NRMM Emission Control Experience in North America

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Advanced Emission Technology Driven By U.S. Mobile Source Emission Regulations including Comprehensive Compliance and Enforcement Programs

Tier 3 Light-Duty
final rule 2014
fully phased in 2025
Diesels held to same standards as gasoline vehicles
Diesel sulfur now < 15 ppm;
Gasoline sulfur at ca. 10 ppm in 2017

Ocean-going Vessels
final rule 2009; IMO ECA in 2010
ECA: 1000 ppm Sulfur in 2015;
80% lower NOx in 2016 (new OGVs)

Heavy-Duty Highway
final rule 2000
Sulfur now < 15 ppm
fully phased in 2010

Locomotive / Marine Tier 4
final rule 2008
Sulfur now < 15 ppm
fully phased in 2017

Nonroad Diesel Tier 4
final rule 2004
Sulfur now < 15 ppm
fully phased in 2015;
basis for new stationary engines

MECA

SCR is the Dominant NOx Control Technology for Mobile and Stationary Engines

Tier 4
Off-Road
Engines

Power Plants

Heavy Duty
Vehicles

Gas Turbines

Tier 4
Locomotive
Engines

SCR
Products

Waste Incineration

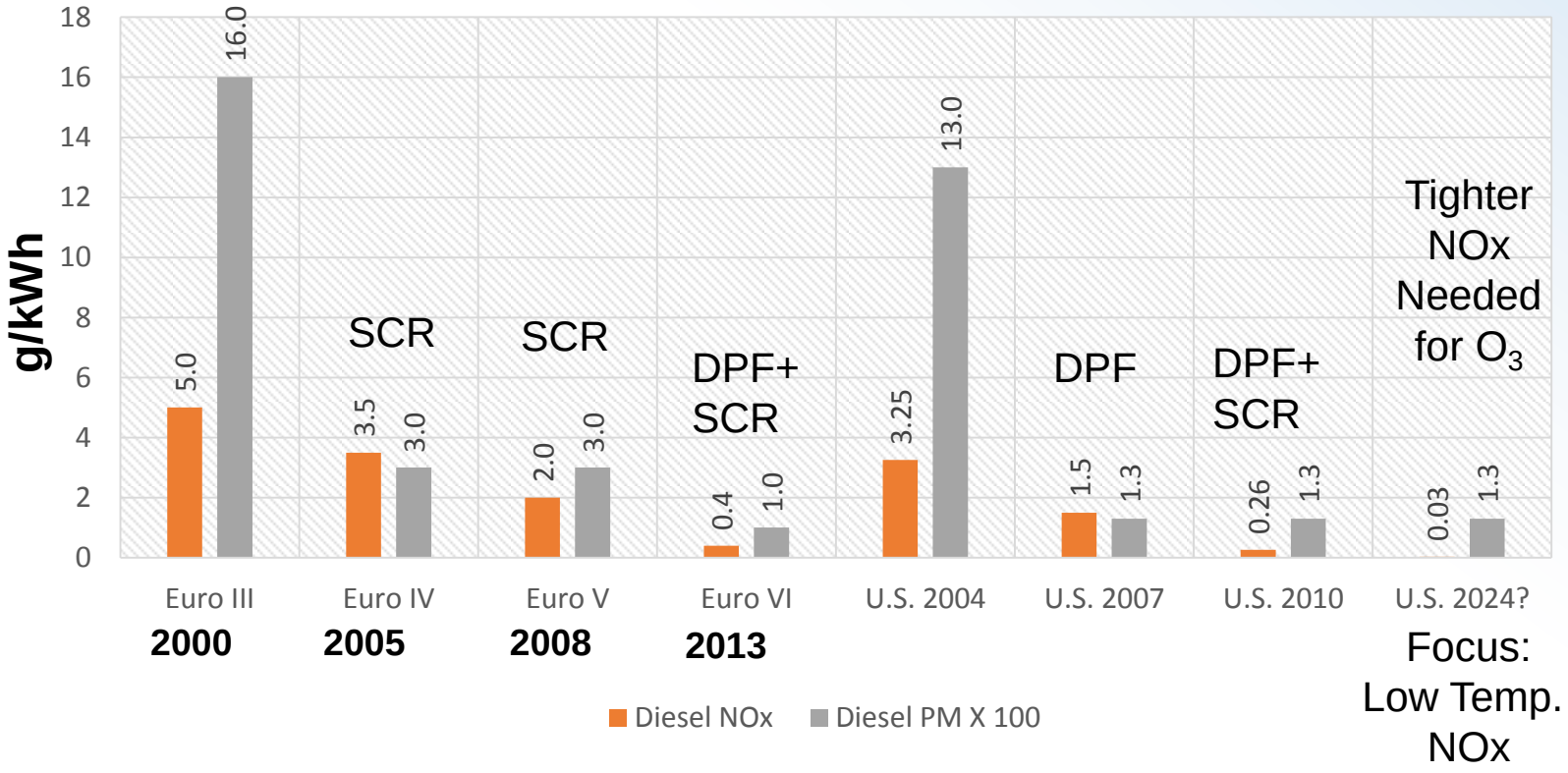
Marine
Engines

Diesel Passenger Cars

Stationary
Engines

Heavy-Duty Standards and Technologies

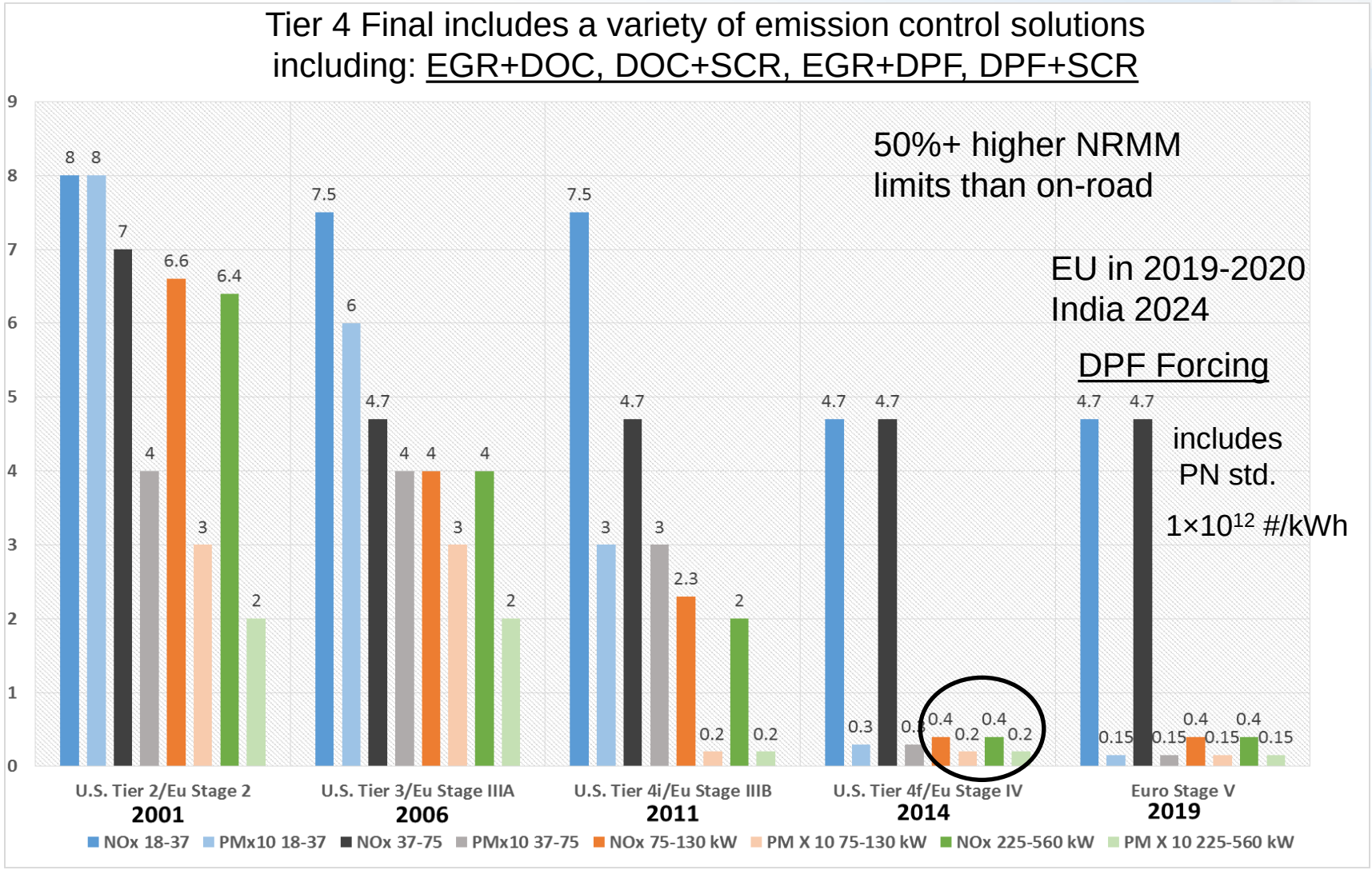
U.S. vs. Europe Heavy-Duty On-Road Engine Transient Cycle Emission Standards



Note: Euro VI NOx limit is 0.46 g/kWh on the WHTC
Euro VI includes 6.0 X 10^{11}/kWh particle number limit for diesels on WHTC

International Nonroad Diesel Emission Standards

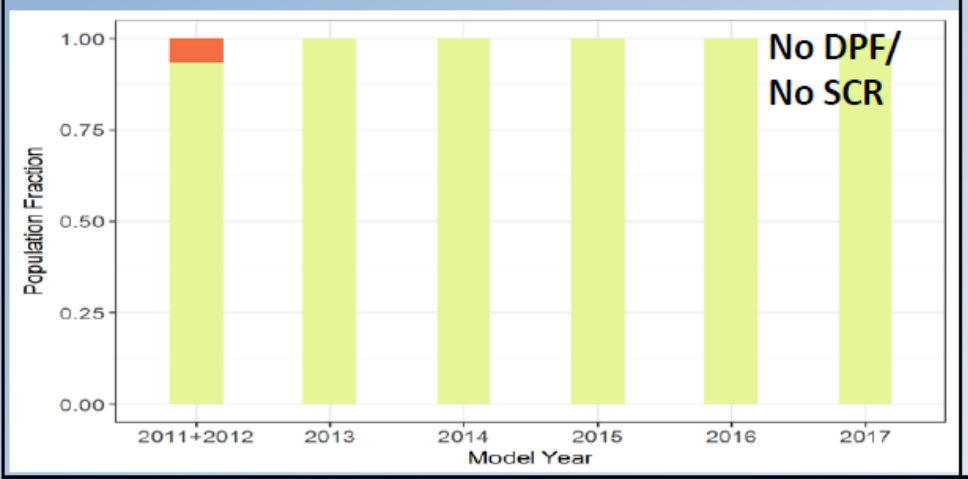
(representative standards only shown for select engine power ratings)



