Using Digital Engineering to Meet the Future Emission Challenges of Agricultural NRMM

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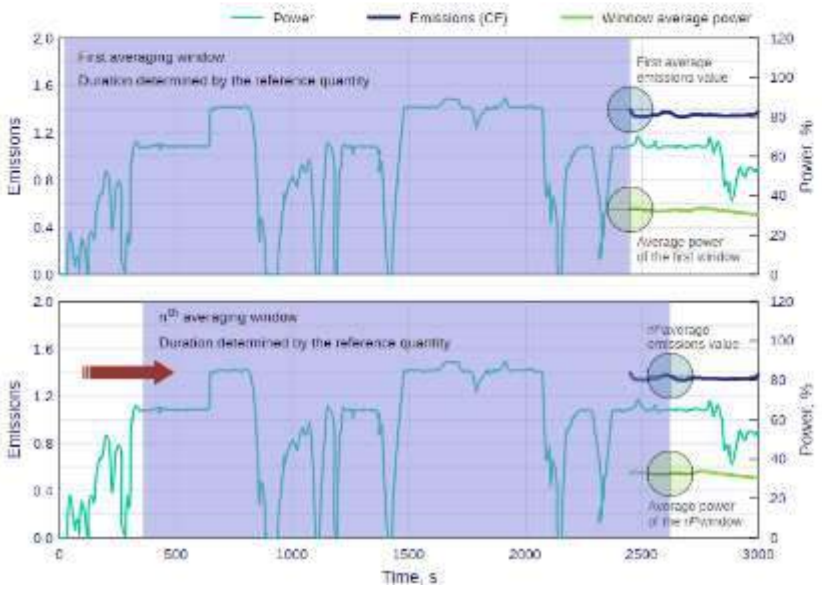
Real World Emissions Compliance & RDE

ISC and RDE will impact the development and certification of NRMM & HDV powertrain

EU Stage VI ISC

- In-Service Monitoring introduced in 2016
  - Commission Delegated Regulation (EU) 2017/655 of 19 December 2016 (56 to 560kW engines)
  - CO, CO_2, NO_X, THC
  - Defined measurement “window” criteria



EU Stage VI

- Objective to introduce In-Service Compliance (ISC)
- **Stage VI in 2032**

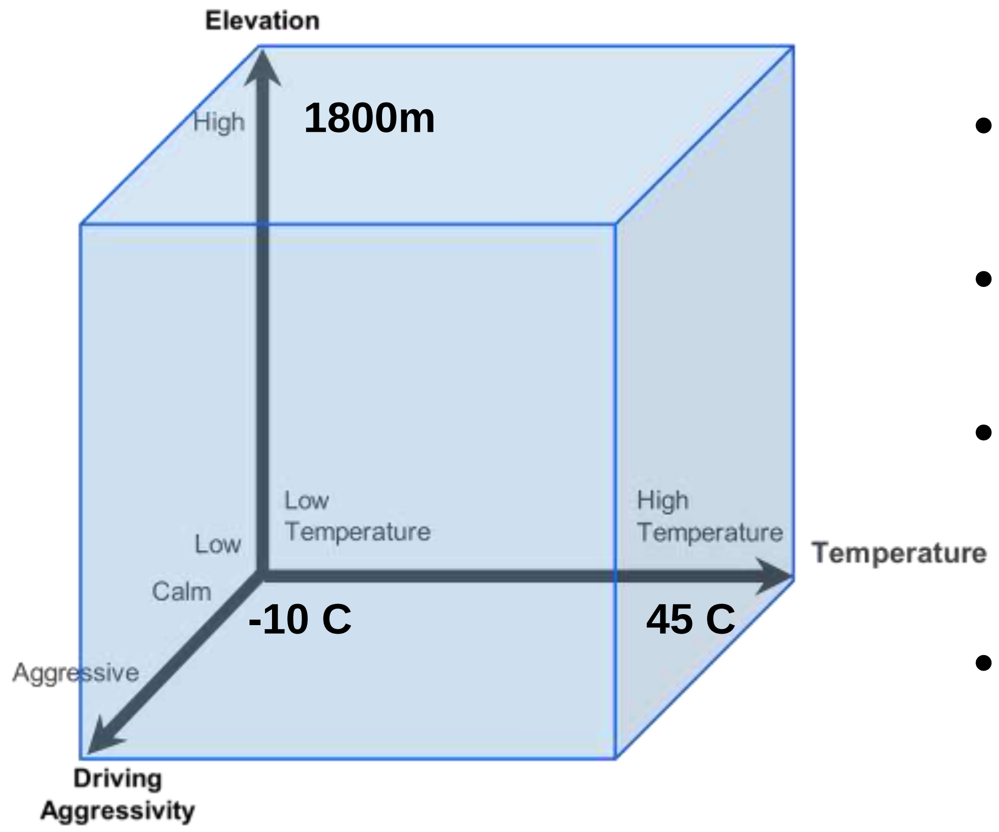
Indian ISM/ISC

- India Stage V ISM planned for October 2026

Heavy Duty Euro 7 – RDE & ISC

- Trip composition governed by Euro6e RDE-like criteria
- Any driver aggressivity
- RDE Conformity Factors of 1.0
- Whole life factor of 1.2
- 875,000k/10 years ISC

- New measurements: + PN10, NMHC..
- Reduction in limit values
- From cold (2km @ <20% power)
- Brake & Tyre PM/PN
- Battery durability
- On-Board Monitoring



- Any trip with >6% rated power condition.
- Any application within legal limits
- Makes engineering and V&V process much harder.
- “Infinite” scenarios

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https://www.horiba.com/deu/applications/mobility-and-transportation/real-driving-emissions/non-road-mobile-machinery-nrmm/

Real-World ISM/ISC Adds Complexity & Cost to Development

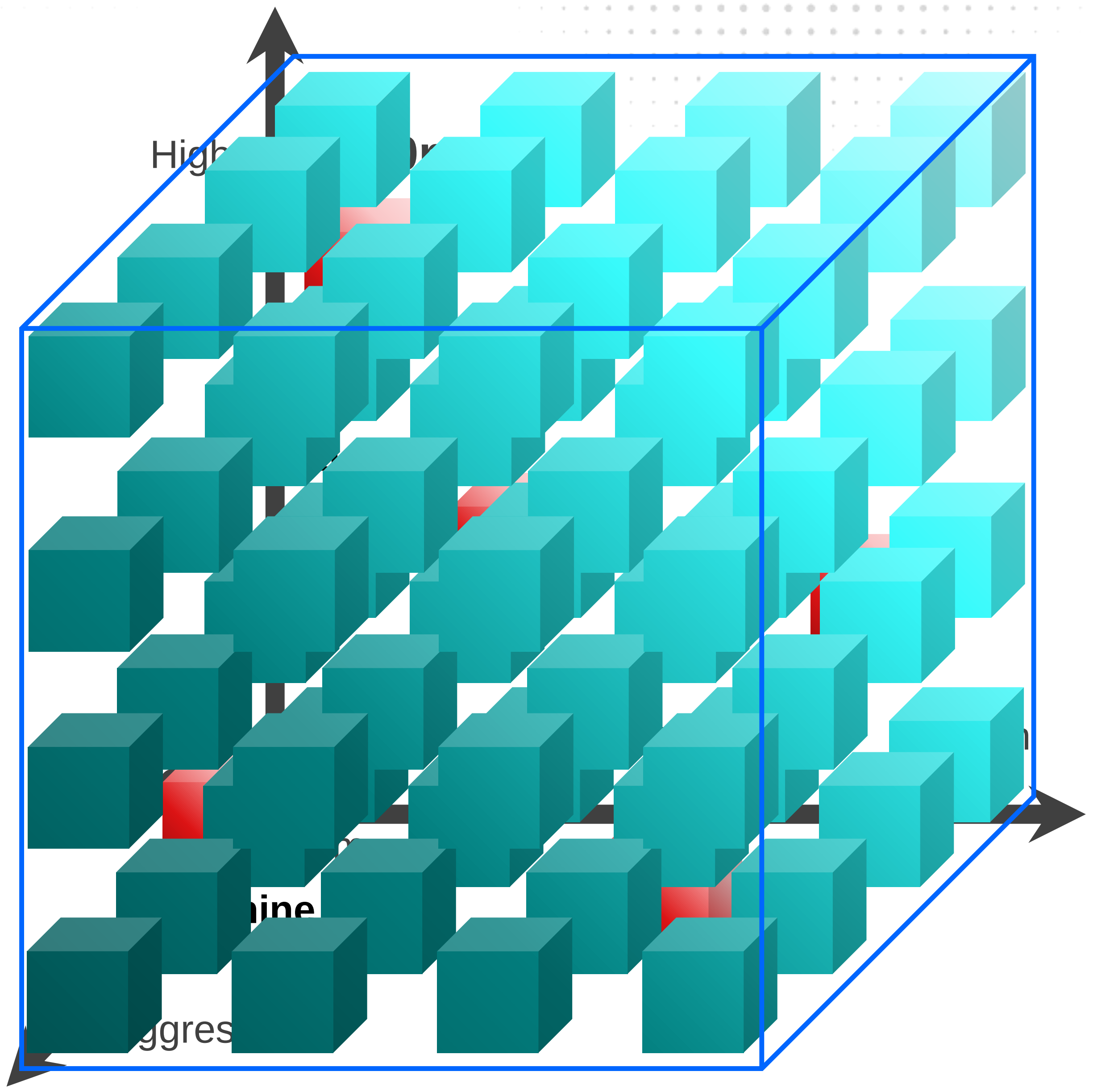
Use Digital Engineering to cover the scenario landscape

- "Infinite" use-case scenarios in NRMM ISC
- Impossible to physically test and validate all cases

Solution

- Achieve sufficient coverage using predictive simulation
- Use simulation to identify worse cases
- Physically test worst cases only (far fewer tests)
- Use simulation to populate the validation

NRMM ISC Space



- **Physical** 'Worst case' Road test
  Lab Replication & Emulation
- **Simulation** Empirical Digital Twin
  + Co-simulation

