

Potential for NRMM real-world CO₂ and NOx emissions reduction

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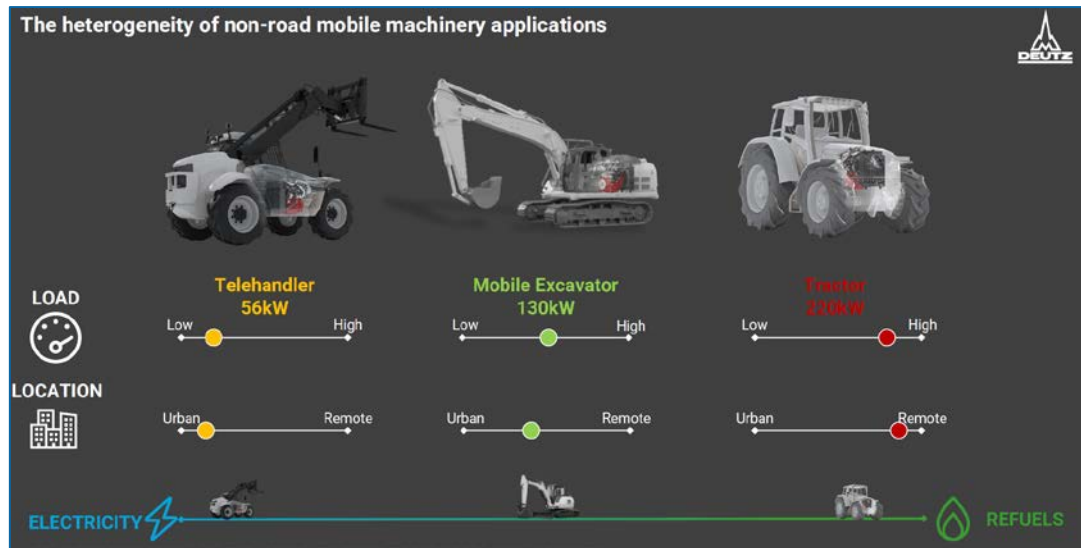
AECC is now the Association for Emissions Control and Climate

- AECC expands its scope
 - Air quality and **climate** requirements
 - Mobile and **stationary** emissions sources
 - Sustainable **components and systems**, including
 - Catalysts
 - Filters
 - Adsorbers
 - Fuel cells
 - Electrolysers
- AECC is listed in EU Transparency Register (# 78711786419-61) and has consultative status with the UN Economic and Social Council (ECOSOC)

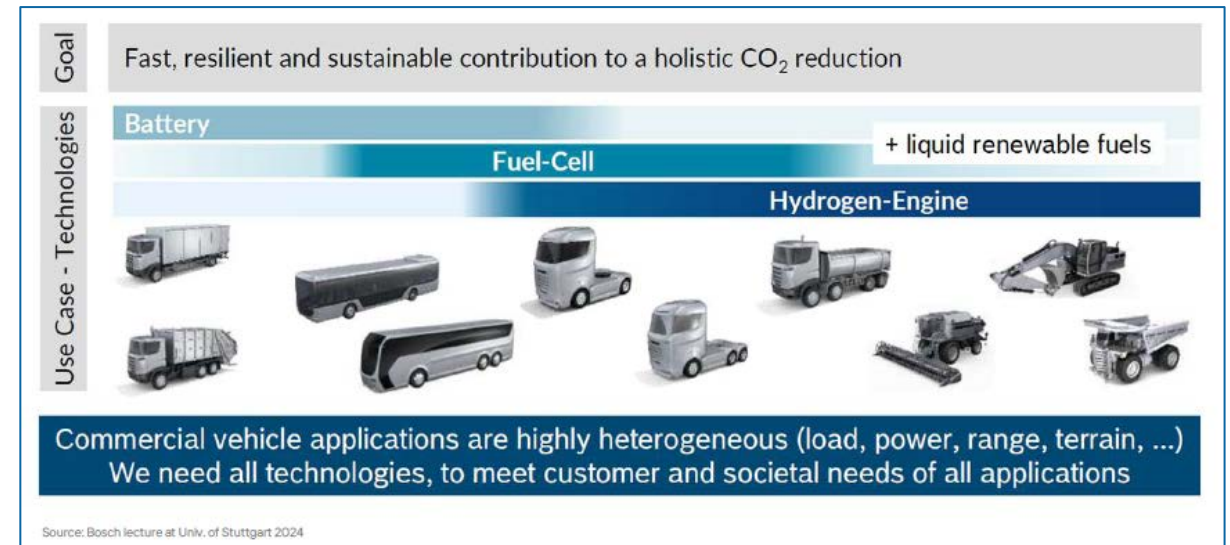


All powertrain technologies needed towards net-zero CO₂

- Internal Combustion Engine (ICE) remains key for the NRMM use cases
- Different sustainable renewable fuels are investigated to reduce the carbon footprint



