HORIBA RDE+ SOLUTION OVERVIEW

REDUCING THE COST OF RDE AND REAL-WORLD POWERTRAIN EMISSIONS DEVELOPMENT

6TH AUGUST 2020

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RDE+

SMART SOLUTIONS FOR CLEANER AIR

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SMART SOLUTIONS FOR CLEANER AIR

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45 minutes (Introduction – Conclusion)

15 minutes (Q&A)

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INTRODUCTION

Steve Whelan

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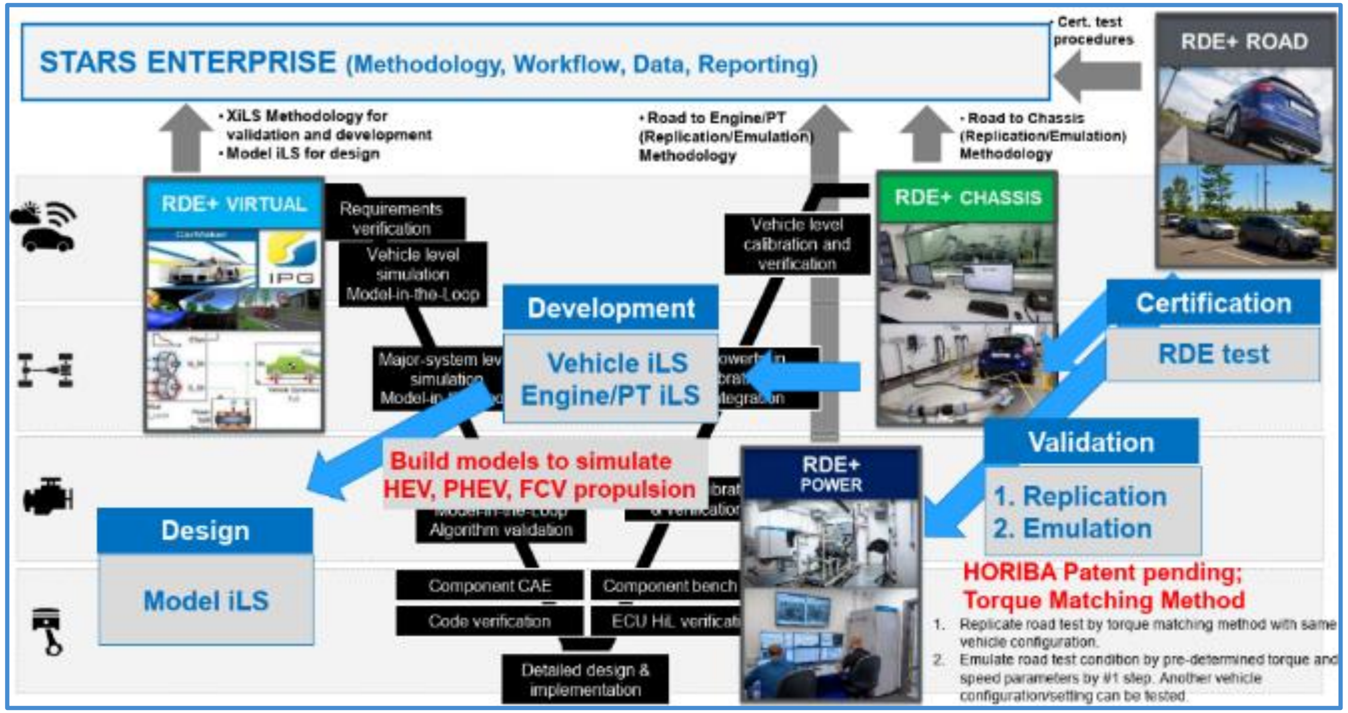
What Is RDE+ ?

- **RDE+ is a development and validation methodology that reduces cost, time & risk**
  - RDE+ is a development toolset and new development process for emissions compliance development
  - RDE+ integrates virtual tools with HORIBA’s advanced real-world testing methodologies, hardware & software
  - RDE+ reduces the number of prototype vehicles required -, saving up to $17M in a vehicle programme

- **RDE+ is a SOLUTION for emissions development and validation**:
  - Enhanced productive road testing
  - “Road-to-Rig” and “RDE in the Lab”
  - Simulation and hardware-in-the-loop (HiL)
- **RDE+ is a MODULAR solution** comprising HORIBA hardware and software with process applications in STARS Enterprise
- **RDE+** is offered as a **solution product** or a **testing/development service**



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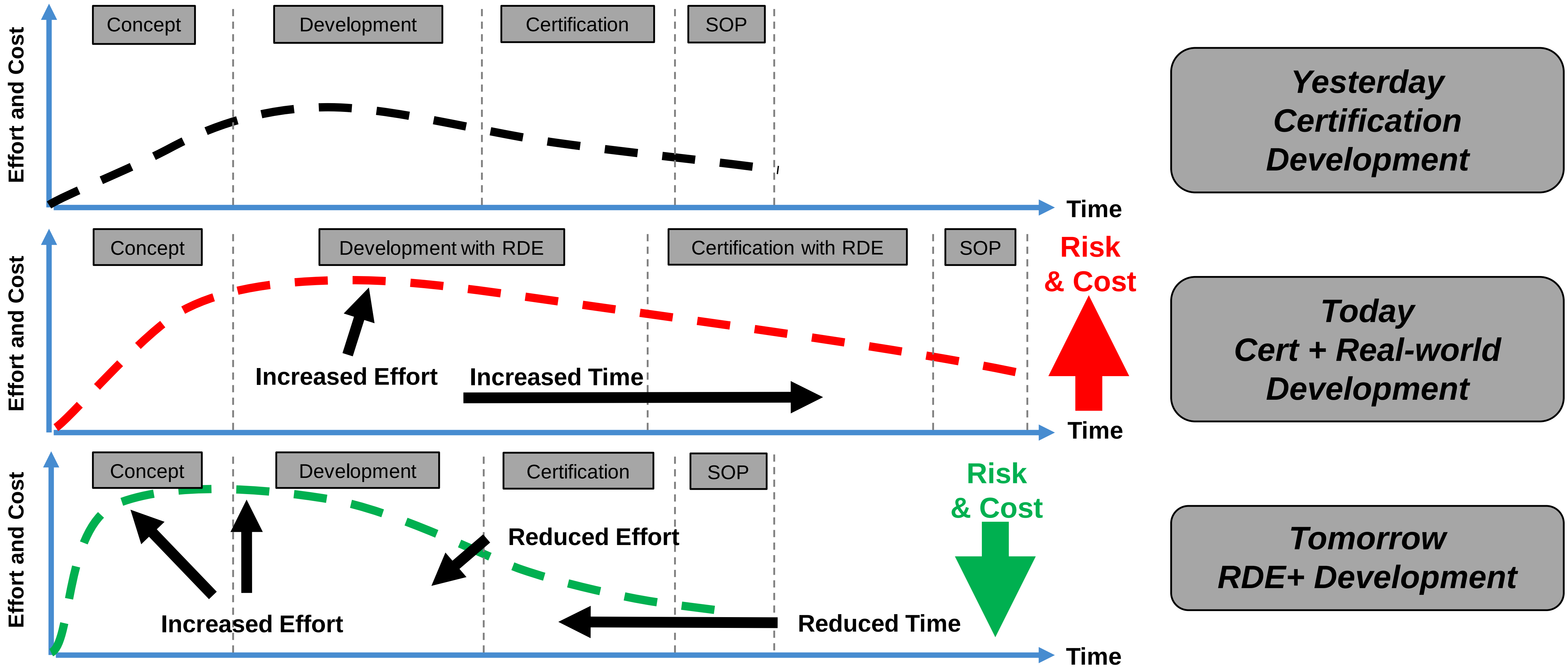
Why do We Need RDE+ Solutions?



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Programme Benefits of RDE+

Cost
- Front-loading and digitisation of development and validation
- Reduction in prototype vehicle numbers and field trips
- Accurate optimisation for lowest cost product solution

Time
- Front-loading for early prototype maturity
- More efficient and automated lab testing
- Reduction in road-testing and de-coupling from seasons

Confidence
- Front-loading gives early confidence in RDE compatibility
- Accurate and repeatable lab testing
- Simulation enables prolific scenario validation

Warranty
- Compliance is more thoroughly validated and understood
- Tier 1 systems validated under RDE conditions in the lab
- Reduced in-service failure and emissions non-conformity

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Programme uses Four Significant Methodologies

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REPLICATION

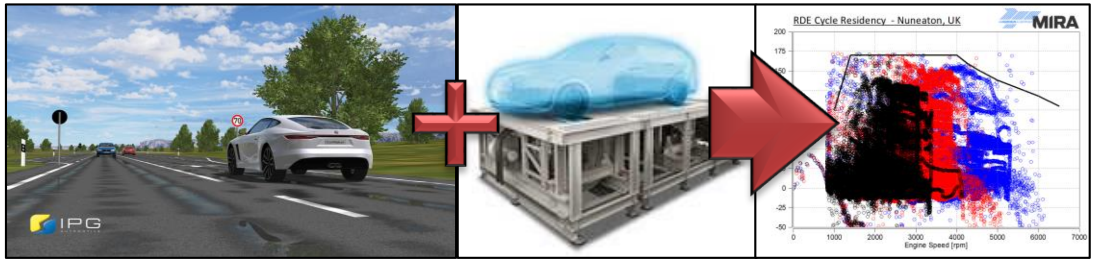
Reproduction of the on-road drives on chassis, powertrain and engine dynos

EMULATION

Ability to repeatedly reproduce realistic scenarios for calibration, development and validation

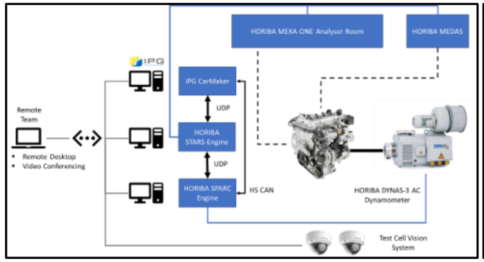
SIMULATION

Simulation of real-world driving connected to chassis, powertrain and engine dynos (HiL)



AUTOMATION

Automated laboratory and dyno control systems integrated with remote connectivity



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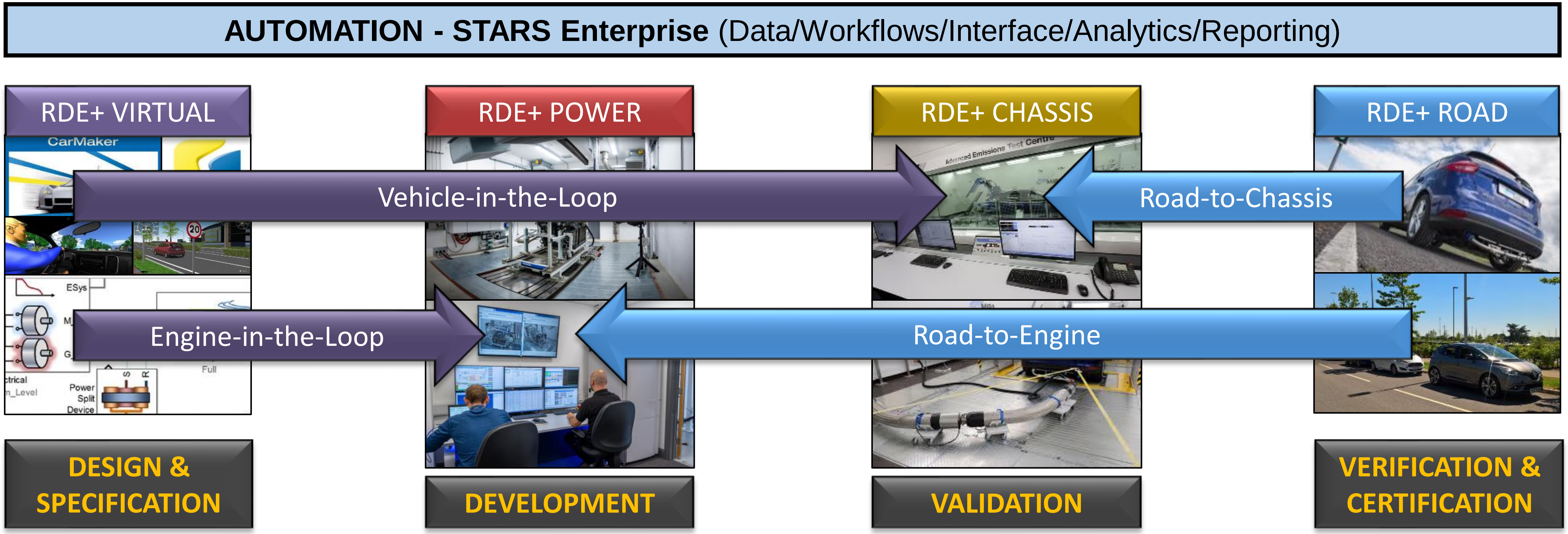
RDE+ Development Solution will be available in four independent but integrated modules with “orchestration”

RDE+

RDE+



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RDE ROAD – Enhances RDE Road Testing

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Benefits

- Time and Cost Savings
  - Increased test success rate
  - Increased resource utilisation
  - More efficient programme planning
  - Higher facility throughput and PEMS utilisation
- Confidence and Accuracy Improvements
  - Improved governance, traceability and data recall
  - Improved accuracy at low NOx and PN
  - Improved correlation with the laboratory

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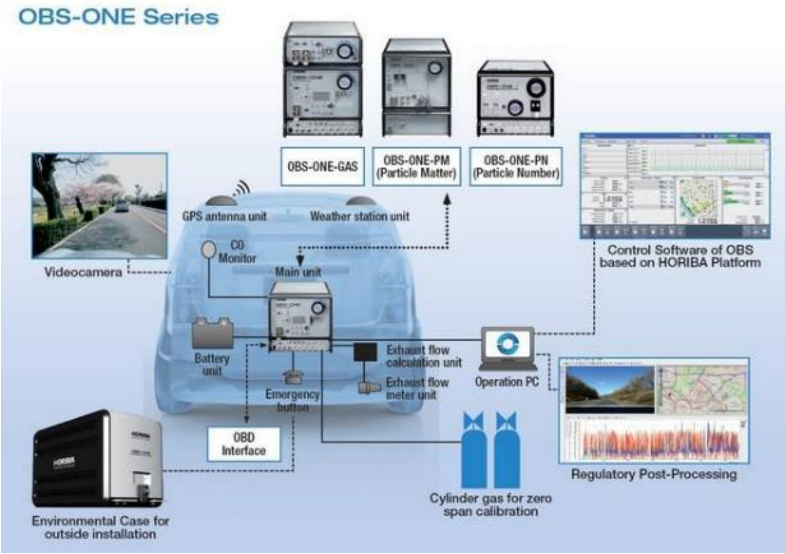
Delivering Reliability and Productivity

- This application uplifts the process of delivering RDE tests to a success rate of over 90%
- Integration of HORIBA CoDriver, OBS-ONE PEMS and STARS Enterprise applications
- Easy data capture for HORIBA's patented "road-to-rig" process



