Potential for Reduction in NRMM Real-World Emissions

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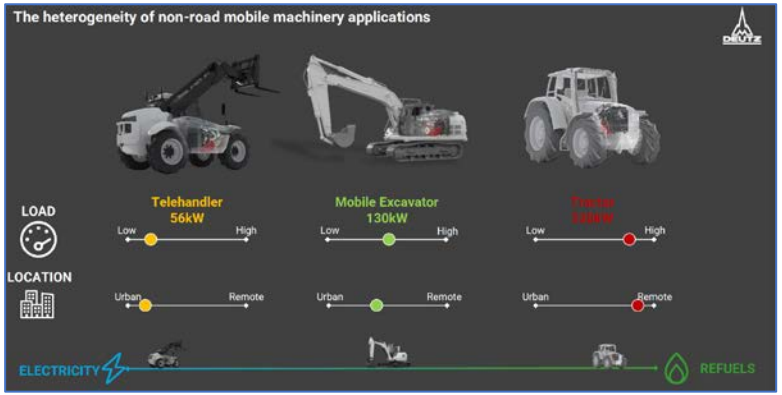
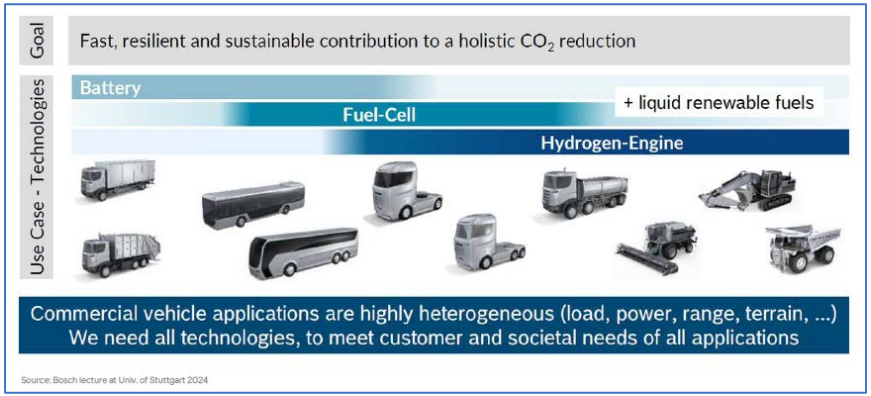
Mix of powertrains needed for net-zero CO_2

- Internal Combustion Engine (ICE) remains key for the NRMM use cases
- H_2 and liquid renewable fuels can reduce the carbon footprint



