Meeting the Challenges of Calibrating HD ICEs for Real-World and In-Service Emissions Compliance using AI-driven Empirical Digital Twins

Steve Whelan, HORIBA Global Applications Leader, HORIBA MIRA Ltd, UK

HORIBA

Contents

- Introduction – What is a Digital Twin and what are the benefits?

- HORIBA Empirical ICE Digital Twinning Toolset

- Non-Road Mobile Machine Training Cycle and Model Validation

- Non-Road Mobile Machine Simulations

- Non-Road Mobile Machine Performance and Emissions Predictions

- Conclusions

Contents

Empirical or Data-Driven 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.

- These models are subsequently used to predict responses for specific inputs.

Physical Object

Test Data

EDT

Models

NOx

Current

Battery

Fuel

Validation

4
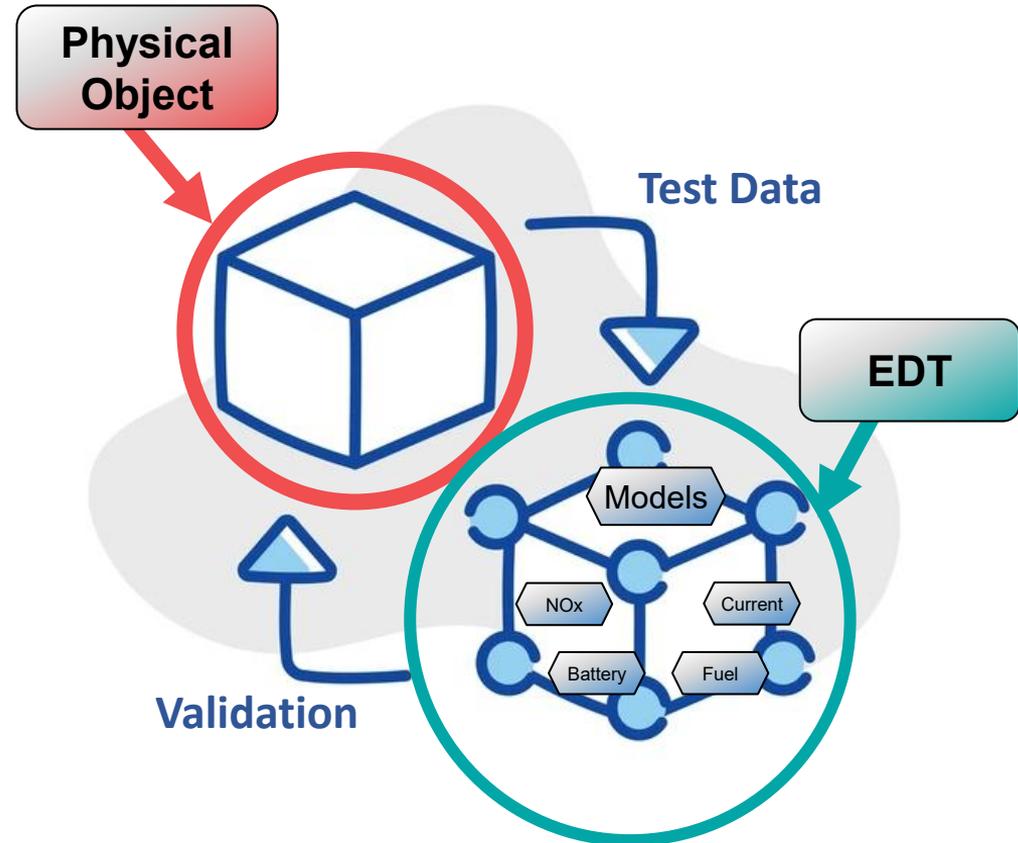
The New HD Challenge of Real World Emissions Compliance

ISC and RDE will impact NRMM & HDV ICEs, whatever type of decarbonised fuel is used
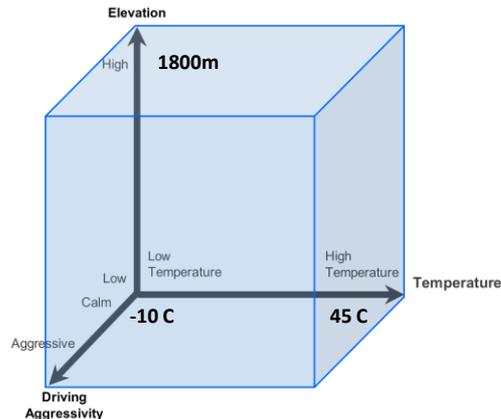
NRMM Stage VI ISC

- 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
    - Reporting due now
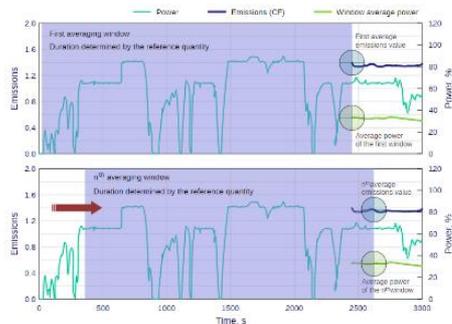
Stage VI:

Mandatory ISC in 2032

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, NH3,
- From cold (2km @ <20% power)
- Brake & Tyre PM/PN
- Battery durability
- On-Board Monitoring

Elevation / High / 1800m

Low Temperature / High Temperature

Low / Calm / -10 C / 45 C / Temperature

Aggressive / Driving Aggressivity

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

Coping with "Infinite" Scenarios Without "Infinite" costs!

Achieve sufficient coverage using predictive simulation

- Almost "infinite" drive-case scenarios in Euro 7 and In-Service Compliance NRMM Stage VI

- Impossible to physically test and validate all drive cases

Solution

- Use simulation to identify worse cases
- Physically test worst cases only (far fewer tests)
- Use simulation to populate the validation
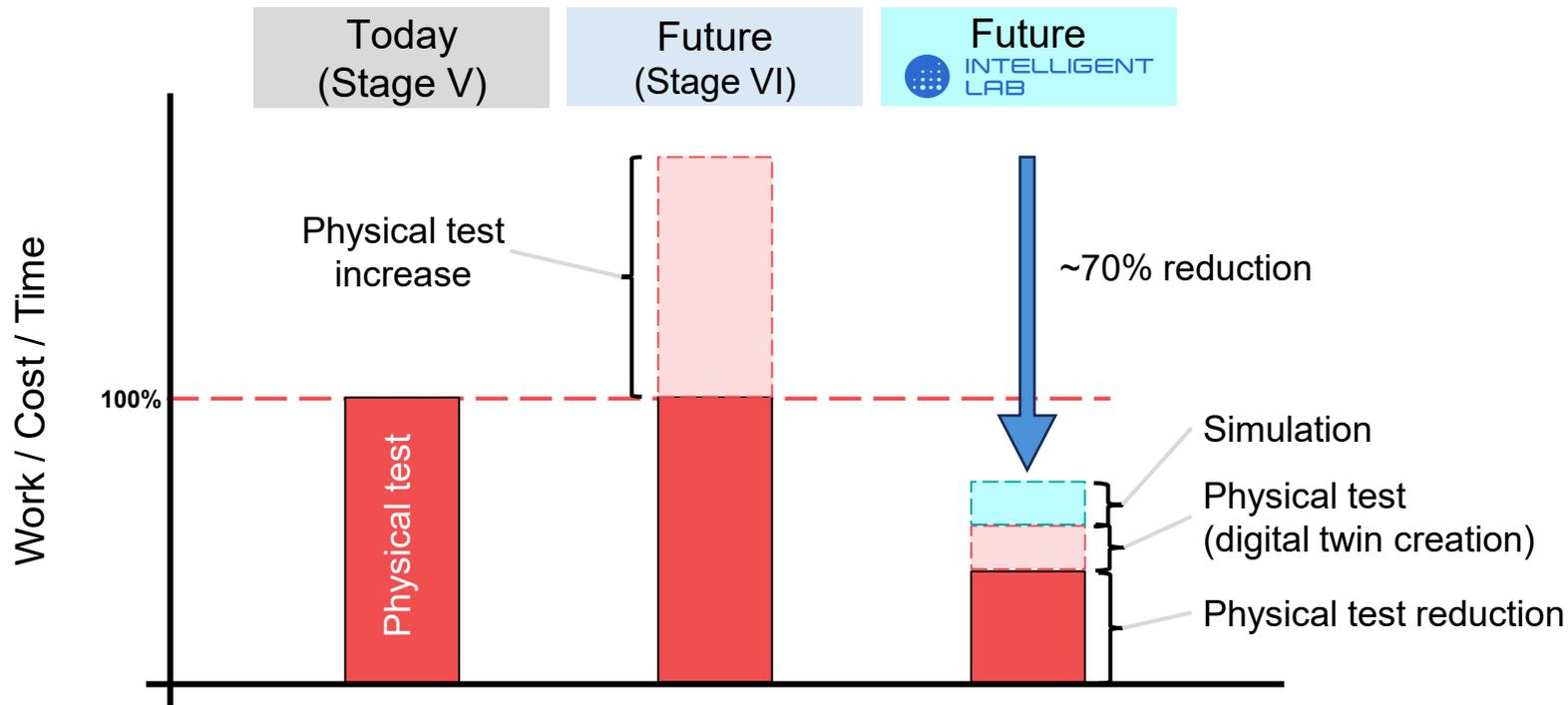
- **Physical** 'Worst case' Road test Lab Replication & Emulation

