Off-Highway Heavy Vehicle Diesel Efficiency Improvement and Emissions Reduction

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Program Overview

Off-Highway Deliverables

Phase I (Tier 3)

- Model Development & Validation
- 3.0 g/(hp-hr) NOx + NMHC
- 0.15 g/(hp-hr) PM
- Tier 2 BSFC

Complete

Phase 2 (Tier 3)

- Multi-cylinder Engine Validation

Same as Phase 1

Complete

Phase 2A (Tier 4)

- Customer requirements documents
- Assess Technical options
- Selection of Tier 4A technology
- 1.5 g/hp-hr NOx
- 0.015 g/hp-hr PM
- Transient certification
- Tier 3 BSFC

In-Progress

Possible Emission Solutions for Tier 4 Interim

Starting Point: Tier 3 Advanced In-Cylinder Emission Control

+

NO_x

- Cooled EGR
- Selective Catalytic Reduction
- Oxygen Membranes
- Combustion Recipe Optimization

+

Particulate

- Oxidation Catalyst
- Soot Filter
- Partial Filter
- Fuel injection strategy
- Combustion Recipe Optimization

Primary Objective: Meet future off-highway emissions requirements while maintaining current fuel economy levels

Increasingly More Stringent Emissions Requirements
Increasing # of Applications/Customer Requirements
Short Development Time