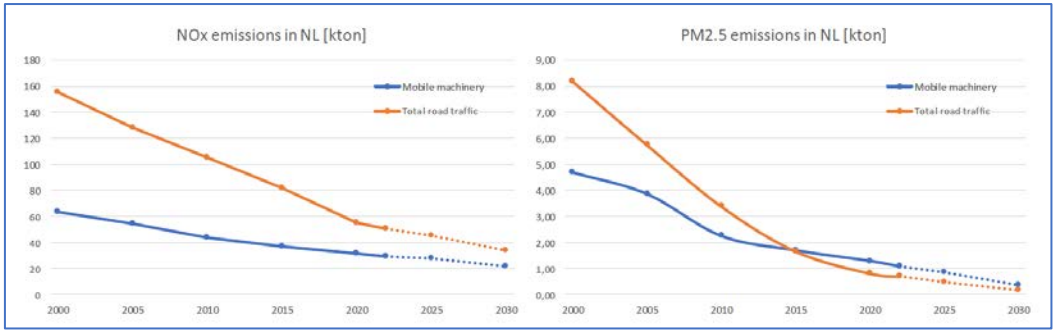
Deutz, Baden-Baden, 2024



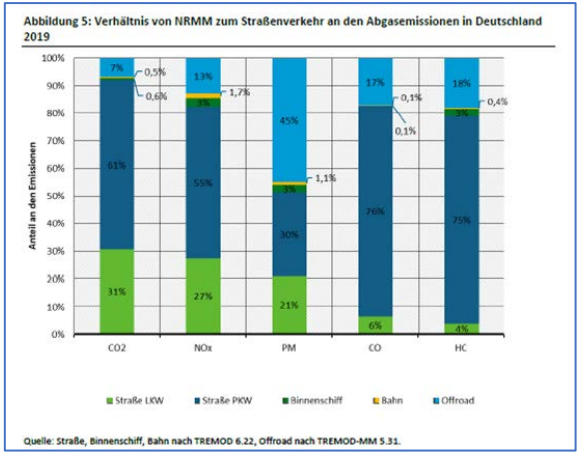
Bosch, lecture at Univ. Stuttgart, 2024

NRMM air quality impact

- In the Netherlands, 2023 GRPE presentation

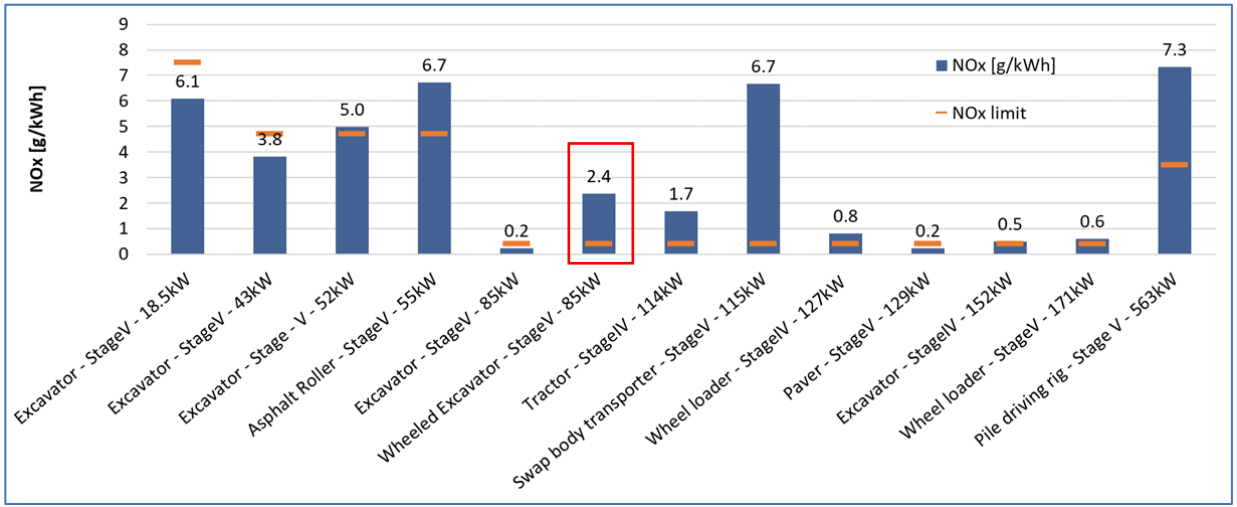


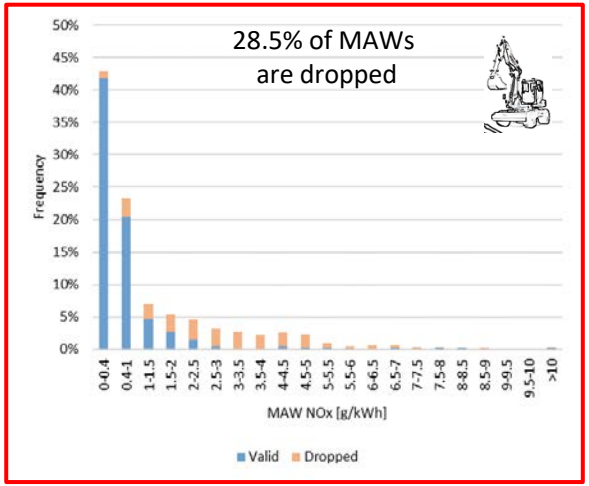
- In Germany, 2023 UBA report



NRMM Stage V legislation expected to evolve

- Large variation observed in real-world NRMM emissions
- NRMM regulation does not consider a substantial share of the conditions





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

MAW: Moving Average Window

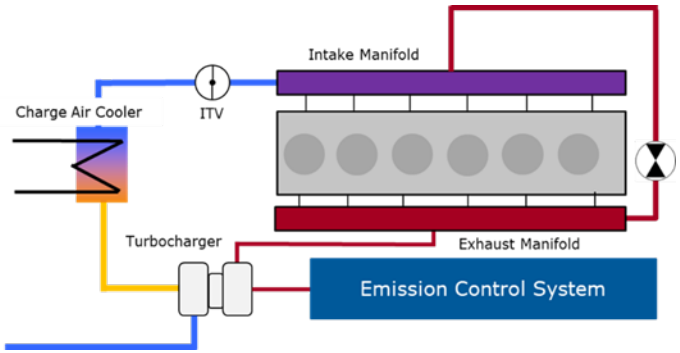
NRMM Stage V legislation expected to evolve

- Typically follows on-road HDV legislation, which evolved 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 Tier 5 proposal for MY2029+, US EPA announcement from 2024 tbc
  - China expected to consider next steps for NRMM

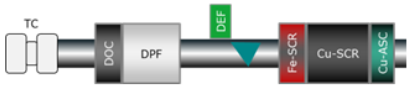
PEMS: Portable Emissions Measurement System

Simulation study concept

- NRMM engine
  - 9litres class
  - Uncooled HP-EGR
  - 8-10 g/kWh engine-out NOx

