35th INTERNATIONAL CAE CONFERENCE AND EXHIBITION

THE ENGINEERING SIMULATION PATH TO DIGITAL TRANSFORMATION

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Engine Virtual Calibration Platform Using Physical Real-Time Integrated Models

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POWERTECH ENGINEERING

Introduction

- Control system development within the automotive industry is evolving rapidly due to three main drivers (in addition to the evergreen **cost-reduction**):

Regulatory Pressure

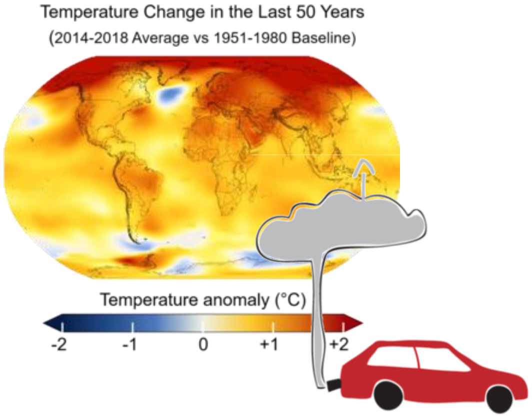
- Pollutants (EU6d w/ RDE)
- CO_2 emissions (CAFE)

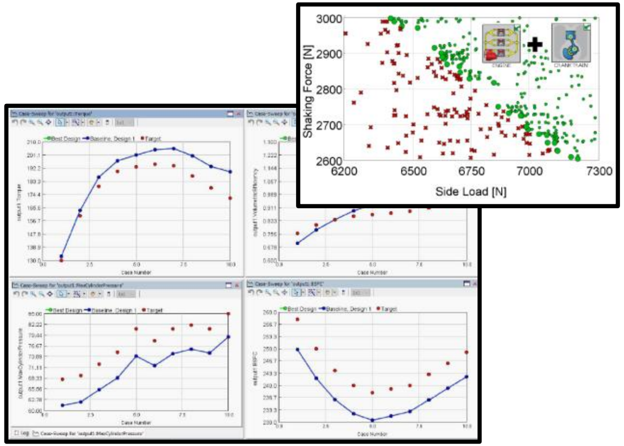
Shorter Time-to-Market

- Shorter lifecycle
- More differentiation

Control System Complexity

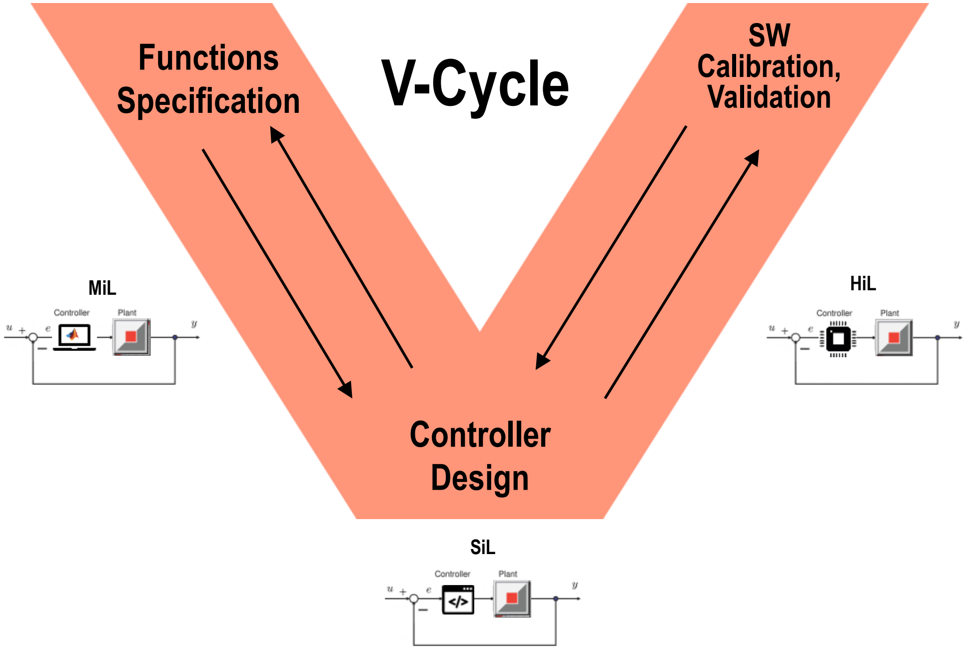
- Vehicle Electrification
- More DoFs



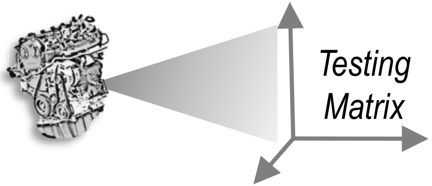


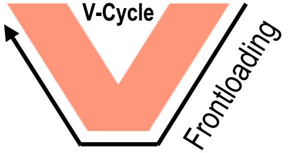
CAE in the Control Development

- **Virtualization** of the product development process (V-Cycle) becomes mandatory, **simulation** is used throughout to replace the plant (prototypes):



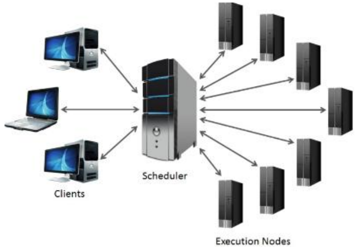
- Reduced need for (costly) experimental tests





