Vehicle Engine Efficiency and Emissions
Review of Regulations & Technology Trends

Sept 11th – 12th, 2019

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SCR
Some advances apply to both LD and HD
Durability of SCR shown to 900 °C. Combination of close-coupled SCR and ASC shown to improve NOx-N₂O trade-off

**SCR on filters**
Improved durability & op. window

**ASC**
Improved selectivity - lower N₂O
While retaining NH₃ ox. performance

Use of close-coupled SCR
Better tailpipe NOx / N₂O trade-off even with 3X higher engine-out NOx → improved fuel economy

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<th>Engine-out NOx g/bhp-h</th>
<th>After-treatment</th>
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<td>9 g/bhp-hr</td>
<td>SCRT®</td>
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<td>4.5 g/bhp-hr</td>
<td>SCRT®</td>
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<td>12 g/bhp-hr</td>
<td>SCR + SCRT®</td>
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</table>
Ammonia creation & conversion technology (ACCT) demonstrated on LD prototype vehicle

Loughborough Univ., SAE 2018-01-0333

Exhaust waste-heat used to convert urea to ammonium carbamate solution

Ammonium carbamate solution decomposes to ammonia at T > 60 °C

Thermolysis/hydrolysis of urea

\[
\text{CO(NH}_2\text{)}_2 + 6.92\text{H}_2\text{O} \rightarrow 2\text{NH}_3 + \text{CO}_2 + 5.92\text{H}_2\text{O}
\]

Products dissolve in steam

\[
2\text{NH}_3 + \text{CO}_2 + 5.92\text{H}_2\text{O} \rightarrow \text{NH}_4(\text{H}_2\text{NCO})_{\text{aq}}
\]

Example 1

Motorway driving

>75% conversion at \(\sim 160\) °C

Example 2

Mountain driving

→ Near complete conversion using ACCT

10L/6000 mi, Conversion rate needed: 0.07L/h, Additional P = 10W
What next for Diesel?
Pre-turbo catalyst combined with electrically assisted turbo < 35 mg/km NOx over a wide range of driving conditions

Vehicle: JLR F-Pace 2.0L EU6b

PTC reduced enthalpy at TC ~ 4% on WLTP
→ 11 kW e-TC added to overcome this loss

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<th>System</th>
<th>Battery</th>
<th>After-treatment</th>
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<td>Ref 1</td>
<td>12 V</td>
<td>DOC 2.0, SDPF 3.0, SCR 5.0</td>
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<td>Ref 2</td>
<td>48 V</td>
<td>Above and e-DOC</td>
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<td>3</td>
<td>48 V</td>
<td>DOC 2.0, SCR 5.0, SDPF 2.0, SCR 5.0</td>
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</table>
Ducted fuel injection (DFI): Near soot-free Diesel combustion

Sandia Natl. Lab, SAE High Eff. ICE 2019

Concept
Fuel injection through small tube
- Leaner fuel-rich mixture in autoignition zone
- “Leaner lifted flame combustion (LLFC)”

Const. vol. combustion vessel experiments

Study of optimum duct geometry
Constant pressure vessel experiments
Caterpillar SAE 2019-01-0545

Free jet
- 6 mm
- 4 mm
- 2.2 mm
- 0.1 mm

Free jet
- 8 mm
- 10 mm
- 12 mm
- 14 mm
Advanced after-treatment systems enable “negative emissions”
But need to address cold start and high emitters

Fleet measurements in Zürich

Tailpipe PM$_{2.5}$ = $2\times10^4$ #/$\text{cm}^3$ $\sim$ 10 $\mu g$/m$^3$
Delhi PM$_{2.5}$ $>$ 100 $\mu g$/m$^3$

Tailpipe soot emissions of Diesels with DPF (# / cm$^3$)

Measurement sample on Los Angeles HWY

1999 vehicle designed for 1/10 of ULEV: 4 mg/mi NMOG (non-methane organic gas) and 20 mg/mi NOx, or roughly SULEV

Honda, Hokkaido 2017
Summary – Light Duty

Fuel economy / CO₂ emissions

- CO₂ reduction targets across the world will require a 3 – 6% improvement in fuel economy per year
- Electrification mandates being proposed: China is now including hybrids in NEVs.