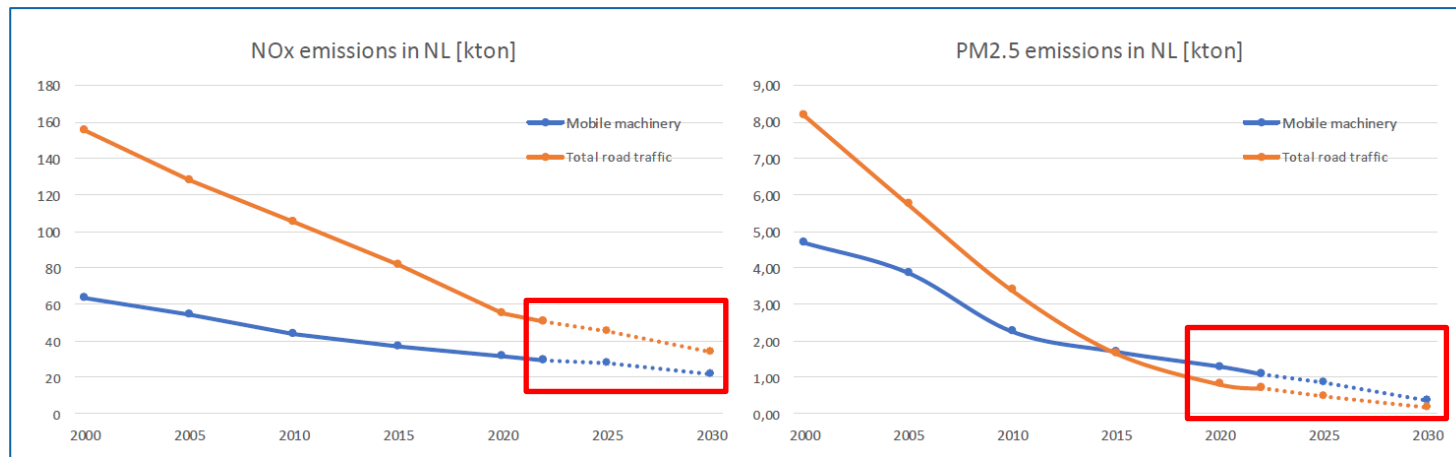
Deutz, Baden-Baden, 2024



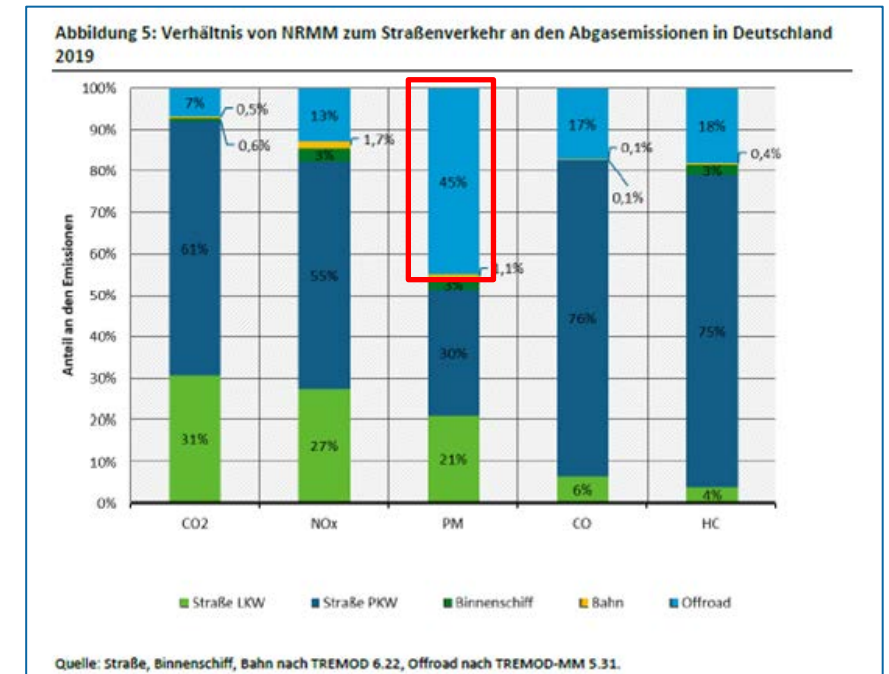
Bosch, lecture at Univ. Stuttgart, 2024

Further reduction of pollutant emissions needed as well

- Increasing contribution of NRMM to EU air quality impact



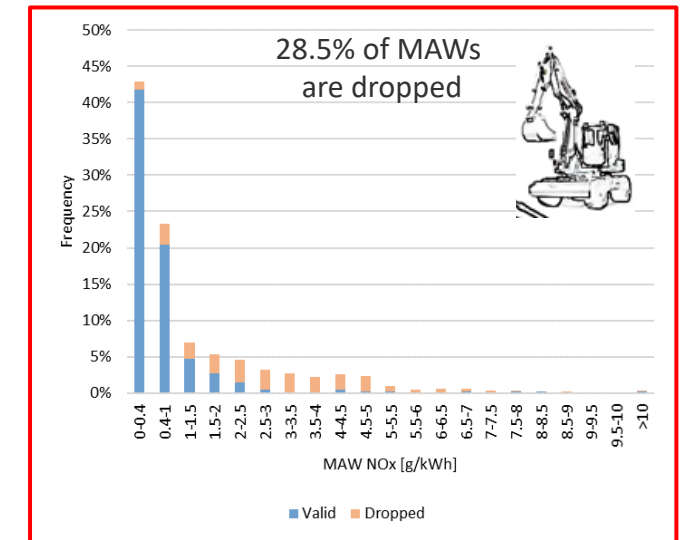
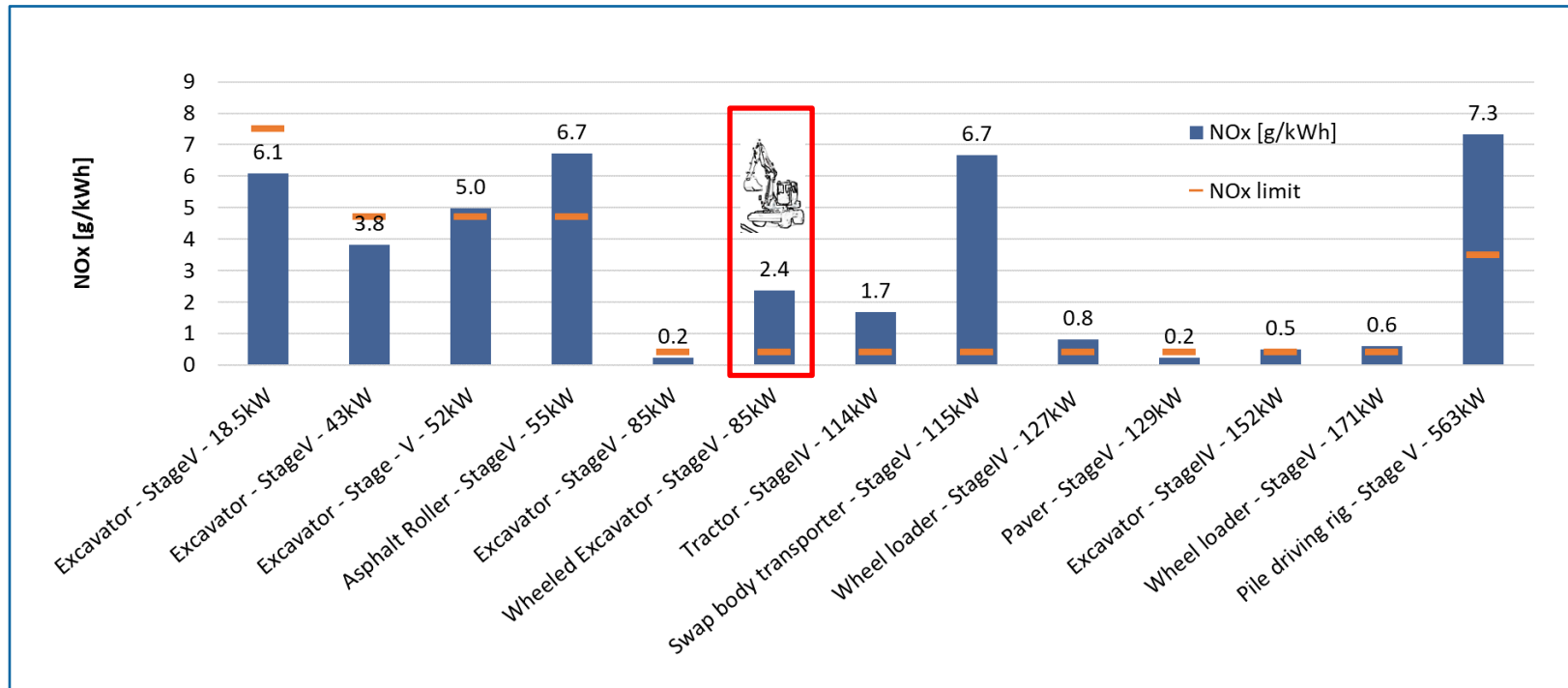
The Netherlands, [GRPE presentation](#), 2023



Germany, [UBA report](#), 2023

Further reduction of pollutant emissions needed as well

- Large variation in real-world emissions is observed over various NRMM applications
- NRMM regulation does not consider a substantial share of the real working conditions



MAW: Moving Average Window

R. Vermeulen, et al.; "[Real-World NOx emissions of Stage V NRMM](#)", Transport and Air Pollution Conference, 2023

Further reduction of pollutant emissions needed as well

- NRMM typically follows on-road HDV legislation, which evolved already towards Euro 7
 - Applying PEMS In-Service Conformity (ISC) instead of monitoring only
 - Removing data exclusions which significantly impact the measurement results
 - Reducing the emission limits
- Ongoing initiatives
