Cummins Tier 4 Technology Overview
Agenda

- Emissions legislation
- Cummins Tier 4 Technology
- Cummins Advantage
TIER 4
EMISSIONS LEGISLATION
Emission Box for Off-Highway Engines
Emission Box for Off-Highway Engines

US EPA

Tier 1

Tier 2

Tier 3

Tier 4.1

Cummins Confidential
Emissions lineage

US Off-highway Emissions (<130kW)

Tier 4 Final requires a 90 percent reduction in PM & NOx compared to Tier 3

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- Tier 4i + SCR - DPF
- T4F
- Tier 4 Final requires a
- T3 – DSA + Cooled EGR + DPF

Achieving more than emissions compliance:
- Reduced fuel consumption
- Improved engine performance
- Minimized installation impact
Achieving ‘Near-Zero’ Emissions

- Emissions from 25 x Tier 4 Final machines will be equivalent to just 1 x Tier 1 machine
Construction and Ag - 2011

Notes:
1. Construction and Ag regulations phase-in by engine horsepower category. The above chart is for engines rated at 300hp.
2. Common standards does not imply the ability to sell a product without certification for that country. Actual regulations should be reviewed for introduction dates and certification requirements.
The machine, engine and aftertreatment are part of a single system designed to optimize performance, reliability, cost and emissions.
Building Blocks for Meeting Tier 4 Emissions

Possible Tier 4 Building Blocks

- Flexible Fuel Systems
- Combustion Optimization
- EGR Cooler
- Cooled EGR
- Air Handling
- Advanced Controls
- Particulate Filter
- NOx Adsorber
- SCR

Cummins Tier 3 Engine
On-Highway ≠ Nonroad
On-Highway ≠ Nonroad

Sample Nonroad Application

Drivetrain
Many Suppliers Of Low Volume Components
Varied Drivetrain Requirements

Engine
Many Ratings
Several Product Families
High Load Factors

Cooling System
Limited Available Space
No Ram Air; fan HP Increases
More Auxiliary Coolers
Dusty Environment
High Vibration & Impact Loads

Fuel sulfur content up to 5000 ppm, gone to 500 then 15 ppm in US by 2010.

Many OEM’s, Global Business
Key Tier 4 Development Areas

- Heat Rejection
  - Minimization
  - Optimization of cooling systems

- Application Variation
  - Robust to installation variation
  - Cost impact for vehicle installation

- Environmental Robustness
  - Dust/Dirt
  - Surface temperature requirements
  - Vibration/Shock

- Develop a solution with the lowest initial and life-cycle cost
“In-Cylinder” Development

- Exhaust Gas Recirculation (EGR)
- Advanced Combustion
- Variable Geometry Turbocharging (VGT)
- Fuel System
How EGR Works

- Cooled exhaust gas recirculation for NOx reduction for Cummins Tier 4/Stage IIIB

Recirculates the exhaust gas back into the cylinder reducing oxygen concentration. This lowers combustion temperature to reduce the formation of Oxides of Nitrogen (NOx)

Upgraded cooling package mitigates increased engine heat rejection

EGR system sensitivity to high sulfur fuel made it less viable for Tier 3 application, but offers potential for Tier 4 with ULSD

Variable geometry turbocharging is required to maintain correct pressure differential across the engine for ideal EGR flow

Control valve modulates the % EGR returned to cylinder
Advanced Combustion

- World class combustion research by Cummins & Sandia National Laboratories
- Laser-optical imaging of the combustion process gives precision modelling of injection spray & diffusion flame
- Enhances Cummins capability to meet emissions & optimize for fuel economy
Cummins VGT

- Cummins variable geometry turbocharger with patented sliding nozzle design
- Improves boost efficiency across all engine speeds/loads
- Proven technology for Tier 4/Stage IIIB
Fuel Systems

- Cummins designs & manufactures high pressure common rail fuel systems

- Tier 4/Stage IIIB fuel systems requires:
  - higher fuel injection pressure
  - very fast response with multiple injection events
  - precise control of fuel metering timing

- Cummins next generation HPCR is recognized as industry leading technology
Aftertreatment Technology

- Diesel Particulate Filters (DPF)
- Diesel Oxidation Filters (DOC)
- Selective Catalytic Reduction (SCR)
Wall Flow Particulate Filter

- A full filter consists of a porous ceramic honeycomb for collecting particles in the exhaust gas.
- The filter can be coated with precious metal for enhancing oxidation of hydrocarbons promoting low temperature oxidation of soot.
- On average, full filters reduce PM by about 90-95%.
How The DPF Works

**Diesel Oxidation Catalyst**
DOC catalytic material reacts above 572°F (300°C) in passive regeneration mode to generate Nitrogen Dioxide (NO$_2$) which oxidizes the carbon soot.

