System and Architecture Approach to Enable Diesel Engine Emission Reductions

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Outline

Look Back of Diesel Engines for Off-road

Engine Development to Enable Emission Controls

Past Examples of System Interactions and Lessons Learned

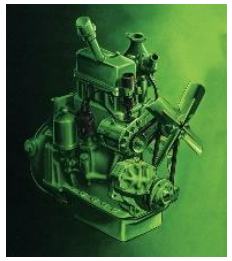
System Engineering and Model Based Development (MBD)

New Examples of MBD for Concept Architectures

Summary

Diesel Engines have Powered Off-Road for 70+ Years

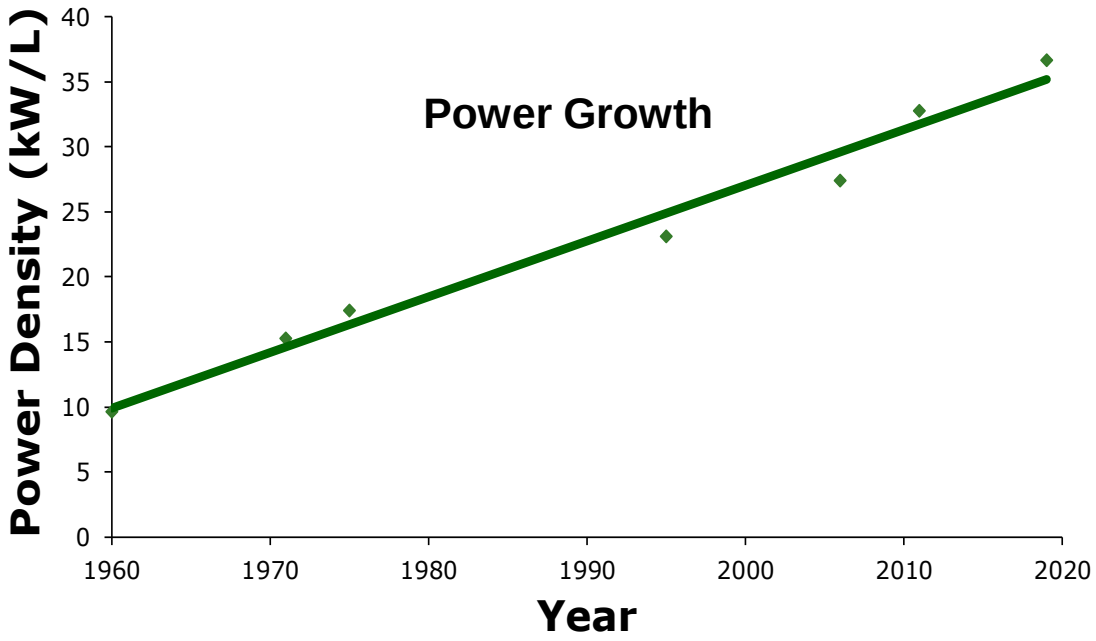
Customer Benefits: Durable, Reliable, Efficient, Low Speed Torque, Safe…

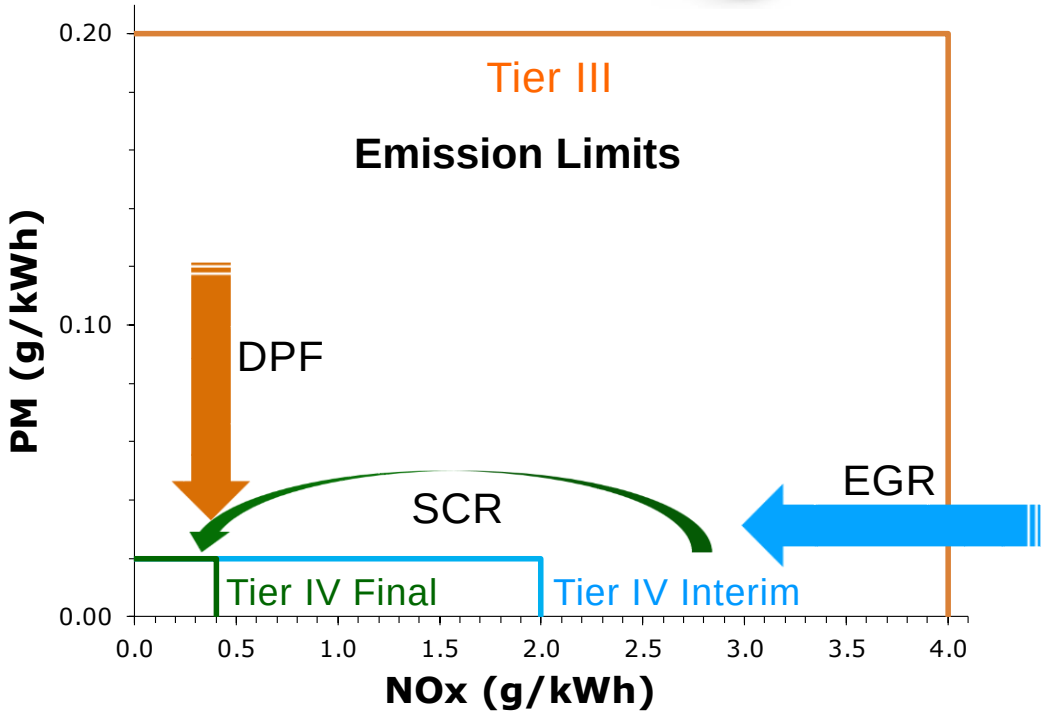


1949

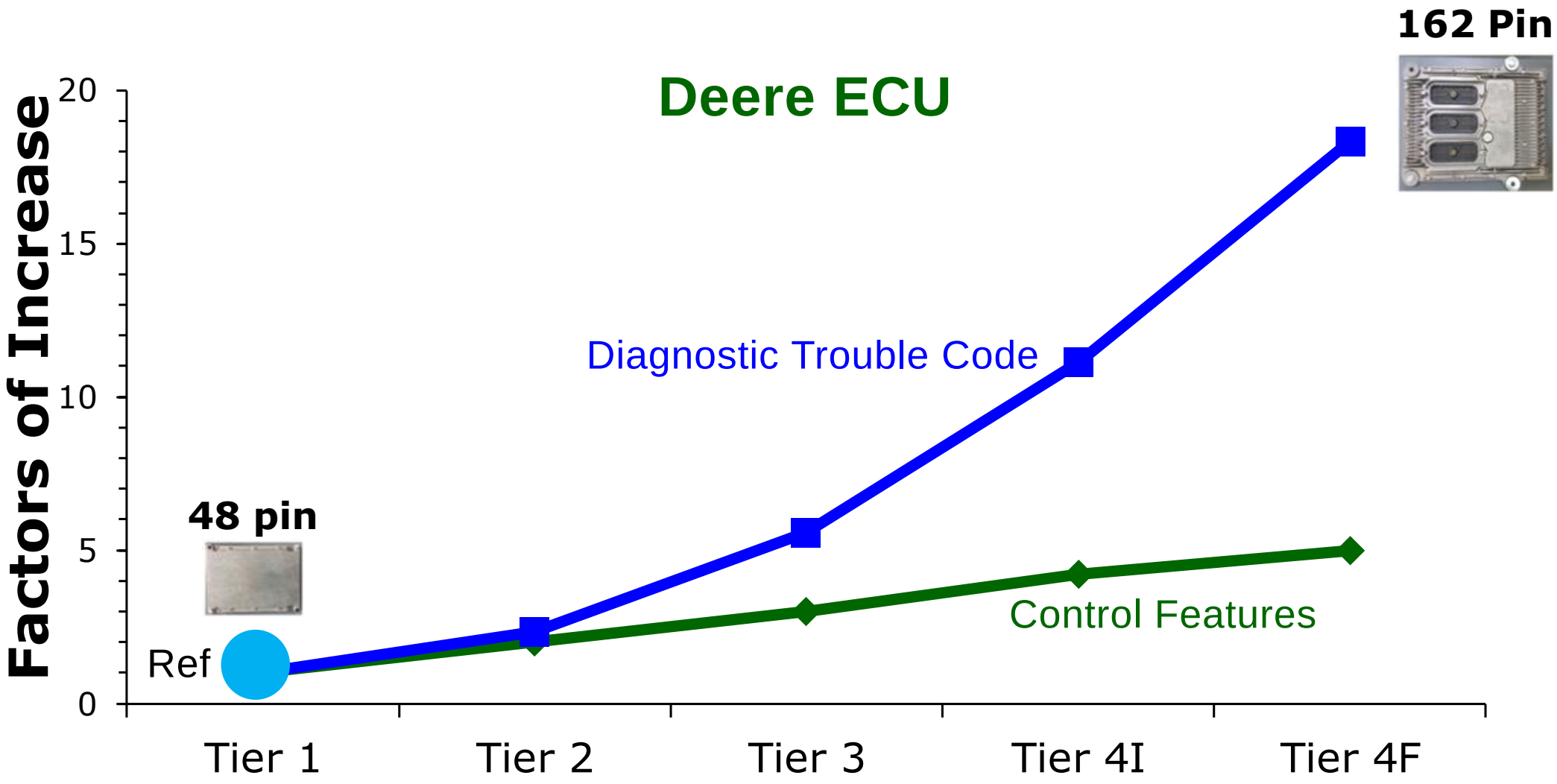
Technology Drivers: power, fuel consumption, emission

Turbo	Electronic	HPCR	EGR/VGT	DPF/SCR
1960	1988	2002	2006	2014





Rapid Growth of Electronic Controls Offers Application Flexibility, Performance Optimization, Engine-Protection and Service Assist



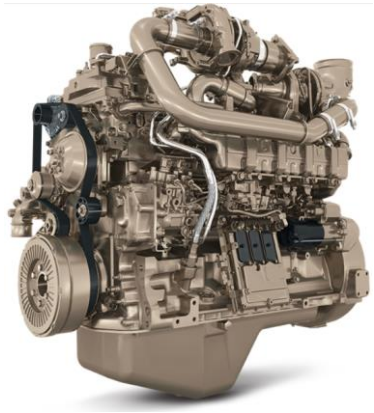
Diesel Engines Will Power Off-Road Machines for Years to Come

