Validation of Aftertreatment Temperature Requirements Using MathWorks Tools

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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


- 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

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

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

Tier 1 / Stage 1 (1996)
Tier 2 (2004)
Stage II (2004)
Tier 3 / Stage IIIA (2006)
Tier 4 Interim / Stage IIIIB (2011)
Tier 4 Final / Stage IV (2014)
Temperature Control is Critical!

Soot Collects Along the Inlet Walls
Particulate Matter or Soot

Cells Fill Up
Clean Exhaust Out (CO₂, H₂O)

Regenerating
Passive
- Fuel Additives
- Catalyzed Filters
- NO₂ Catalyst + Filter

Active
- Engine Management
- Fuel Combustion
- Electrical
- Other

Passive-Active Combinations
- Fuel Burners
- Catalytic Fuel Combustion

Disposable

Problem Zone
In > Out

Flow

Soot Rate (g/hr)
Soot Removed
Soot Collected

Engine Load

Cracked DPF Damaged Due To Exothermic Reaction Melted DPF
Cat Regeneration System Overview

Hardware Overview:

- Air Valve
- Turbos
- Exhaust
- Air Line
- Fuel Manifold
- Fuel Pump
- Coolant
- CRS
- Spark

Caterpillar: Non-Confidential
Regeneration Optimization

- CRS Heat Required
  - \( Q = m \times (T_{\text{target}} - T_{\text{exhaust}}) \)

- 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
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
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

3 to 6 mins

~ 2 hrs

~ 6 hrs
Simulation Tools

CATERPILLAR®

PROCESS DATA
- Matlab
- Simulink
- Parallel Computing Toolbox

Field Data

Engine Configuration Data

CORSICA
- 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

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

Control Calibration

Test Cycle

Control Output

Feedback

Simulation Results

Data Analysis
Matlab DatK

Model Improvement

CORSICA

ENGINE AFTERTREATMENT MODEL
Dynasty - In House Modeling SW

CAT ECM

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

Software

Production Software

Caterpillar: Non-Confidential
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
• 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
Tier 4 Interim Results

• 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

Monument Pass, Colorado
High Speed Operation
10,000+ feet
-40 C
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
Regulatory Challenges:
- Near-zero targets
- NOx and PM are inversely related

SCR (Selective Catalytic Reduction)
Aftertreatment Required To
Meet Tier 4 Final NOx Regulations
"Standard" SCR reaction

\[ 4\text{NO} + 4\text{NH}_3^* + \text{O}_2 = 4\text{N}_2 + 6\text{H}_2\text{O} \]
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
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
> 560 KW Engine Requirements

- **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

CORSICA

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SOFTWARE DEVELOPMENT
Matlab
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V&V Toolbox

ADDED SCR MODELS TO CORSICA

Control
Calibration

Production Software
HIL
Matlab
Simulink
StateFlow
Embedded Coder
Matlab Coder
Simulink Coder

Hardware In The Loop Testing

CAT ECM

Engine
Test Data

Field
Data

Engine
Configuration
Data

Model
Improvement

Simulation
Results

Data
Analysis
Matlab
DatK

Control
Algorithm

Test Cycle

Software

Software

Control
Output

Feedback
Tier IV Final > 560 KW Engines

• >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

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

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