HORIBA Intelligent Lab

Rapid Development methodologies for Prediction of Real-world Performance and Emissions using a Powertrain Empirical Digital Twin

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Agenda

1. Digital Twinning Methodology
2. Empirical Model Validation
3. Hotspot Results
4. Methodology Effectiveness
5. Conclusions

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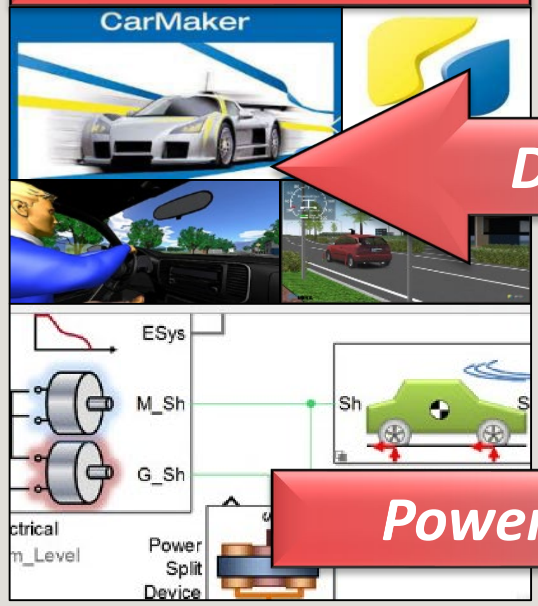
Introduction

- A powertrain performance and emissions digital twin for a light-duty passenger vehicle has been developed. It utilises HORIBA's Intelligent Lab solutions including Powertrain-in-the-Loop, dynamic Design of Experiments and environmental emulation hardware methodologies.
- Performance and emissions can be predicted using the digital twin for real-world driving scenarios with reduced reliance on physical and extensive engine and vehicle testing (climatic test trips and prototype machines).
- This enables the early and faster than real-time identification of unfavourable areas of the powertrain operating map or real-world driving scenarios where performance and emissions output are undesirable; known as "hotspots".
- Traditional calibration methods can then be adopted to mitigate these "hotspots" resulting in an improved cycle result.

HORIBA Intelligent Lab Application Portfolio

STARS Enterprise

VIRTUAL



POWER

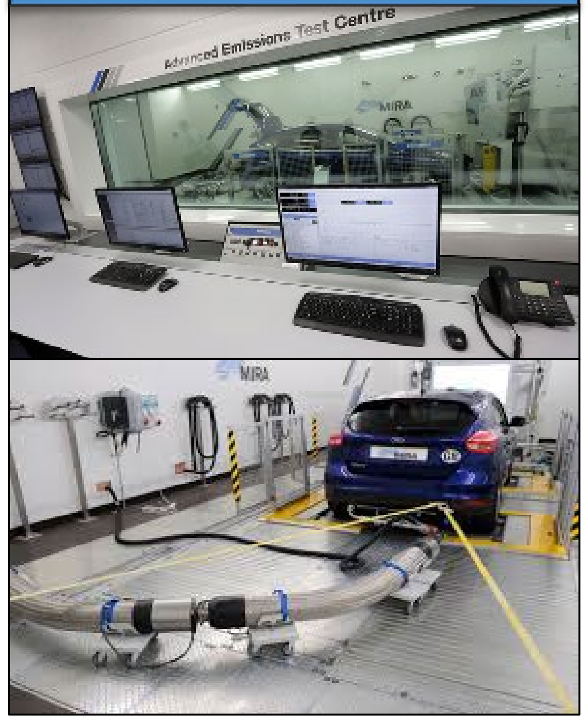
Digital Twin Creation

Powertrain-in-the-Loop

DESIGN & SPECIFICATION

DEVELOPMENT

CHASSIS



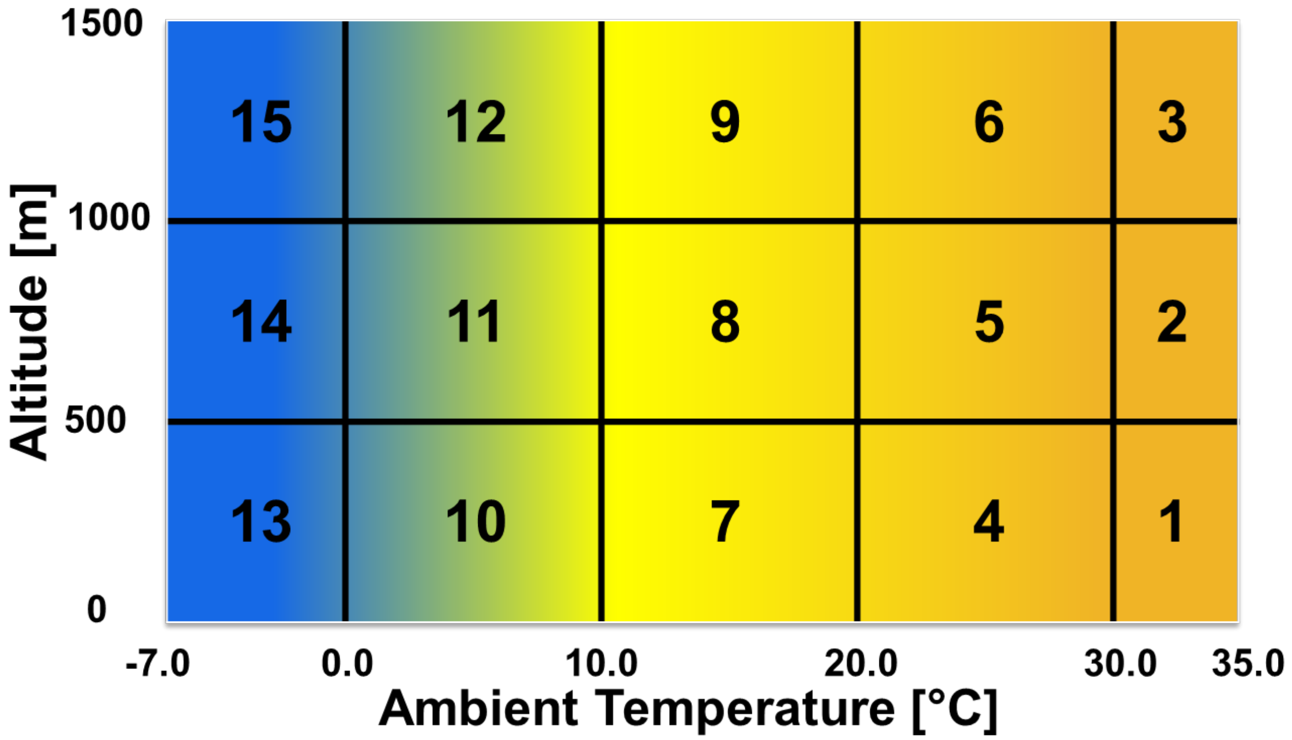
VALIDATION

ROAD

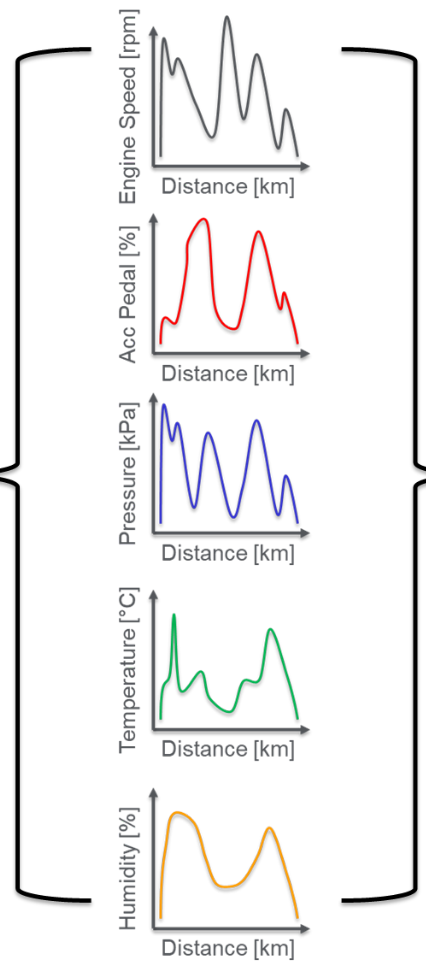
VERIFICATION & CERTIFICATION

Digital Twin Methodology

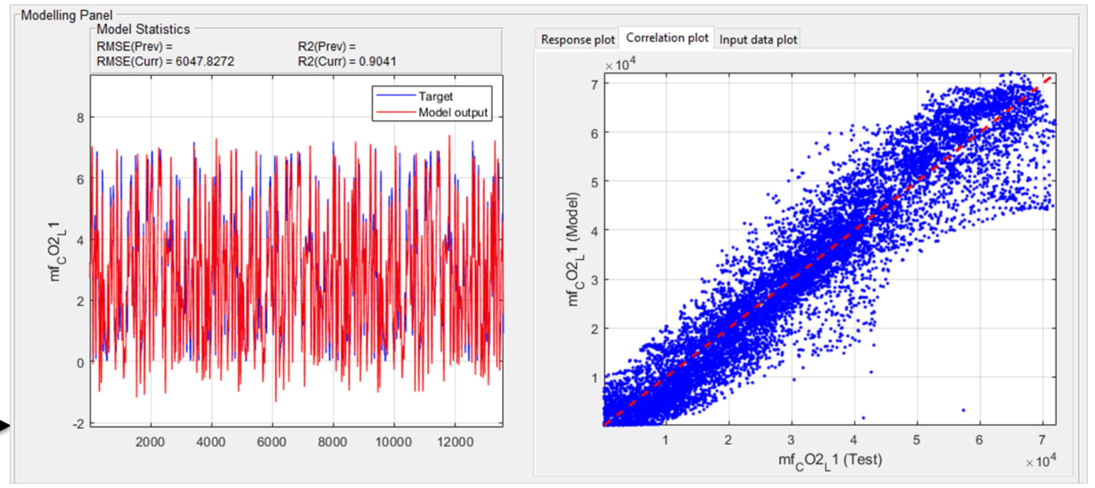
- Euro 6d RDE boundary conditions of altitude and temperature split into 15 sections; dynamic DOE designs created for each section.
- The dynamic DOE designs have four design parameters: **engine speed, accelerator pedal position, altitude (pressure) and temperature**
- The digital twin accounts for the effects engine speed, load and the environment on performance and emissions.
- Dynamic designs ran on a contemporary light-duty 4-cylinder, 2 litre diesel powertrain.
- Training data captured, models created, models validated, predictions made.



