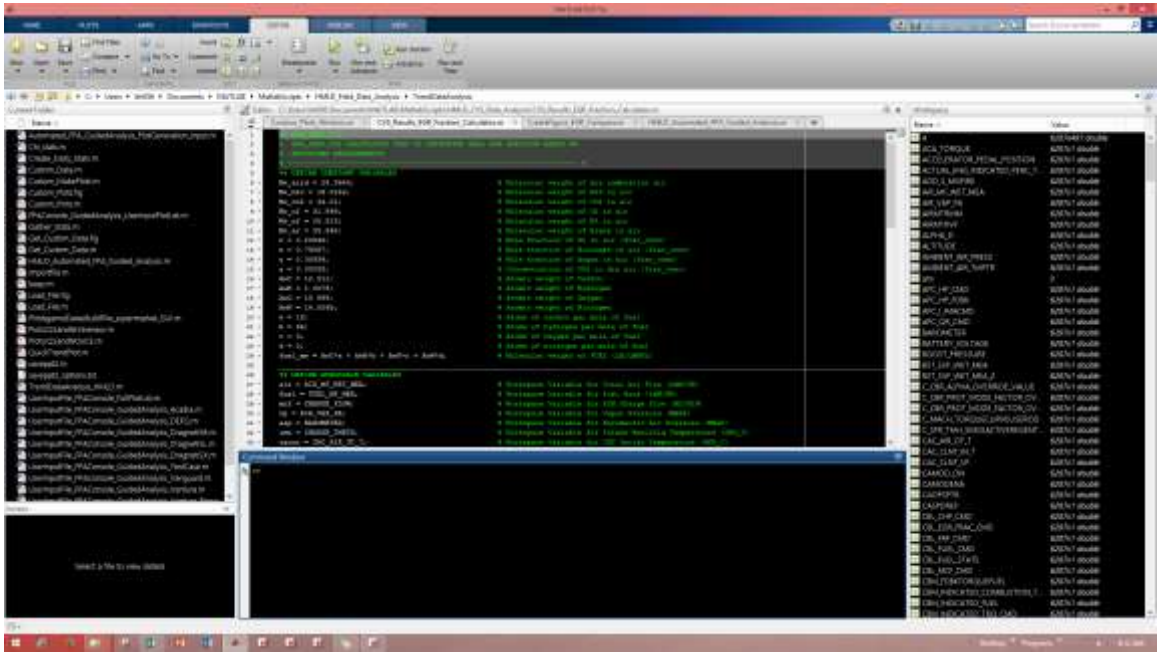


- **CyberCal** - Integrated MATLAB tool which performs Multivariate Local Regression (MLR) to build models from test data utilized for performance optimization
  - Develop DOE test sequences
  - Develop regression models
  - Perform optimization → Parameter tuning

Parameter Tuning

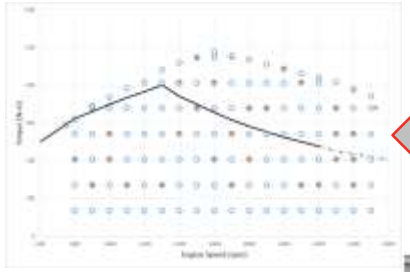
- Utilizing MATLAB to visualize and assemble calibration parameters for tuning
  - Visualize surfaces
  - Visualize parameter tuning trade-offs with constraints
  - Create parameter tuning tables
- MATLAB code development by users to streamline processes

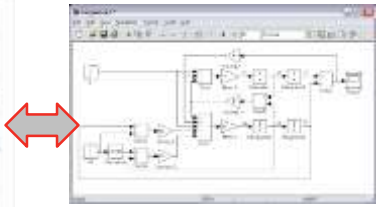


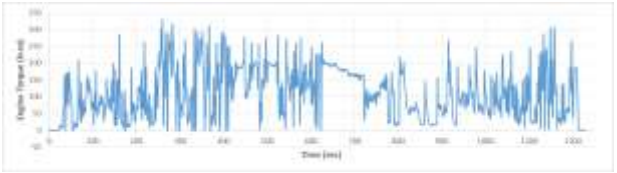


Control System Integration

- Integration of Simulink with real engine data
- Integration with Controller, Hardware, and Engine In-Loop (CIL, HIL, EIL)
- Mission Simulation through MATLAB