 - European Commission will review Stage V in 2025 based on PEMS monitoring data
 - Informal discussions at UNECE GRPE about UN Regulation No. 96
 - US CARB started [development for Tier 5](#) by 2029 since November 2021
 - China includes NRMM in China 7 considerations

PEMS: Portable Emissions Measurement System



Agenda

- Initial NRMM data from a HDV Euro 7 bench demonstrator
- NRMM simulation study
 - Set-up with 3 emission control variants
 - NO_x and N₂O emissions
 - CO₂ emissions
- Conclusions

Initial data from HDV Euro 7 bench demonstrator

- NRTC data obtained from on-road HDV project as starting point for NRMM investigation
- AVL demonstrator set-up

- HDV engine

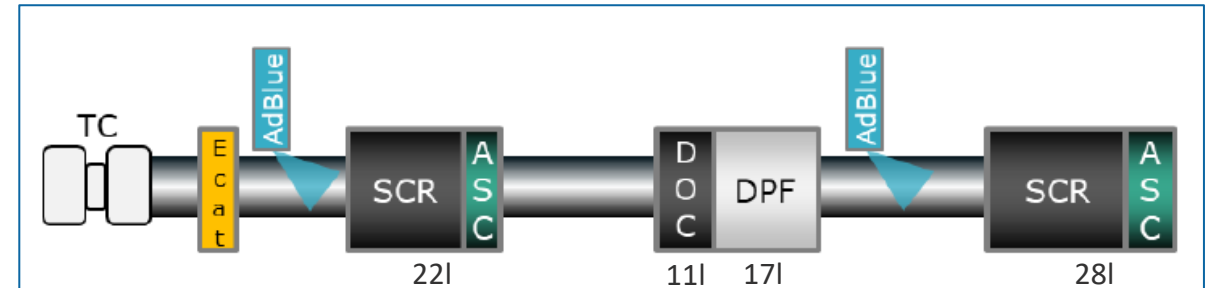
- 13l class, 25kW/l
- Uncooled High Pressure EGR
- Fixed geometry turbocharger
- 8-10 g/kWh engine-out NOx

- Emission control system, screening for Euro 7

- Dual-SCR with ASC, DOC and DPF
- Without and with EHC (7-10kW)

- Control strategy

- EHC enabled if temperature before close-coupled SCR < 250 °C, disabled if > 300 °C
- SCR based on closed-loop NH₃ storage control, except when mean Temperature of main SCR < 250 °C