Transient DOE designs including engine speed, acc pedal, pressure and temperature – cover RDE moderate and extended boundary conditions



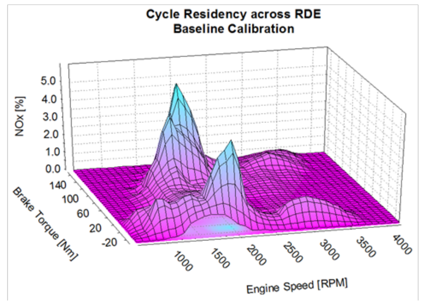
Generation of response models from real engine testing



IPG CarMaker test scenarios run with data from testing used with models (>x30 faster than realtime)

IPG CarMaker
Virtual Driver, Route and Vehicle

Predicted engine responses and "hotspot" determination



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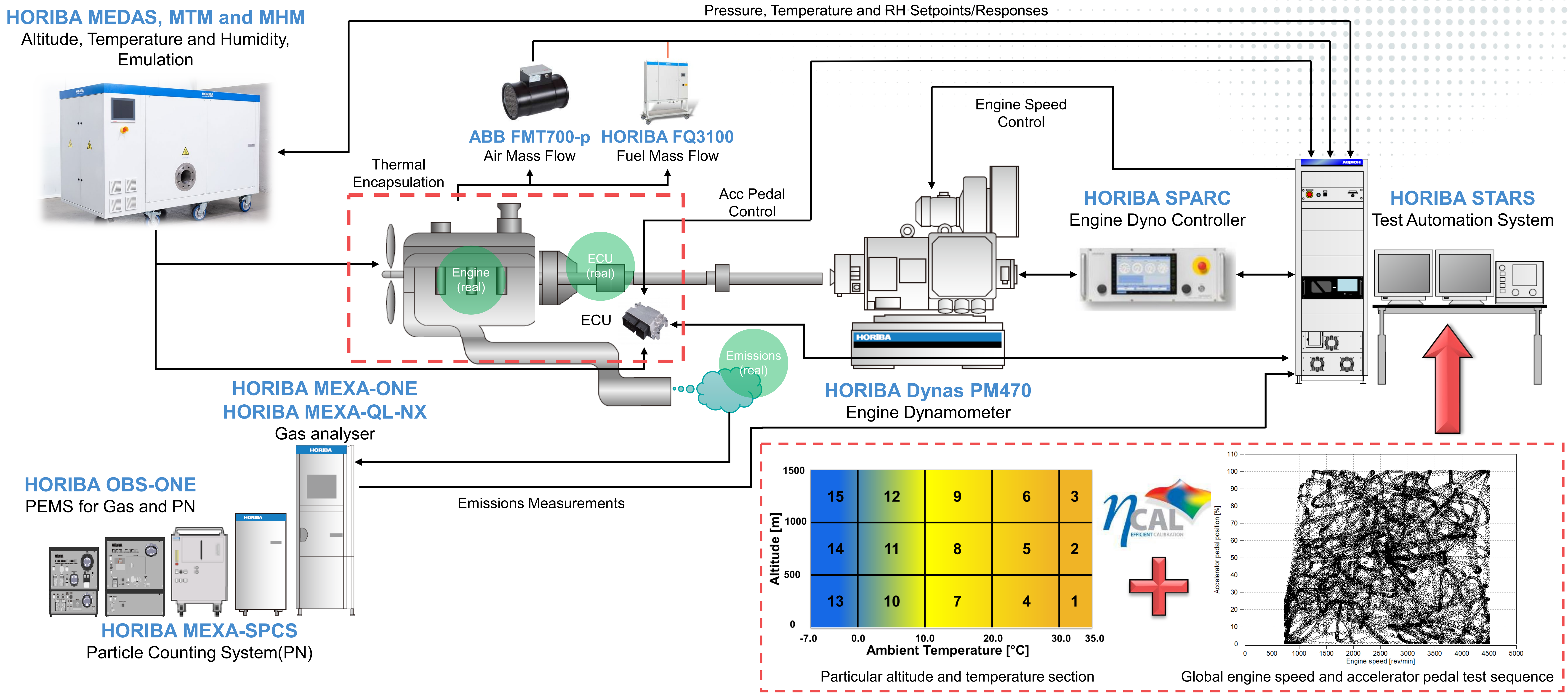
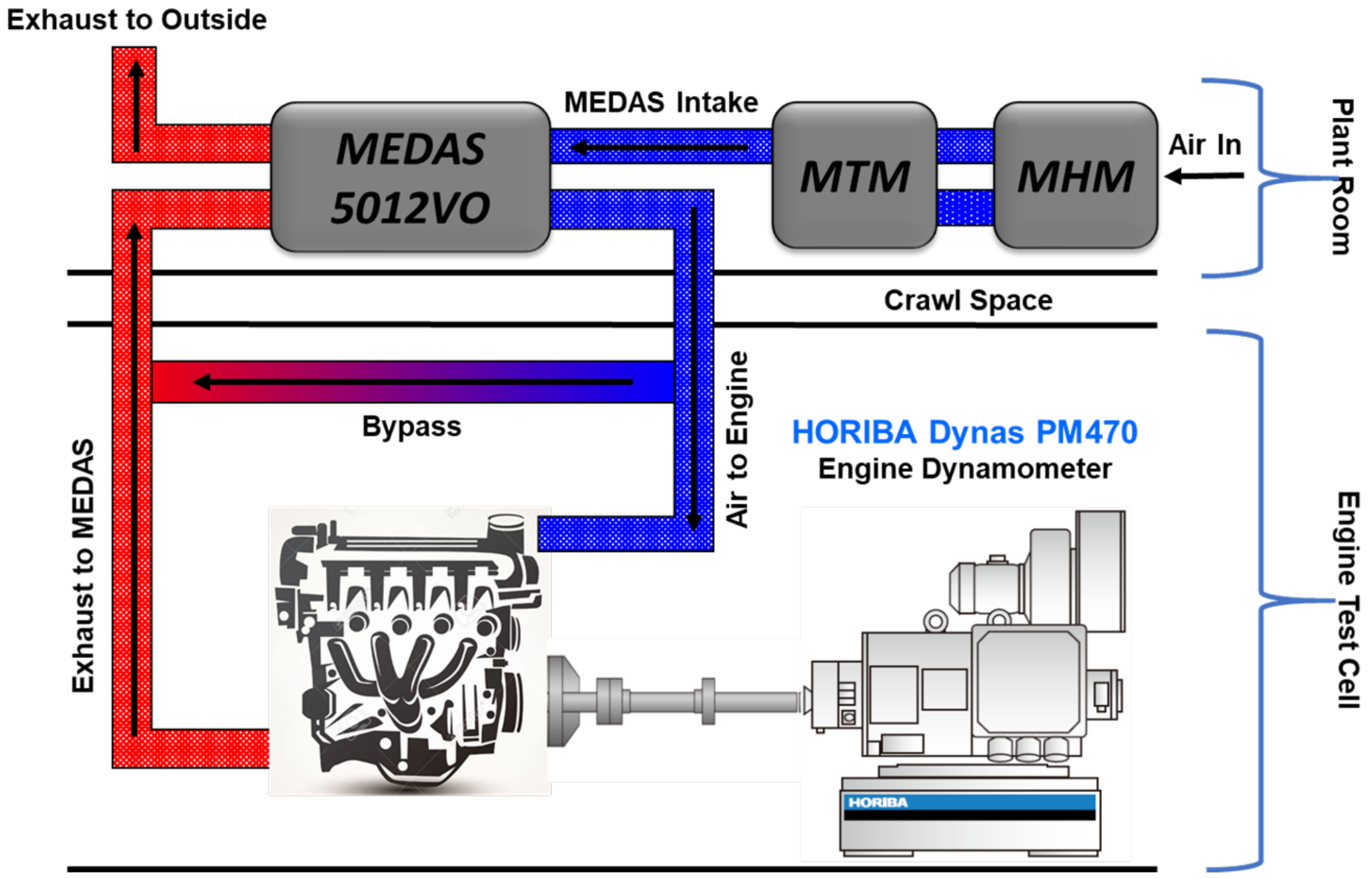
Powertrain-in-the-Loop Configuration



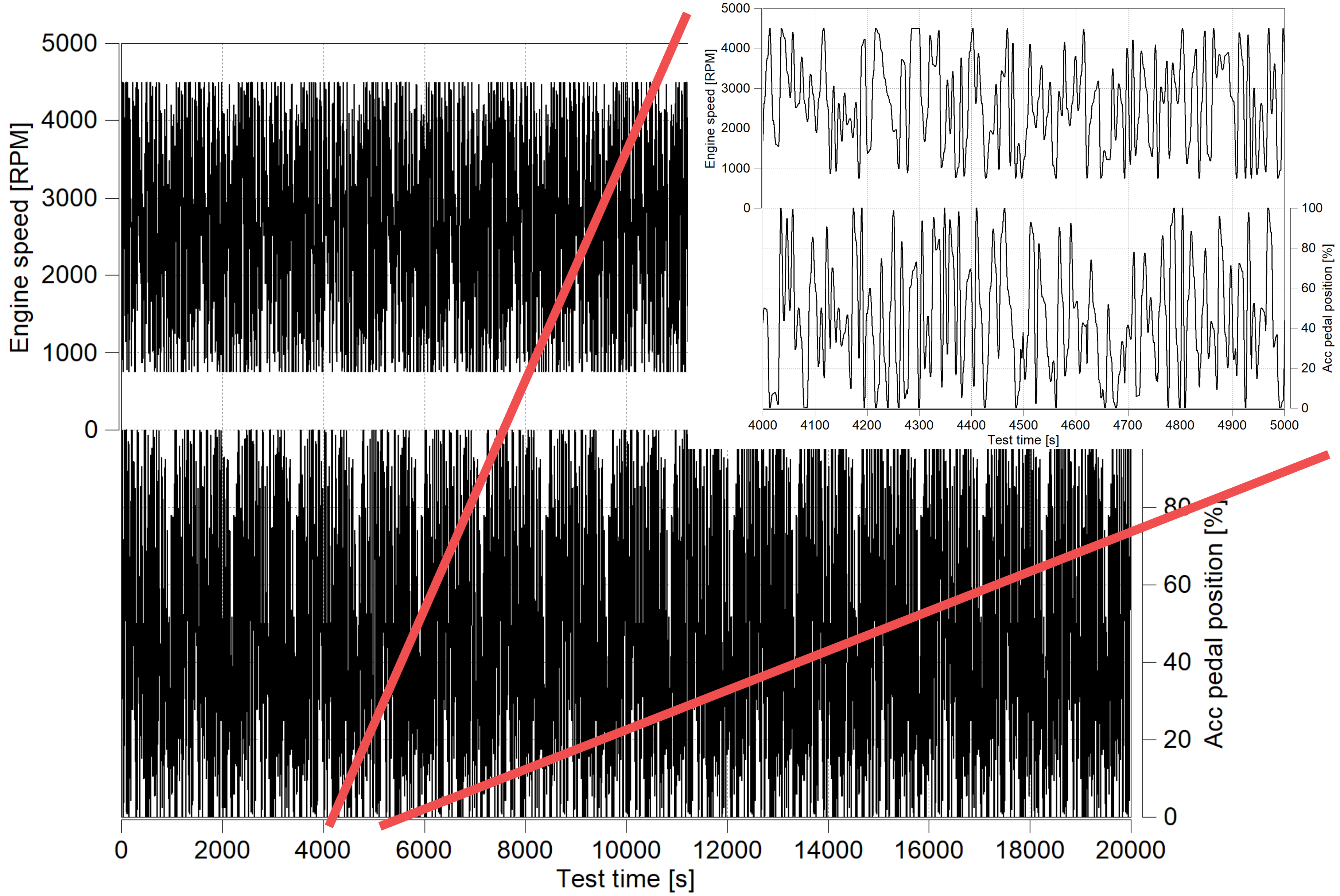
Environmental Emulation using HORIBA MEDAS