- Control system development moved earlier in the process

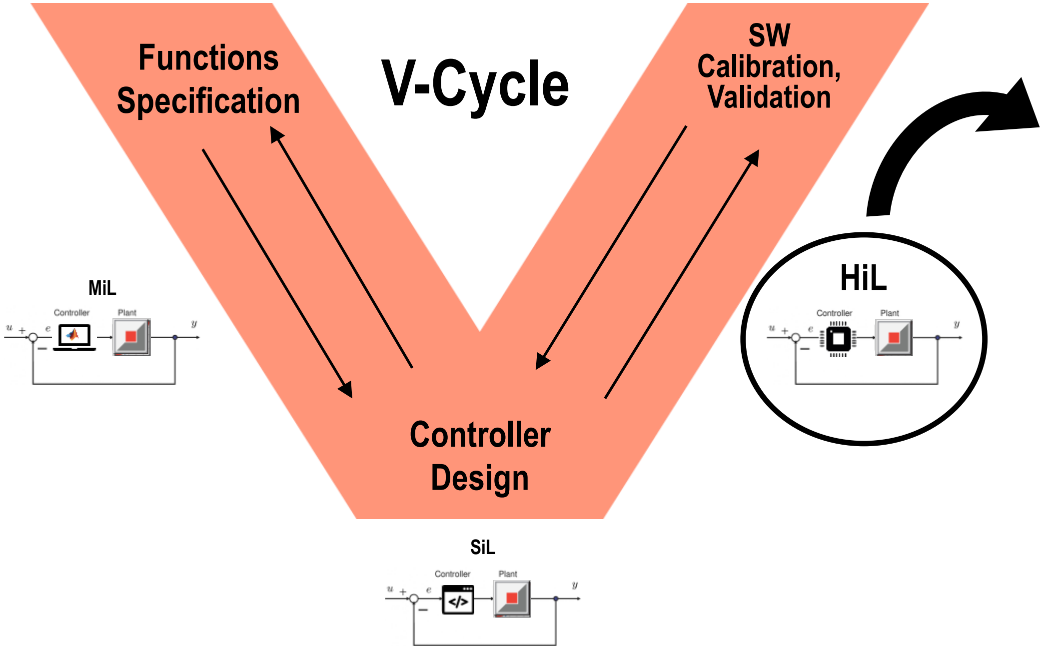
- Shorter lead time for DoEs, optimizations (scalability)

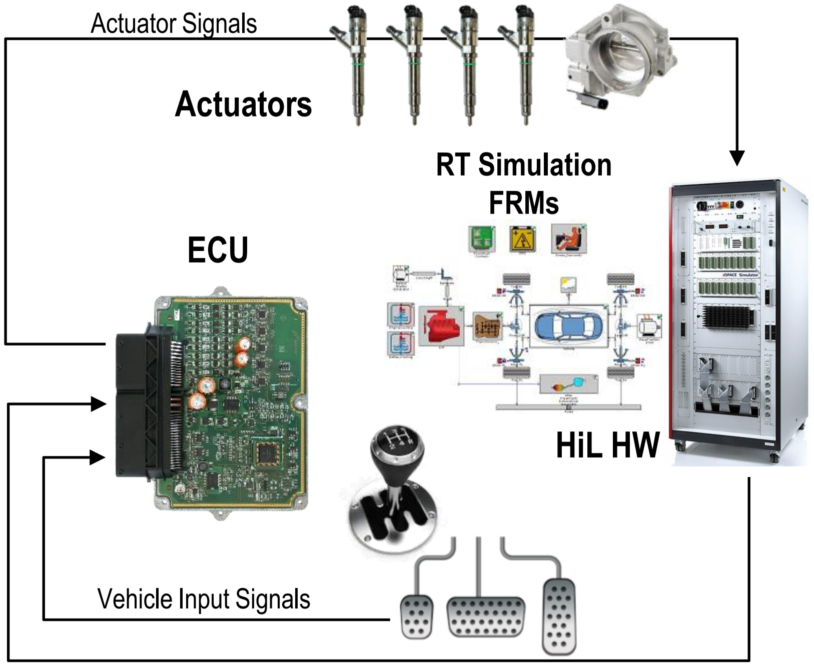


Hardware-in-the-Loop Simulations

- HiL is a fundamental enabler for control **Virtual Calibration** and **Validation**

  → SHORTER TIME-TO-MARKET



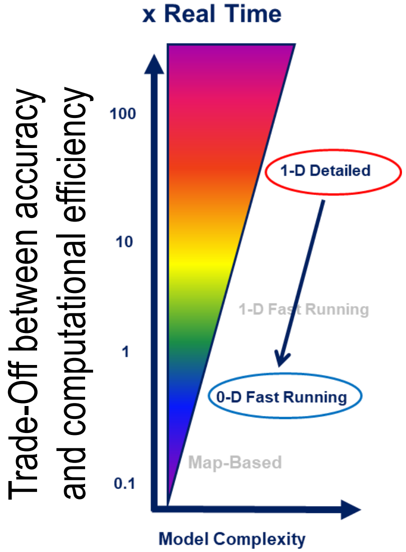


- HiL requires **Real-Time** (RT) Engine/Vehicle plant models

  → FAST-RUNNING MODELS

Fast-Running Fully-Physical Engine Model

- GT-SUITE 1D fluid-dynamics engine models a de-facto standard in automotive industry
  - Detailed models ~50x slower than RT but can be simplified into fully physical 0.5xRT FRMs