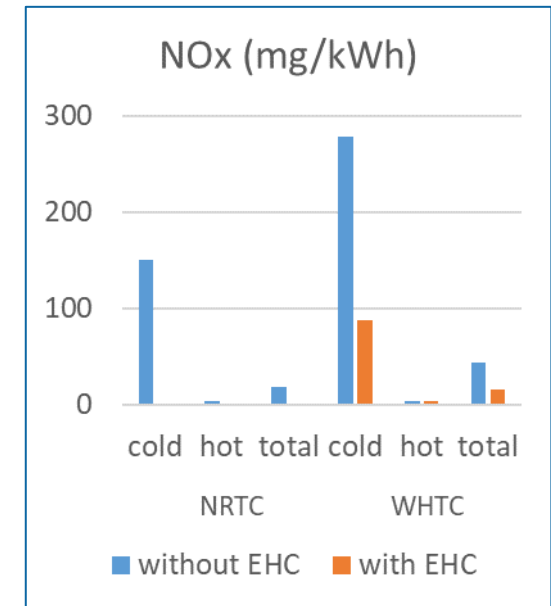
EGR: Exhaust Gas Recirculation
TC: Turbocharger
EHC/Ecat: Electrically Heated Catalyst

SCR: Selective Catalytic Reduction
ASC: Ammonia Slip Catalyst
DOC: Diesel Oxidation Catalyst
DPF: Diesel Particulate Filter

Initial data from HDV Euro 7 bench demonstrator

- Results on type approval cycles
 - NRTC, only w/o EHC
 - WHTC, with both variations of the system
- Relevant data, but several constraints identified
 - Majority of NRMM applications < 6l engine
 - NRMM power density can be up to 38kW/l
 - NRMM has variable geometry turbocharger
 - Operation at high engine speed and load not covered
 - Emission control system screening was for HDV Euro 7
- AECC launched an additional NRMM activity

CARB Tier 5 interim limit
Euro 7 lab limit
CARB Tier 5 final limit



EHC: Electrically Heated Catalyst

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Simulation study on 3 emission control systems

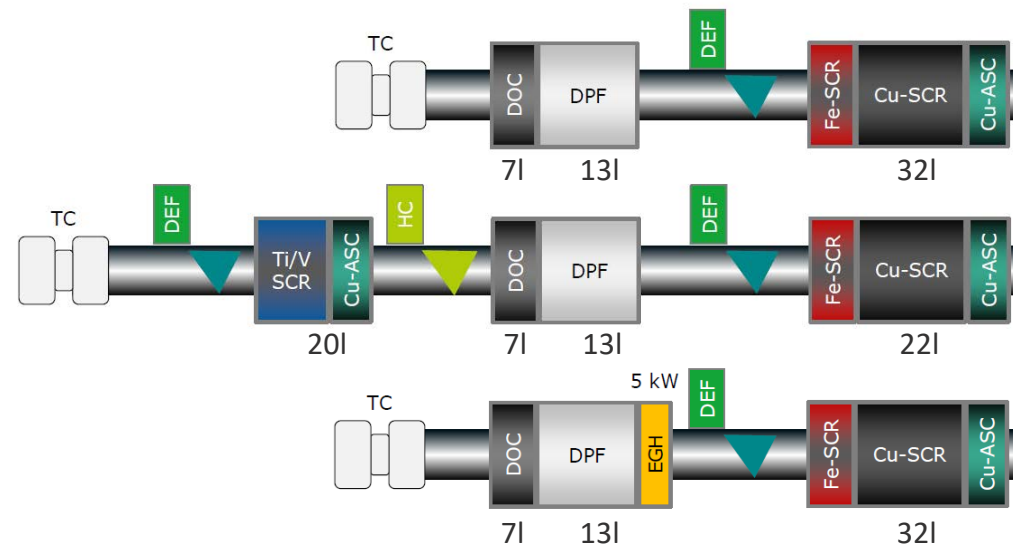
➤ AVL simulation set-up

➤ NRMM engine

- 9l class
- Uncooled High Pressure EGR
- 2-stage turbocharger
- 8-10 g/kWh engine-out NO_x

➤ 3 emission control systems

- Variant 1 – enhanced Stage V
- Variant 2 – dual-SCR
- Variant 3 – variant 1 incl. EGH



EGR: Exhaust Gas Recirculation
TC: Turbocharger
EGH: Exhaust Gas Heater
SCR: Selective Catalytic Reduction
ASC: Ammonia Slip Catalyst
DOC: Diesel Oxidation Catalyst
DPF: Diesel Particulate Filter