- **Simulation** Empirical Digital Twin + Co-simulation

Altitude

Euro7 RDE & ISC "Envelope"

Temperature

Driving Aggressivity
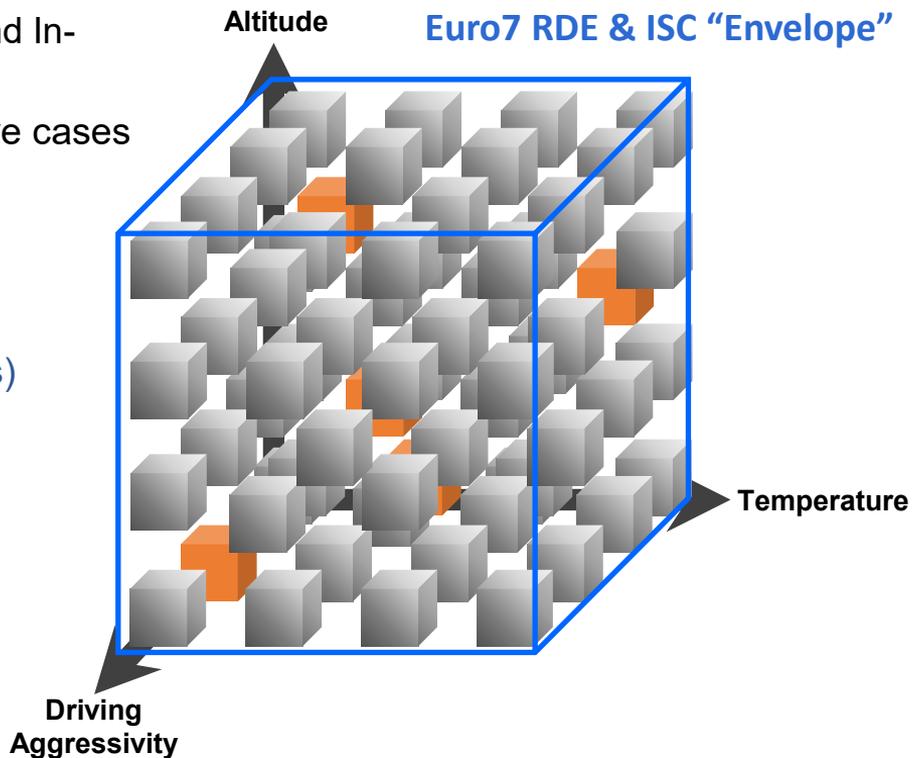
Reducing the Need for Physical Testing – Reduce Time & Cost

- Include accurate simulation as part of the validation and sign-off process to avoid extra testing
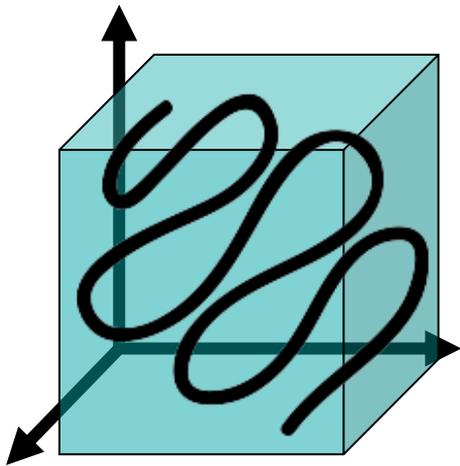
Contents

HORIBA Empirical (Data-Driven) ICE Digital Twin

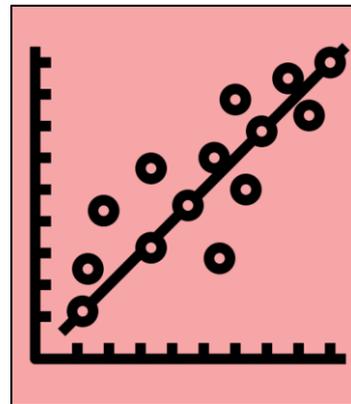| Test Designer	AI Modeller	Predictor	Optimiser

Transient excitation signal design specific to the unit under test
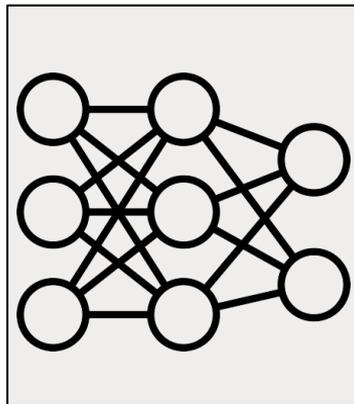
Rapid generation of transient empirical models using AI recurrent neural networks

Prediction of attributes using transient empirical models at faster than real-time
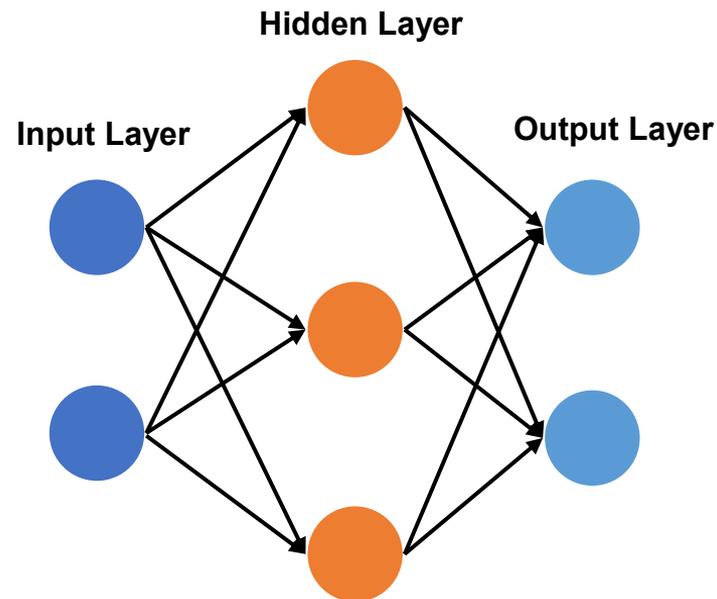
Multi-objective optimiser and 'hot-spot' identification toolset for improved performance

Neural Networks
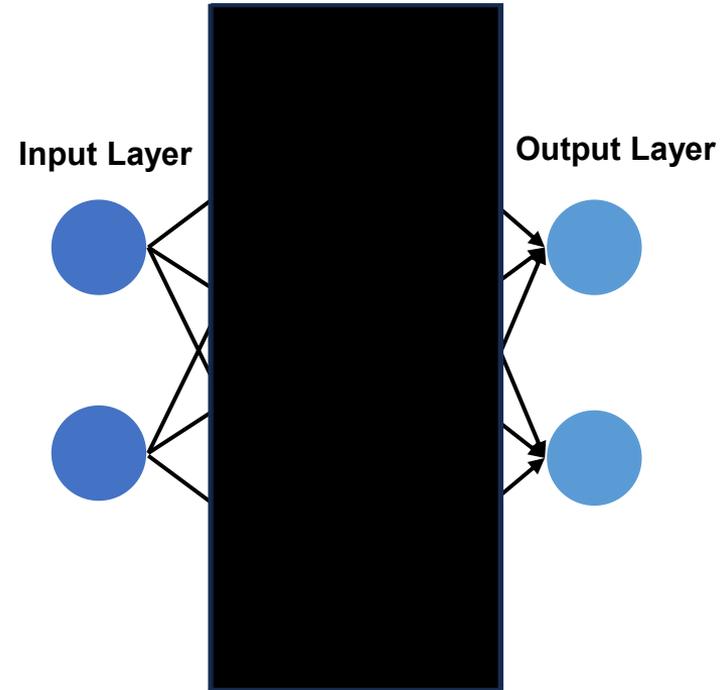
General Purpose Predictor

- Neural networks are a complex structure of simple operations

- They are generated by varying those simple operations and comparing the resultant output to a measured value. The aim is to minimise the difference across the whole dataset

- Completely Black Box and uninterpretable, but well established and have been shown to exhibit very good performance across a wide range of applications