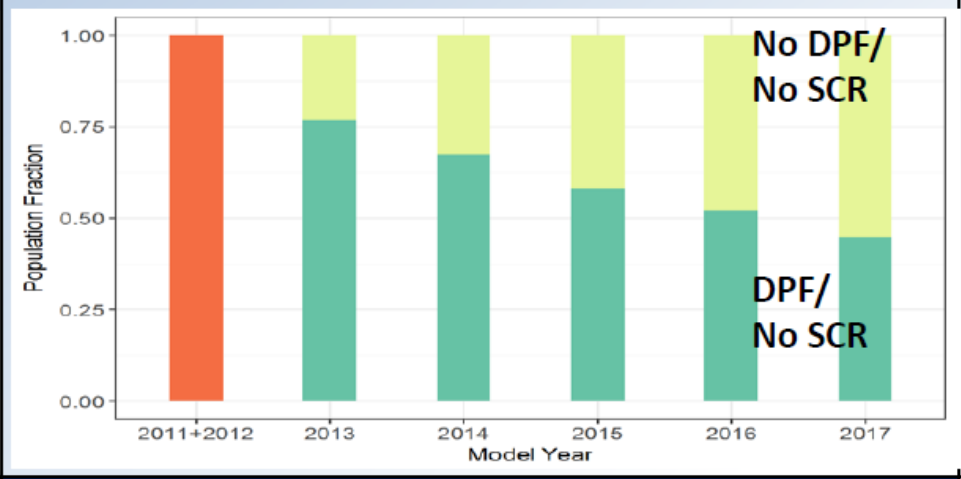
Notes: Change from steady-state cycle to NRTC starting with U.S. Tier 4i/Euro Stage IIIB