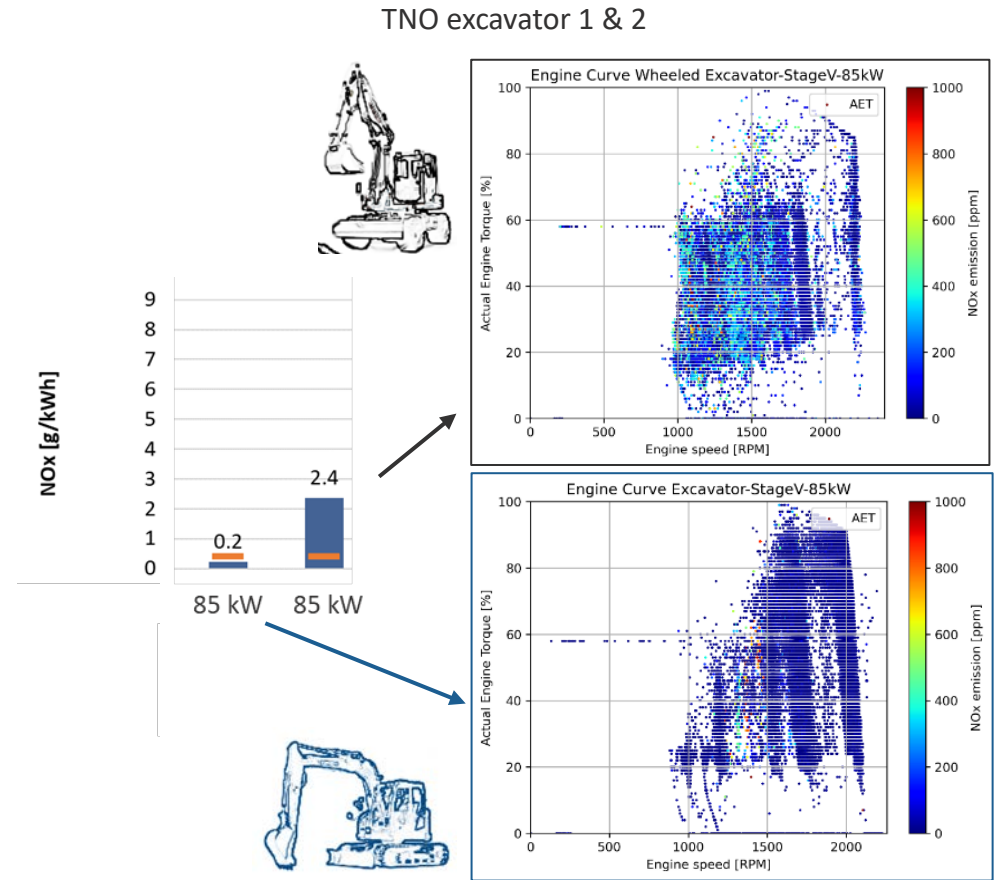
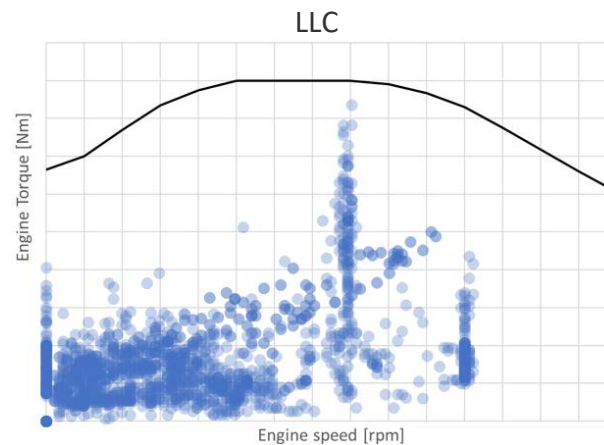
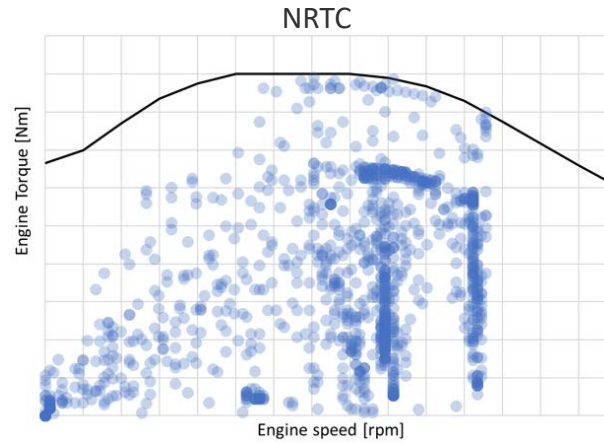
Covering wide variation in NRMM applications

▶ Type approval cycles

- ▶ NRTC cold and hot
- ▶ NRSC
- ▶ RMC
- ▶ LLC

▶ In-use application cycles

- ▶ AVL wheel loader 1
- ▶ AVL wheel loader 2
- ▶ AVL bulldozer
- ▶ AVL hay mover
- ▶ TNO excavator 1
- ▶ TNO excavator 2