- (Usually) takes a lot of data and time to train

- Predict extremely quickly

- Readily accelerated with GPU computation

Hidden Layer

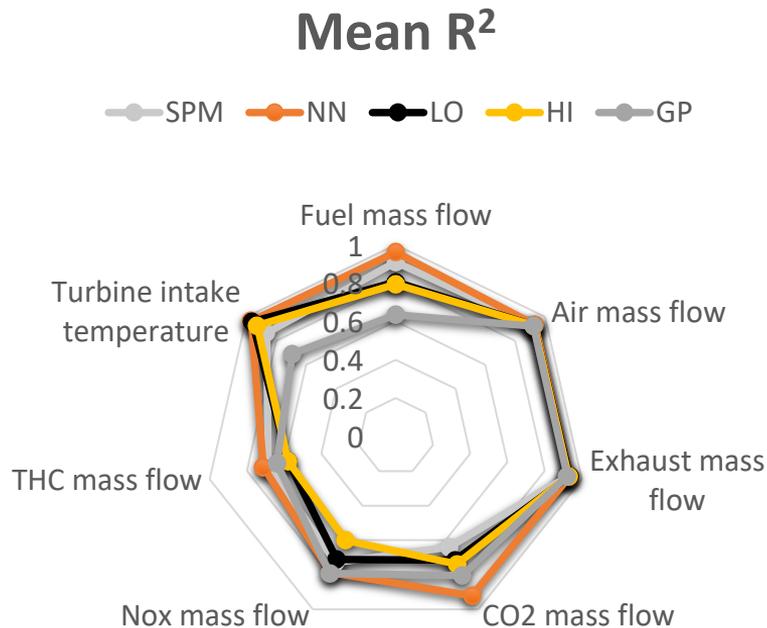**Input Layer**

Output Layer

HORIBA

Neural Networks

General Purpose Predictor

- Neural networks are a complex structure of simple operations

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Input Layer   **Output Layer**

Modelling Method Evaluation

Model	Training Time (dynamic DOE dataset)	Prediction Time (test dataset)
SPM	Several minutes	~60 seconds
Neural Network	~1.5-5 minutes	~0.1-0.5 seconds
LOLIMOT	~2.5–25 minutes	~0.01-0.5 seconds
HILOMOT	~10-100 minutes	~0.02-0.1 seconds
Genetic Programming	~5-45 minutes	~0.01-0.1 seconds
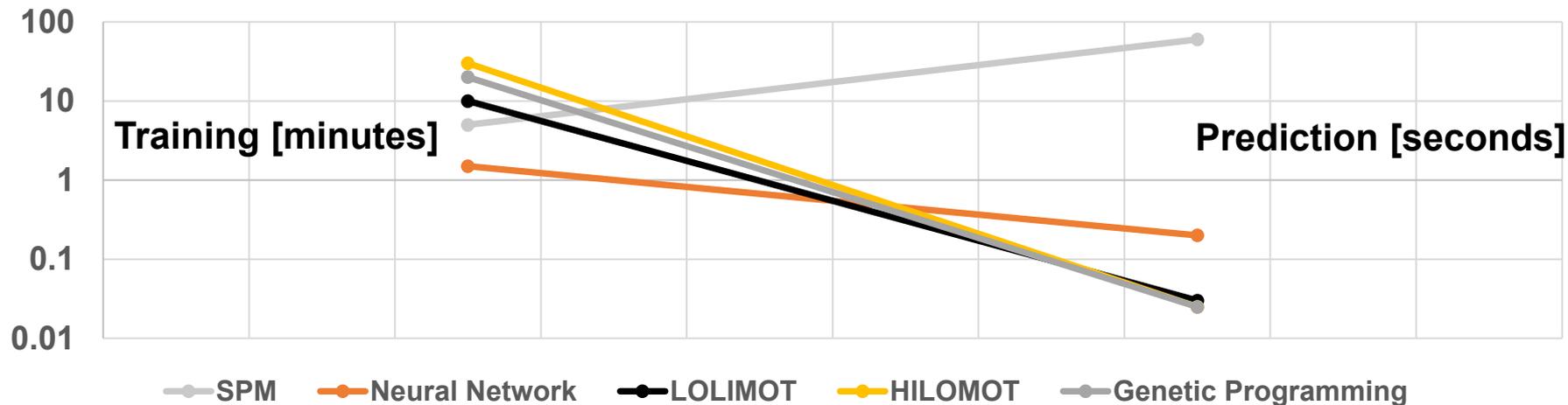
Intelligent Lab Recurrent Neural Network (RNN) Approach

Adding Memory, Dynamic Capability

- Adding LSTM (Long Short Term Memory) nodes to the network allows the model to look at not just the instantaneous data, but sequences of data and the history of the system.

- Systems with time dependent phenomena (dynamics) can be accurately reproduced.

- Dynamic capability allows prediction of e.g. NO_X

- Scales to meet the complexity of your problem

- Intelligent test design allows fast training times with minimal data due to high data quality and information density.

- **RNN delivers optimum solution for training & prediction**

Mean R^2

SPM — NN — LO — HI — GP

Fuel mass flow
Air mass flow
Exhaust mass flow
CO2 mass flow
Nox mass flow
THC mass flow
Turbine intake temperature

1
0.8
0.6
0.4
0.2
0

Digital Twining Creation & Validation

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)
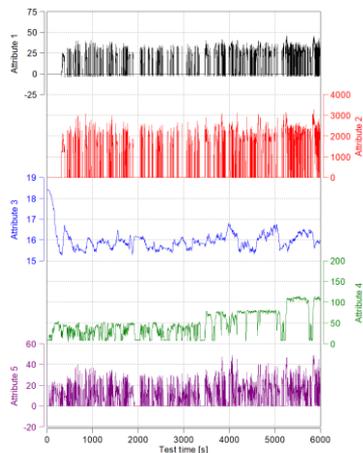
3. Model creation

Create transient empirical models of various performance and emissions attributes
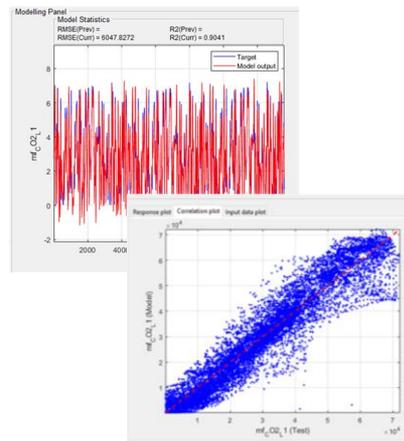
4. Model validation

Validate transient empirical models to ensure high quality and fidelity
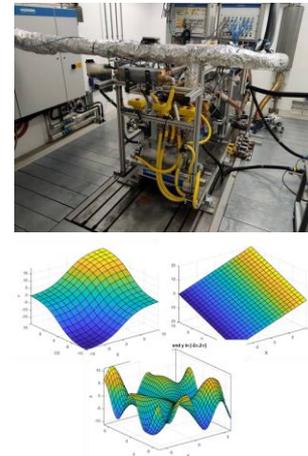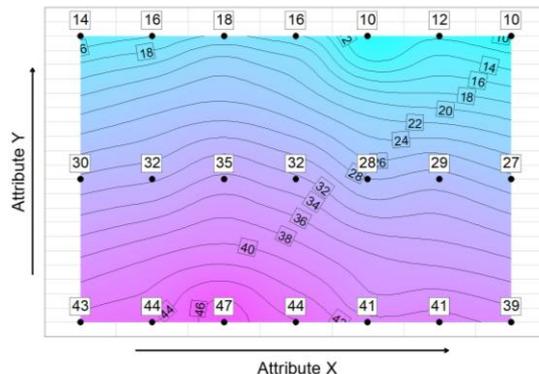
Digital Twin Usage – ICE Application Calibration

5. Virtual or Real Scenarios	6. Predict Responses	7. 'Hotspot' Recalibration

Create real-world machine cycles using software or use physical real-world data and couple with EDT

Predict attributes for the scenarios created using the empirical models

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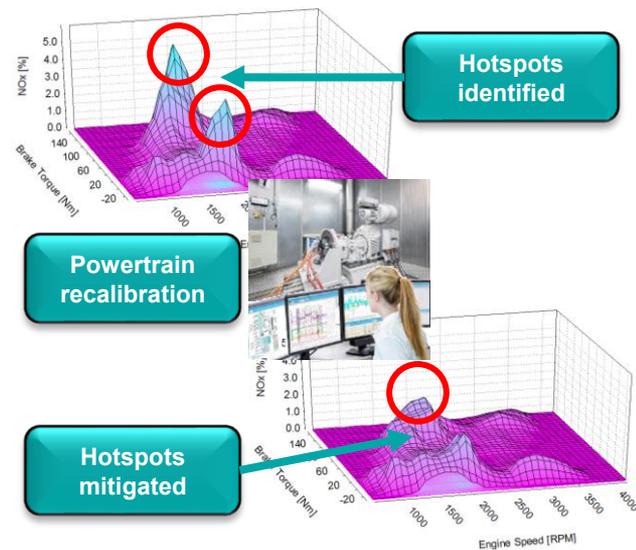
Hotspots identified