Criteria Pollutant Regulations

- Particulate emissions is a key health concern: PN regulations in EU/CN/IN
- US still the tightest for gas emission standards
- With tailpipe emissions approaching near-zero, focus now on real-world and in-use compliance
- Key elements of post Euro 6 regulations are being discussed

Technology trends / implications

- Various advanced ICE technologies still to be deployed. Pathways to 50% BTE outlined.
- Hybrids offer a 20 – 30% reduction in CO₂ today
- Lower comb. temperatures emphasize the role of advanced after-treatment systems

Technologies to reduce criteria pollutants

- Gasoline particulate filters (GPFs) widely being deployed in EU and China
- Reduction of cold start emissions is critical: TWC, HC-traps, SCR, DOCs are improving
- Euro 6 RDE compliant gasoline and Diesel vehicles certified and exceed the requirements
- Hybrids can have unique emission challenges which must be tackled
Heavy-Duty
Europe has first CO$_2$ targets for Heavy-Duty Vehicles
Fleet average reduction of 15% by 2025, 30% by 2030, compared to 2019
# Global Heavy Duty Regulations

## On-Road

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<td>US 2010 + ARB Optional low NOx</td>
<td>Tier 4F</td>
<td>Tier 5 (?)</td>
<td>ARB Low NOx 20 mg/bhp-hr</td>
<td>EPA CTI</td>
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<td>CO2 / FC</td>
<td>GHG Phase 1</td>
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<td>CO2 / FC</td>
<td>HD CO2 : 15% vs. 2019</td>
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<td>CN V</td>
<td>CN VI - Key areas</td>
<td>CN Via (July 2020)</td>
<td>CN V (July 2023)</td>
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In-use NOx emission limits continue to reduce across major markets
Coupled with significant cuts in CO₂ / GHGs

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<td>EPA 2010 : NOx 200 mg/bhp-h, PM 10 mg/bhp-h</td>
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<td>Optional low NOx : 0.1, 0.05 &amp; 0.02 g/bhp-hr</td>
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<td>EU VI A, B, C ISC: Power threshold 20%, Max payload 50 - 100%</td>
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<td>EU VI D ISC: Power threshold 10%, Max payload 10 - 100%</td>
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<td>EU VI E Trip share (for N3): 30% urban (up from 20%), 45% motorway Include cold start PN CF = 1.63</td>
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<td>CO₂ measurements for 2019 baseline</td>
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<td>15% reduction in 2025</td>
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Emphasis on reducing cold-start NOx emissions without impact on fuel consumption
Various after-treatment system concepts being evaluated
HD Low NOx rule: CARB proposing 60-75% NOx tightening and MAW ISC testing for 2024. 2027: increased warranty and durability requirements, and use of telematics.

<table>
<thead>
<tr>
<th>Step</th>
<th>Timing</th>
<th>Proposed Change</th>
<th>Technology Implications</th>
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</thead>
</table>
| Step 1 | MY 2022 – 23 | **Minor modifications to NTE**  
- Min ambient T = 7°C  
- Min after-treatment T = 200°C | Hardware modifications not likely needed                      |
| Step 2 | MY 2024 – 26 | **Reduced limits for NOx**  
FTP / RMC-SET: 0.05 to 0.08 g/bhp-hr  
**New low load cycle (LLC)**  
NOx: 1 to 3 x FTP std  
**New HDIUT program**  
MAW method, CF = 1.5 ~ Euro VI-D  
PM: 0.005 g/bhp-hr on FTP / RMC-SET  
**Durability Demonstration Program** | Engine calibration +  
Some engine and aftertreatment hardware modifications |
| Step 3 | MY 2027+  | **More stringent NOx standards 0.0x TBD**  
HDIUT ~ Euro VI-E (incl. cold-start, etc.)  
Possible compliance using NOx sensors / telematics warranty and useful life requirements | Major hardware upgrades to engine & aftertreatment |
**China VI Heavy-Duty Regulations**

- **End of 2022:**
  - Nationwide, all
  - PM, PN, NOx limits same as Euro VI
  - RDE PEMS testing for gas emissions
  - Remote OBD hardware in place