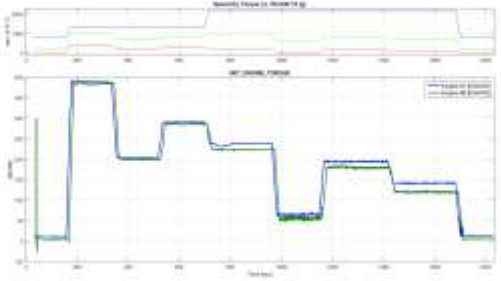


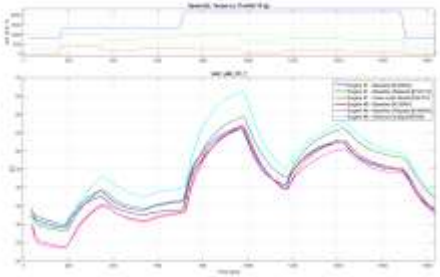


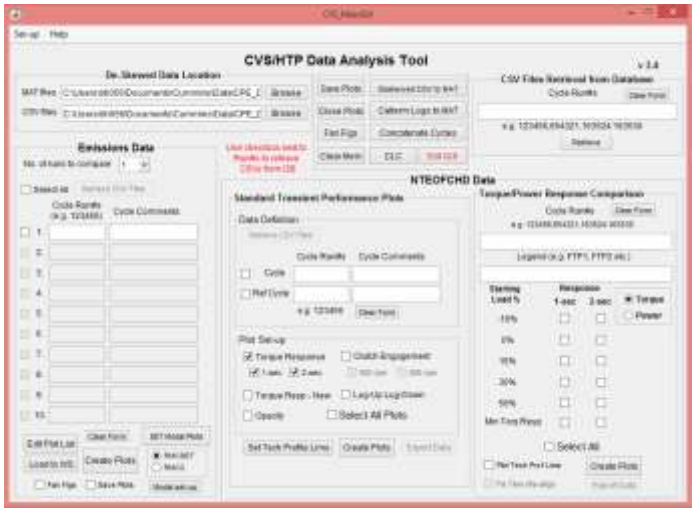


Emission Cycle Visualization

- Transient/Steady-State Emissions Data Analysis Tool
- MATLAB GUI interface - internal distribution to engineering community
- Load single or multiple emission cycle data to compare results
  - Engine-to-Engine
  - Cycle-to-Cycle
  - Platform-to-Platform
- Rapid and easy visualization of data
- Able to accept User input calculations
- Conversion of file formats from .csv to .mat
- Analysis of transient response, torque response, load acceptance