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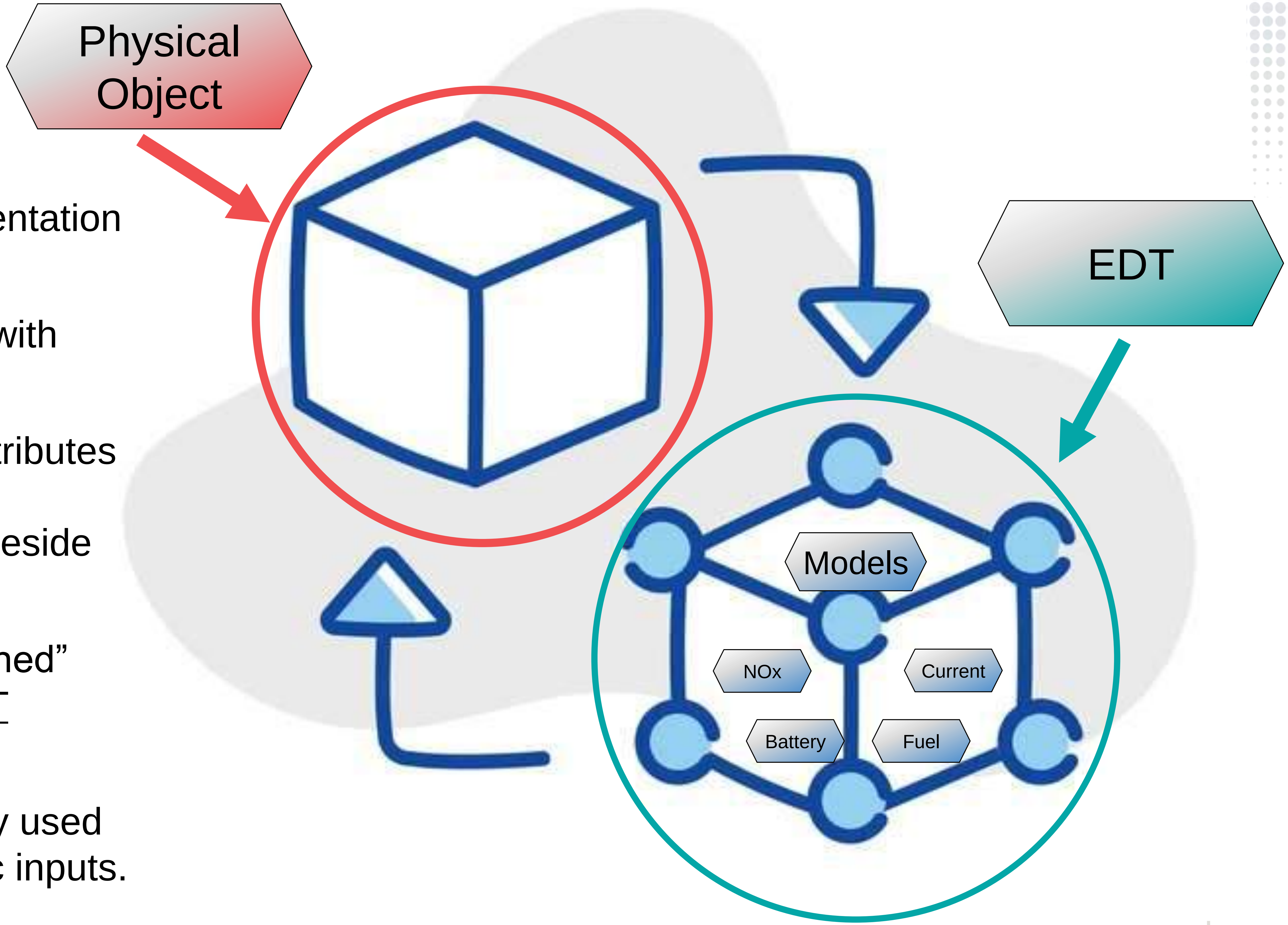
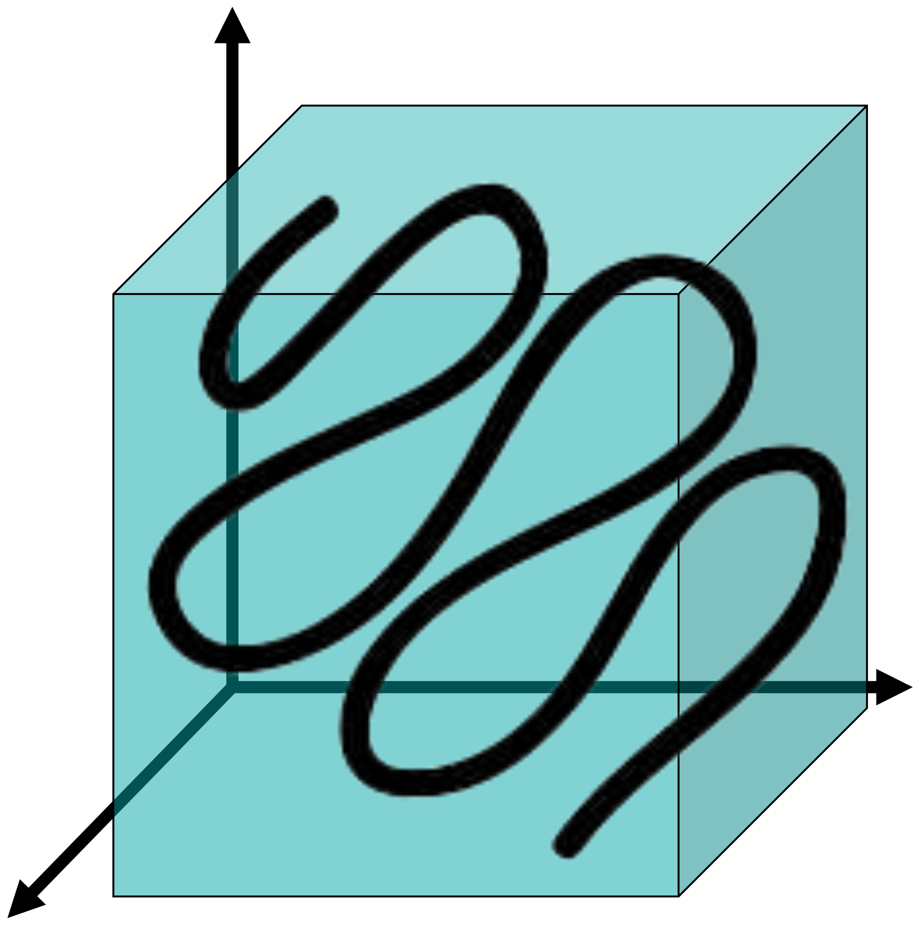
Empirical Digital Twin
What is it?



- A pseudo-perfect digital representation of a physical object.
- Empirically based and created with ‘real’ data.
- Empirical models of different attributes i.e., fuel economy, NOx, battery attributes, power consumption reside within the EDT
- Our EDTs use dynamically “trained” neural networks – they are NOT “physics” models
- These models are subsequently used to predict responses for specific inputs.

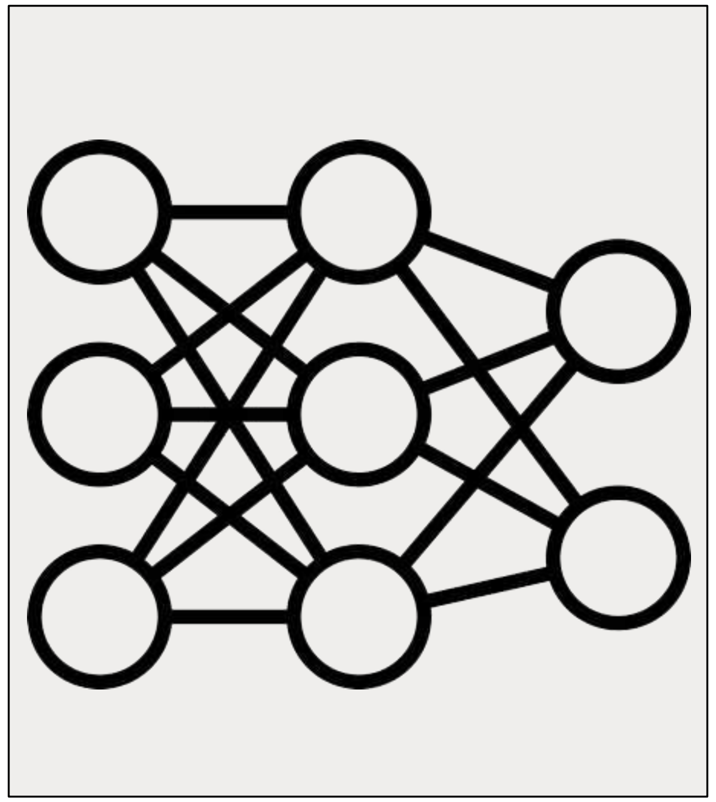
Intelligent Lab EDT Toolset

Test Designer



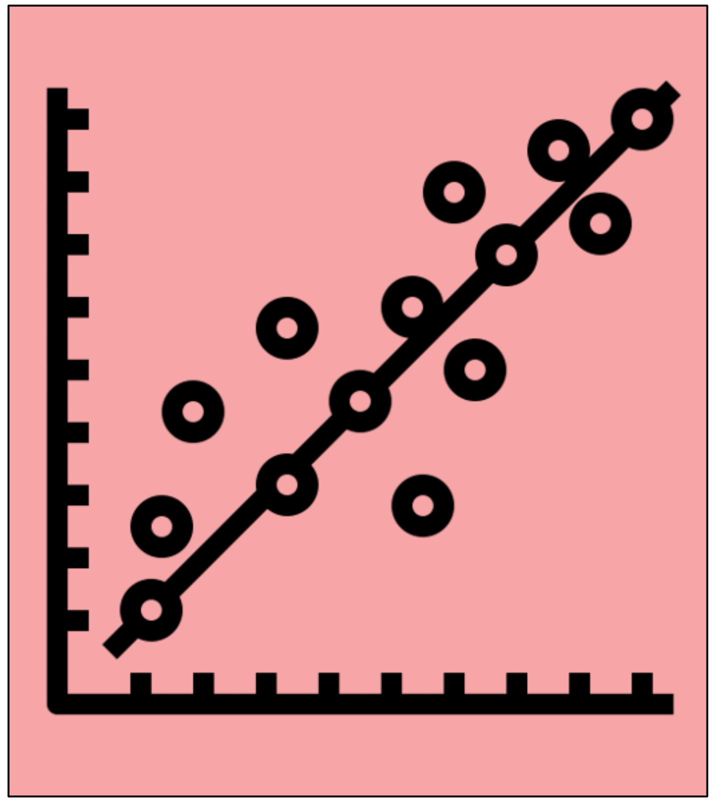
Transient excitation signal design specific to the unit under test

Modeller



Rapid generation of transient empirical models using recurrent neural networks

Predictor



Prediction of attributes using transient empirical models at **faster than real-time**

Optimiser

Multi-objective optimiser and 'hot-spot' identification toolset for improved performance

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Digital Twining Methodology (1)

1. Experiment design

Create the transient training cycle using HORIBA Intelligent Lab toolset

2. Training data

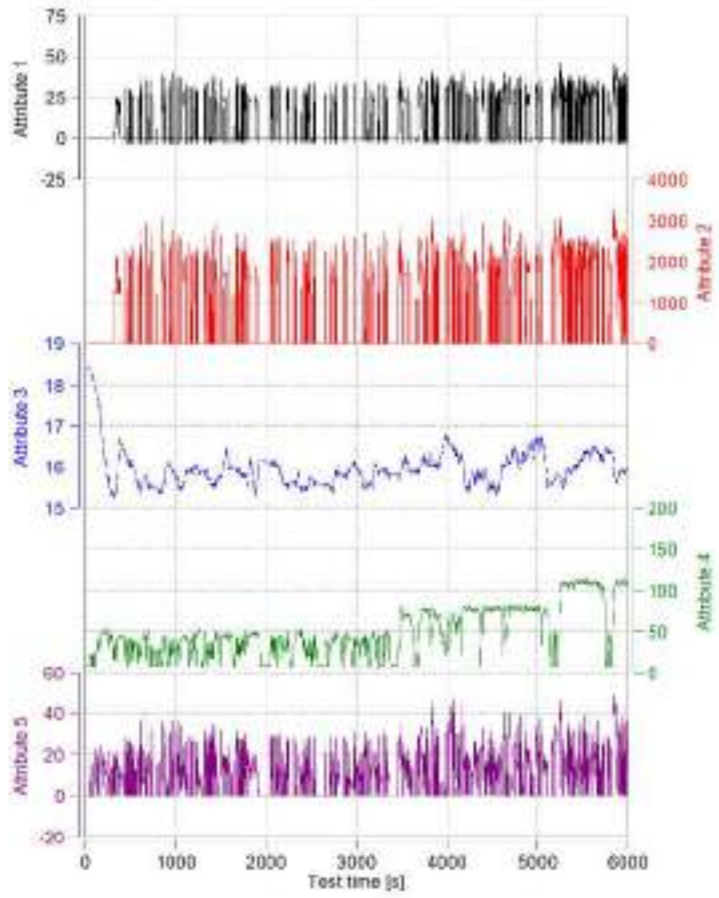
Record training data from the unit under test (engine, powertrain, motor, battery)