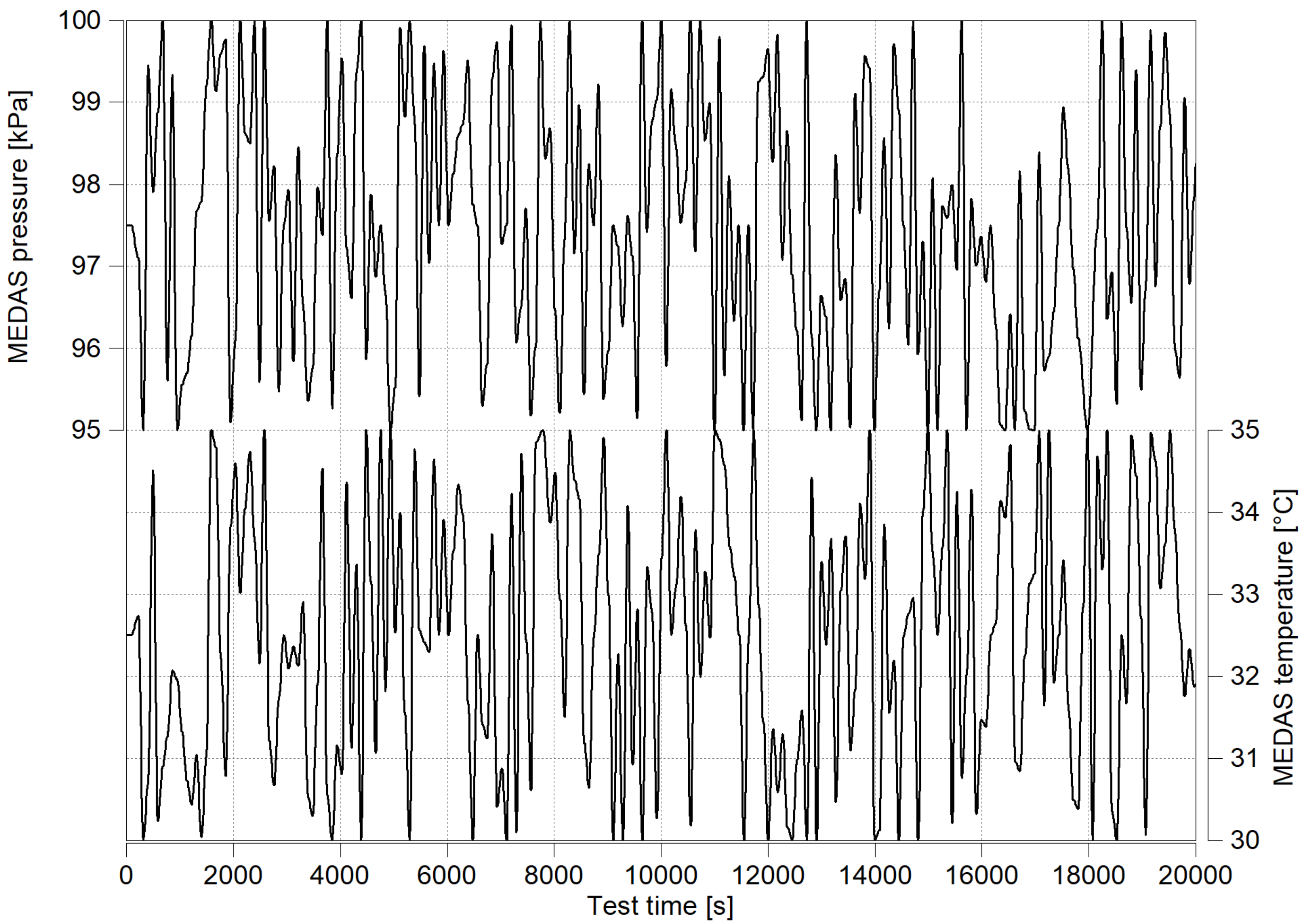
- HORIBA MEDAS has a key role in developing the digital twin and is used for environmental emulation.
- Shown here is a schematic of how the powertrain is configured with MEDAS. This system can also be used as part of a chassis dyno setup.



Dynamic Design Example

- Sample dynamic design shown below for Section 1 altitude and temperature.
- Typical dynamic design is ~6 hours; therefore ~90 hours total testing time to dynamically map the engine across Euro 6d boundary conditions.
- No aftertreatment fitted to the engine; all models were generated with a warm engine.





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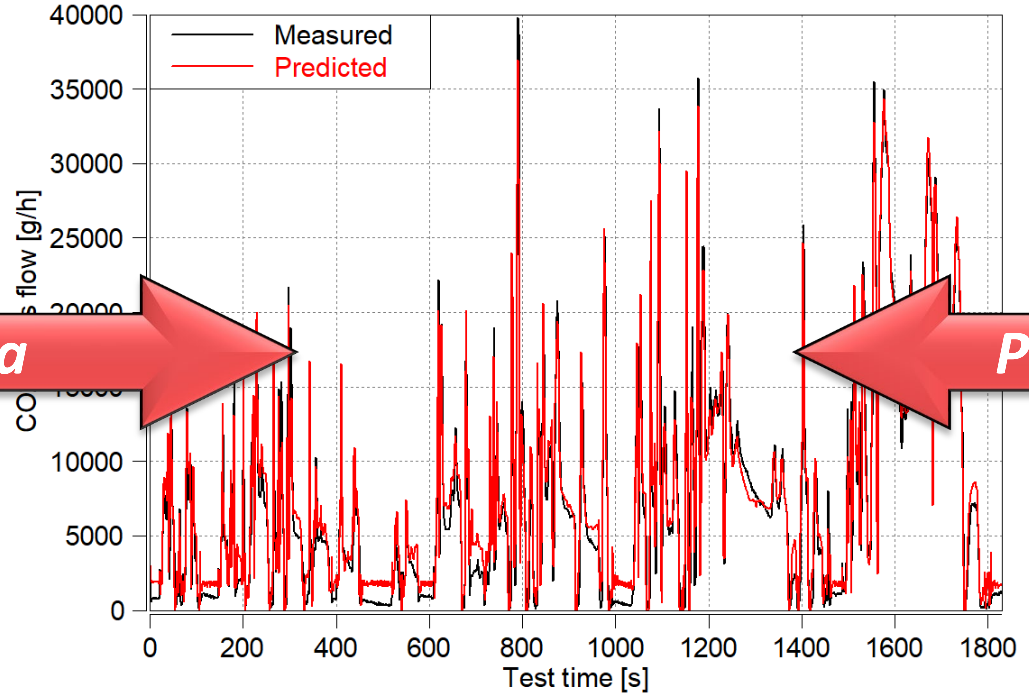
Empirical Model Validation (1)

- Performance and emissions models were created using the training data from the powertrain and Ricardo Efficient Calibration DOE Toolkit
- Real-world driving cycles were used to validate model accuracy.
- Real-world driving cycles ran on the real powertrain; engine speed, acc pedal position and MEDAS pressure and temperature used with models
- Determine measured vs. predicted correlation for several powertrain attributes. Accurate models can then be used for P&E predictions.

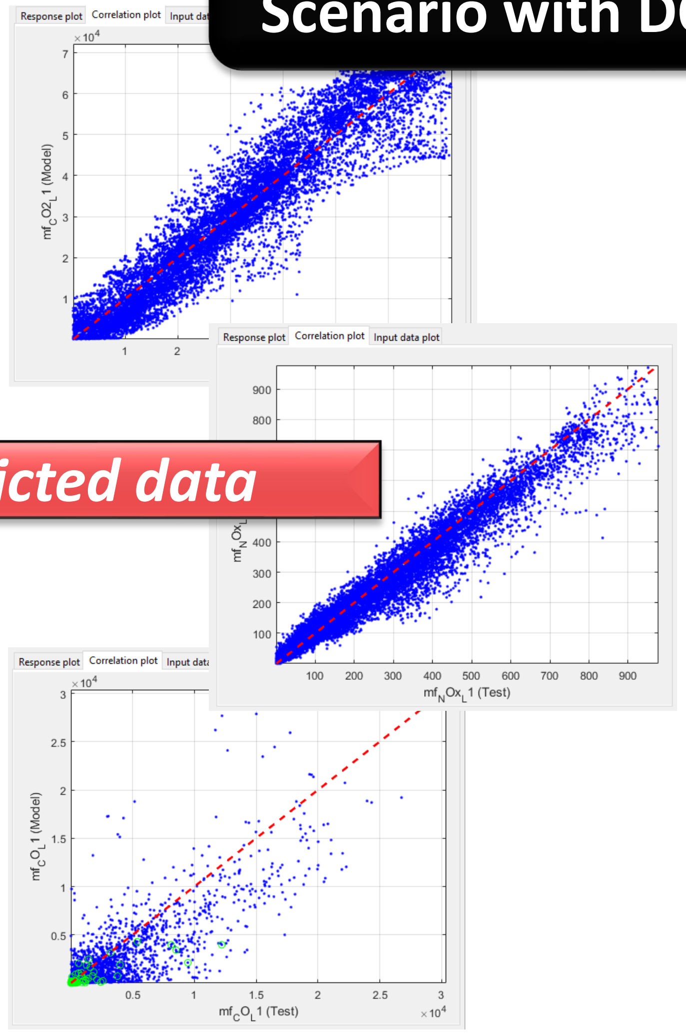
Validation scenario using real-world scenario and PiL

Comparison of Real EiL Data vs. Predicted Data



Real data → ← **Predicted data**

Use inputs from validation Scenario with DOE models



Acc pedal pos [%]	Engine speed [rpm]	Pressure [kPa]	Temperature [°C]
-	-	-	-
-	-	-	-
-	-	-	-
-	-	-	-
-	-	-	-

