Validation of Aftertreatment Temperature Requirements Using MathWorks Tools

2014 MathWorks Automotive Conference

Travis E. Barnes
Engineering Technical Steward
Large Power Systems Division Engineering
Introduction

Aftertreatment Development For U.S. EPA Tier 4 Interim, 9 – 18 Liter Non-Road Engines

Aftertreatment Development For U.S. EPA Tier 4 Final, 9 – 18 Liter Non-Road Engines

Aftertreatment Development For U.S. EPA Tier 4 Final, > 560 KW Non-Road Engines

Conclusions

* “Tier 4” Is Intended To Encapsulate U.S., EC, EU And Japan Standards
Introduction

• Caterpillar’s Large Power Systems Division Process To Improve Development Efficiency Using A Mix Of Simulation / On-engine Testing.

• Focus On Cat Aftertreatment Systems
  – 9 To 106 Liter (C175-20) Machine/Commercial Engines
  – T4 Interim And Final, Above And Below 560 KW
Aftertreatment Development
For Tier 4 Interim,
9 – 18 Liter Non-Road Engines
Tier 4 Interim Emissions Standards

Tier 1 / Stage 1 (1996)

Tier 2 / Stage II (2004)

Tier 3 / Stage IIIA (2006)

Tier 4 Interim / Stage IIIIB (2011)

Tier 4 Final / Stage IV (2014)

< 560 KW (750 HP)

*Highly Regulated Countries (HRC)

Regulatory Challenges:
- Near-zero targets
- NOx and PM are inversely related

DPF (Diesel Particulate Filter)
Aftertreatment Required To Meet T4i Regulations
DPF Regeneration Technology

Temperature Control is Critical!

Cracked DPF ← Damaged Due To Exothermic Reaction → Melted DPF

Caterpillar: Non-Confidential
Cat Regeneration System Overview

Hardware Overview:

- Air Valve
- Turbos
- Exhaust
- Air Line
- CRS
- Spark
- Coolant
- Fuel Pump
- Fuel Manifold
- Fuel
DPF With Cat Regeneration System
Regeneration Optimization

- CRS Heat Required
  - $Q = \dot{m} \times (T_{target} - T_{exhaust})$
- Increased Mass Flow
  - Increased Heat Input Required
- Hotter Exhaust
  - Decreased Heat Input Required
- Optimization Problem
  - Soot Load
  - Vs. Machine Operating Cycle
  - Vs. Fuel Consumption

- Low Ambient Temperature Requires More Heat To Reach Regeneration Temperatures
- CRS Enables Regenerations Under Cold Ambient Conditions
Caterpillar: Non-Confidential

Regeneration Requirements

• **Integration With Cat® Machines**
  – Vertical Integration With Machine Controls
  – Improve Machine Performance Over Tier 3
    • Increased Productivity
    • Lower Life-cycle Cost
    • Improved Fuel Economy

• **Robust Operation**
  – No Operator Intervention/Interruption Or Productivity Loss
  – Steady-State & Transient Work Cycle Capability
  – Ambient Conditions (Temperature, Altitude)

• **Optimize Regeneration To Minimize Fuel Consumption**
  – When To Perform Regeneration
  – Optimize Duration / Frequency / Temperature Profile

• **Control Regeneration Temperature**
  – Oxidize Soot In DPF
  – Protect DPF From Exothermic Events

Caterpillar: Non-Confidential
Machine Work Cycles

Hydraulic Excavator

Articulated Truck

Medium Wheel Loader

Aggressive Truck Load

Load Carry

Tracked Type Tractor

Motor Grader

Caterpillar: Non-Confidential
Industrial Work Cycles

Drill Rig

Reclaimer
Regeneration Development/Validation

- Generate Regeneration Requirements
  - Application Cycle Analysis Using CORSICA
    - Identify Regeneration Opportunity
    - Optimize Fuel Consumption
    - No Loss In Machine Productivity

- Developed Control Strategies
  - Simulink/Stateflow Models For Algorithm Development
  - A/F Ratio, Temperature, Regeneration Triggers
  - Validated Algorithms using CORSICA