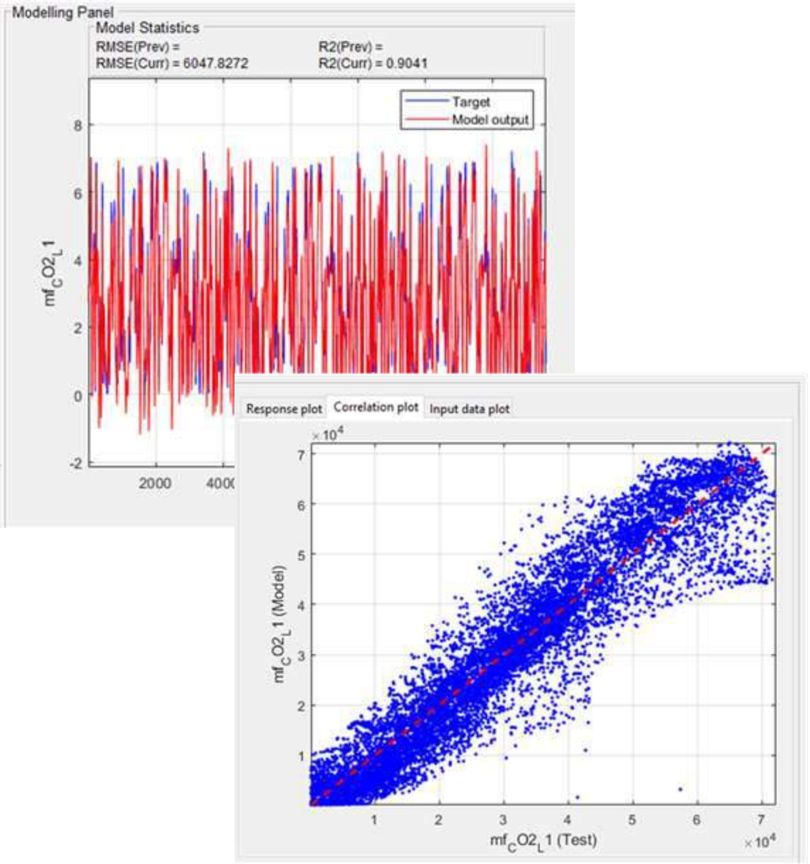
3. Model creation

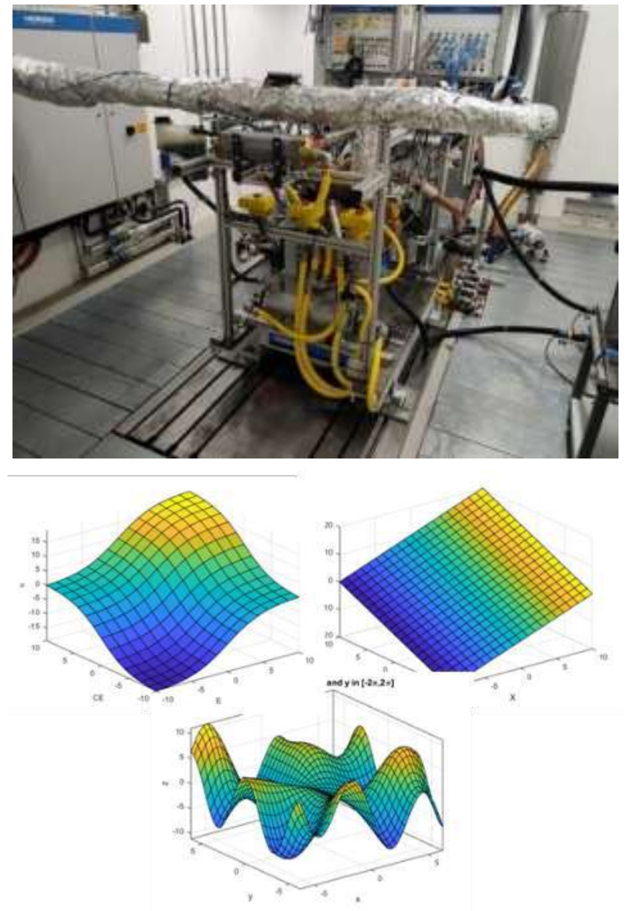
Create transient empirical models of various performance and emissions attributes

4. Model validation

Validate transient empirical models to ensure high quality and fidelity

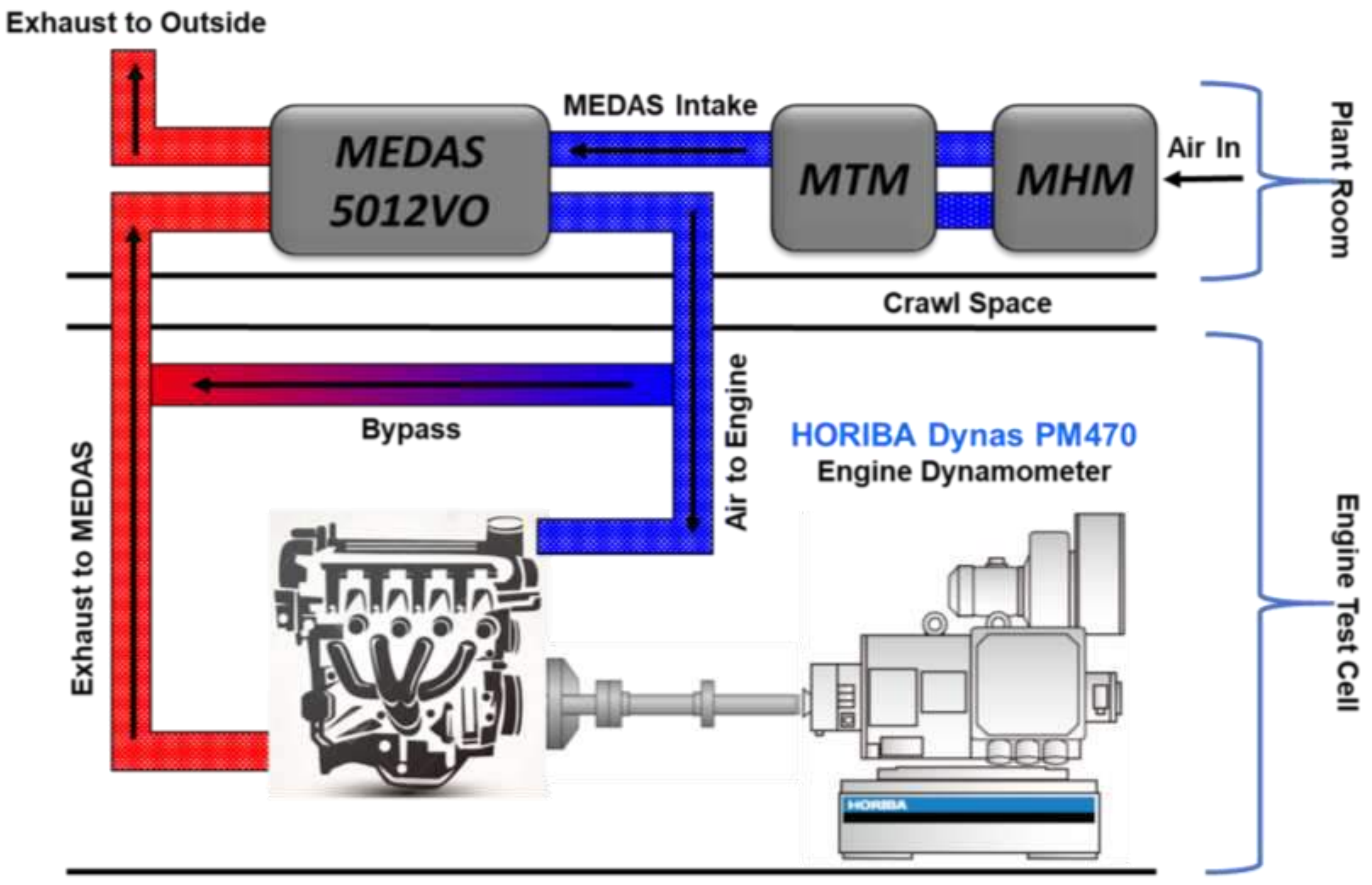






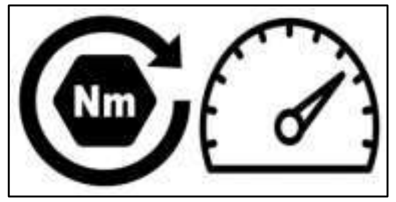
Environmental Emulation using HORIBA MEDAS

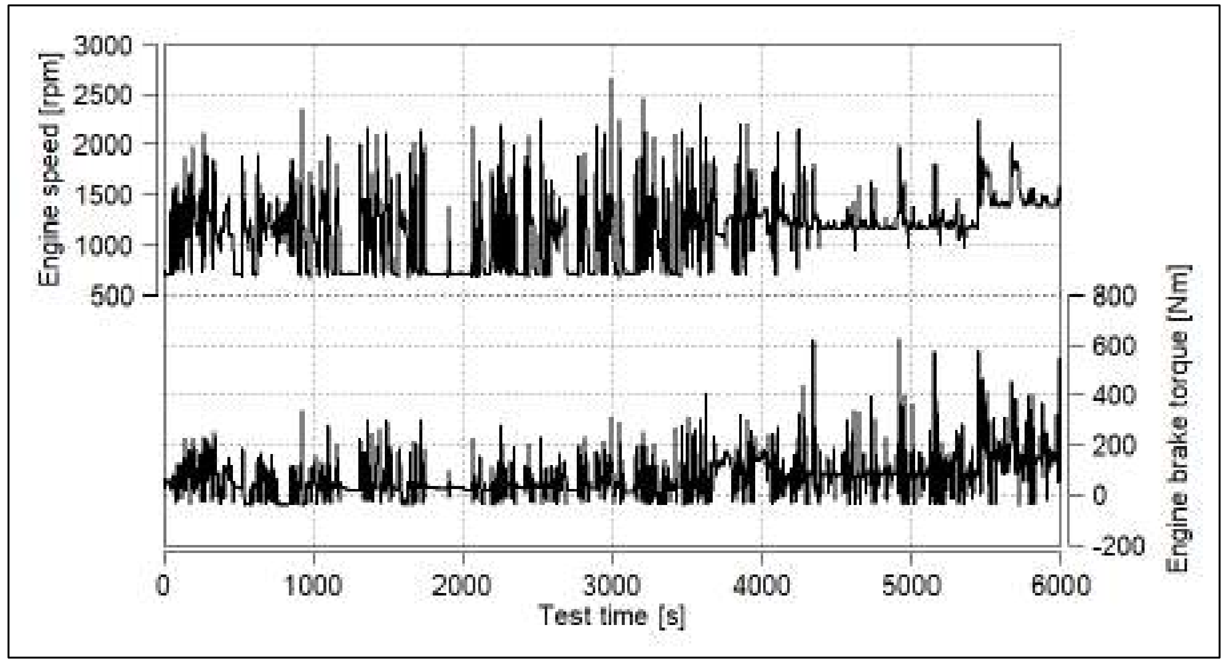
- The HORIBA MEDAS has a key role in helping create the powertrain empirical digital twin and is used for environmental emulation.
- Altitude and temperature can be added as inputs to the dynamic design with the subsequent empirical models therefore incorporating the effects of altitude and temperature on powertrain performance and emissions.
- Shown here is a schematic of how the powertrain is configured with MEDAS. This system can also be used as part of a chassis dyno setup.



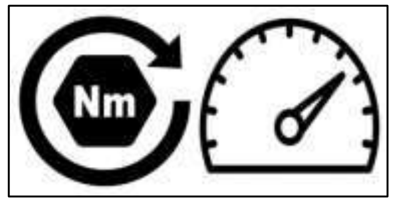
EDT Model Validation

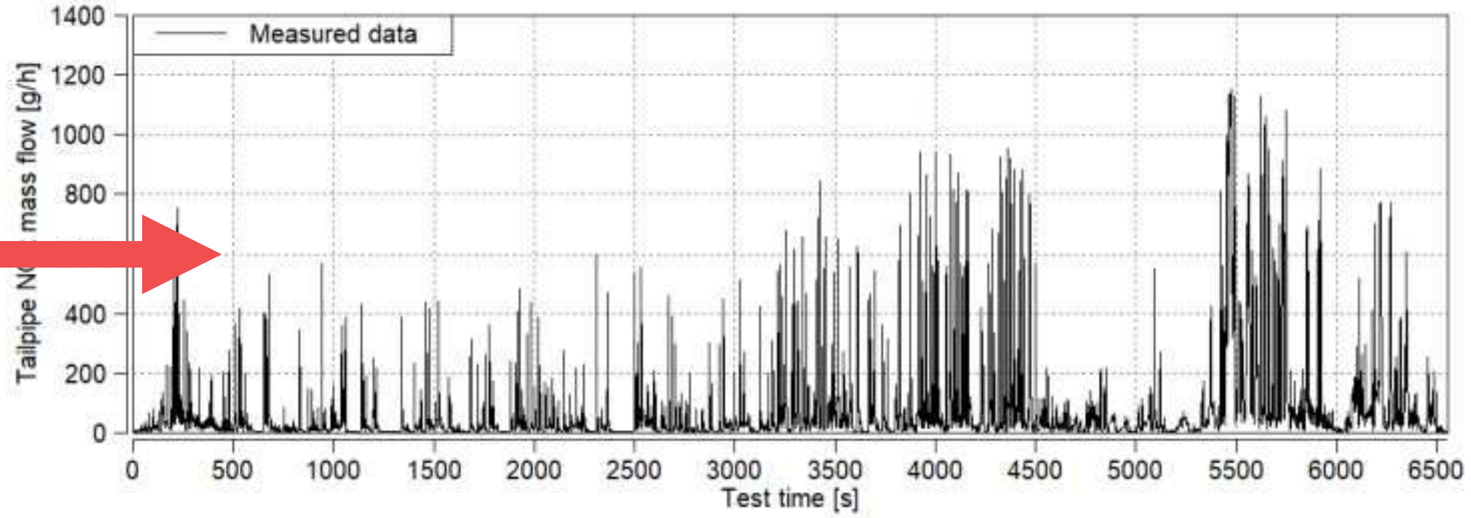
Validation cycle
Run the cycle on the engine