Cummins New Approach to Technology Development

Selecting the Right Technology – A Six-Sigma Based Approach

Invent/ Innovate

Understand Customer Requirements

Balance VOC & VOT with Business/Prod. Line Goals…

Develop

Leverage Analysis Led Design

Develop & Model Critical Parameters…

$$Y = f(x_1, x_2, x_3, x_4, \ldots x_n)$$

Optimize

Optimize Critical Parameters

TDFSS

Optimize Critical Parameter Robustness…

$$S/N(Y) = (S/N(x_1)+S/N(x_2)+ \ldots S/N(x_n))$$

Certify

Certify Capability

I^2DOC

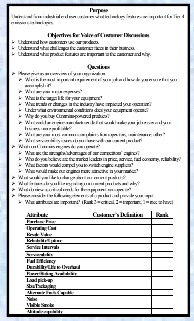
Certify Critical Parameter Capability…

$$Cp/Cpk(Y_1 , Y_2, \ldots Y_n)$$

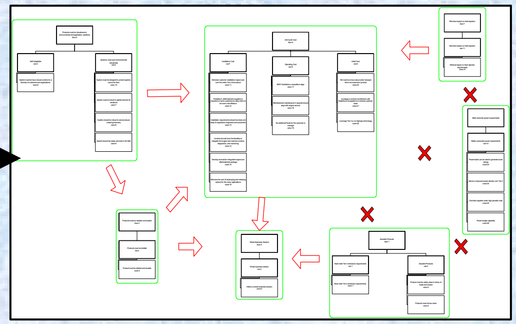
→ **Product Development**

Understanding Customer Requirements

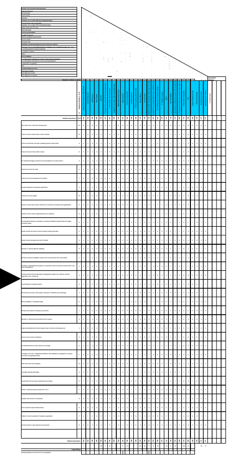
Customer Selection Matrix



Customer Discussion Guide

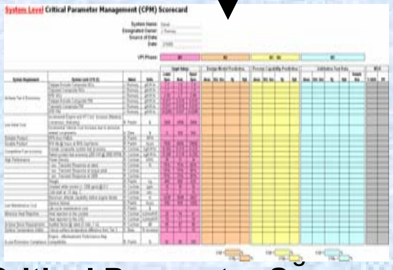


Requirements KJ



HOQ/QFD

CPM Flowdown

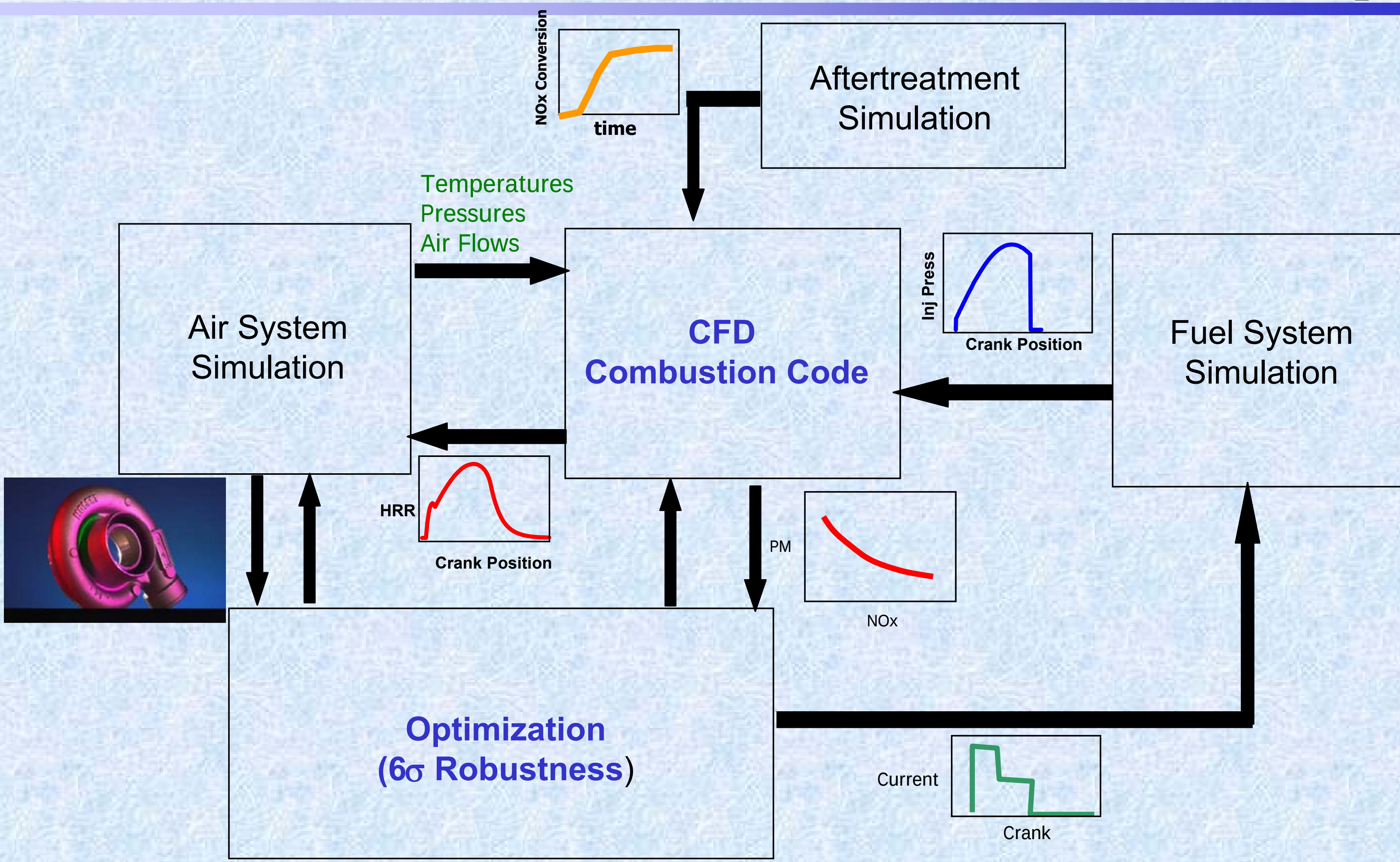


Critical Parameter Scorecard

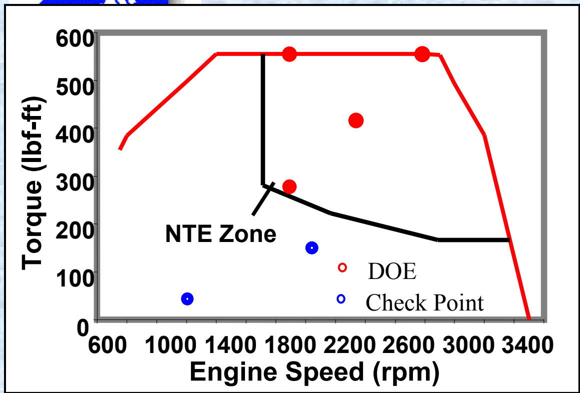
5 Basic Steps

1. Segmentation & Selection
2. Develop Discussion Guide
3. Collect the Voices
4. Translate and Classify Needs
5. Prioritize & Identify Measures