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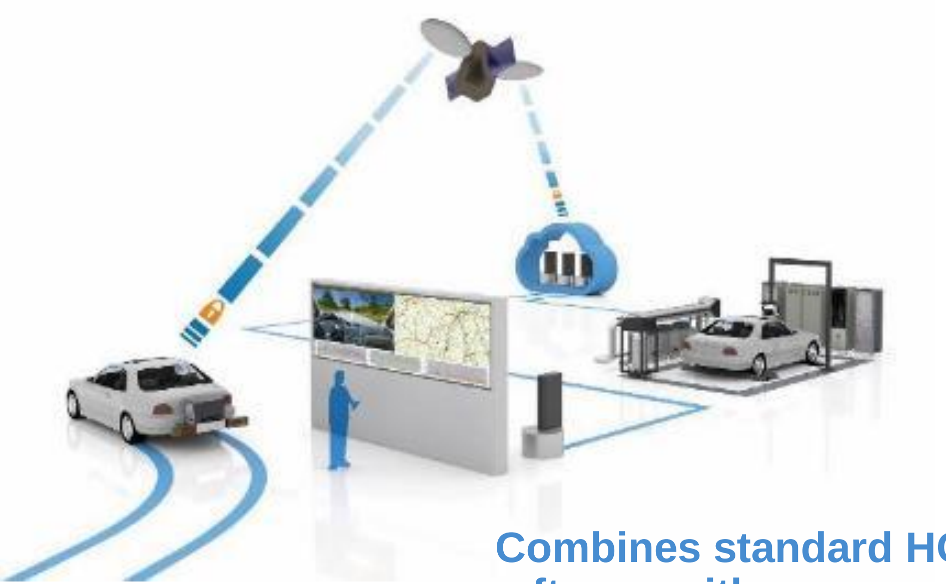
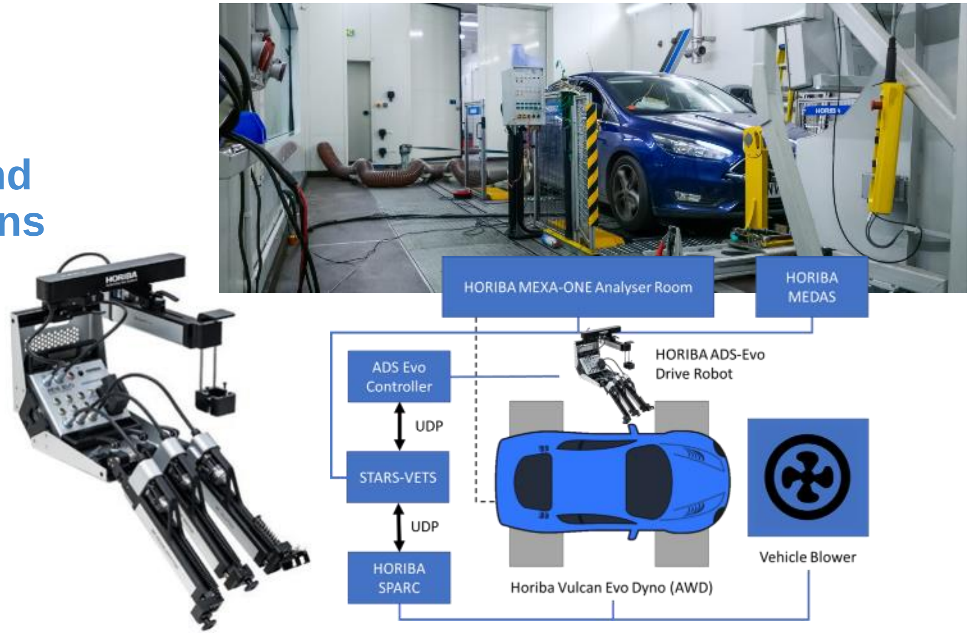
RDE CHASSIS – RDE Vehicle Testing in the Lab



Rapid, Repeatable and Accurate RDE Testing in the Lab

- HORIBA Torque Matching – patented new road-to-rig process
- Faster, more accurate RDE test replication methodology
- Low-cost process with minimum vehicle instrumentation
- Enables further RDE test emulation for vehicle emissions development

Combines standard HORIBA hardware and software with new process and applications



Benefits

- Lower cost, efficient replication and emulation of RDE tests
- Rapid, accurate RDE testing and measurement on the chassis dyno
- Elimination of road tests – reduced time, cost and prototype vehicles
- Emulation of any RDE climatic conditions at any time

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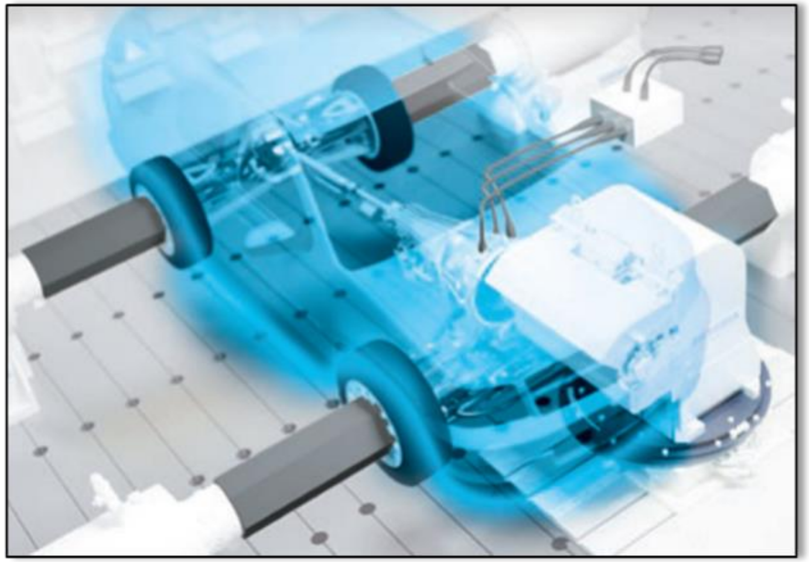
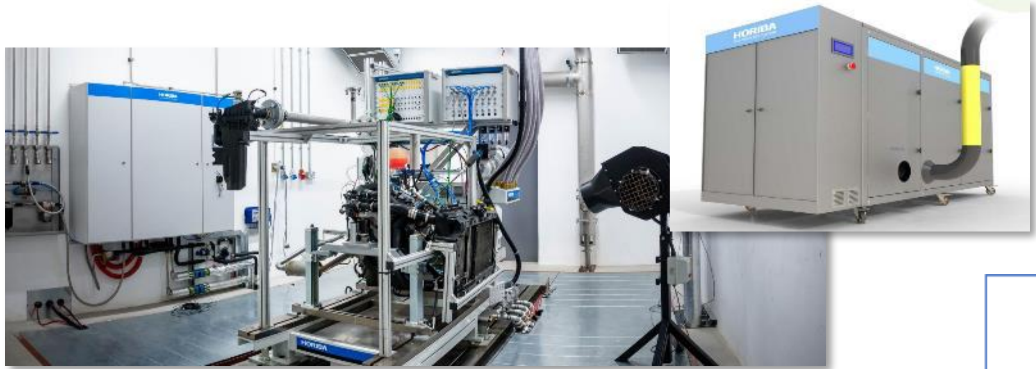
RDE POWER – RDE PT Testing in the Lab

RDE



Rapid, Repeatable and Accurate RDE Powertrain Development in the Lab

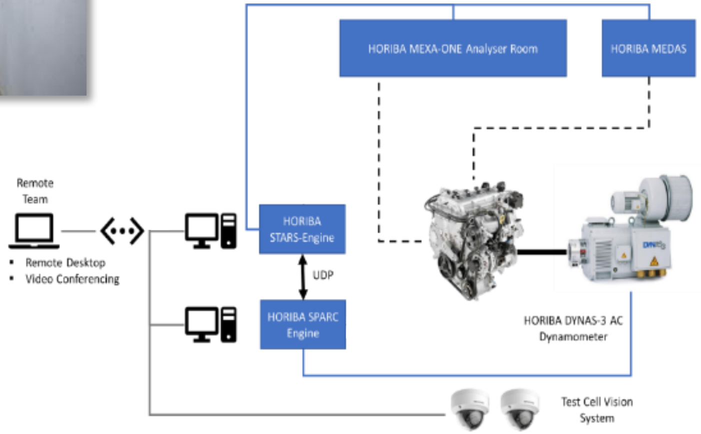
- HORIBA Torque Matching – patented new road-to-rig process
- Faster, more accurate RDE test replication methodology
- Low-cost process with minimum vehicle instrumentation



Combines standard HORIBA hardware and software with new process & applications

Benefits

- Lower cost, efficient replication and emulation of RDE tests
- System development and calibration under emulated RDE environmental and driver conditions
- Rapid and accurate calibration development with advanced transient optimisation
- Reduced development time, cost and elimination of prototype vehicle testing



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RDE VIRTUAL – RDE Simulation in the Office

Creation of the Virtual World

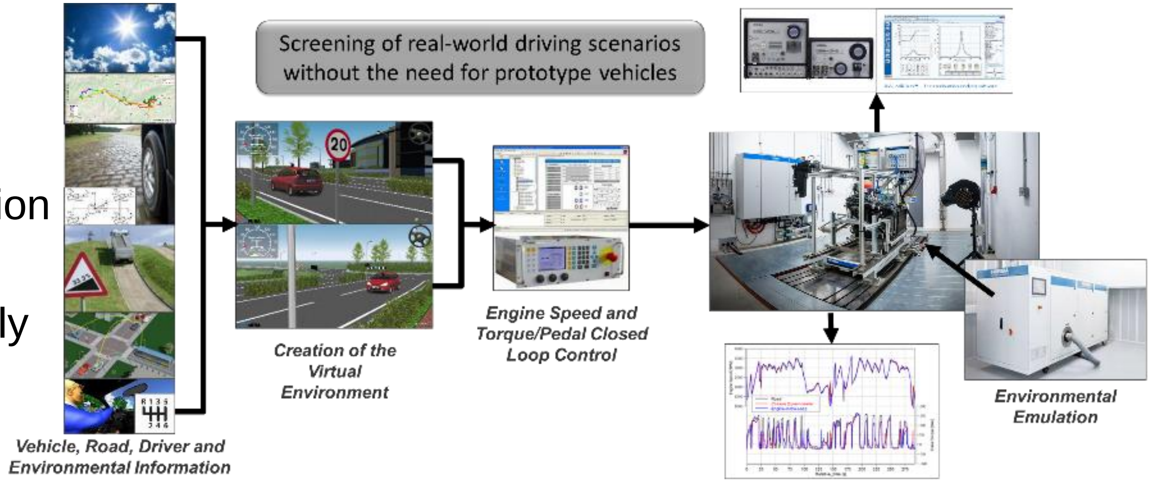
- Real or virtually generated RDE tests and scenarios can be modelled including the environment, traffic and driver behaviour

Digital Twin Vehicle

- Vehicle models can be driven in the Virtual World to rapidly determine worse-case RDE scenarios and the impact of system optimisation of RDE attributes

Benefits

- Time and cost savings from programme frontloading
- Identification of worst-case RDE scenarios for robust validation from model-based and scenario based development
- Explore more of the design space more effectively and rapidly
- Accelerated maturity of concept design and confidence in product conformity to RDE regulations



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RDE+ SMART SOLUTIONS FOR CLEANER AIR

RDE+ CHASSIS
RDE+ POWER

Leo Breton

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RLS Chassis Dyno Operation Not Suitable

Accuracy and Precision Limitations

Chassis Dyno

$$F(t) = (A + B * v\ \ (t) + C * v\ \ (t)^2) + M * \frac{dv\ \ (t)}{dt} + M * g * sin\alpha(t)$$

- F(t) has always been an approximation – it is no longer “good enough”
- A,B,C are not constant over real-world road routes
- Does not consider steady or changing winds
- $v\ \ (t)$ errors on chassis dynos due to inertia/controls
- $\alpha(t)$ is difficult and expensive to measure – GPS with pressure compensation not adequate for precision work

Chassis/Powertrain/Engine Dyno

- Using real-world throttle trace in lab is only valid when combined with ambient conditions replication

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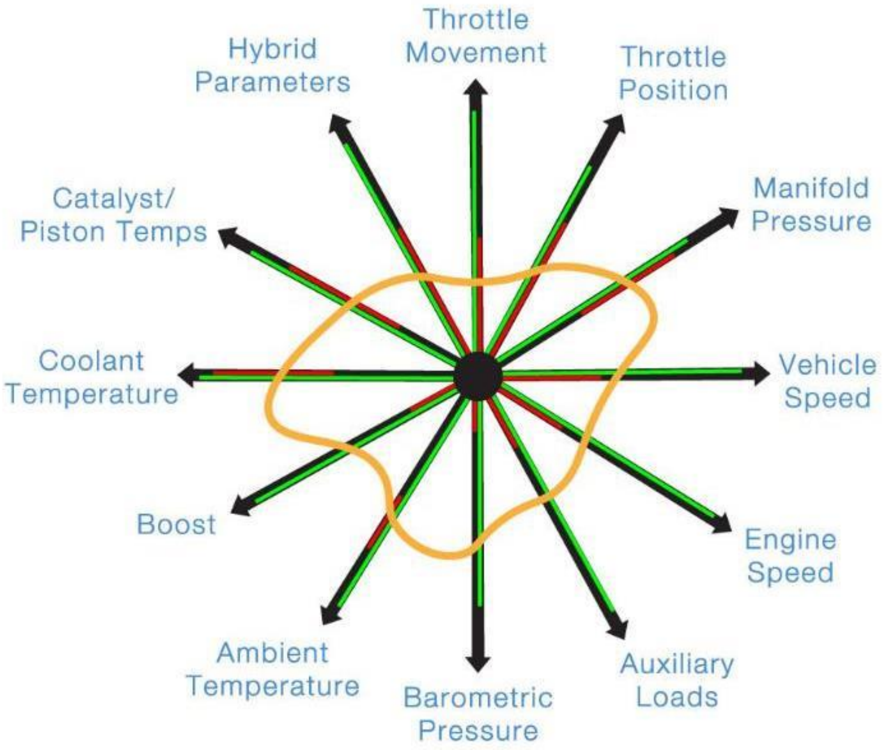
A Robust Method Requires Simultaneous Replication/Emulation of all Relevant Inputs

RDE

PEMS Marathon Test - Courtesy USEPA

“Road-to-Rig”



Powertrain Operational Space

Traditional Lab Range

Real World & Future Lab Range

Complete Operational State at time t

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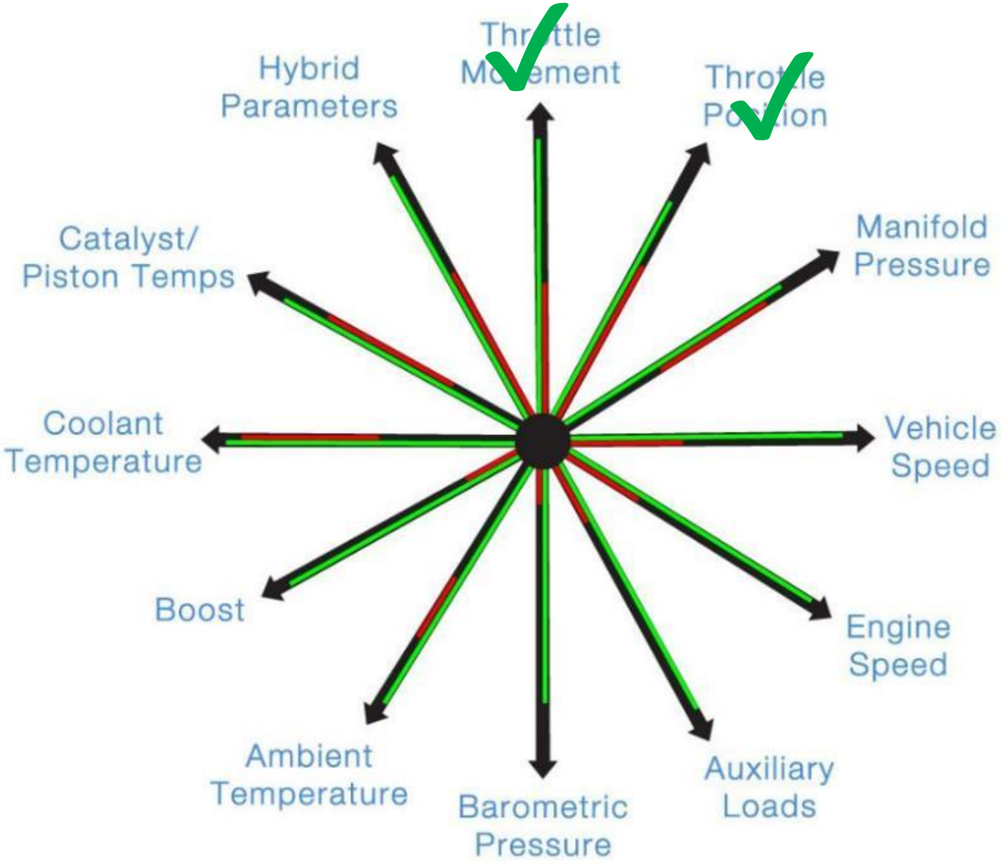
…….Throttle by Robot or by Wire