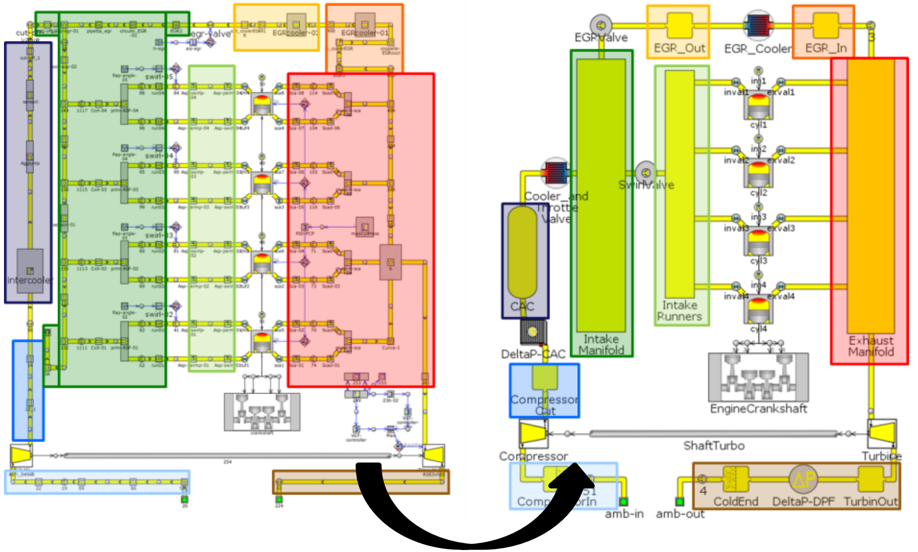


Detailed Model already present within OEMs!

Efficient Re-Use of Available Information

Detailed model: **191 volumes**

0D FRM: **18 volumes**

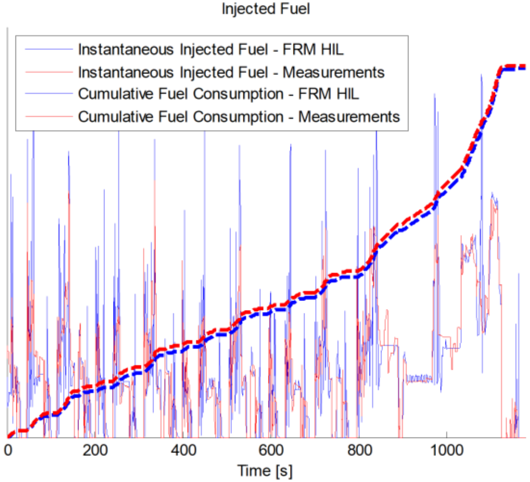


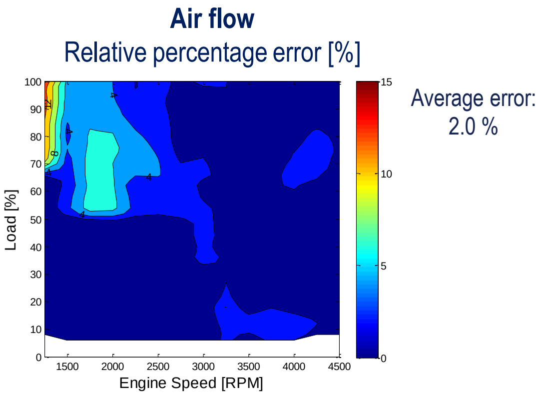
- RT-Capable GT-POWER FRMs still based on the very same templates and fluid-dynamic solution
  → HIGHLY PREDICTIVE

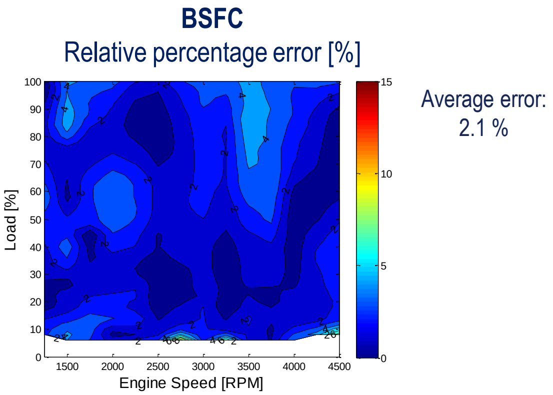
"Development and assessment of a Fully-physical 0D Fast Running Model of an E6 passenger car Diesel engine for ECU testing on a Hardware-in-the-loop system" SIA Conference, 2015, PWT - FCA

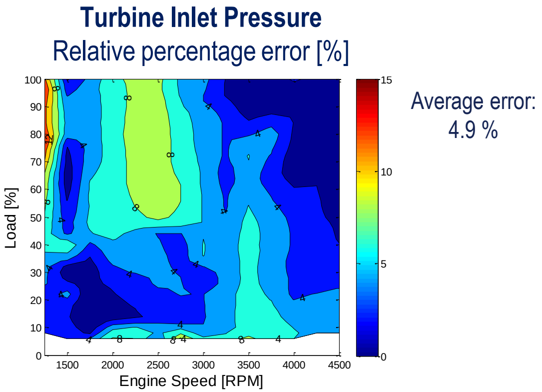
Fast-Running Fully-Physical Engine Model

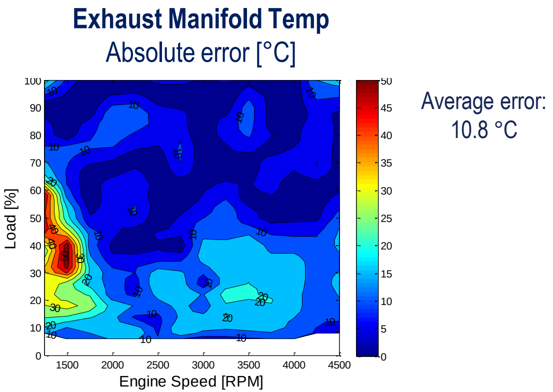
- Albeit very computational efficient, FRMs are still very accurate
- Predictive and highly flexible, no need to rebuild them when changes occur
- Can be run in steady-state and transient conditions