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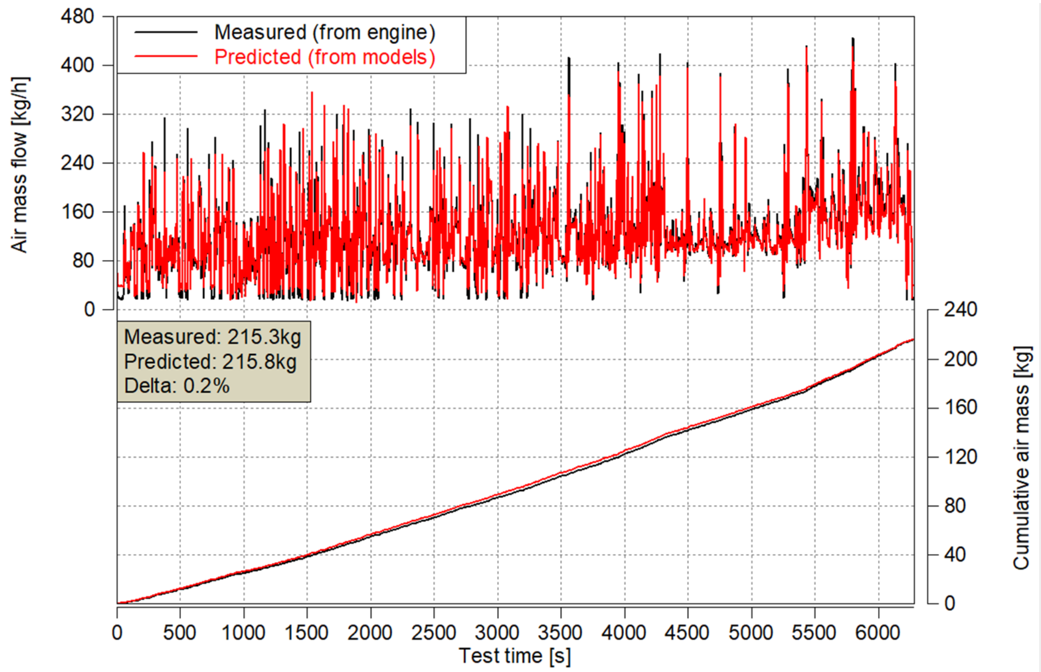
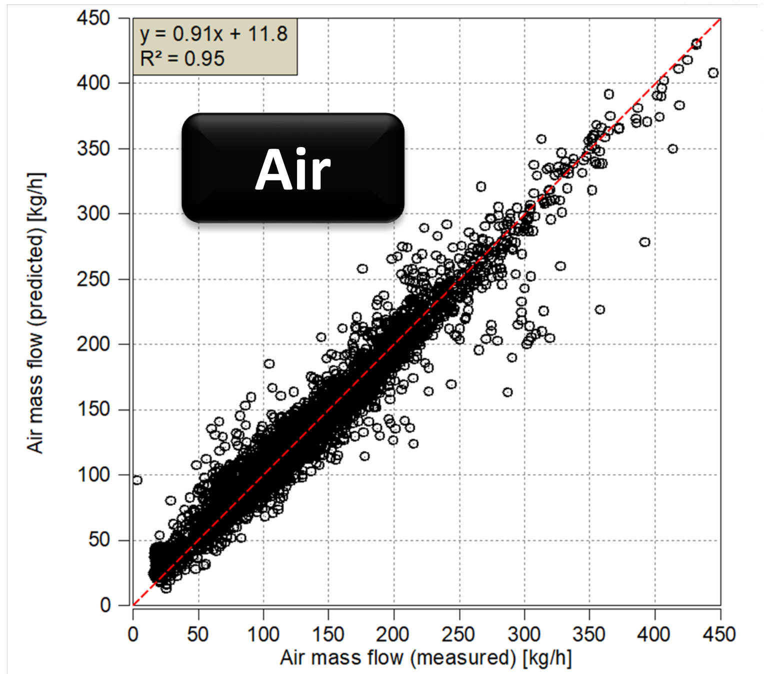
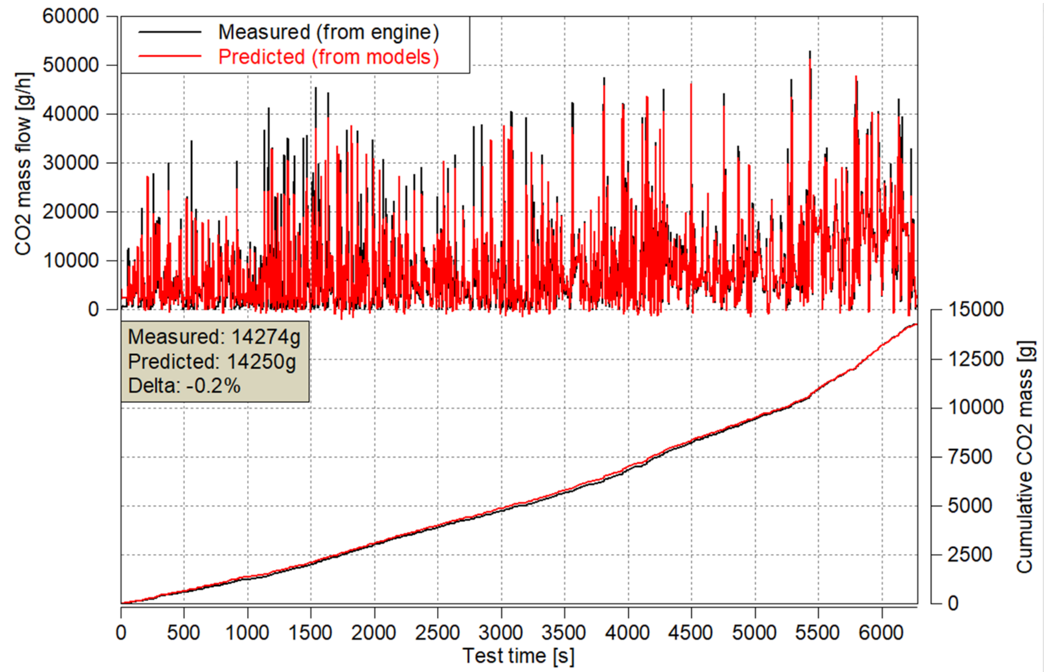
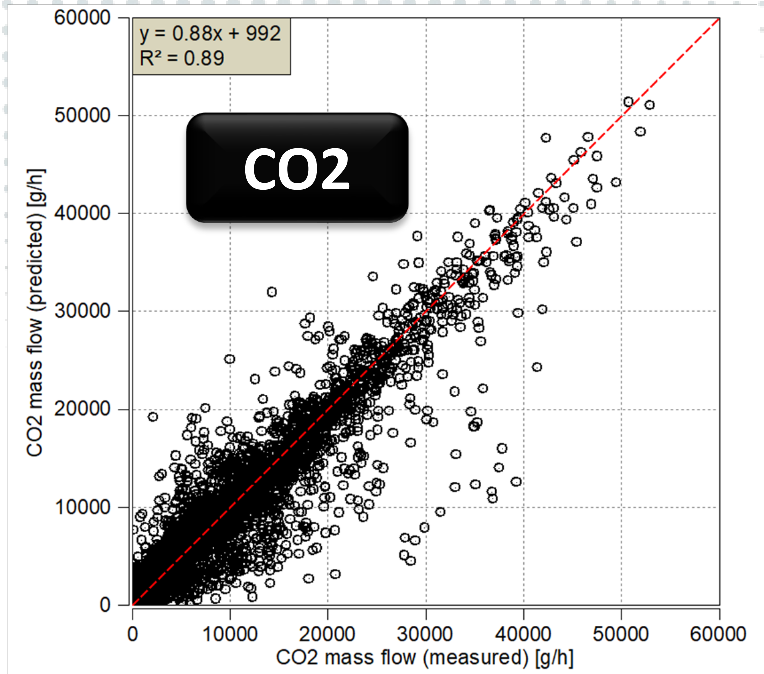
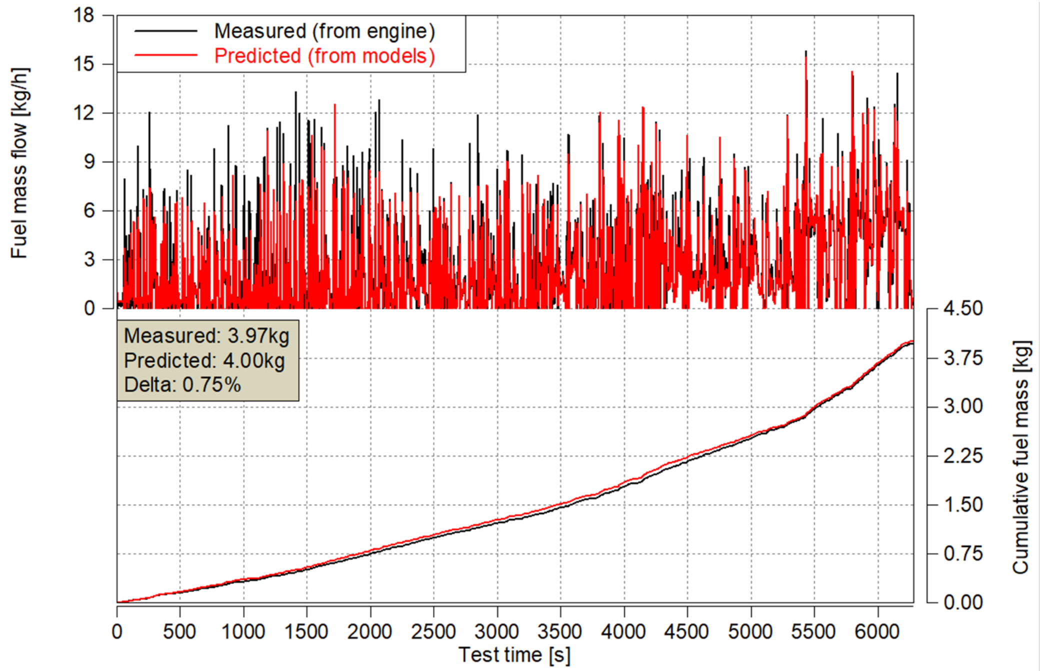
Empirical Model Validation (2)