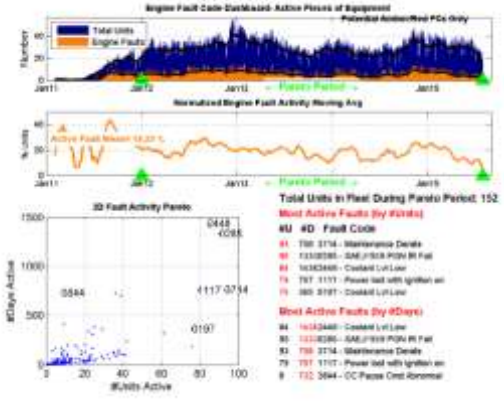


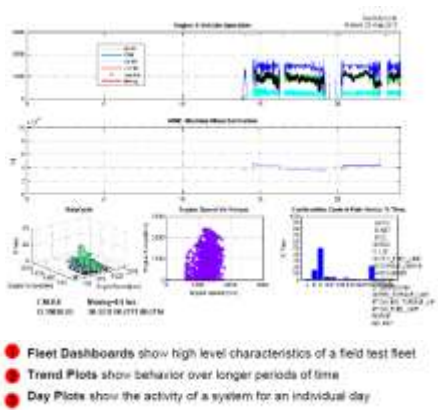




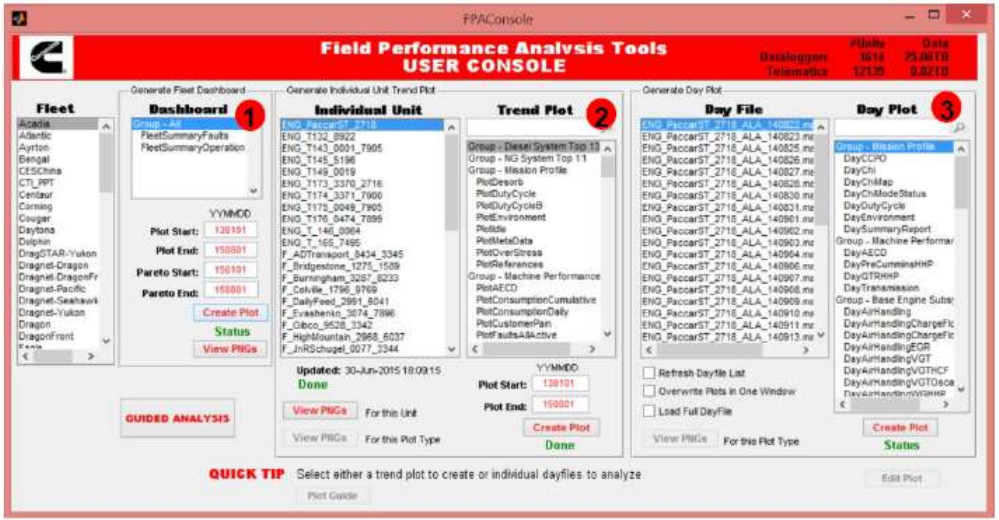
Field Test Validation

- Field Performance Analysis (FPA) Tools
- MATLAB GUI interface - Cummins Global distribution
- Ability to access field data from over 1700 data loggers, plot trend data, plot daily data, run fleet metrics
- Deep dive into data analysis with access to multiple system-level plots created by multiple engineering groups



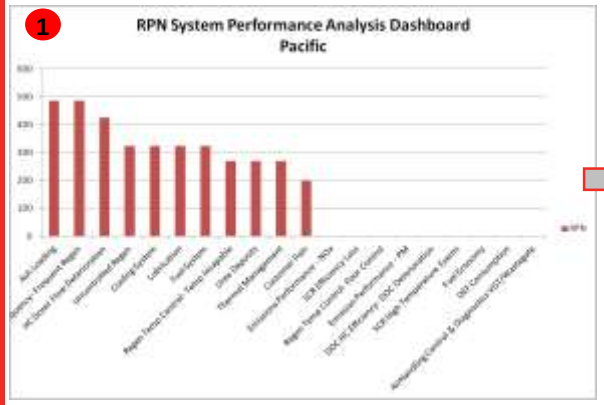


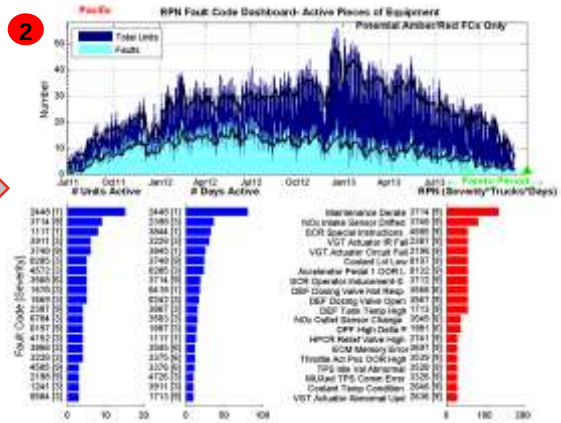
- **Fleet Dashboards** show high level characteristics of a field test fleet
- **Trend Plots** show behavior over longer periods of time
- **Day Plots** show the activity of a system for an individual day

