
# 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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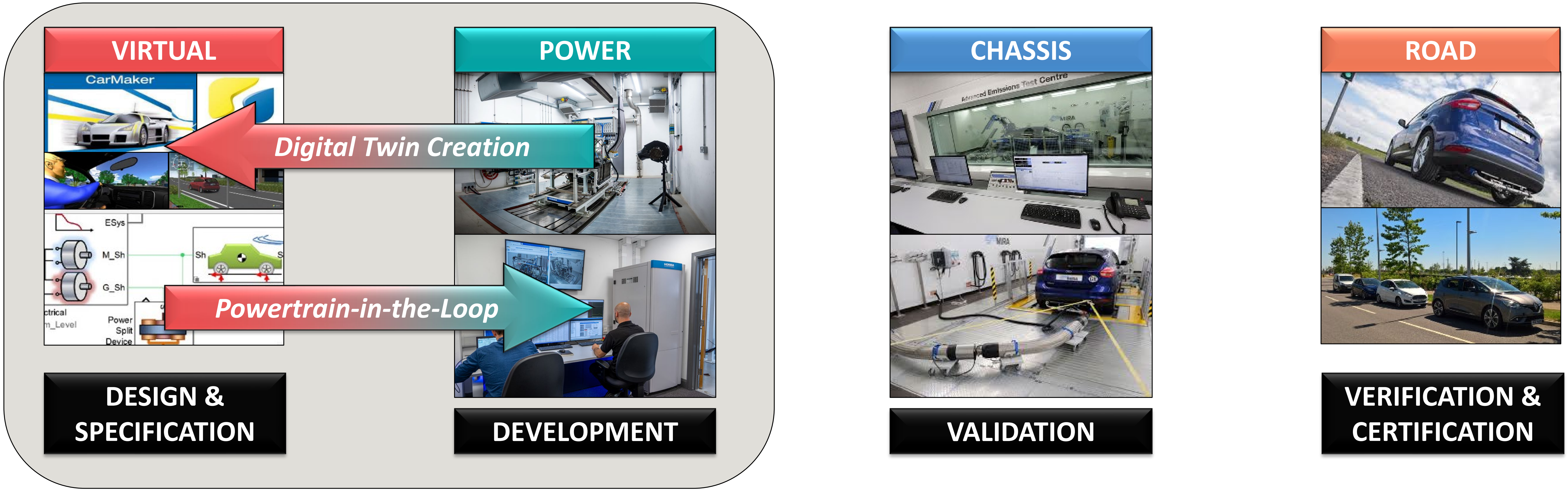
# Introduction

- 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

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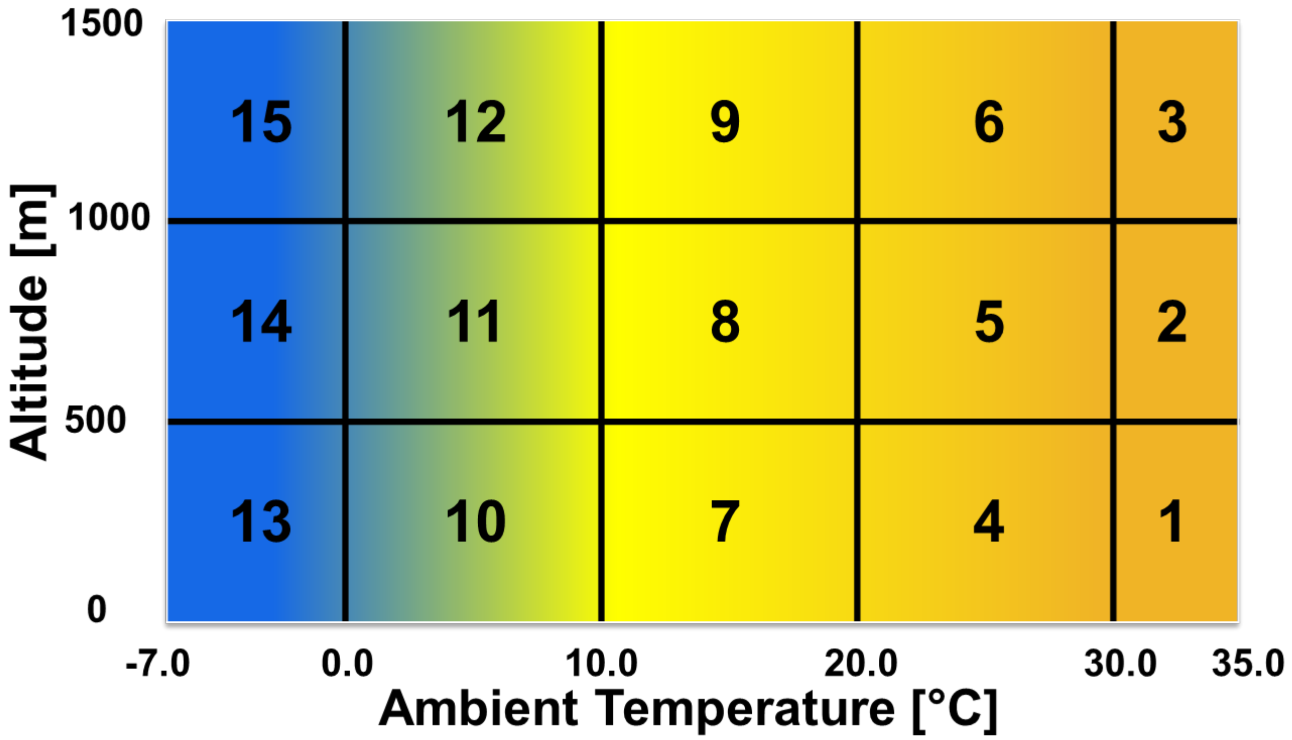
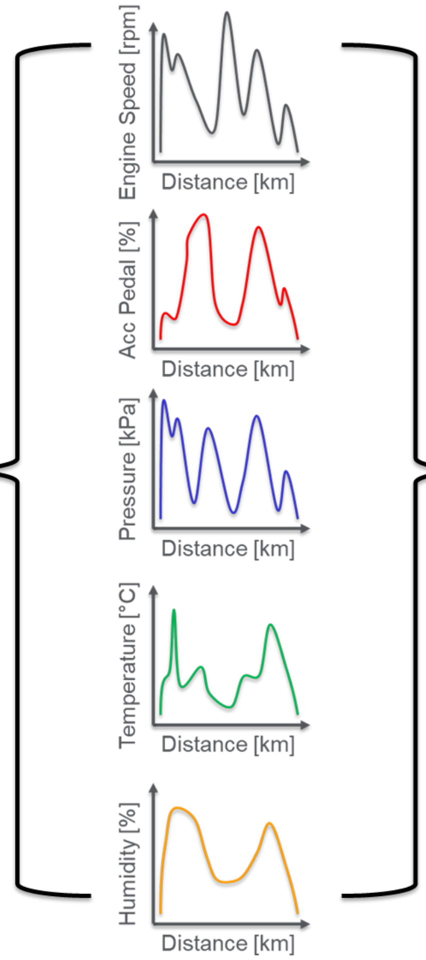
# Digital Twin Methodology

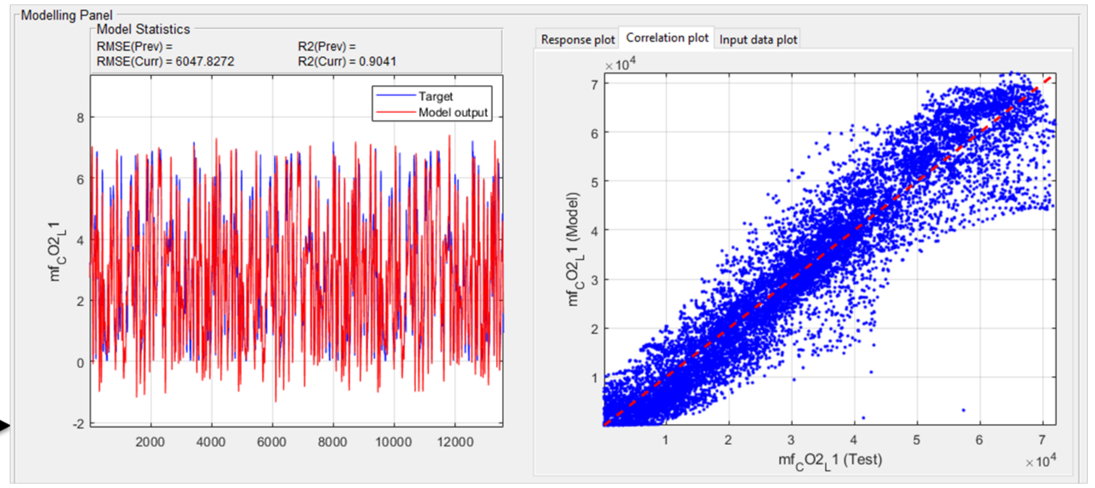
- Euro 6d RDE boundary conditions of altitude and temperature split into 15 sections; dynamic DOE designs created for each section.
- The dynamic DOE designs have four design parameters: **engine speed, accelerator pedal position, altitude (pressure) and temperature**
- The digital twin accounts for 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