**Diesel Particulate Filter**
Ceramic wall flow filter captures up to 95% of the carbon soot (PM) carried by the NO$_2$. This collects on the filter to form Carbon Dioxide (CO$_2$) which leaves the tailpipe as clean gas.

**Active Regeneration**
When soot accumulation in the DPF exceeds soot oxidation a periodic active regeneration mode is performed to prevent filter plugging. This is actuated by small quantities of fuel from a dosing injector or HPCR injection pulse during exhaust blow down. The heat released (no flame or burning) at 1022°F (550°C) ensures sufficient oxidation to remove soot.

**Filter Service**
Build up of incombustible ash will eventually require filter service cleaning, though only required at very long intervals.
Urea Based SCR: Overview

- A vanadia or zeolite based catalytic coating is applied to a honeycomb substrate
- A urea-water solution ("AdBlue" or "DEF") is used as a reagent for converting NOx to N2

- The urea is converted to ammonia in the exhaust above 200 deg C
- NOx conversion efficiency is high above 250 deg C.
- Averages 70-85% NOx reduction
How SCR Works

Selective Catalytic Reduction

Urea solution is injected ahead of the catalyst. This converts to ammonia in the exhaust stream above 392°F (200°C)

The ammonia reacts with Oxides of Nitrogen (NOx) over the SCR catalyst to form harmless nitrogen & water

Urea is injected at a ratio of typically 5% to diesel fuel use, depending on duty cycle. Urea tank sizes vary, but must be refilled to ensure emissions compliance

Urea Solution

The urea-water solution (AdBlue in Europe, DEF in USA) is a clear liquid, non-hazardous & non-flammable with a 12 month shelf life. Heaters are required to prevent urea freezing at 11°F (-11°F)
DPF & SCR Aftertreatment Configurations Examples

- Vertical End-In End-Out
- Horizontal End-In End-Out
- Horizontal End-In Side-Out
- Horizontal Side-In End-Out
- Horizontal Side-In Side-Out
- Vertical Side-In End-Out
### Estimate of Application Impact of Cooled EGR & Aftertreatment for T4 QSB6.7

<table>
<thead>
<tr>
<th></th>
<th>Estimated Change from Tier 3</th>
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<tbody>
<tr>
<td>Heat Rejection to Coolant</td>
<td>40% increase</td>
</tr>
<tr>
<td>Heat Rejection to CAC</td>
<td>25% decrease</td>
</tr>
<tr>
<td>Engine Package</td>
<td>Addition of cooled EGR components</td>
</tr>
<tr>
<td>Aftertreatment Size</td>
<td>~ 12 inch diameter X 27 inch long canned with inlet &amp; outlet sections</td>
</tr>
<tr>
<td>System Weight</td>
<td>Engine ~ 1180 (wet)</td>
</tr>
<tr>
<td></td>
<td>Aftertreatment ~ 85 lb</td>
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</table>
TIER 4
CUMMINS ADVANTAGE
Experience Counts

- No engine manufacturer has this experience with Tier 4 technology:
  - 1,000,000 EGR Engines
  - 650,000 DPFs
  - 350,000 SCR systems produced
  - 100,000 XPI systems produced
  - 3 million VGTs produced

- The emissions requirement for later off-highway markets were part of the initial design profile of EGR, VGT & DPF

- We leverage our automotive platforms to develop products that are validated for the off-highway market
System Integration

- Unique in the industry – we design, build and integrate the complete system

- Filtration
- Diesel Exhaust Fluid
- Direct Flow
- Electronic Controls
- Aftertreatment System
- Turbochargers
- Fuel Systems
- Combustion Technology
# Clear Advantage: Fuel-Efficiency

<table>
<thead>
<tr>
<th></th>
<th>Tier 4 Interim fuel saving over Tier 3</th>
<th>up to 5% typical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tier 4 Final fuel saving Over Tier 4 Interim</td>
<td>Preliminary estimates: additional 2-3% (more than offsetting DEF cost)</td>
<td></td>
</tr>
<tr>
<td>Typical fuel saving at 5% (2500 hours / 6 gals hr)</td>
<td>750 gallons per year $3000 saved</td>
<td></td>
</tr>
<tr>
<td>C02 savings (1 gal = 22.2 lbs)</td>
<td>8 tons less per year</td>
<td></td>
</tr>
<tr>
<td>Power Output / Transient Response</td>
<td>Retain Tier 4 Interim high output &amp; improved response</td>
<td></td>
</tr>
</tbody>
</table>
Tier 4 Final Architecture