Engine Systems Will Become More Efficient, Cleaner and Smarter

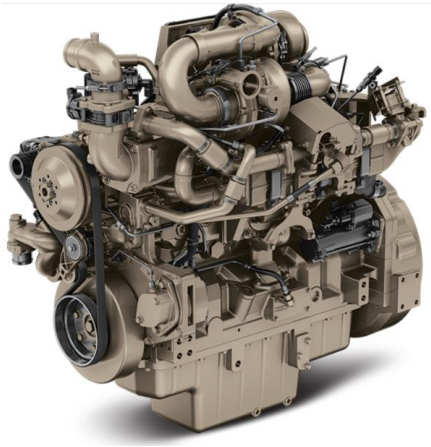
JD 2.9L

JD 4.5L

JD 6.8L



JD 9.0L

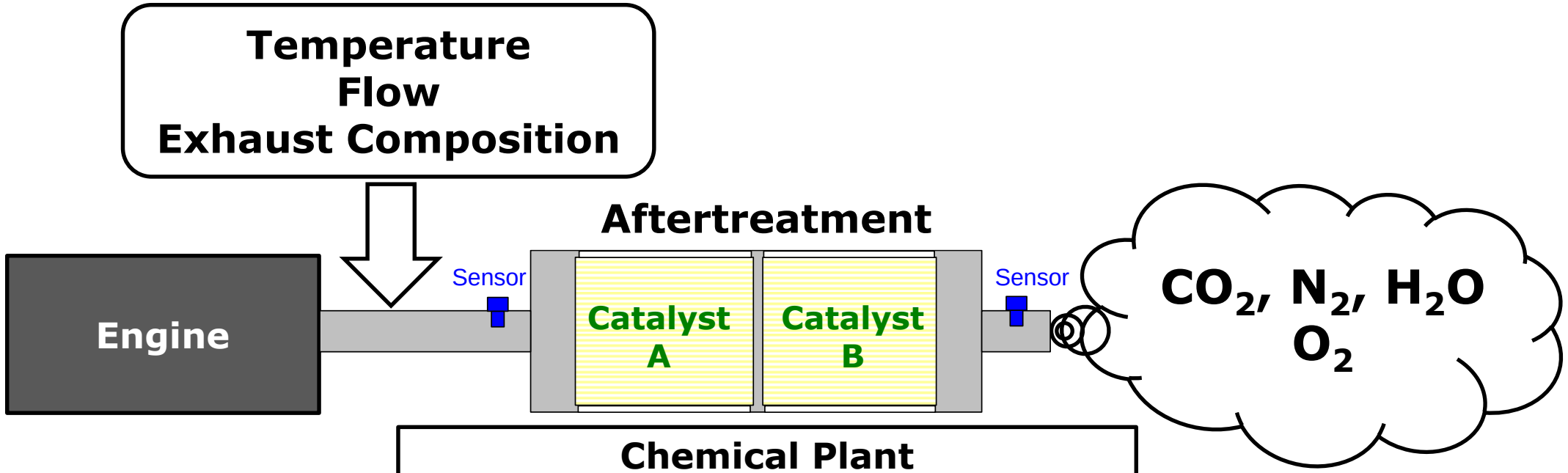


JD 13.6L

JD 18L

Aftertreatment is a Reactive Chemical Plant

Activity Controlled by Engine out Conditions



Chemical Plant

$HC + O_2$	$\rightarrow$	$CO_2 + H_2O$
$CO + ½\ O_2$	=	CO_2
$NO + ½\ O_2$	=	NO_2
$C + 2NO_2$	=	$CO_2 + 2NO$
$C + O_2$	=	CO_2
$2NH_3 + NO + NO_2$	=	$2N_2 + 3H_2O$
PM(Soot)	$\rightarrow$	Filter

Oxidative Reactions*

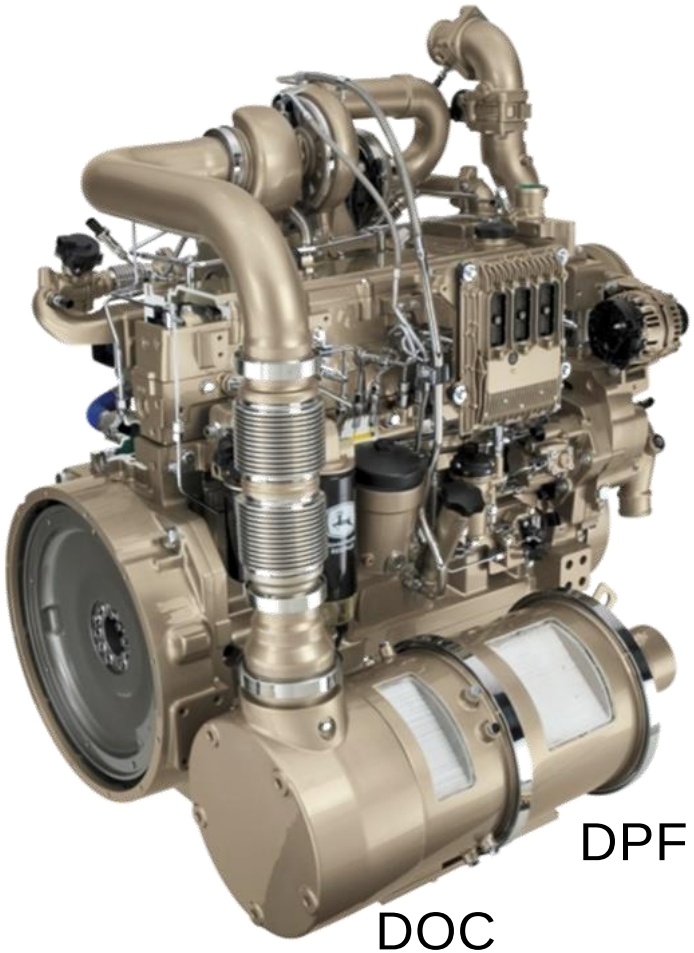
Reductive Reactions*

Physical Filtration

*** Ref to a pollutant**

Hardware Upgrades to Enable Interim Tier IV (2g/kWh NOx)

Technical Solution: EGR + DOC|DPF



Engine

- Upgraded fuel and air systems
- Venturi for EGR flow measurement
- Air throttle (intake or exhaust)
- Fuel supply and HC injector
- New ECU hardware(bin, memory, speed…)
- Low oil consumption kit
- Upgraded cooling system
- Engine harness

AT

- DOC|DPF assembly
- AT sensors (temperature, ΔP)
- Thermal shield and exhaust diffuser etc.

Software Upgrade to Enable Interim Tier IV (2g/kWh NOx, >130kW)

Technical Solution: EGR–DOC|DPF

Engine

- New sensors and actuators controls
- Enhanced Air/EGR controls
  - Increase EGR, lower NOx and transient
- New operating modes (like ETM*)
- Diagnostics and service features
- Engine protection and derate

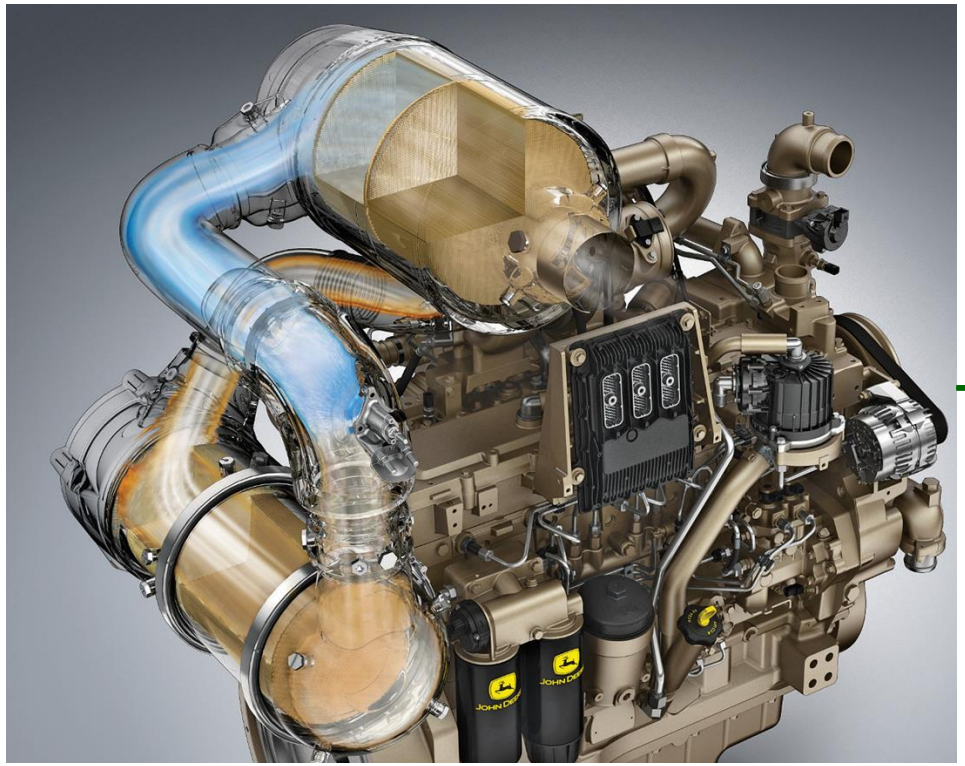
Aftreatment

- Engine out emission model
- Exhaust thermal and pressure models
- DPF soot and ash models
- DPF regeneration controls
- Operator interface (display)
- Diagnostics and fault management

* Exhaust Temperature Management

Hardware Changes to Enable Final Tier 4 Emissions (0.4g/kWh)