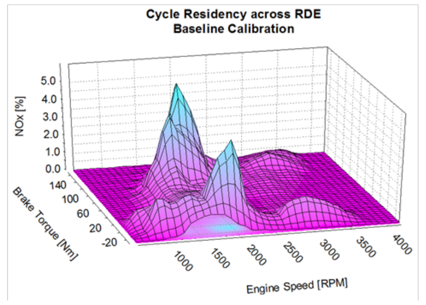



IPG CarMaker test scenarios run with data from testing used with models (>x30 faster than realtime)


IPG CarMaker

Virtual Driver, Route and Vehicle

Predicted engine responses and "hotspot" determination

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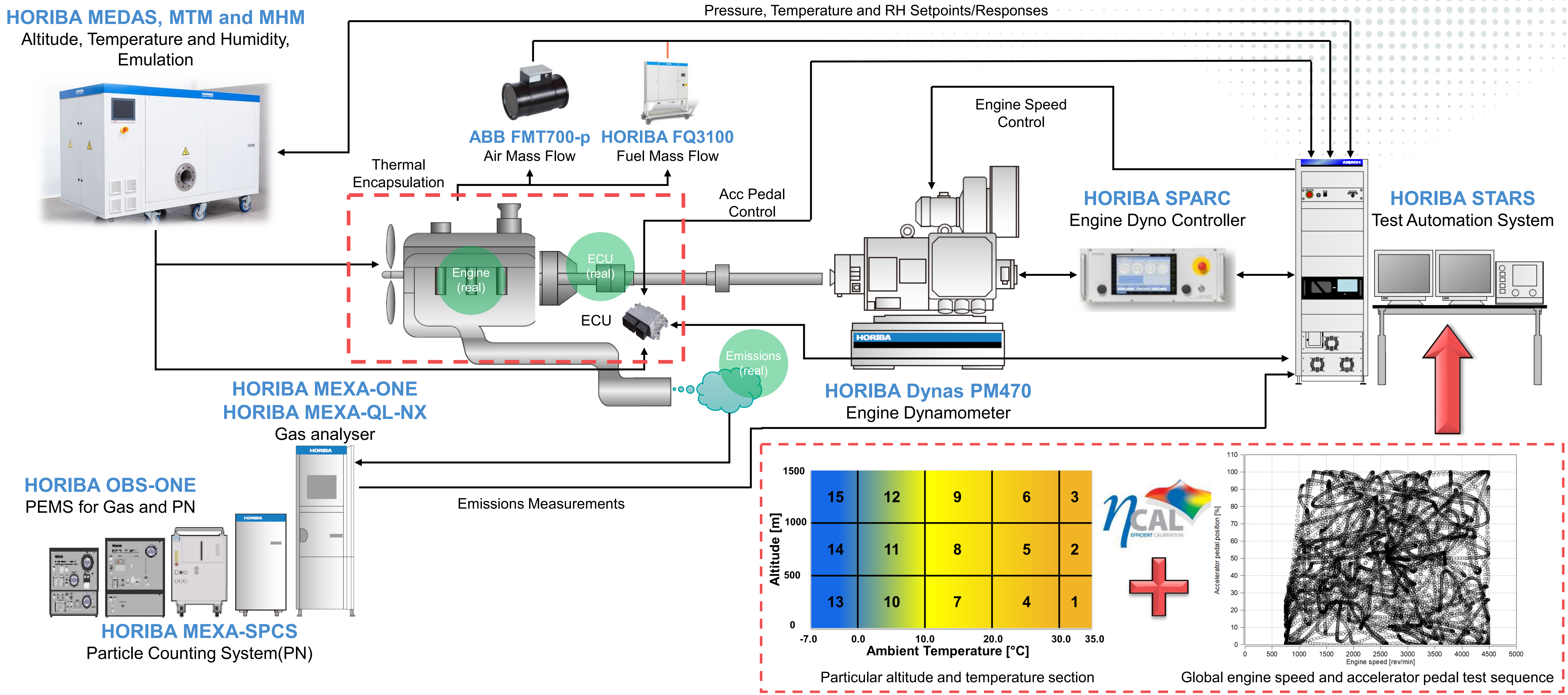
# Powertrain-in-the-Loop Configuration

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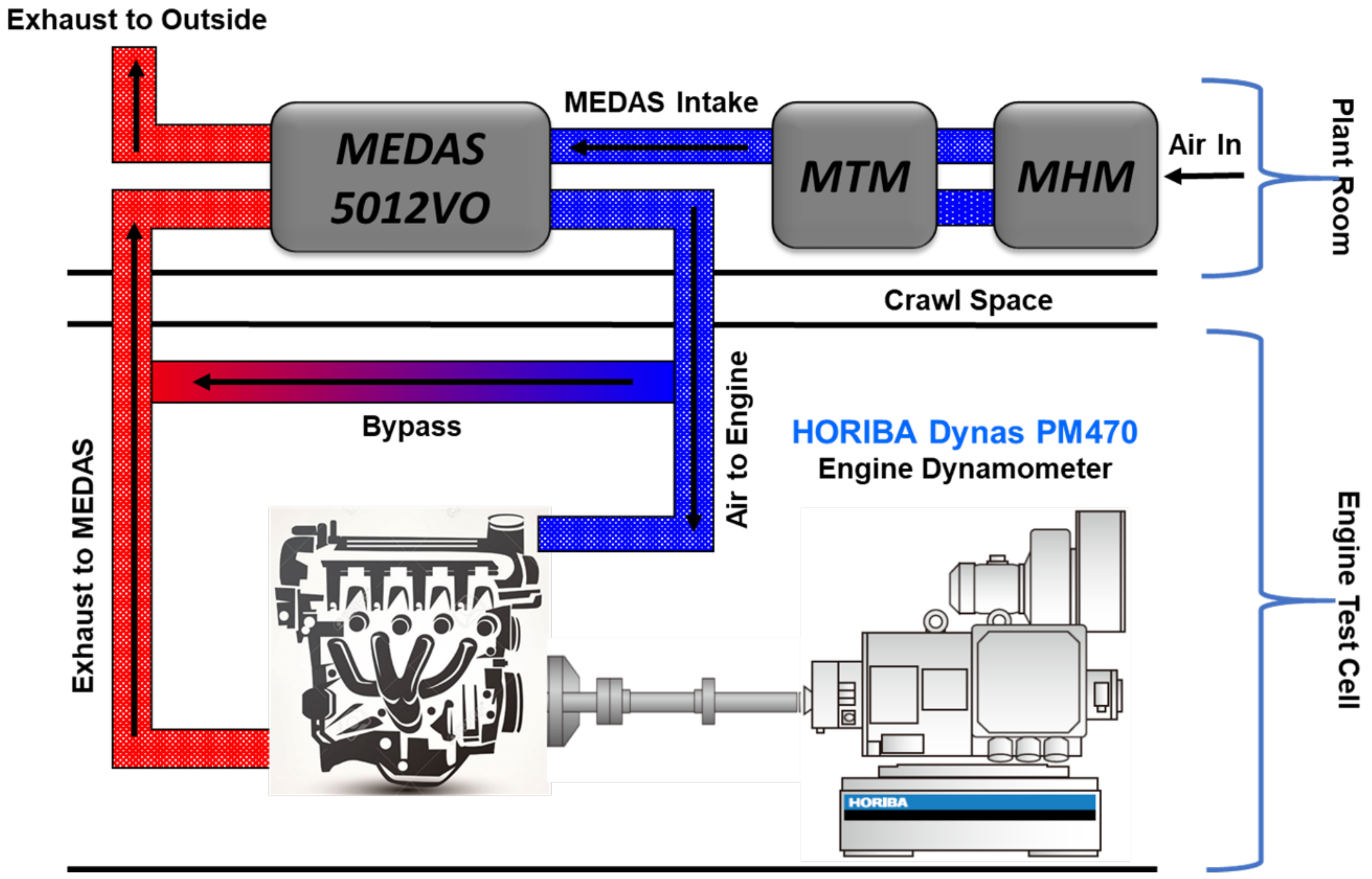
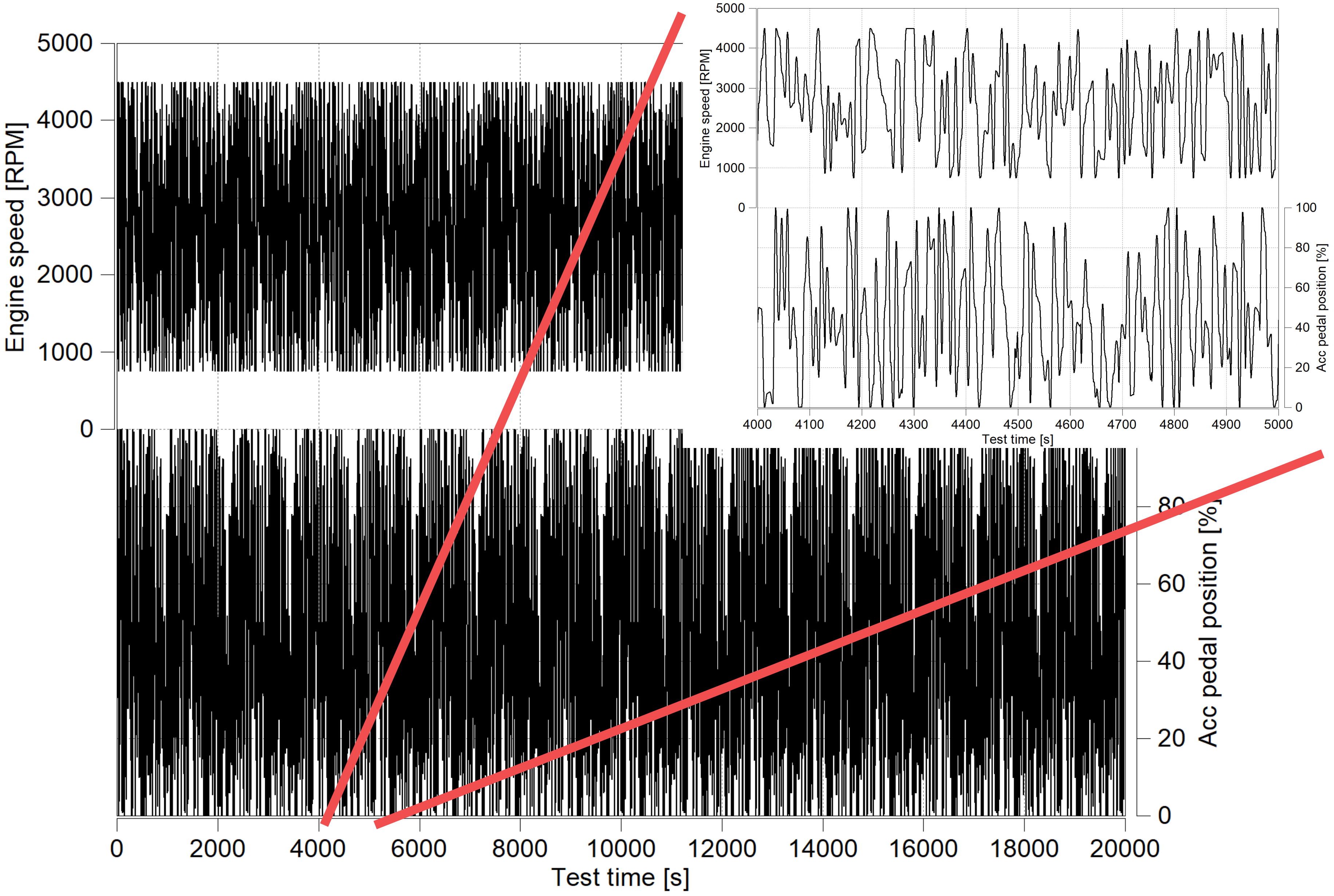
# Environmental Emulation using HORIBA MEDAS