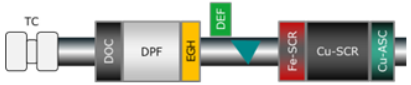


- 3 emission control system configurations



Configuration 1: Enhanced Stage V

Configuration 2: Dual SCR system



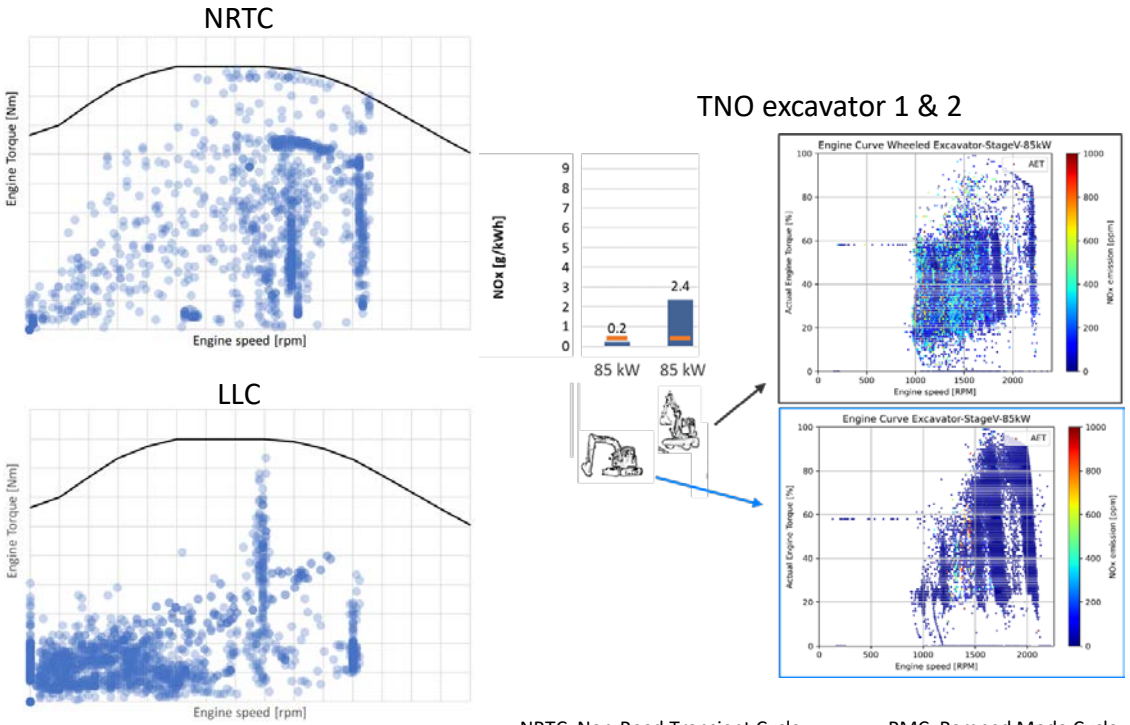
Configuration 3: Enhanced Stage V + Heater

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

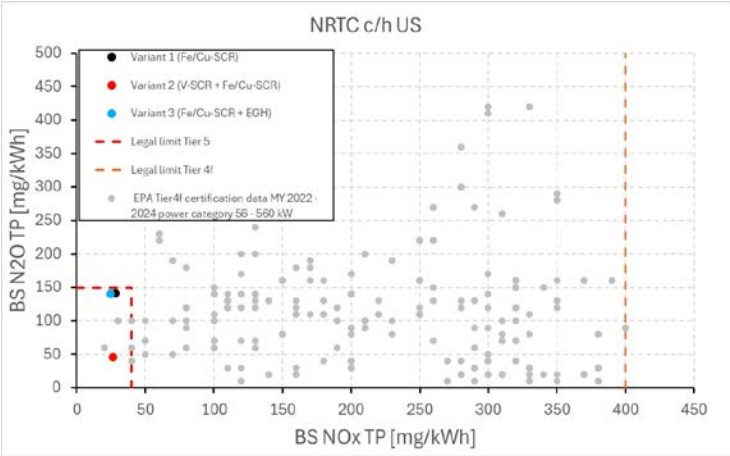
- Type approval cycles
  - NRTC cold and hot
  - NRSC
  - LLC
- In-use application cycles
  - AVL wheel loader 1&2
  - AVL bulldozer
  - AVL hay mover
  - TNO excavator 1&2

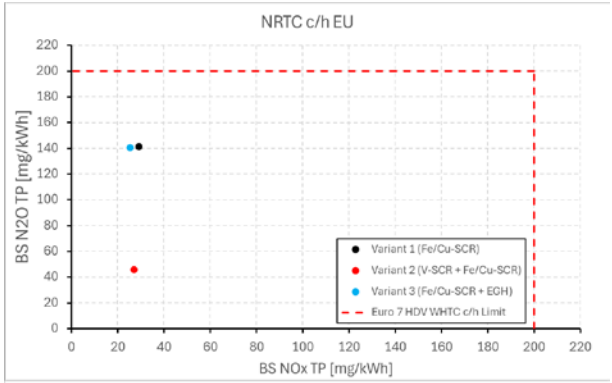


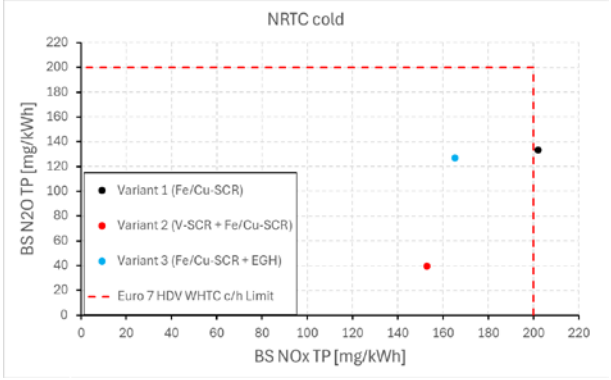
NRTC: Non-Road Transient Cycle
NRSC: Non-Road Steady-state Cycle
RMC: Ramped Mode Cycle
LLC: Low-load Cycle