- Robustness Testing
  - Component Variability – Corners of box
  - Environmental Factors (Temperature, Altitude)

- Developed Engine Test Cycles
  - Analyzed 7000+ Hours Data From ~200 Machines
  - Generated Cycles For Machine/Commercial Applications

- Ran 76 Validation Test Cycles
  - Validated Models And Control Algorithms
  - Validated No Loss In Machine Productivity
  - Verified Robustness Using DOE (Design of Experiment) / Taguchi
Tier 4 Interim Simulation Results

- **Aftertreatment Control Development**
  - Simulation Used To Develop Strategies
    - Confirmed Regeneration Path → CRS
    - Identified Regeneration Opportunities Transparent To Operator/Machine Performance
    - Optimized CRS Control System
    - Optimized Fuel Consumption (CRS + Engine)

- **Aftertreatment Validation**
  - Engine Validation Cycles Developed For Each Engine Platform
    - 76 Total Cycles To Insure Robust Performance On 125 Engine Platform/Applications
    - Validated CORSICA Models
  - Enabled Simulation To Be Used For
    - Additional 49 Tier 4 Interim Applications
• **Customer Value**
  - Up To 4% Fuel Consumption Improvement Over Tier 3 Engines
  - Seamless and Completely Automatic Regeneration
    - DPF Regeneration With No Disruption Of Work Cycle
    - Robust To Highly Transient Work Cycles
    - Robust To Challenging Environmental Conditions
Tier 4 Interim Results

• Tier 4 Engines Sold
  – Over 86,000* Cat Machines And Over 16,000* Cat Commercial engines
• Customers Have Accumulated Over 55 Million* Working Hours On 43,000* Cat Machines With Remote Monitoring (~½ Total Field Population)
• Most Successful Product Launch In Cat History
• Tier 4 Interim Machine Reliability Better Than Target
• Customers Not Requiring Tier 4 Regulations Desire Tier 4 Products

950 to 980K Medium Wheel Loaders

Customer Feedback:
• Superior Fuel Economy
• Faster & More Productive
• Completely Automatic Regen
• Plenty Of Power
• Great Quality

*data valid as of Jan 31, 2014
Aftertreatment Development
For Tier 4 Final,
9 – 18 Liter Non-Road Engines
Tier 4 Final Emissions Standards

< 560 KW (750 HP)

*Highly Regulated Countries (HRC)

- Near-zero targets
- NOx and PM are inversely related

Regulatory Challenges:

SCR (Selective Catalytic Reduction) Aftertreatment Required To Meet Tier 4 Final NOx Regulations
**Selective Catalytic Reduction (SCR)**

**“Standard” SCR reaction**

\[ 4\text{NO} + 4\text{NH}_3^* + \text{O}_2 = 4\text{N}_2 + 6\text{H}_2\text{O} \]

**Diagram Description**

- **Catalyst Surface**
  - Conversion
  - Release
  - Storage
- **Exhaust Gas Flow**
  - NH\textsubscript{3}
  - H\textsubscript{2}O
- **DEF Fluid**
  - Metering Unit
  - Engine Exhaust
  - DEF Fluid Injected Into Exhaust Stream
  - NH\textsubscript{3} and NO\textsubscript{x} React In Catalyst To Form Nitrogen and Water
  - DEF Solution “Hydrolyzes” Into Ammonia Gas Which Mixes With Exhaust Gas
- **NO\textsubscript{x} Conversion Efficiency**
  - Efficiency
  - Space Velocity
  - Temperature

**Legend**

- N\textsubscript{2}
- H\textsubscript{2}O
- N\textsubscript{2}H\textsubscript{2}O
- N\textsubscript{2}
DEF System Overview

Pump & Electronics Tank Unit

Clean Emissions Module
• **Integration With Cat® Machines**
  – Vertical Integration With Machine Controls
  – Improve Fuel Economy Over Tier 4 Interim
  – Minimize Fluid Consumption (Fuel and DEF Fluid)