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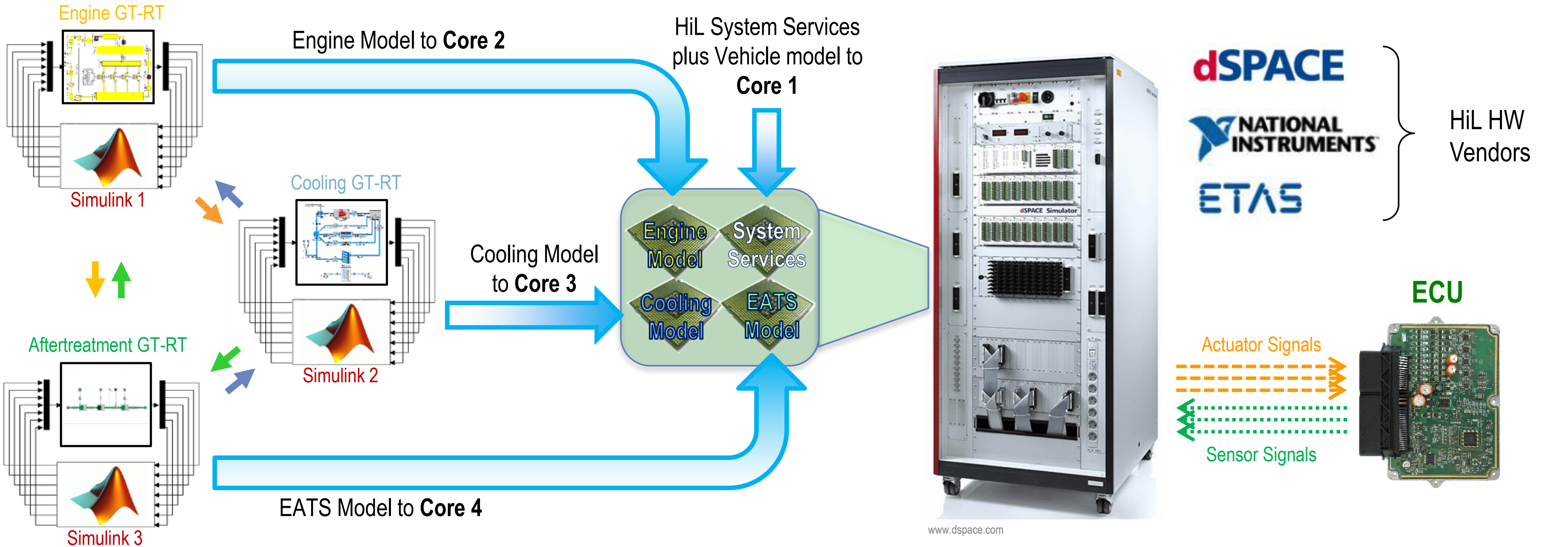
FRMs Deployment on HiL Machines

- GT-SUITE FRMs are encapsulated into Simulink I/O masks, compiled and deployed onto HiL Hardware (e.g. dSpace). Multi-Model and Multi-Core simulations are supported:



"Multi-Core HiL Simulation of an Integrated Engine & Cooling Model" GT-SUITE European User Conference, 2015, PWT - FCA

The problem of Engine Calibration

Diesel Engine

Injection Strategy:

- 2 → 4 Auxiliary injection events
- 2x Parameters ∀ Injection event
- Pattern Positioning (SOI)
- Injection pressure

→ **10 Parameters** only for injection pattern

Air Management Strategy

- Boost Pressure
- EGR level and split (Dual Loop Circuit)
- Swirl Flap

→ **4 Parameters**

TOT: 14 Parameters → 3 levels ∀ params → **~5 millions** Combinations!

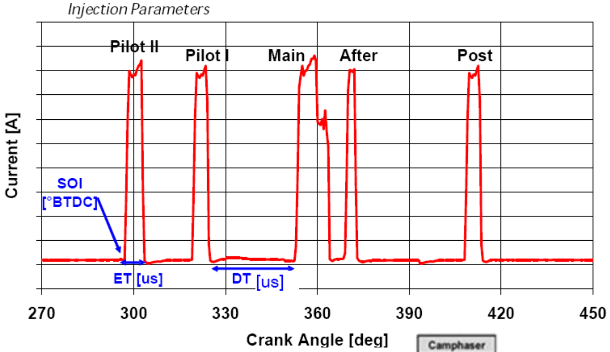
VIRTUAL TEST BENCH

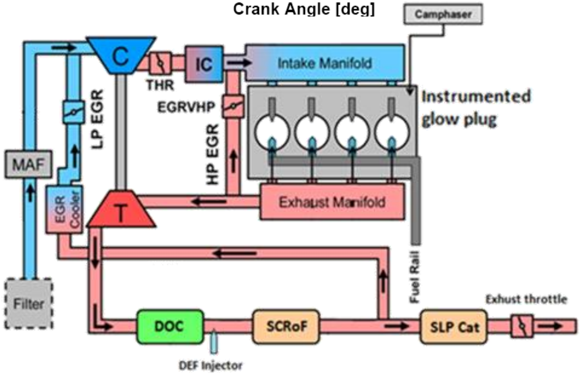
huge saving potentials

→ Engine Performance
→ Engine Out Emissions
→ Tailpipe Emissions

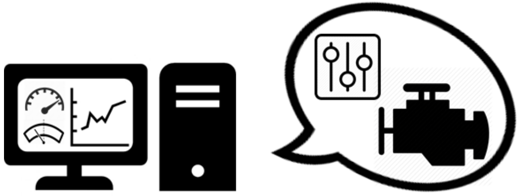
TARGET:

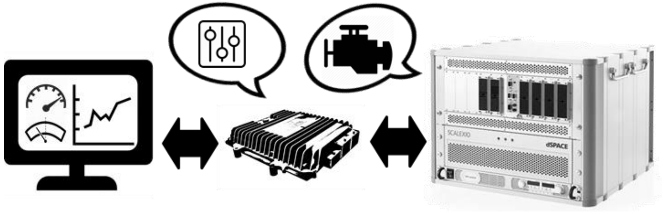
Optimization of emissions and fuel consumption