NRMM Tier 3 and 4 Certification and Technology

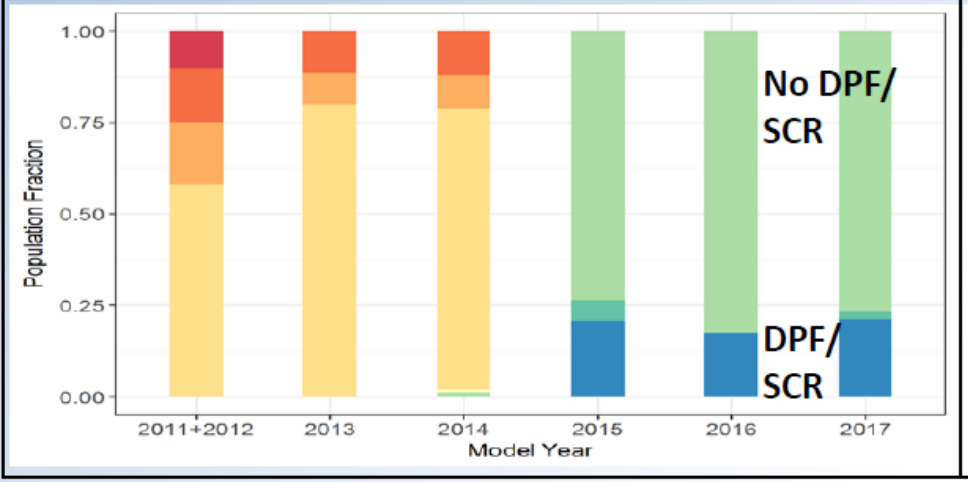
HP <=25



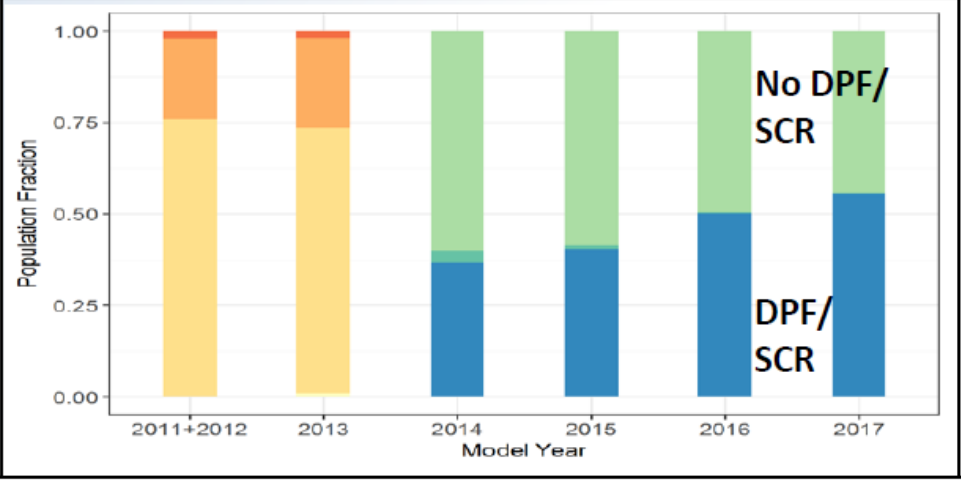
HP 50 to 75



HP 100 to 175

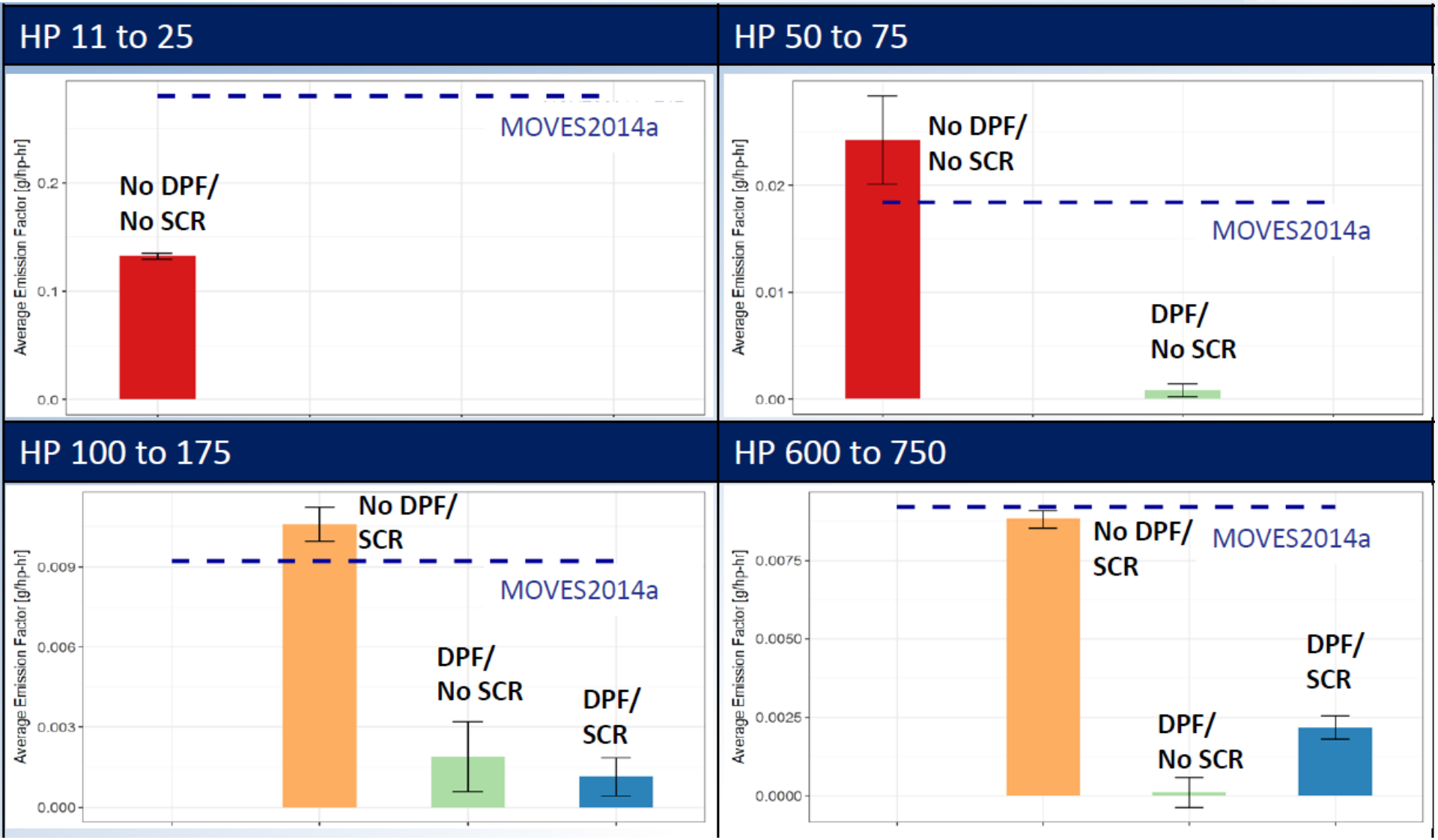