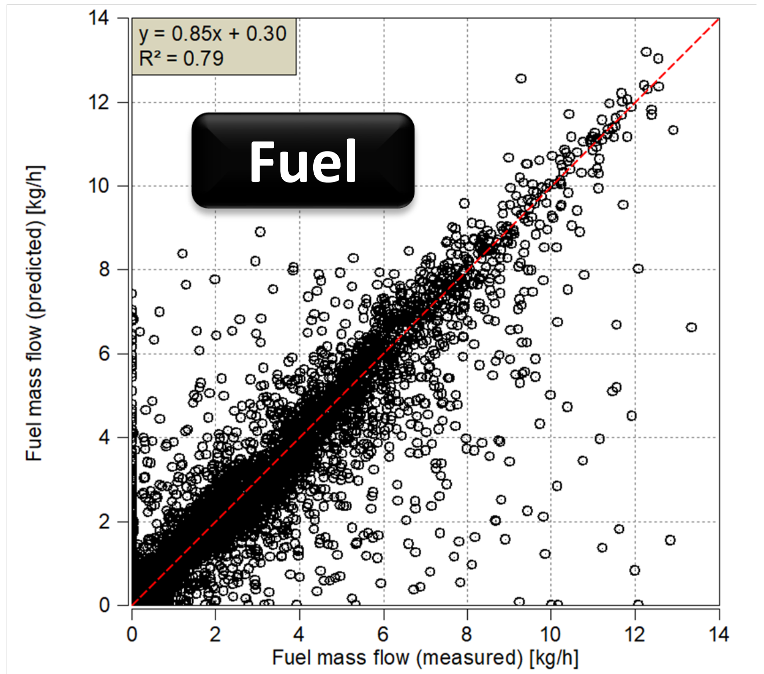


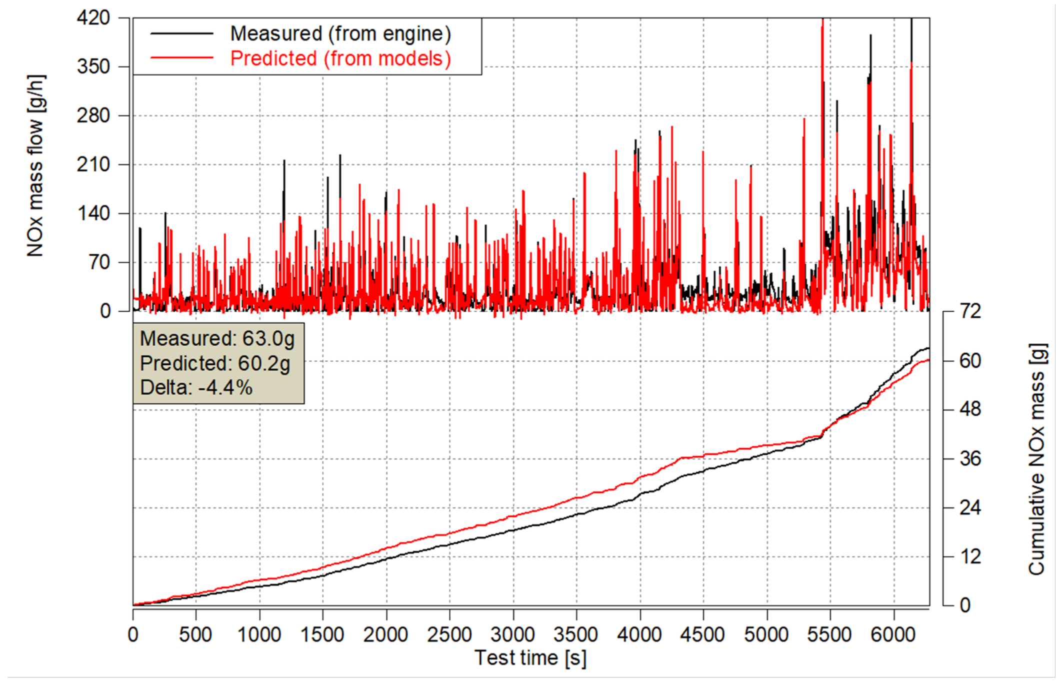


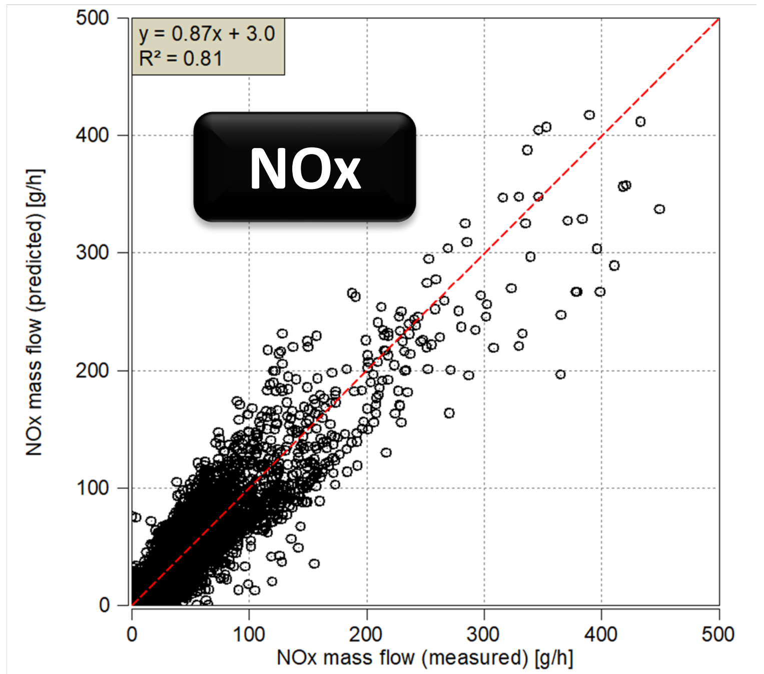












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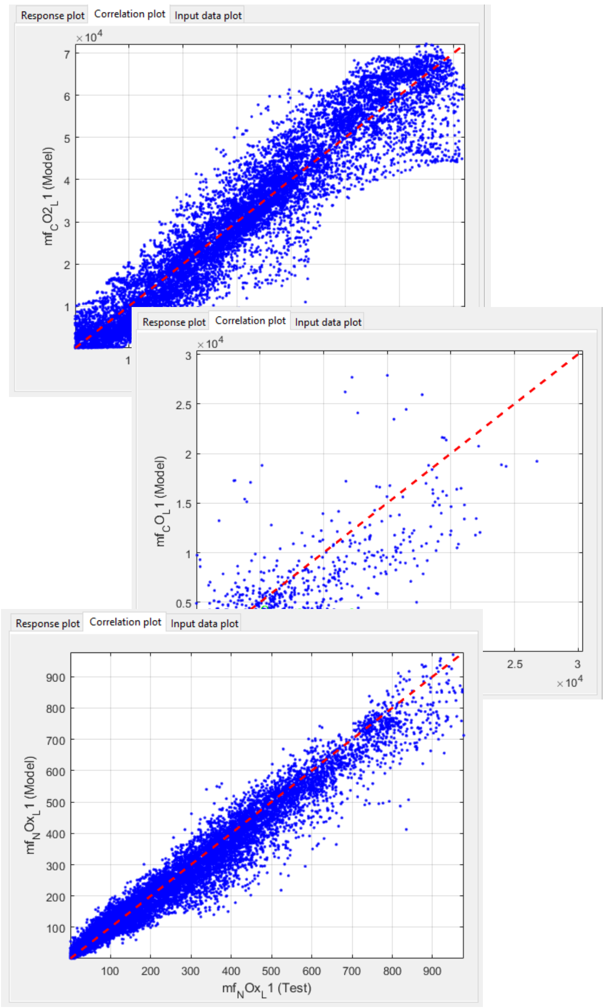
Deployment of the Powertrain Digital Twin

- The validated empirical performance and emissions models were coupled with IPG CarMaker real-world driving scenario development software.
- Real-world driving scenarios can be ran in simulation; powertrain performance and emissions predicted accordingly.

Run scenario in CarMaker (driver dynamics, traffic etc)

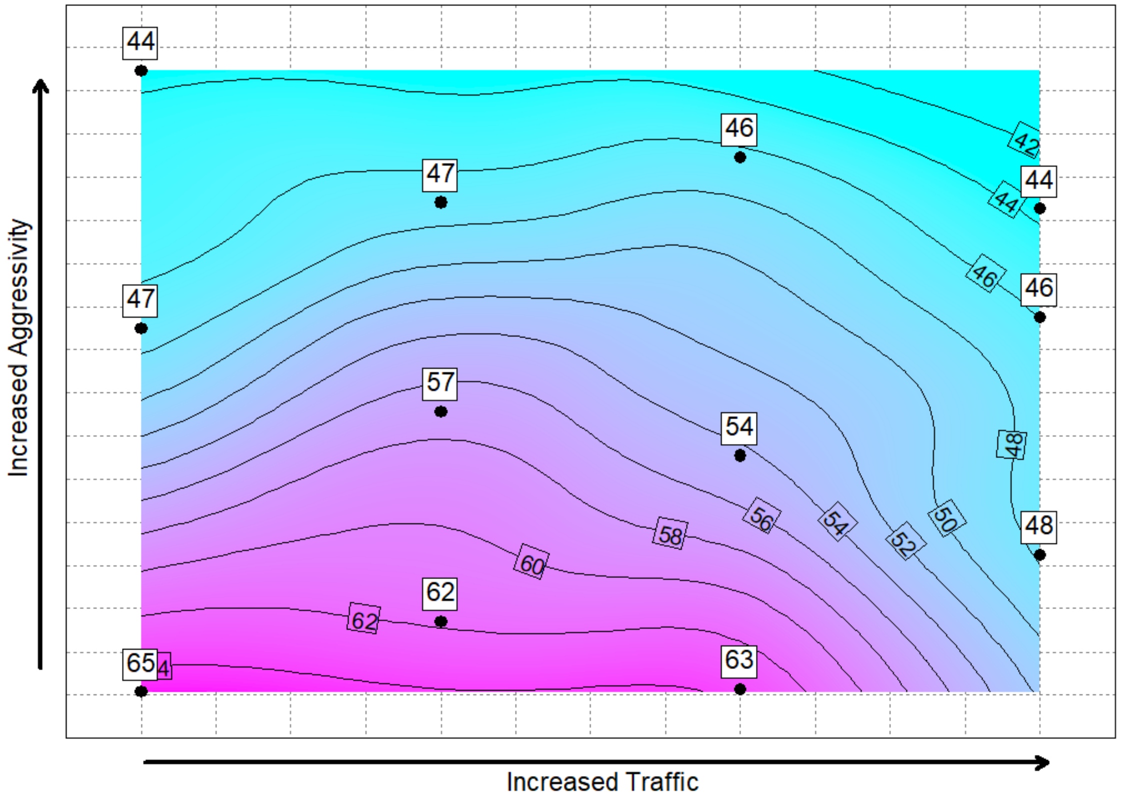
Acc pedal pos [%]	Engine speed [rpm]	MEDAS Pressure [kPa]	MEDAS Temperature [°C]
-	-	-	-
-	-	-	-
-	-	-	-
-	-	-	-
-	-	-	-

Extract data for use with models



Couple extracted data with models

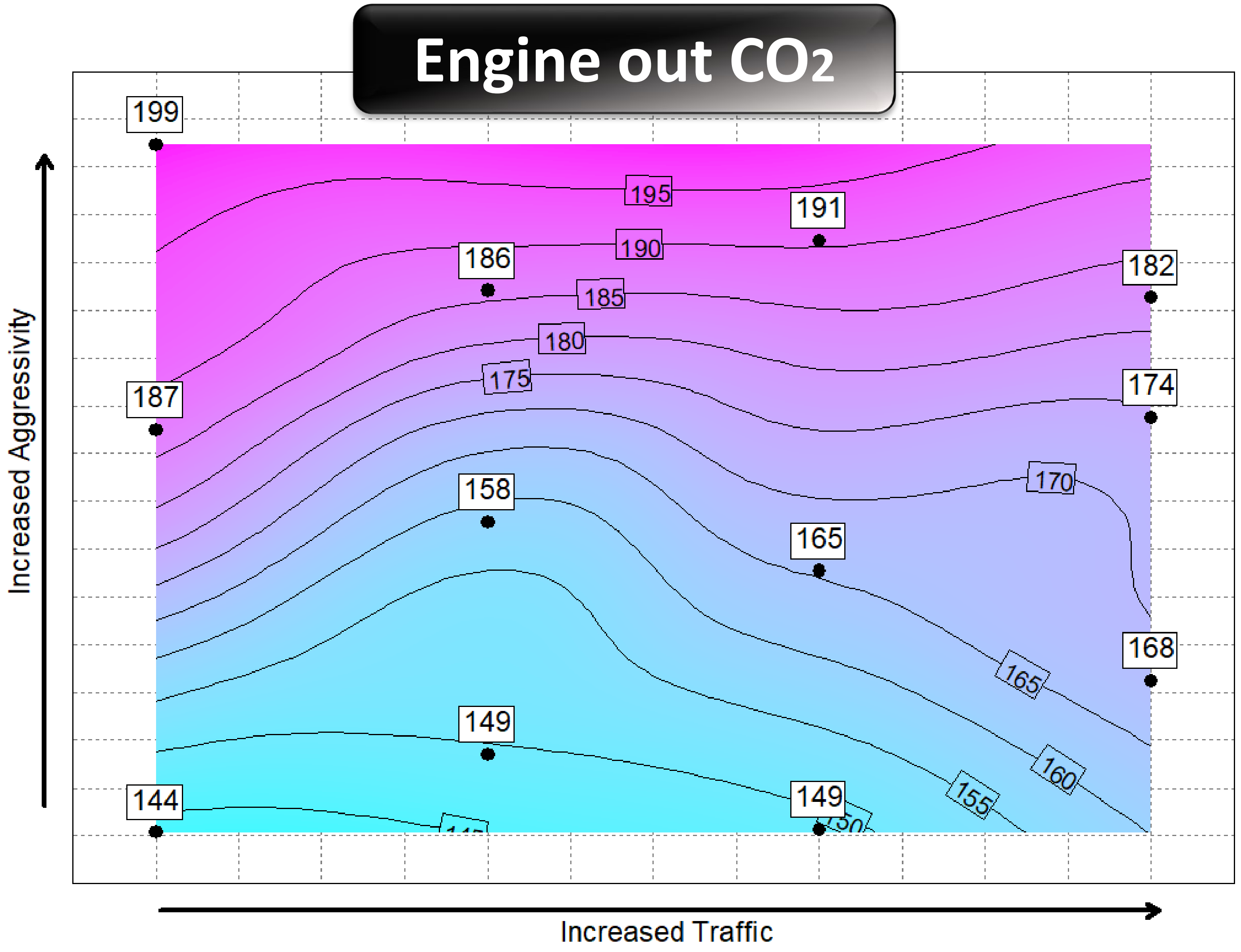
Vera, Spain (100m, 35°C) - Fuel Economy (mpg)