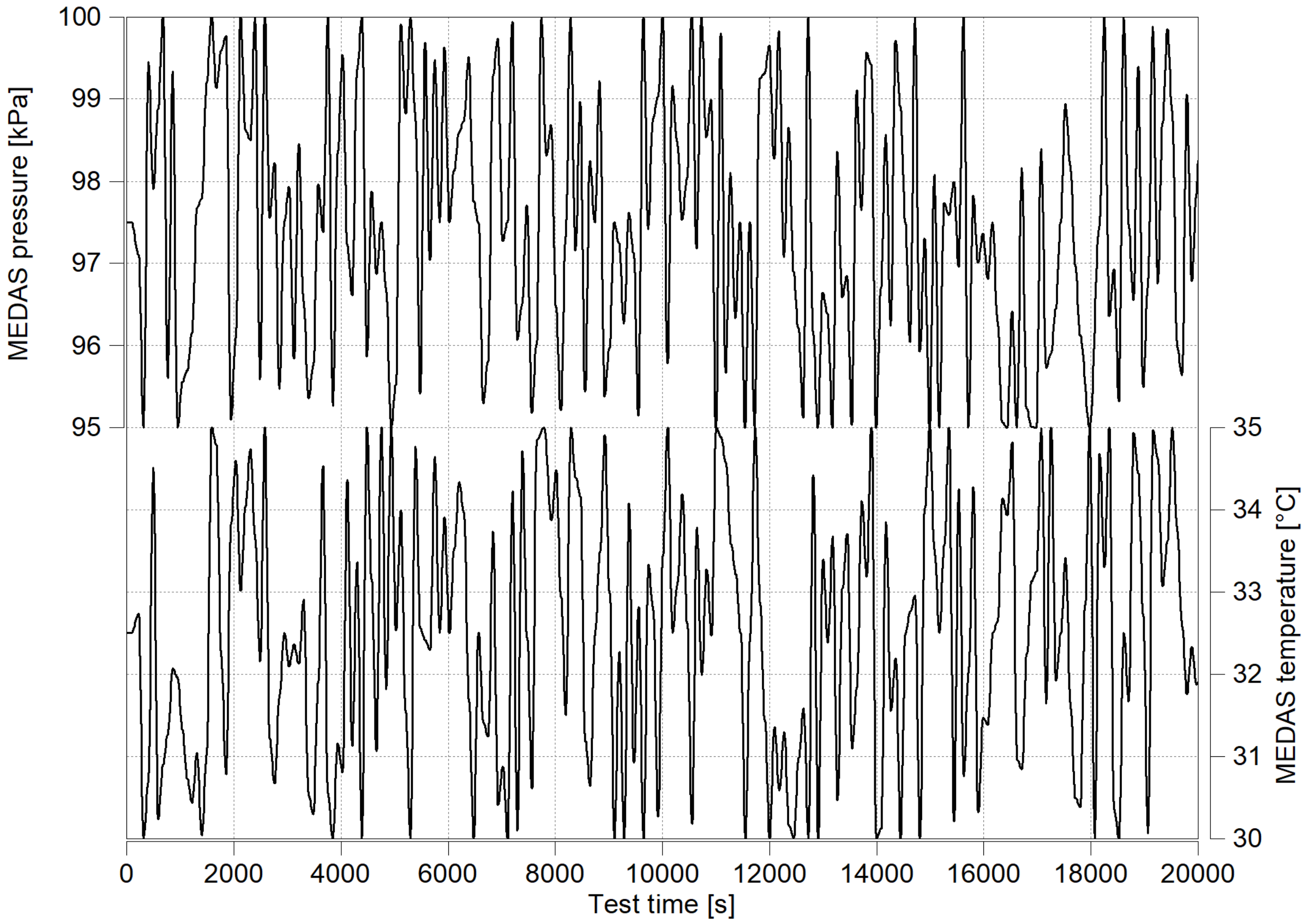
- HORIBA MEDAS has a key role in developing the digital twin and is used for environmental emulation.
- Shown here is a schematic of how the powertrain is configured with MEDAS. This system can also be used as part of a chassis dyno setup.




# 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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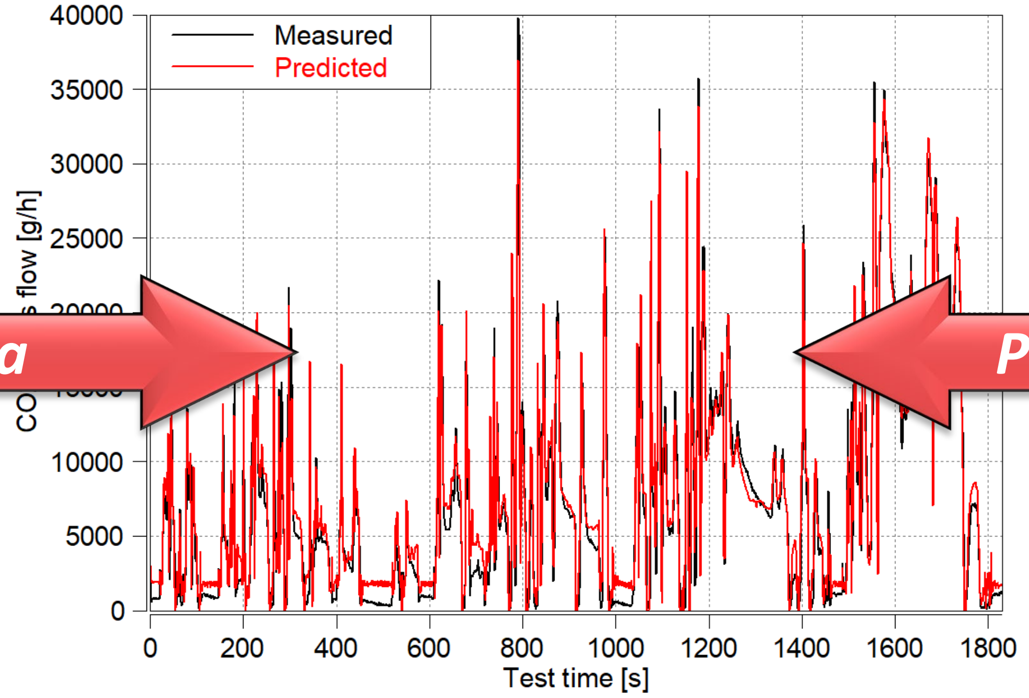
# Empirical Model Validation (1)