HP 600 to 750



Source: U.S. EPA, CRC 2018, Han

NRMM Tier 4 final PM Emission Factors



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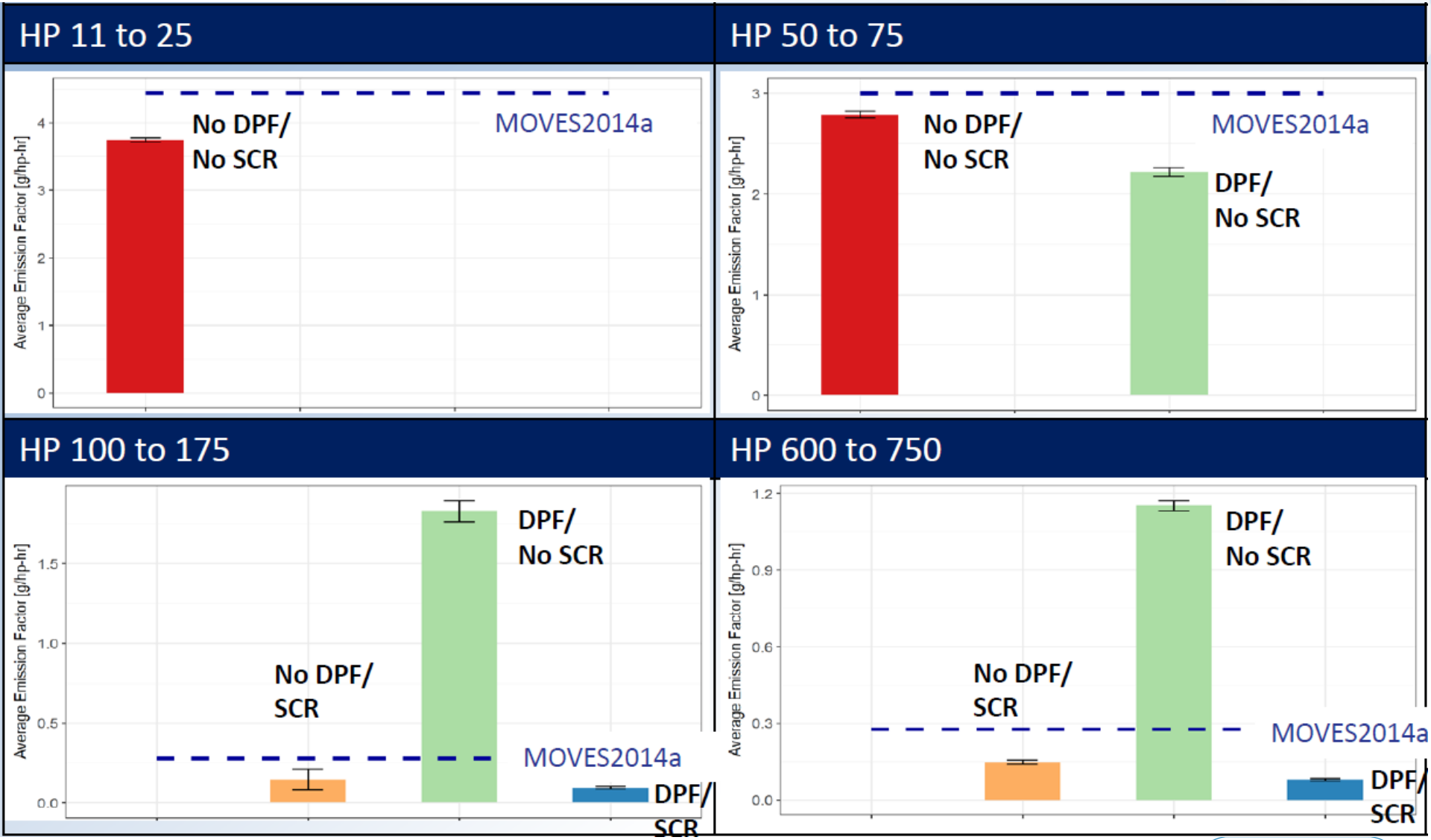
NRMM Tier 4 final NOx Emission Factors