Technical Solution: EGR–DOC|DPF–SCR|AOC



Engine

- No hardware change
- EGR removal feasible with fluid penalty

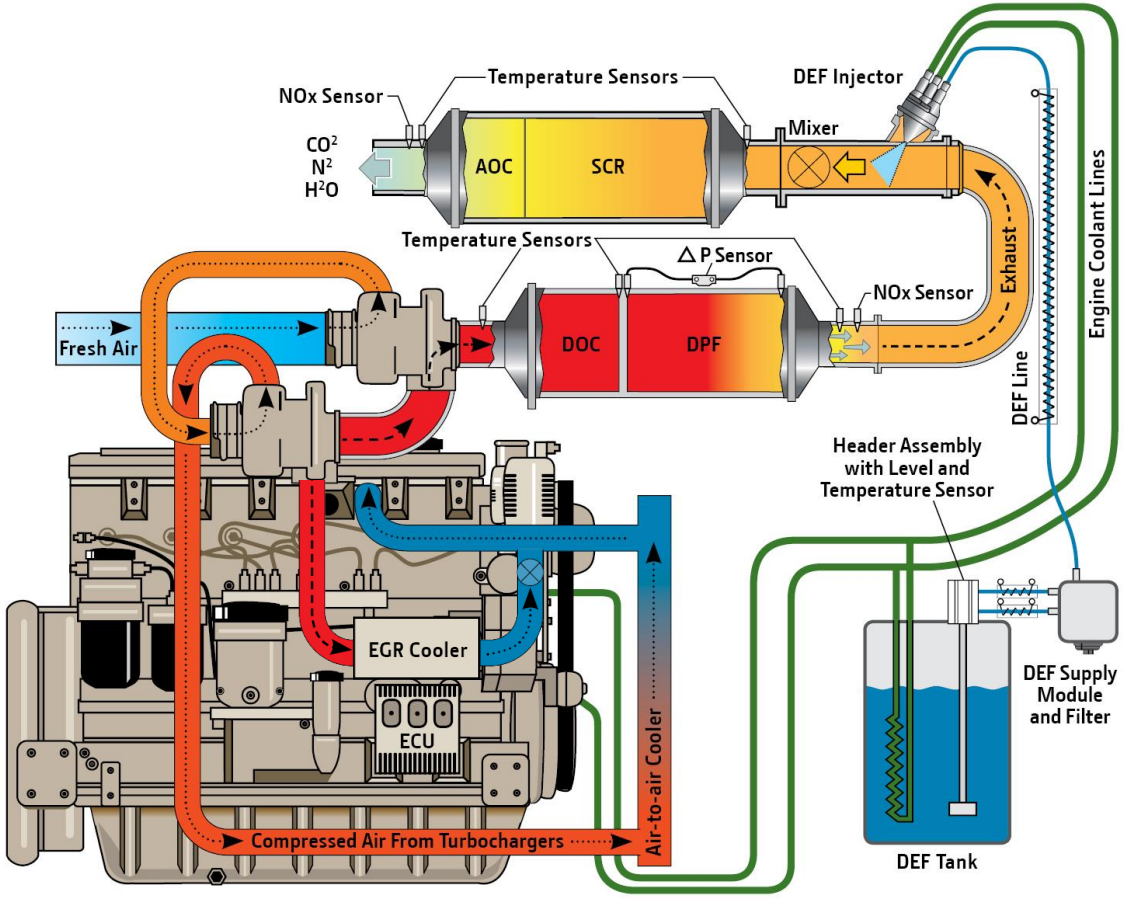
AT

- NOx sensors and temperature sensors
- DEF tank, filter, sensors, lines
- DEF storage thermal management
- DEF pump and injector
- DEF mixer assembly
- SCR and AOC catalyst assembly

AOC: Ammonia Oxidation Catalyst

Software Changes to Enable Final Tier 4 Emissions (0.4g/kWh)

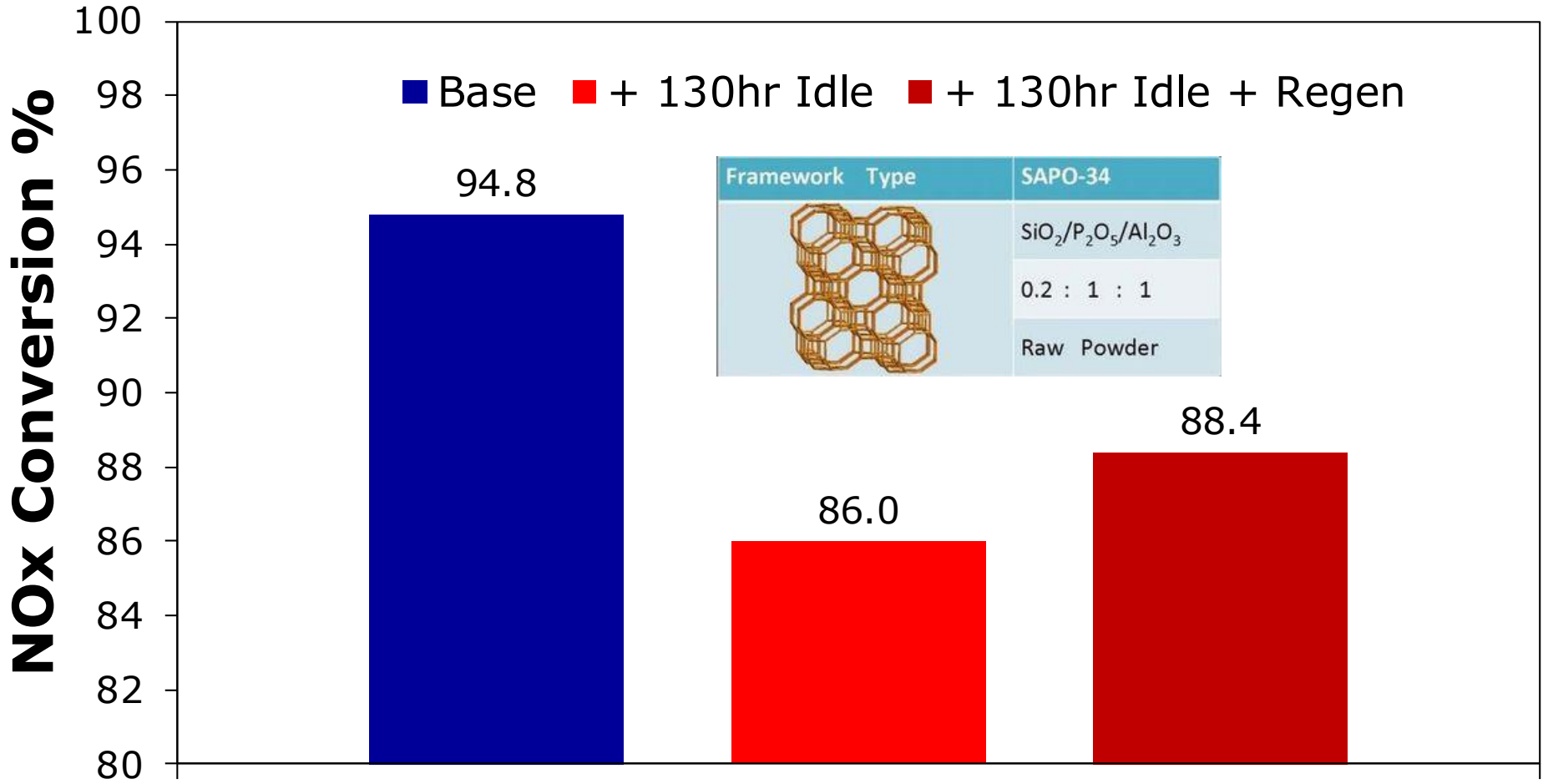
EGR-SCR Improves Performance and Reduces Fluid Consumption



- SCR temperature management
- NOx calibration optimization
- SCR thermal model
- SCR chemistry model
- DEF dosing strategy
- DEF pump and injector control
- DEF thawing control
- Operator interface and display
- Diagnostics and inducement

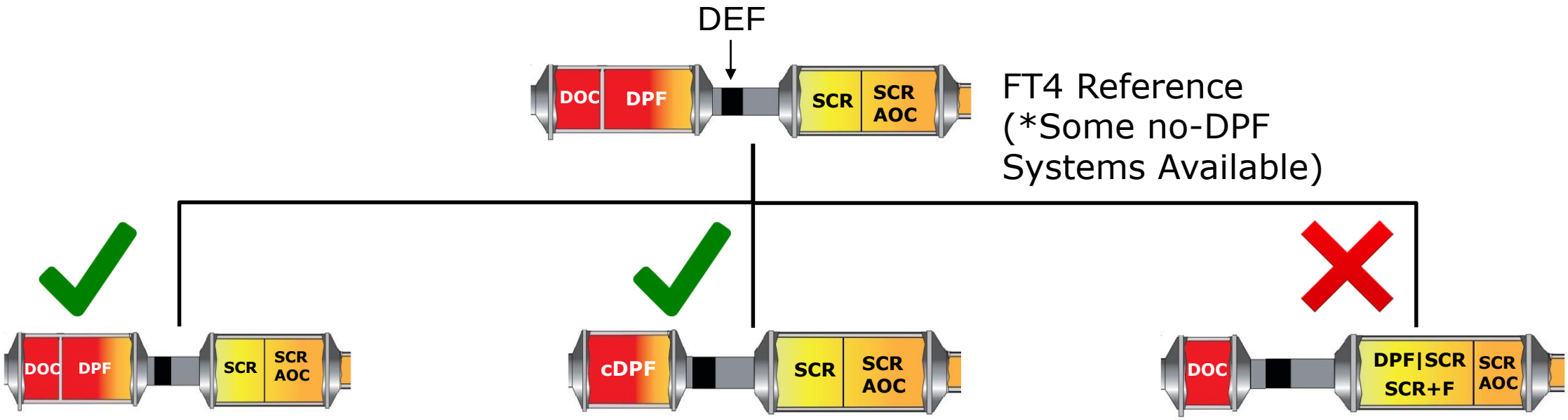
Lessons Learned – Failure from System Interaction