- 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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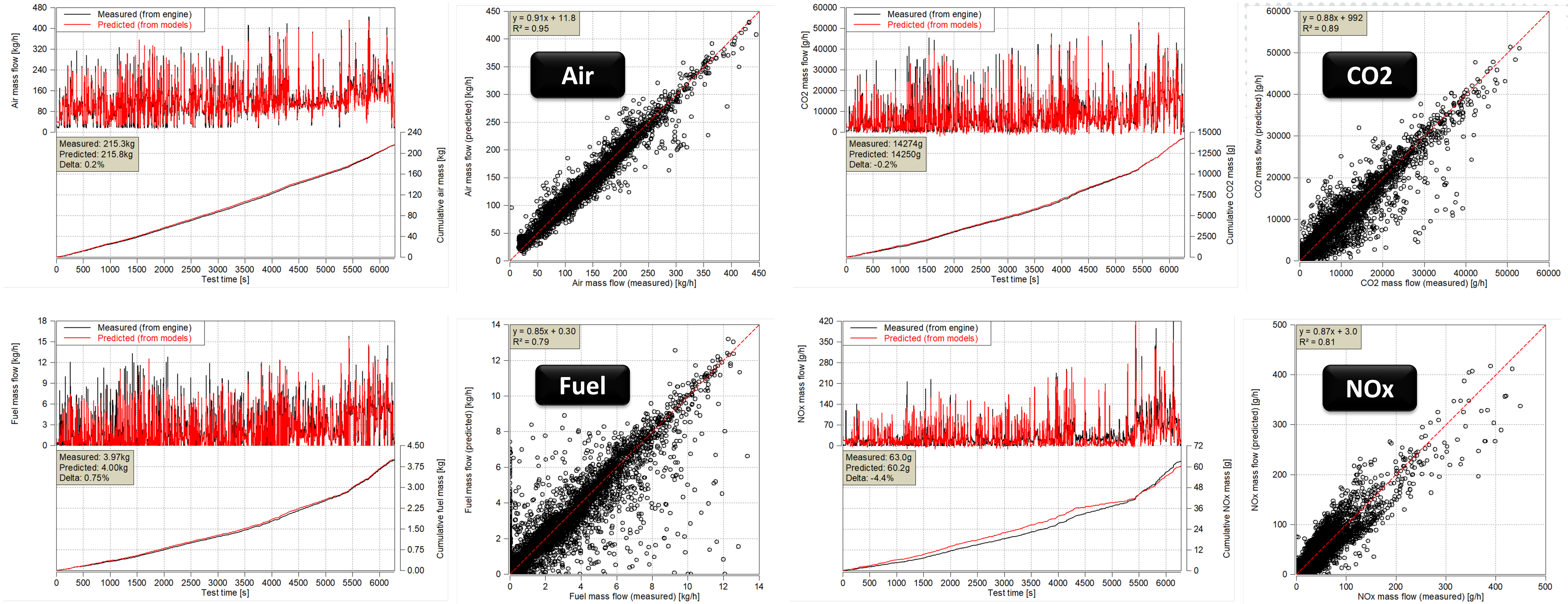
# Empirical Model Validation (2)

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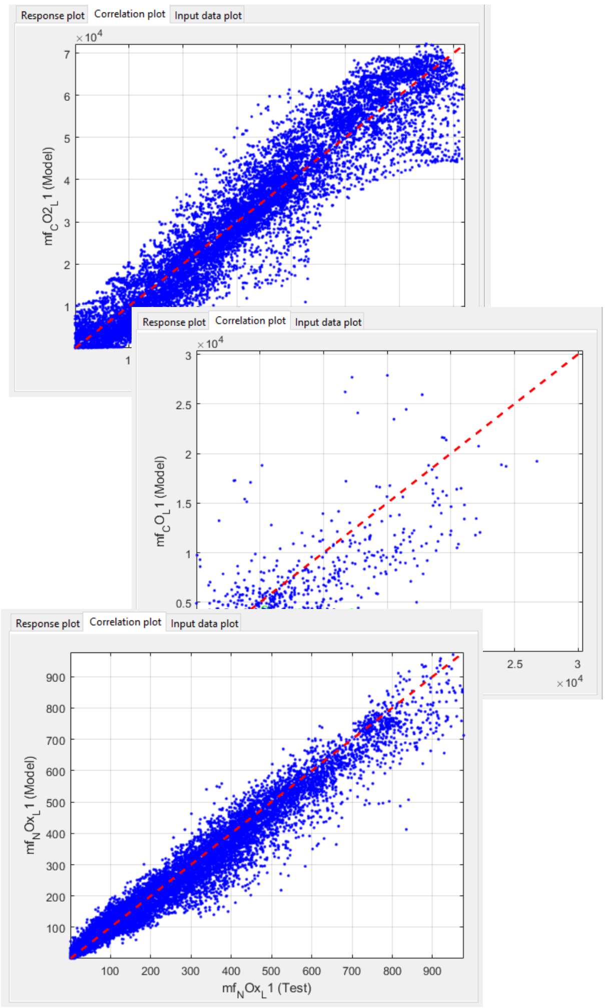
# Deployment of the Powertrain Digital Twin

- 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.

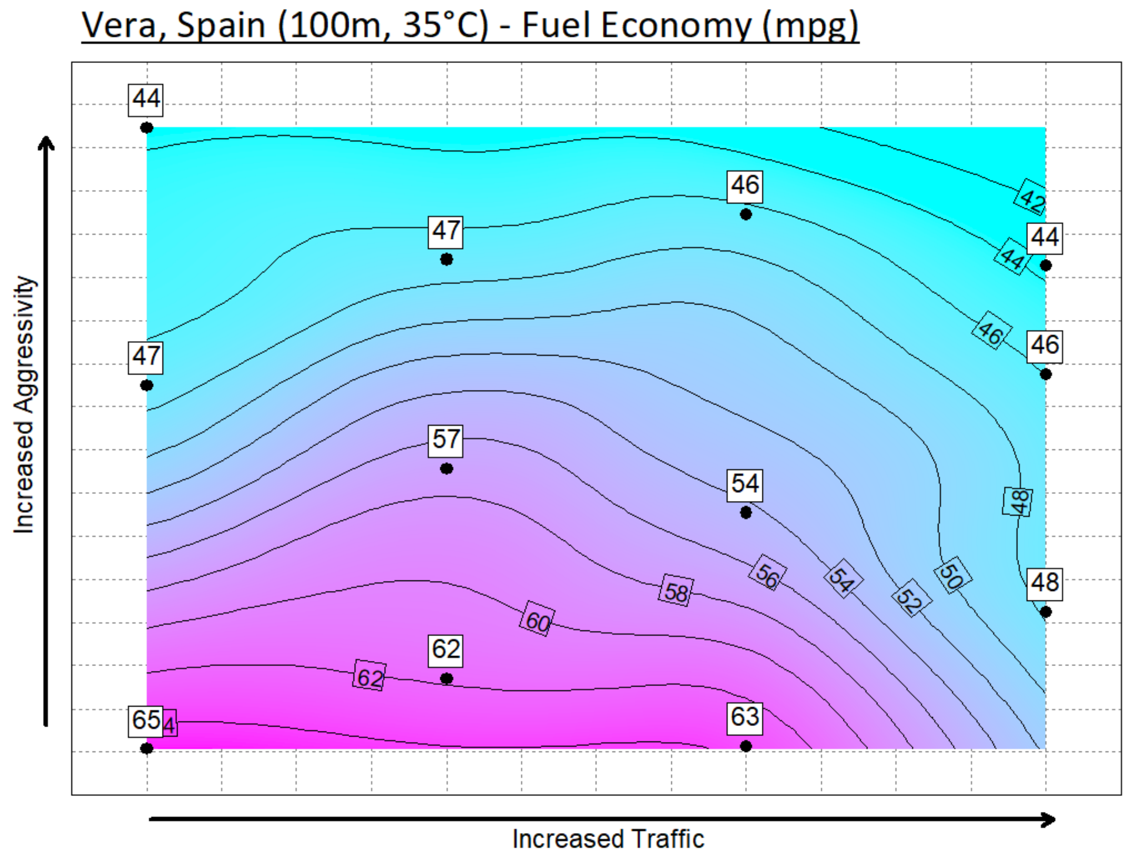

Run scenario in CarMaker (driver dynamics, traffic etc)

