High Dimensional Fast-Response Particle Number (PN) Surrogate Model Building Methodology for Heavy Duty (HD) Diesel Engine Applications

by
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CMCL Innovations

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Session 4: Emission Control and Aftertreatment

Overview

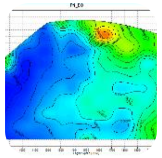
Objective:
Develop capability to robustly estimate engine-out PN for HD Diesel Engines with physico-chemical engine models and a high dimensional, fast response surrogate model over transient cycle simulation.

Workflow

Data Acquisition & Analysis
(In-cylinder and engine-out measurement)

Physico-chemical Engine Model
(Combustion characteristics & emissions)

Model Calibration
(Model calibration with 40% of measured data)



Model Validation (Blind Test)
(Model validation with 60% of measured data)

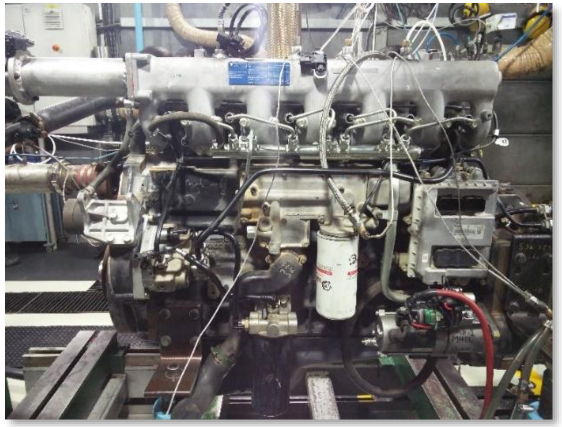
Surrogate Model Generation
(High dimensional model generation)

Real-time FRM Creation
(Surrogate model integrated to MATLAB via API)

This presentation is part of a project:

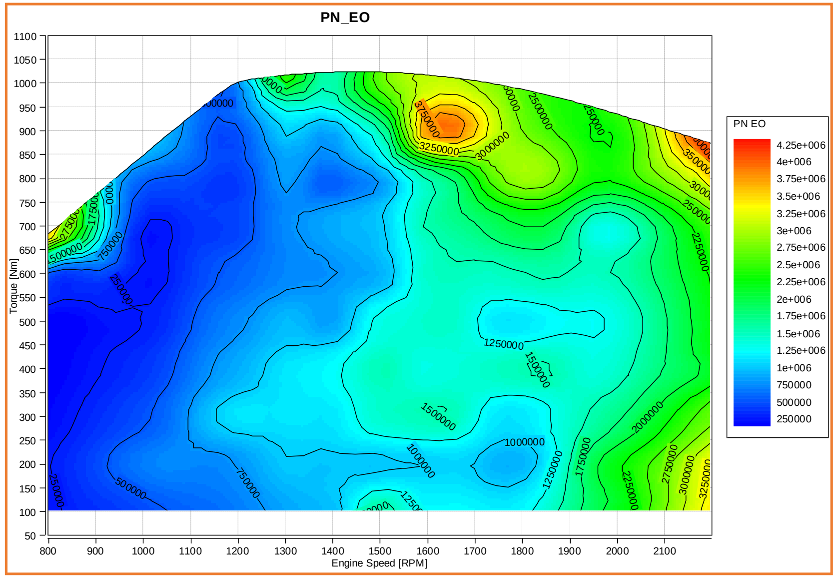
Title: Establishment of calibration strategy for BS VI Real Driving Emission (RDE) by virtual technique
Funded by: Department of Heavy Industries, Govt. of India
Sanction no: 7(7)/2019-AEI (19245) dt. 19.08.19