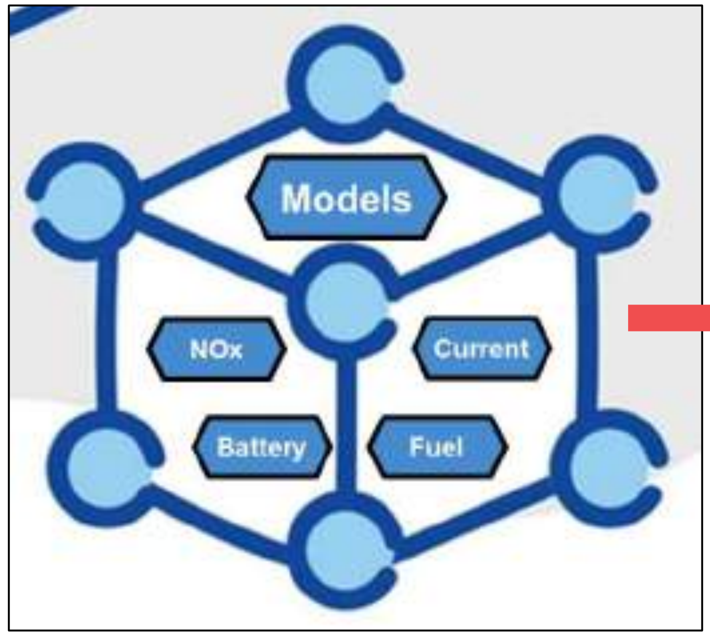


Validation cycle
Run the cycle through the EDT

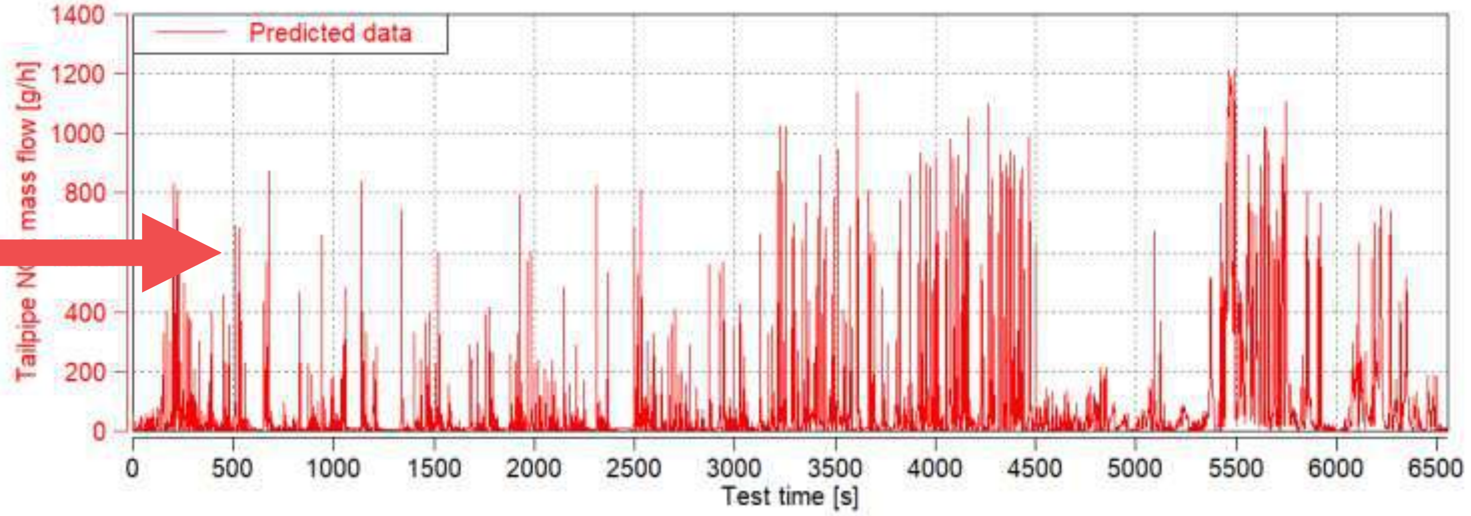




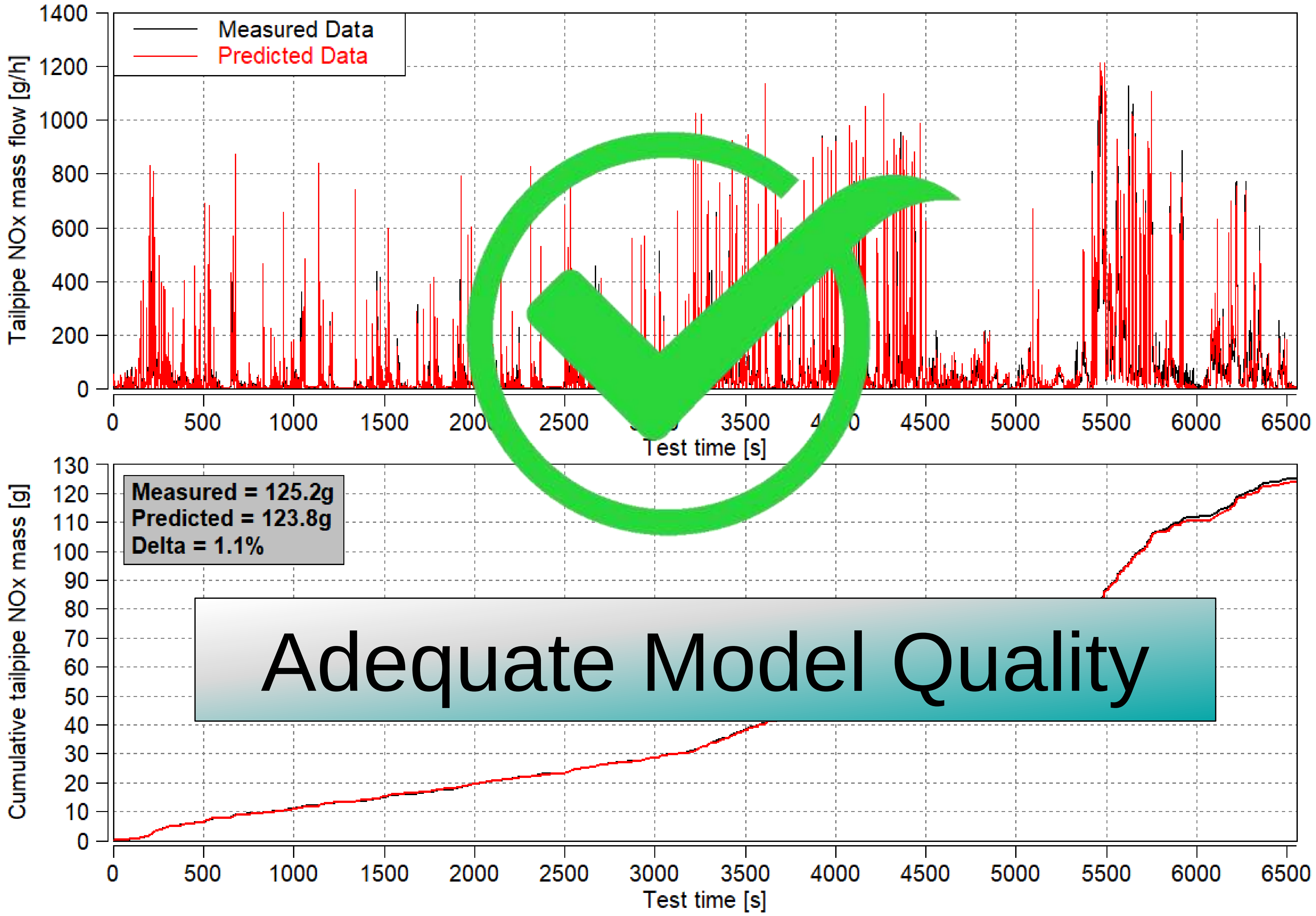
Measured data



Predicted data



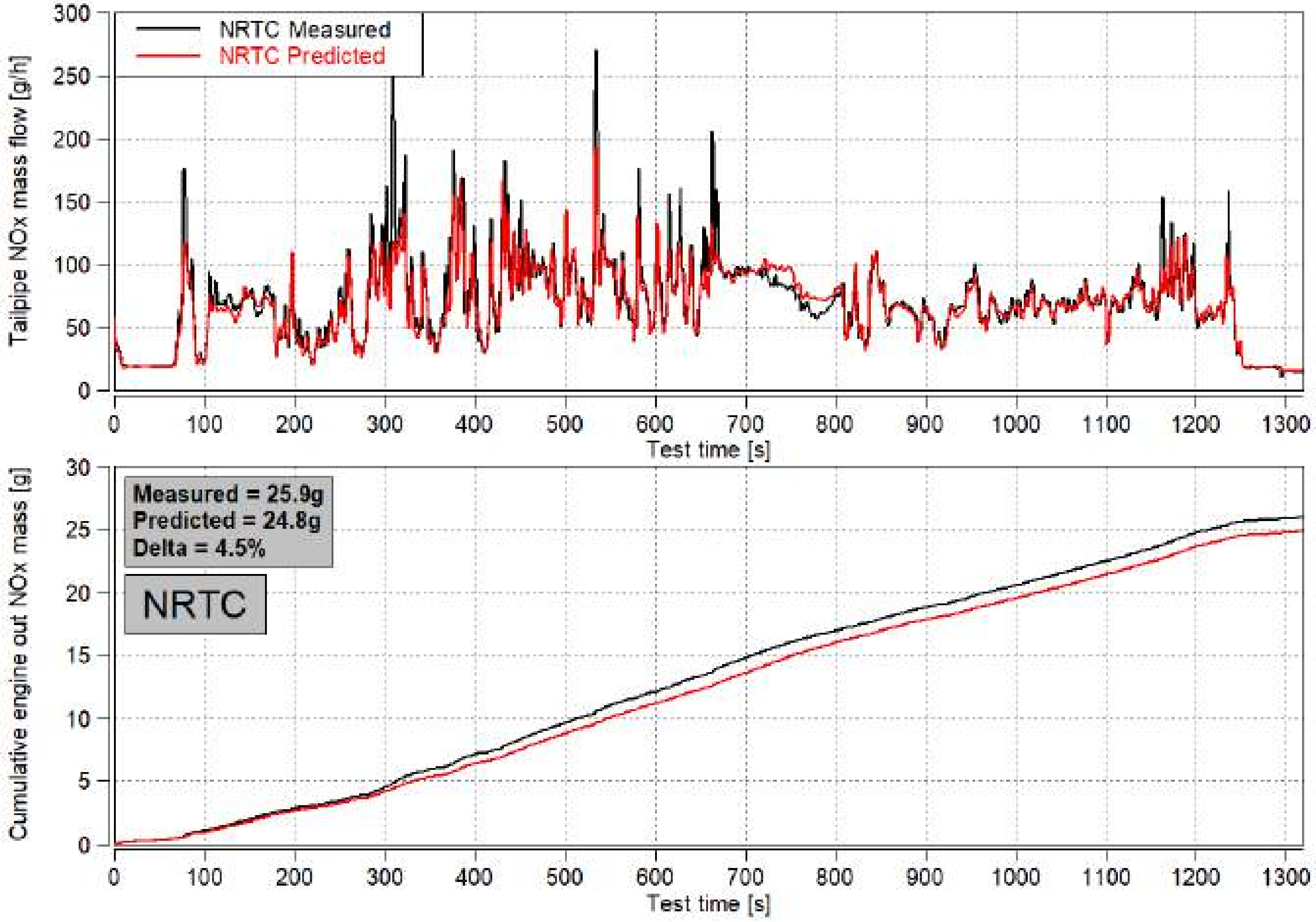
EDT Model Validation



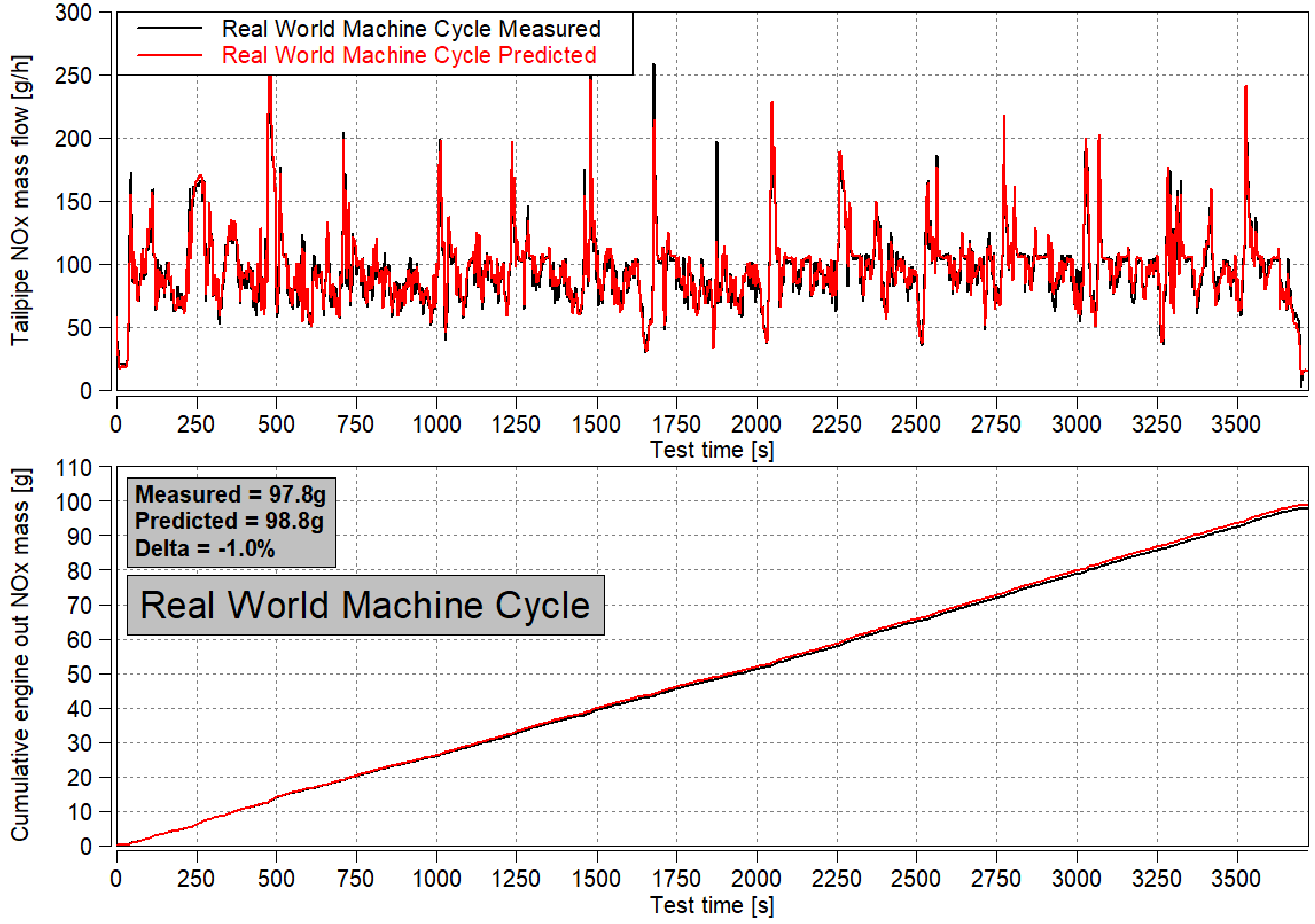
Model Quality Examples – Performance Attributes – Off Highway Engine