• **Robust Operation**
  – No Operator Intervention/Interruption Or Productivity Loss
  – Steady State and Transient Work Cycle Capability
  – Ambient Conditions (Temperature, Altitude)

• **SCR Control Requirements**
  – DEF Control
    • Optimize Fluid Consumption
    • Minimize DEF Deposits
    • Minimize Ammonia Slip
  – Prevent Over Heating Of Catalyst / Loss of Conversion Efficiency
  – Thermal Management
    • Optimize Regeneration Duration / Frequency / Temperature
    • Oxidize Soot In DPF, Mitigate DEF Deposits, and Desulfate SCR Catalyst
    • Protect DPF / SCR Catalyst From Excessive Temperatures
Caterpillar: Non-Confidential

Simulation Tools

- **PROCESS DATA**
  - Matlab
  - Simulink
  - Parallel Computing Toolbox

- **CONTROL DEVELOPMENT & TUNING**
  - Matlab
  - Simulink
  - Stateflow
  - Fixed Point Toolbox
  - Control Toolbox
  - System ID toolbox
  - Signal Processing Toolbox

- **SOFTWARE DEVELOPMENT**
  - Matlab
  - Simulink
  - Stateflow
  - Fixed Point Toolbox
  - V&V Toolbox

- **CONTROL**
  - Matlab
  - Simulink
  - Stateflow
  - Fixed Point Toolbox
  - Embedded Coder
  - Matlab Coder
  - Simulink Coder

- **ADDED SCR MODELS TO CORSICA**

- **CORSICA**
  - Matlab
  - Simulink
  - Stateflow
  - Parallel Computing Toolbox
  - Embedded Coder
  - Matlab Coder
  - Simulink Coder

- **ENGINE / AFTERTREATMENT MODEL**
  - Dynasty
  - In House Modeling SW

- **DATA ANALYSIS**
  - Matlab DatK

- **CAT ECM**
  - ADDED SCR MODELS TO CORSICA

- **SOFTWARE DEVELOPMENT**
  - Matlab
  - Simulink
  - Stateflow
  - Fixed Point Toolbox
  - V&V Toolbox

- **PRODUCTION SOFTWARE**
  - Matlab
  - Simulink
  - Stateflow
  - Fixed Point Toolbox
  - V&V Toolbox
  - Embedded Coder
  - Matlab Coder
  - Simulink Coder

- **ENGINE TEST DATA**

- **FIELD DATA**

- **ENGINE CONFIGURATION DATA**

- **TEST CYCLE**

- **SOFTWARE DEVELOPMENT**

- **CONTROL CALIBRATION**

- **CALIBRATION**

- **OUTPUT**

- **FEEDBACK**

- **MODEL IMPROVEMENT**

- **SIMULATION RESULTS**

- **ENGINE ECM**

- **AFTERTREATMENT MODEL**

- **CORSICA**

- **ADDED SCR MODELS TO CORSICA**

- **SOFTWARE DEVELOPMENT**

- **CONTROL CALIBRATION**

- **CALIBRATION**

- **OUTPUT**

- **FEEDBACK**

- **MODEL IMPROVEMENT**

- **SIMULATION RESULTS**

- **ENGINE ECM**

- **AFTERTREATMENT MODEL**

- **CORSICA**

- **ADDED SCR MODELS TO CORSICA**

- **SOFTWARE DEVELOPMENT**

- **CONTROL CALIBRATION**

- **CALIBRATION**

- **OUTPUT**

- **FEEDBACK**

- **MODEL IMPROVEMENT**

- **SIMULATION RESULTS**

- **ENGINE ECM**

- **AFTERTREATMENT MODEL**

- **CORSICA**

- **ADDED SCR MODELS TO CORSICA**

- **SOFTWARE DEVELOPMENT**
Tier 4 Final Results

• Significant Reduction in Engine Test
  – Minimal Engine Testing For Model Validation
  – Validated CRS / SCR on 235 Tier 4 Final Engine Platform/Applications Using Simulation Models
  – 30% Reduction in Engine Test for SCR Component Robustness DOE

• Have 369* Tier 4 Final machines in the field with over 488,000* operating hours