Leveraging Analysis Led Design in Combustion Design

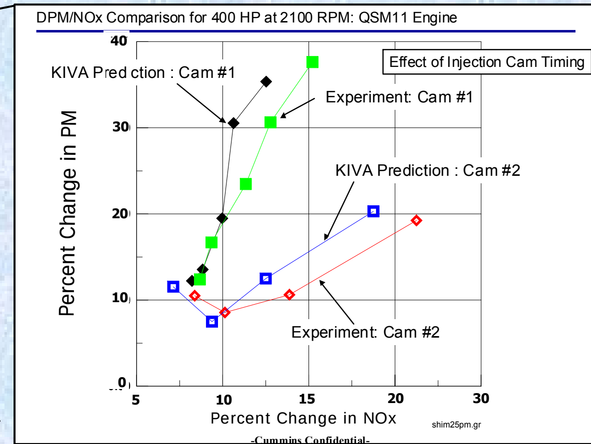


Combustion Design Process

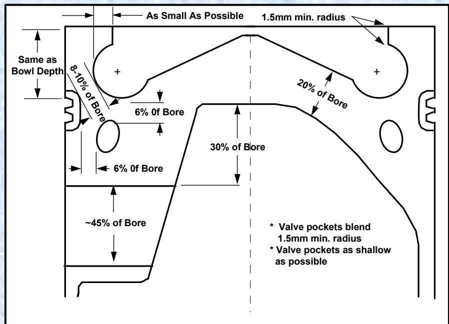


Select Operating Points Representative of Duty Cycle

Perform Baseline Calculations at Each Operating Point (Model Validation)



Determine Physical Constraints



Perform Fixed Bowl DOEs

Percent Change in NOx

Does Combustion Recipe Meet Emissions and Fuel Consumption Requirements?

No

Yes

Provide Recommendation for Hardware Procurement

Engine Testing

Compare Engine Results to Predicted (Model Validation)

Does Combustion Recipe Meet Emissions and Fuel Consumption Requirements?

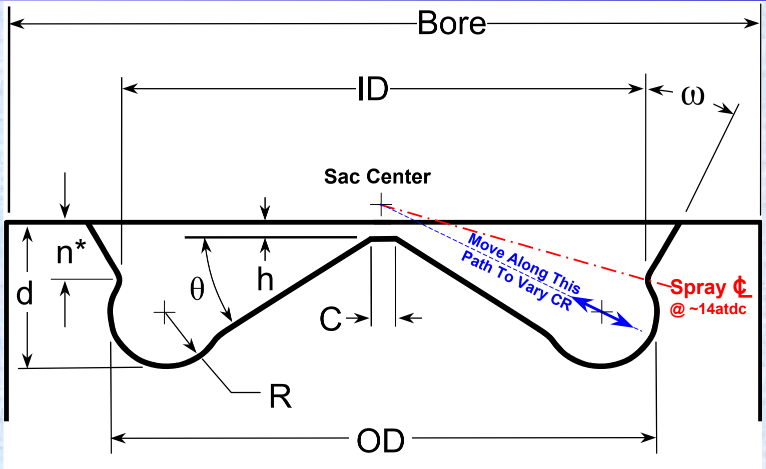
No

Yes

Progress to Engine Calibration

Combustion Design of Experiment Parameters

Bowl Parameters :