All NRTC results within CARB Tier 5 and Euro 7

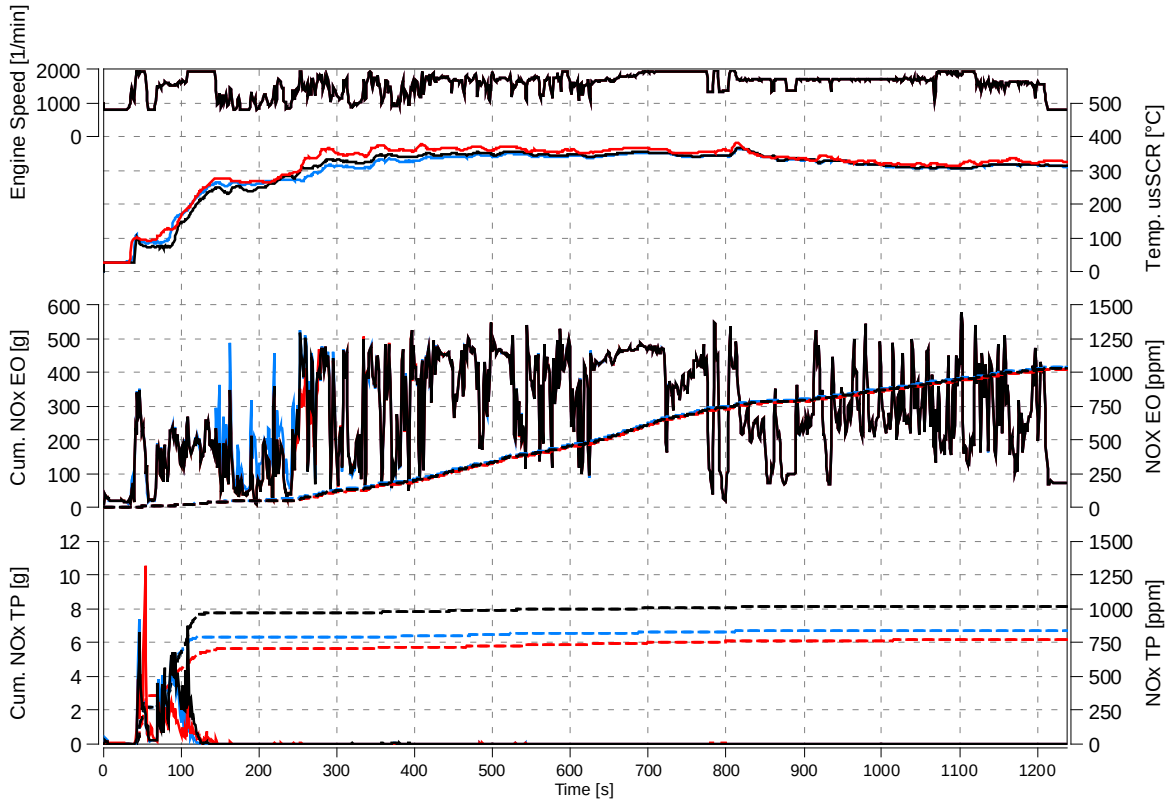
- At lower end of existing US EPA Tier 4 certification data
- Variant 2 and 3 show lower cold-start NOx emissions (diluted with c/h weighing)
- Variant 2 shows lower N_2O emissions