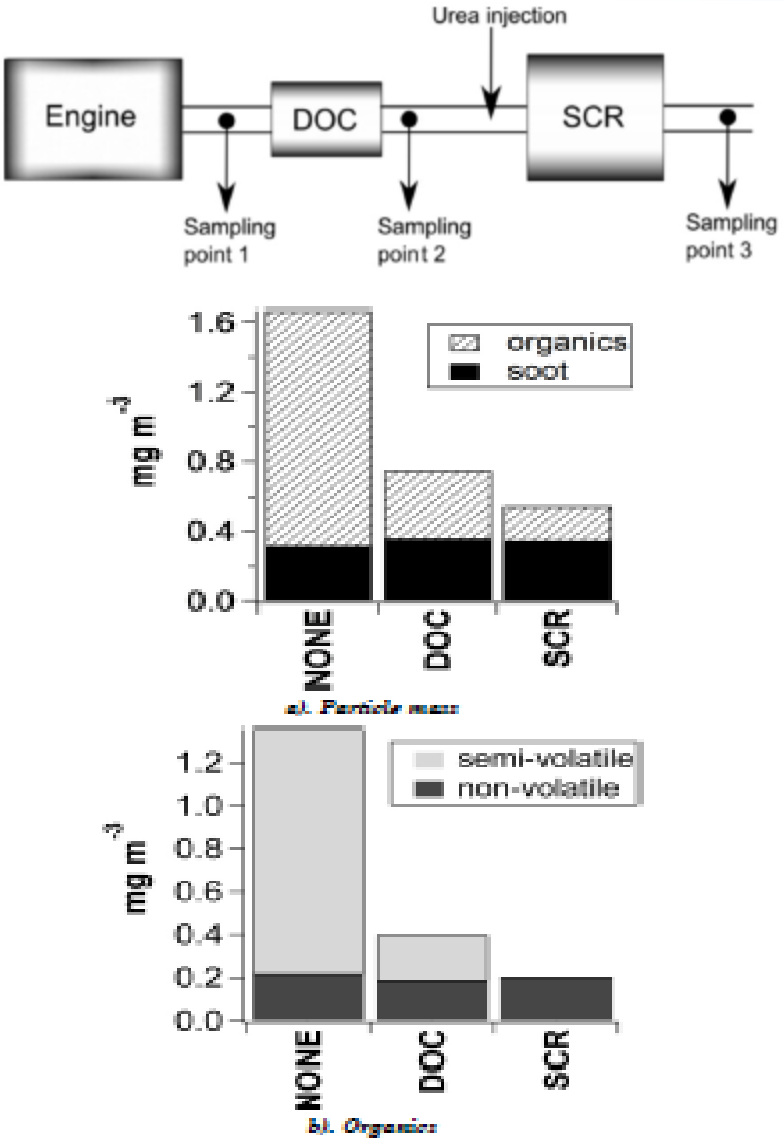


Source: U.S. EPA, CRC 2018, Han

Technology Solutions

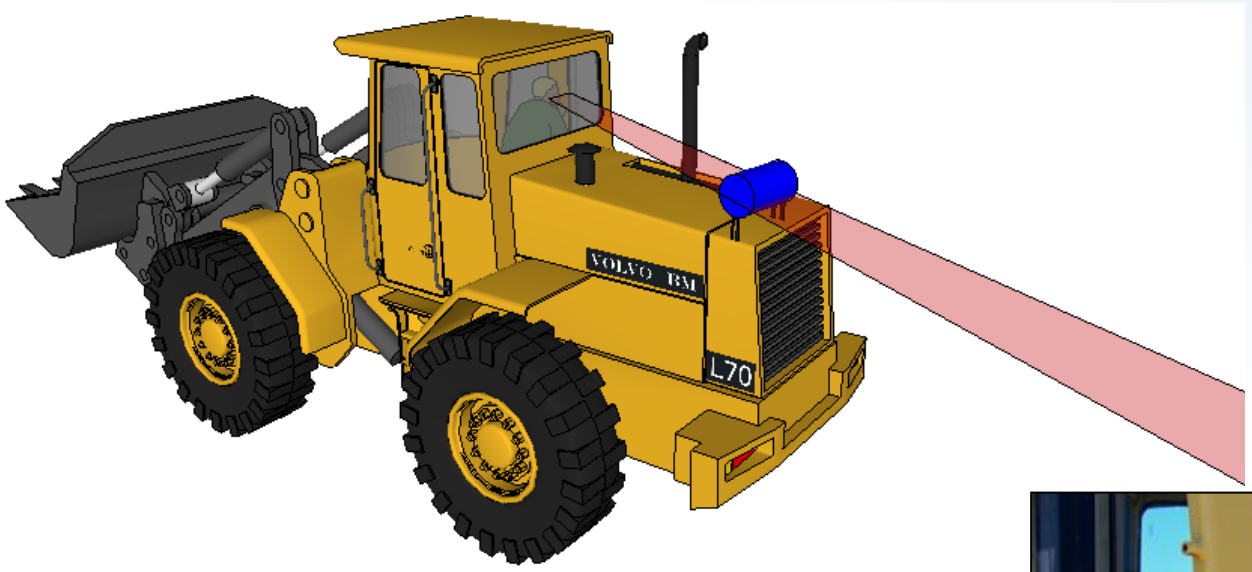
What is “Clean Diesel?”