Powertrain Operational Space

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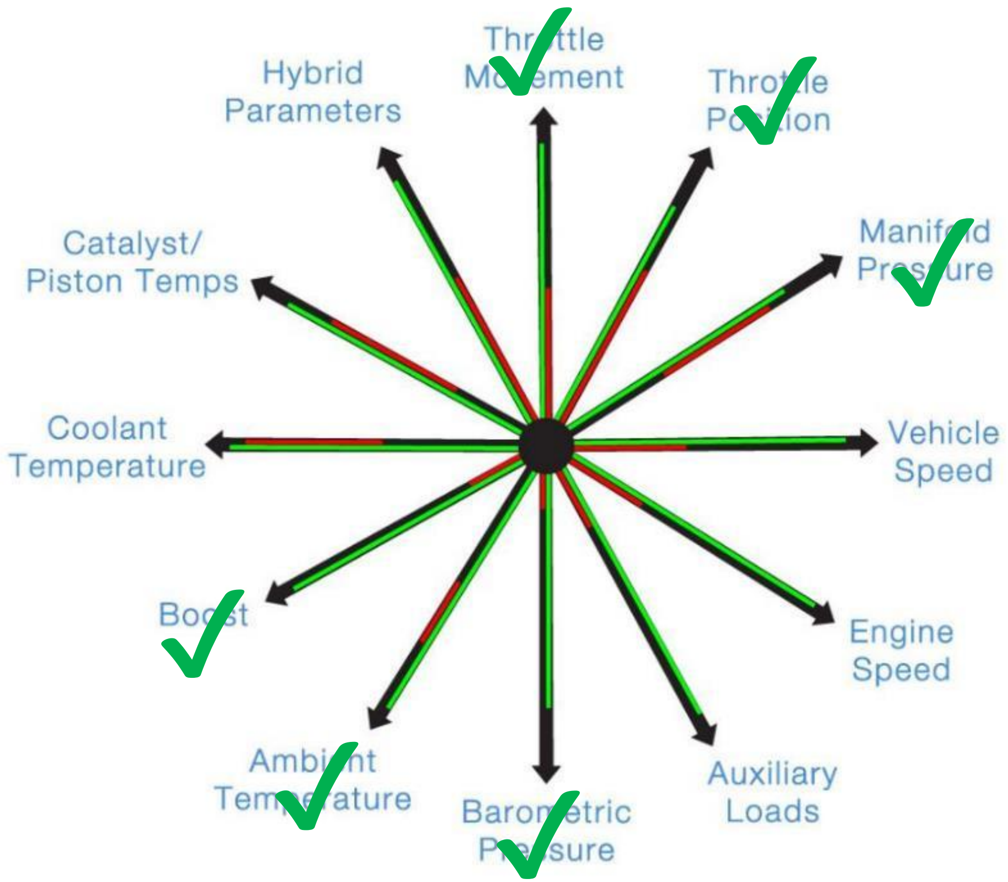
…….Ambient Conditions

RDE



Powertrain Operational Space

HORIBA MEDAS Altitude, Temperature and Humidity Emulator

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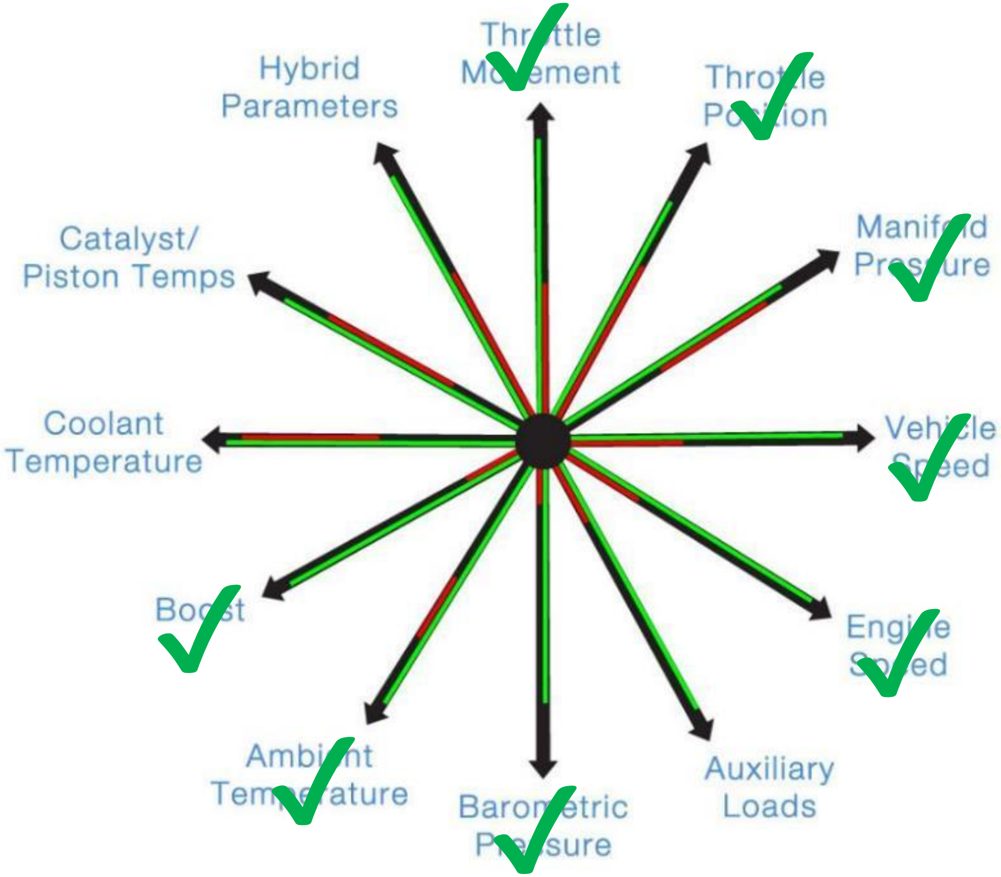
…….Vehicle or Engine Speed



Powertrain Operational Space

Chassis or Engine Dynamometer in Speed Control Mode

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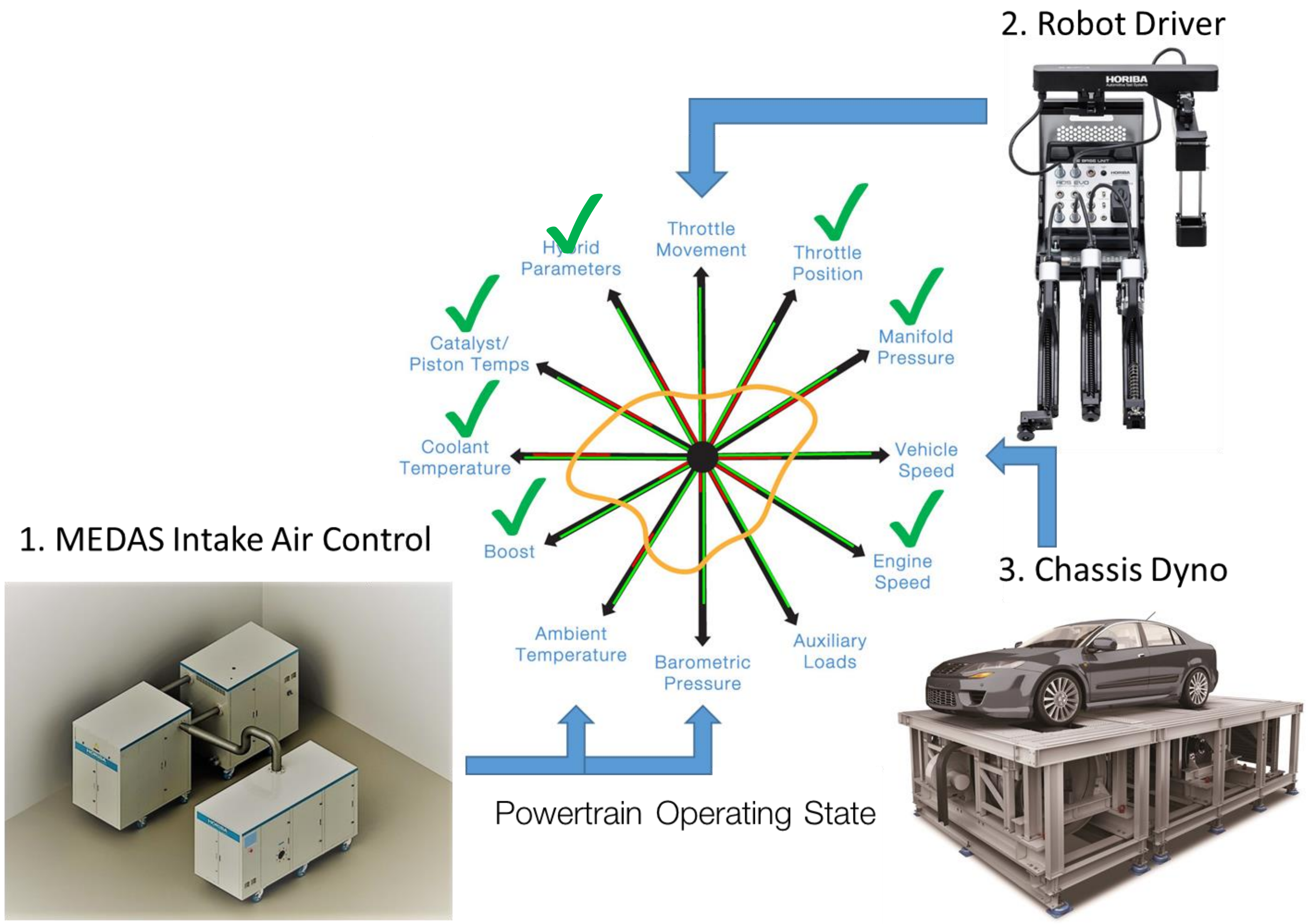
…….Other Parameters Follow



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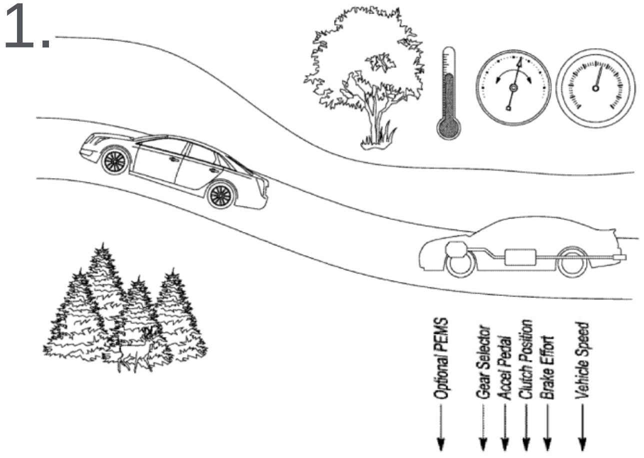
Summary of HORIBA Torque Matching (HTM)

RDE

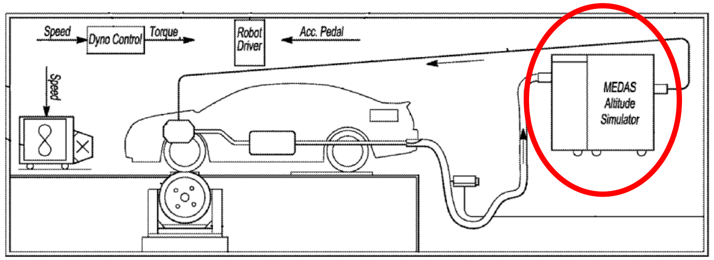
3 Steps to Precision Real-World Testing in the Laboratory Under Any Real-World Conditions

Road Test | **Lab Replication/Validation** | **Optional Lab Emulations**

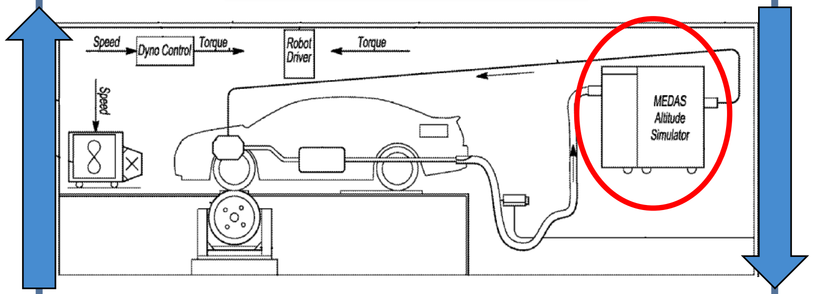
1.



2. REPLICATION



3. EMULATION



- Record velocity, pedal and ambient conditions
- Any road gradient, surface, weather, altitude and cornering

- MEDAS replicates ambient
- Dyno replicates velocity
- Robot driver replicates pedal or throttle
- Dyno torque recorded
- Emissions and load match road test

- MEDAS emulates ambient
- Dyno replicates <u>velocity</u>
- Robot driver replicates <u>dyno torque</u>
- Change engine calibration or emissions controls as desired and repeat
- Emissions and load match road test if run

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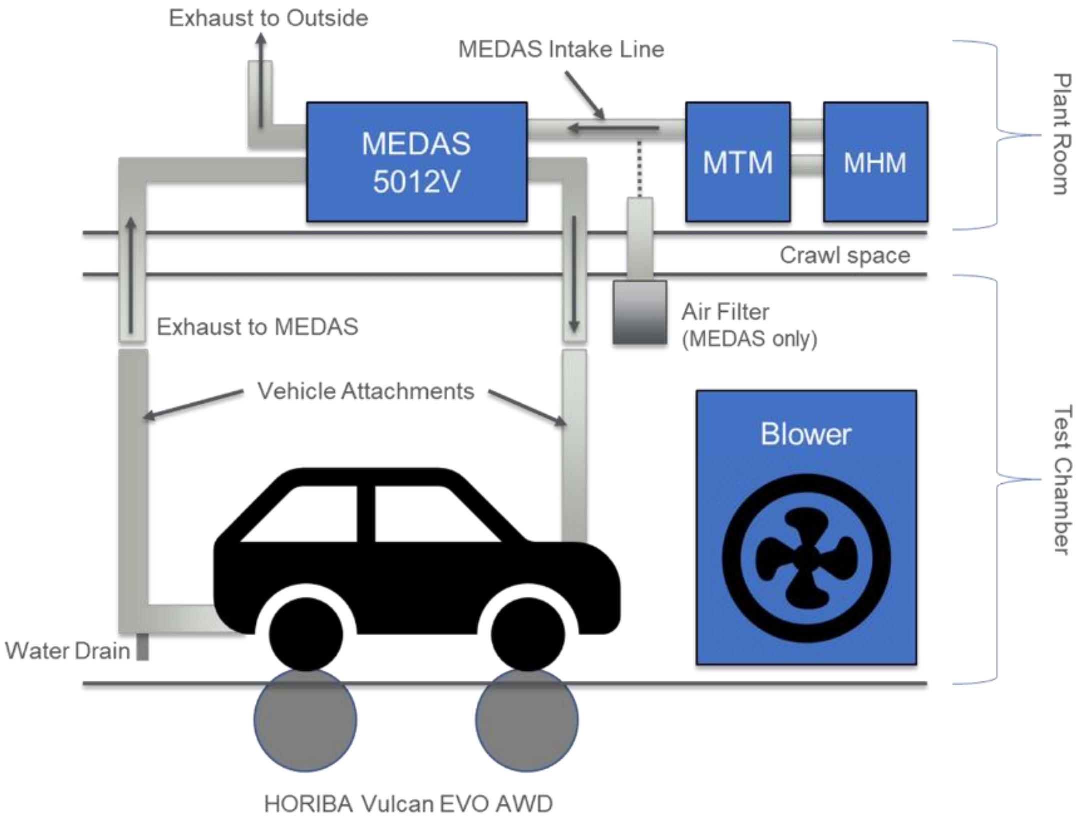
MEDAS Altitude Replication or Emulation