Powertrain recalibration

Hotspots mitigated

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NRMM ICE EDT Training Cycle – Dynamic DoE Design

Operating Space Coverage
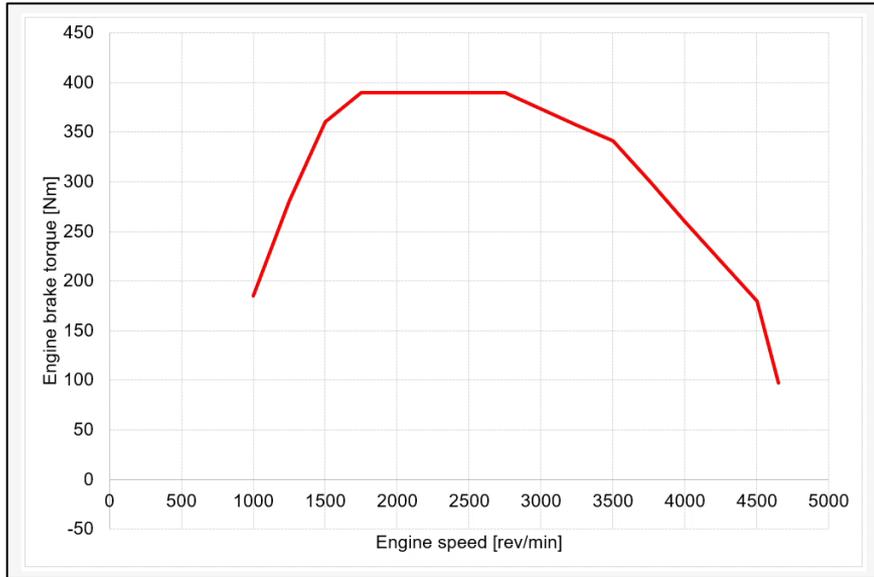
The transient training cycle should cover the entire operating space of the unit under test; mitigates the need for extrapolation during modelling
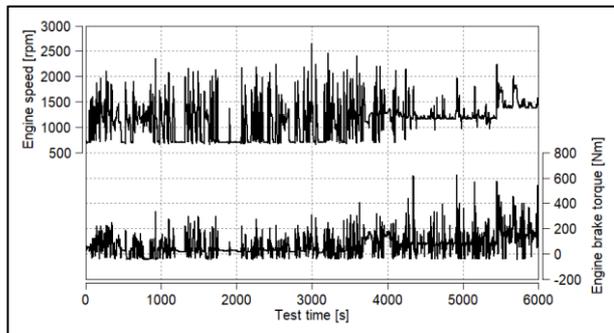
Real-world Representative Transients
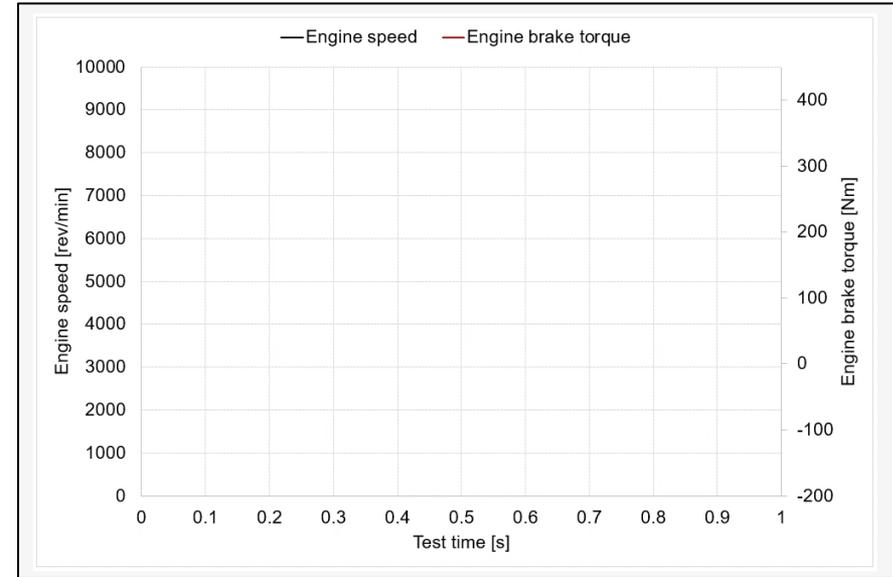
Real-world transient operation of the unit under test should be considered during design of the training cycle; variable transient operation is possible
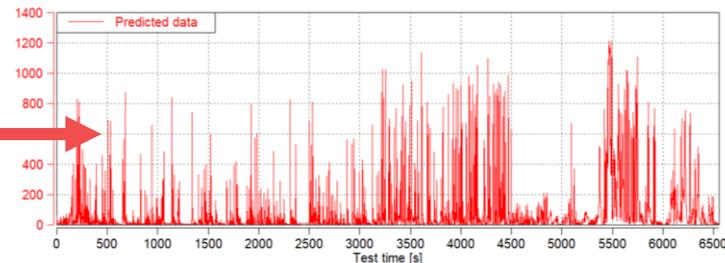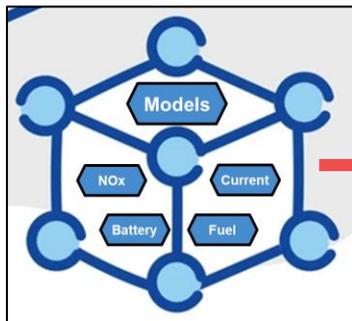
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EDT Model Validation Technique

Validation cycle
Run the cycle on the engine

Validation cycle
Run the cycle through the EDT

Measured data

Predicted data

EDT Model Validation Technique

Validation cycle
Run the cycle on the engine

Validation cycle
Run the cycle through the EDT

Measured Data
Predicted Data

Measured = 125.2g
Predicted = 123.8g
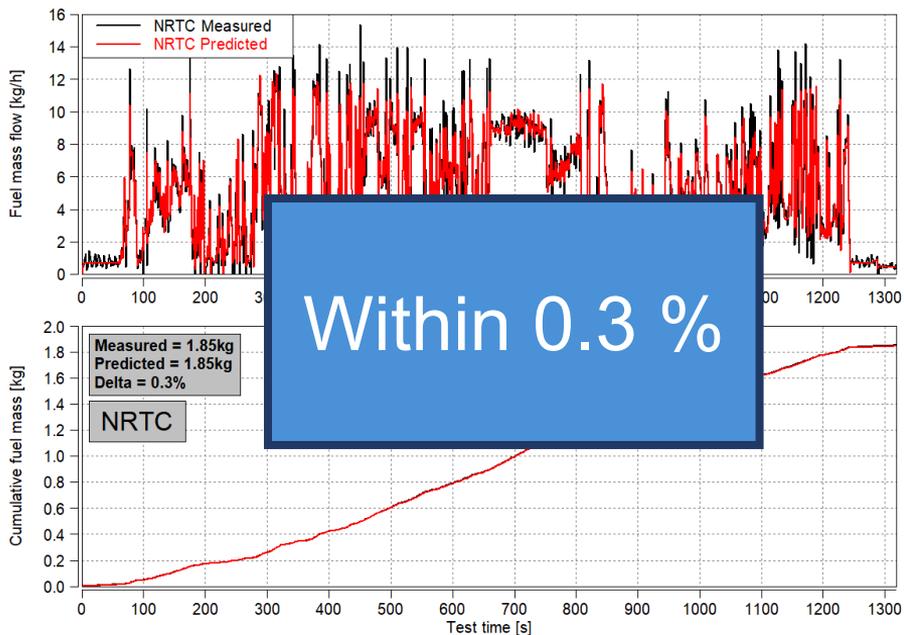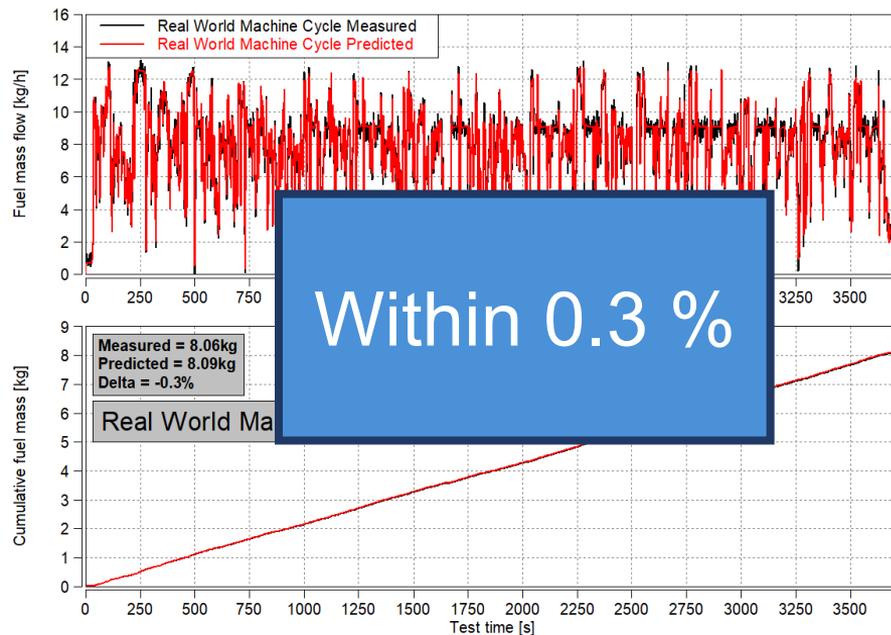Delta = 1.1%