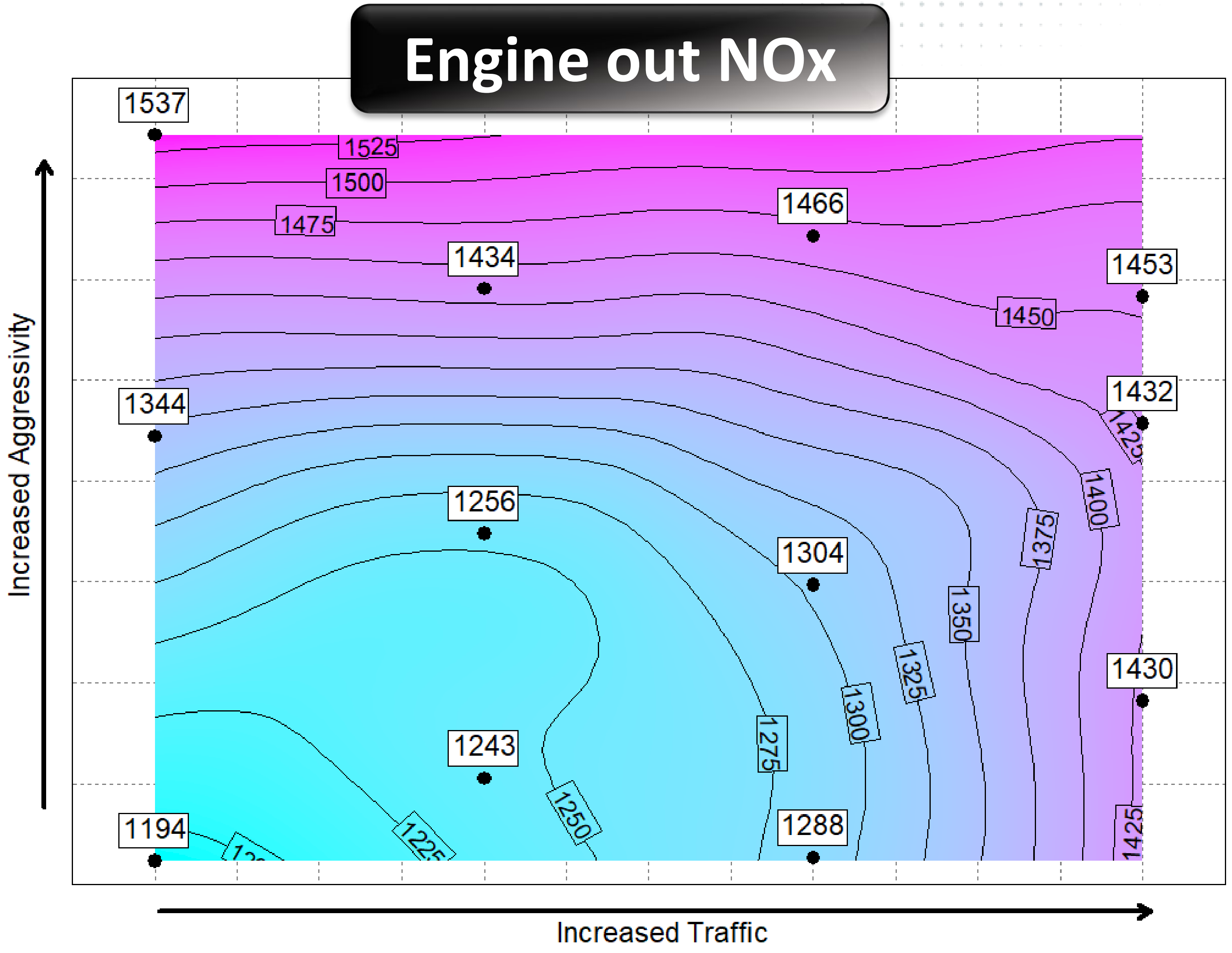


Predict performance and emissions responses

Hotspot Screening (1)
Models from Section 1

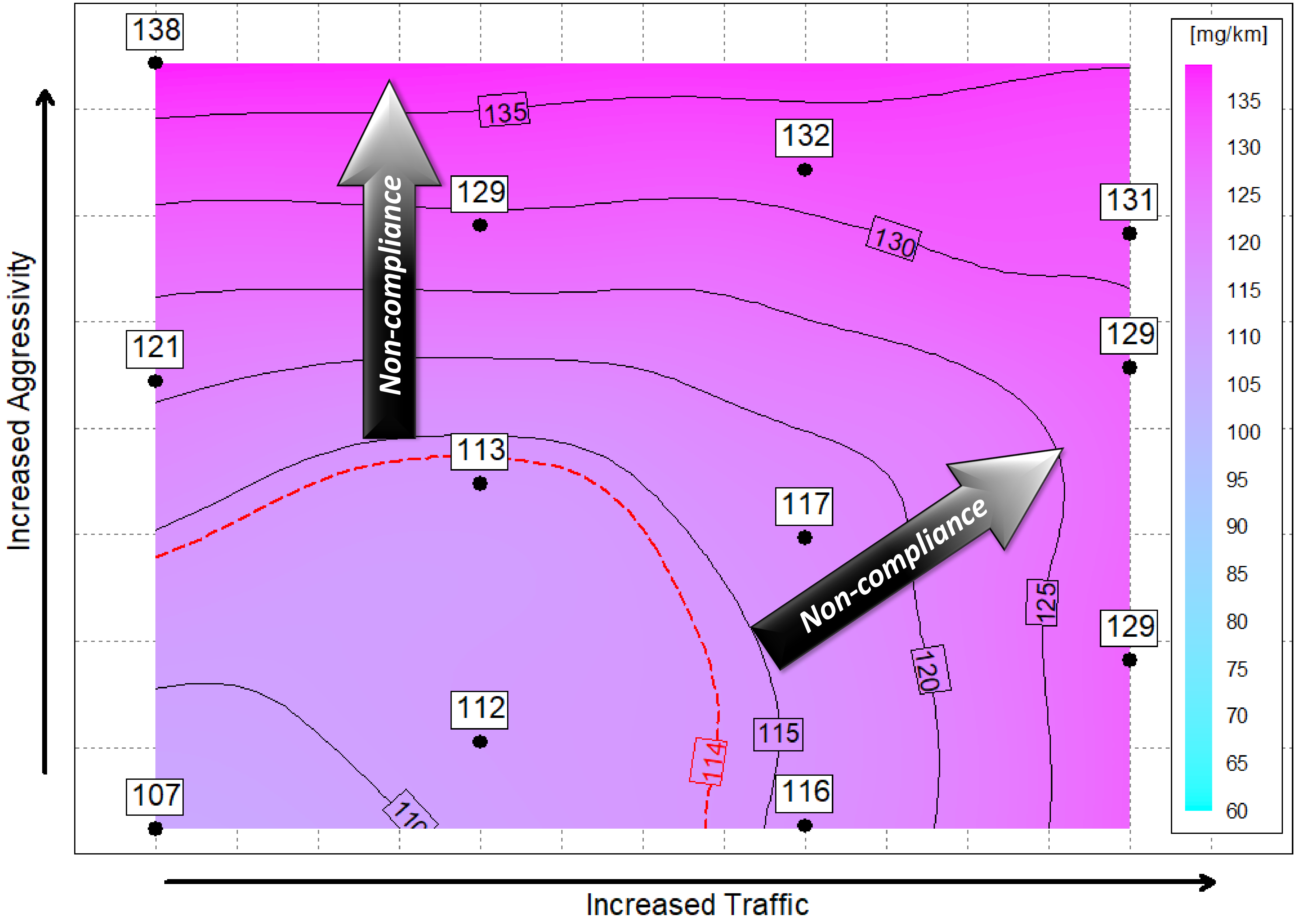
- Engine out cycle CO_2 and NOx predicted for different driving styles and traffic densities for an RDE route at 500m (95kPa), 35°C.
- 11% and 8% variation in CO_2 and NOx respectively due to changes in driving style and traffic density – all are completely compliant RDE cycles.
- This type of analysis provides an insight into unfavourable RDE conditions across a given route and environmental profile.





Hotspot Screening (2)
Models from Section 1

- Take engine out NOx data from previous slide and assume **90%** SCR efficiency.
- Tailpipe NOx (mg/km) shown accordingly. Euro 6d real driving emissions limit highlighted by the red line.



90% SCR efficiency

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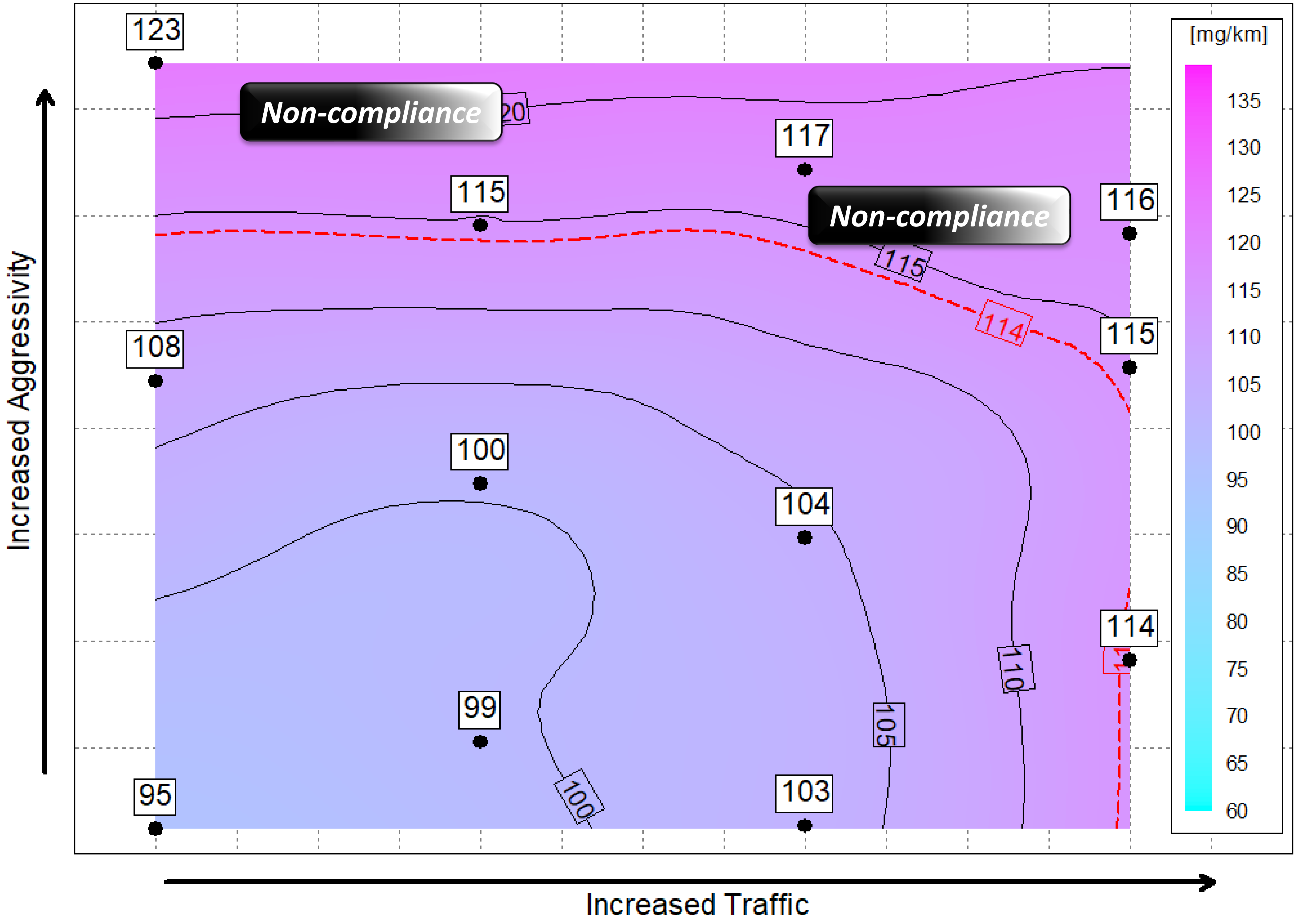
Hotspot Screening (3)
Models from Section 1

- Take engine out NOx data from previous slide and assuming **<u>92%</u>** SCR efficiency.
- Tailpipe NOx (mg/km) shown accordingly. Euro 6d real driving emissions limit highlighted by the red line.