Virtual Calibration in a Nutshell





Offline Approach (SiL)

5x FRM: TimeStep: ~0.05 ms, Flow Volumes: ~100

- Accurate gas dynamic
- Wall Temperature Solvers
- Predictive Combustion Models
- Predictive Emissions Models

EXP Data Needed: Engine Maps (10^2)

Development Time: 1-2 Months

Online Approach (HiL)

0.8x FRM: TimeStep: ~0.30 ms; Flow Volumes: ~15

- Coarse gas dynamic
- Mapped Wall Temperatures
- Mapped Combustion
- Mapped or SP Emissions

EXP Data Needed: DoE (10^3)

Development Time: 3-6 Months

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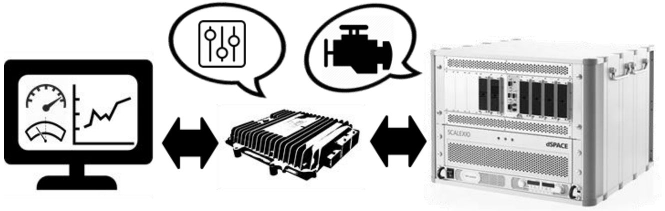

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Semi-Predictive Diesel Emissions

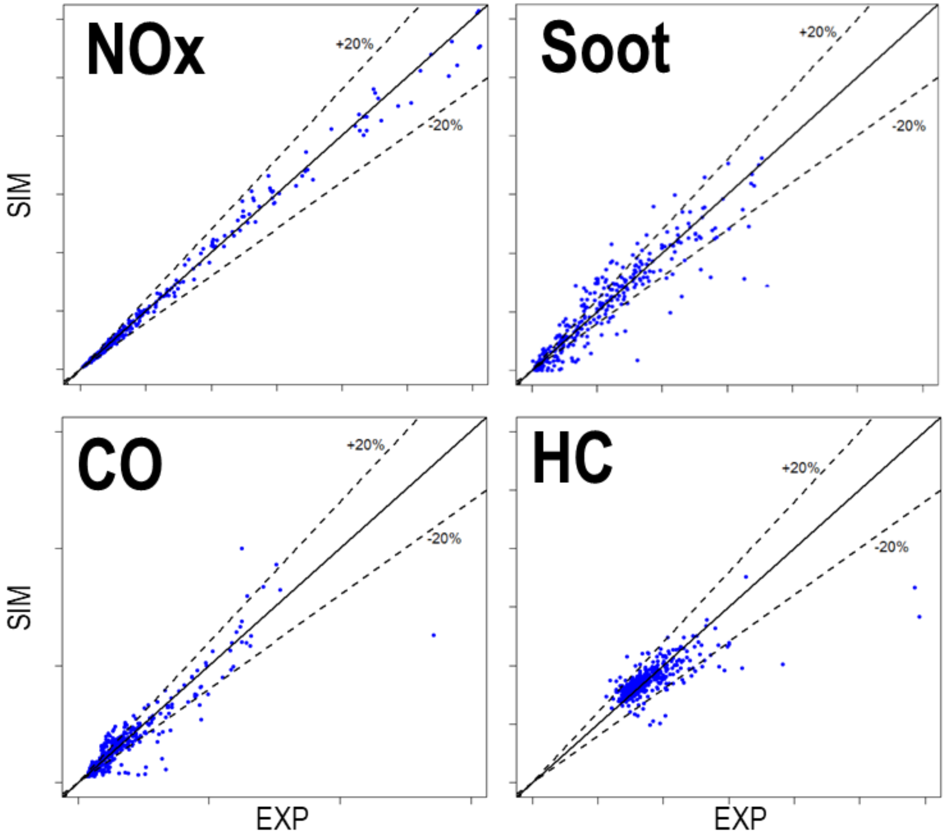
- **Semi Predictive Emission Models**

  Light-duty Truck Diesel (Euro VI)

- **Engine Map Results**

$$NO_x, CO, HC, SOOT = a_0 * \prod_{k=1}^{p} x_k^{a_k}$$

  - x_k are the independent variables
  - a_k are the coefficients, result of the calibration process
  - p is the number of regressors, index of the model complexity



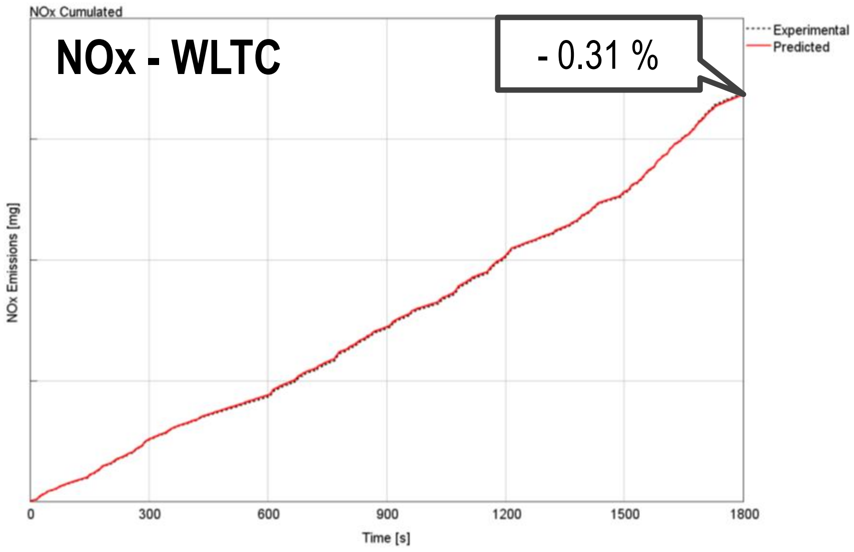
*Percentage error bands limited to 1% absolute error