Multi-function **E**fficient **D**ynamic **A**ltitude **S**imulator with Humidity and Temperature control modules (AETC)



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MEDAS Altitude Replication

- Results with MEDAS (dynamic altitude 500-800m)
- Innsbruck, Austria RDE, 87km, Hot Start, 0°C ambient temperature
- Gasoline vehicle (Euro 6b, TWC)
- x3 replication in RLR mode (drive to target velocity, use gradient control to generate known road load)

	Road Test	Replication Average	CoV (%)	Diff %	Fraction of Euro6
CO [g]	14.41	16.70	11.0*	16.08*	0.19
CO_2 [kg]	12.41	12.25	1.4	-1.25	N/A
NOx [g]	23.00	24.34	1.6	6.03	4.66**
PN [#]	1.5E+14	1.6E+14	4.2	8.13	3.06**
Work [MJ]	43.8	43.3	4.2	2.4	

* Equates to 0.16 vs 0.19 g/km, limit = 1 g/km,
** Euro6b vehicles well known for exceeding Euro6 limit in real world driving

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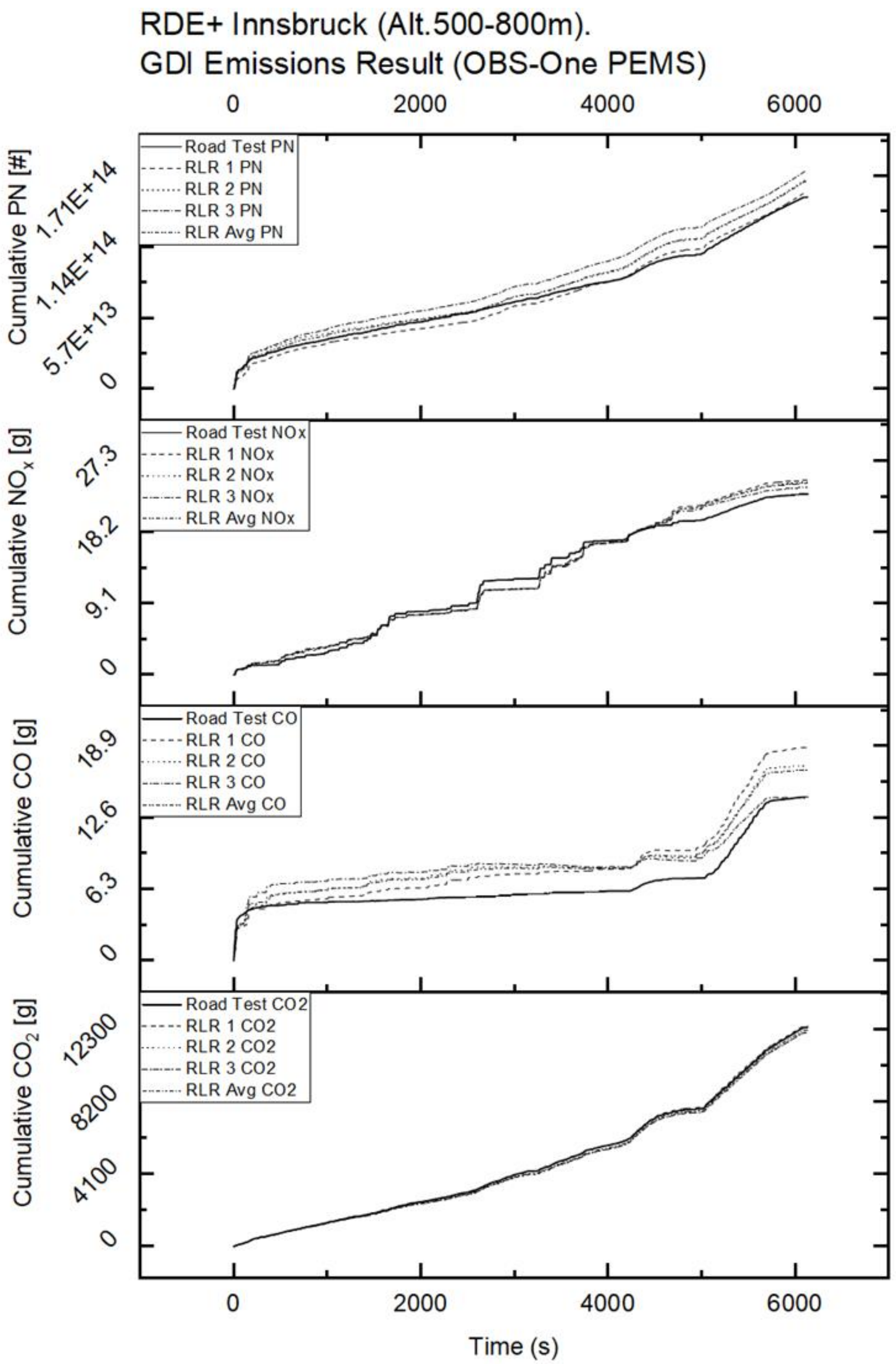
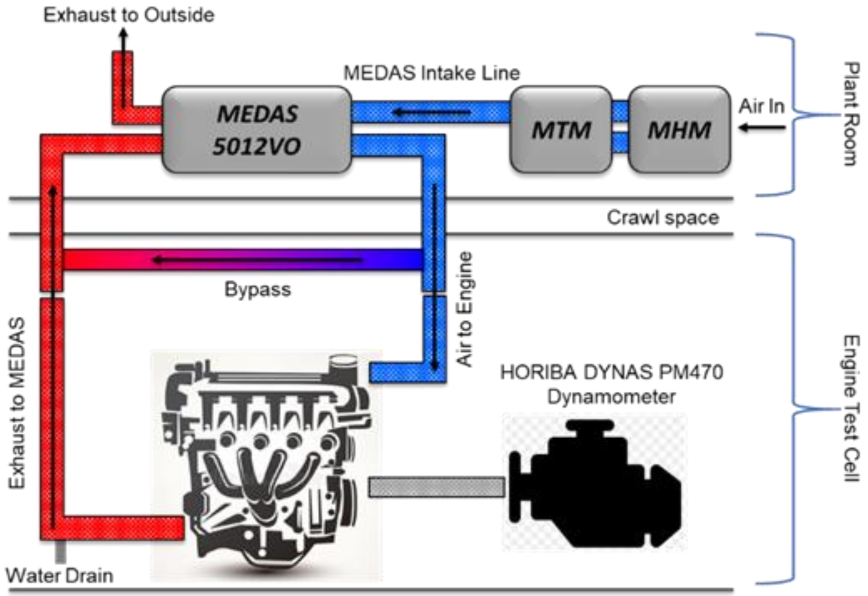
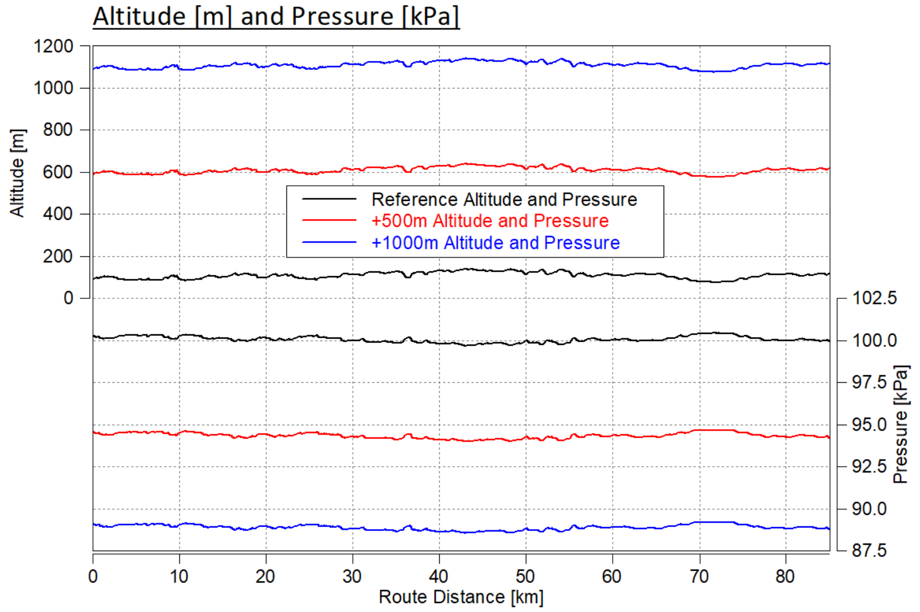


Environmental Emulation with MEDAS

- MEDAS control is linked to pressure, temperature and relative humidity vs. route distance within CarMaker.
- Allows different pressure, temperature and humidity profiles to be scheduled for the same route.
- For example, the sea-level Nuneaton, UK RDE route can be offset by 500, 1000m and 2000m with the corresponding pressure delivered to the engine, ECU, and tailpipe.
- Hot/cold thermal engine encapsulation is being added for emulating under-bonnet conditions.





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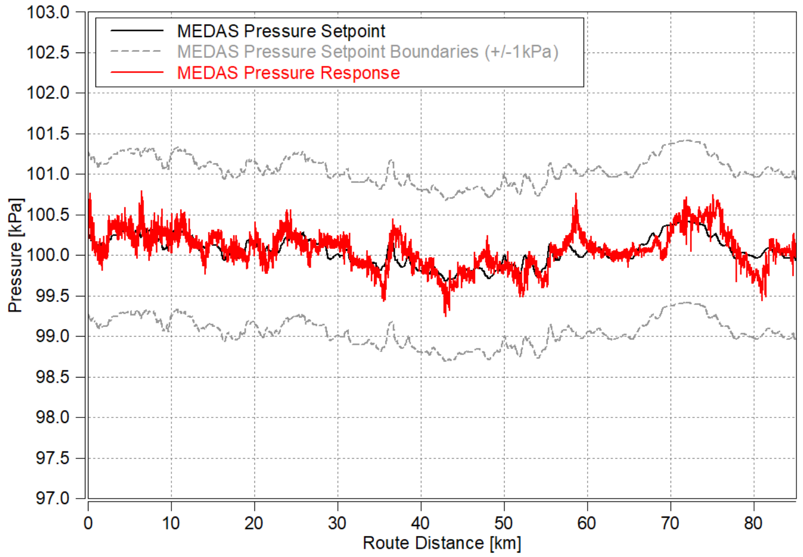
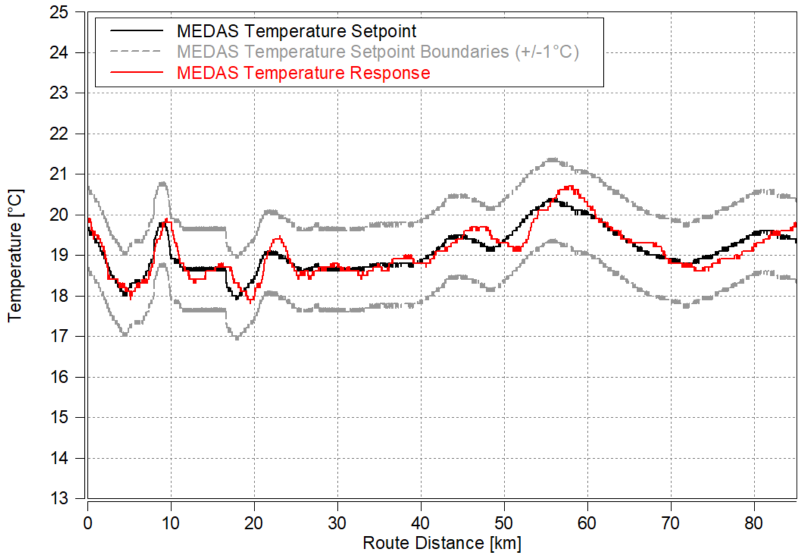
Environmental Emulation with MEDAS

- Very good control of pressure, temperature and relative humidity for the baseline Nuneaton profile (and profiles at +500m, +1000m and +2000m).
- These “sea-level” environmental profiles were used for an investigation into the effects of driving style engine performance and emissions.

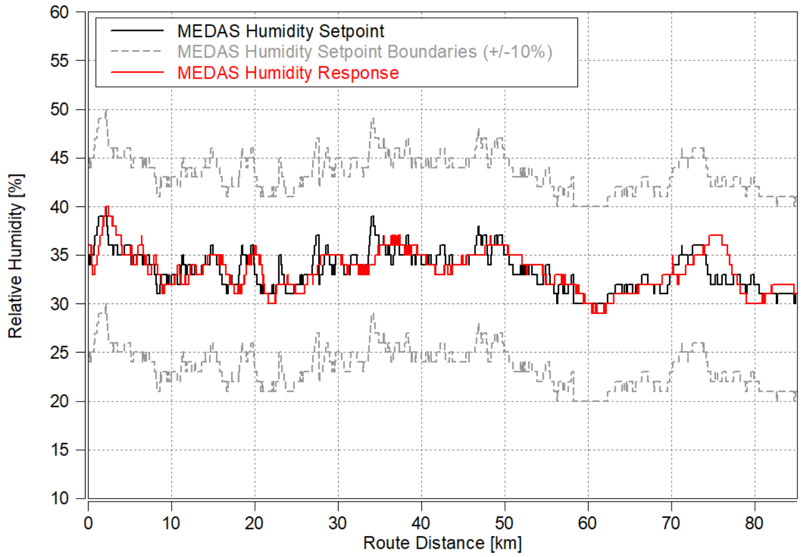
MEDAS Pressure Performance



MEDAS Temperature Performance



MEDAS Humidity Performance



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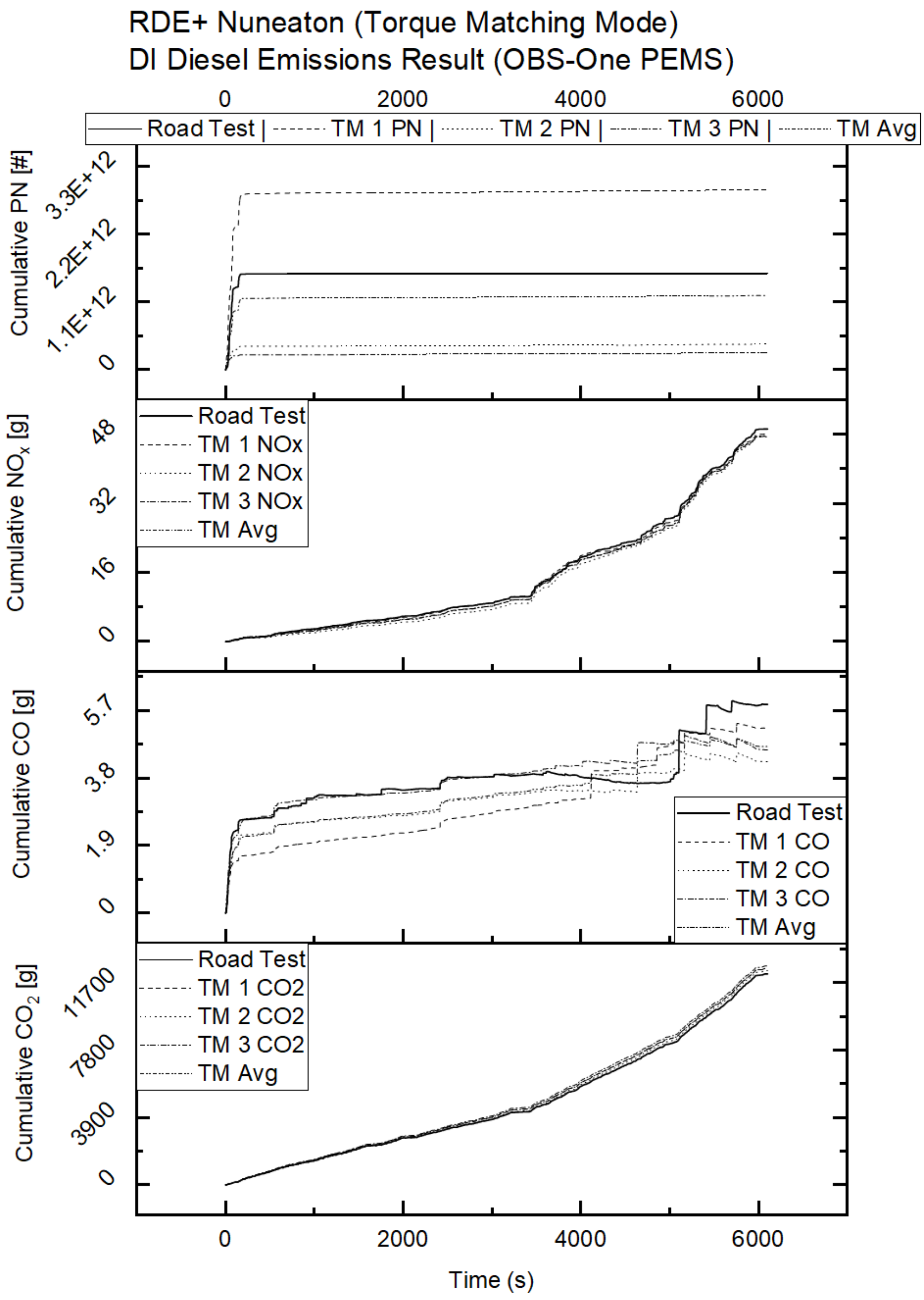
Chassis Dyno Torque Matching