Commonly Defined as: DOC + DPF + SCR



- Euro Stage IIIB (Interim Tier 4)
  200 kW, 6 cyl. engine fueled with 10 ppm max. S fuel
  (SAE 2012-01-1664)
- Low temperature, transient testing (portion of NRTC)
  282 +/- 21 C after turbo
  239 +/1 3 C before SCR
- DOC+SCR impacts organics/ semi-volatile particles but little impact on soot/non-volatile particles
- Exhaust chemistry will be different from DPF applications - PAHs with soot, PM levels with lower compliance margins

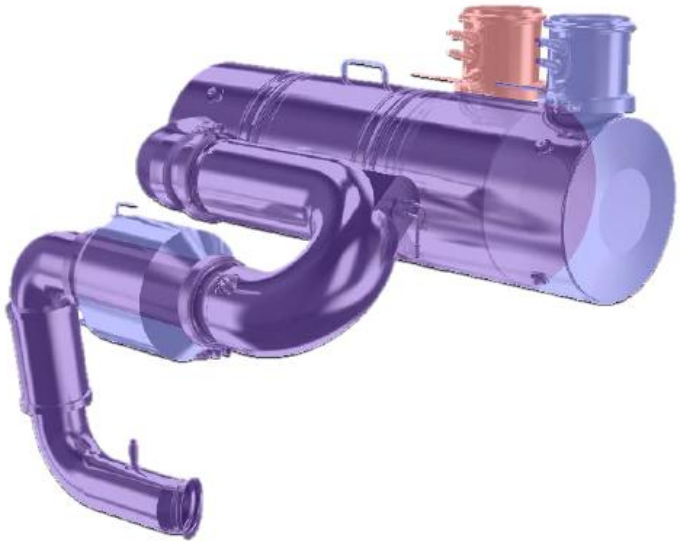
NRMM Solutions Must Consider Packaging and Visibility



Under hood installation is best combined with larger cowling and higher seating positions

Stage V will Demand Best Available Control for both PM and NOx

- Particle number limit in Stage V will require the use of wall flow filters.
- Many NRMM applications have limited space under hood for DOC, DPF and SCR without impacting visibility
- Coating SCR catalyst on DPF (SCRF) offers small package system for clean diesel solution.



Stage V exhaust system with SCRF
only 20% larger than previous Stage IV SCR

SAE HD Symposium 2016, Liebherr

Large Off-Road Heavy-Duty Engines – Marine Vessels and Locomotives

- Current standards do not require the use of exhaust emission controls
- EPA finalized Tier 4 standards for locomotive and marine diesel (C1, C2) engines in 2008; requires ULSD
  - Tier 4f PM (0.04 g/kWh) and NOx (1.8 g/kWh)
    - Line haul, switcher locomotives: 2015 for PM & NOx
    - Commercial marine 600 kW and larger: 2014-2017 for PM & NOx (phase-in based on power rating; 3700 kW & larger Tier 4f PM limit is 0.06 g/kWh)
- North American Emission Control Area (ECA) established, effective August 2012 (consistent with IMO limits)
  - 0.1% sulfur max. since January 2015 (scrubbers are allowed)
  - Tier 3 NOx limits within ECA for new ship started in 2016 (SCR, EGR, LNG all options)