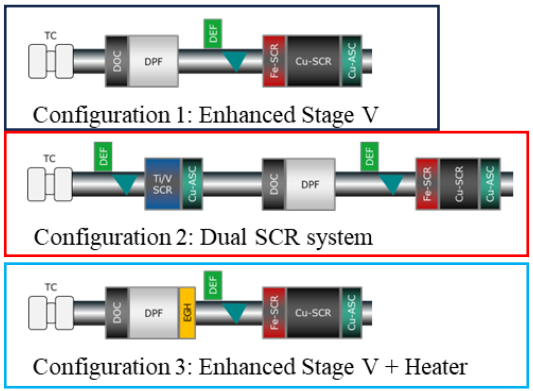




All NRTC results within CARB Tier 5 and Euro 7



- Earlier catalyst light-off in variant 2 and 3 due to cc SCR or EGH



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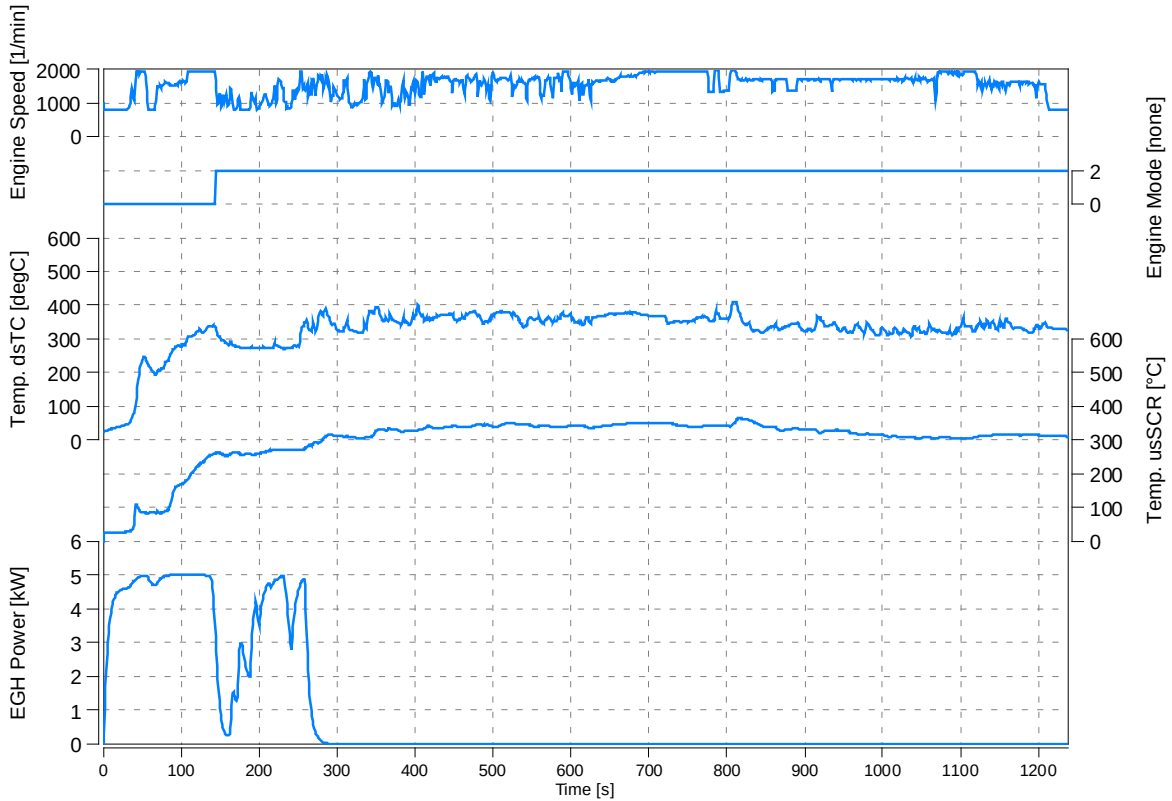
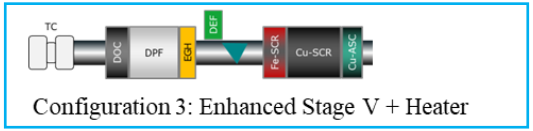


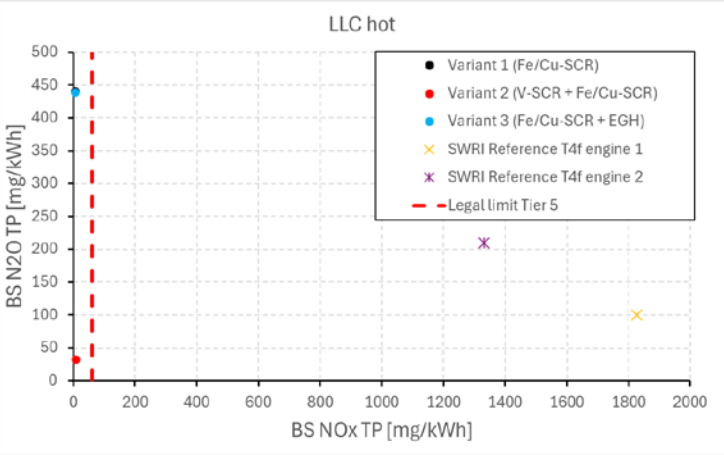
- EGH mainly active in the beginning of the cycle