Adequate Model Quality
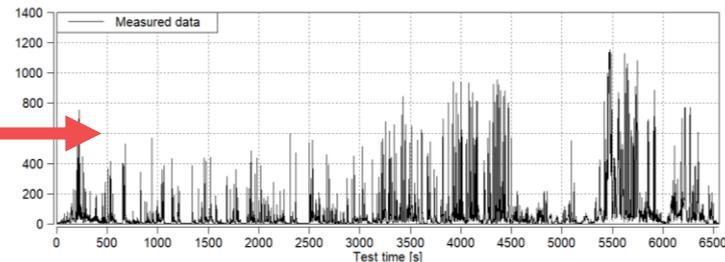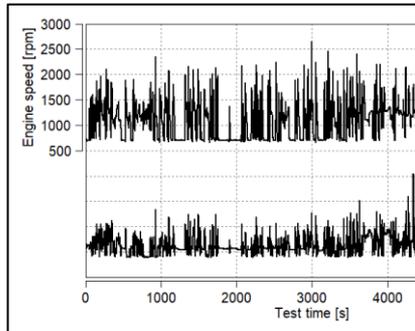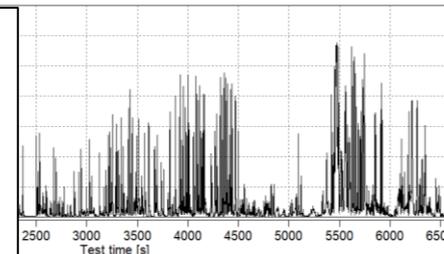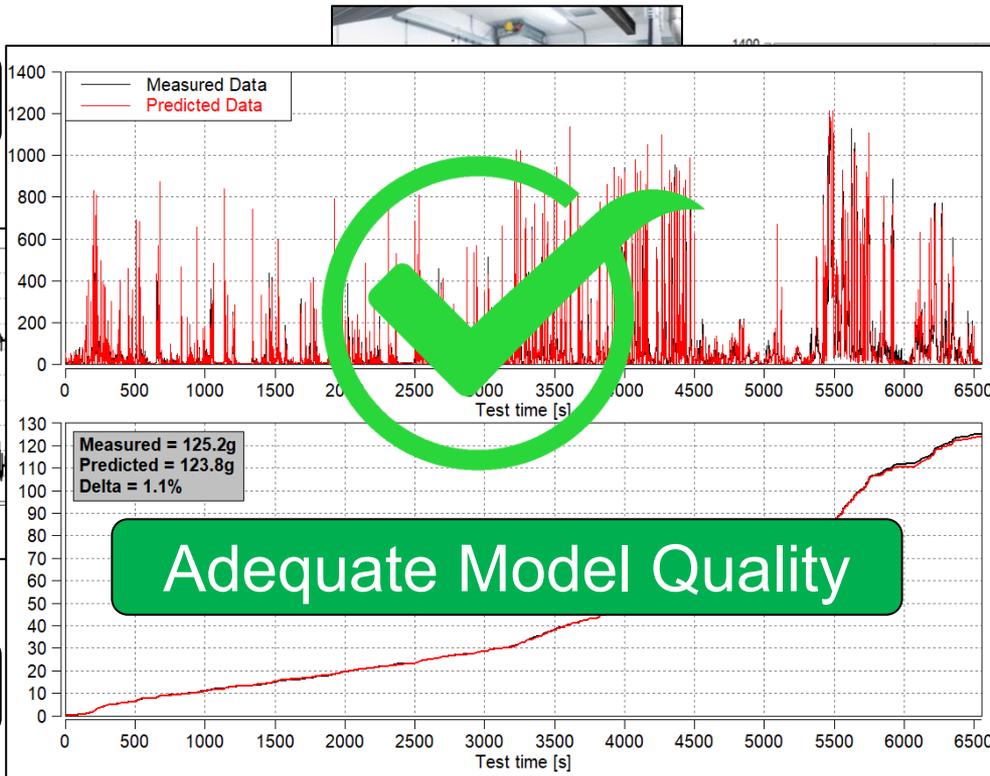
Measured data

Predicted data
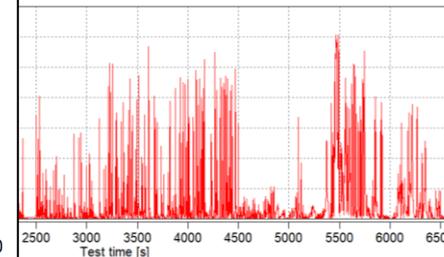
Empirical Model Quality – Fuel Mass Flow

NRTC Validation Cycle

Real World Validation Cycle

Within 0.3 %

Within 0.3 %

Measured = 1.85kg
Predicted = 1.85kg
Delta = 0.3%
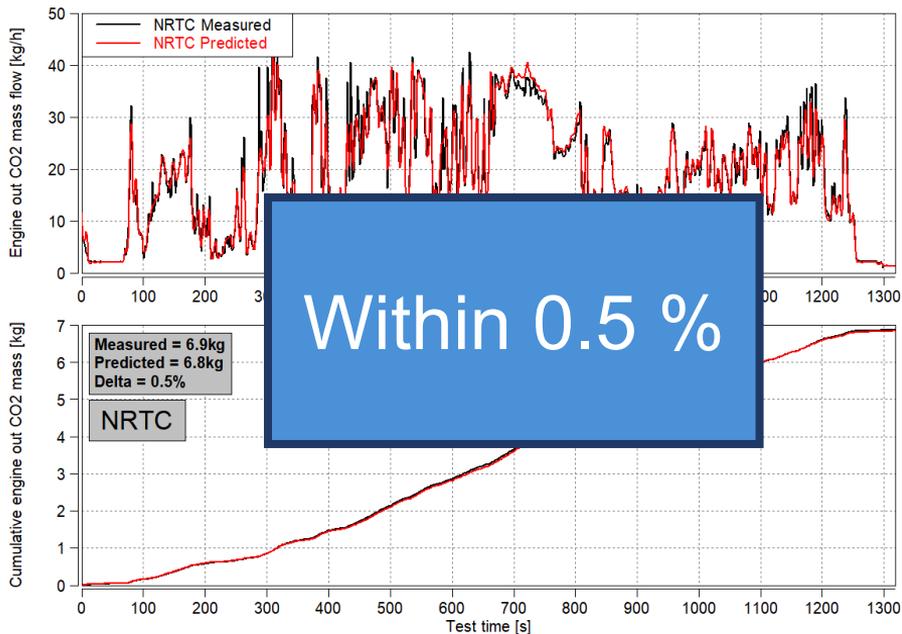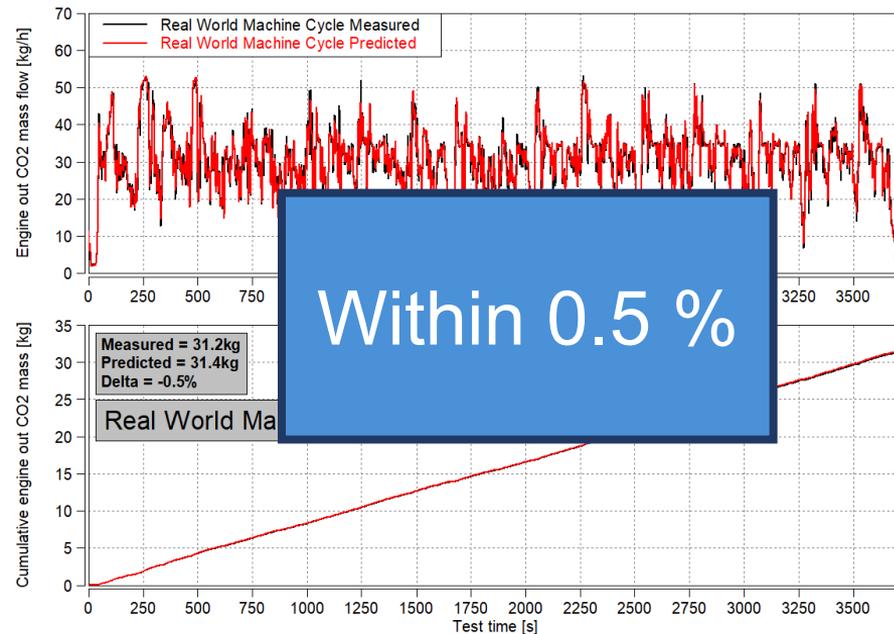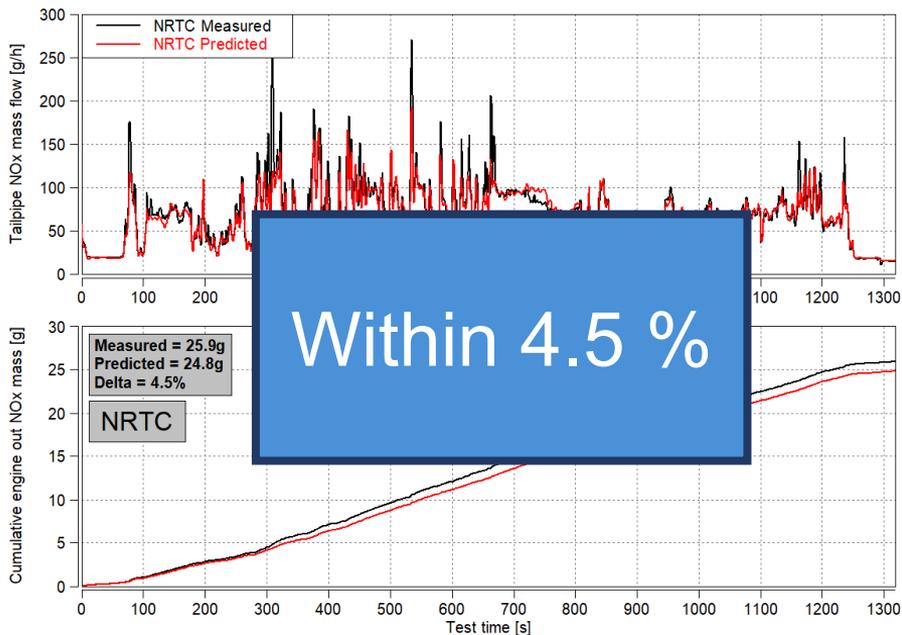
NRTC