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

Extract data for use with models



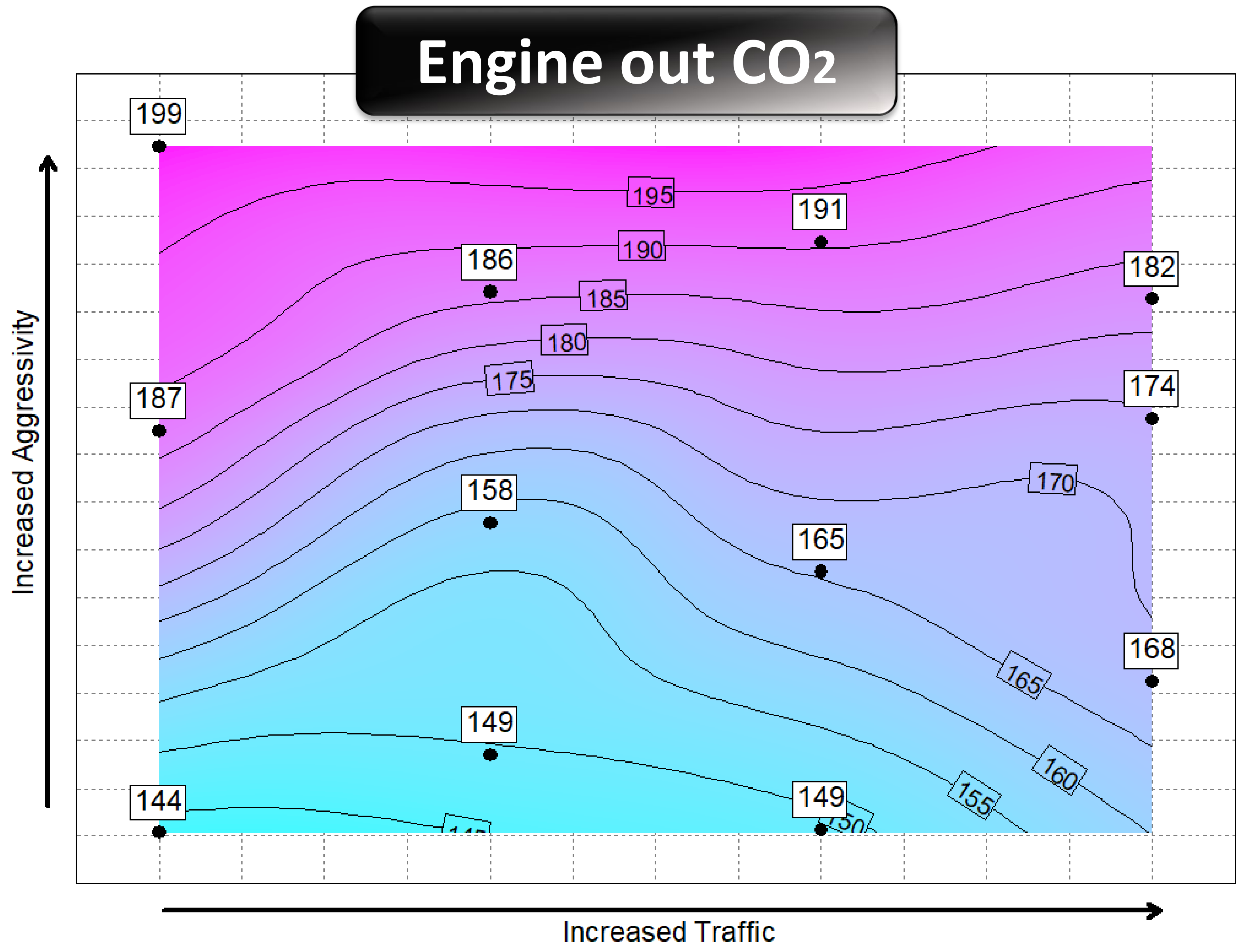

Couple extracted data with models

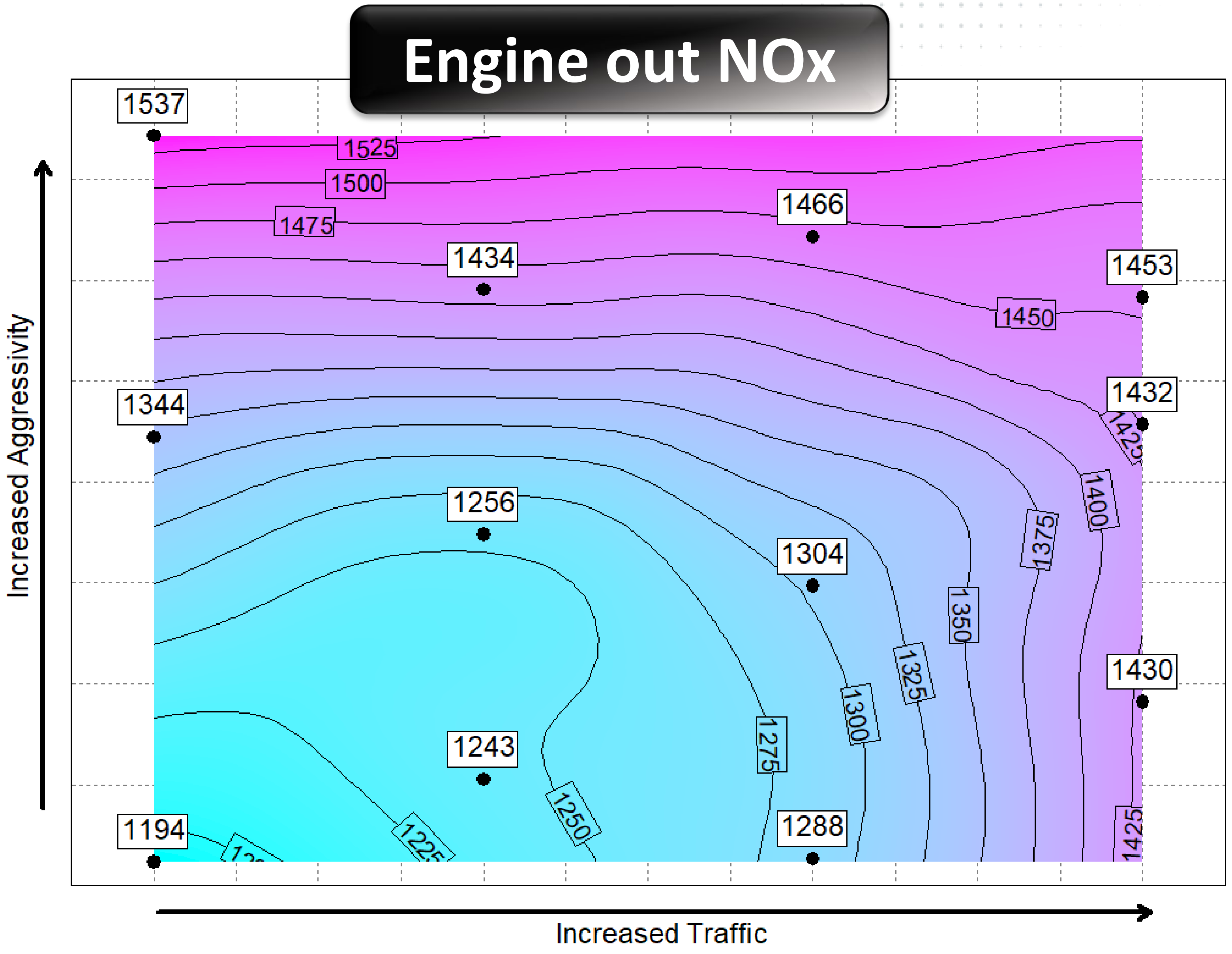



Predict performance and emissions responses

# Hotspot Screening (1)
# Models from Section 1

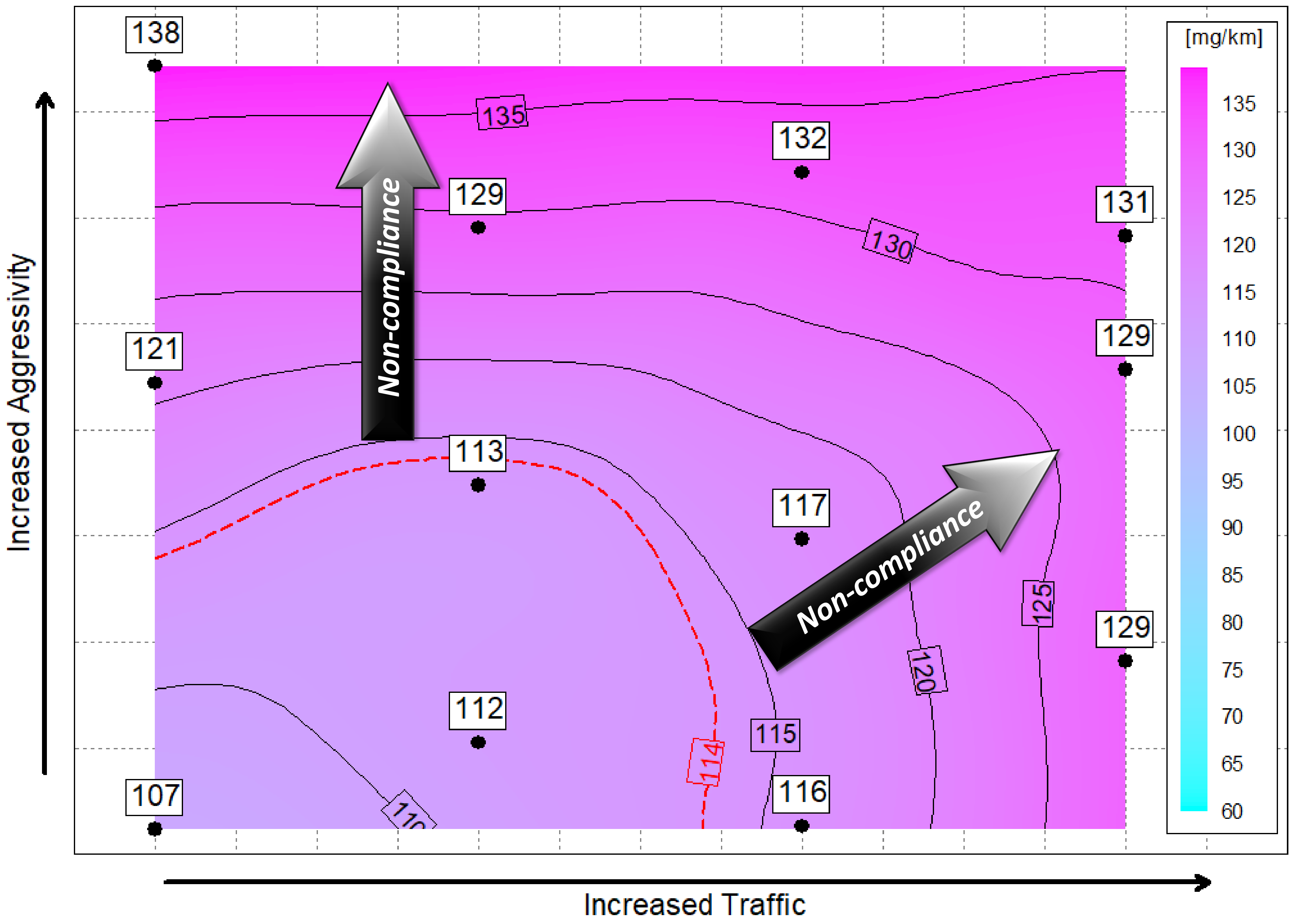
- Engine out cycle $CO_2$ and NOx predicted for different driving styles and traffic densities for an RDE route at 500m (95kPa), 35°C.