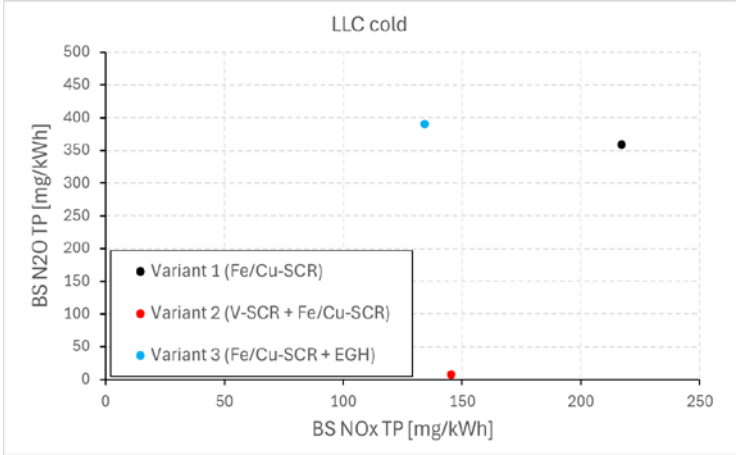


Configuration 3: Enhanced Stage V + Heater

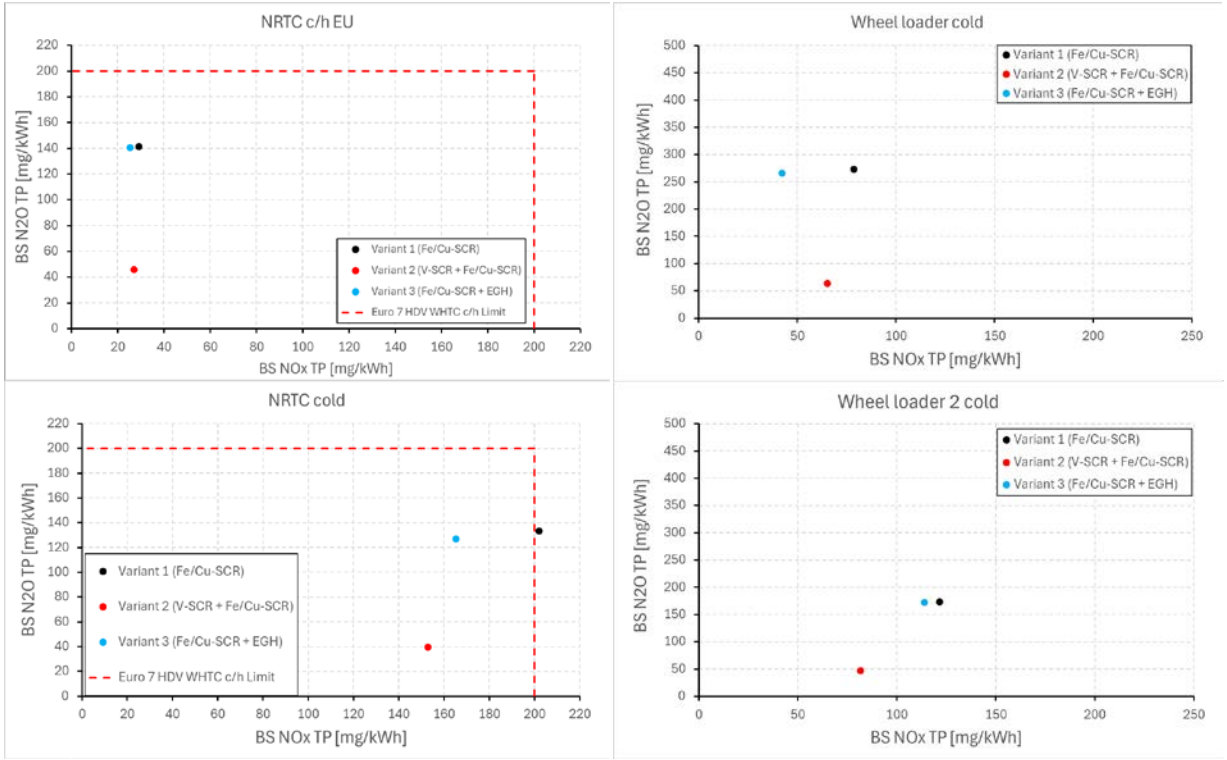
Low-load emissions improvement

- Data on LLC hot is compared to SwRI data of Tier 4 engines
- Variant 2 and 3 show lower cold-start NOx emissions
- Variant 2 shows lower N_2O emissions

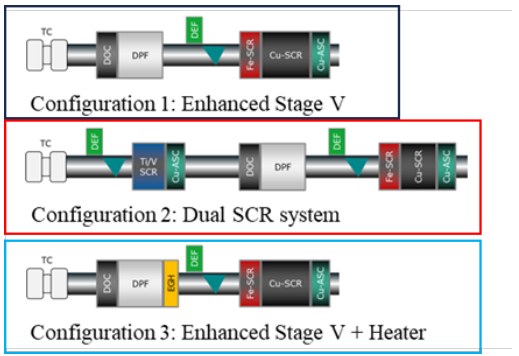




Low emissions on in-use cycles incl. cold-start



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



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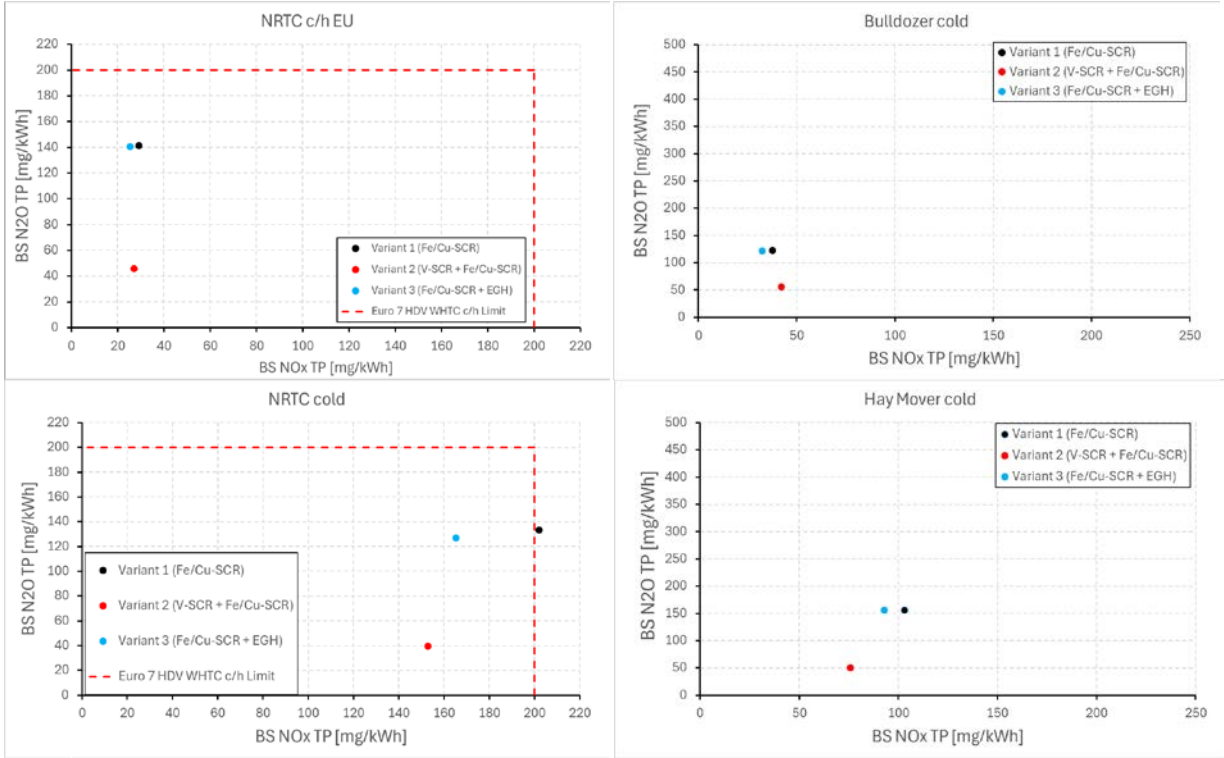