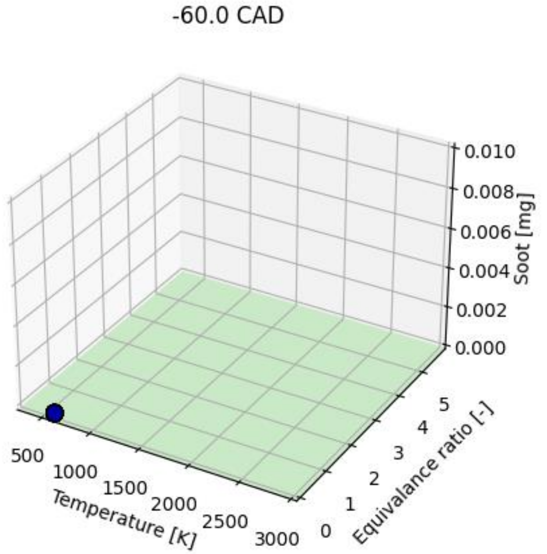
Engine Measurement Campaign at ARAI



Engine Description	
Displacement	~7 L
No of cylinders	6
Aspiration	Turbocharged (WG)
Injection	Common rail DI
EGR	Yes

- In-cylinder data measurement on engine with parametric variation
- PM + PN measurement with AVL APC 489
- Data outliers removed based on overall emission trends
- 40% of acquired measurement data used for model calibration
- 60% of acquired measurement data reserved for model validation

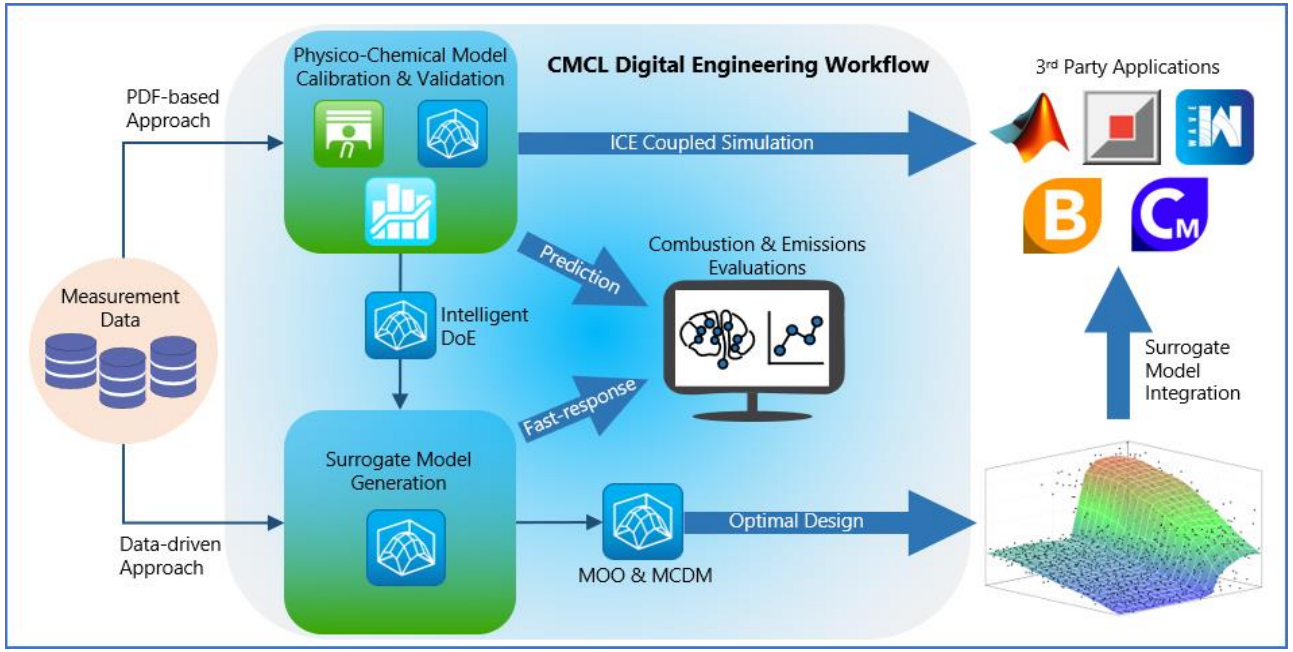




CMCL's MoDS-SRM Engine Suite Workflow for ICEs

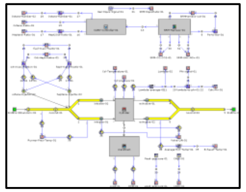
MoDS-SRM Engine Suite Workflow

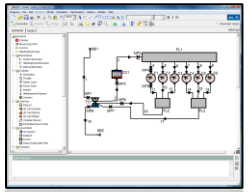
- SRM Engine Suite, MoDS, and CMCL Explorer (post-processing)
- Physico-chemical models + advanced statistical algorithms
- Conventional and alternative fuels
- All aspects of digital engineering:
  - Model calibration (parameter estimation)
  - Validation (blind test)
  - Intelligent DoE (digitally populate data)
  - Surrogate model generation
  - Multi-objective optimisation
  - Multi-criteria decision making
- Applications:
  - Combustion characteristics
  - Gas phase emissions (CO, HC, NOx)
  - Particulate emissions (PM and PN)
- Steady state and transient cycle simulations