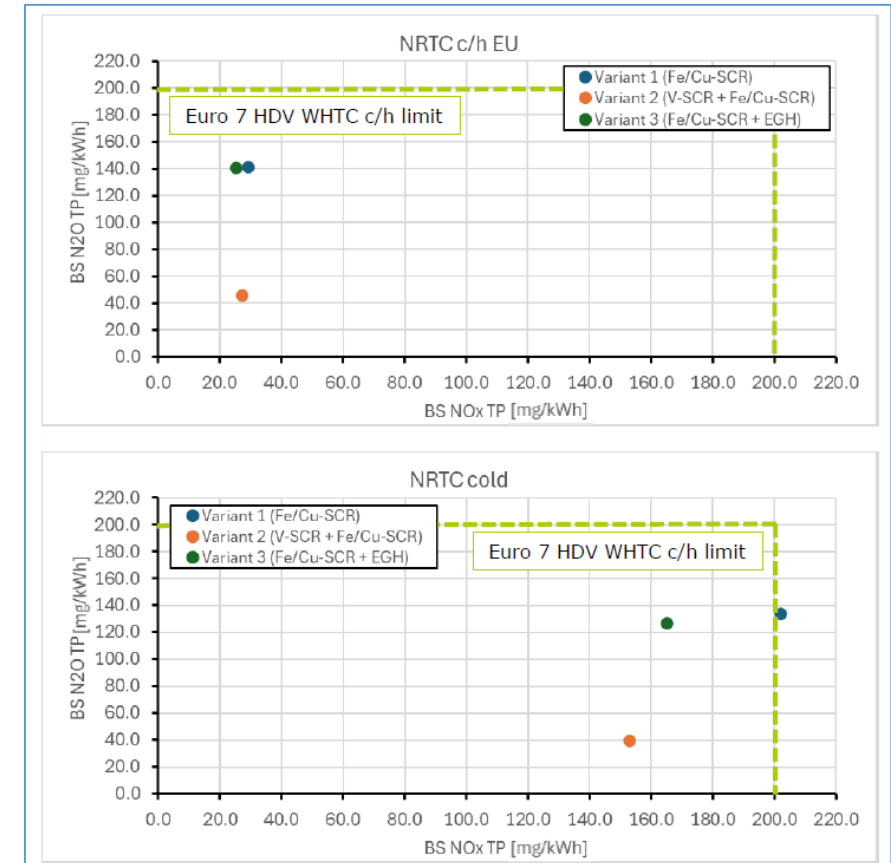
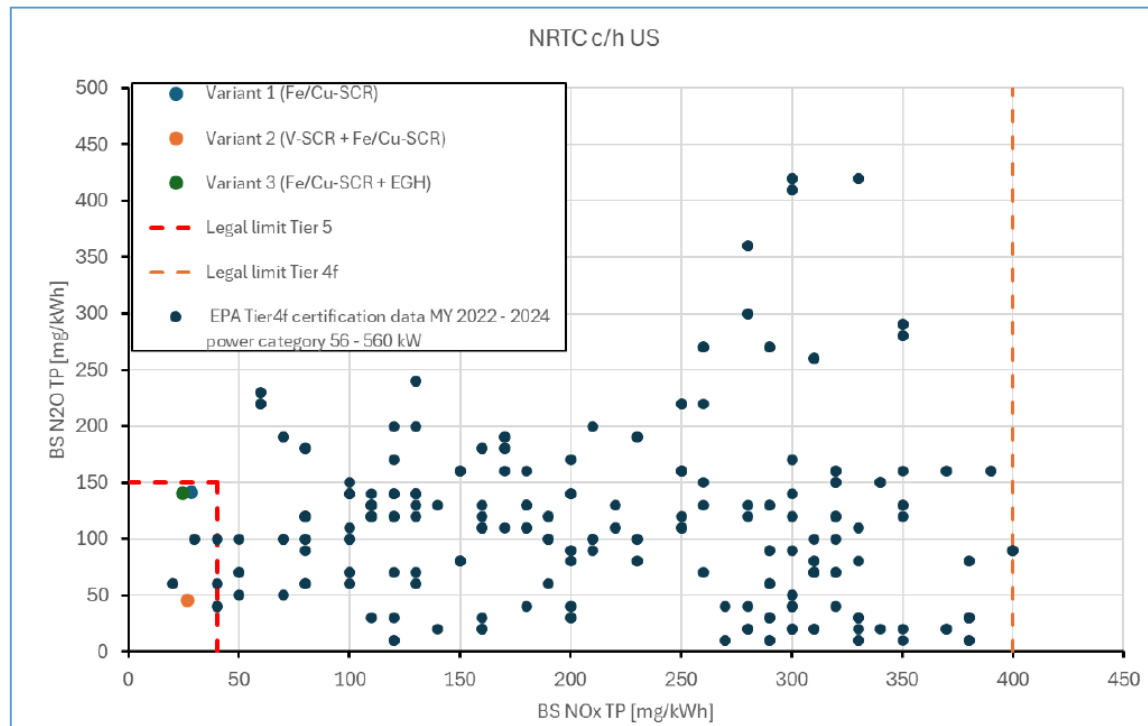