- 11% and 8% variation in $CO_2$ and NOx respectively due to changes in driving style and traffic density – all are completely compliant RDE cycles.
- This type of analysis 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 **<u>90%</u>** 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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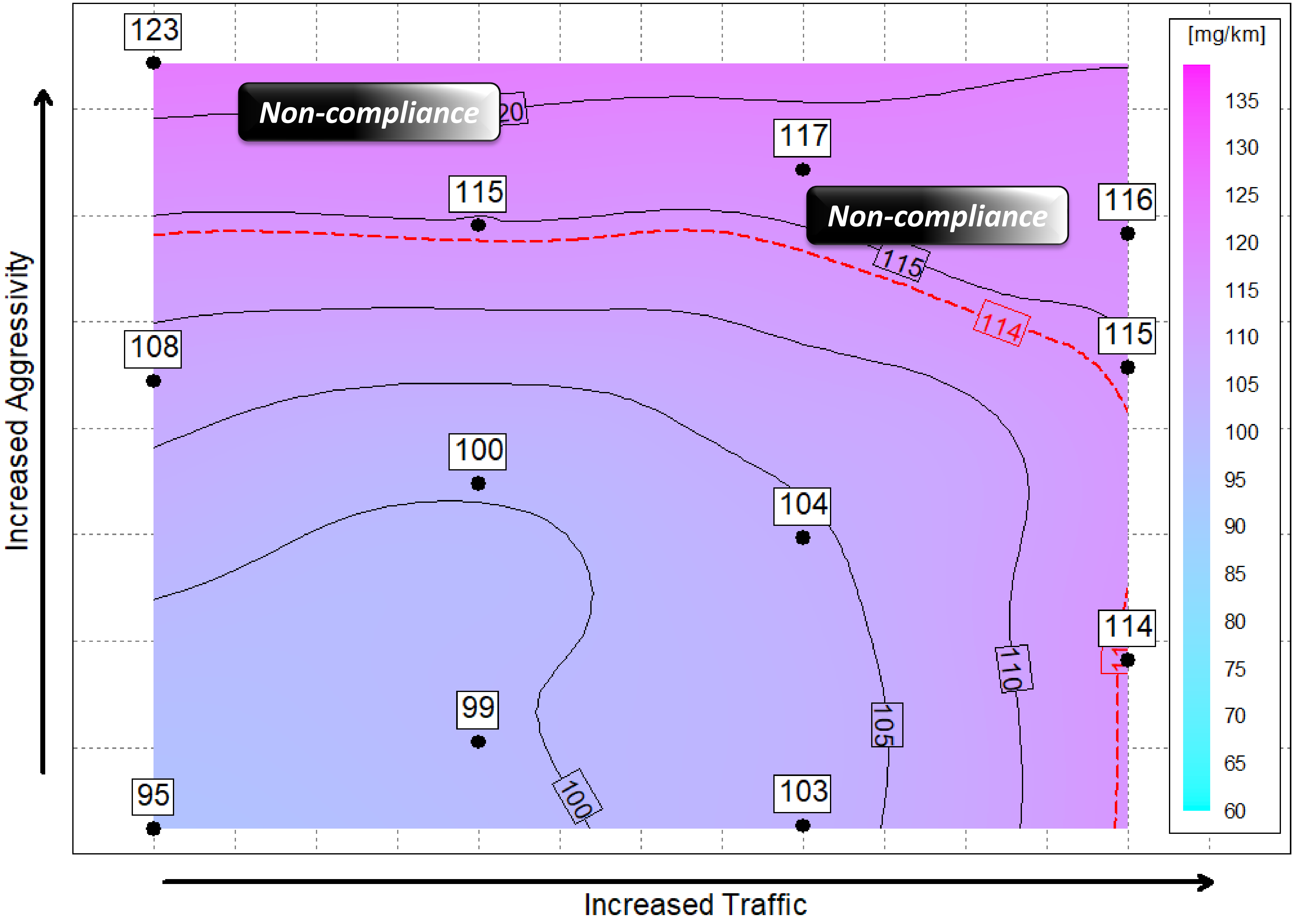
# Hotspot Screening (3)
# Models from Section 1