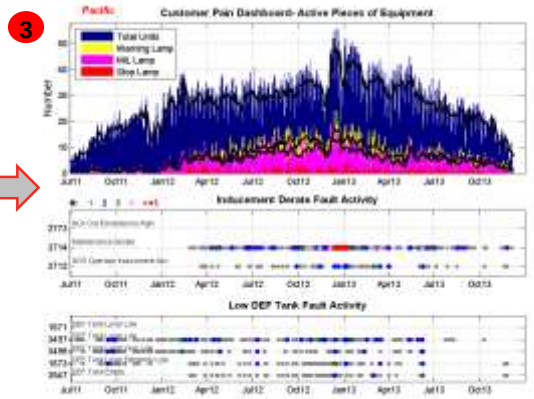


Field Test Validation

- Proactive Guided Analysis through MATLAB
- Breakdown of System Level issues observed in Field Test
  - Severity and Occurrence ranking
  - Inclusion of focus on customer impact from system level issues
- Enable focus on “Big Darn Deals” and drive towards assignable root cause

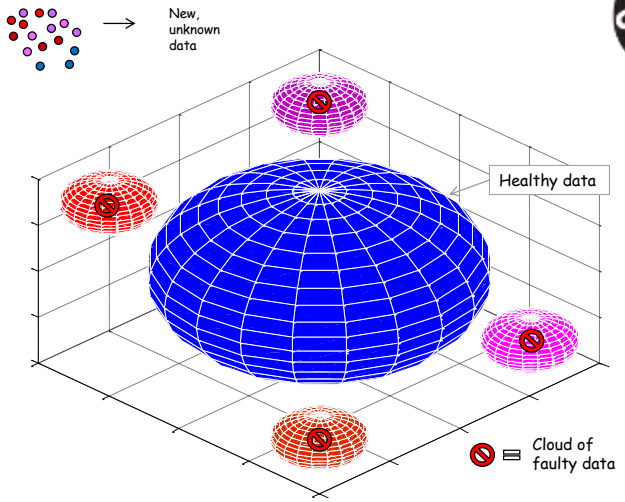




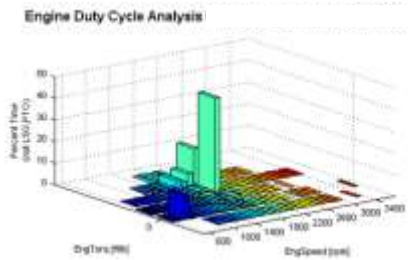


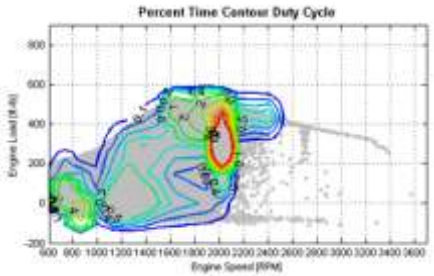
Field Test Validation

- **Cumulative Data Analysis through MATLAB**
- "Build" large data sets through combination of multiple MAT day files → Data range: weeks / months / years
  - Mapping of duty cycle over seasons
  - Application of parameter filters to segment data
  - Visualization of data trends and statistics
  - Creation of "data models", transfer functions, data pattern recognition, machine learning, etc.



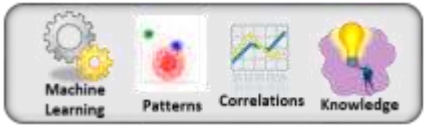
Modeled from previously known healthy and faulty data sets





Future Utilization

- Future Expectations
  - More System Complexity
  - More Total System Integration
  - Shared Analytics
  - Connected Systems
- Future Utilization of MATLAB
  - Machine Learning
  - Classifications
  - Predictive Analysis
  - Integration of Big Data



Summing It All Up

- System complexity has seen substantial growth within the diesel engine industry responding to changes in technology, regulations, requirements, and customer needs
- Total System Thinking has led to an evolution of "engineering specialists" that provide expertise across all system boundaries
- Within Cummins, the System Performance Integration ties Total System Thinking with Total System Performance development
- MATLAB provides essential tools to assist System Performance Integration in managing system complexity at all stages of diesel engine platform development

Thank You For Your Attention