• Seamless Operation
  – No Intervention by Operators
  – No Loss in Machine Productivity
  – Robust Performance in All Work Cycles / Environmental Conditions

• Customer Value
  – 3-4 % Engine Fuel Consumption Improvement Over Tier 4 Interim
  – 2-3% DEF Reduction Over SCR w/o DPF

*data valid as of Feb 14,2014
Aftertreatment Development
For Tier 4 Final
> 560 KW Non-Road Engines
• Emission Requirements
  – Regulations Based on Application
  – Site Regulations Can Be More Stringent

• Engine System Requirements
  – No Operator Intervention/Interruption Or Productivity Loss
  – Robust To Steady State And Transient Work Cycles
  – Robust To Environmental Conditions (Altitude, Temperature)
  – Minimize Total Fluid Consumption (DEF, Diesel)
  – No Thermal Management Via CRS

• SCR Control Requirements
  – Prevent Over Heating Of Catalyst / Loss of conversion Efficiency

• SCR Package
  – Multiple SCR Catalyst Configurations
  – Significant Space Claim
> 560 KW Applications

Rail

Electric Power
Simulation Tools

ADDED SCR MODELS TO CORSICA

CONTROL DEVELOPMENT & TUNING
MATLAB
Simulink
Stateflow
Fixed Point Toolbox
Control Toolbox
System ID toolbox

SOFTWARE DEVELOPMENT
MATLAB
Simulink
Stateflow
Fixed Point Toolbox
V&V Toolbox

PROCESS DATA
Matlab
Simulink
Parallel Computing Toolbox

ENGINE / AFTERTREATMENT MODEL
Matlab
Simulink
Stateflow
Parallel Computing Toolbox
Embedded Coder
Matlab Coder
Simulink Coder

CONTROLLER
Matlab
Simulink
Stateflow
Fixed Point Toolbox
Embedded Coder
Matlab Coder
Simulink Coder

EXECUTION SOFTWARE
Matlab
Simulink
Stateflow
Fixed Point Toolbox
V&V Toolbox
Embedded Coder
Matlab Coder
Simulink Coder

HIL
Matlab
Simulink
Stateflow
Embedded Coder
Matlab Coder
Simulink Coder

CAT ECM
Hardware In The Loop Testing

Data Analysis
Matlab DatK

Model Improvement

Simulation Results

CORSICA

Field Data
Engine Configuration Data
Engine Test Data

Control
Output
Feedback
Control
Calibration

Production Software

ENGINE
Dynasty
In House
Modeling SW

SOFTWARE
Matlab
Simulink
Stateflow
Control Toolbox

Data
Analysis

Engine Test Data

Caterpillar: Non-Confidential
• **>560KW Engine Development**
  – Engine And Test Cell Cost / Availability
  – Low Volumes With Significant Application Diversity
  – Focus Engine Testing: Model Validation & Durability Testing

• **Utilize dSpace Hardware-In-the-Loop (HIL)**
  – Utilize Existing Matlab/Simulink Model Libraries
  – Control Strategy/Diagnostic Development
  – DOE (Design Of Experiment) / Taguchi Robustness Testing
  – Validation of Production Intent Hardware and Software
  – Driven by Machine Application Cycle Data
Conclusions
Simulation Process Benefits

- Simulation Growth 4-5X
- Doubled Applications From Tier 4 Interim
- Reduced Engine Tests by 3X
- Reduced DOE Test Time By 30%
- Doubled Use Of Simulation
- Potential Growth

**Tier 4 Interim**
- Platform/Applications
- Engine Tests
- DOE Test Time
- Simulations

**Tier 4 Final**
- Platform/Applications
- Engine Tests
- DOE Test Time
- Simulations

**Tier 4 Final > 560 KW**
- Platform/Applications
- Engine Tests
- DOE Test Time
- Simulations
Appropriate Mix Of Simulation And Engine/Component Level Testing, Robust Controller Design Practices, Has Enabled Caterpillar To Provide Industry Leading Tier 4 Products To Our Customers.

THANK YOU