- **2023: Nationwide, all**

- **2024:**
  - Nationwide, all

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**China VIa**

- Focus areas*, Buses, garbage vehicles

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**China VIb (proposed)**

- Beijing: VIb
  - 7/2019: CNG, City vehicles
  - 1/2020: All HDVs

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**China VIb**

- RDE PEMS testing for gas and PN (CF = 2.0)
  - payloads 10% - 100% of rated weight
  - Extended BCs: -7 to 35 °C, 2,400 m (vs 1700 m)
  - Report engine-out NOx
  - Vanadia SCR $T_{\text{max}}$ 550 °C for FUL
  - OBD III – Remote transmission

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**Durability:** 700K km for heaviest vehicles
China’s Clean Diesel Program
ICCT, 2019

Eliminate 1M pre-China IV diesel & NG trucks by 2020

Environmental information disclosure
- Agencies will check emission control devices, OBD against form, and conduct RDE tests

In-use I&M program
Remote OBD
Remote sensing
Transmission of data to authorities
Random roadside & onsite inspections

NEVs to power > 8% of new urban fleets (buses, sanitation trucks, postal vehicles, taxis, and commuting coaches)

Early China VI implementation in “Key Regions”
Beijing, Tianjin, Hebei, Shanxi, Shandong, Henan, Shanghai, Jiangsu, Zhejiang, Anhui, Shaanxi, Nei Mongol, Sichuan, Chongqing

Fuel / urea quality
> 95% compliance of Diesel fuel (10 ppm) and urea quality

China IV Off-road: Dec 1st 2020
OBD and telematics as key in-use compliance tools

July 1st 2019

+ Sichuan, Chongqing
NOx control

Systems
Euro VI HDD vehicles can meet NOx limits under real-world testing. Emissions higher during low speed driving, low amb T. NO$_2$ fraction is a concern.

RDE testing:
200 km, urban, rural, hwy, 3 repeats
Speed bins (km/h):
Low < 30, Med 30 – 70, High > 70
Payload: 60 – 65% of max.
Cold start excluded (30 min warm up)

NOx/CO$_2$ for long haul: 0.15 – 0.25 g/kg

Tailpipe NO$_2$: 10 – 67% of total NOx

PN one order of magnitude below limit

Euro VI Limit: 0.46 x 1.5 (CF)

Veh. 3

 Ambient T: 7 – 11 °C

Veh 3 Long haul

Veh 4 Long haul

Veh 5 Coach
CARB: New test cycle proposed to include low load emissions

In-use tailpipe NOx
0.11 – 3.14 g/bhp-hr

No data < 150 °C due to sensor limitations
NTE limit = 1.5x0.2 = 0.3 g/bhp-h

Line-hauls
Generally cleaner
< 0.3 g/bhp-hr
(account for 2/3rd of VMT in CA)

Vocational
Some have very high NOx
> 60% VMT and NOx in urban areas

Low load idling is ~ 1/3rd of total activity
And accounts for 14% of total NOx emissions

72 HDDVs

CARB, UC Riverside Env. Sci. Tech. 2019, 53, 5504 - 5511
Various technologies are being developed to reduce NOx

- Engine methods e.g. CDA, EGR, calibration, etc.
- Improved SCR catalysts
- Dual SCR (cc-SCR)
- SCR on filters
- Passive NOx adsorbers
- Thermal mgmt. (e.g. burners)
- Alternative engine architectures (Opp. Piston)
- Low T NOx Conversion
- NH₃ delivery at low T

Two leading approaches being evaluated:
Southwest Research Institute / CARB

© 2019 Corning Incorporated
Combination of engine-out reduction & improved A/T necessary
Need to watch for N$_2$O, higher soot, fuel consumption penalty

IAV, SAE HDD Symposium, Gothenburg 2018

Baseline

Low NOx

Simulation study: 6-cyl. HD EuroVI engine, EGR, 2-stage TC
US HD FTP cold & hot
Thermal management: Early post injection + intake throttle idle + intake throttle in low load + retarded start of main inj. + exhaust throttle load + idle

Potential for further improvement through PNA, gas NH3

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<tr>
<th>Vol., l</th>
<th>ccSCR</th>
<th>ccAMOX</th>
<th>DOC</th>
<th>DPF</th>
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<td>15</td>
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<td>4.4</td>
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H. Rauch et al., 7th MinNOx 2018

Weighted raw NOx (g/bhp-h)