NRTC: Non-Road Transient Cycle
NRSC: Non-Road Steady-state Cycle

RMC: Ramped Mode Cycle
LLC: Low-load Cycle

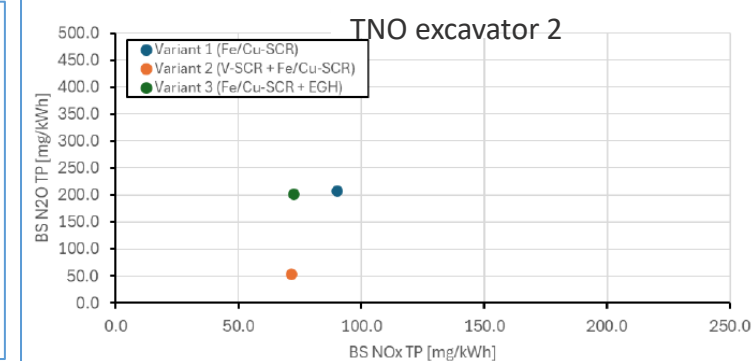
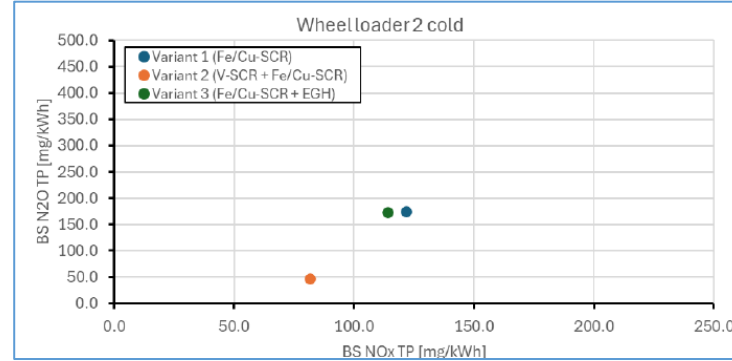
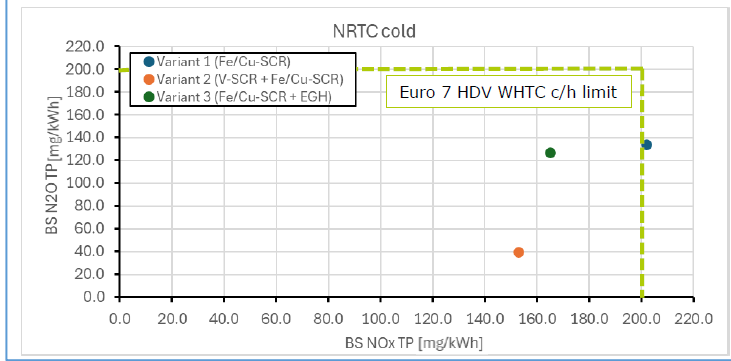
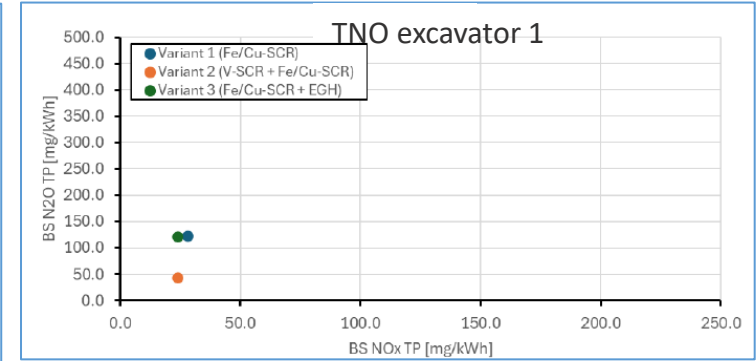
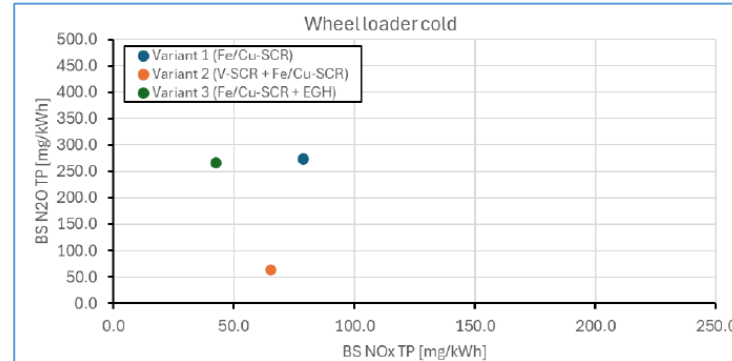
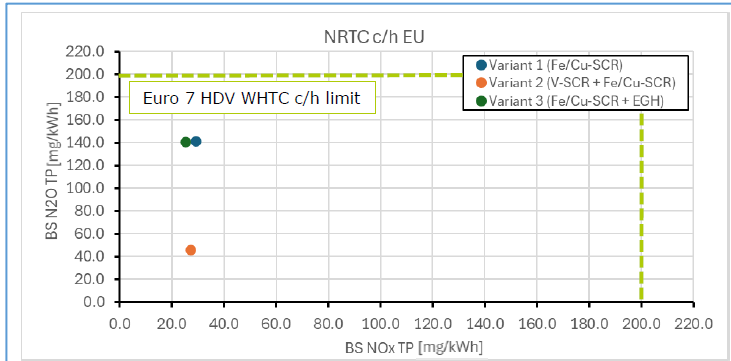
All 3 variants within CARB Tier 5 and Euro 7 limits on NRTC

- At lower end of existing US EPA Tier 4 [certification data](#)
- Variant 2 and 3 show lower cold-start emissions, but not visible after cold/hot weighing
- Variant 2 shows lower N₂O emissions



Consistent low emissions on in-use cycles

- Variation of in-use cycles is higher than NRTC with cold-hot weighing
- NRTC cold has highest result due to shorter cycle

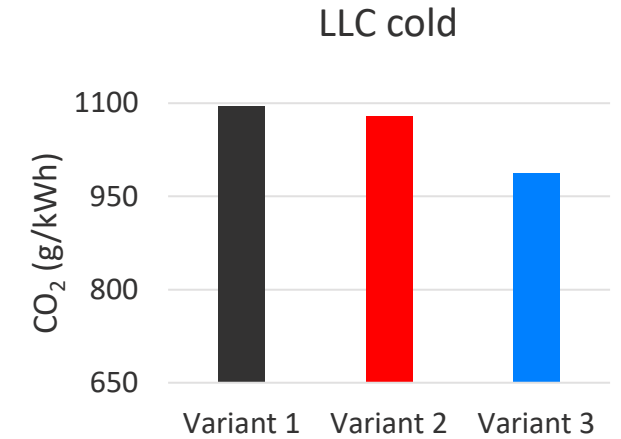
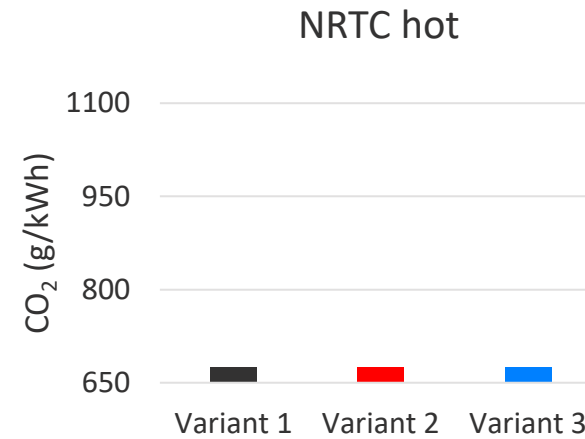