U.S. Clean Diesel Locomotive Demonstrations

Passive DPF Retrofits on Tier 2 Gen-Set Switcher Loco

Tier 4 Gen-Set Switcher with DPFs

Tier 2 Loco Retrofit with EGR and DOCs/DPFs

GE Tier 4 Line Haul Loco with EGR

U.S. Clean Diesel Marine Demonstrations

SCR Retrofits on 2 Staten Island Ferries

DOC + Crankcase Filter Retrofits
On Mississippi Barge Tugs

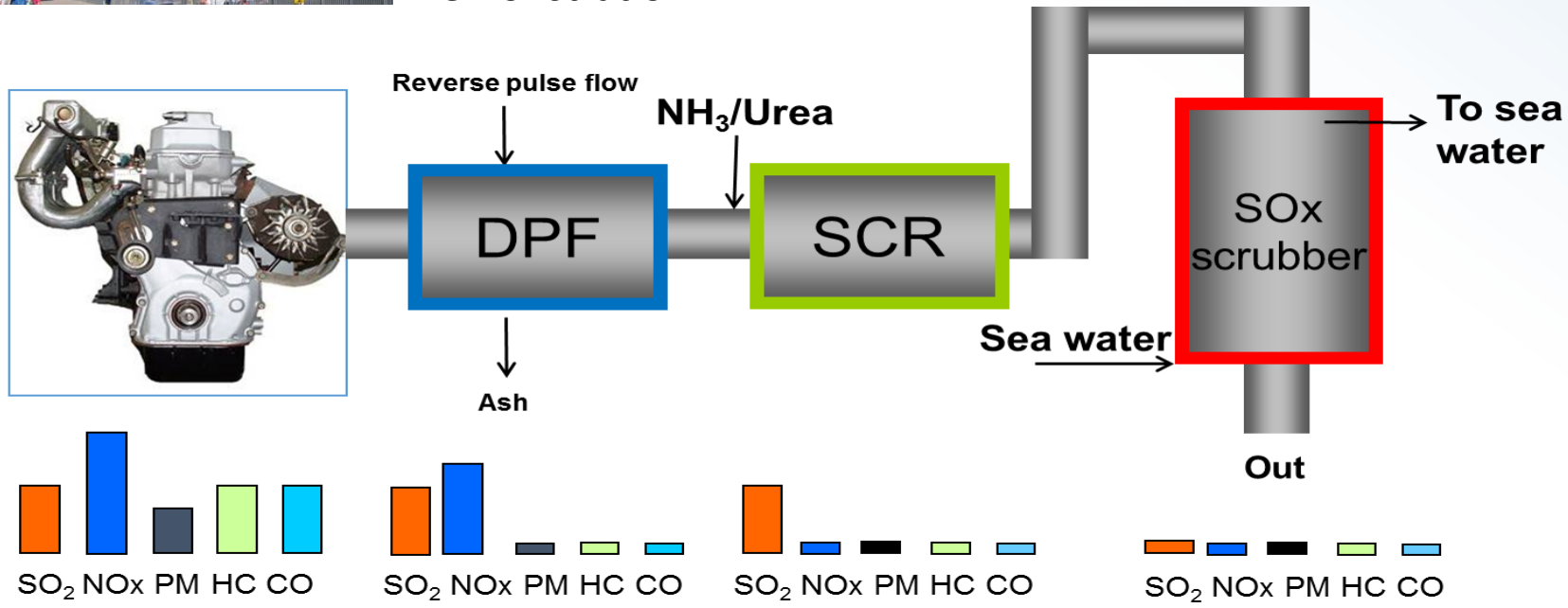
DPF+SCR Retrofit on LA Port Tug

Long Beach Hybrid Tug Retrofit

Multi-Pollutant Control from Ocean Going Vessels

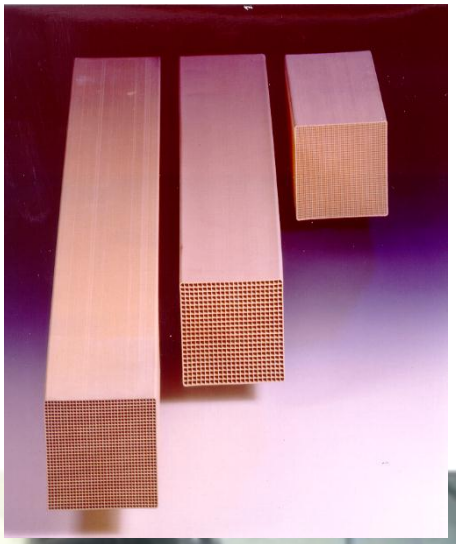
Queen Victoria Cruise Ship Demonstration

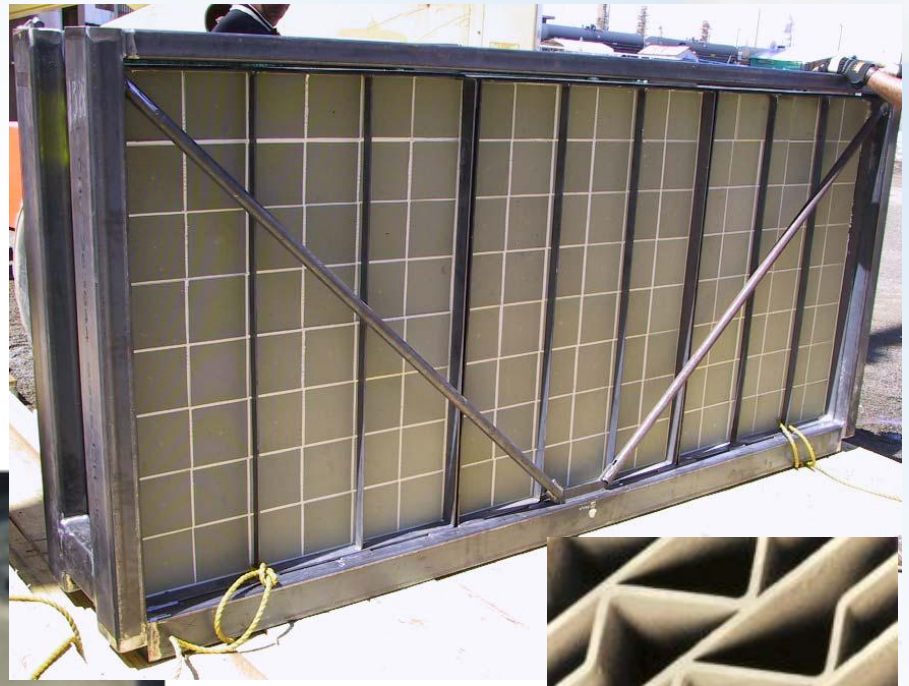
Three-Way Control of PM, NOx and SOx
DPF: SiC substrate, Pd/V_2O_5 Catalyst with reverse pulse ash cleaning
V-SCR and urea for NOx control
Scrubber allows use of HFO fuel