- Nuneaton, UK, 85km, Gentle Driver, Cold Start, 10°C, 90% RH
- Diesel vehicle (Euro 6b, DPF + LNT)
- x3 replication

	Road Test	Replication Average	CoV (%)	Diff %	Fraction of Euro6
CO [g]	5.87	4.75	8.4	-19.0*	0.11
CO_2 [kg]	12.2	12.37	0.8	1.1	NA
NOx [g]	49.3	47.1	0.5	-4.4	9.23**
PN [#]	1.6E+12	1.2E+12	**100***	-23*	2.35
Work [MJ]	49.96	49.09	1.2	-1.75	-
Dyno [MJ]	-	42.23	0.5	-	-
Fuel [L]	4.4	4.46	0.6	1.7	-

* High diff/variation. PN result is 14E9/km, and spans just 2-3% of the allowed Euro 6b Limit (6e11/km)
* CO represents approx. 10% of the Euro 6b limit (0.5g/km)
** Euro6b vehicles well know to exceed euro6 NOx limit in real world driving



Torque Matching Lab Replication – Single Test

OBS ONE Emissions	Road Test (23°C)	HTM Mode (23°C)	Diff %
CO [g]	73.17	72.11	-1.45
CO_2 [kg]	15.11	15.09	-0.13
NOx [g]	22.26	23.86	7.19
PN [#]	2.0E+14	1.8E+14	-10.08
Work [MJ]	46.36	46.07	-0.63

Nuneaton, UK RDE Route, Test Cell Temperature Set to Real-World Temperature

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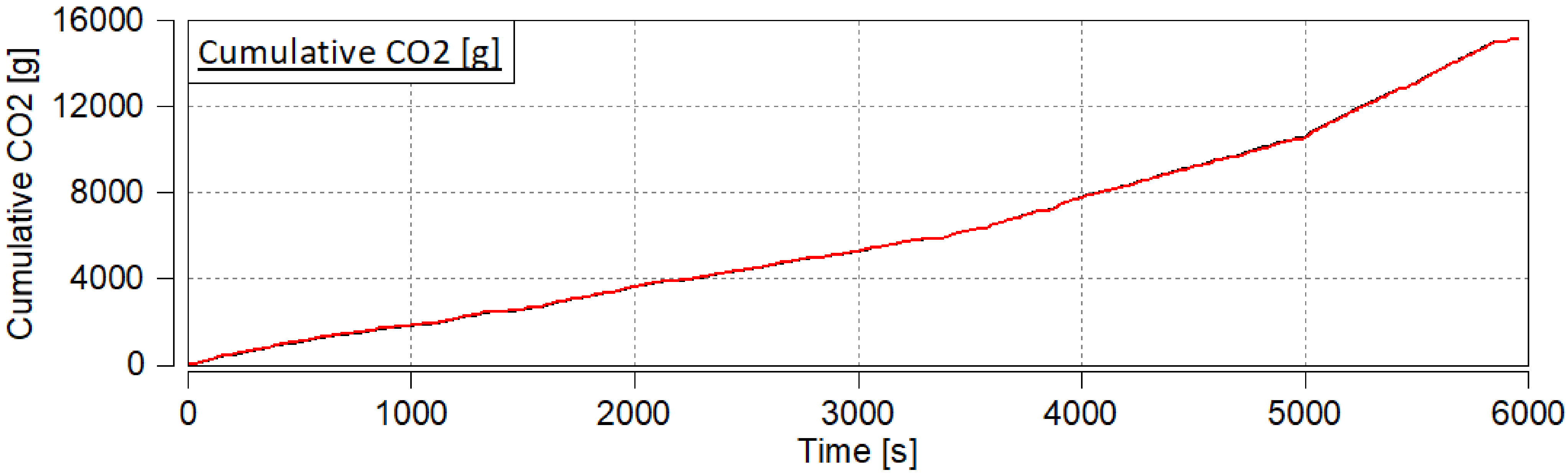
Torque Matching Lab Replication



Nuneaton, UK RDE Route, Test Cell Temperature Set to Real-World Temperature

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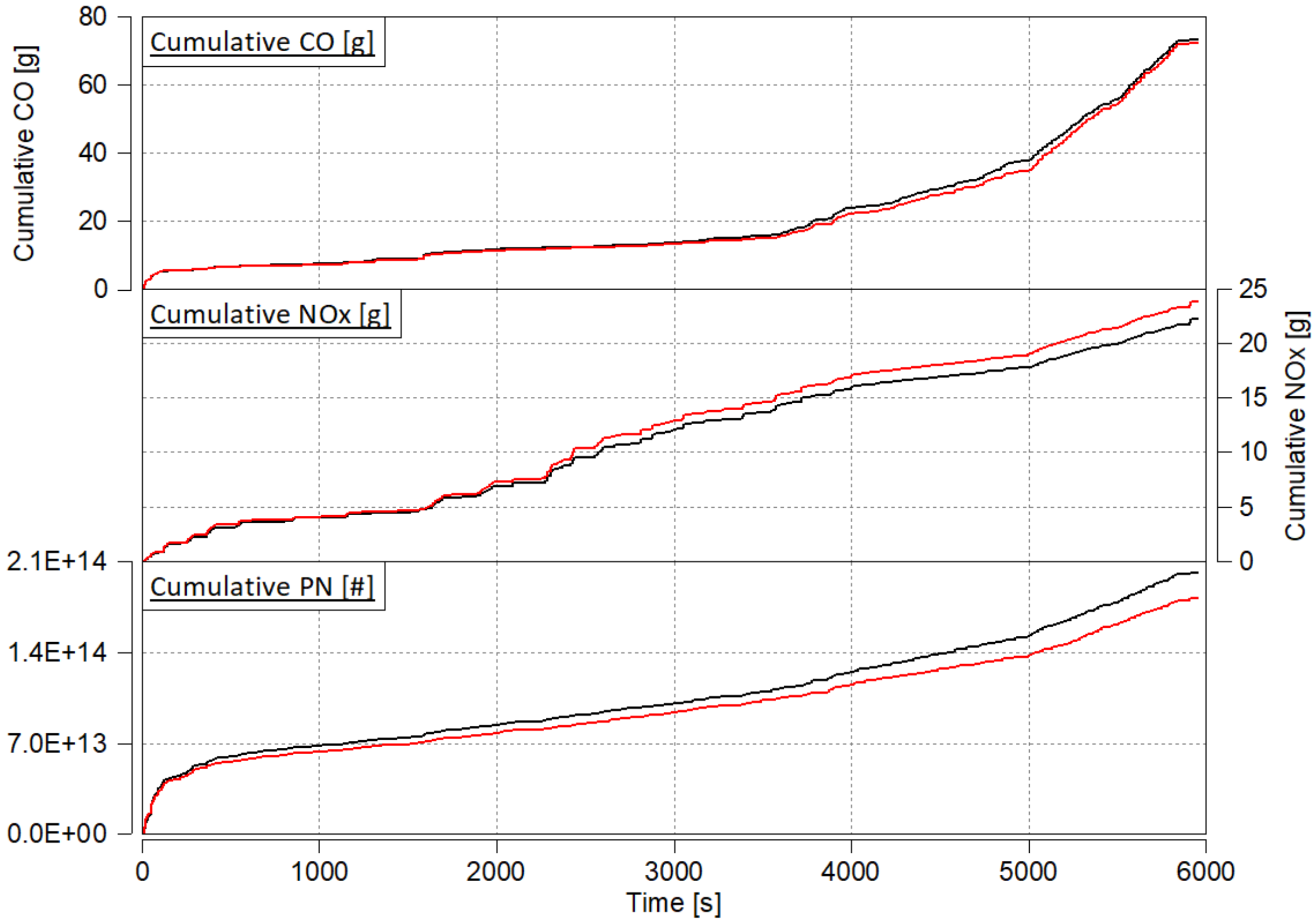
Torque Matching Lab Replication



Nuneaton, UK RDE Route, Test Cell Temperature Set to Real-World Temperature

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Some Practical HTM Benefits

RDE

	RLC	HTM
Road Grade Knowledge Not Required		✓
Coastdown Coefficients Not Required		✓
Immune to Dyno Load Errors From Changes in Road Surface Conditions		✓
Dynamic Barometric Chamber Pressure Not Required		✓
Dynamic Test Cell Temperature and Relative Humidity Control Not Required		✓
Real-World Wind Measurements and Dynamometer Load Compensation Not Required		✓

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RDE+ VIRTUAL

Dr. Phil Roberts

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Engine-in-the-Loop and Virtual Tools

Engine Testcell Specification

	Equipment
Analysers	MEXA ONE D2 EGR exhaust gas analysis system OBS ONE PEMS GS12 kit (gaseous and particle) MEXA-2100SPCS Real Time Particle Counter MEXA ONE QL NX Quantum cascade laser system (NOx speciation)
Test Cell	HORIBA DYNASPM LI 470 AC Dyno Hot and cold box (engine containment) -30°C to HORIBA MEDAS, MTM and MHM
Misc	AVL Indicom X-Ion high-speed data acquisition ETAS INCA HORIBA STARS SPARC HORIBA STARS Calibrate IPG CarMaker

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Engine-in-the-Loop and Virtual Tools

Engine-in-the-Loop Setup

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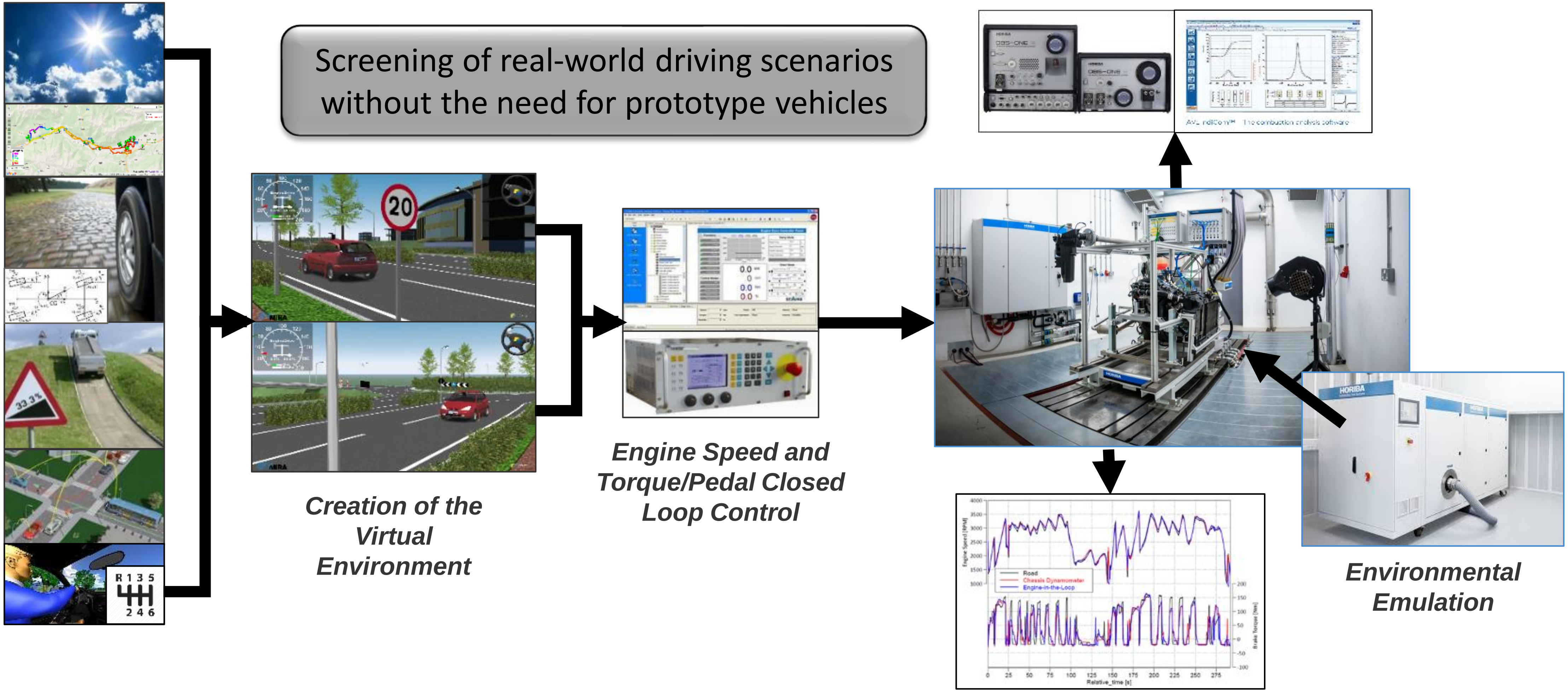

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Engine-in-the-Loop and Virtual Tools
Virtual Aspects (1)

RDE

- IPG CarMaker is used as the virtual toolset.
- Flexible approach allowing:
  - Configurable driver
  - Virtual routes and traffic scenarios
  - Environments
  - Model interfaces (Simulink, GT-SUITE etc)
- Used in two formats currently:
  - CarMaker Office (simulation)
  - CarMaker Testbed (simulation + hardware)
- Importantly, Office and Testbed simulation environments are equivalent.
- Results in equal Office and Testbed cycle metrics.