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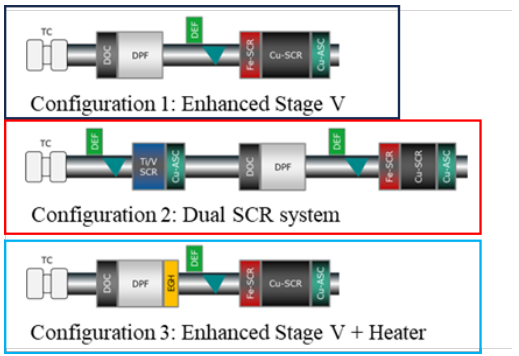

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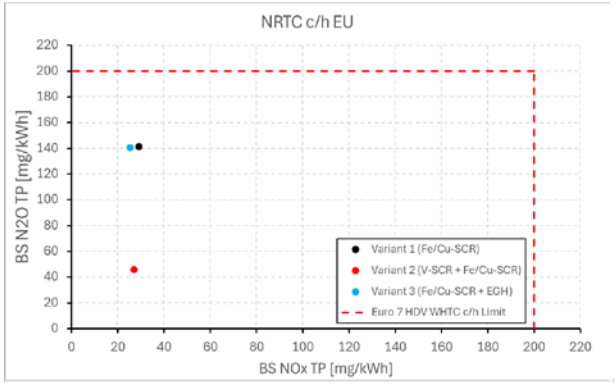