Physico-chemical Simulation: SRM Engine Suite

1st Generation: 1D multi-cycle

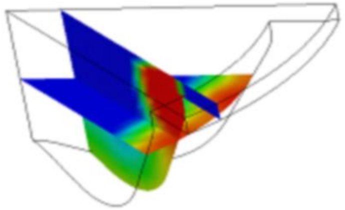




Breathing, valve train and engine optimisation

- CPU time seconds/cycle
- **Poor predictive combustion**
- **Poor predictive emissions**

2nd Generation: 3D CFD



In-cylinder optimisation

- CPU time days/cycle
- Predictive combustion
- Predictive emissions in some cases
- Many parameters
- Lengthy meshing/pre-/post-processing
- **Limited by workflow & CPU time**

3rd Generation: Advanced and application-focused PDF-methods – SRM Engine Suite

- CPU time - minutes
- No meshing

- Predictive combustion and emissions
- Accurate sub-models for turbulence, heat transfer, MDI, EGR, fuel volatility

- **Properly account for chemical kinetics**
  i.e. ignition, extinction, misfire, flame propagation and emissions
- Easy to integrate into 1D cycle tools
- **More efficient solution for fuels, combustion and emissions**

Statistical Algorithms: MoDS

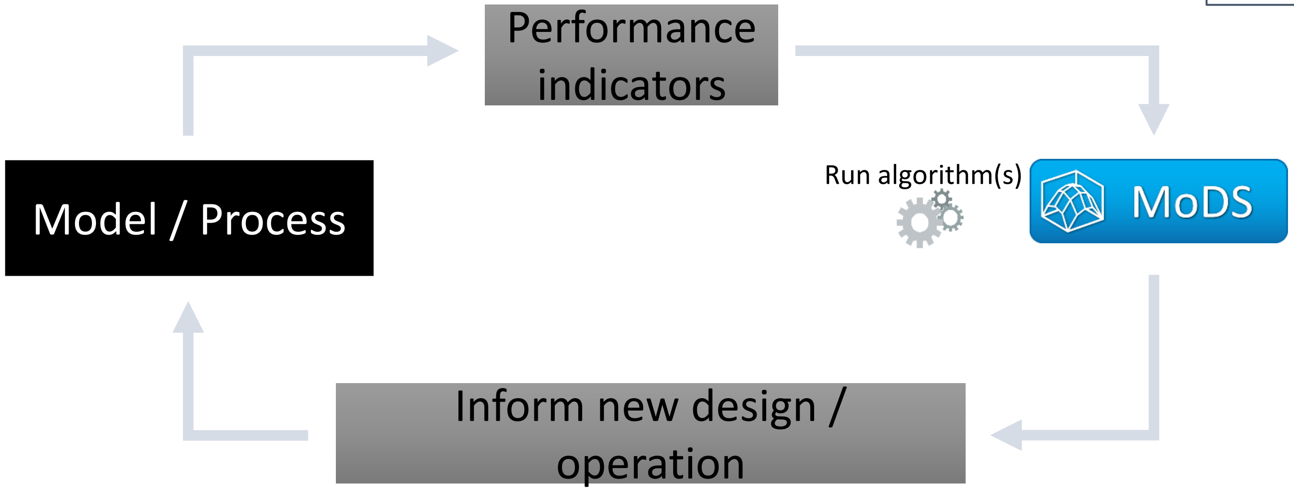
MoDS is a highly flexible model development application that uses statistical algorithms to automate common tasks, such as:

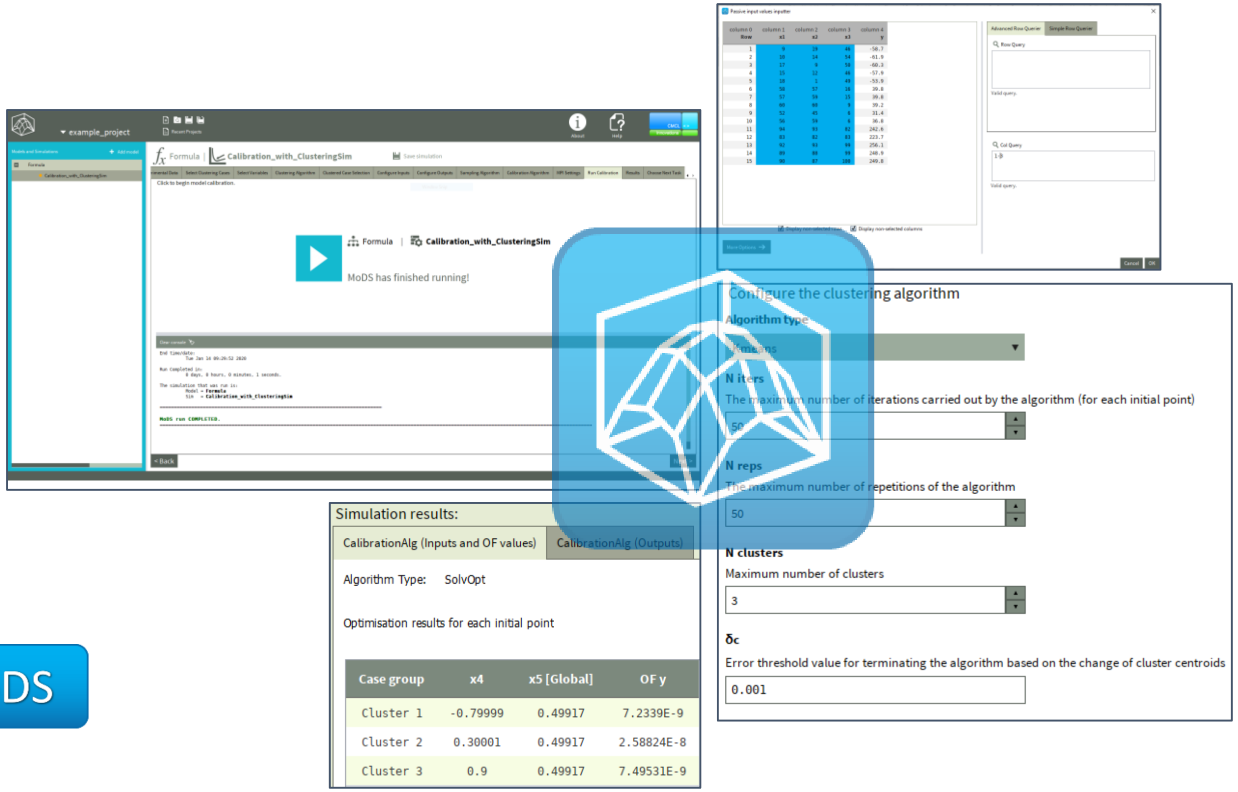
Purpose-built workflows

- Model calibration / parameter estimation
- Model validation
- Surrogate generation and evaluation
- Multi-objective optimisation
- Global sensitivity analysis