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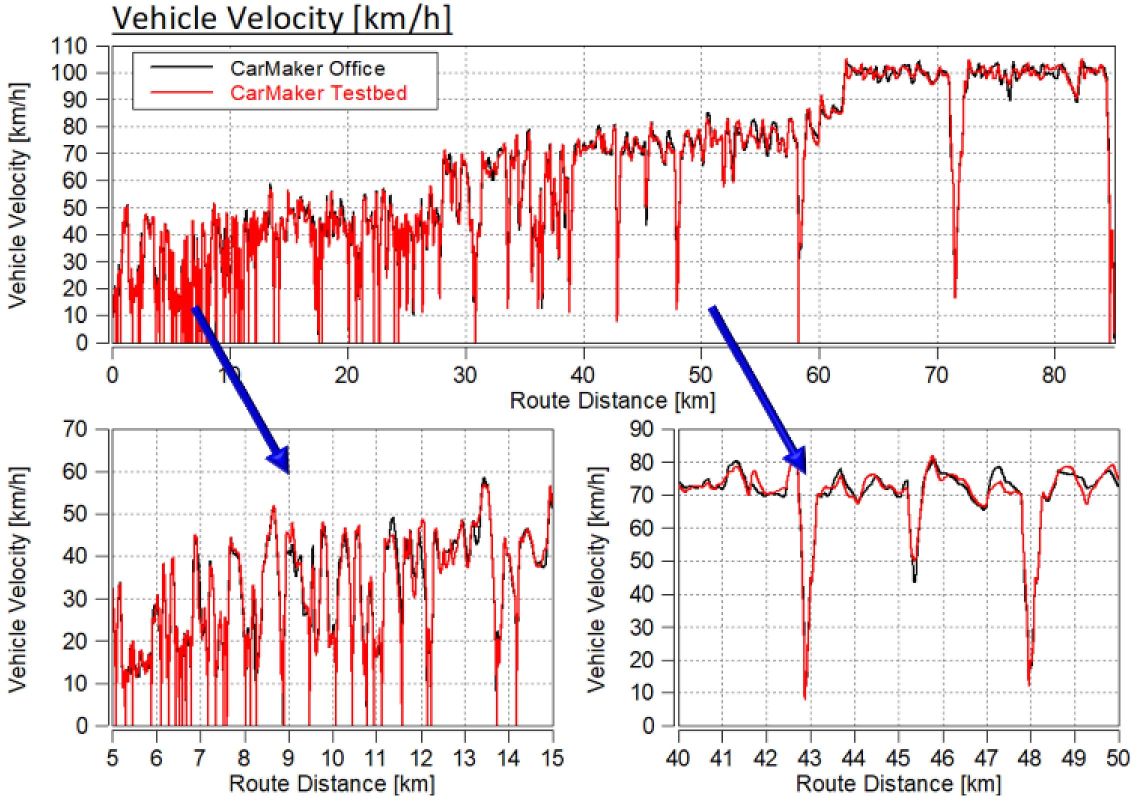
Engine-in-the-Loop and Virtual Tools

Virtual Aspects (2)

- CarMaker Office (simulation only) vs. CarMaker Testbed (simulation + hardware)
- Identical RDE route (Nuneaton, UK), vehicle (B-segment) and driver models
- Addition of engine with CarMaker Testbed runs.

RDE Cycle Metric	CarMaker Office	CarMaker Testbed
Urban distance [km]	35.6	35.9
Urban distance share [%]	41.9	42.2
Urban va_pos[95] [m²/s³]	11.6	11.5
Rural distance [km]	28.5	28.1
Rural distance share [%]	33.5	33.0
Rural va_pos[95] [m²/s³]	16.4	17.5
M'way distance [km]	21.0	21.1
M'way distance share [%]	24.7	24.8
M'way va_pos[95] [m²/s³]	12.1	12.4
Cycle va_pos[95] [m²/s³]	12.4	12.6
Cycle va_pos[95] % limit [%]	60	61
Test time [mins]	114.6	115.1
Urban stop time share [%]	8.2	8.3
Urban average velocity [km/h]	27.2	27.1
Time > 100km/h M'way [mins]	6.5	7.0



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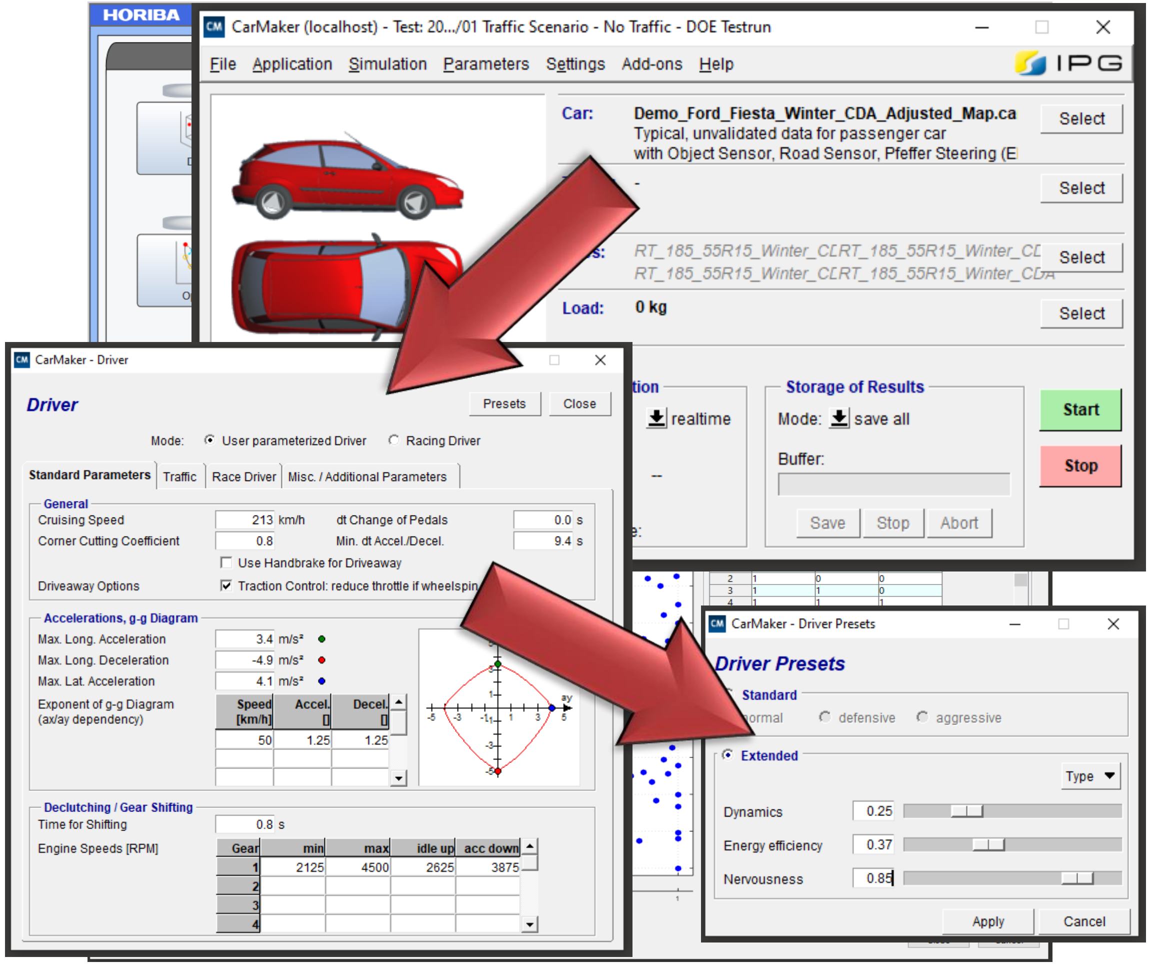
Engine-in-the-Loop and Virtual Tools

Driver Parameterisation

- CarMaker Office and Testbed equivalency allows the driver model to be parameterised within the Office environment.
- Current default CarMaker driver models do not adhere to HORIBA’s definition of driving style.
- To parameterise the model to HORIBA’s standard, HORIBA STARS Calibrate DoE toolset was used.
- Extended Driver Presets within CarMaker were varied according to the DoE test points generated.
- 100 different combinations of Extended Driver Presets run within CarMaker Office (per route).
- 5 hours computational run-time time.
- Minimum of 150 hours physical engine runtime would otherwise be required.



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Engine-in-the-Loop and Virtual Tools

Results: Decoupling Driver and Traffic Effects

RDE

VARY DRIVING STYLE FIXED TRAFFIC

Moderate Density

Nuneaton, UK, RDE R

Fixed Altitude, Temperature and

Fixed Vehicle Model

Vary Driving Style

60, 70, 80, 90% va_pos[95] % of the cycle limit

VARY TRAFFIC FIXED DRIVING STYLE

70% va_pos[95] % of cycle limit driver

eaton, UK, RDE Route

mperature and Humidity Profiles

Fixed Vehicle Model

Vary Traffic Density

No Traffic, Light, Moderate and Heavy

This would be almost impossible to achieve with road testing alone!

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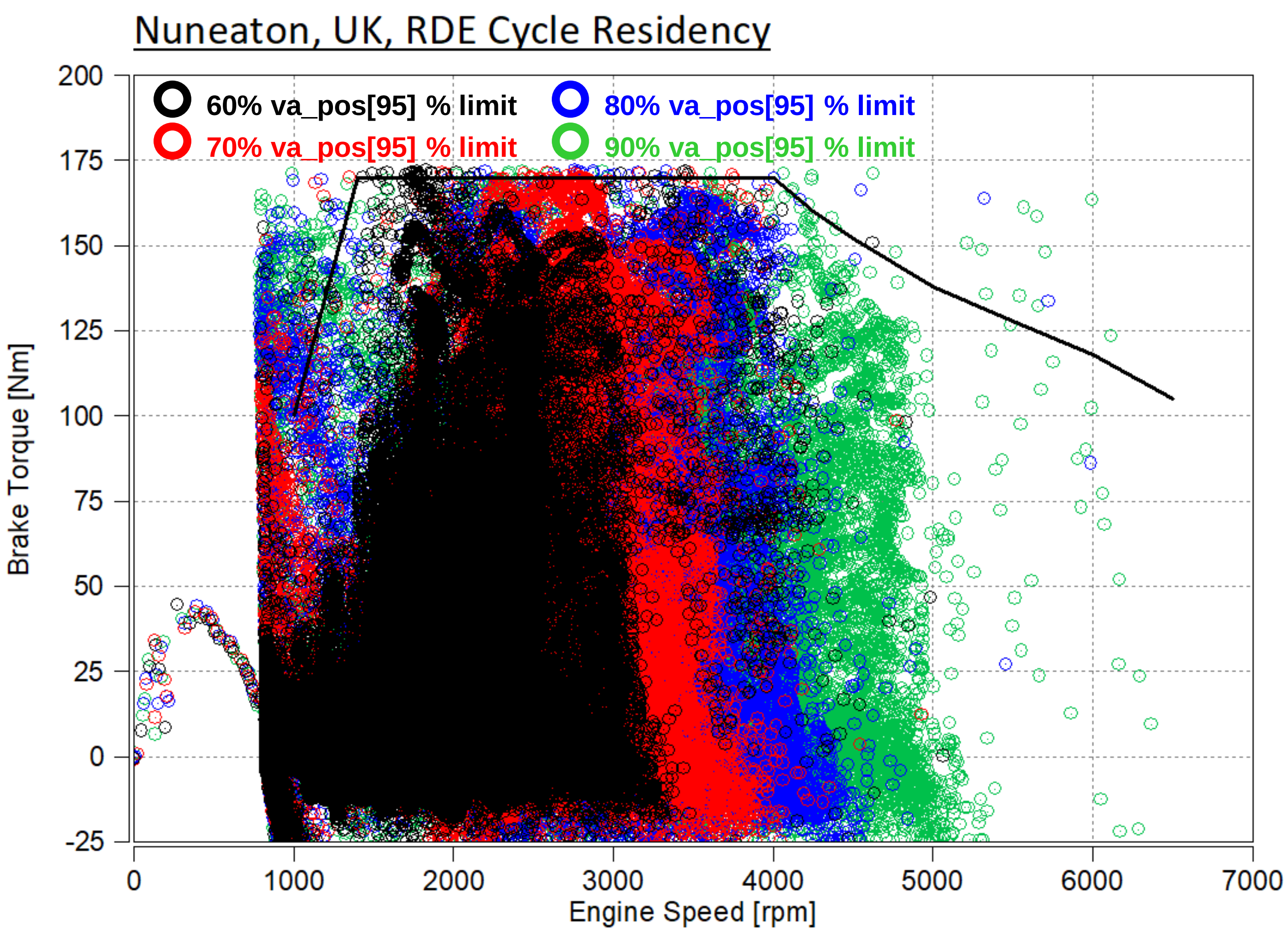
Engine-in-the-Loop and Virtual Tools

Results: Fixed Traffic Density, Altered Driver Dynamics (1)

- Engine speed and load range is extended with more aggressive driving.
- Average cycle power increased as driver aggressivity increased: 8.7, 10.8, 13.2 and 15.1kW.
- Engine starts to operate within areas that require Auxiliary Emissions Systems (AES); these systems will likely have to be declared.
- The most aggressive driving here is non-typical. Importantly though, it is within the RDE regulations.
- Non-typical, but completely compliant scenarios, still need to be addressed however.



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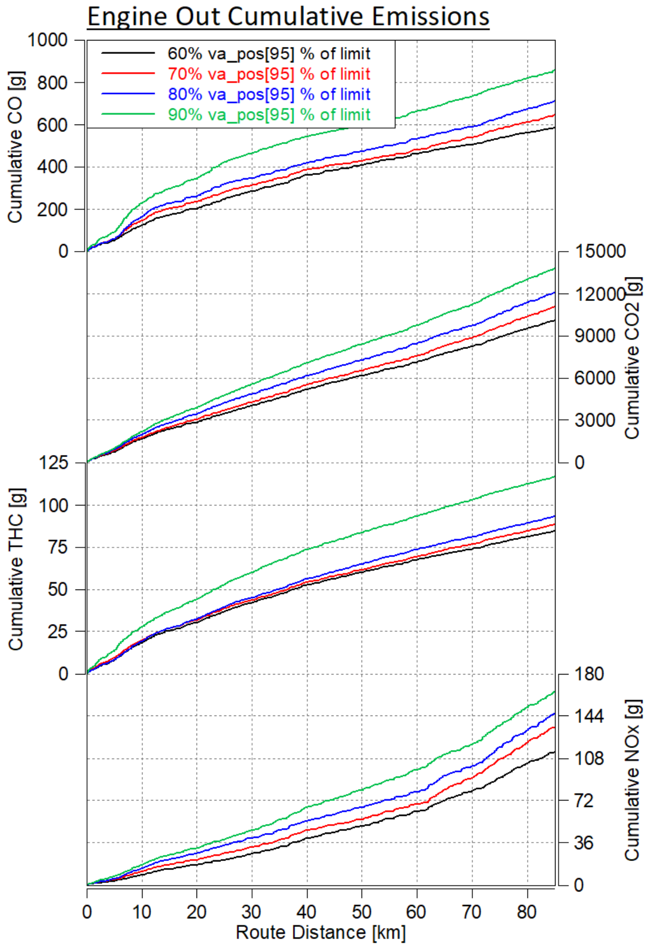
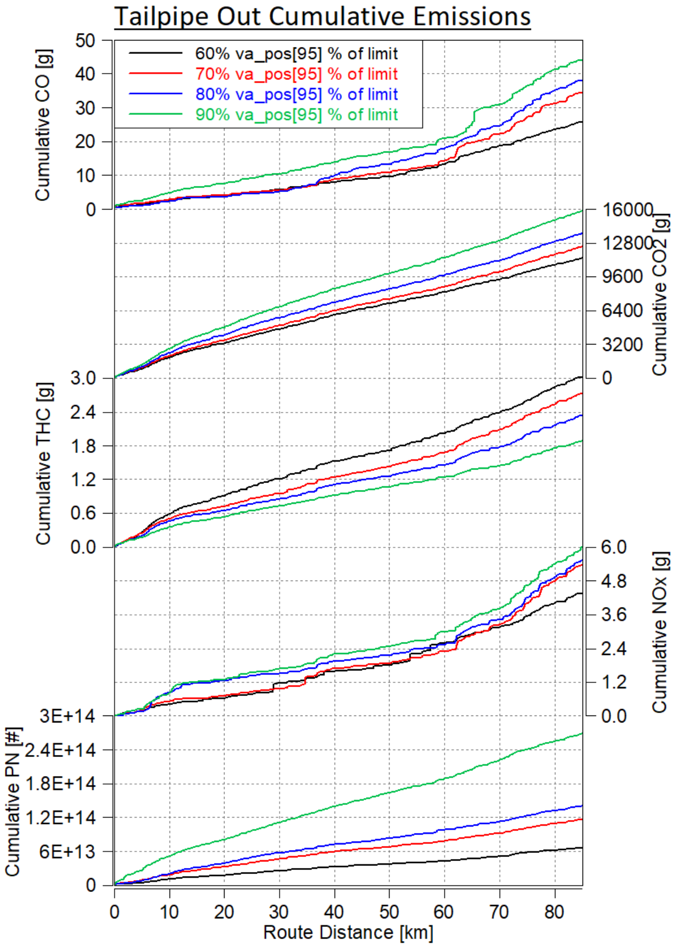
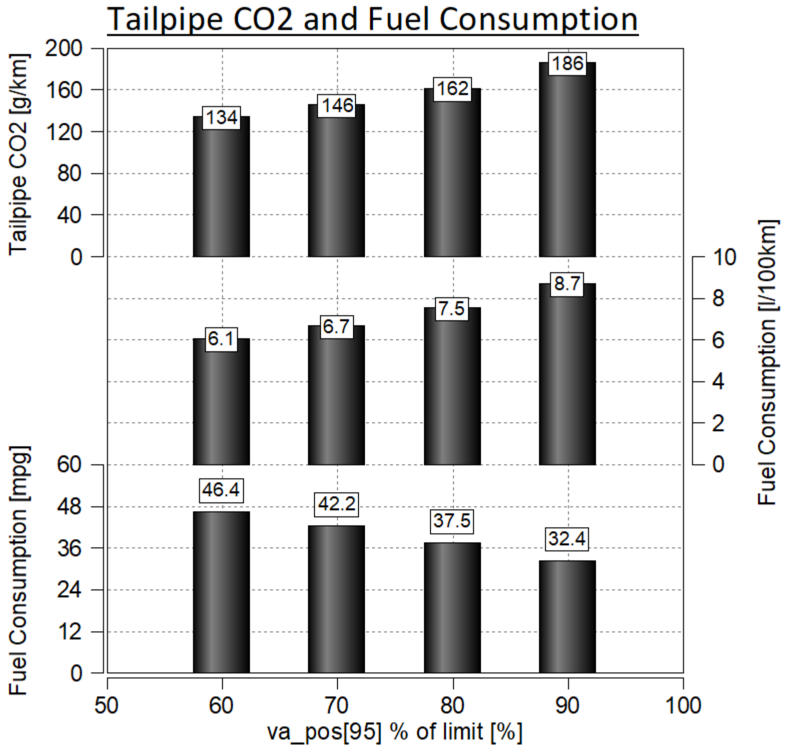
Engine-in-the-Loop and Virtual Tools