Low Temperature SAPO-34 SCR Degradation has Led to Recalls



NSR= NH_3/NOx
Stoichiometric Ratio

Stage V Aftertreatment Architecture Overview and Recommendations



John Deere

Majority OEMs

Selected OEMs

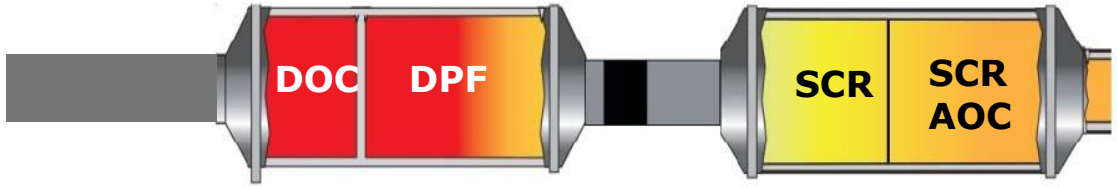
Few OEMs

Precious metal migration to filter*
NOx performance degradation*

* SAE 2019-01-0740

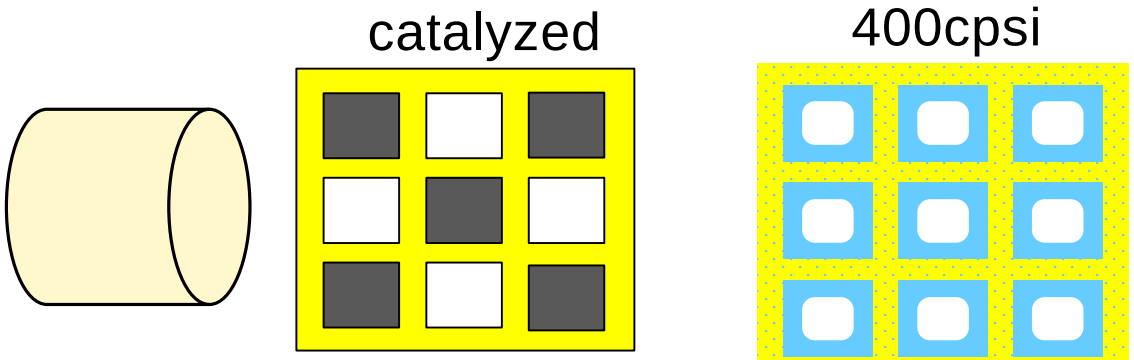
cDPF: catalyzed DPF
DPF: non catalyzed (bare) DPF
SCR+F: SCR on filter
AOC: Ammonia oxidation catalyst

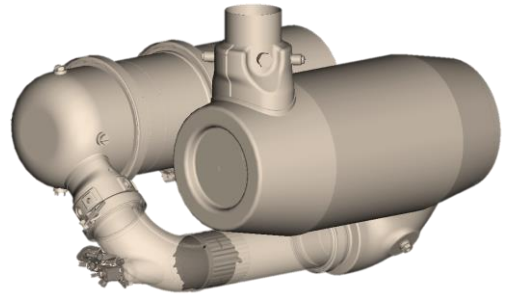
Aftertreatment Design Advancement and Packaging Optimizations Achieve 40% Size Reduction With Installation Simplification



Gen 1

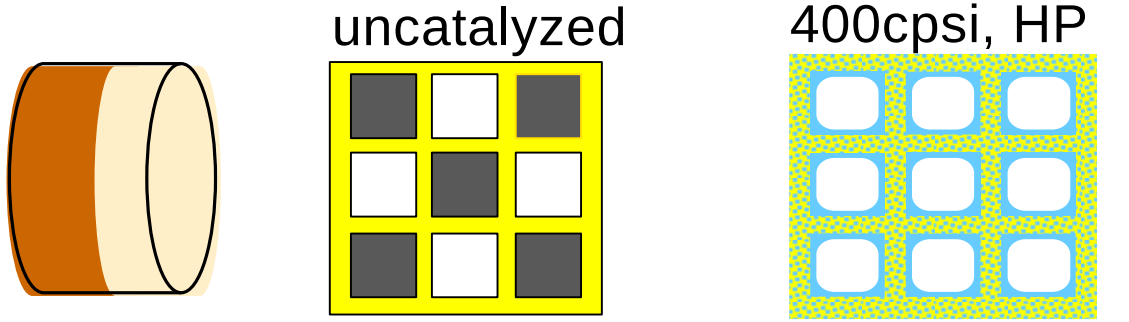
Base





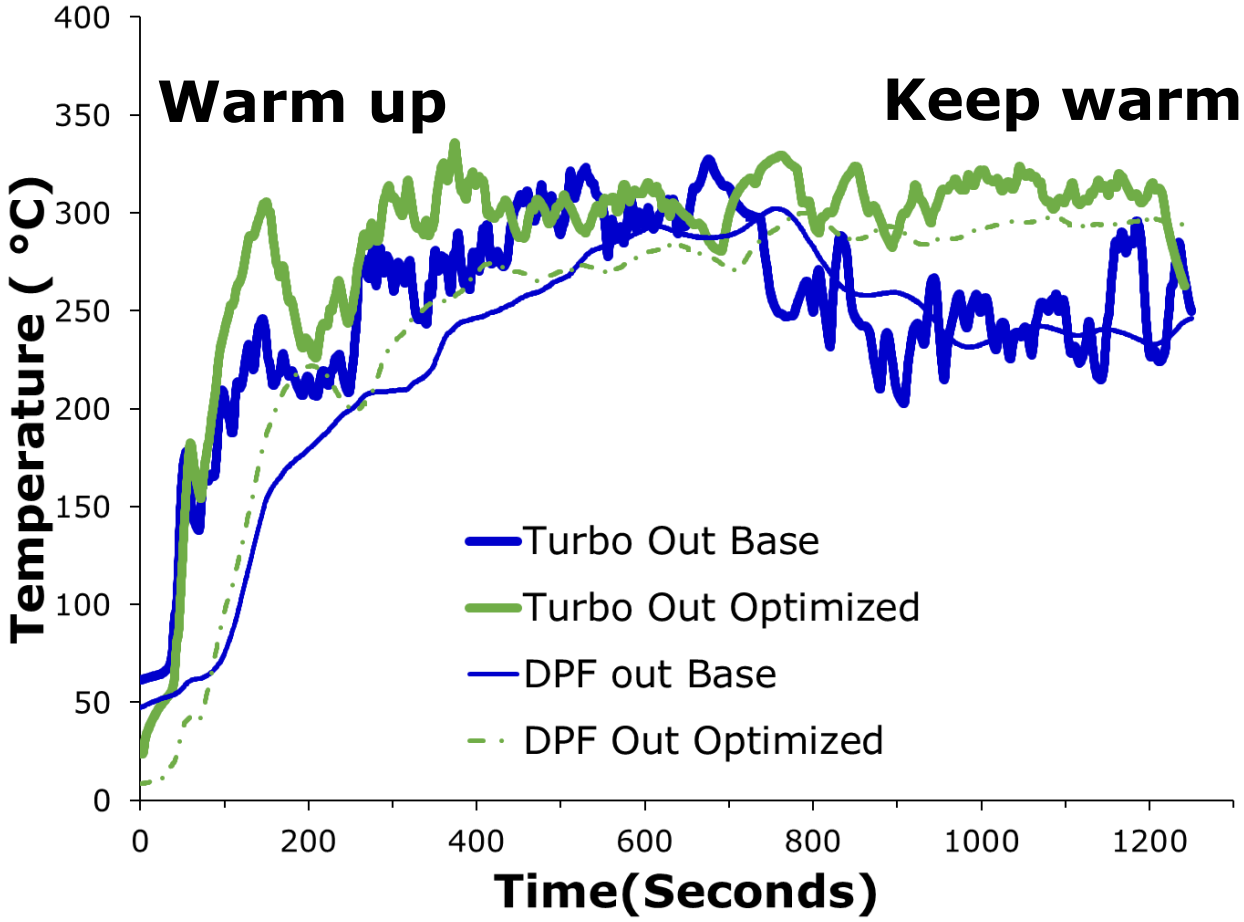
Gen 2

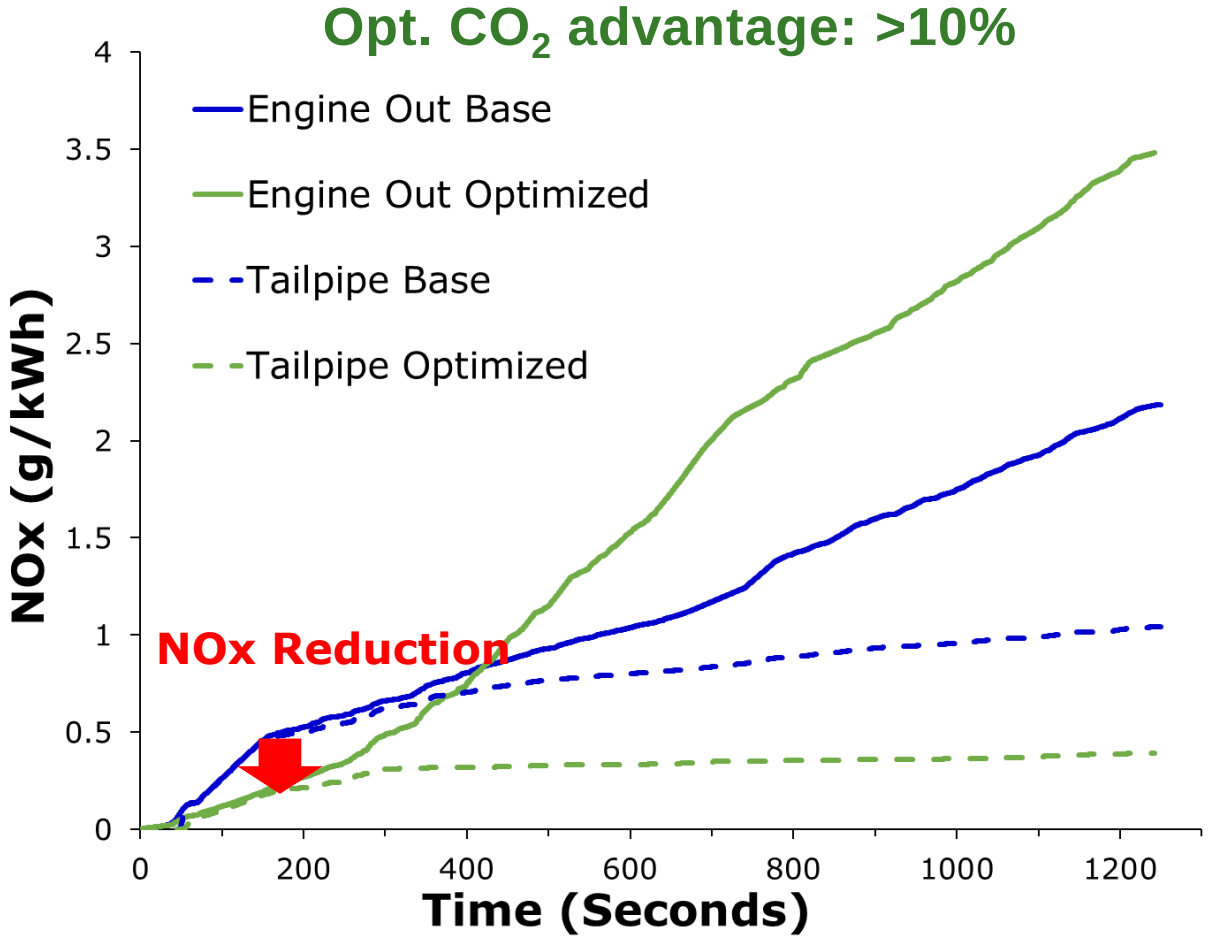
Optimized



Lessons Learned: System Optimization Reduces Both NOx Emissions and Fuel Consumption (9L Min Power Output Case)