Engine Out NOx

NRTC Validation Cycle



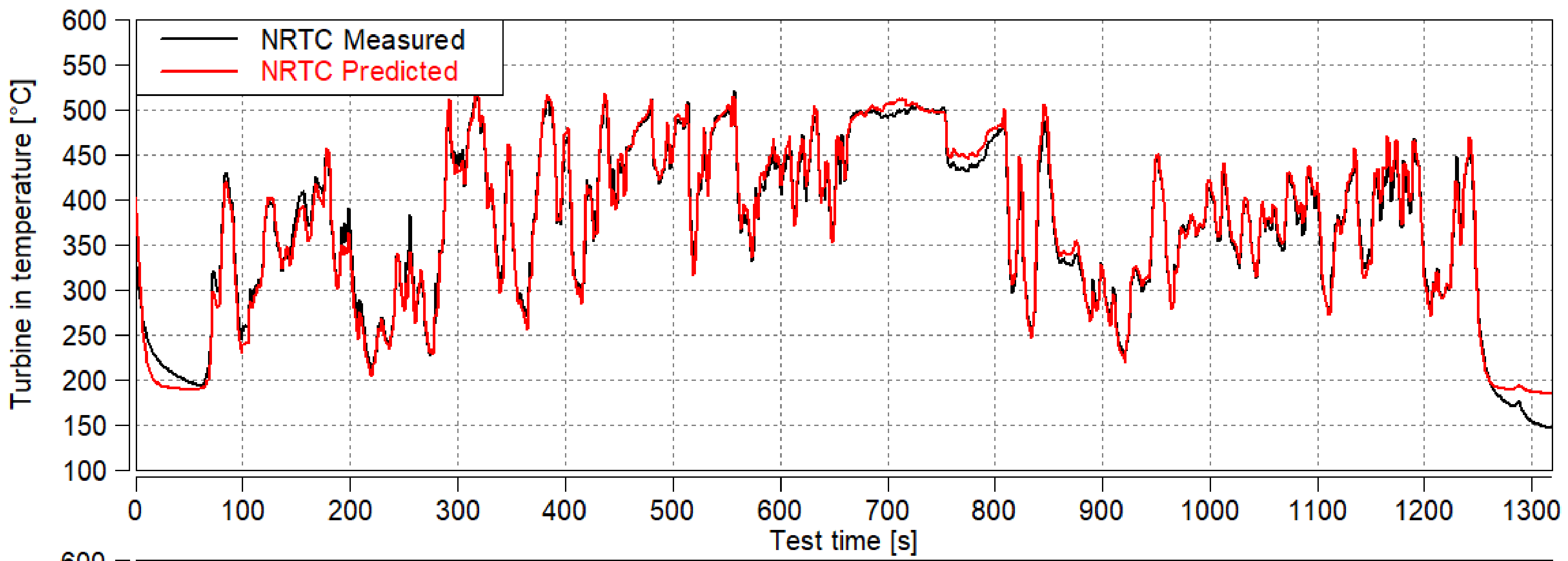
Real World Validation Cycle

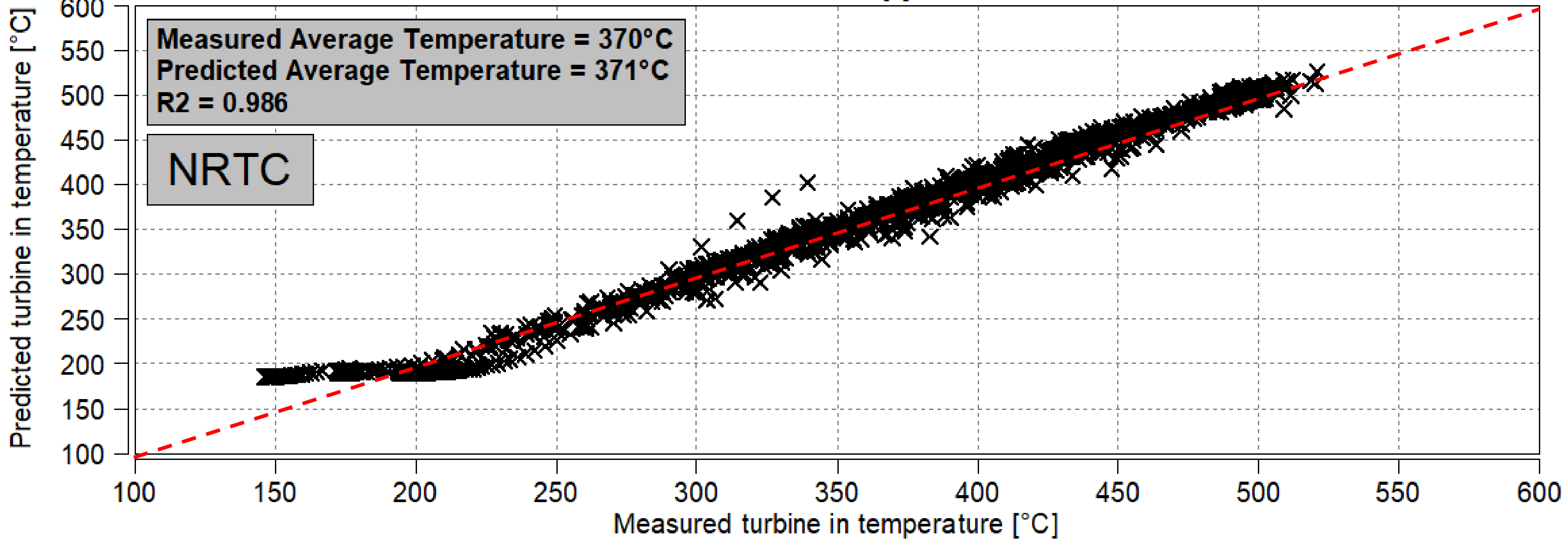


Model Quality Examples – Performance Attributes – Off Highway Engine

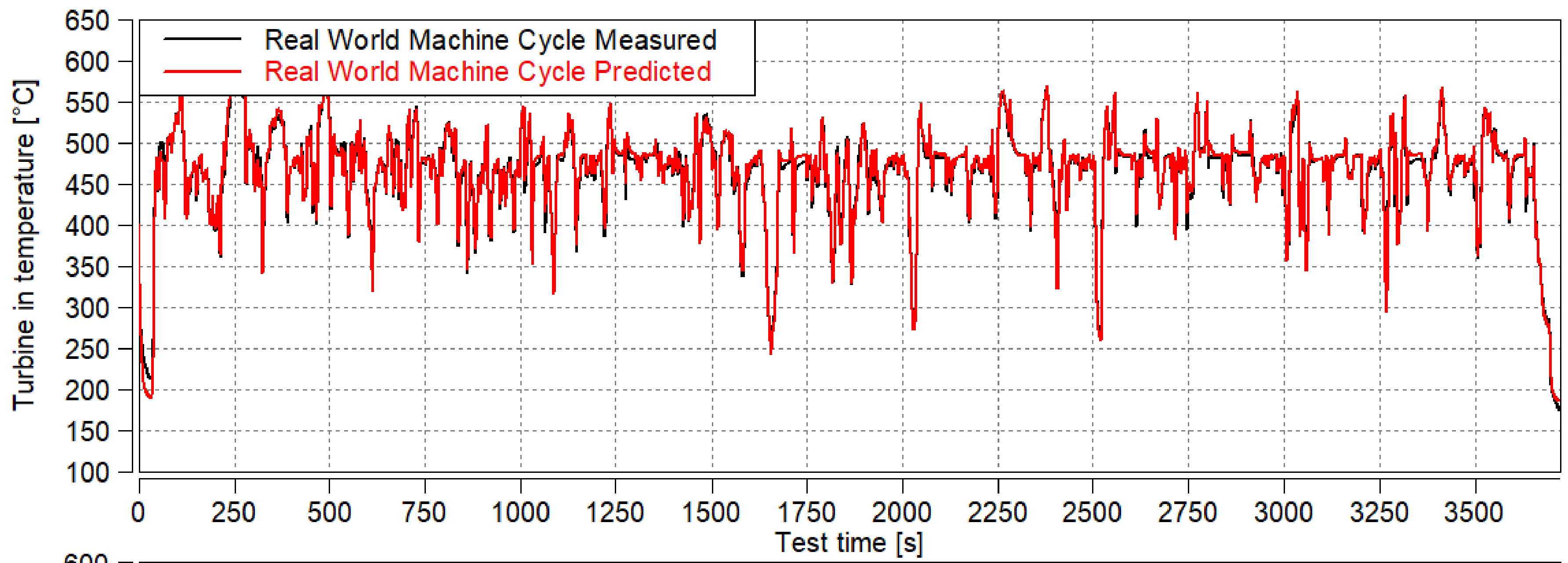
Exhaust Temperature

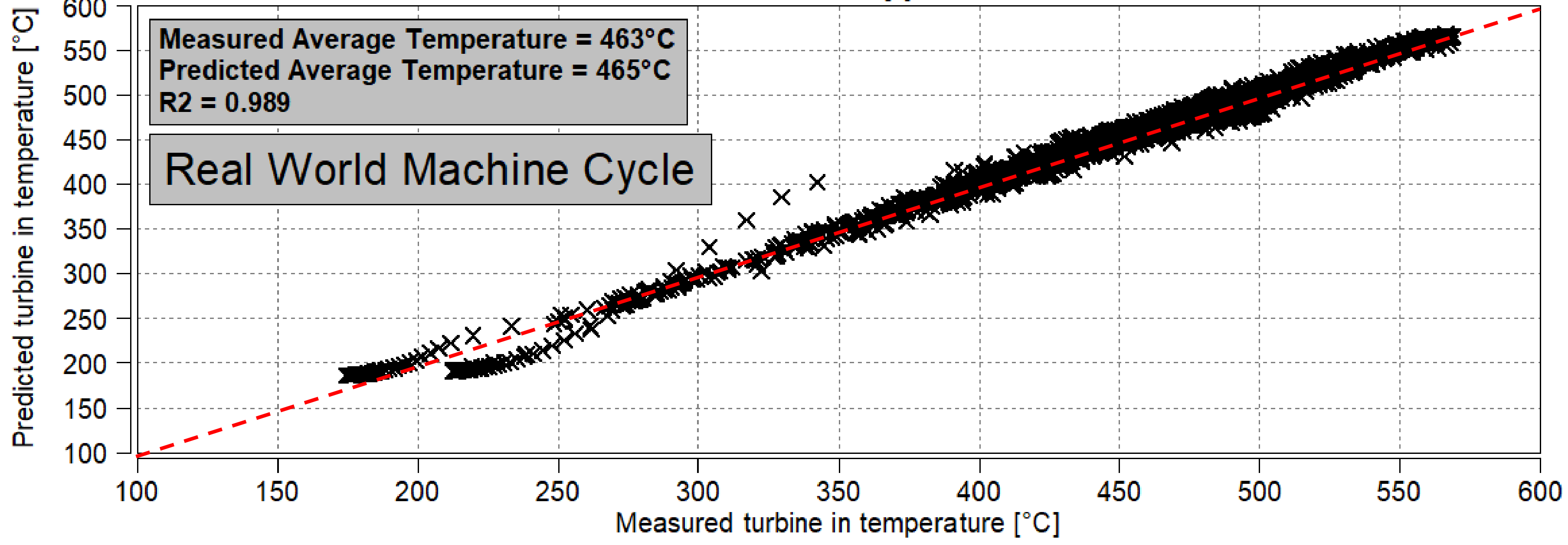
NRTC Validation Cycle





Real World Validation Cycle





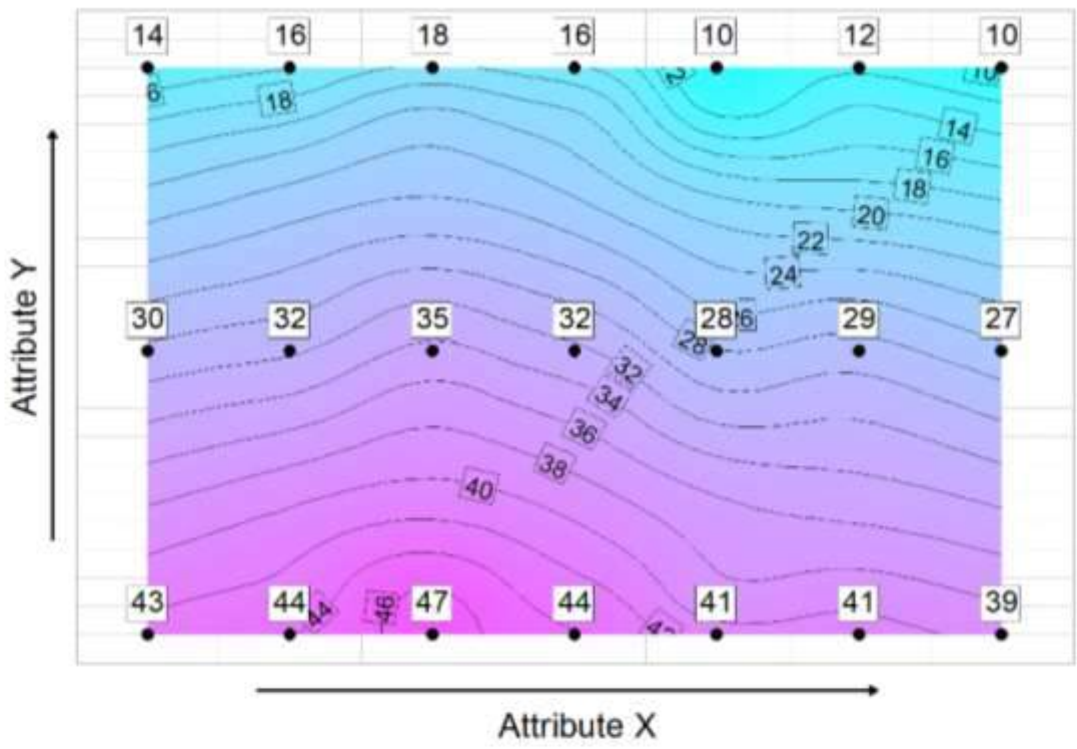
Digital Twining Methodology (2)

5. Virtual or real scenarios

Create synthetic real-world machine operating scenarios using 3rd party software or utilise physical real-world data and couple with transient empirical models

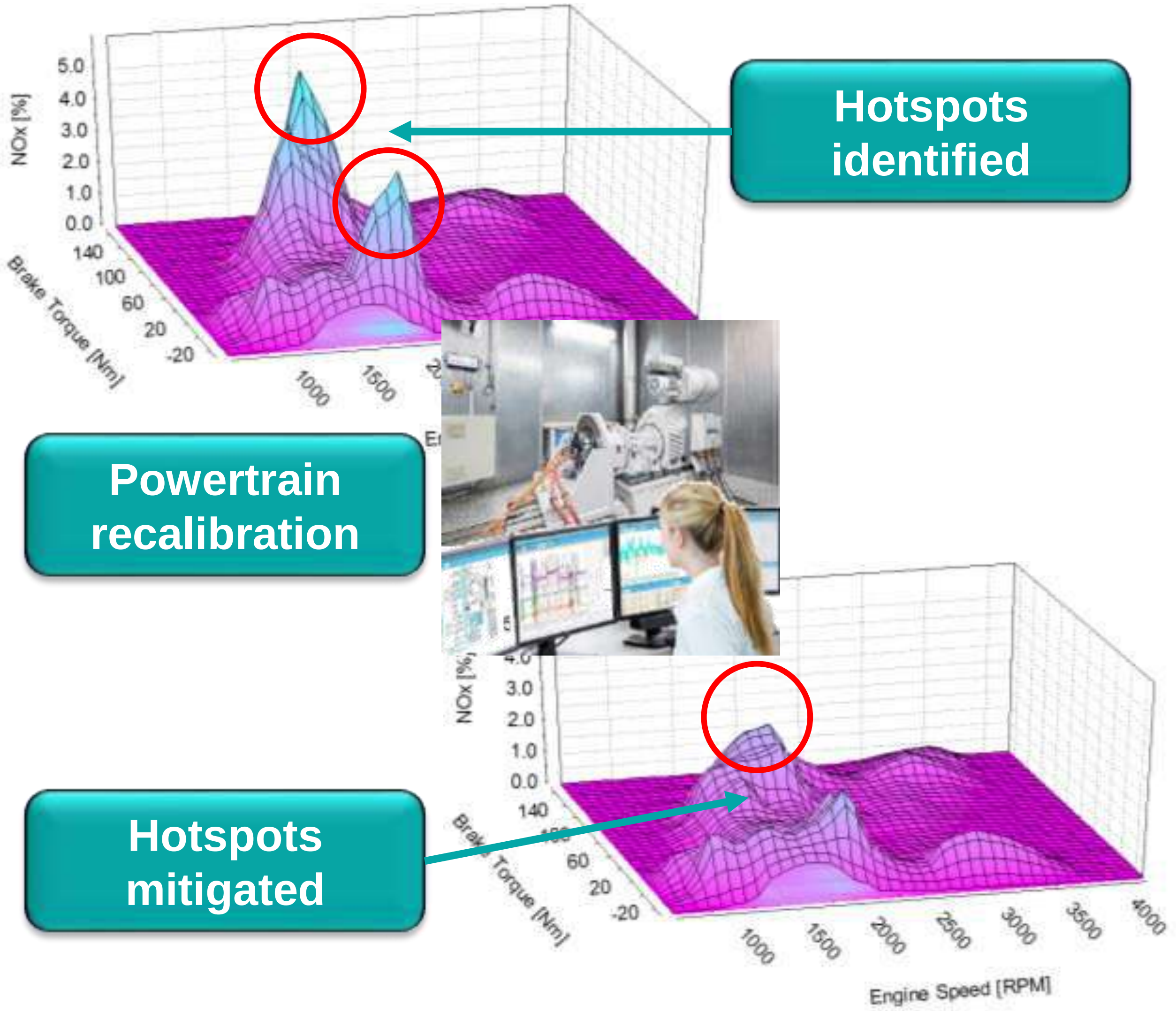
6. Predict responses