Results: Fixed Traffic Density, Altered Driver Dynamics (2)







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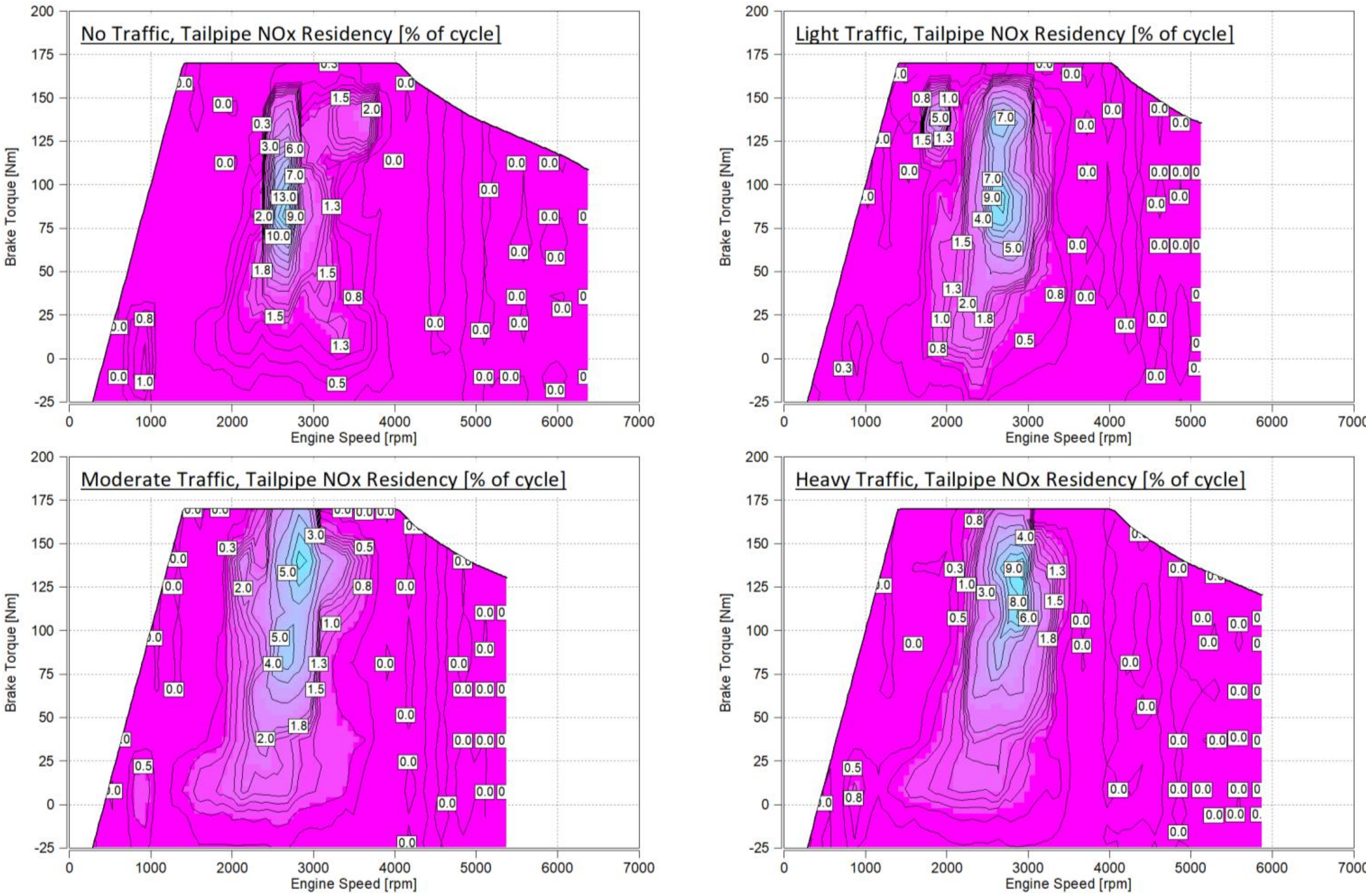
Engine-in-the-Loop and Virtual Tools

Results: Fixed Driver Dynamics, Varied Traffic Density (1)

- **Fixed driving style, varying traffic – NOx Residency.**
- Overall metric used to define cycle driving style (va_pos[95] % of limit) was equal for each traffic density tested.
- However, urban, rural and motorway dynamics were very different; thereby very difficult to decouple driving style and traffic effects in this case.
- Nevertheless, all cycles were still RDE compliant and highlight spread in tailpipe out emissions for different traffic densities.



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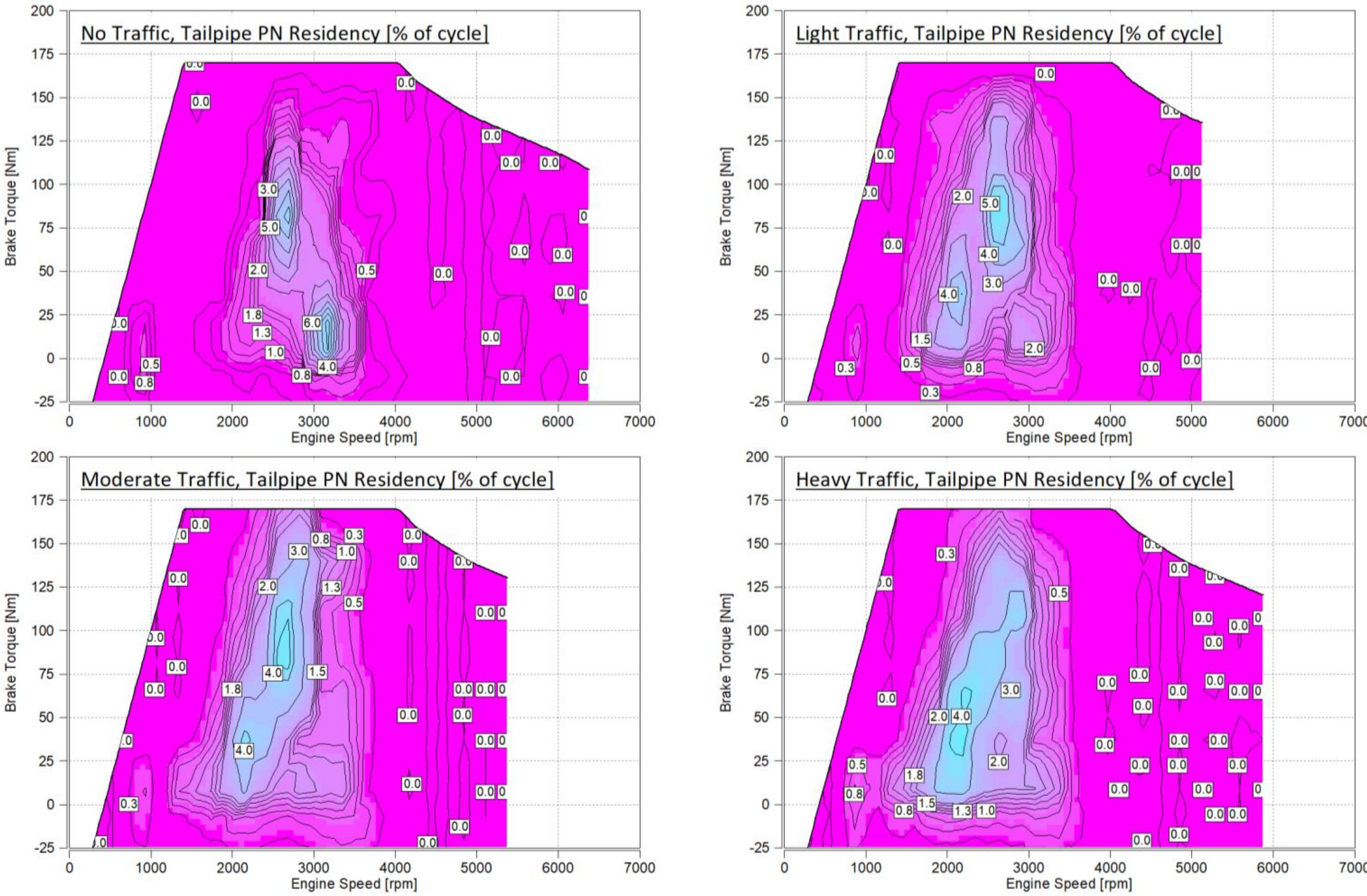
Engine-in-the-Loop and Virtual Tools

Results: Fixed Driver Dynamics, Varied Traffic Density (2)

- **Fixed driving style, varying traffic – PN Residency.**
- Overall metric used to define cycle driving style (va_pos[95] % of limit) was equal for each traffic density tested.
- However, urban, rural and motorway dynamics were very different; thereby very difficult to decouple driving style and traffic effects in this case.
- Nevertheless, all cycles were still RDE compliant and highlight spread in tailpipe out emissions for different traffic densities.



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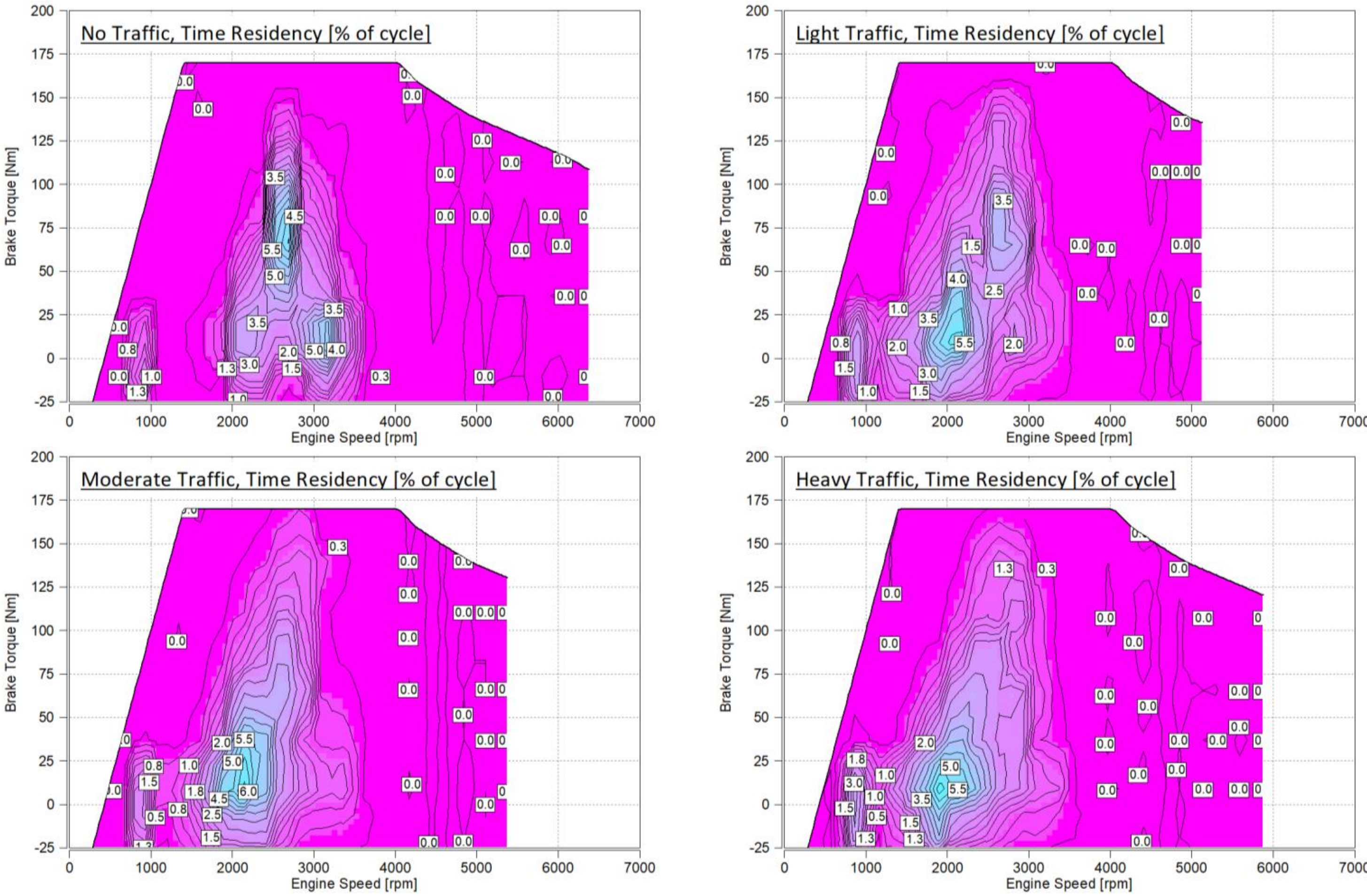
Engine-in-the-Loop and Virtual Tools

Results: Fixed Driver Dynamics, Varied Traffic Density (3)

- **Fixed driving style, varying traffic – Time Residency.**
- Overall metric used to define cycle driving style (va_pos[95] % of limit) was equal for each traffic density tested.
- However, urban, rural and motorway dynamics were very different; thereby very difficult to decouple driving style and traffic effects in this case.
- Nevertheless, all cycles were still RDE compliant and highlight spread in tailpipe out emissions for different traffic densities.



