CATERPILLAR®

Validation of Aftertreatment Temperature Requirements Using MathWorks Tools

2014 MathWorks Automotive Conference

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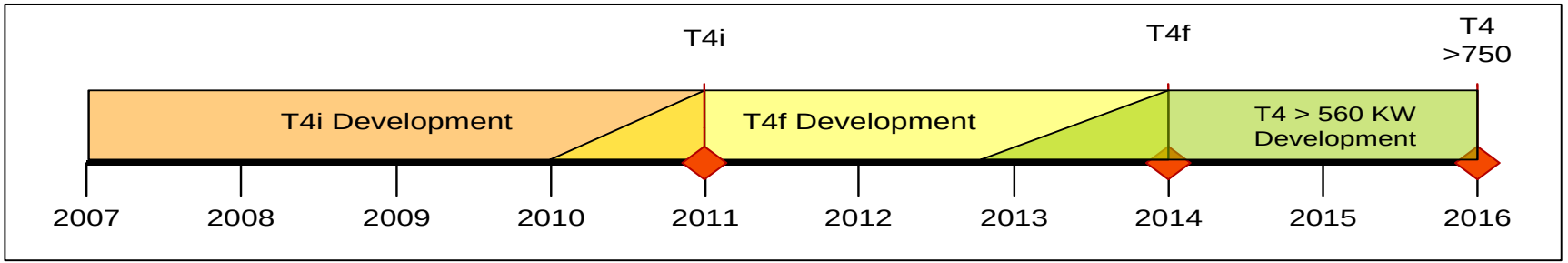
Agenda

- 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**

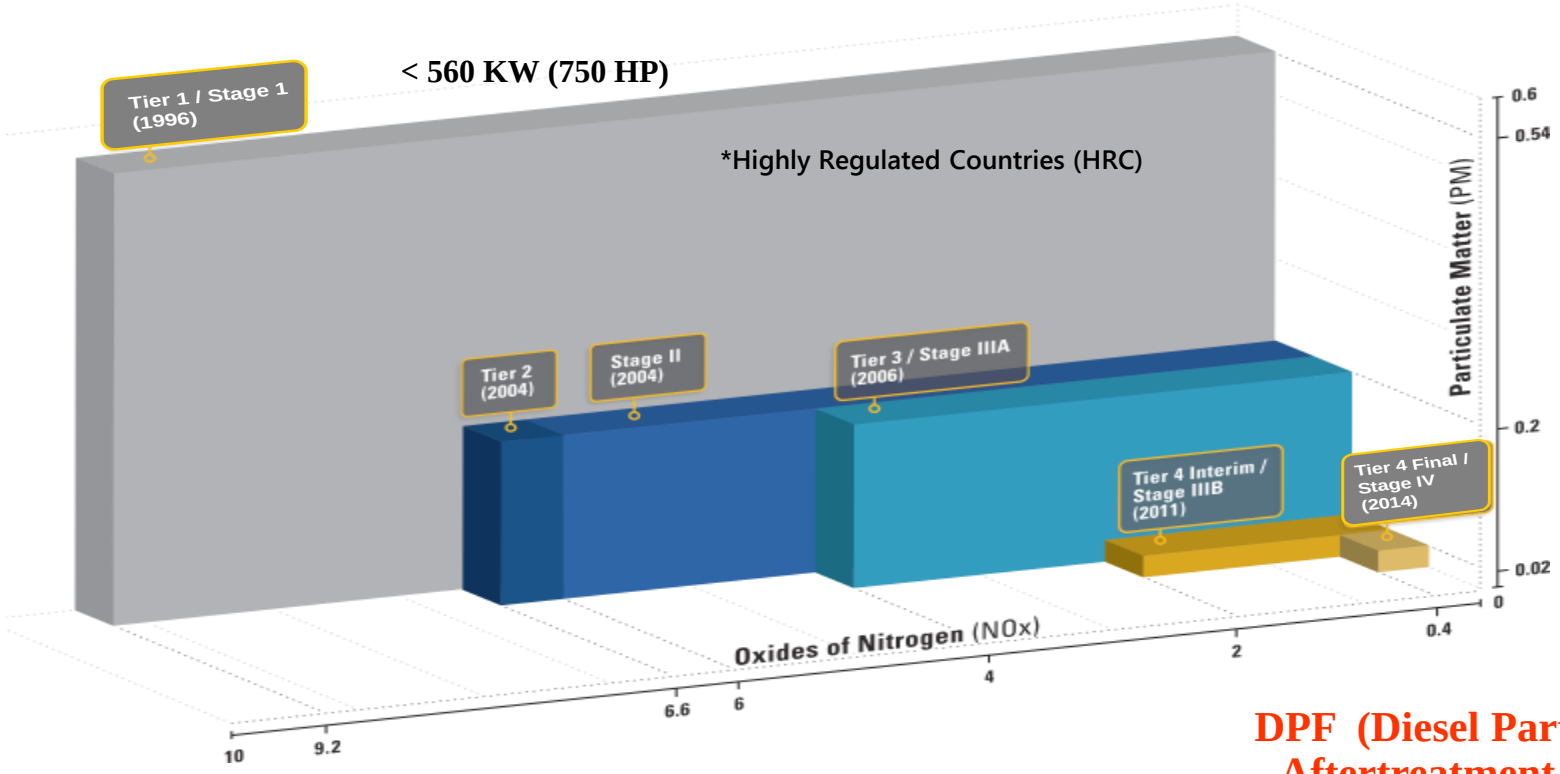
Introduction

- 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

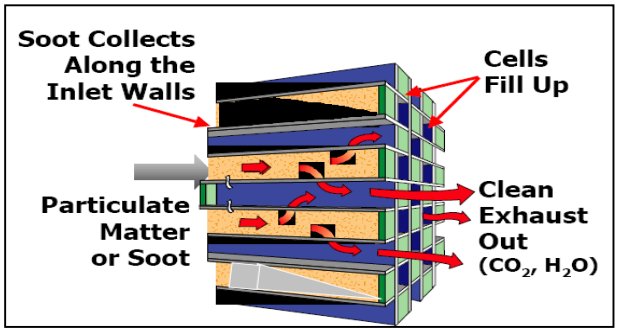


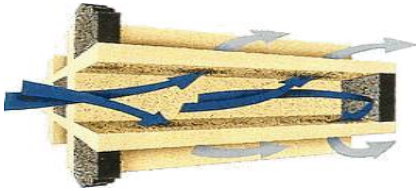
Regulatory Challenges:

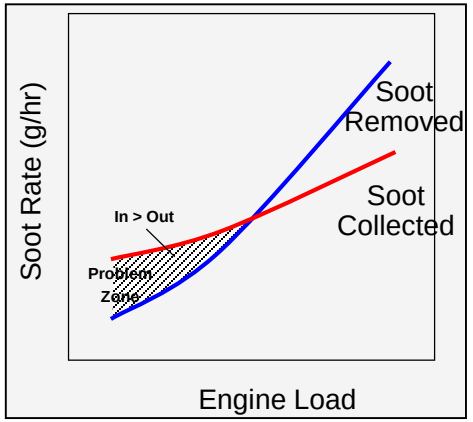
- Near-zero targets
- NOx and PM are inversely related