Predict attributes for the scenarios created using the light-weight transient empirical models created



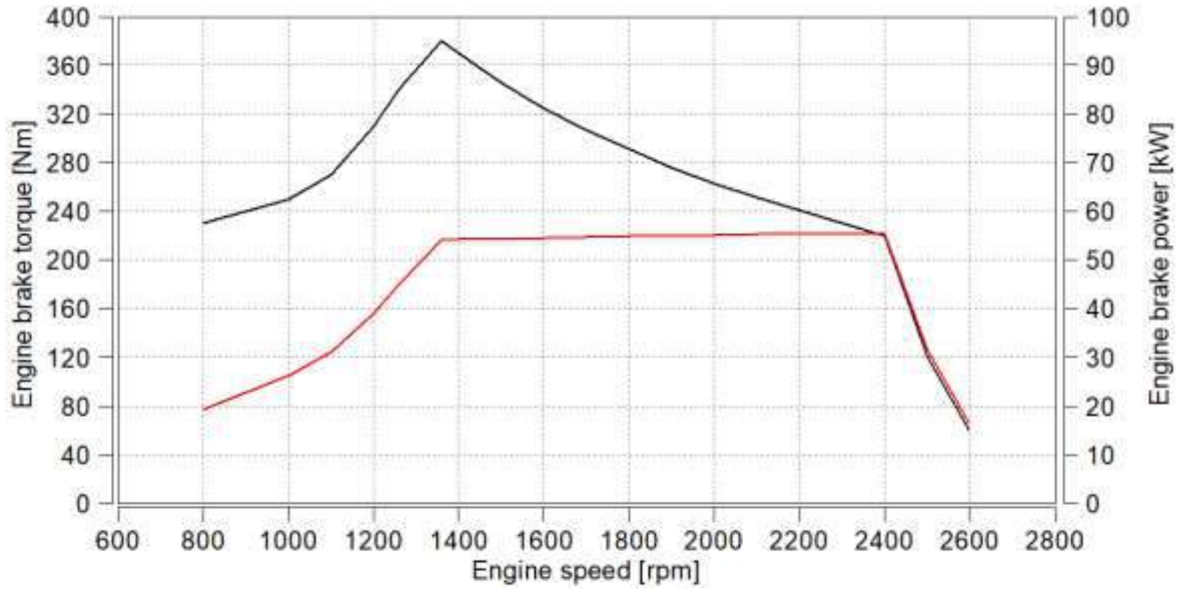
7. 'Hotspot' recalibration

Identify 'hotspots' and recalibrate/change hardware to improve cycle results



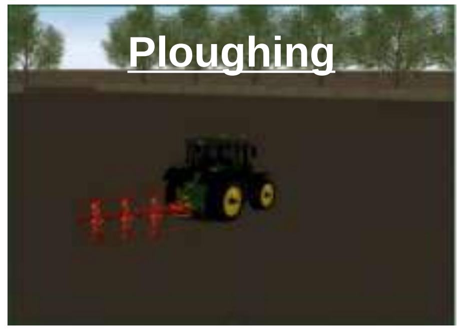
Prediction of Performance and Emissions: *Simulated* Virtual Machine Duty Scenarios

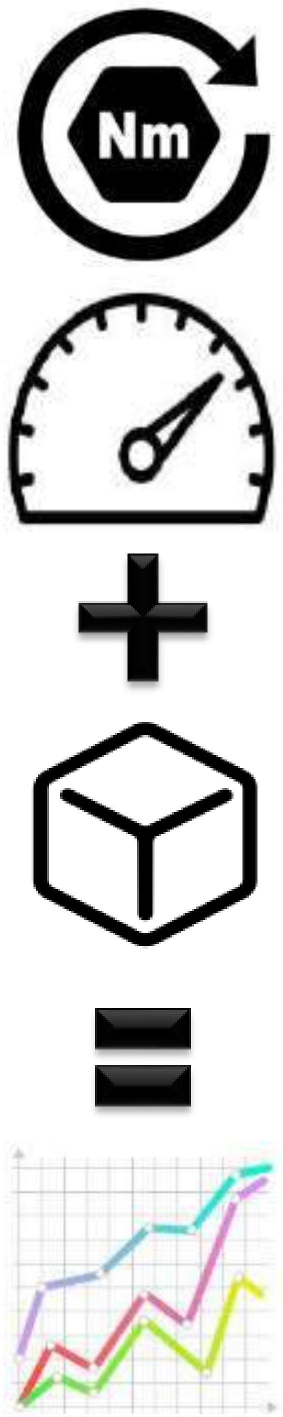
- Demo tractor from AgriSI standard library
- Parameterised from experimental data
- Total weight: 6,200kg
- Front axle: twisting
- Rear axle: rigid
- Tyre models for plastic soil (from ASAE specification and experimental data)
- Torque curve from mule engine tested at HORIBA MIRA; 55kW peak power