Measured = 8.06kg
Predicted = 8.09kg
Delta = -0.3%

Real World Ma

* Non-Road Transient Cycle

Empirical Model Quality – Engine Out CO_2

*NRTC Validation Cycle

Real World Validation Cycle

Within 0.5 %

Within 0.5 %

Measured = 6.9kg
Predicted = 6.8kg
Delta = 0.5%

NRTC

Measured = 31.2kg
Predicted = 31.4kg
Delta = -0.5%

Real World Ma

* Non-Road Transient Cycle

Empirical Model Quality – Engine Out NOx
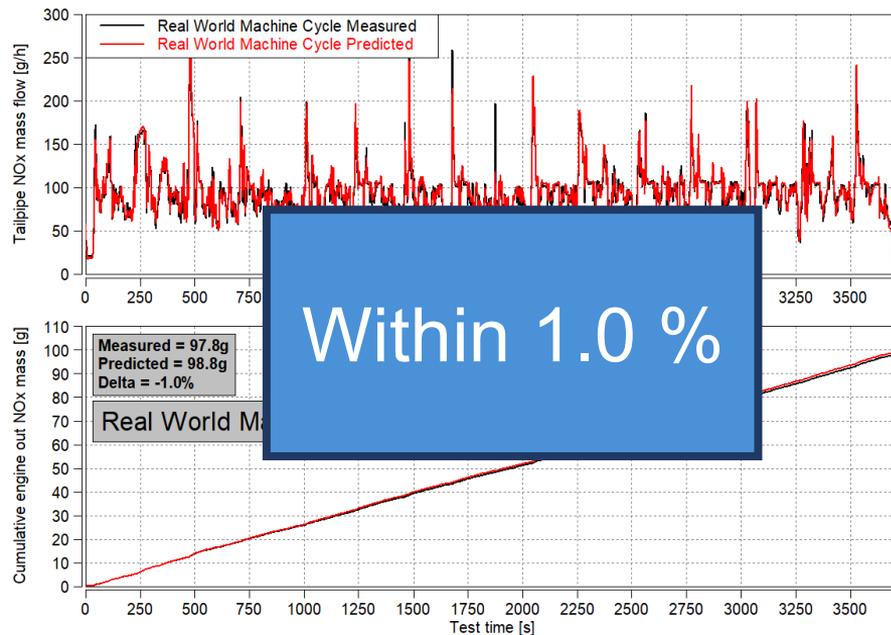

*NRTC Validation Cycle

Real World Validation Cycle

Within 4.5 %

Within 1.0 %

Measured = 25.9g
Predicted = 24.8g
Delta = 4.5%

NRTC

Measured = 97.8g
Predicted = 98.8g
Delta = -1.0%

Real World Ma...

* Non-Road Transient Cycle

Contents

Co-simulation of Virtual Scenarios with Empirical Models (1)

- 1.) Machine operation – field, accessories, hydraulic loadings, or roading including trailer towing using AgriSI software from Soluzioni Ingegneria virtual agricultural simulation software.

- 2.) Extract data for use with models e.g. engine speed and torque.

- 3.) Couple with empirical models from the EDT.

- 4.) Predict performance and emissions attributes.
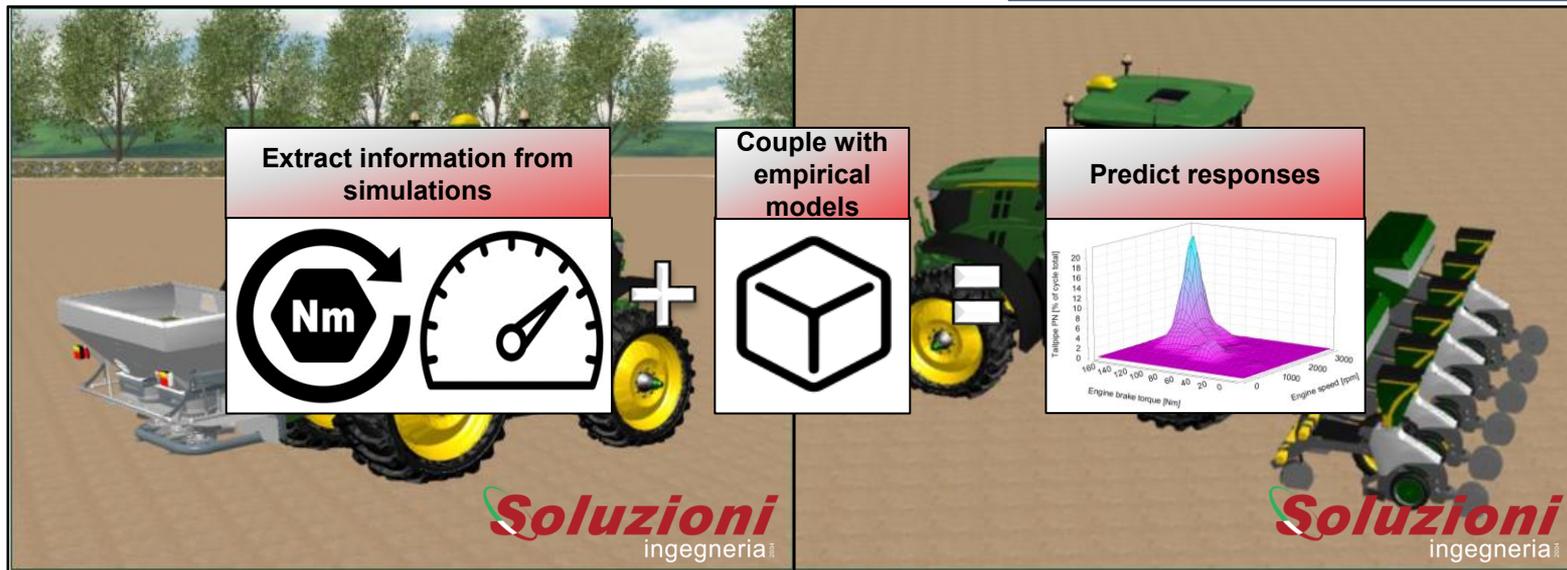
Co-simulation of Virtual Scenarios with Empirical Models (2)

- 5 different types of simulations were created: fertilising, spraying, ploughing, seeding, and roading.

- The terrain and soil depth were varied along with trailer weight during roading.

- Engine out performance and emissions were subsequently predicted for a total of 10 simulations.

# Co-simulation of Virtual Scenarios with Empirical Models (2)

Contents

- Introduction – What is a Digital Twin and what are the benefits?