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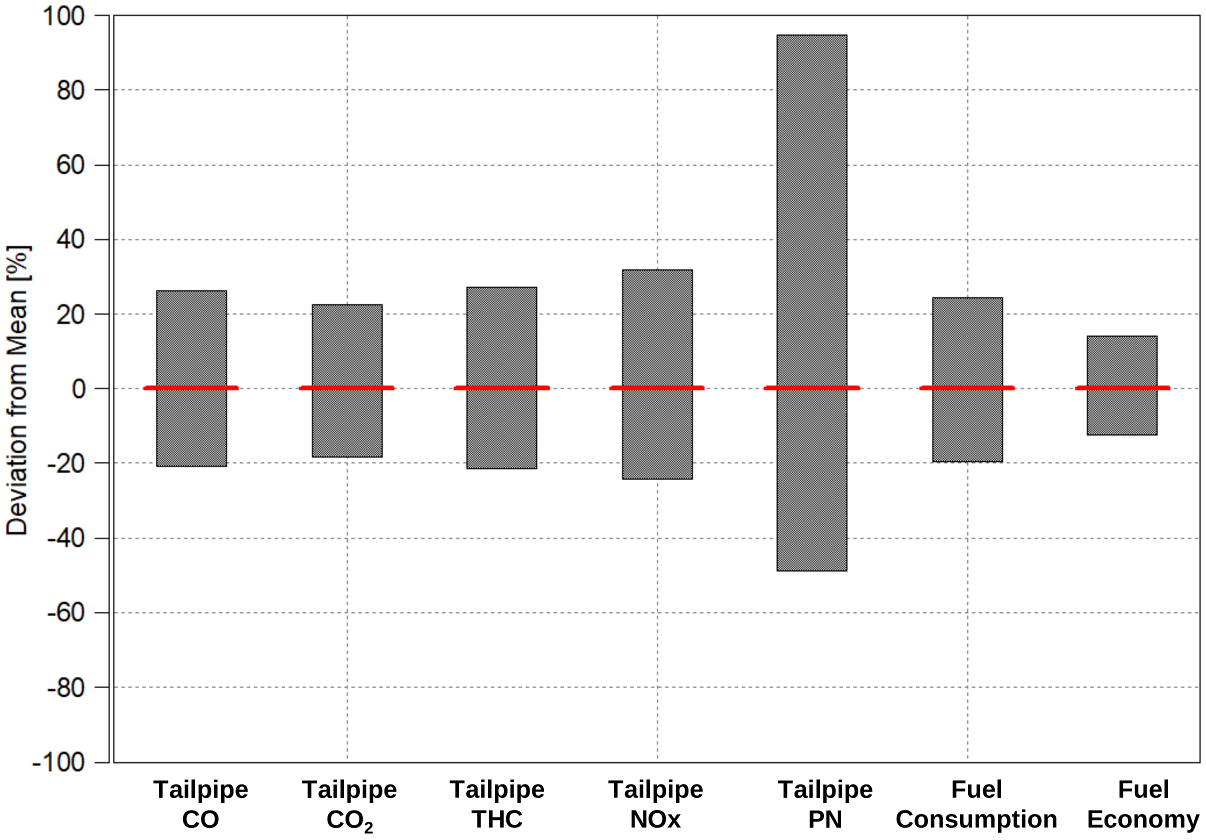
Engine-in-the-Loop and Virtual Tools

Results: Overview

- Emissions spread from mean tailpipe emissions for all test concluded thus far.
- All cycles tested adhere to RDE regulations.
- Significant spread in emissions for one RDE route; this spread is likely to increase when other routes are tested with the same powertrain and vehicle.
- OEMs will need robust calibrations to ensure emissions limits are not compromised when the vehicle is tested at the moderate and extended boundary conditions.
- Similar testing is taking place using the Innsbruck, Austria RDE route and MEDAS for environmental emulation.



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Engine-in-the-Loop and Virtual Tools

RDE

- Allows driving scenarios to be screened at faster than real-time and cycle metrics calculated without the need for physical hardware.
- Ensures scenarios (RDE or other) are “compliant” with regulations without the need for physical testing.
- The powertrain and/or vehicle is physically tested to resolve performance and emissions using completely compliant scenarios.

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RDE+

SMART SOLUTIONS FOR CLEANER AIR

RDE+ VIRTUAL Advanced R&D

Kunio Tabata

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HORIBA

HORIBA's RDE solution will be developed for PHEV RDE with focus on EiL-based approach with PHEV system model

RDE+ POWER

EiL DESIGN / SPECIFICATION

Road / Environment

Driver

Vehicle

Transmission / Driveline

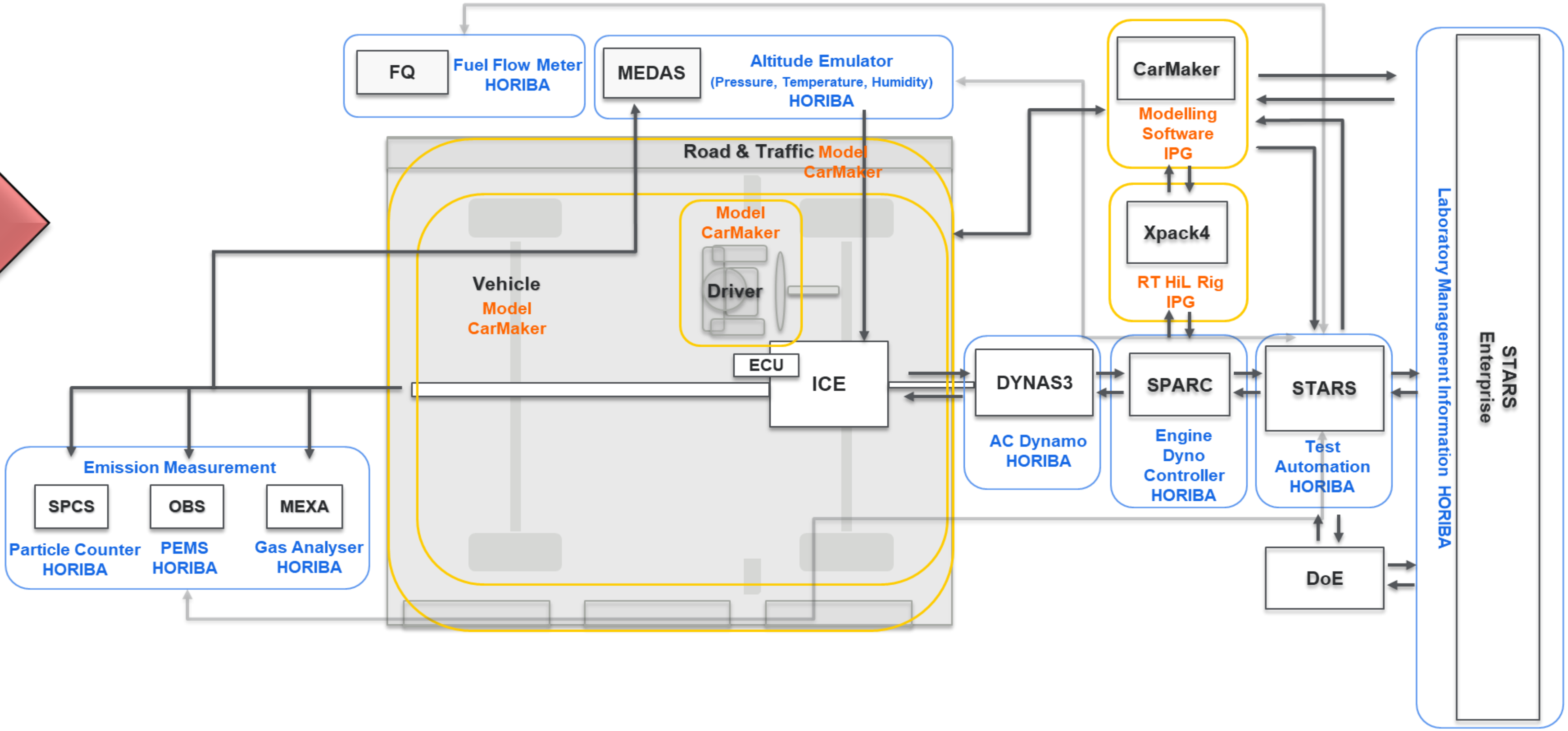
ECU

Engine

Aftertreatment

Virtual

Real



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HORIBA

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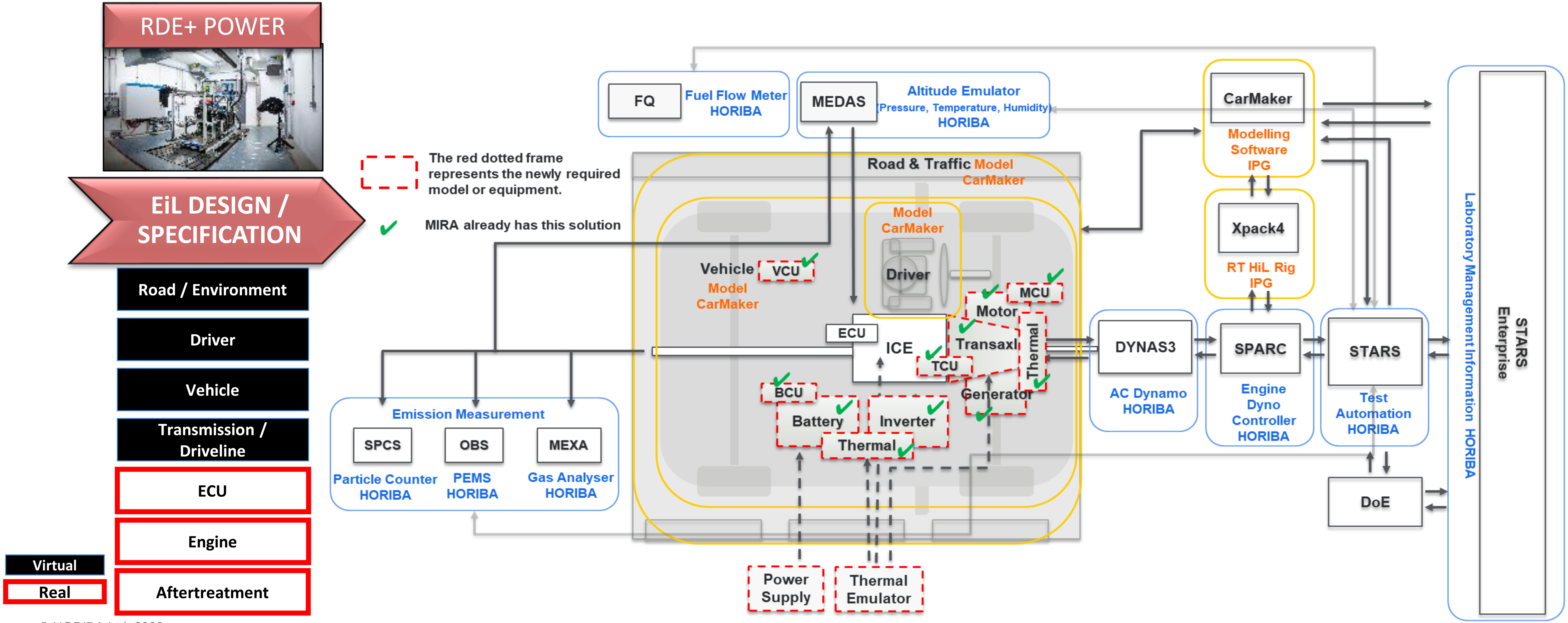

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CONCLUSIONS

Steve Whelan

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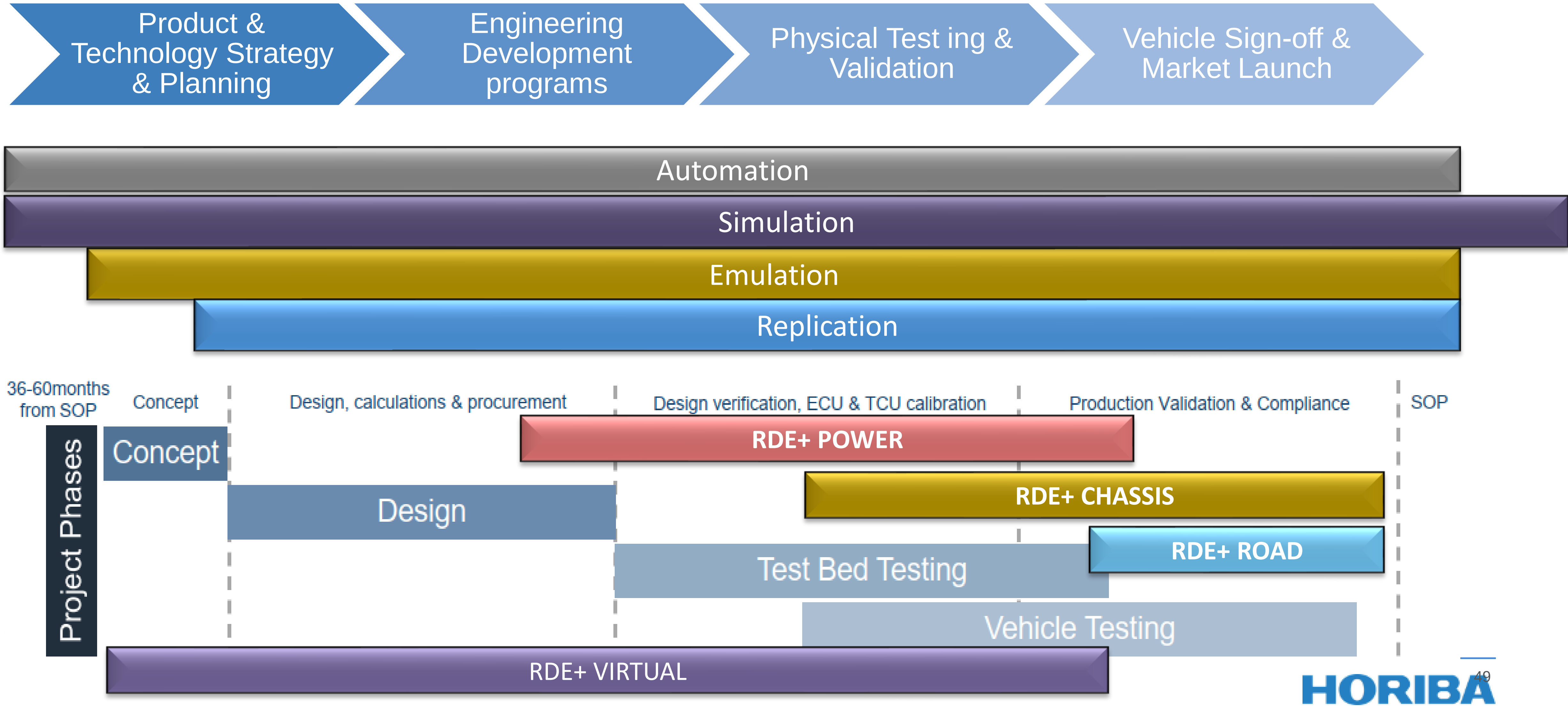
RDE+ can be applied throughout the whole powertrain programme, reducing time, costs and risk



RDE+

SMART SOLUTIONS FOR CLEANER AIR

REDUCED COST

- Fewer prototype vehicles and road tests
- Fewer environmental trips and tests – lower logistic costs
- Improved testing productivity
- Front-Loading reduces costs in later phases
- Lower cost product

REDUCED TIME

- Front-Loading reduces subsequent development timescale
- Potential to eliminate a prototype phase
- De-couples environment testing from the seasons
- Fewer on-road vehicle tests / fewer chassis tests

REDUCED RISK

- Front-loading delivers early confidence in design
- Better and earlier RDE optimisation prevents late changes to HW and SW in vehicle
- More thorough emissions optimization reduces risk of failure and non-compliance

REDUCED WARRANTY

- All components and sub-systems exposed and validated under real-world conditions throughout development
  - EATS / EGR / Turbo / Fuels and Lubes
- More thorough optimization reduces risk of failure

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RDE+
SMART SOLUTIONS FOR CLEANER AIR

THANK YOU.
NOW TIME FOR Q&A ....

Contact: RDEplus@horiba.com www.horiba.com/RDEplus

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