Soluzioni ingegneria

IPG





Extract torque and speed from simulations

Couple with empirical models

Predict responses

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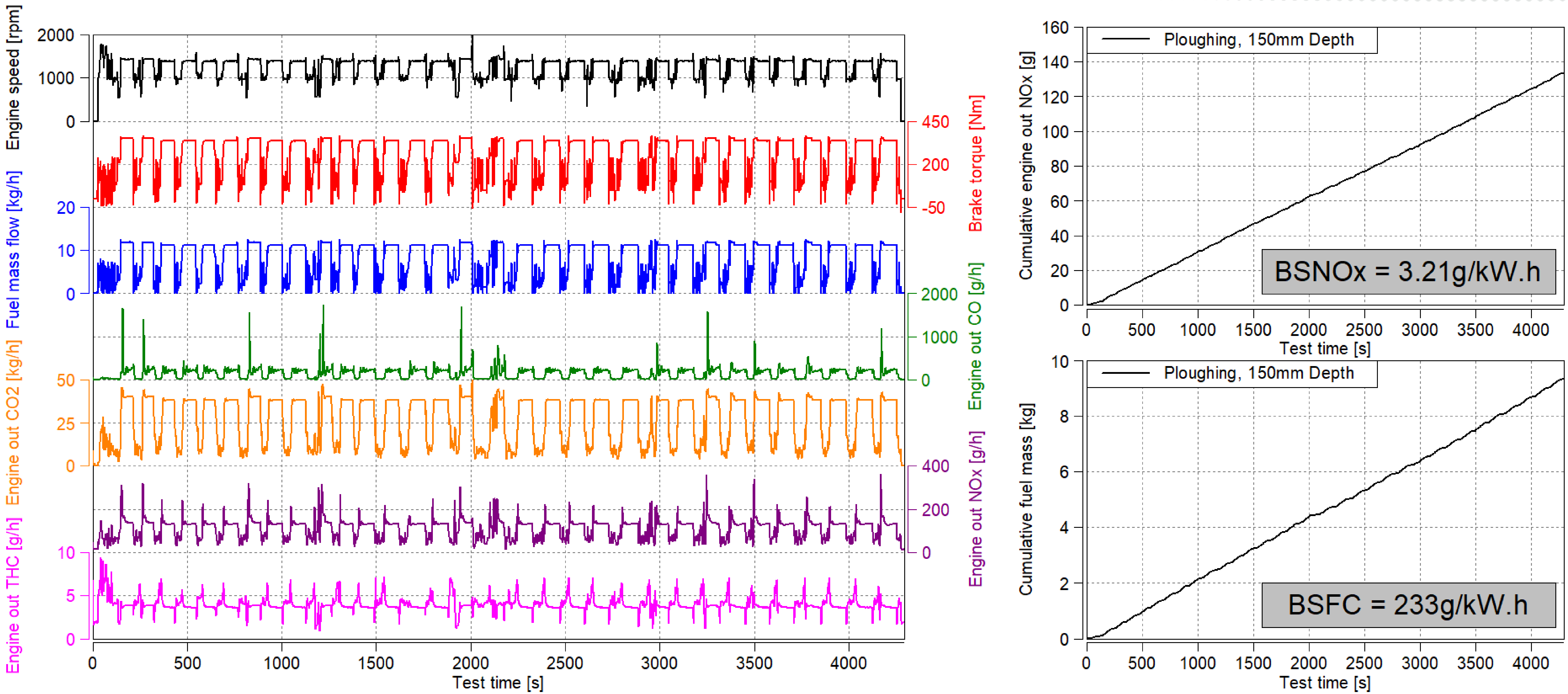
Prediction Examples from Simulation – Ploughing 150mm Depth



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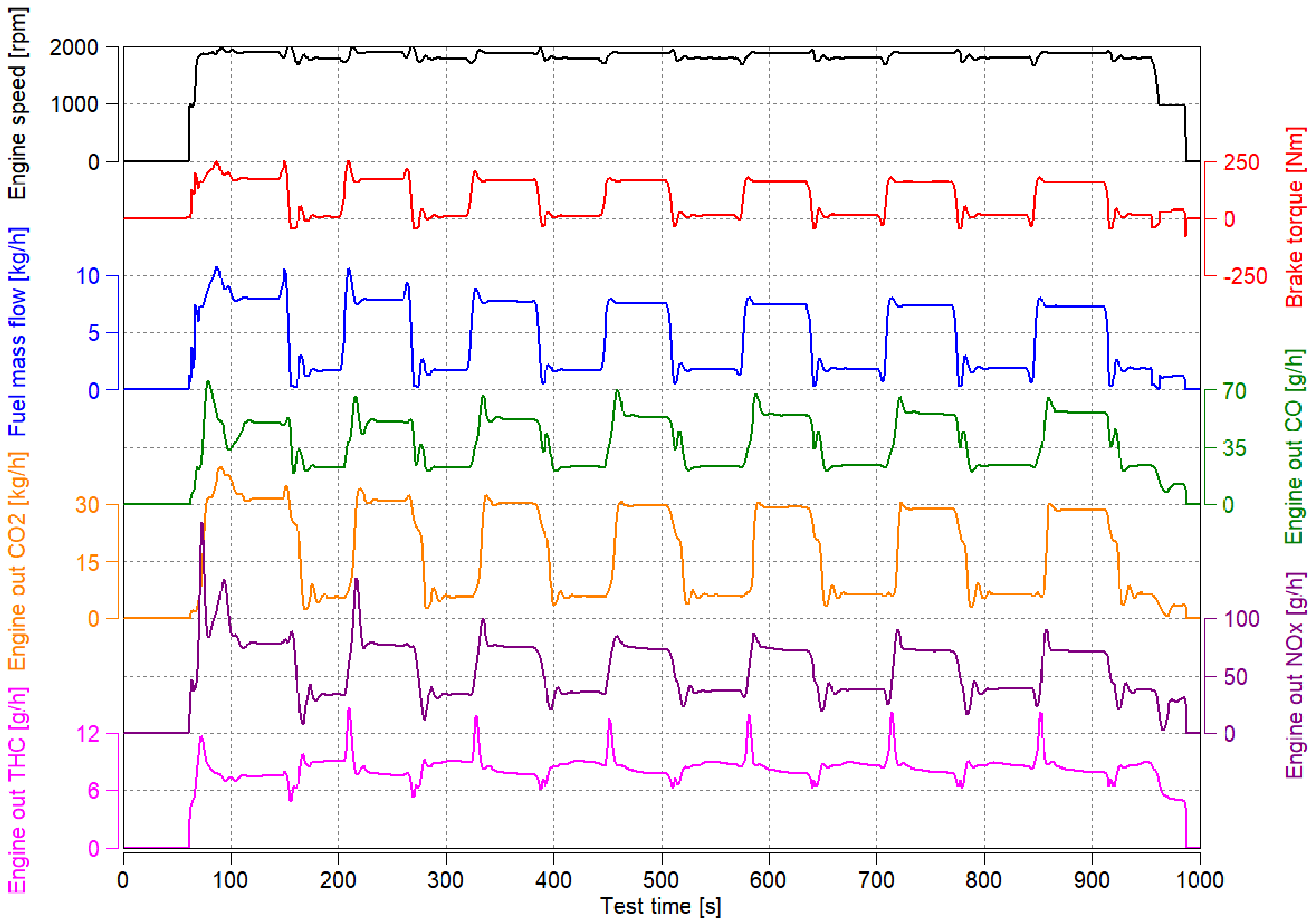
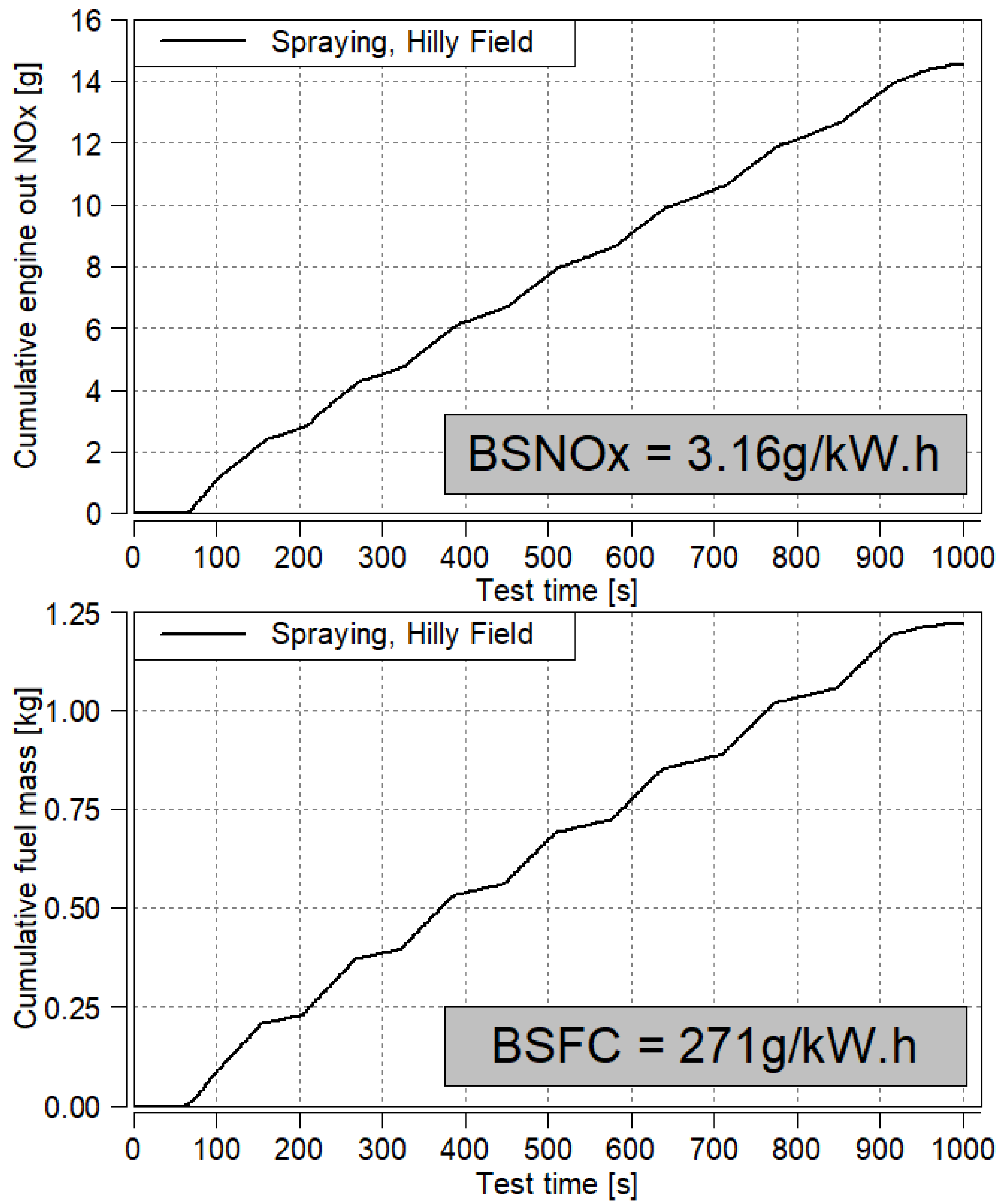
Prediction Examples from Simulation – Spraying, Hilly Field