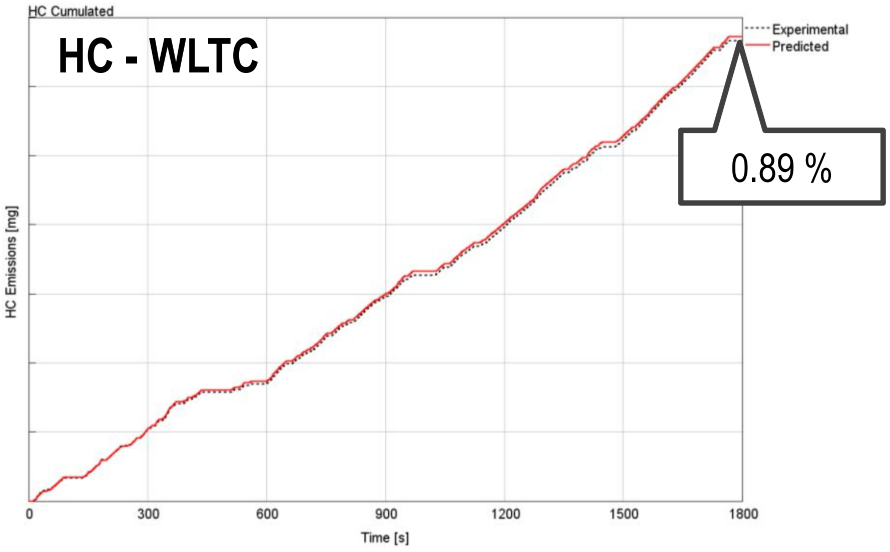
Semi-Predictive Diesel Emissions

- **Semi Predictive Emission Models**
  - Medium-size passenger car Diesel (Euro VI)
  - Emission maps tested on different Driving Cycles

EXPERIMENTAL: Driving cycle simulation with experimental emission map

PREDICTED: Driving cycle simulation with emission map evaluated via SP emission model





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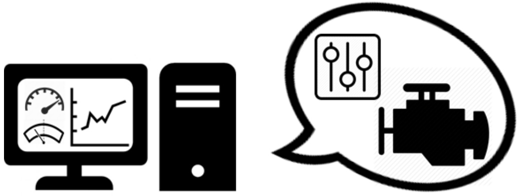

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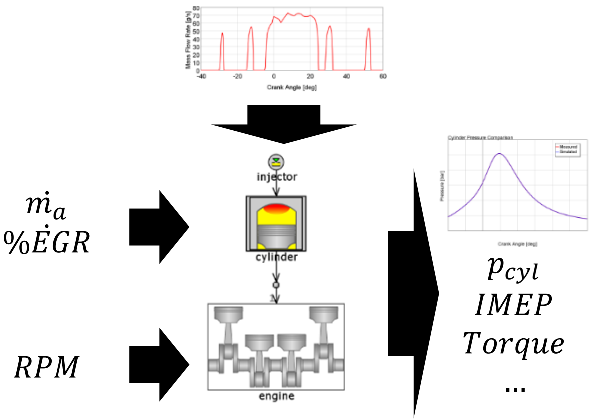
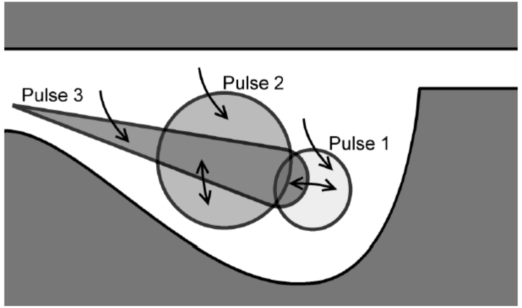
Physical Diesel Emissions Modeling

- **Predictive Diesel Combustion Model: DI-Pulse**
  - Phenomenological combustion model developed by GT.
    - Designed to handle modern multi-pulse injection
  - Multi-zone approach (3 zones per pulse)
    - Improved thermal description of in-cylinder phenomena
    - Improved results of emissions models
  - Combustion rate is predicted based on injection rate & in-cylinder conditions:
    - Injection timings and profiles
    - Pressure and temperature
    - Mixture composition (fresh air, fuel, EGR/residuals)