92% SCR efficiency

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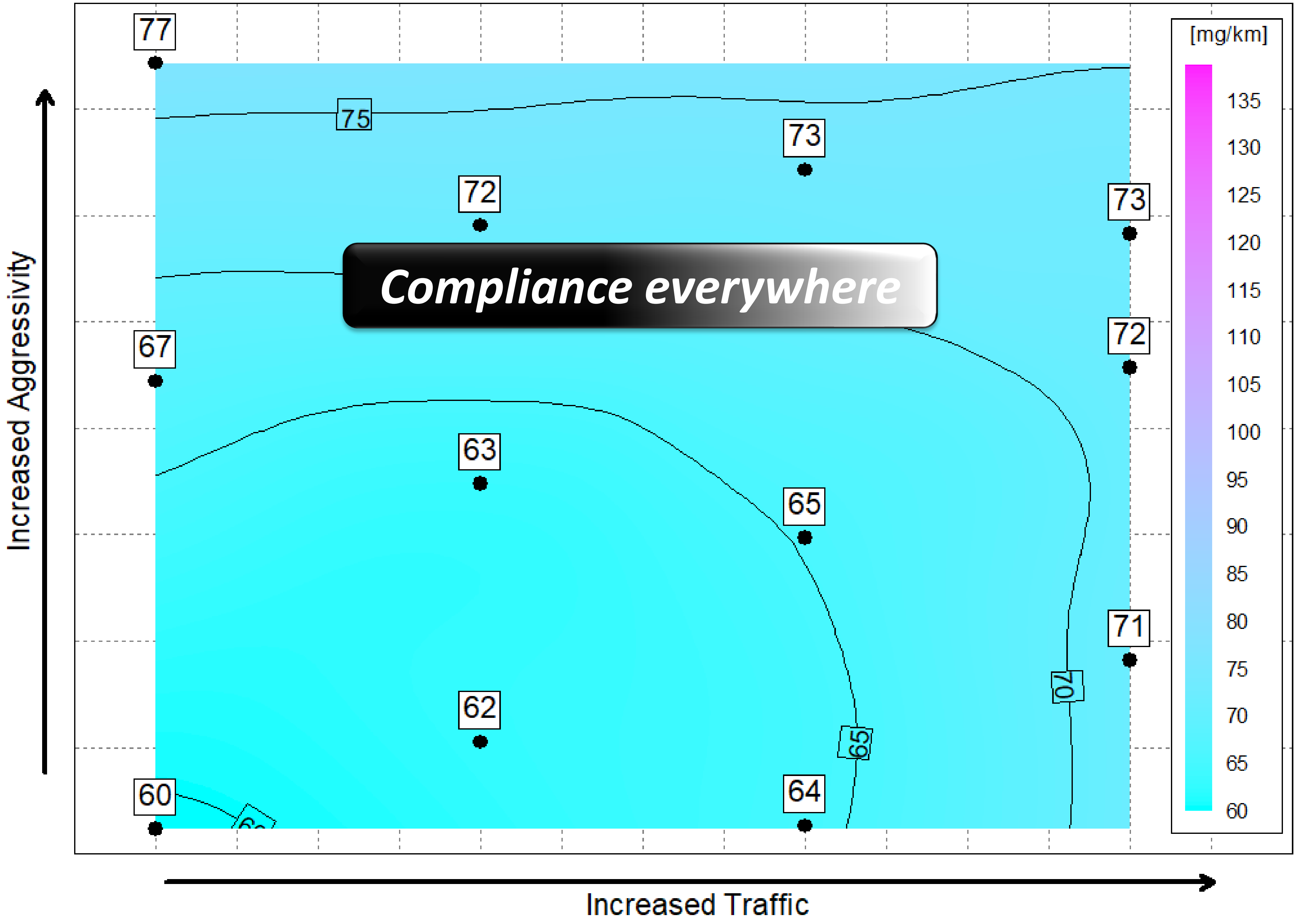
Hotspot Screening (4)
Models from Section 1

- Take engine out NOx data from previous slide and assuming **95%** SCR efficiency.
- Tailpipe NOx (mg/km) shown accordingly. Euro 6d real driving emissions limit highlighted by the red line.



95% SCR efficiency

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Multiple Vehicles, Common Powertrain

- Powertrain sharing is commonplace amongst light-duty OEMs.
- Prediction of performance and emissions for multiple vehicles sharing a common powertrain is possible utilising a single digital twin.

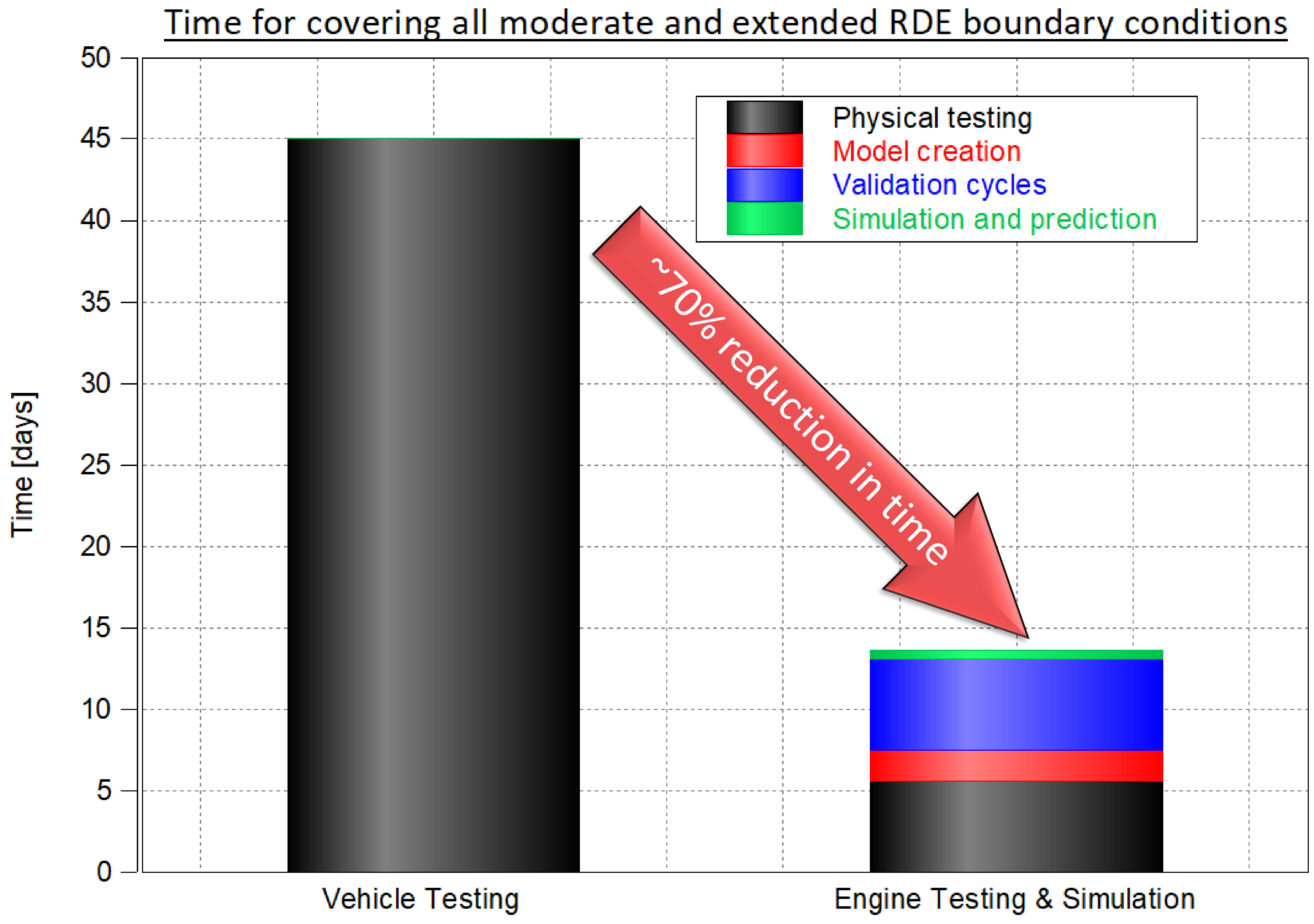
Test Scenario
Vehicle, Terrain and Environment

Dynamic Empirical Models
Performance and emissions

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

Methodology Effectiveness (1)
Light-duty Vehicle Example

- Physical testing using vehicle
  - 45 days physical testing (2 shifts per day) to cover the RDE (or other) boundary conditions; allows for changes in vehicle operating “style” and other stochastic instances.
  - Does not including timings for logistics or travel to locations to meet the climatic requirements and assuming right-first-time testing.
- Hotspot using EiL and dynamic DOE:
  - 13.6 days for the complete RDE (or other) boundary conditions
  - Evaluation of additional vehicles is ~0.5 days per vehicle
- Effectiveness
  - For one vehicle, ~70% reduction in test time using Digital Twin



	Vehicle Testing	Engine Testing and Simulation
Physical testing [days]	45	5.6
Model creation [days]		1.9
Validation cycles [days]		5.6
Simulation and prediction [days]		0.5

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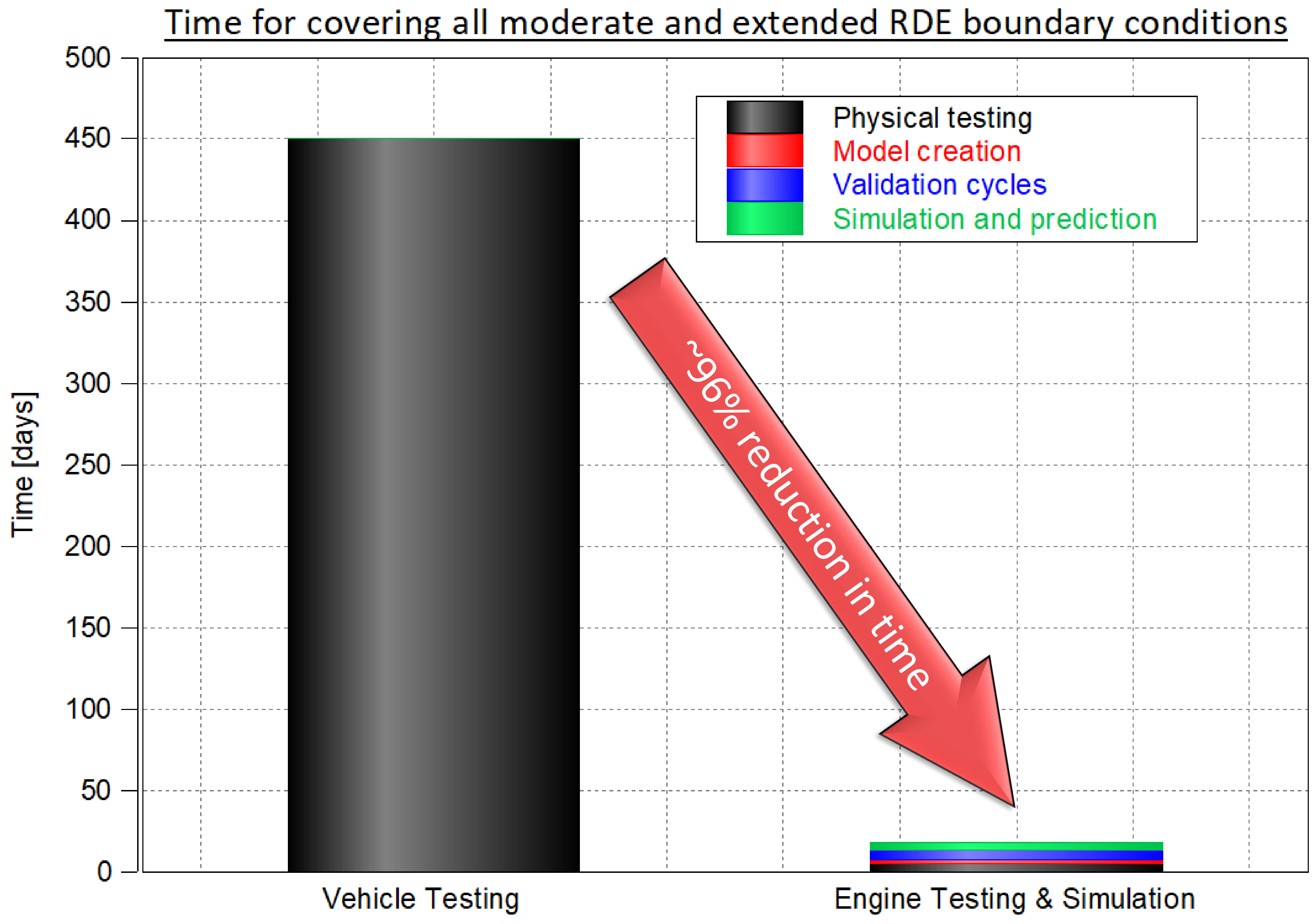
Methodology Effectiveness (2)
Light-duty Vehicle Example