DOE Parameters for HPCR

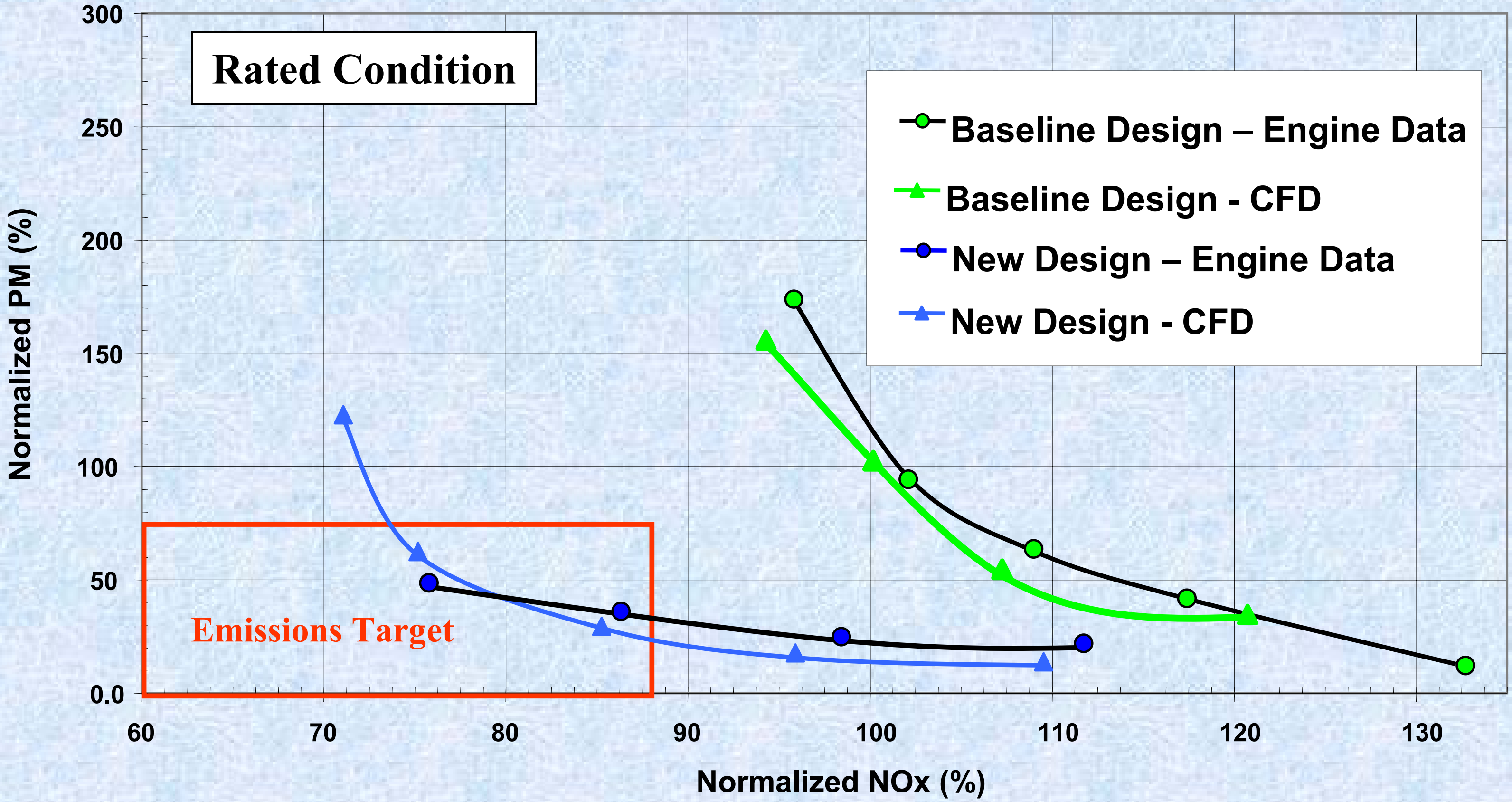
- Spray Angle
- SOI
- Injector Protrusion
- Nozzle Cup Flow
- Swirl
- %EGR
- % AFM for Nozzle
- Squish Height
- Number of Nozzle Holes
- Injection Rail Pressure
- Number of Injection Pulses
- Quantity of Each Pulse
- Separation Between Pulses