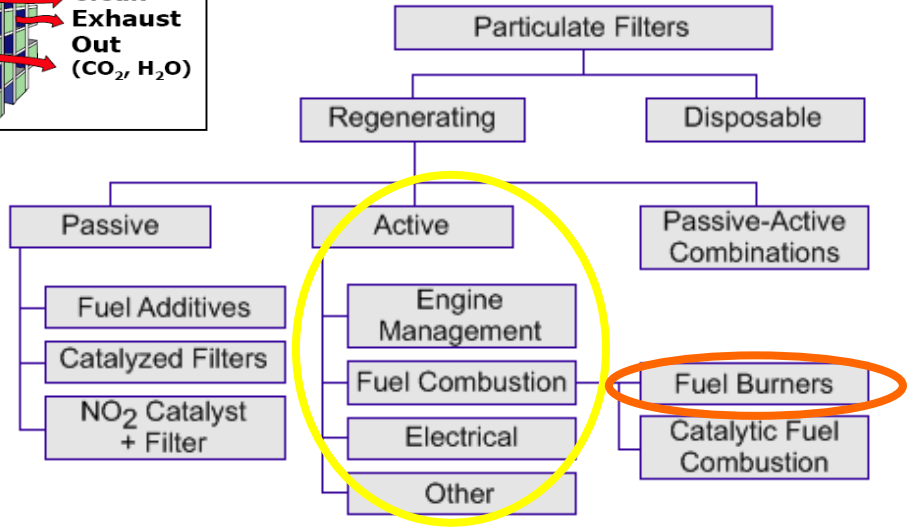
DPF (Diesel Particulate Filter) Aftertreatment Required To Meet T4i Regulations

DPF Regeneration Technology

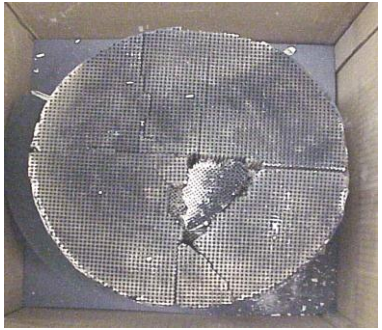


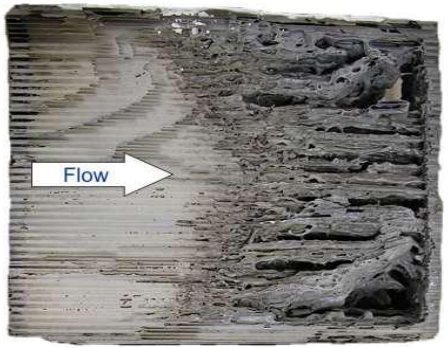






Temperature Control is Critical!

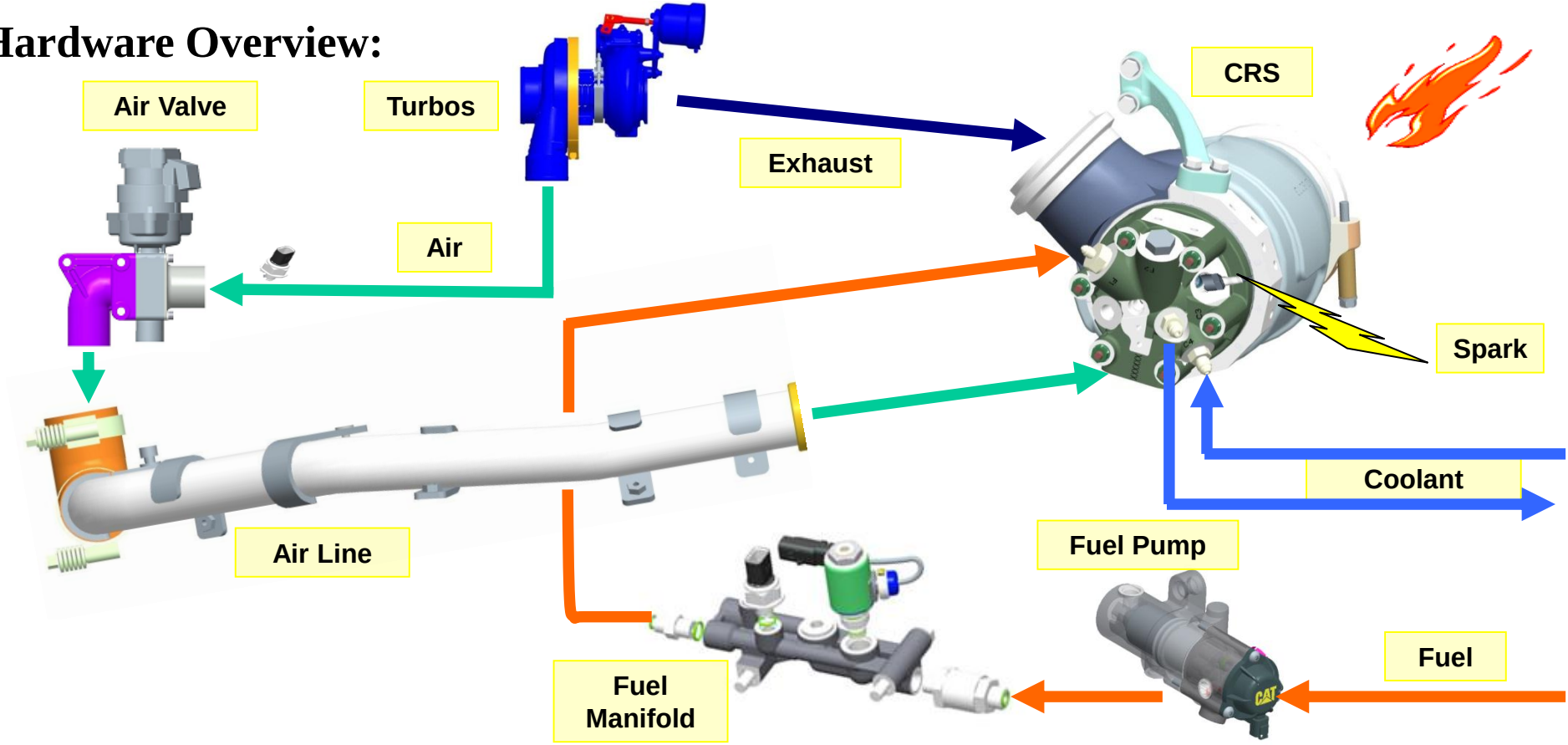




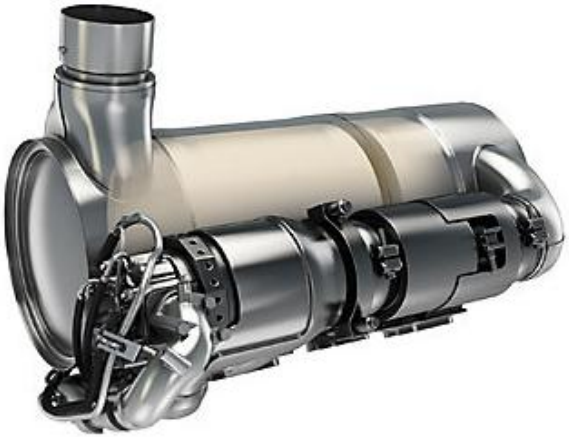
Cracked DPF ← **Damaged Due To Exothermic Reaction** → **Melted DPF**