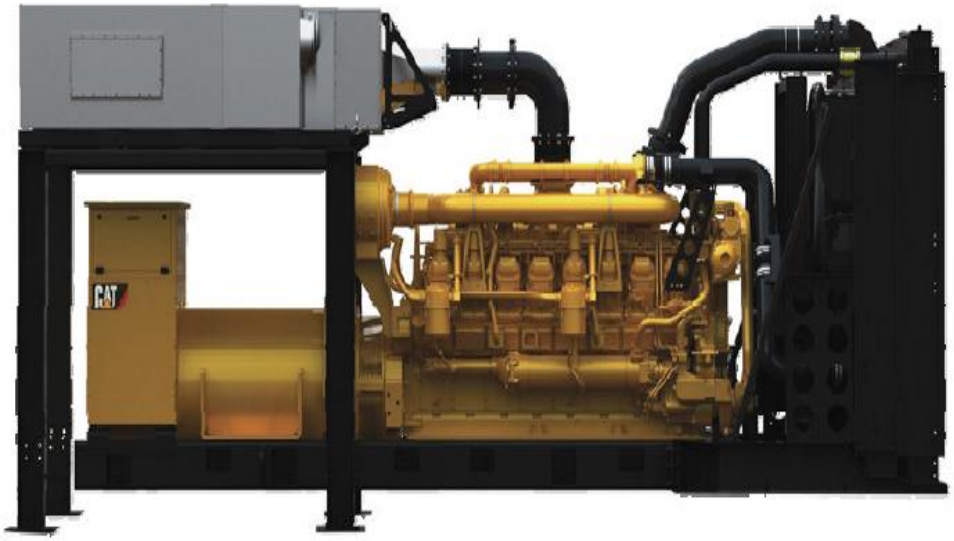
Johansen, Catalysis Today, 258 (2015): pp. 2-10

SCR NOx Emission Controls in Stationary Applications

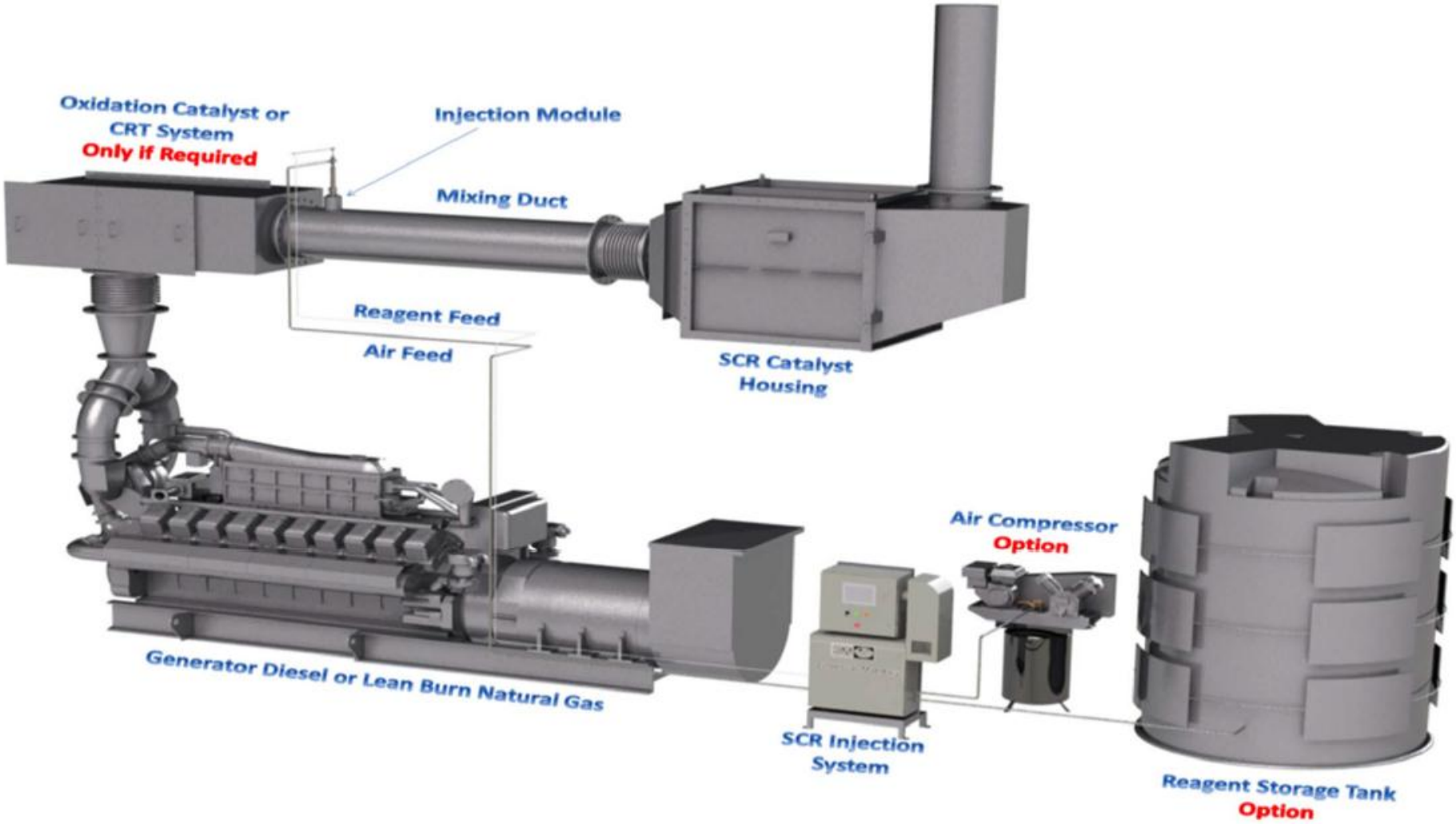




DOC and Filter Stationary Installations



DPF and SCR on Diesel Generator



Conclusions

- Regulations have driven the development and introduction of clean diesel emission technologies in both on-road and off-road diesel engines
- Use of ULSD allows for the opportunity to employ best available technologies for controlling PM and NOx
- U.S. Tier 4 emission regulations for nonroad diesel engines (stationary, marine, locomotive) are less stringent than in the heavy-duty highway sector allowing for engine-based controls for PM (no DPFs), and solutions including EGR or SCR for controlling NOx
- Stage V will require the addition of DPFs or SCRFs where space is limited