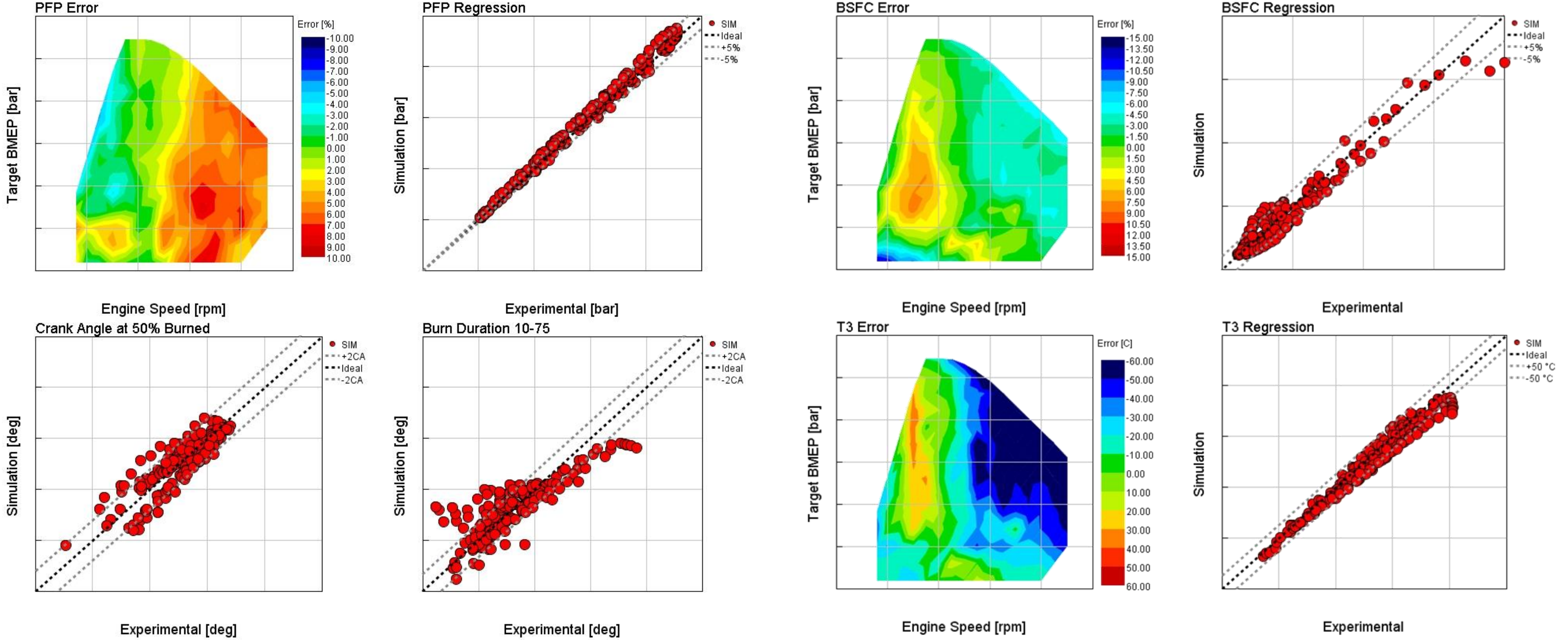


Courtesy of Gamma Technologies

Physical Diesel Emissions Modeling

- **Predictive Diesel Combustion Model: DI-Pulse**

  Medium-size passenger car Diesel Engine (Euro VI) with predictive combustion.



"Set-up and Validation of an Integrated Engine Thermal Model in GT-SUITE for Heat Rejection Prediction" SAE Paper 2019-24-0078, PWT – Jaguar Land Rover

Physical Diesel Emissions Modeling

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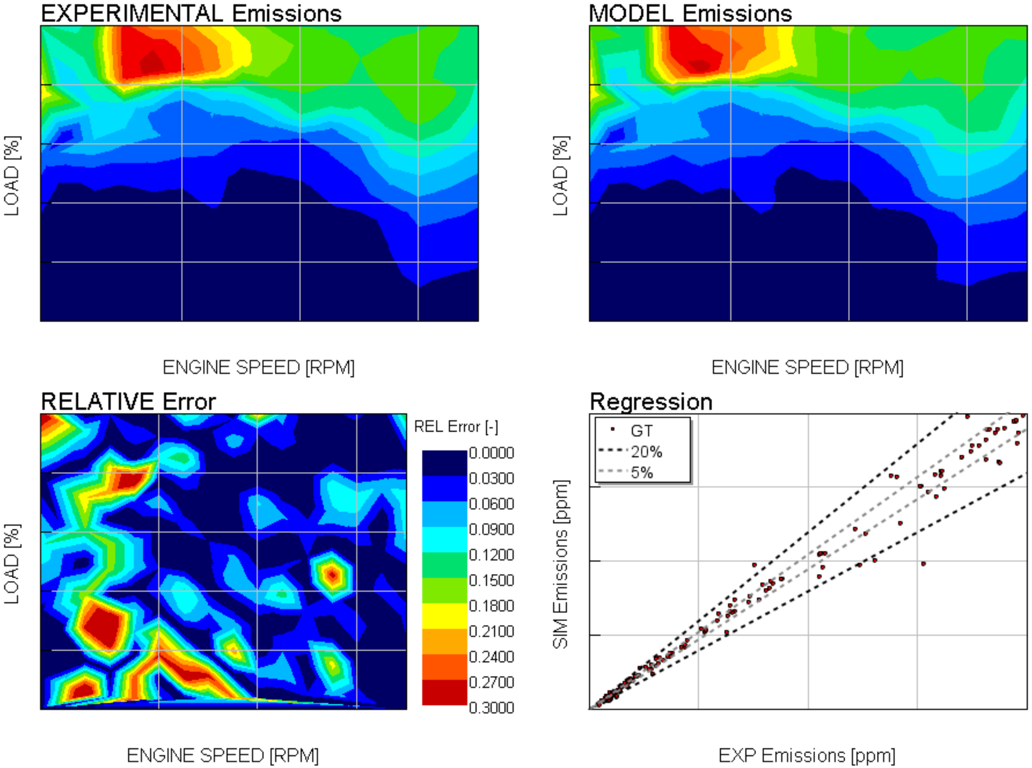
- **Predictive Diesel Emission Model: NOx**