Cat Regeneration System Overview

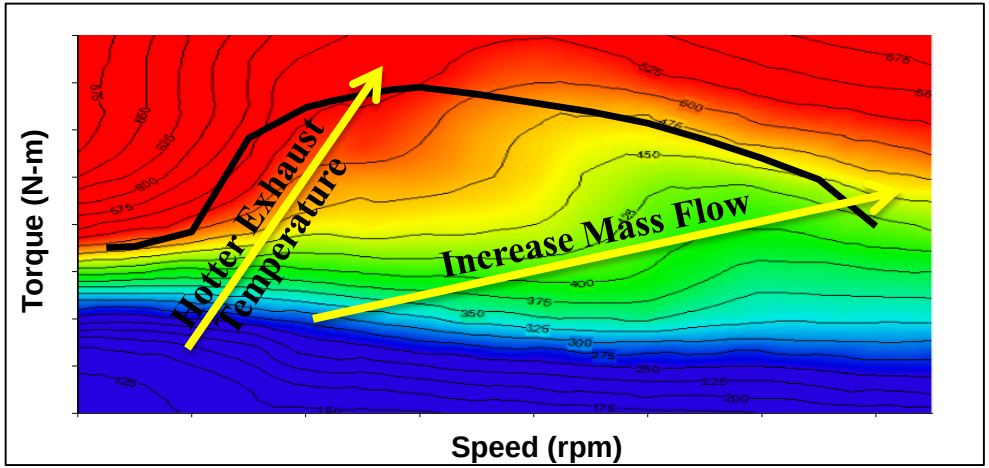
Hardware Overview:



DPF With Cat Regeneration System

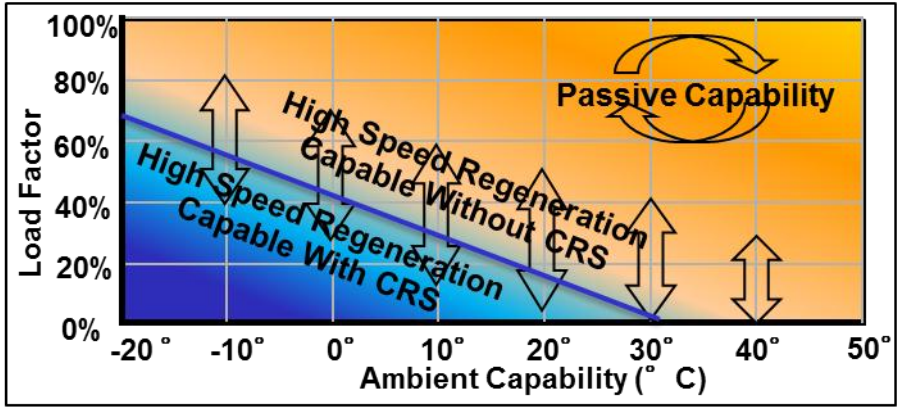


Regeneration Optimization



- CRS Heat Required
  - $Q = \dot{m} * (T_{target} - T_{exhaust})$
- 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

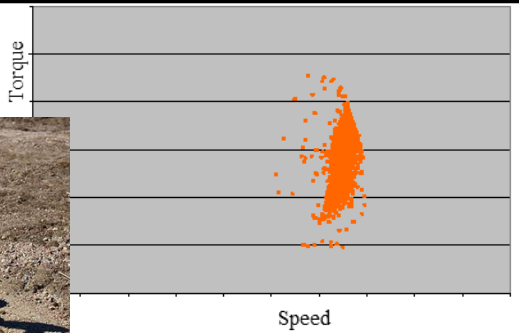


Regeneration Requirements

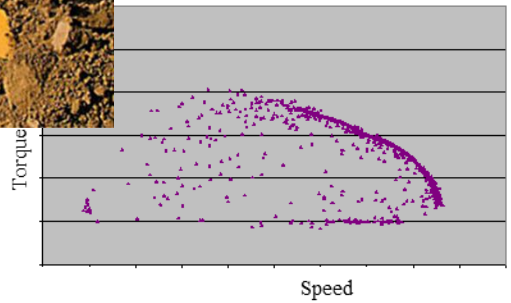
- **Integration With Cat® Machines**
  - Vertical Integration With Machine Controls
  - Improve Machine Performance Over Tier 3
    - Increased Productivity
    - Lower Life-cycle Cost
    - Improved Fuel Economy
- **Robust Operation**
  - No Operator Intervention/Interruption Or Productivity Loss
  - 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