Weighted TP NOx (g/bhp-h)

Weighted TP N$_2$O (g/bhp-h)

Fuel cons. (kg)

Soot raw emissions (g)

+3 %

+31 %
HD opposed piston engine simulations show path towards ultra-low NOx emissions

Achates, SWRI SAE 2018-01-1378

Data from 4.9L OP engine used to simulate 10.6L Class 8 engine

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<th>Specification</th>
<th>Value</th>
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<td>Arrangement, no. cyls.</td>
<td>Inline 3</td>
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<td>Bore</td>
<td>120 mm</td>
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<td>Total Stroke</td>
<td>312 mm</td>
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<td>Stroke-to-Bore Ratio</td>
<td>2.6</td>
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<td>Compression Ratio</td>
<td>17.5:1</td>
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<td>Nominal Power (kW @ rpm)</td>
<td>336 @ 1700</td>
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<td>Max. Torque (Nm @ rpm)</td>
<td>2373 Nm @ 950</td>
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<td>Exhaust mass flow at rated power</td>
<td>1412 kg/hr</td>
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Elevated exh. T through increased residuals
With close-coupled SCR, deNOx can start in < 100 sec.

In progress: The CALSTART and Achates contract with CARB to install 10.6 liter 2SOP engines into two Class 8 trucks to be placed in revenue service.

Objectives: 20 mg/hp-h NOx, at lower FC than standard diesel
Natural Gas
Solid PN emissions measured on RDE from 24 diesel, CNG, and LNG trucks and buses

PN measured under real world driving:

- Stoichiometric NG trucks
  $3.3 \times 10^{11} - 4.5 \times 10^{12}$ #/km

- Diesels with DPF
  $8 \times 10^9 - 7 \times 10^{11}$ #/km

- CNG vehicles found to have > 50% of sub-23 nm particles

- Diesels with DPF also have high sub-23 nm particles, but total emissions are less than limit
Pd-based catalysts for methane oxidation
Enhanced activity and improved stability, water resistance

Doubly Confined Pd-Ce NW@SiO₂ for enhanced methane activity and stability

Single Atom Pd/Rh-CeO₂
Light-off < 300 °C, >80% at 350 °C

Other learnings (data not shown here)
• High Si/Al ratios → higher hydrophobicity → improved activity & stability
• PdO nanoparticles are more active than isolated Pd ions of PdOx clusters
Methane conversion: PGM activity can be enhanced by adding spinels, coupled with lambda modulation.

U. Houston, CDTi, U. Virginia, ORNL DOE AMR 2019

**Catalyst**
- PGM: 95% Pt, 5% Pd, 30 g/ft³
- Spinel: Mn₀.₅Fe₂.₅O₄, 100 g/L

**Flow reactor**
- \( \lambda = 0.981 - 1.009, \langle \lambda \rangle = 0.995 \)
- CH₄ = 1500 ppm, O₂ = 4500 ppm – 8900 ppm, CO 8000 ppm, H₂ 2000 ppm, NO 1000 ppm, 10% H₂O, 10% CO₂, rest N₂
- Light-off < 350 °C

**Dual Layer**
- PGM/Alumina
- Spinel
- Cordierite

**Single Layer**
- PGM/Alumina + Spinel
- Cordierite

Coating architecture does not have a significant impact on performance.

Increasing amplitude:
- Methane conversion also improves with modulation.
- NO conversion also improves with modulation.

Lambda Cycling
- No Cycling
Summary – Heavy Duty

- Regulations are tightening in California; China VI beginning soon (?); Brazil in motion
  - CARB 2024: 50-80 mg/bhp-hr NOx and MAW; 2027: further NOx tightening and increased durability and warranty
  - Continued emphasis on in-use emissions in major markets
- Engine research aimed at 55% BTE under road load – impressive progress in SuperTruck 2 program. Mixed approaches with common themes.
- NOx control developments are targeting low-load and high efficiency, in line with CARB program. Durability is also topic.
  - EU success on WBW ISC;
- Oxidation catalysts advancing with LT CO control, consolidation of DOC and ASC, methane conversion getting to $T_{50} \sim 300-350^\circ C$.
- Incremental PM control advances and understanding – stoichiometric NG truck PN, DOC+CSF integration
CORNING