- Physical testing using vehicle
  - 45 days physical testing (2 shifts per day) to cover the RDE (or other) boundary conditions; allows for changes in vehicle operating “style” and other stochastic instances.
  - Does not including timings for logistics or travel to locations to meet the climatic requirements and assuming right-first-time testing.
- Hotspot using EiL and dynamic DOE:
  - 13.6 days for the complete RDE (or other) boundary conditions
  - Evaluation of additional vehicles is ~0.5 days per vehicle
- Effectiveness
  - For one vehicle, ~70% reduction in test time using Digital Twin
- For 10 vehicle variants:
  - Physical testing = 450 days (scales with vehicle number)
  - Frontloading = 18.1 days
  - Reduction in time = 96%



	Vehicle Testing	Engine Testing and Simulation
Physical testing [days]	450	5.6
Model creation [days]		1.9
Validation cycles [days]		5.6
Simulation and prediction [days]		5.0

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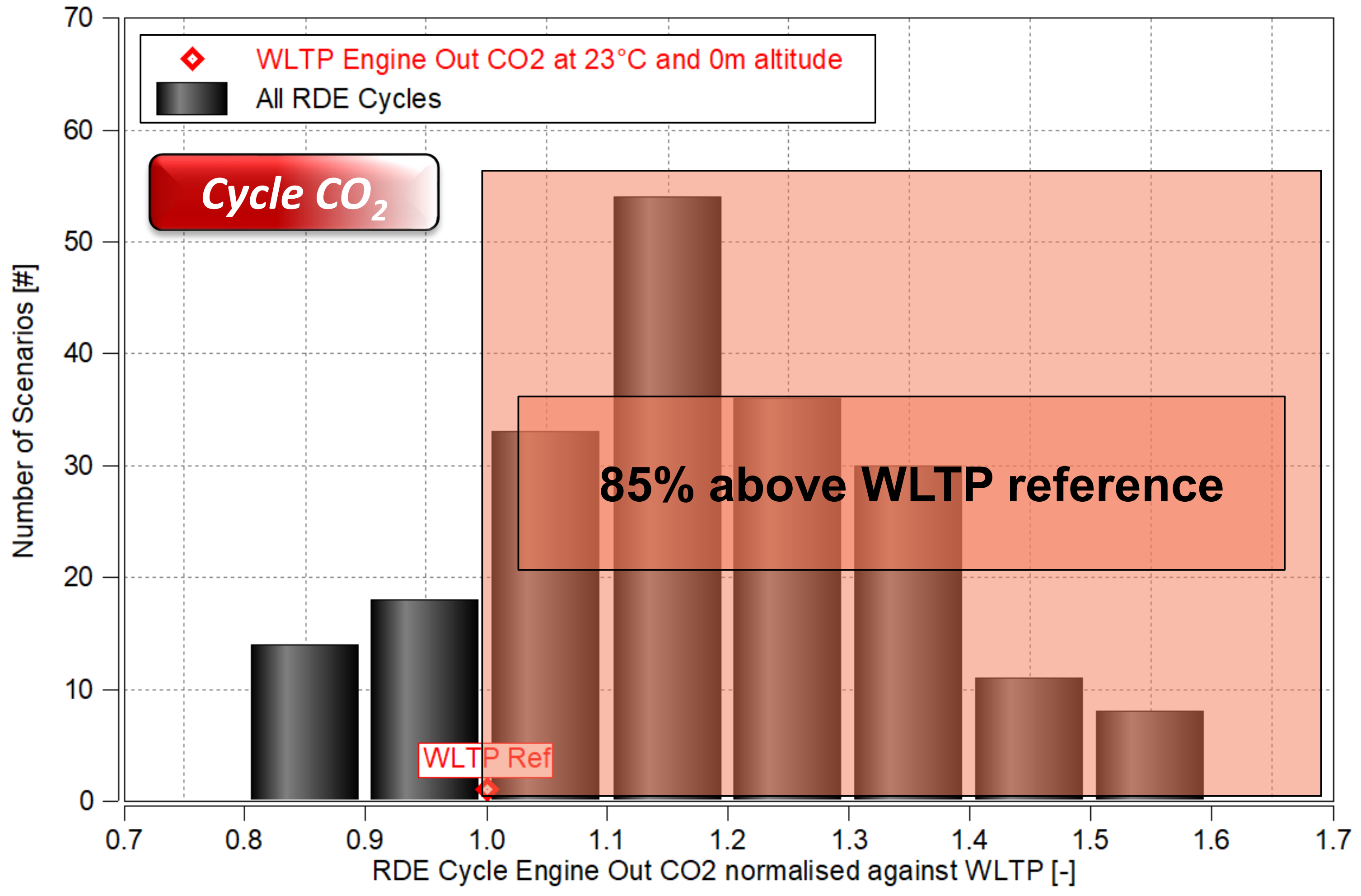
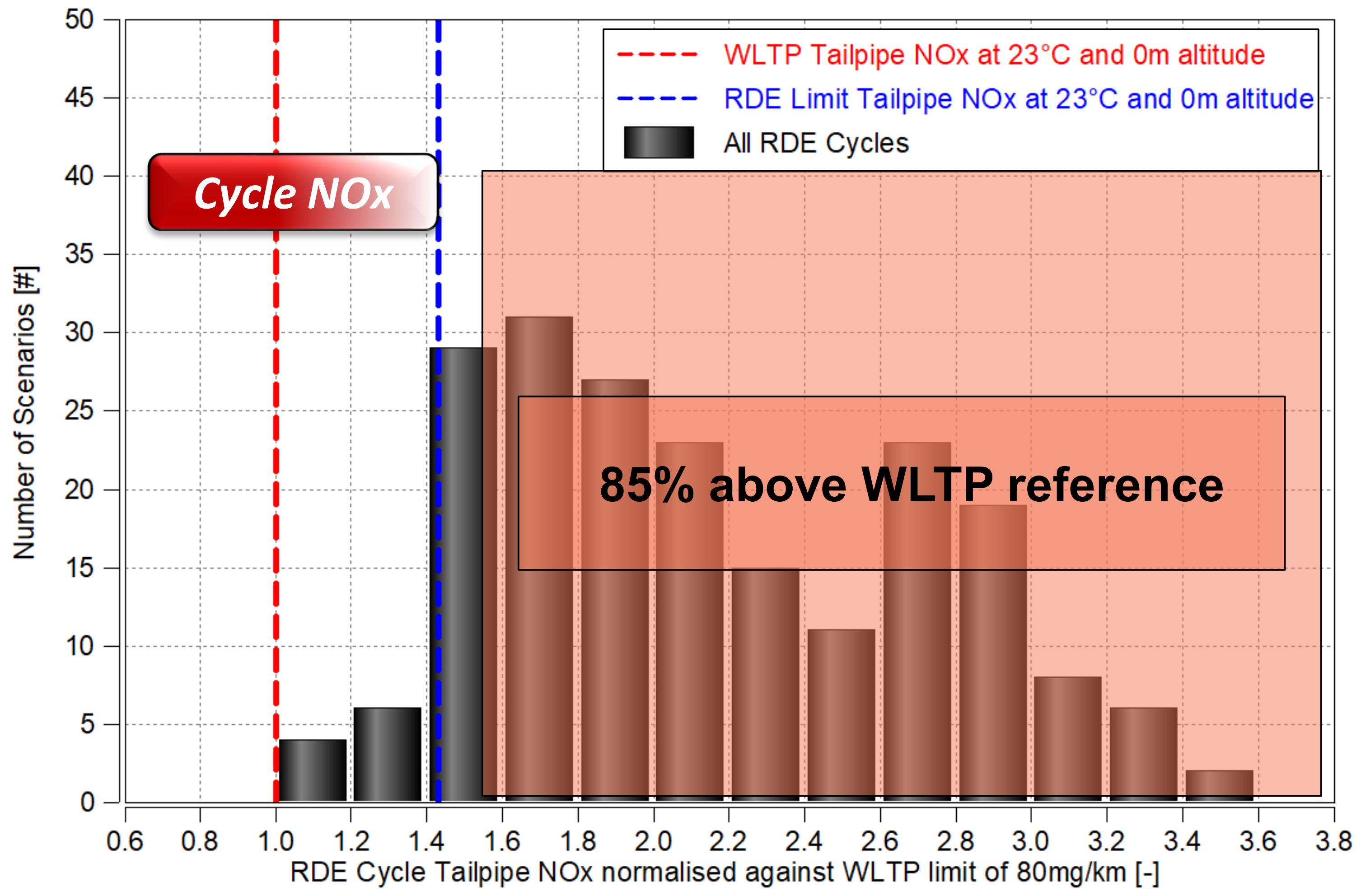
Methodology Effectiveness (3)
Light-duty Vehicle Example

- Powertrain digital twin coupled with virtual driving software (driver, routes and vehicle).
- Performance and emissions for 200 completely compliant RDE cycles were predicted in 15 hours – only limited by computational power.
- 85% of RDE cycles produce higher tailpipe CO_2 and NOx than WLTP and RDE limits respectively; favourable RDE scenarios would be required for compliance.
- Doesn't only apply to emissions; can be easily converted to electric-only range and other electrified powertrain parameters.





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Conclusions and Next Steps

- Test times for covering all Euro 6d boundary conditions for a given vehicle can be reduced from 45 days to 13.1 days.
- Testing times can be reduced further when different vehicles adopt a common powertrain.
- A global picture of unfavourable testing conditions can be rapidly established without the need for expensive prototype vehicles and climate test trips.
- Calibration robustness and hardware suitability can be rapidly assessed using a combination of physical and virtual engineering across variations of:
  - Route characteristics, ambient conditions, driving style and stochastic events amongst others
- Can be readily applied to determine real-world efficiency use cases of electrified powertrains and BEVs.

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