- QSB3.3
- QSB4.5
- QSB6.7
- QSL9
- QSX11.9
- QSX15

- CCC-SCR
- CCC-SCR
- CPF-SCR

- Retain T4i Power Output
- Increase Power Output / Density
- Retain CCC Installation Simplicity
- Utilize CCC Simplicity
- Retain or Lower Cost Of Operation
- Particulate Filter ‘virtually’ passive
- Lower Cost Of Operation
Engines Pre-designed For Final

- Tier 4 Interim engines pre-designed for Final
- No significant change to engine installation envelope
- Ready to integrate with incremental SCR aftertreatment

Tier 4 Interim and Tier 4 Final
Tier4 Final QSB6.7 Architecture

Cummins Emissions Solutions

CCC

SCR

DEF

EGR-Cooler

Cummins Turbo Tech. VGT

Cummins Filtration DirectFlow air filter

6.7L Tier4 Interim engine with increased fuel pressure
Interim to Final: QSB6.7

2011/12 146-300 hp 2014/15

Ultra-Clean Aftertreatment
CCC-SCR
Cummins Compact Catalyst Selective Catalytic Reduction
Interim to Final: QSB6.7

- Same power output and performance
- Fuel consumption further reduced
- No change to engine installation

- Balanced EGR with SCR aftertreatment
- ECM upgraded for faster processing & SCR logic
- Single VGT for 300 hp output
- Enhanced HPCR system with higher fuel injection pressure
# QSB6.7 engine lineage

<table>
<thead>
<tr>
<th>QSB6.7 GT174hp</th>
<th>T3</th>
<th>T4i</th>
<th>T4F</th>
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<tbody>
<tr>
<td>ECM</td>
<td>CM850</td>
<td>CM2250</td>
<td>CM2350</td>
</tr>
<tr>
<td>Fuel pressure</td>
<td>1600 bar</td>
<td>1800 bar</td>
<td>2200 bar</td>
</tr>
<tr>
<td>Turbocharger</td>
<td>WGT</td>
<td>VGT</td>
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<td>NOx control</td>
<td>DSA</td>
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<td>OCV, impactor only</td>
<td>OCV, coalescing filter</td>
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<tr>
<td>Aftertreatment</td>
<td>None</td>
<td>DOC+DPF</td>
<td>DOC+SCR</td>
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QSL9
Tier 4 Final QSL9 Architecture

- DEF
- Cummins Emissions Solutions
  - CCC
  - SCR
- Cummins Filtration DirectFlow air filter
- Cummins Turbo Tech VGT
- EGR-Cooler
- EGR valve

8.9L Tier 4 Interim engine with Cummins Fuel Systems XPI fuel system
Interim to Final: QSL9

2011 190-400 hp 2014

Ultra-Clean Aftertreatment CCC-SCR
Cummins Compact Catalyst Selective Catalytic Reduction
Interim to Final: QSL9

- Same power output and performance
- Fuel consumption further reduced
- No change to engine installation

Balanced EGR with SCR aftertreatment

Single VGT for 400 hp output

ECM upgraded for faster processing & SCR logic

XPI fuel system capable for Tier 4 Final
## QSL9 engine lineage

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Program Schedule

- Alpha build       Q4 2011/Q1 2012
- Beta build        Q4 2012/Q1 2013
- Limited Production Q4 2013
- Full Production - January 1, 2014
Field Test Activity

- Tier 4 VPI Service Team has compiled over 30,000 field test hours during Tier 4 Interim testing
- Tier 4 Final field test plan should achieve over 50,000 field test hours prior to launch
  - Several T4i field tests continuing on to T4F
- Field testing has incorporated 1) Cummins QSB6.7/QSL9 engines, 2) Cummins Emission Solutions Aftertreatment Systems, and 3) Cummins Filtration Direct Flow Air Filtration to understand how our Tier 4 solution performs as a package
- Field test engines are monitored daily for issues
- Ultimate goal: release a reliable product
Summary

- Cummins Tier 4 work has been underway since 2004
- We are leveraging our on-highway experience with these potential technologies while using standard tools and processes to ensure we select the right technology for off-highway
- Cummins Inc. is uniquely positioned to deliver an integrated and optimized system for Tier 4
Questions?