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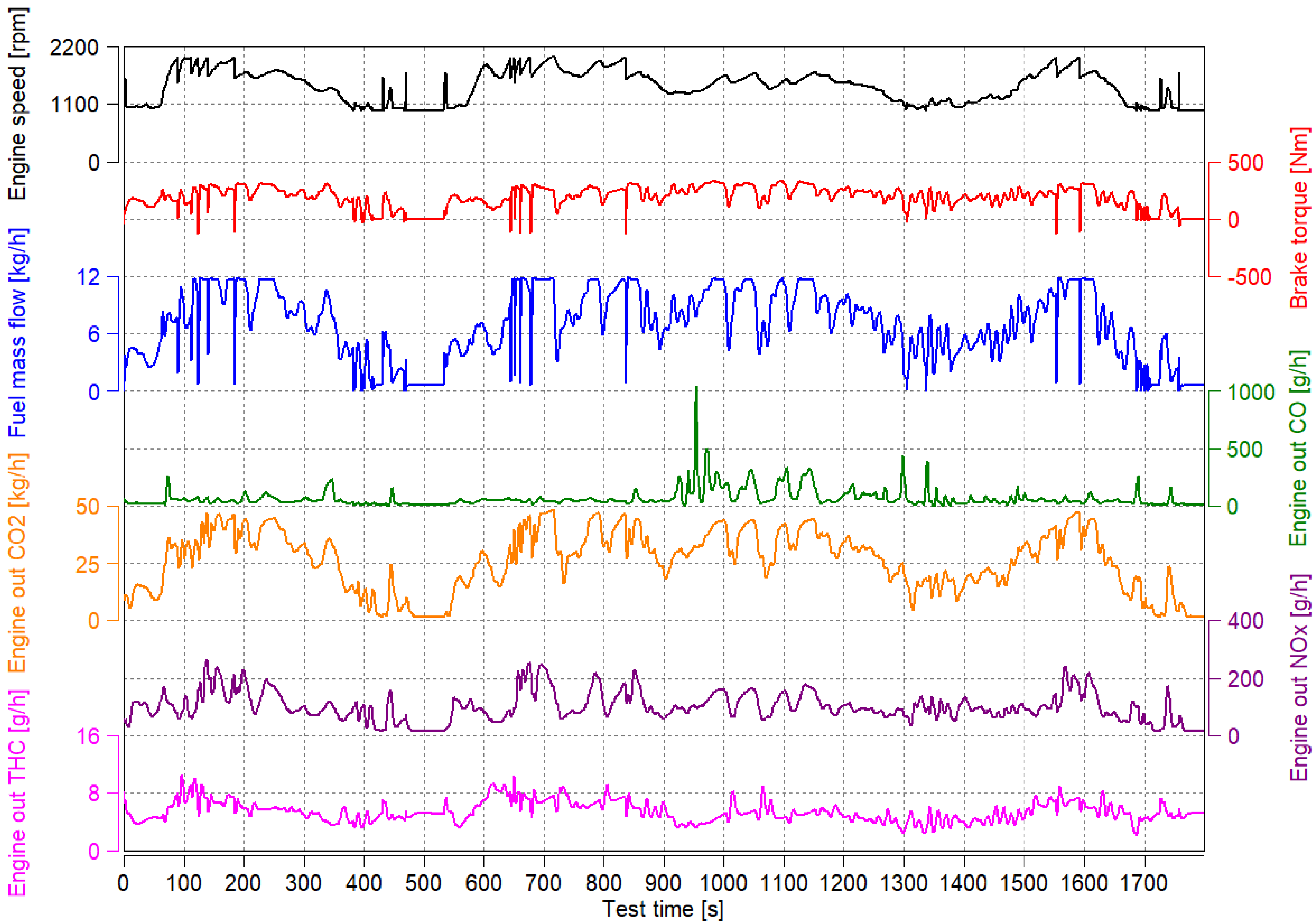
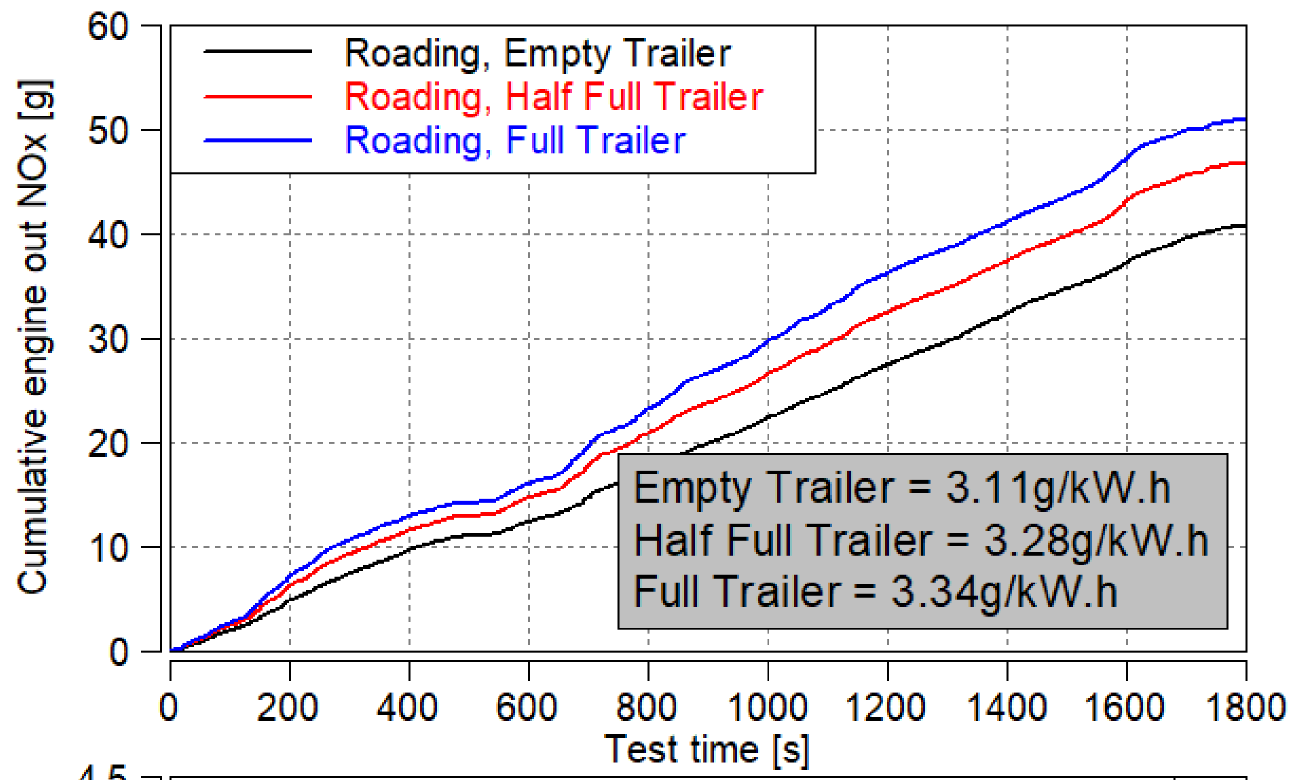
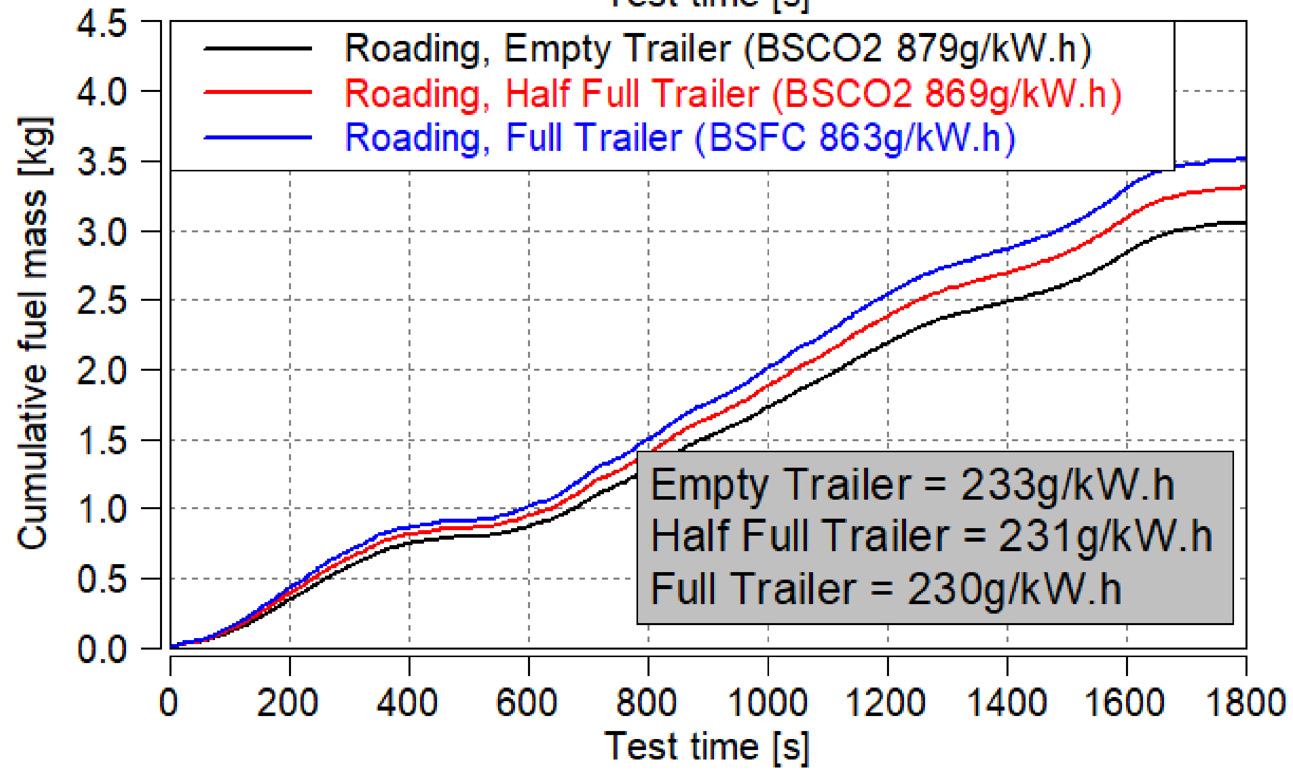
Prediction Examples from Simulation – Roading with Trailer (empty, half, full)







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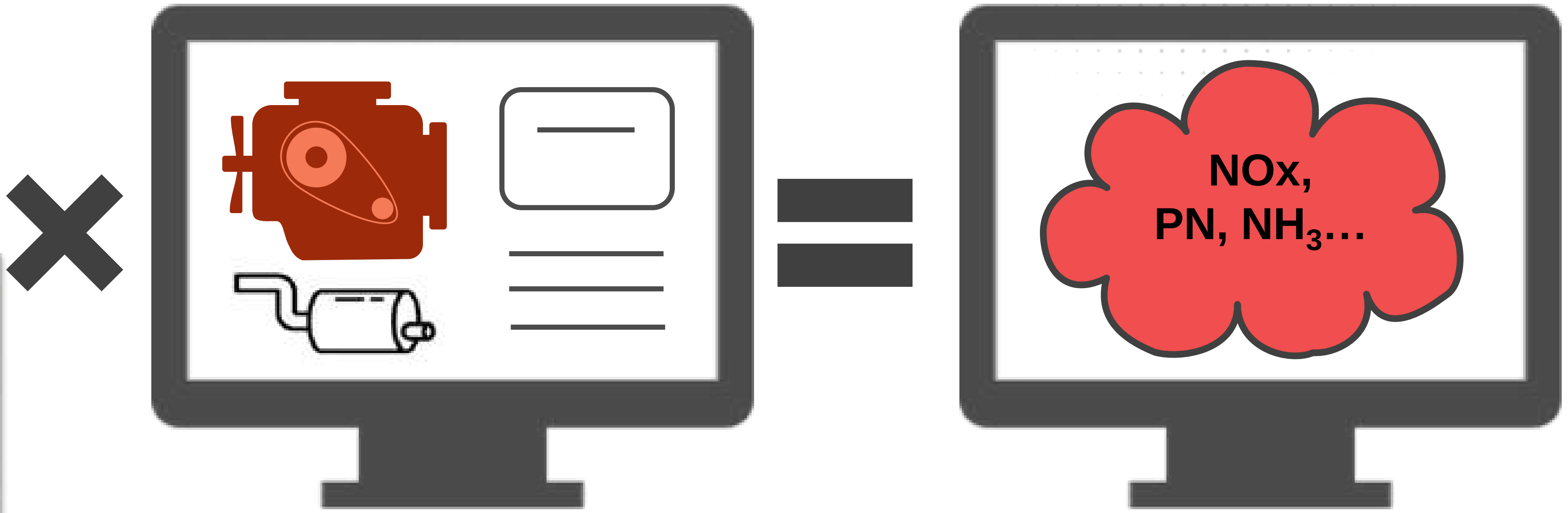
Multiple Machines, Common Powertrain, Decreased Workload…..

- Powertrain sharing is common for off-highway manufacturers
- A single powertrain digital twin can be deployed for multiple machines



Test Scenario
Vehicle, Terrain and Environment

Dynamic Empirical Models
Performance and emissions

Predictions
Fuel, air, NOx, PN, NH_3, N_2O,, CO_2eq

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Conclusions

- Future direction of global NRMM regulation will bring in real-world emissions and in-service compliance
- Real-World emissions scenarios add significant complexity to the development and certification process
- New methods must be used to mitigate the impact of such complexity
- HORIBA and partners have demonstrated the use of empirical digital twins in NRMM simulation
- Digital Engineering solutions will be required to meet the demands of real-world ISC compliance for NRMM

Thank you

Cảm ơn

감사합니다

ありがとうございました

Dziękuję

धन्यवाद

Grazie

Merci

谢谢

நன்றி

ขอบคุณครับ

Gracias

Obrigado

Σας ευχαριστούμε

Děkuji

Teşekkürler

شكرا

Tack ska ni ha

Danke

Большое спасибо