→

Responses

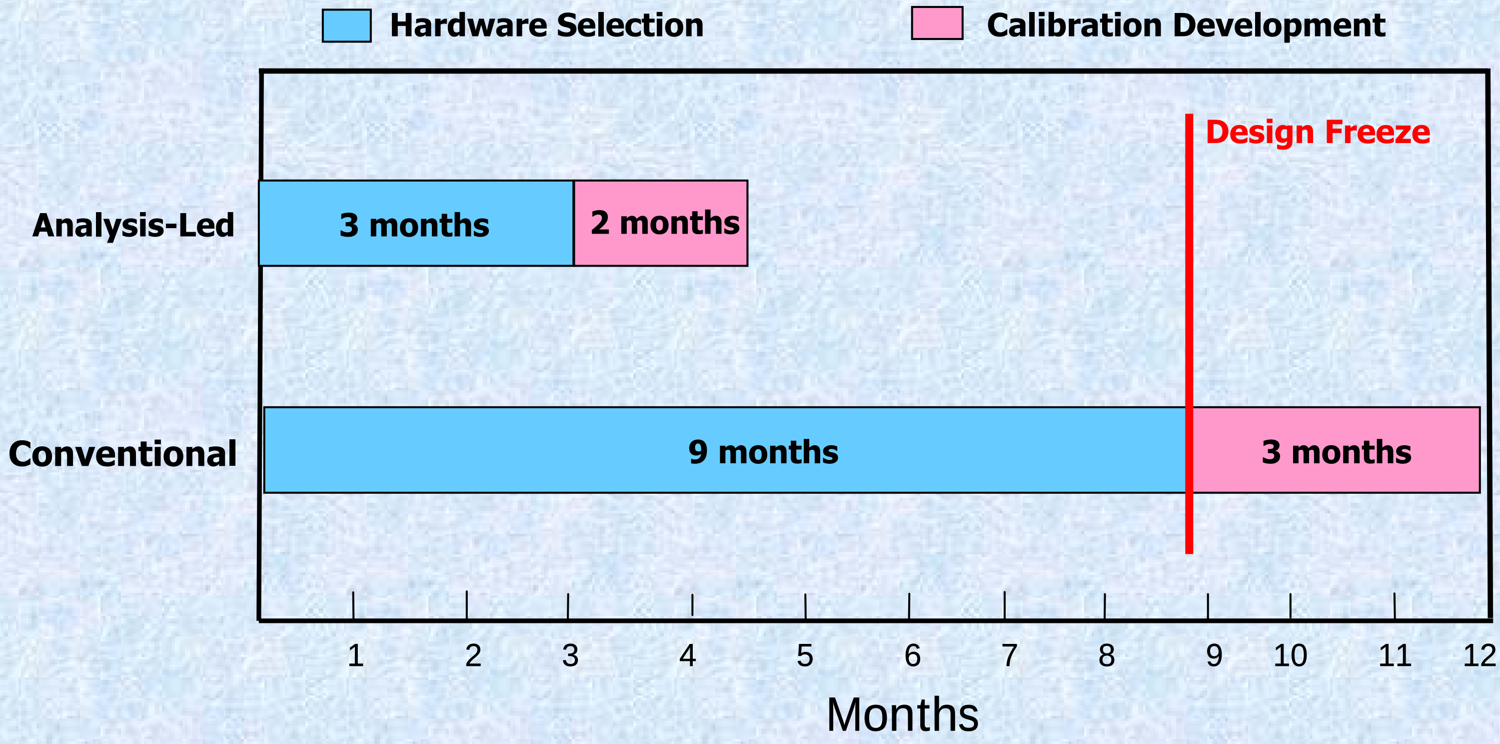
- PM
- NOx
- Lube oil soot
- gisfc
- Noise
- UHC
- CO
- PCP
- Turbine Inlet Temp
- Liquid impingement on the liner
- Surface heat flux
- Formaldehydes
- Heat rejection*