Cold NRTC





System Engineering Principles Applied to Off-road Equipment: Final Tier 4 Gen 2 Example

Operating Environments

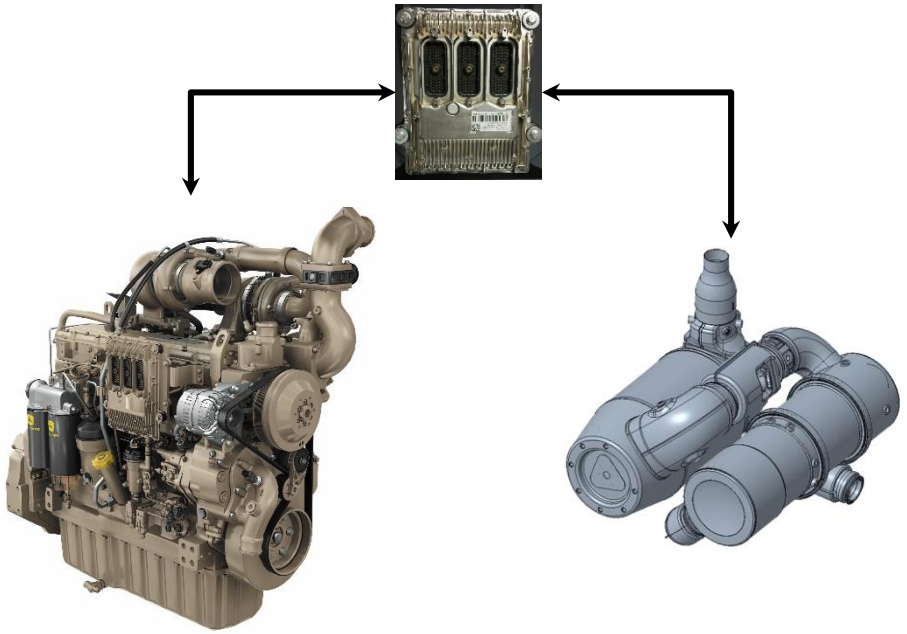
Customer Operating Cycles

Integrated Product Requirements

Customer Needs
- Productivity
- Uptime
- Cost
- …

Additional Requirements
- Regulations
- Standards
- …

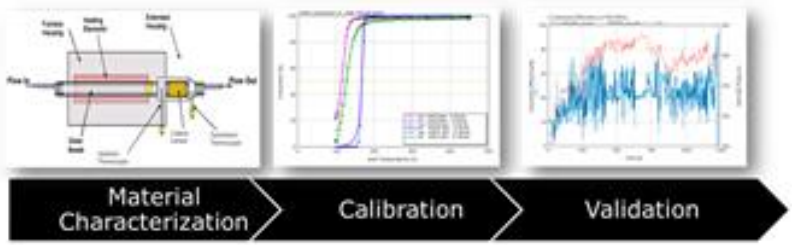
Sub-System Boundaries
- Controls
- Engine
- Aftertreatment



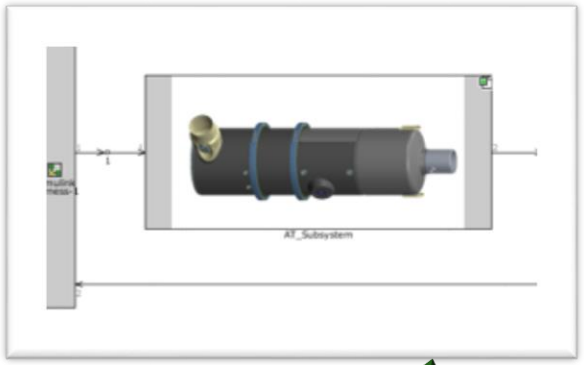
Power Train Sub-System

Simulation Tools Processes Allow for Rapid Concept Development

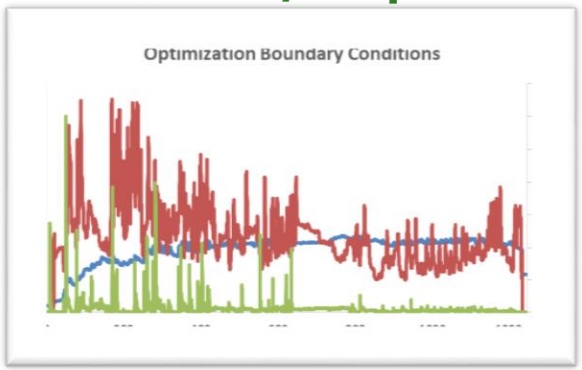
Component Model Library



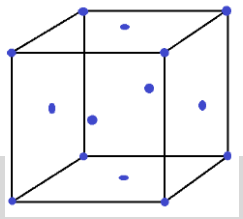
Model Assembly from library



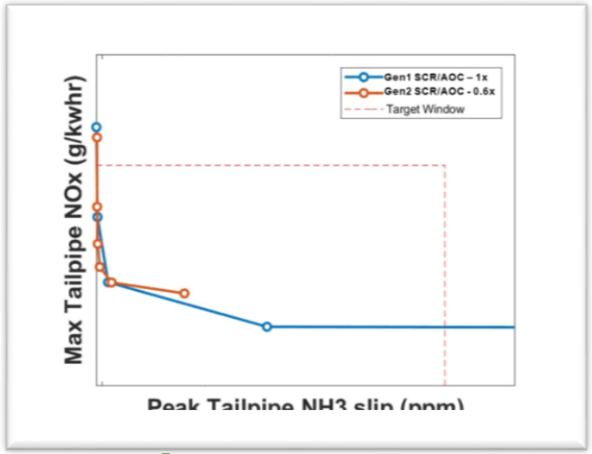
System Boundary Conditions/Requirements



System Simulation vs Design Parameters



Design Trade-offs vs Requirements



Updated Boundary Conditions/ Requirements

Simulation Activities Vital to Successful Gen 2 Aftertreatment!

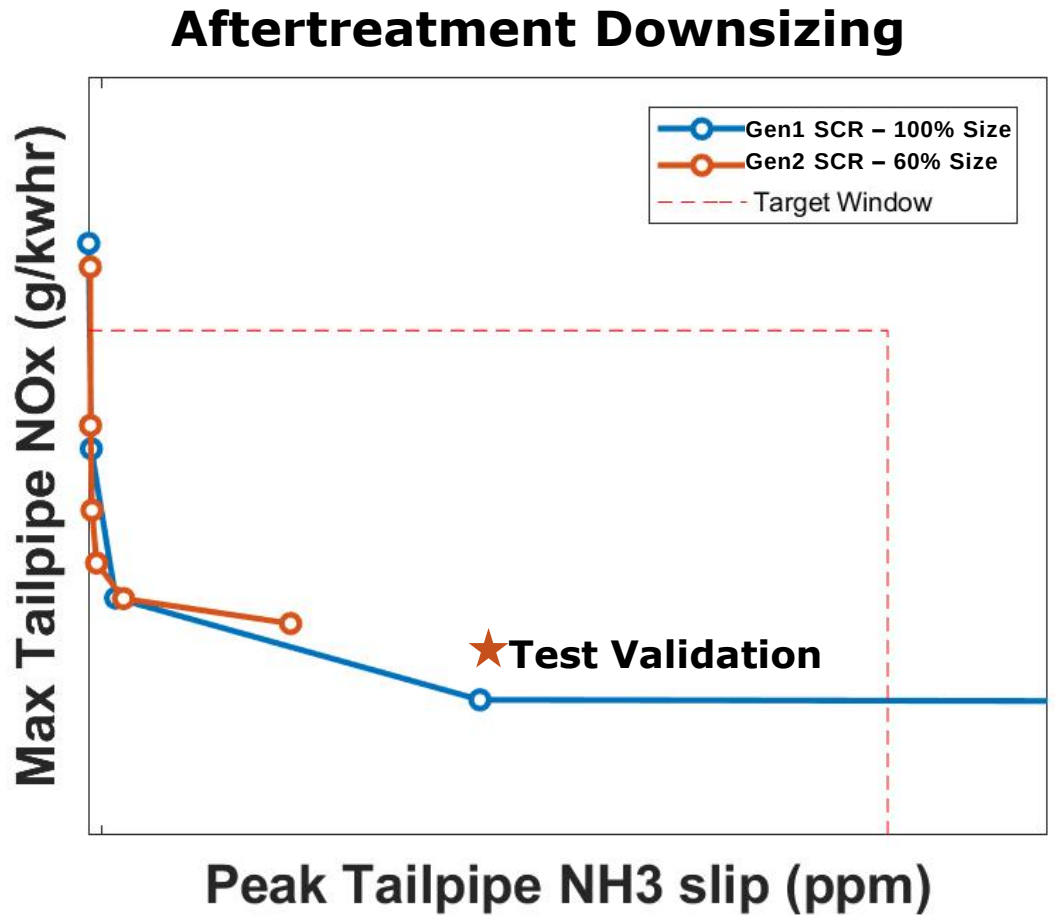
Catalyst and Controller Model Calibration (MIL)