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- Non-Road Mobile Machine Training Cycle and Model Validation

- Non-Road Mobile Machine Simulations

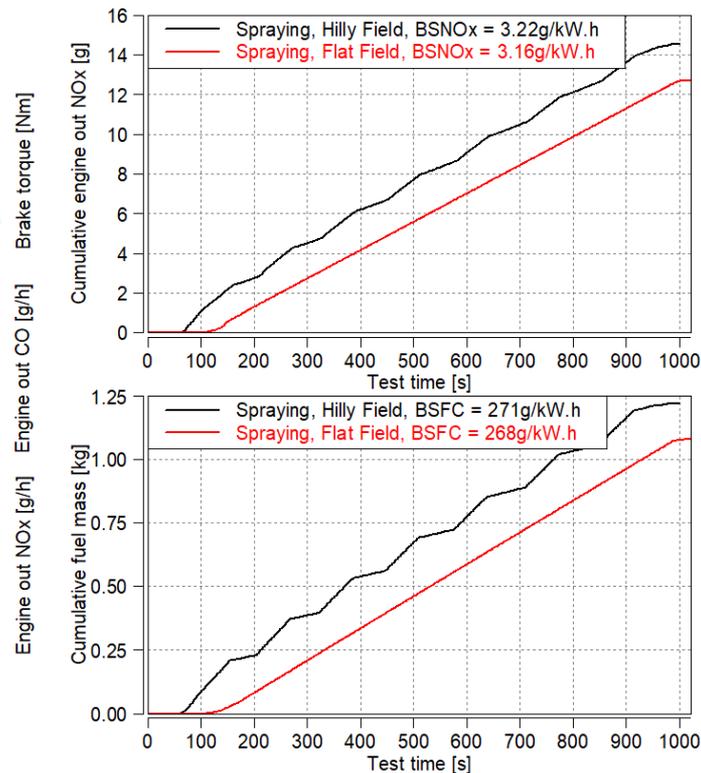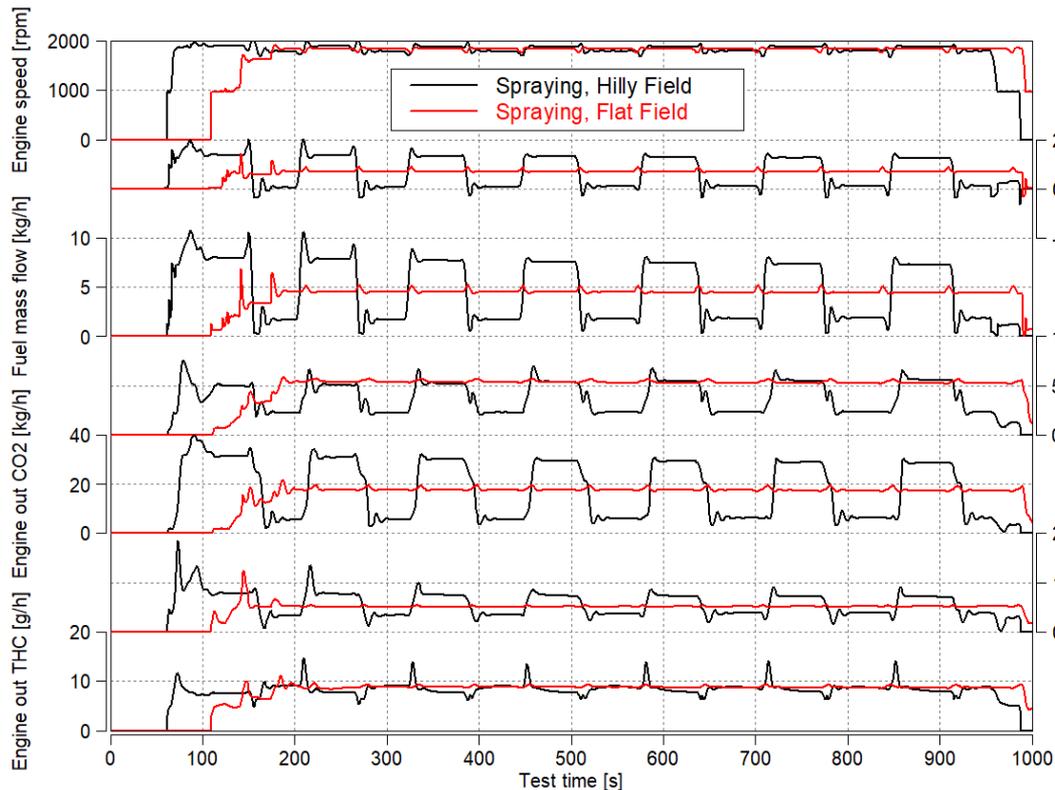- Non-Road Mobile Machine Performance and Emissions Predictions

- Conclusions

Prediction of Performance and Emissions
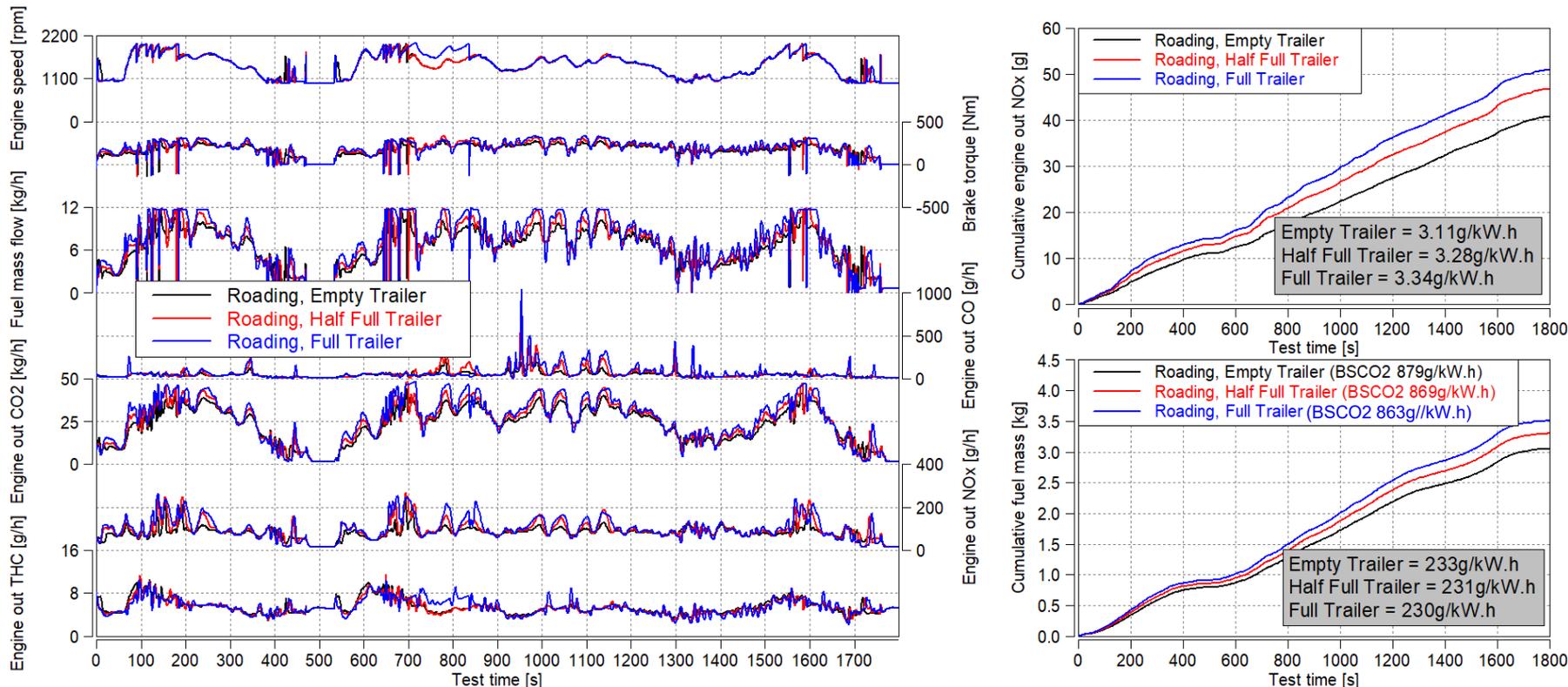# Ploughing, 150mm & 200mm Soil Depth