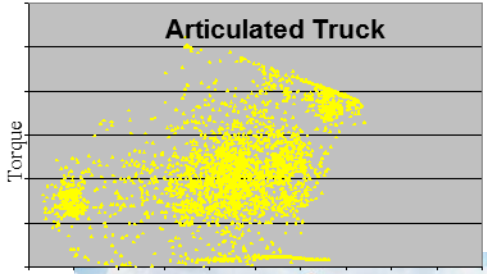
Machine Work Cycles

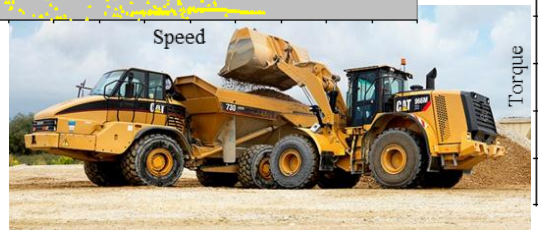
Hydraulic Excavator



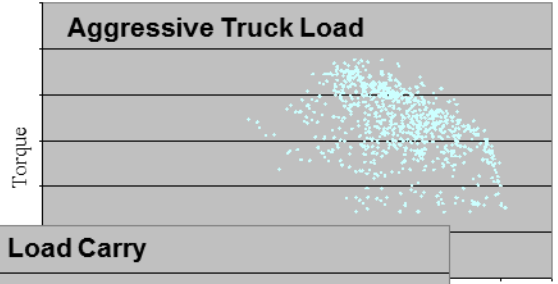
Tracked Type Tractor

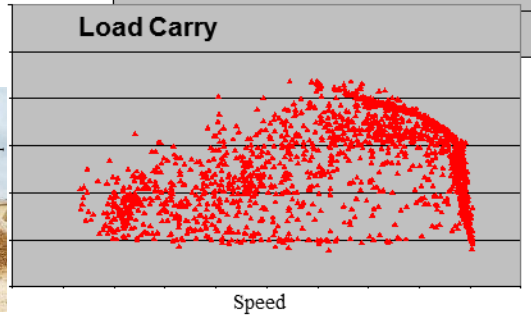




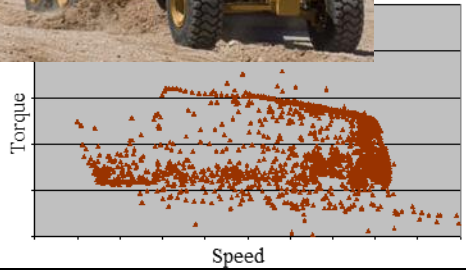


Medium Wheel Loader

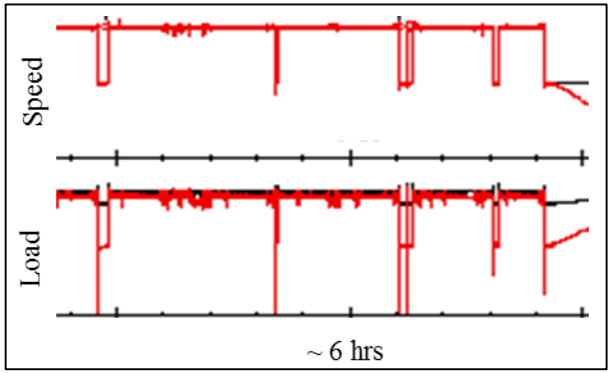


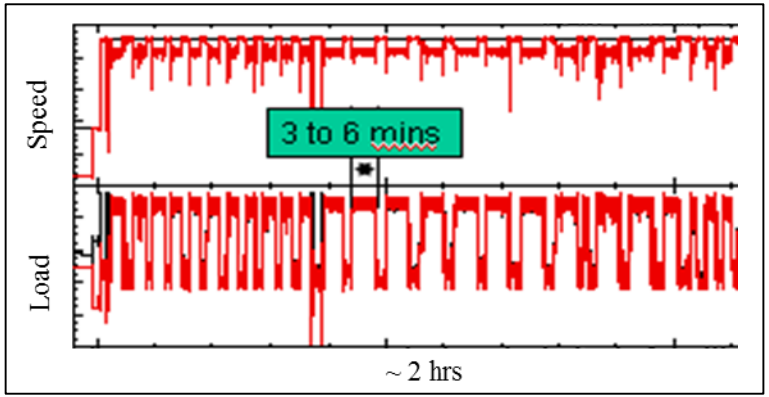


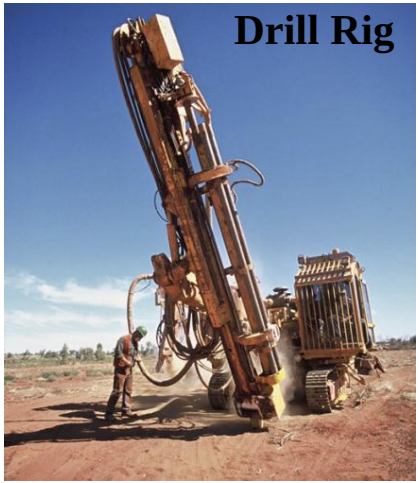
Motor Grader



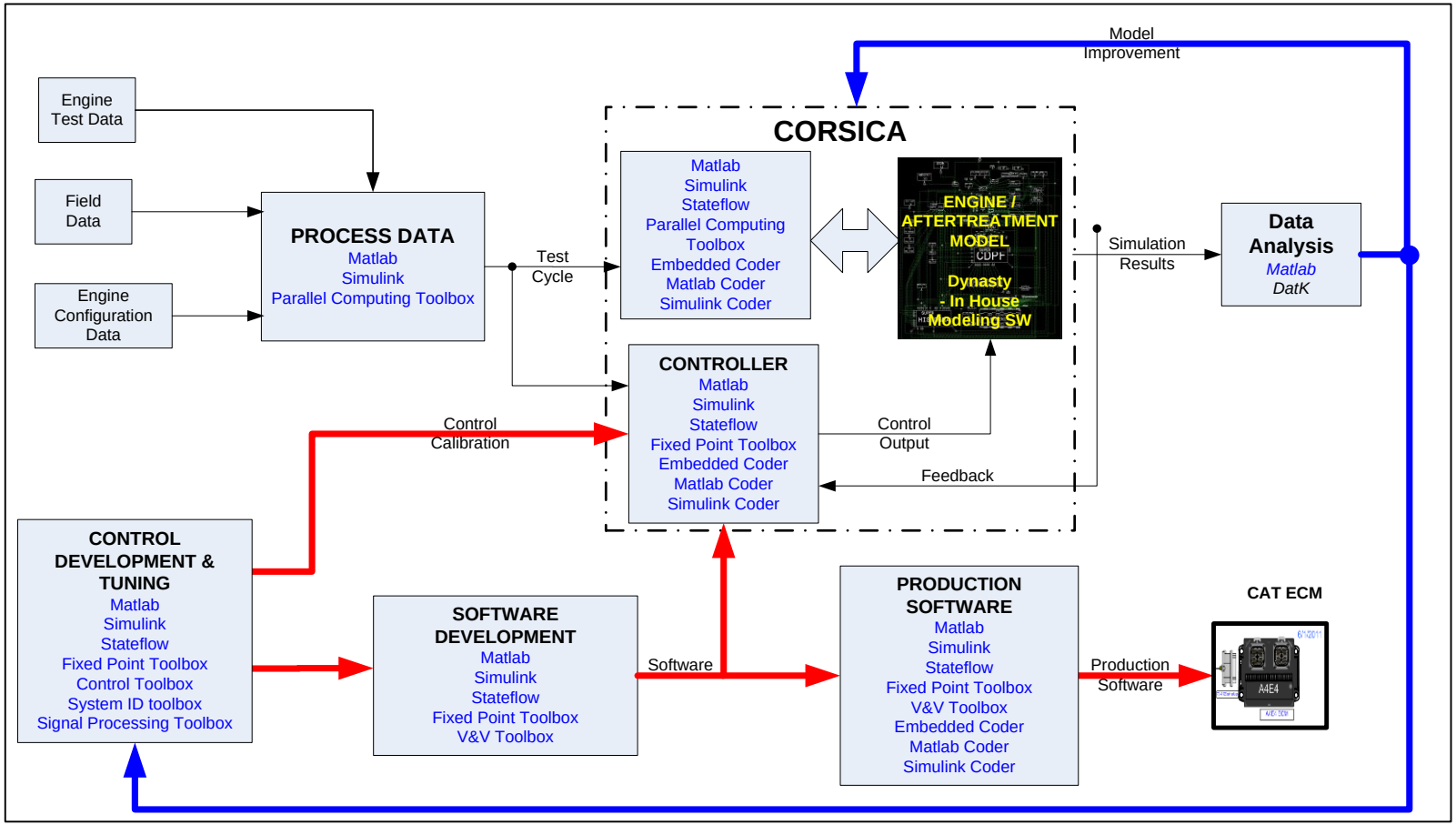