Combustion Model Validation

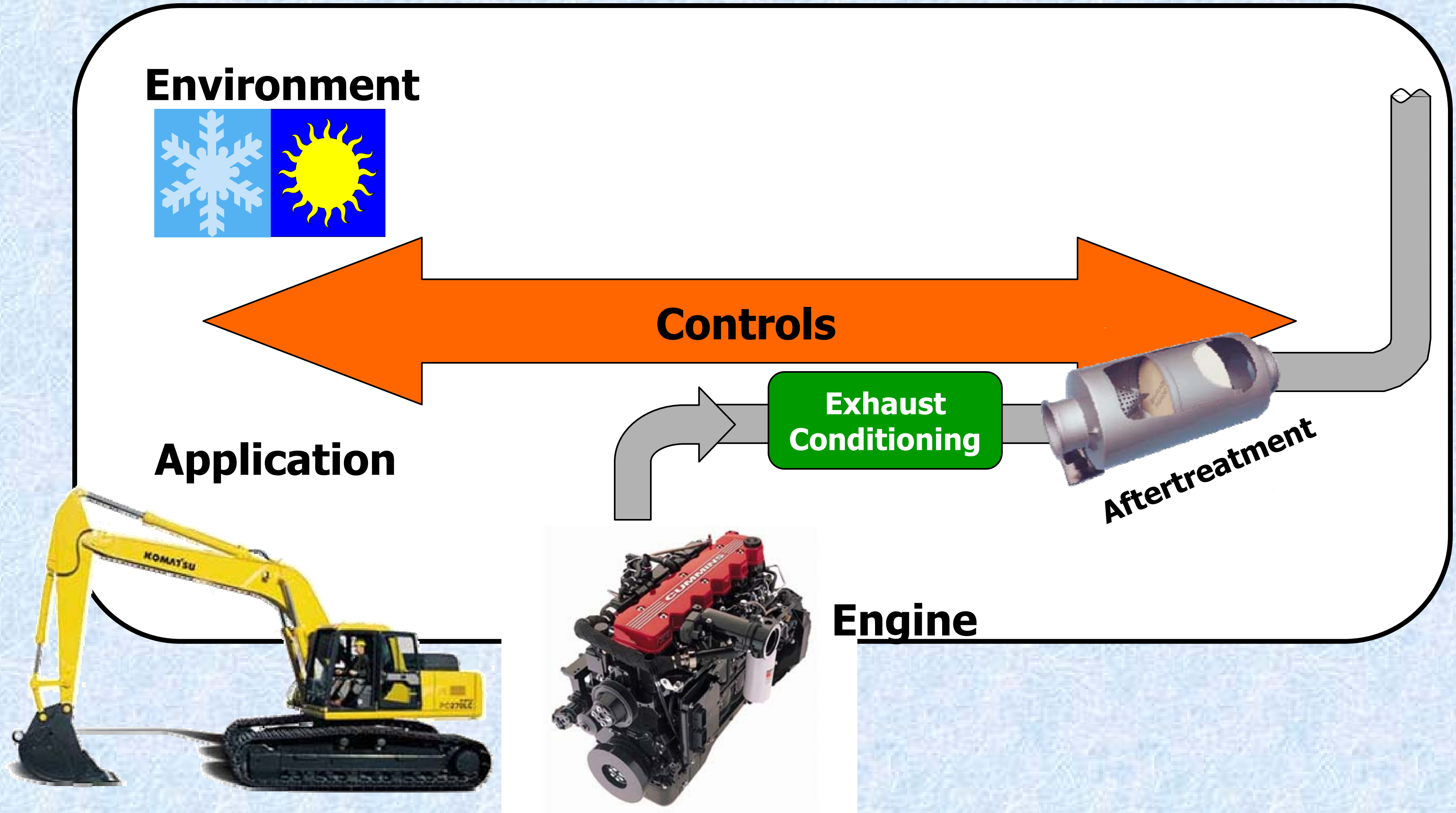


Impact of Analysis-Led Combustion Design

- Analysis led design reduces hardware selection time
- Explore a larger design space
- Increased ability to optimize fuel economy
- Tailor technology to customers' needs
- Substantial cost avoidance has already been realized



Optimize Critical Parameter Robustness – System Integration



Optimize Critical Parameter Robustness

- Understand the subsystem interactions
- Understand environment & application variations
- Optimize system for best fuel economy
- Design for system robustness

Optimize Critical Parameter Robustness – CyberApps System Modeling Tool

CyberApps (Application)
- Environment
- Route
- Vehicle / Test Cell
- Simulation Control
- Simulation Analysis
- Engine
- Application Cooling System

MODEST (Engine)
- Air Handling
- Power Cylinder
- Emissions
- Cooling System
- Lubricating System (future)
- Controller
- Aftertreatment
- Fuel System (future)

Application Cooling System

Controller
- Machine Layer Governor Controls
  - Engine Layer Controls
    - Engine Subsystem Controls

Aftertreatment
- Individual Aftertreatment Components

Fuel System (future)

Matlab/Simulink Based

Conclusions

- More stringent emissions standards & increasing pressures to maintain fuel economy while minimizing impact on cost and customer application drive the need for a new approach to technology development
- Cummins is leveraging Six Sigma and Analysis-led design to develop the right technology for our customers
- Analysis results for Tier 4 Interim are promising –> opportunities to maintain or improve Tier 3 fuel economy

Cummins Inc. thanks –

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