- Take engine out NOx data from previous slide and assuming **92%** 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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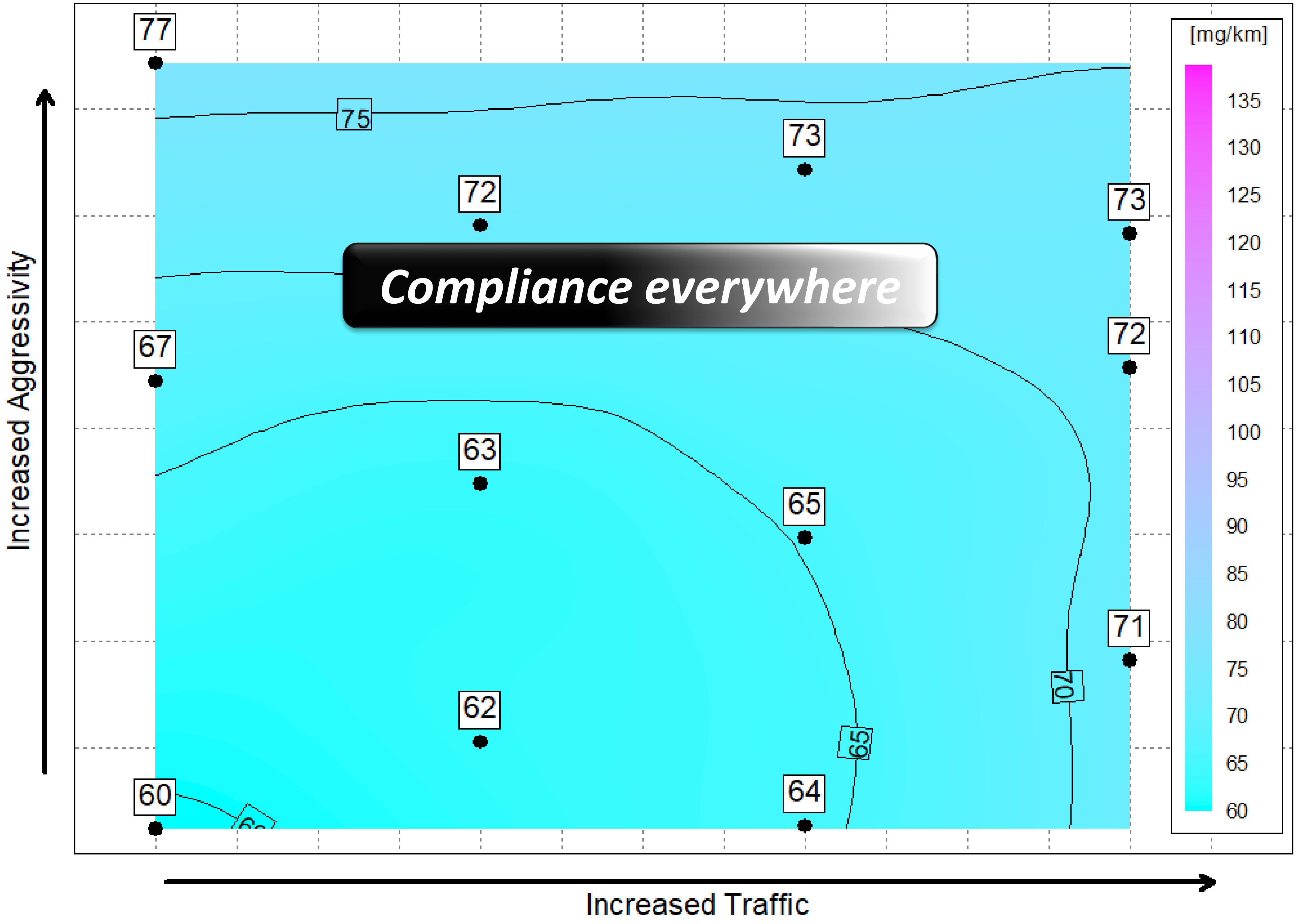
# Hotspot Screening (4)
# Models from Section 1

- 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.



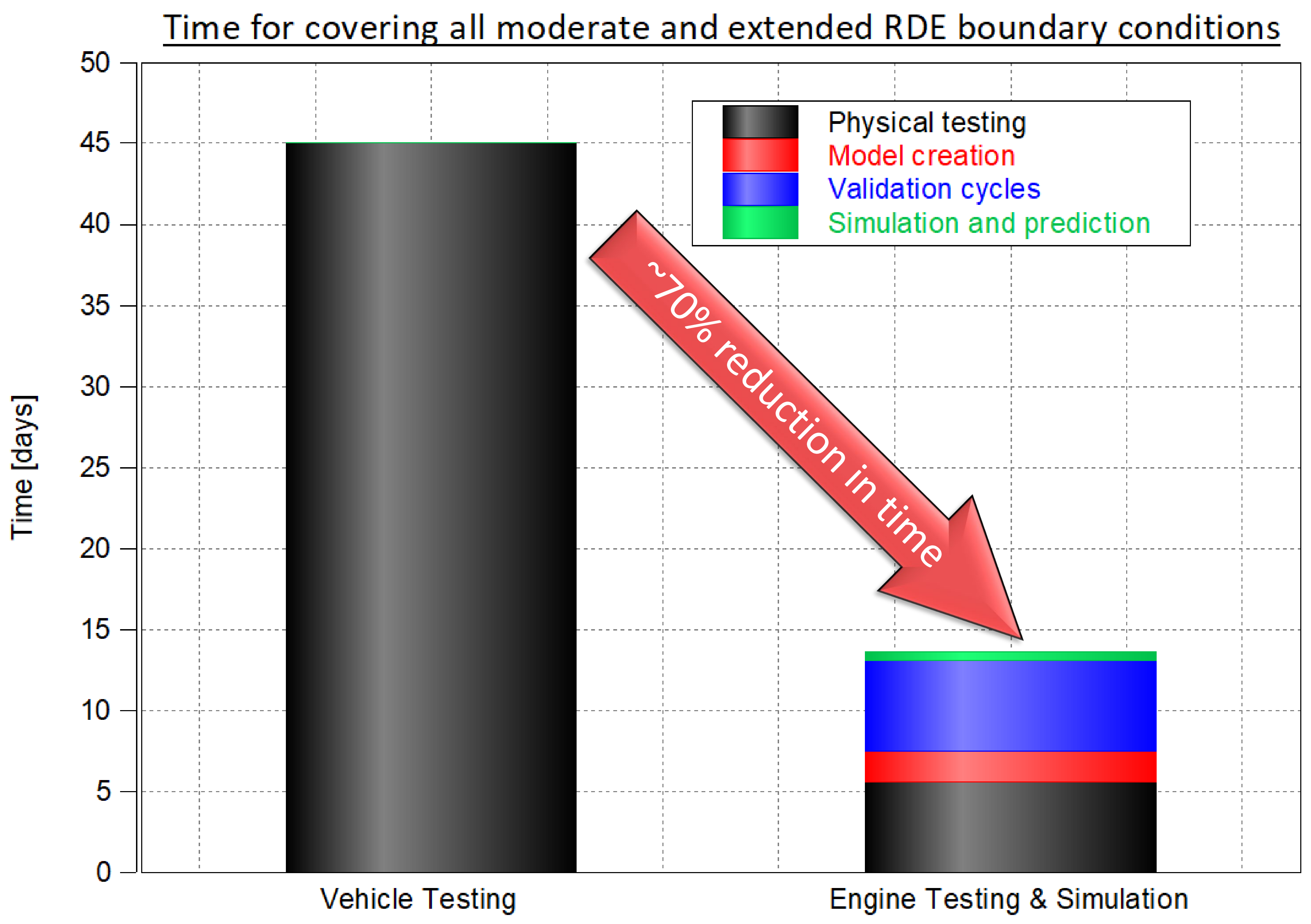
**Test Scenario**
Vehicle, Terrain and Environment

**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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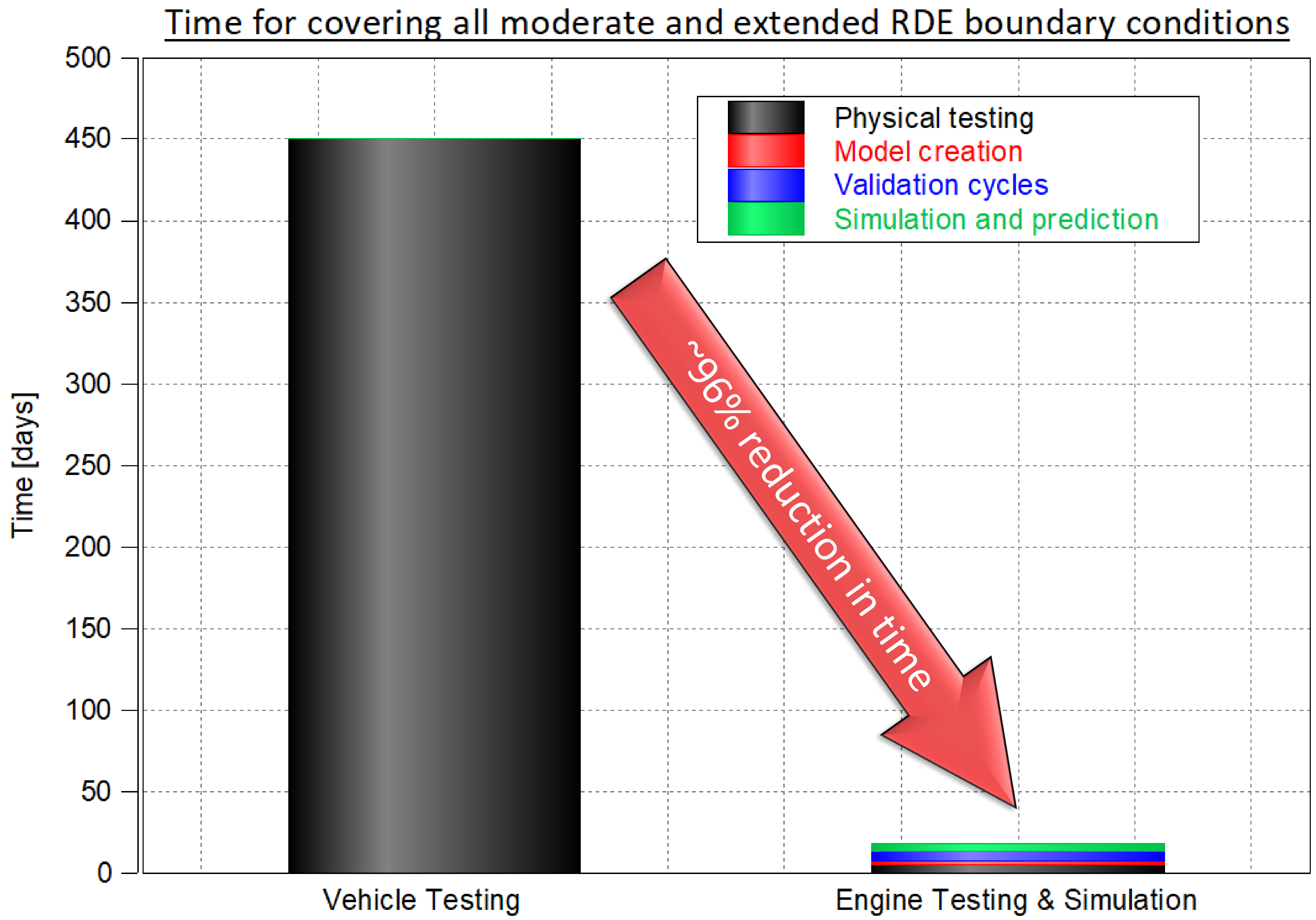
# Methodology Effectiveness (2)
# Light-duty Vehicle Example