Industrial Work Cycles



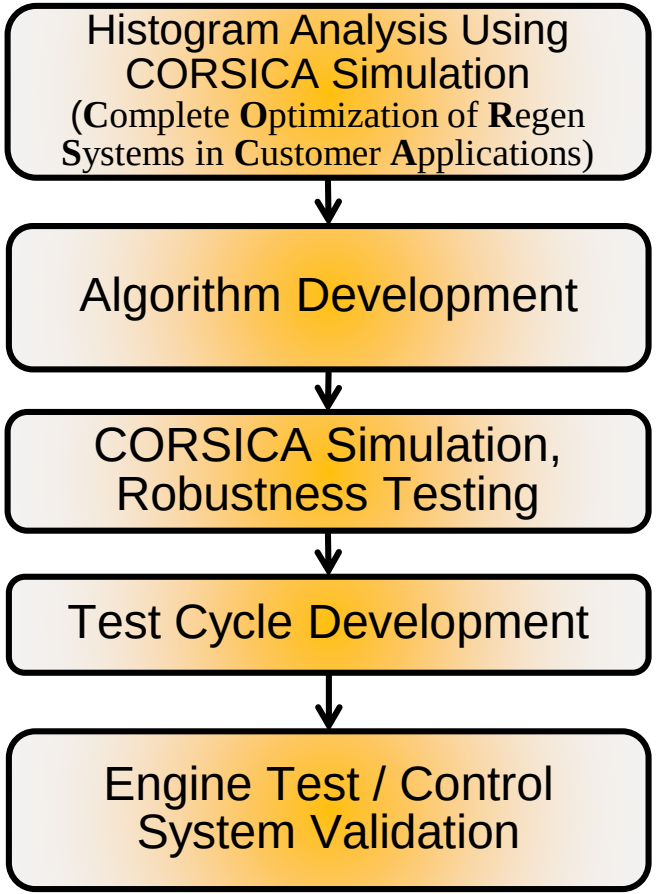




Simulation Tools



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

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

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

Industry Leading Productivity

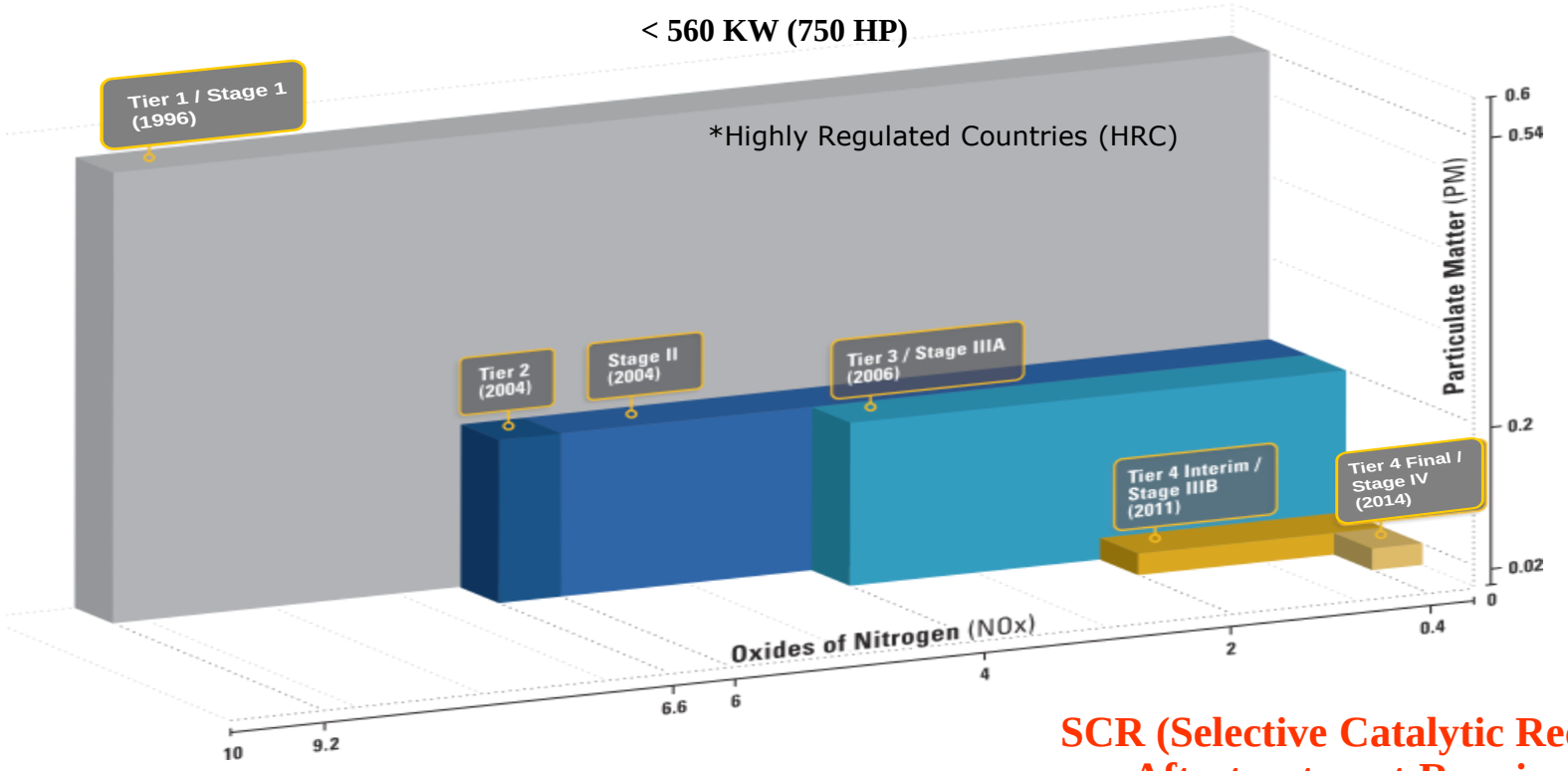
Customer Feedback:

- 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

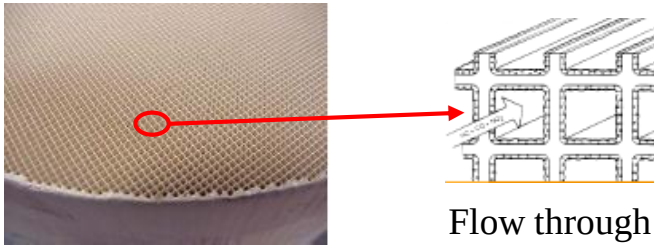


Regulatory Challenges:

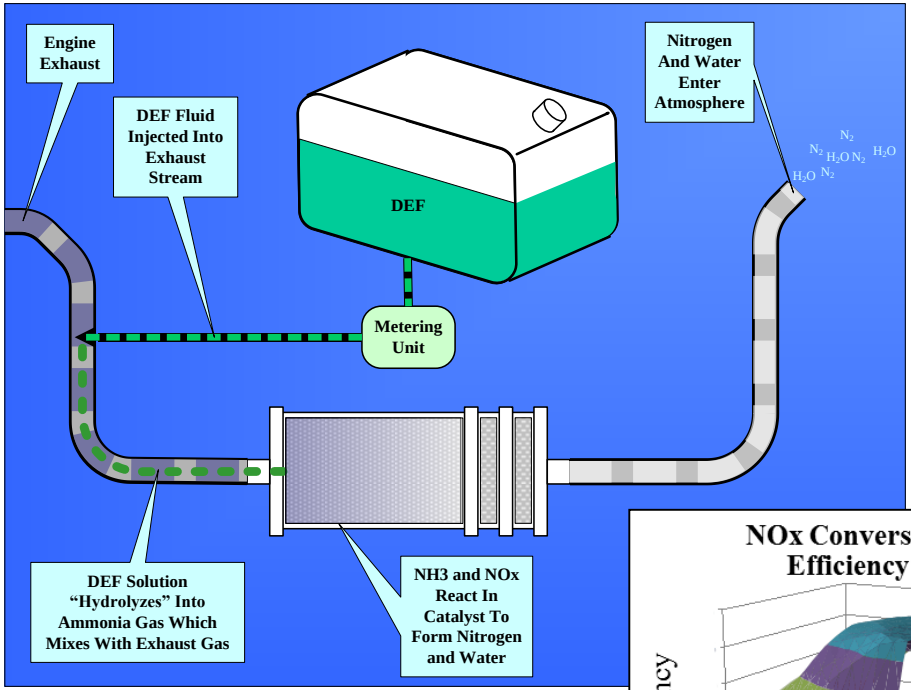
- Near-zero targets
- NOx and PM are inversely related

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

Selective Catalytic Reduction (SCR)