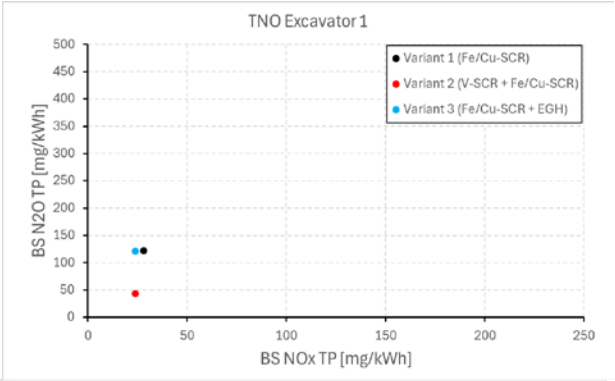

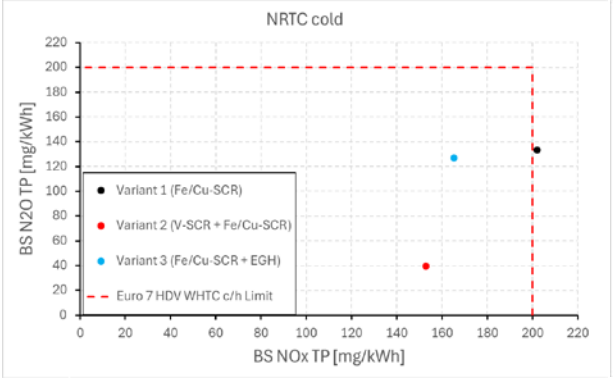

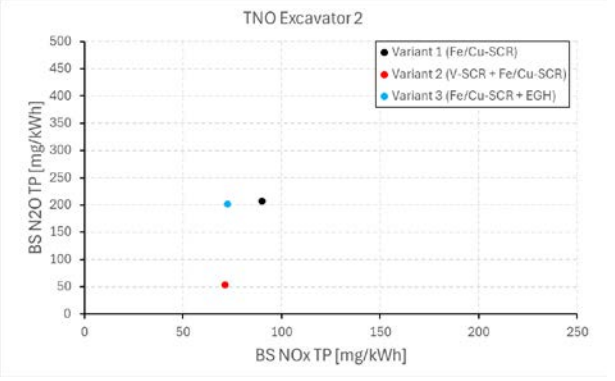

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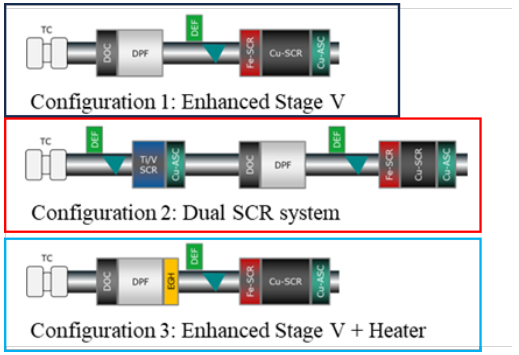
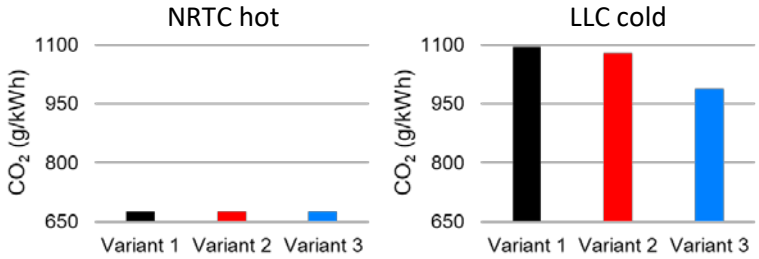
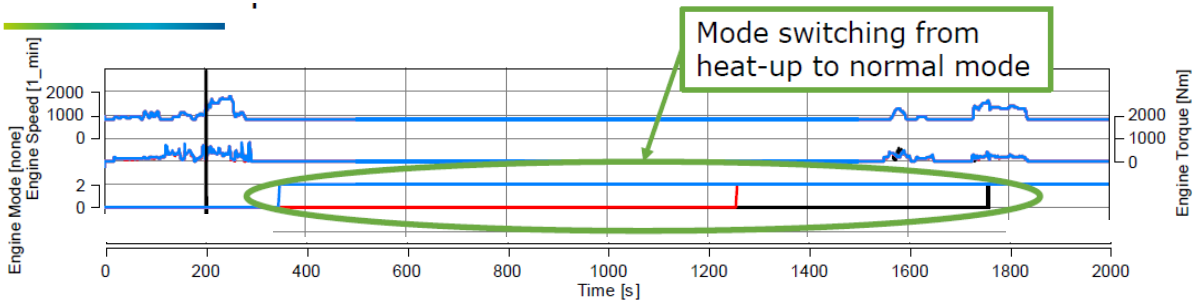


Tailpipe CO_2 emissions

- Similar for all 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



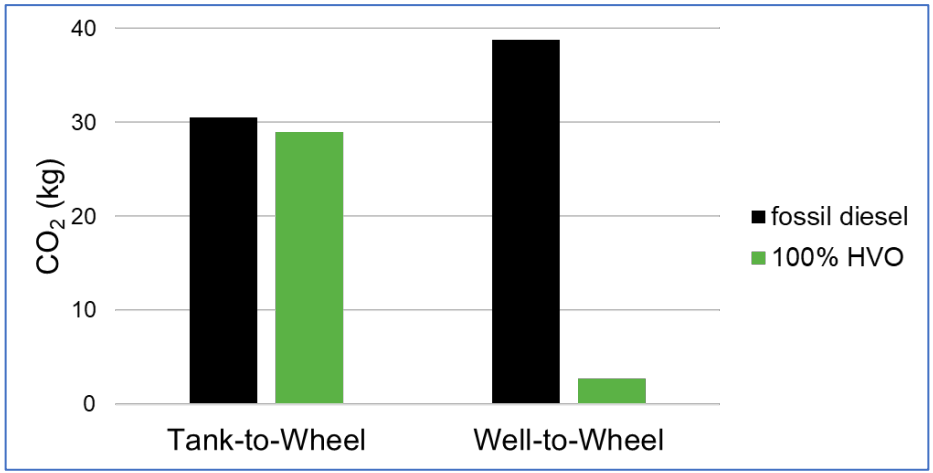


Boundary Conditions:

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

Well-to-Wheel CO_2 emissions

- Can nearly be eliminated by running on CO_2-neutral fuels (CNFs)
  - Exemplary calculation for NRTC hot
    - Fossil diesel
    - 100% HVO from Used Cooking Oil (UCO)

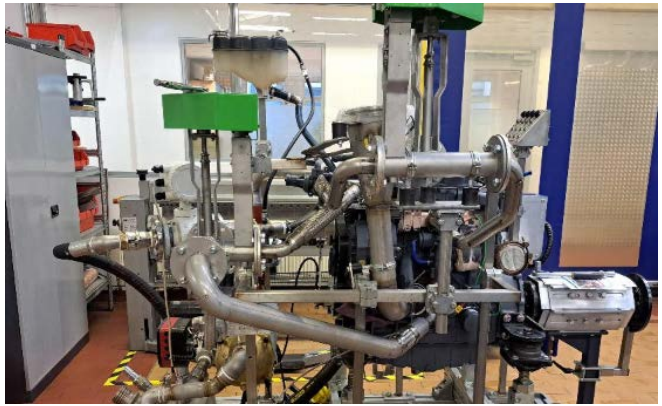


Conclusions

- Technologies are available to achieve low NRMM pollutant emissions
- Single-dosing SCR can 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 NOx emission level
  - Alternating operating conditions
  - Continuous low-load operation
  - Initial cold-start
- Together with operation on CO_2-neutral fuels including HVO, e-diesel and H_2 the Internal Combustion Engine is a future-proof NRMM powertrain option

Outlook

- Demonstration project currently ongoing @ AVL Graz
  - NRMM engine ~ 100 kW rated power
  - Cooled EGR
- Exhaust gas temperature management concept with uncooled EGR and charge-air-cooler bypass (via EGR cooler)
- All 3 emission control systems from simulation study will be tested in modular approach



Demonstrator engine with advanced airpath concept

Emission control system (modular approach)

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