↓

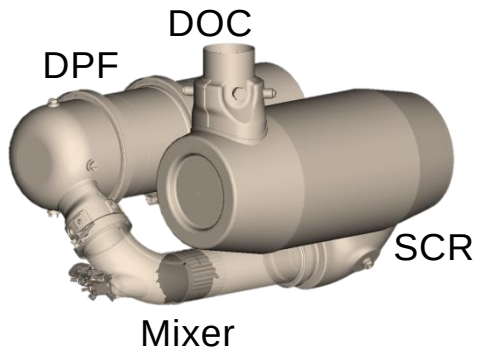
DOE on Design and Control Parameters

↓

Trade-off Output vs Design Targets



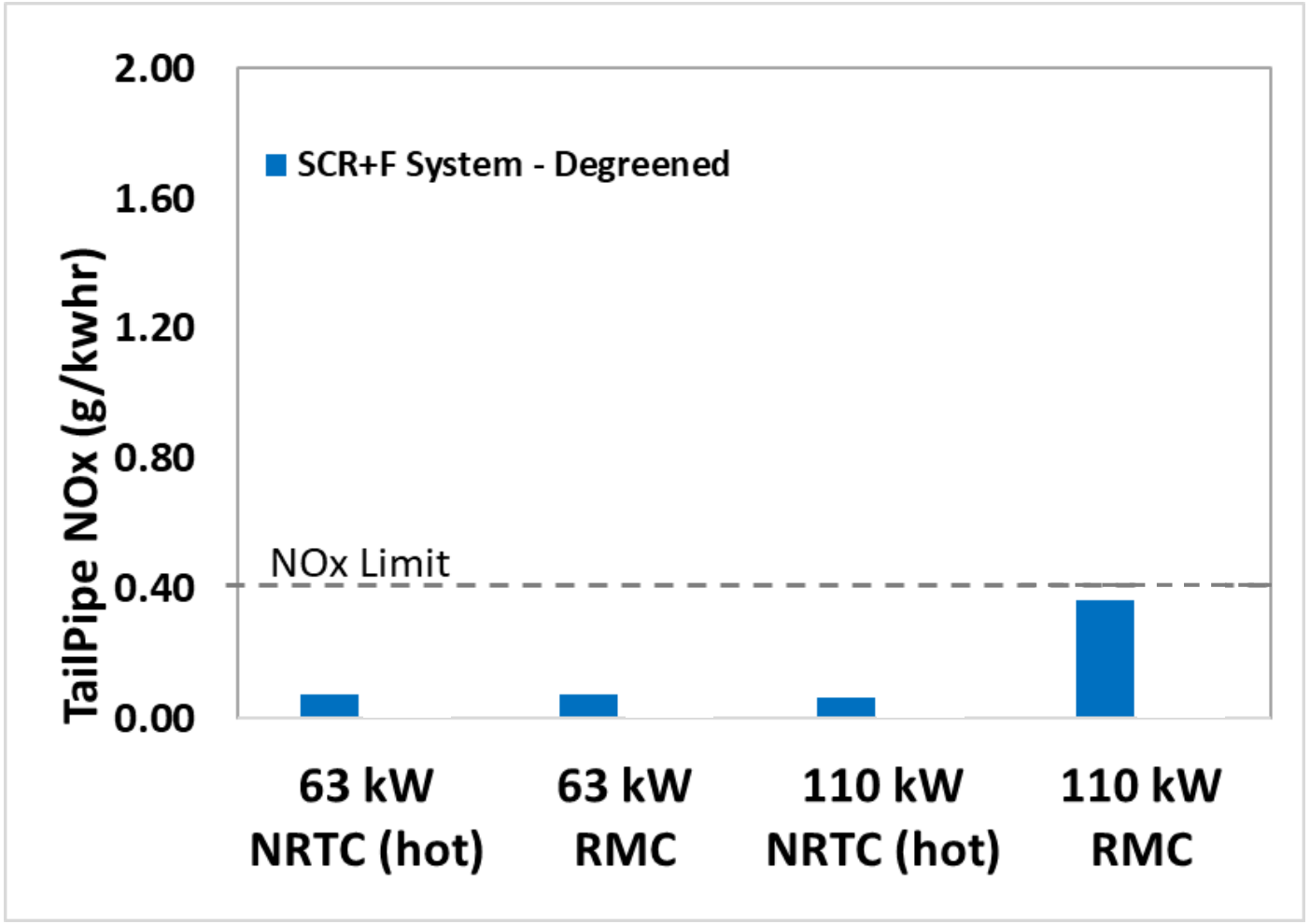
Gen 1



Gen 2

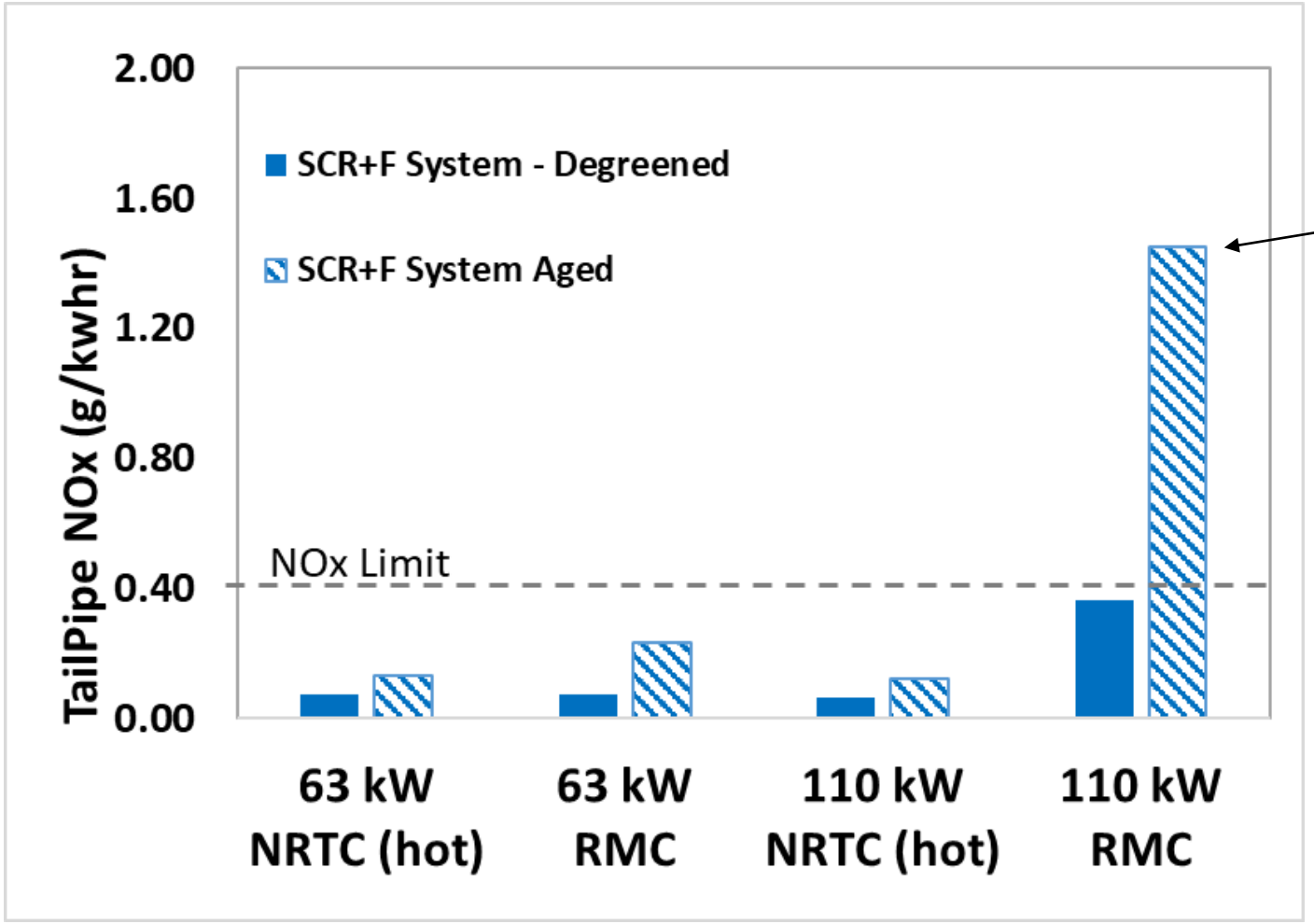
MIL : Model in the loop

Stage V Test Case: Simulation Tools Successfully Design a New Concept and Validated in Physical Test



Reference: SAE 2019-01-0740

Lesson Learned: Simulation Tools cannot Answer all the Questions, and are Blind to Unknown Failure Modes