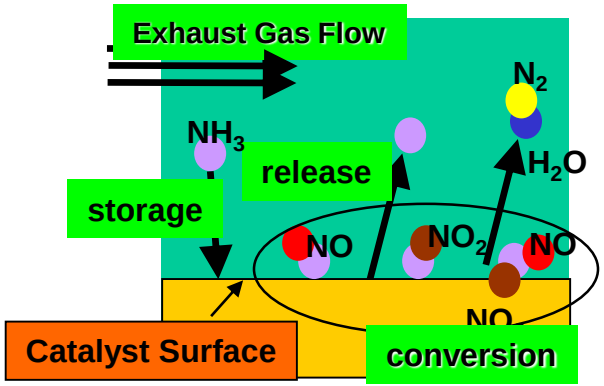


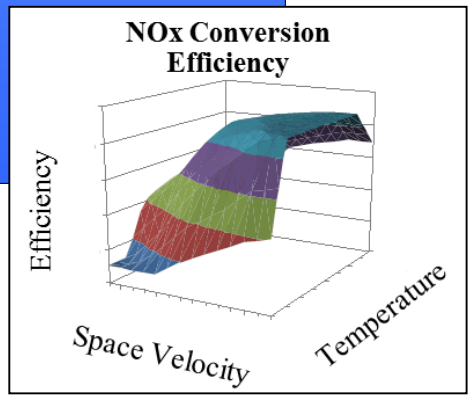
Flow through substrate



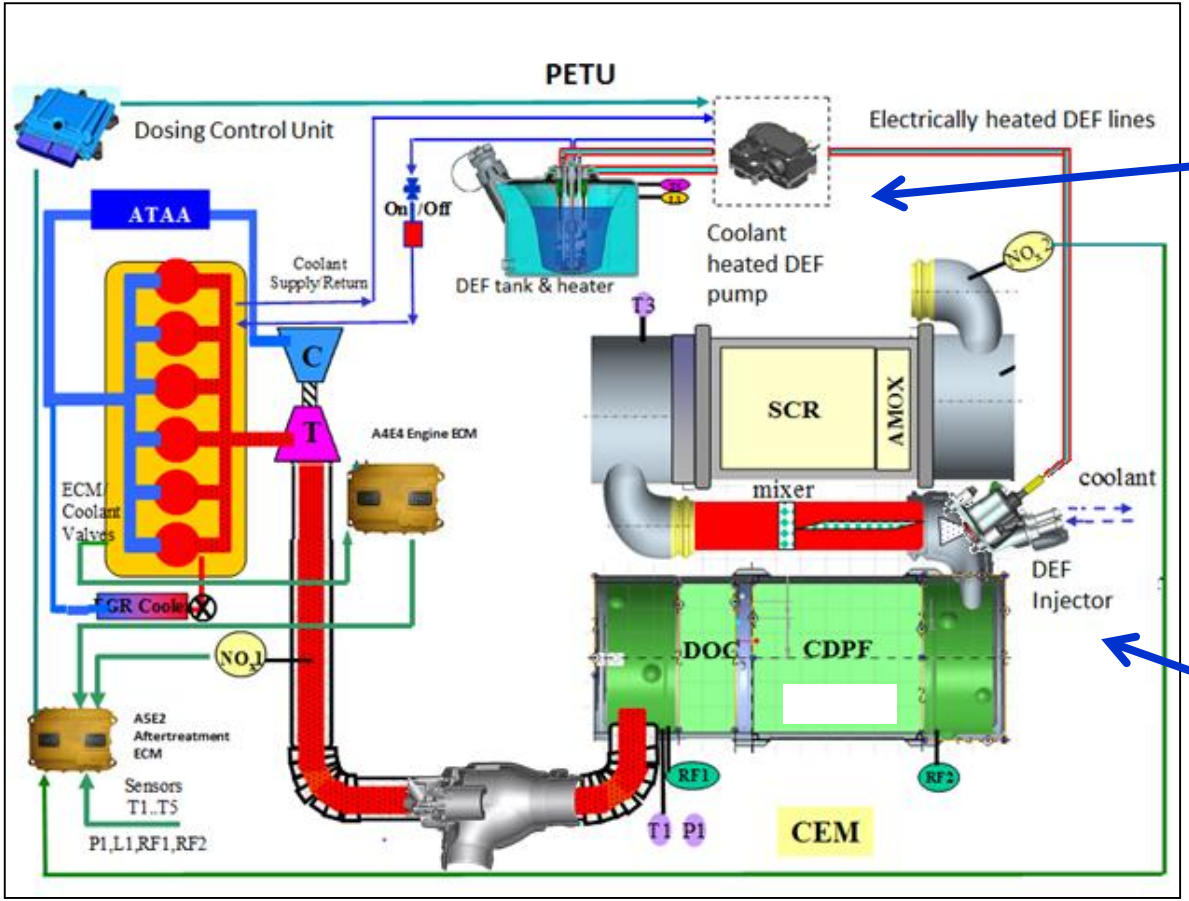
"Standard" SCR reaction

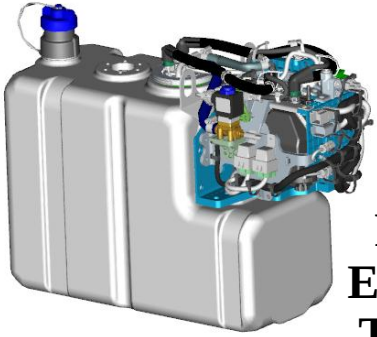
$4NO + 4NH_3^* + O_2 = 4N_2 + 6H_2O$





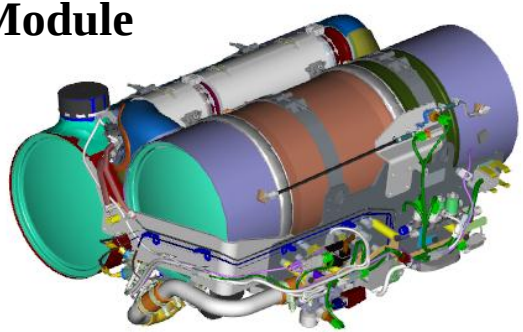
DEF System Overview





Pump & Electronics Tank Unit

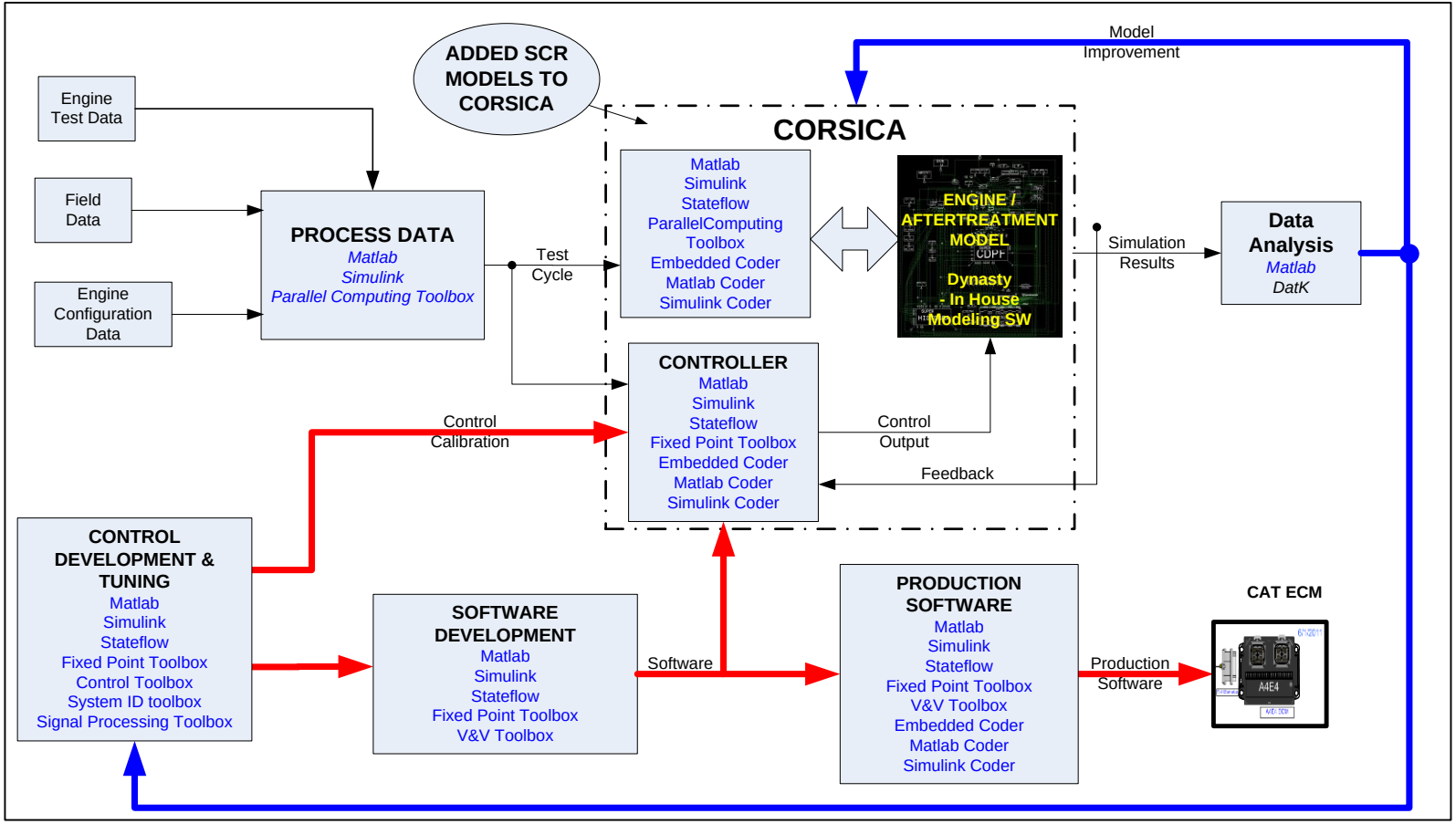
Clean Emissions Module



Tier 4 Final Requirements

- **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

Simulation Tools



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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