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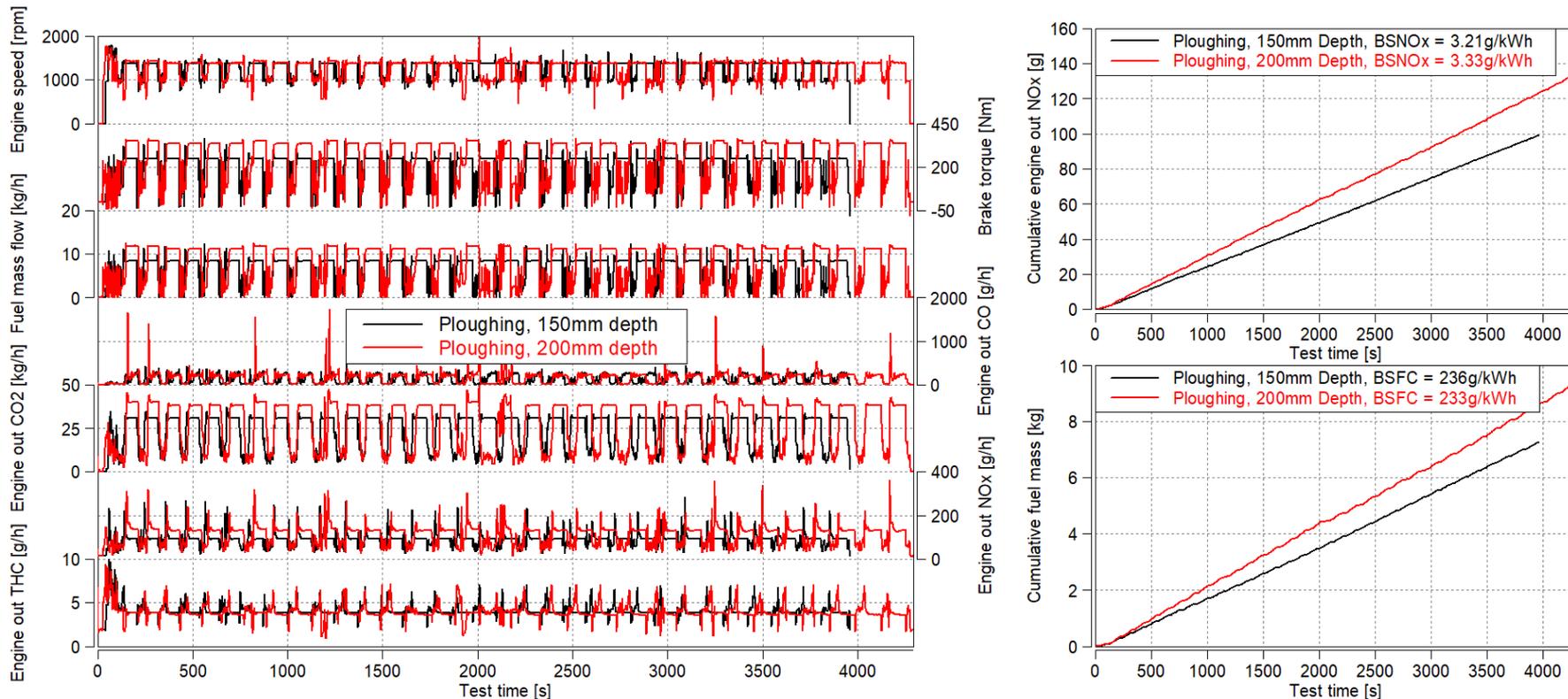
Prediction of Performance and Emissions
# Spraying, Hilly Field & Flat Field

Prediction of Performance and Emissions
Roading with Trailer, Empty, Half Full, Full

Rapid Focus on Critical Attributes

- Data from all simulations was combined. NOx and time data was 'binned' for given speed/load ranges.

- Residency plots allow identification of **Hotspots** – small time residency, high emissions.

- **Improve the calibration** or **hardware** at **Hotspot** location – **improved efficiency, reduced emissions.**

- Time residency – identification of most common operating conditions across cycles or machines = **robust calibration**.
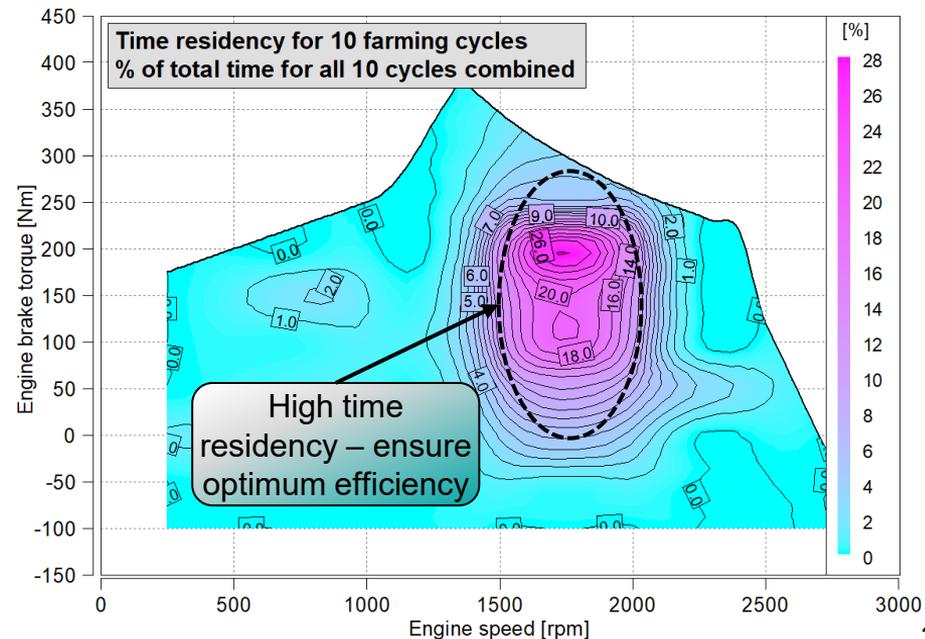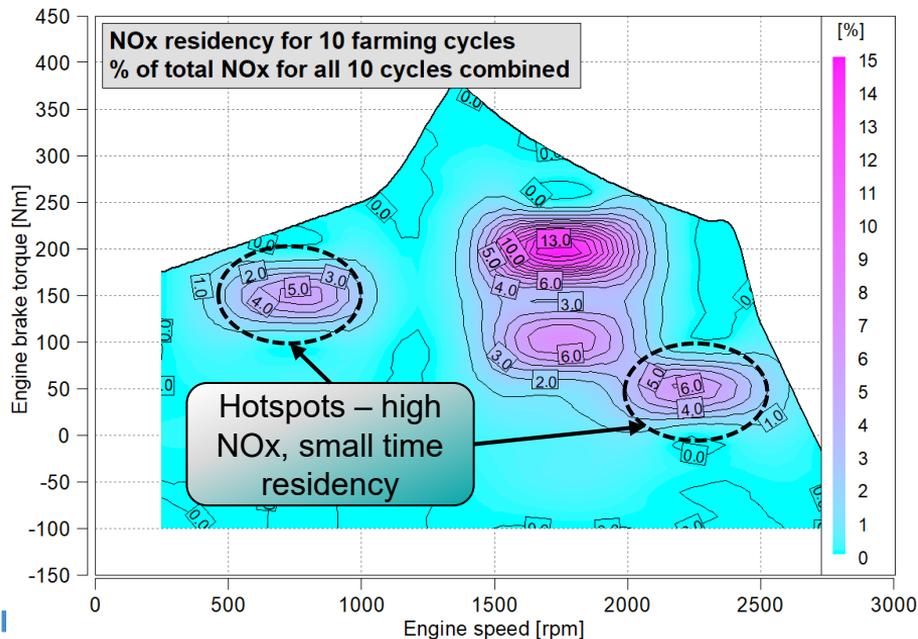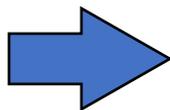

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Multiple Machines, Fuels & Applications

- Powertrain sharing is common for off-highway manufacturers
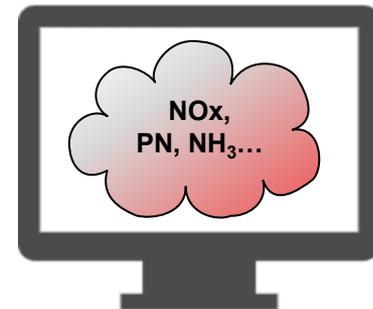- Powertrain digital twins with new fuels can be applied to machines and scenarios

- **Accelerated software development**
- **Increased certainty with decarbonised fuels**
- **Reduced product cost, risk & warranty**

Test Scenarios
Vehicle, Fuels, Terrain and Environment
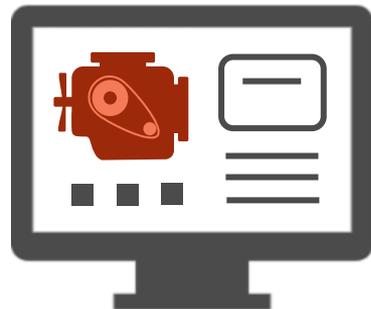
Dynamic Empirical Models
Performance and emissions

Predictions
Fuel, air, NOx, PN, NH3, N2O, electric range, CO2eq

NOx, PN, NH$_3$…

Omoshiro-okashiku
Joy and Fun

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