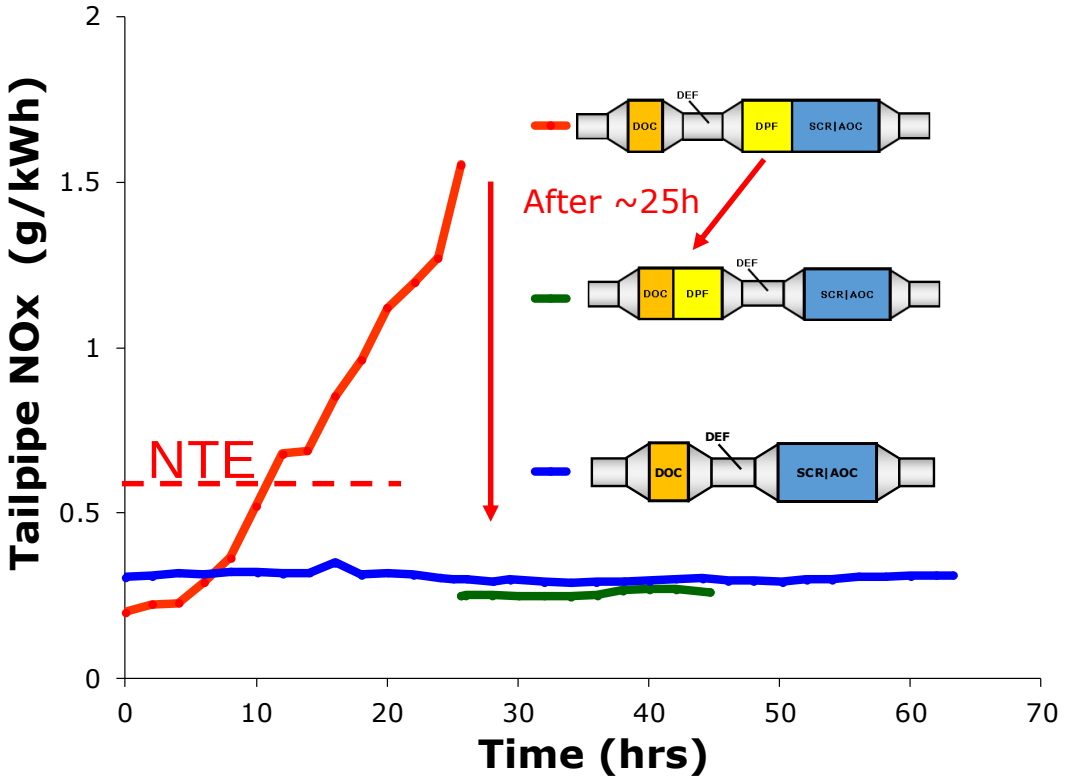
Platinum migration observed

Reference: SAE 2019-01-0740

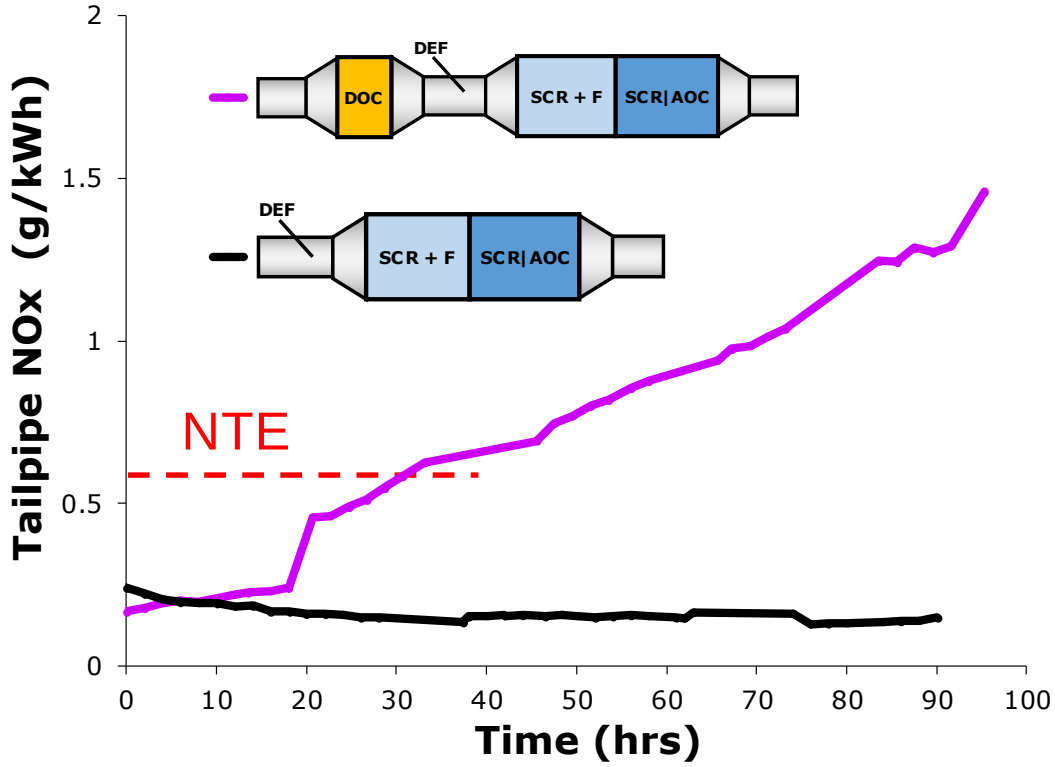
Lessons Learned Continued: Failure from System Interaction

NOx emission degradations-exceeding NTE limit
(4.5L engine at 110kW rated power without EGR)

Bare DPF Case



SCR+F Case



Reference: SAE 2019-01-0740

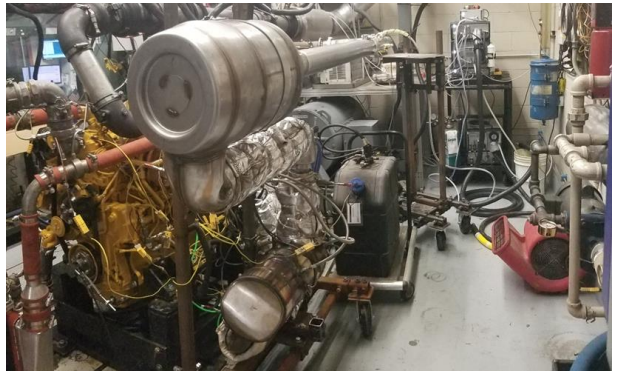
Off-road Future Trends

Reducing real world emission with extended useful life and compliance monitoring

OEM

Final T4 Optimizations
New generation aftertreatment
High performance/space efficient

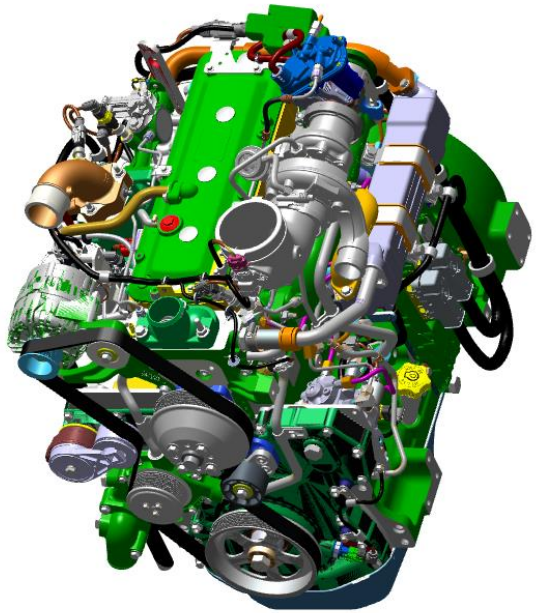
Emission Regulations



Engine Certifications
New Test Protocols (light loads)
Reduced NOx limits

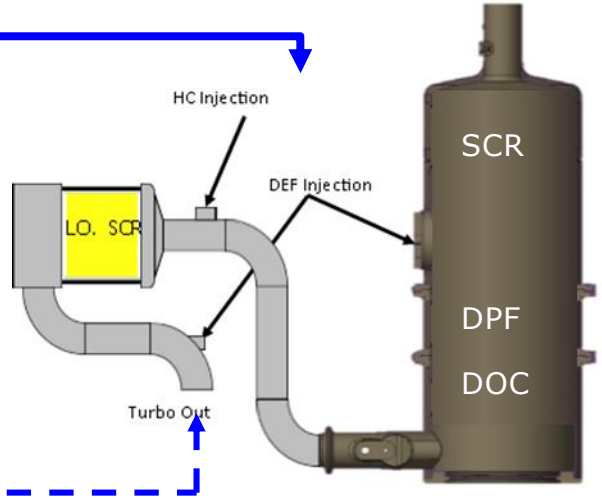
Vehicle Real World Emissions
Telematic data/monitoring
In use emission & compliance

Test Case: Off-road Future Emission Understanding



Offline
Digital
Interface

Modeled Controls



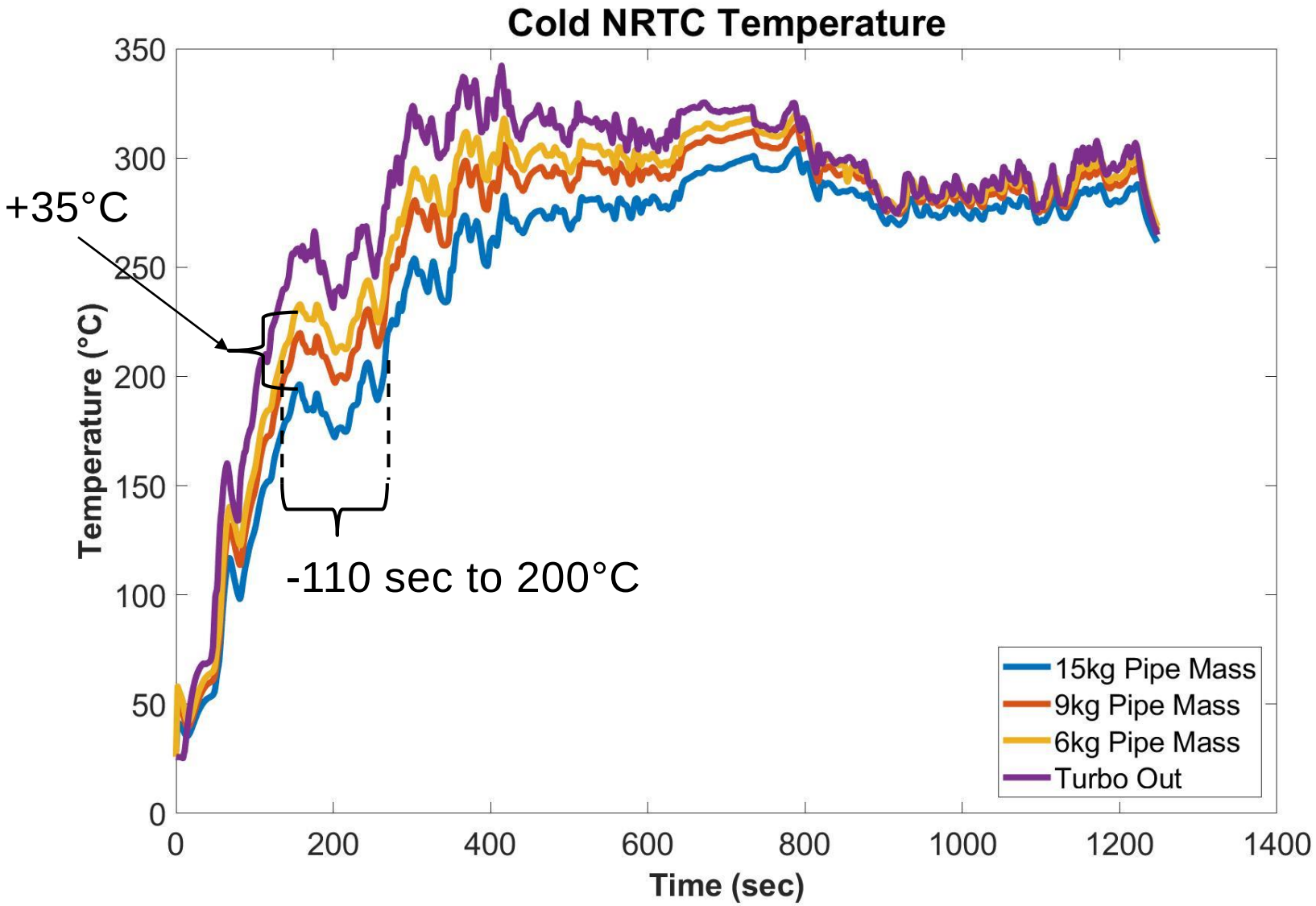
Physical engine data:

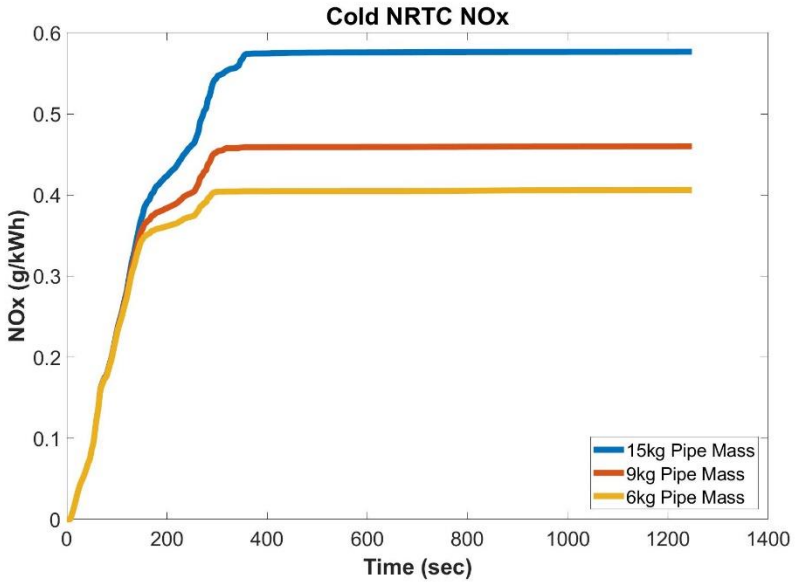
- Existing Certified FT4 4.5L lab data
- Mature calibration, w/ hardware constraints managed
- Low power density (emission challenge)
- ~4.0 g/kWh NOx on hot NRTC

Architectural approach (model based):

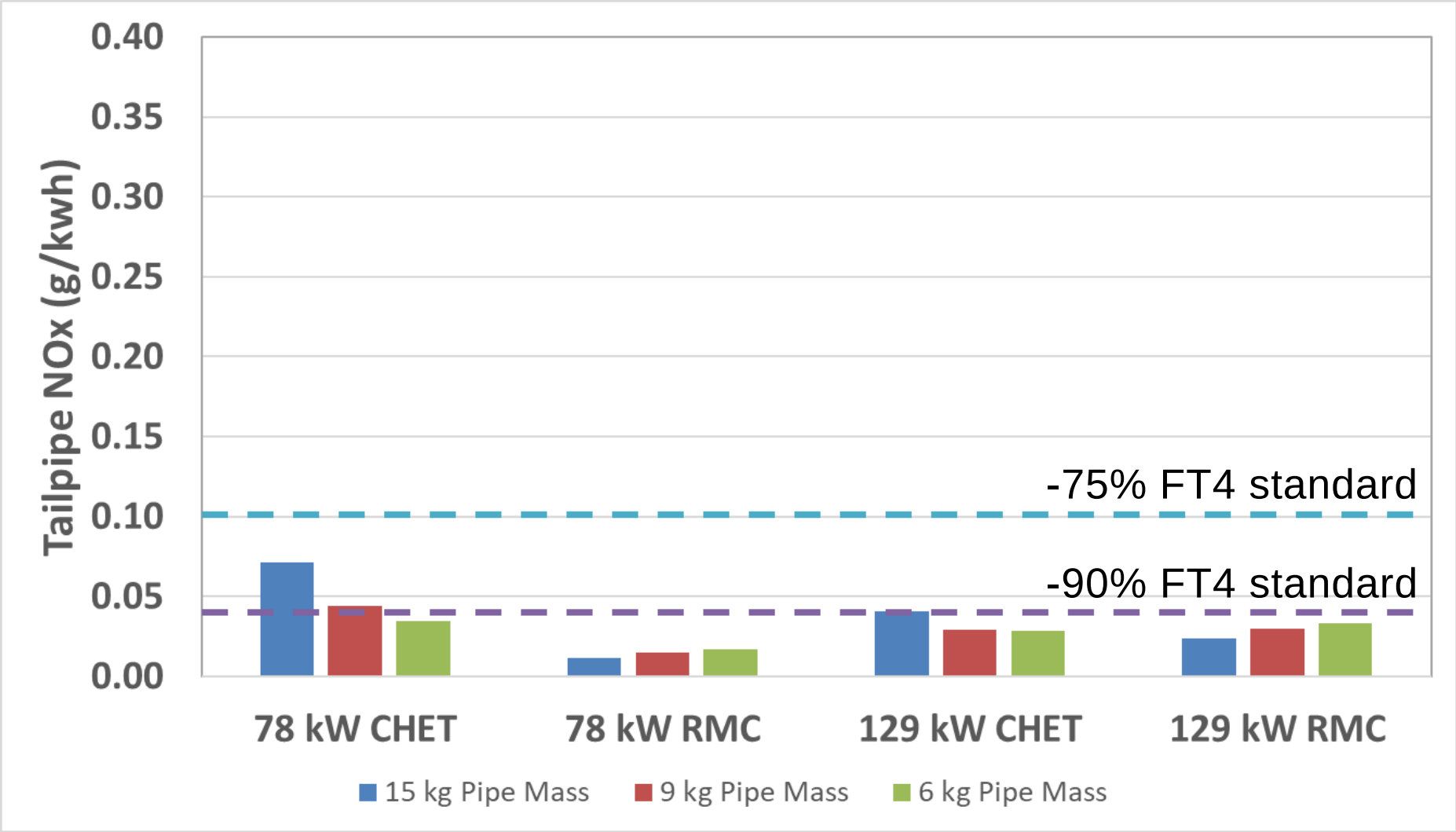
- Chemistry well characterized/validated
- Controls integrated
- Modified to represent new generation ATD
- DOE on parameters of impact
  - Structural thermal mass (inertia)

Component Design as Important as Architecture (78 kW rating)



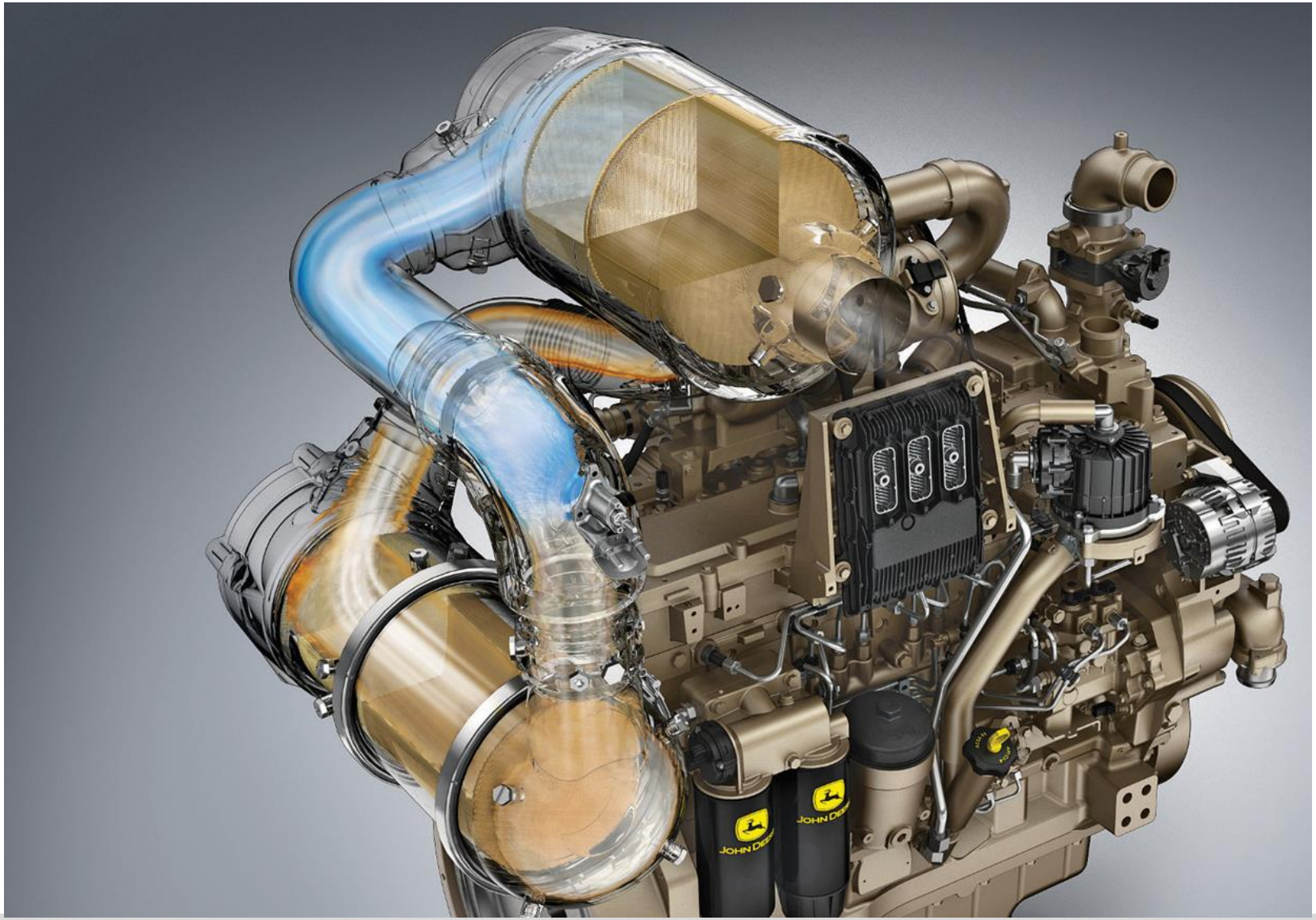


Low thermal mass upstream of light-off SCR systems allows for meeting goals without additional fuel penalties in degreened state



Summary

- Off-highway diesel engine applications remain essential for the future
- New technologies and systems will increase in complexity
- Systems engineering, MBD, and architecture choice are key to manage growing complexity
- Simulation tools provide early critical feasibility/trade-off analysis with controls as part of systems engineering
- Testing will remain vital to validate simulation results and expose unforeseeable failure modes and system interactions (including controls/diagnostics)
- Many of these advances shown today were built off of technical communities like the CLEERS community researching the fundamentals of catalysts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