- 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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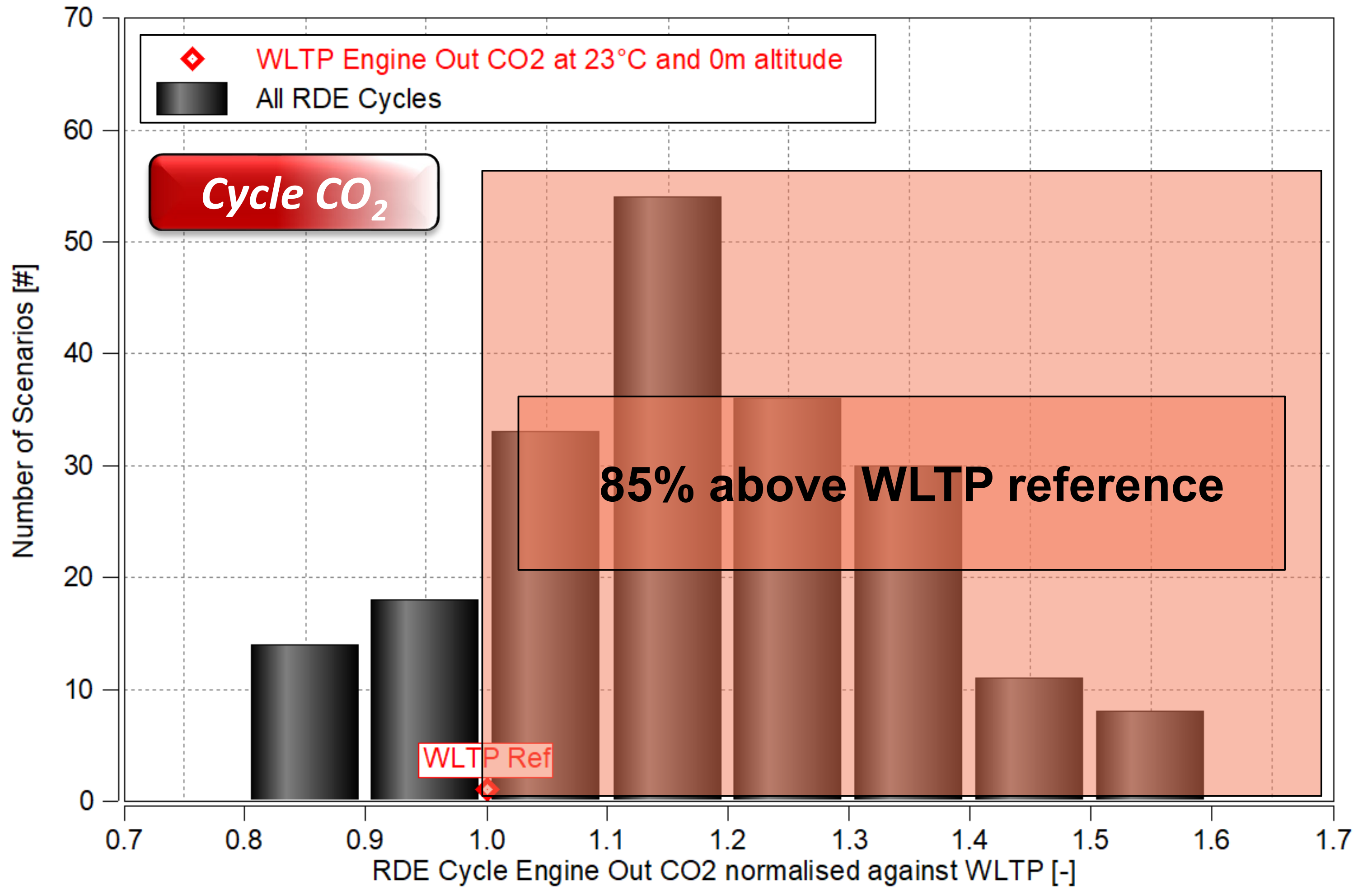
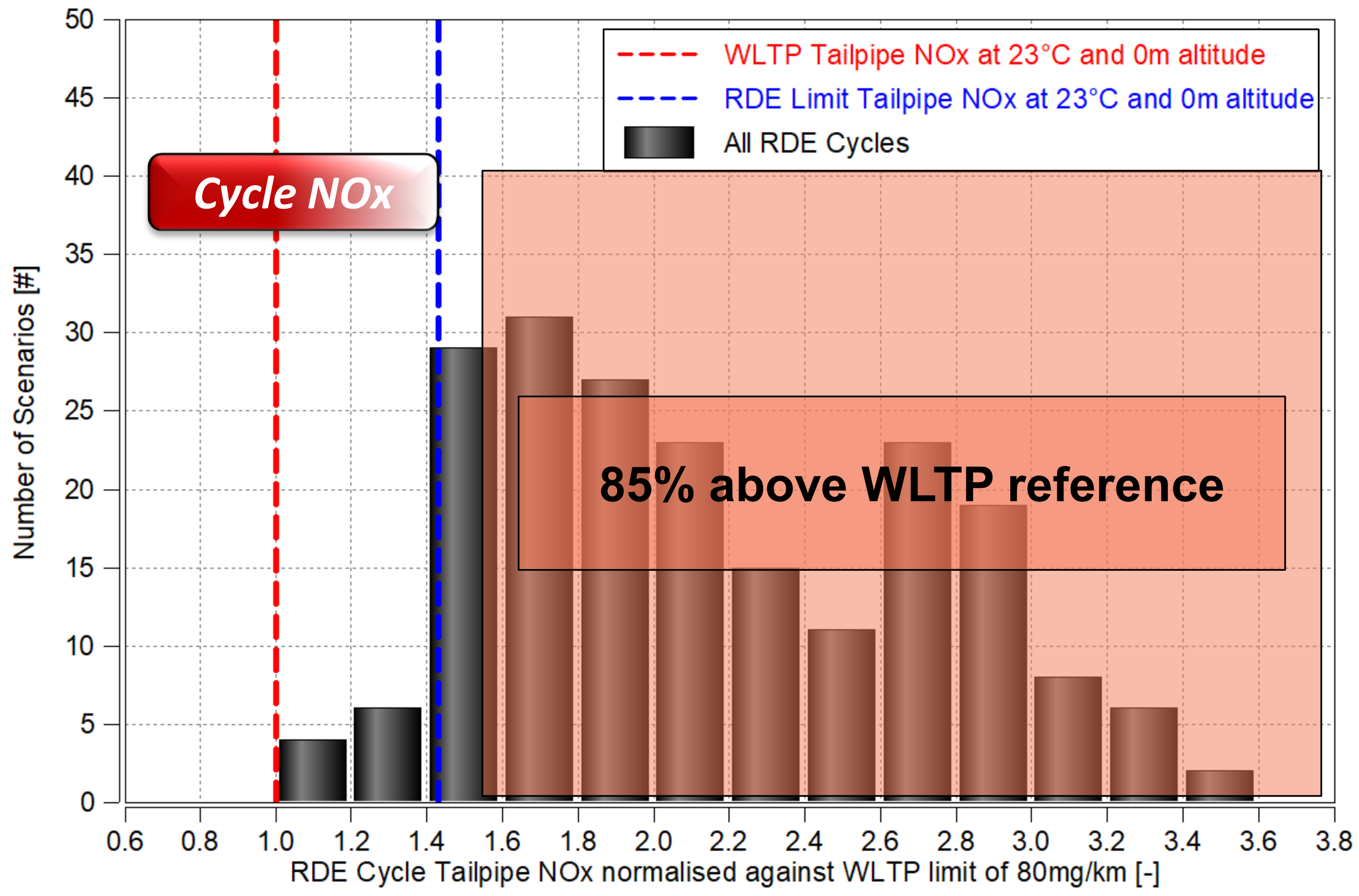
# Methodology Effectiveness (3)
# Light-duty Vehicle Example

- 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