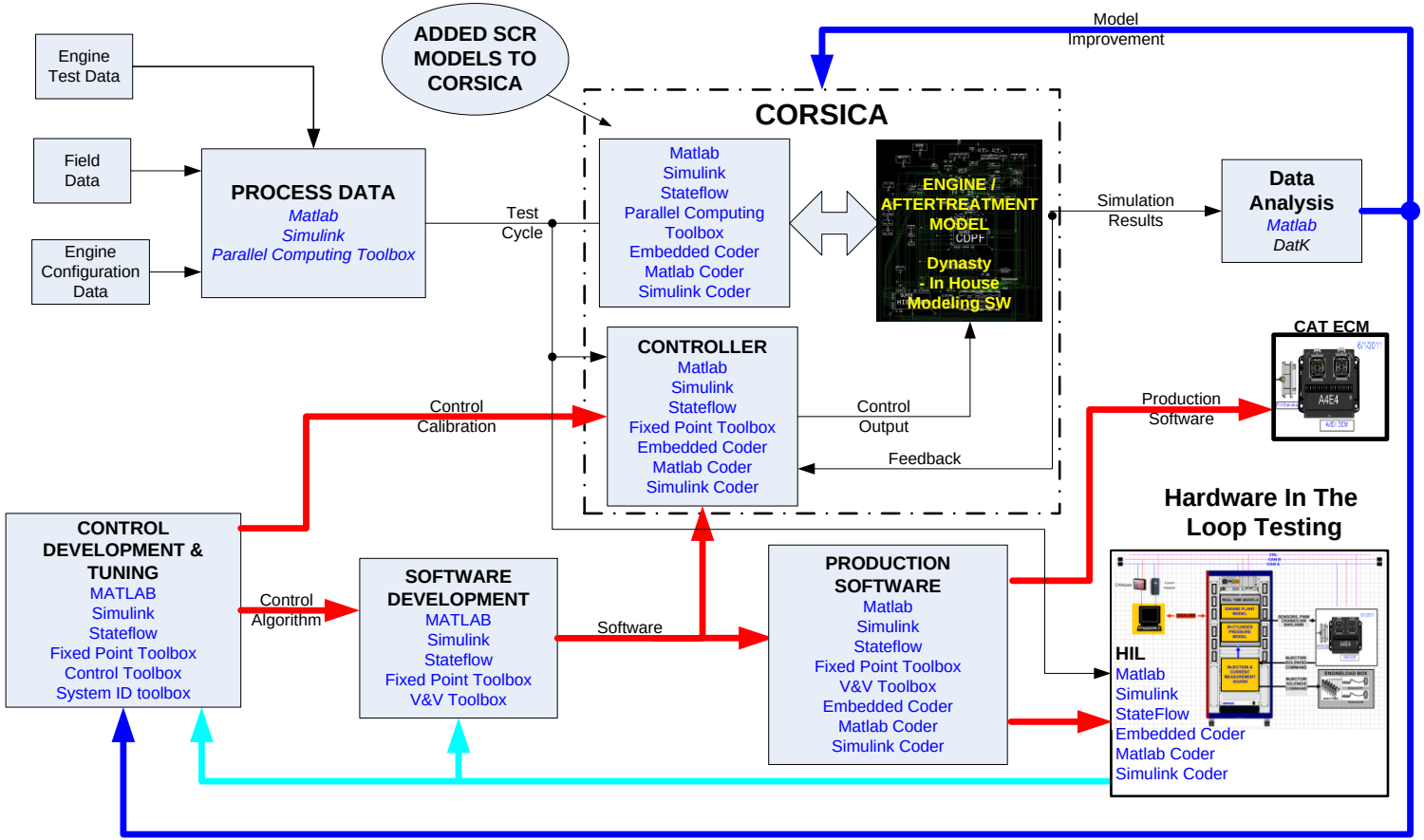
- **Emission Requirements**
  - Regulations Based on Application
  - Site Regulations Can Be More Stringent
- **Engine System Requirements**
  - No Operator Intervention/Interruption Or Productivity Loss
  - Robust To Steady State And Transient Work Cycles
  - Robust To Environmental Conditions (Altitude, 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



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

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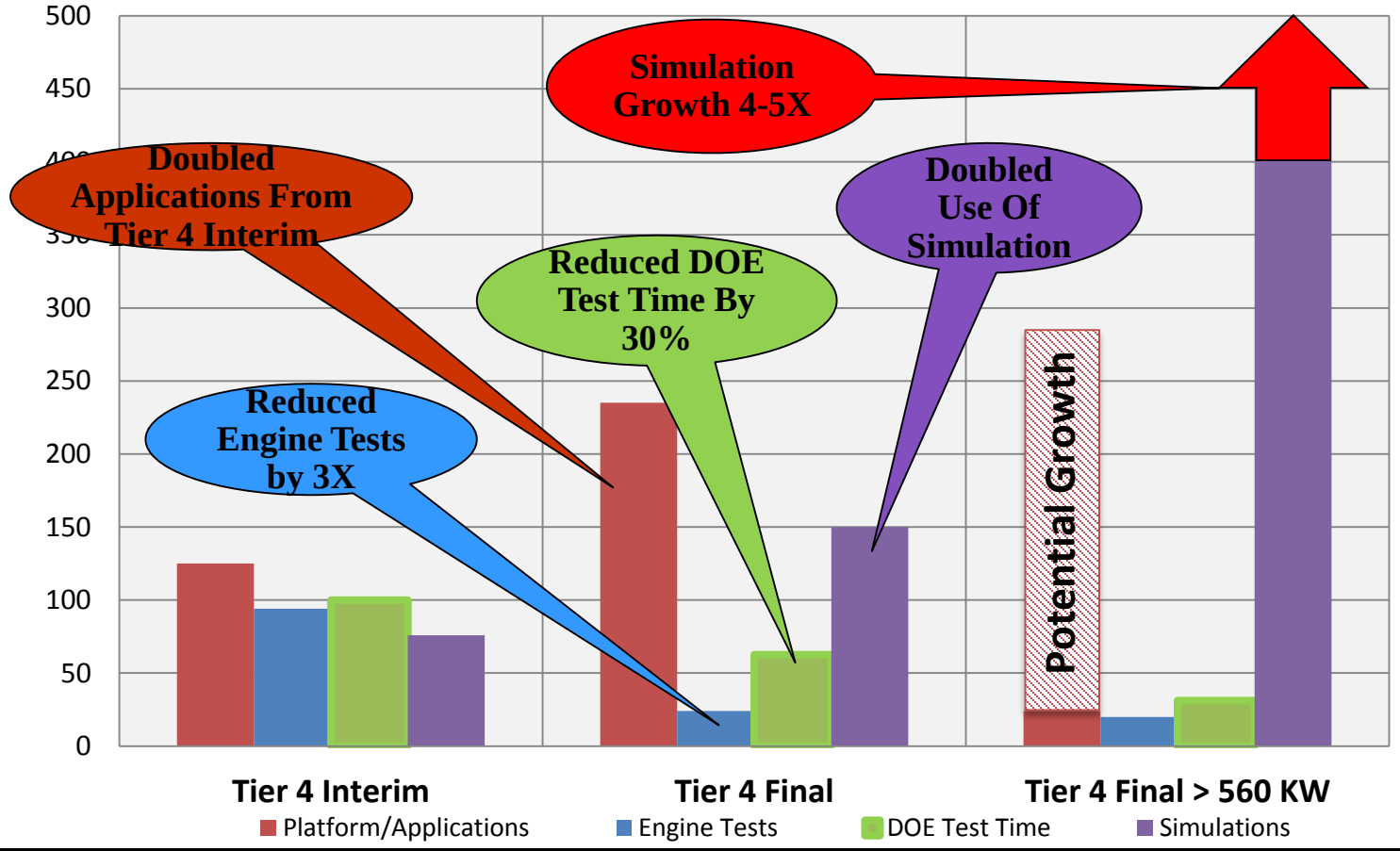
Simulation Process Benefits



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