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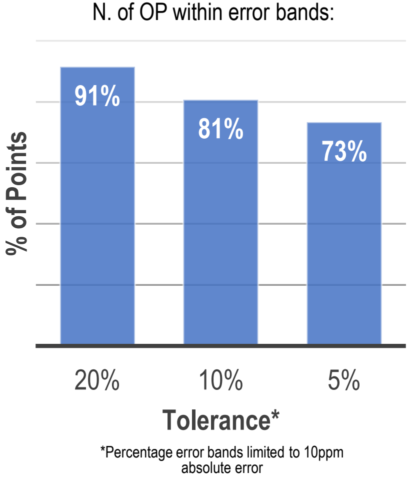
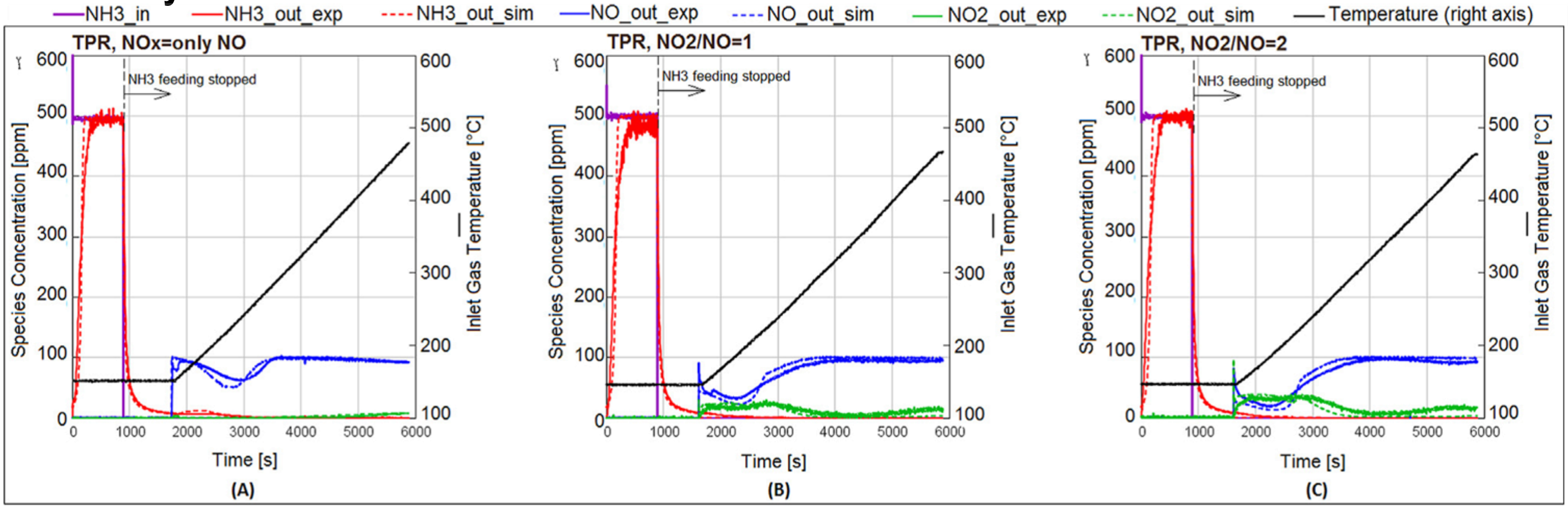


Aftertreatment Modeling

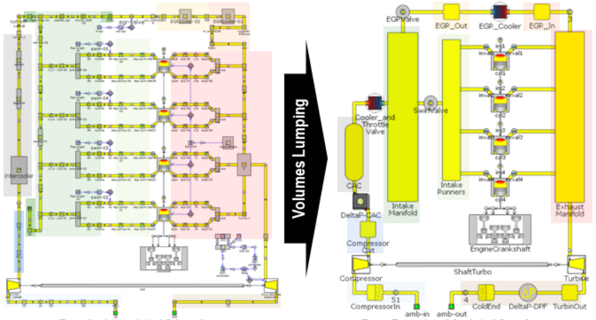
- **Physical Catalyst modeling:**
  - Requires dedicate testing of a Lab-Scale reactor sample on a synthetic flow bench.
  - Real time and fully predictive
- **Ex: Physical Model of a SCR on Filter**



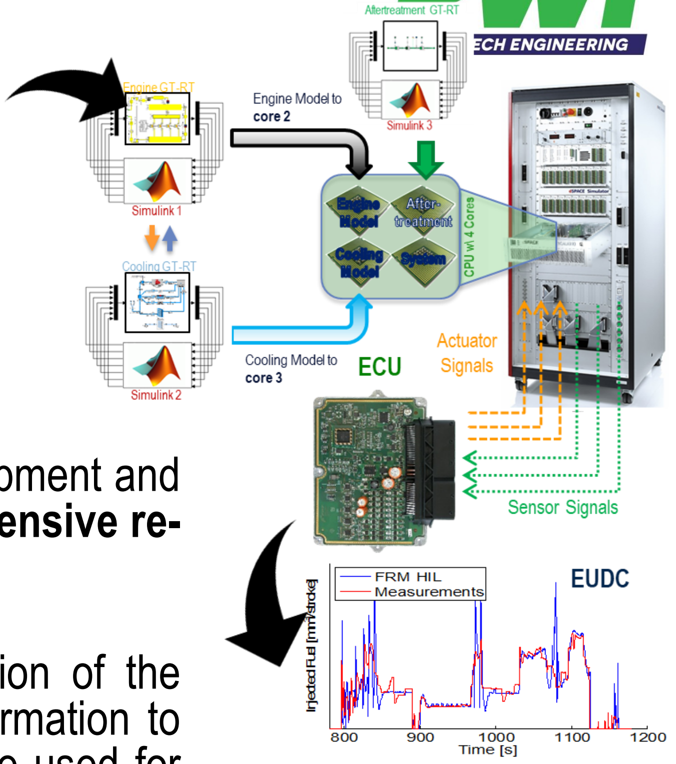
Millo F., Rafigh M., Fino D., Miceli P. , *Application of a global kinetic model on an SCR coated on Filter (SCR-F) catalyst for automotive applications*, Fuel Volume 198

Conclusions

- **Control system** development within the automotive industry is evolving rapidly towards an **ever-increasing complexity**.



Detailed model: **191 volumes**   Fast Running Model: **18 volumes**



- A process was identified which consents the virtualization of the engine control development and calibration **reducing the need for testing** and making an **extensive re-use of available resources**.

- This process relies heavily on state-of-the-art CAE simulation of the engine gas-exchange, combustion and pollutant emission formation to realize a **digital-twin of an engine test bench** which can be used for **online and offline control calibration and optimization**.

THANK YOU FOR YOUR ATTENTION

Any Question?

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