Agenda

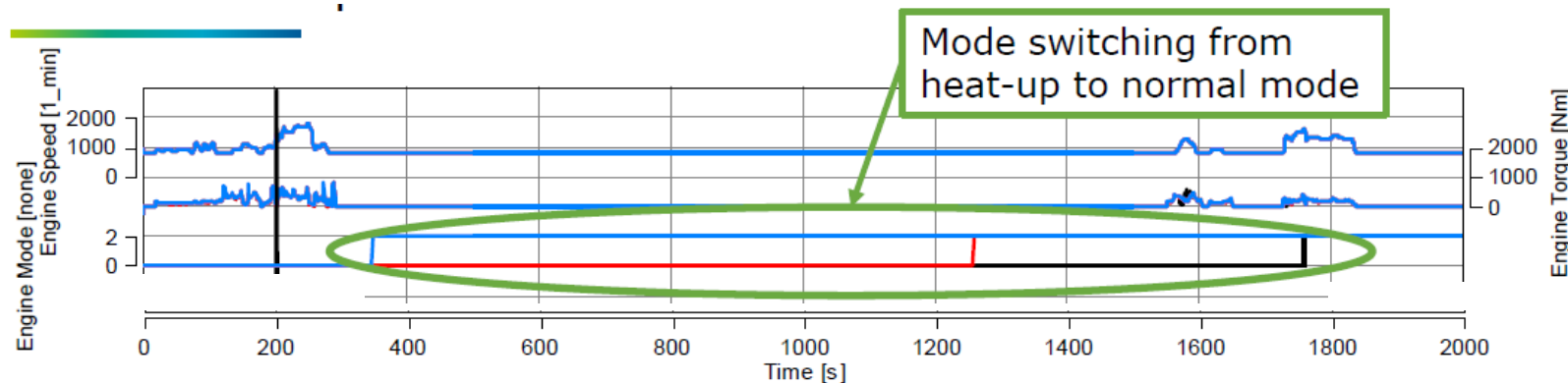
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Tailpipe CO₂ emissions

- Similar for all 3 variants on most of the tests
- Except for low-load conditions
 - Up to 10% difference on LLC cold test



- Due to different occurrence of engine mode switching



Boundary Conditions:

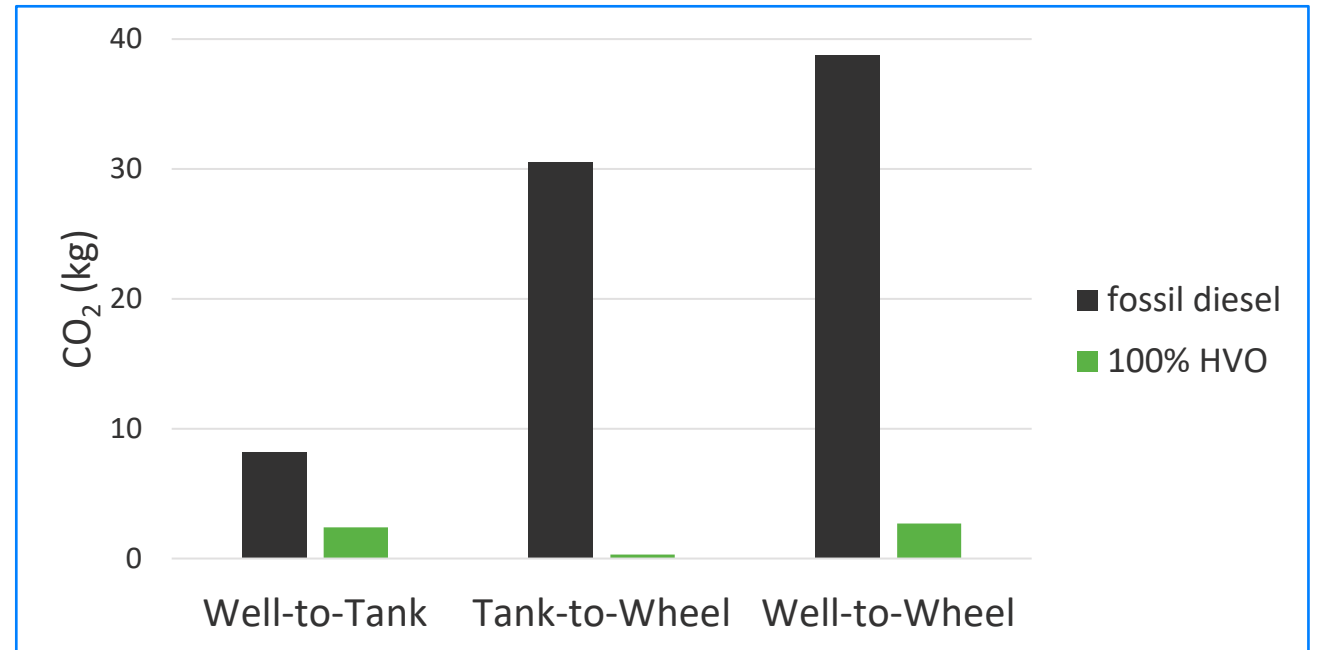
- LLC cold
 - 0 – 2000 seconds
- ATS Variant 1 (black)
- ATS Variant 2 (red)
- ATS Variant 3 (blue)

Well-to-Wheel (WtW) CO₂ emissions

➤ WtW CO₂ can nearly be eliminated by running on CO₂-neutral fuels

➤ Exemplary calculation for NRTC hot

- Fossil diesel
- 100% HVO from waste cooking oil



Conclusions

- The Internal Combustion Engine (ICE) is a key powertrain for the NRMM use cases
- Future-proof ICE concept requires zero-impact pollutant and net-zero GHG emissions
- Emission control technologies are available to achieve zero-impact pollutant emissions
 - Single-dosing SCR system can already address some shortcomings of Stage V regulation
 - Dual-dosing SCR and Exhaust Gas Heater are available with further benefits to cover the varying needs of wide range of NRMM applications
 - Depending on OEM engine concept and engine-out NO_x emission level
 - Alternating operating conditions
 - Continuous low-load operation
 - Initial cold-start
- Transition to CO₂-neutral fuels needed to achieve net-zero CO₂ emissions

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