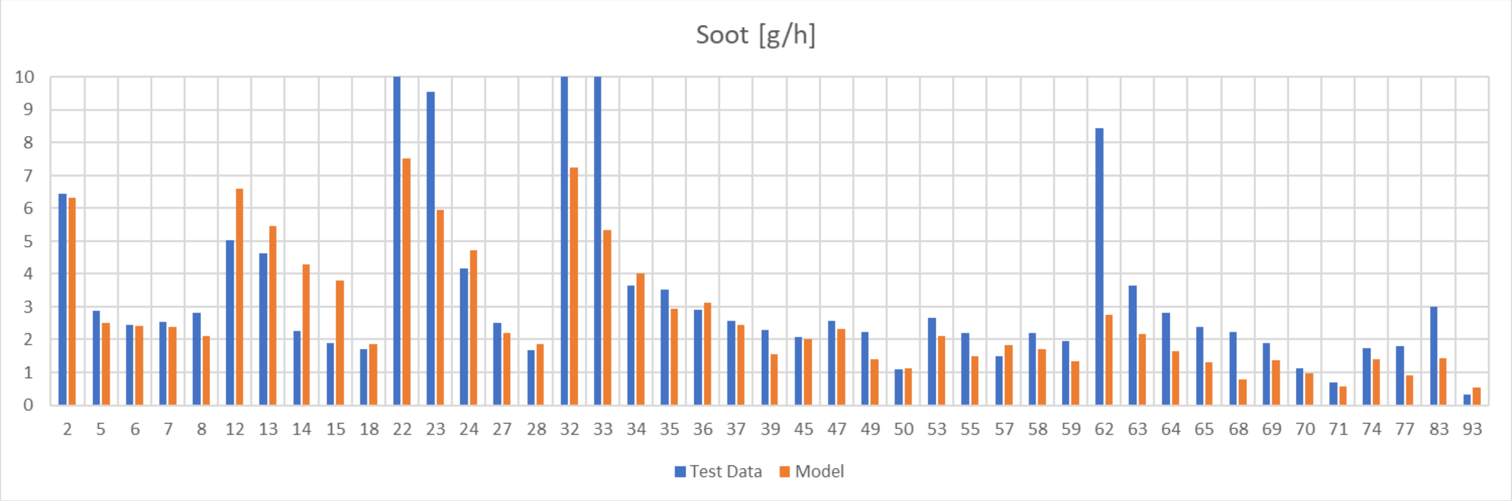
Currently backend only

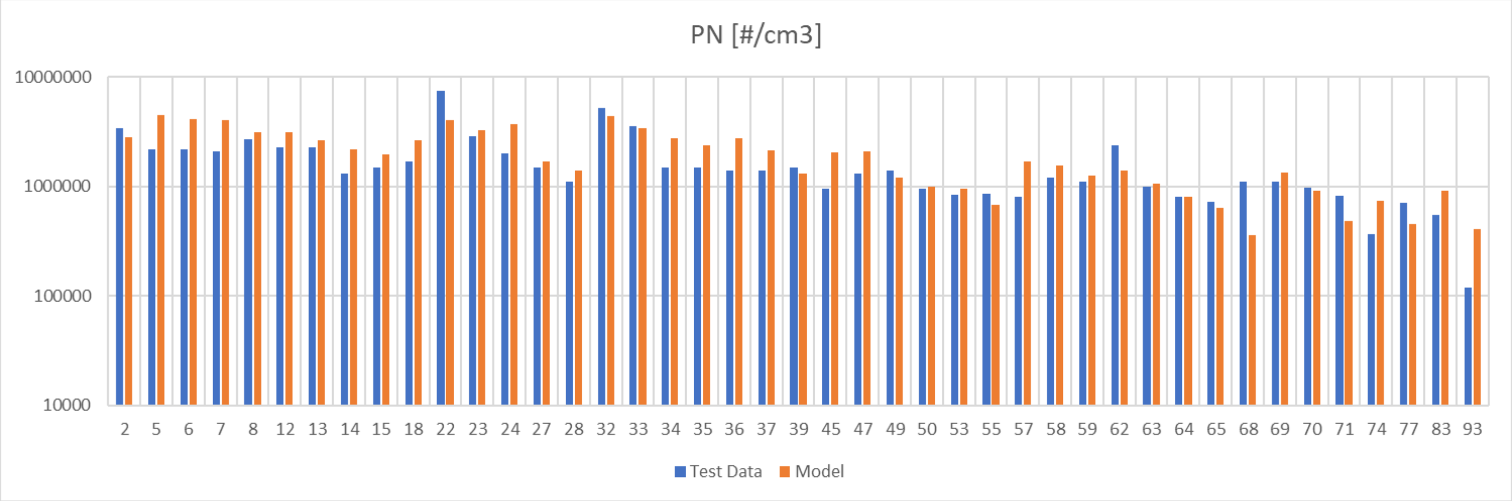
- Intelligent DoE / space filling
- Local sensitivity analysis
- Uncertainty propagation





Results



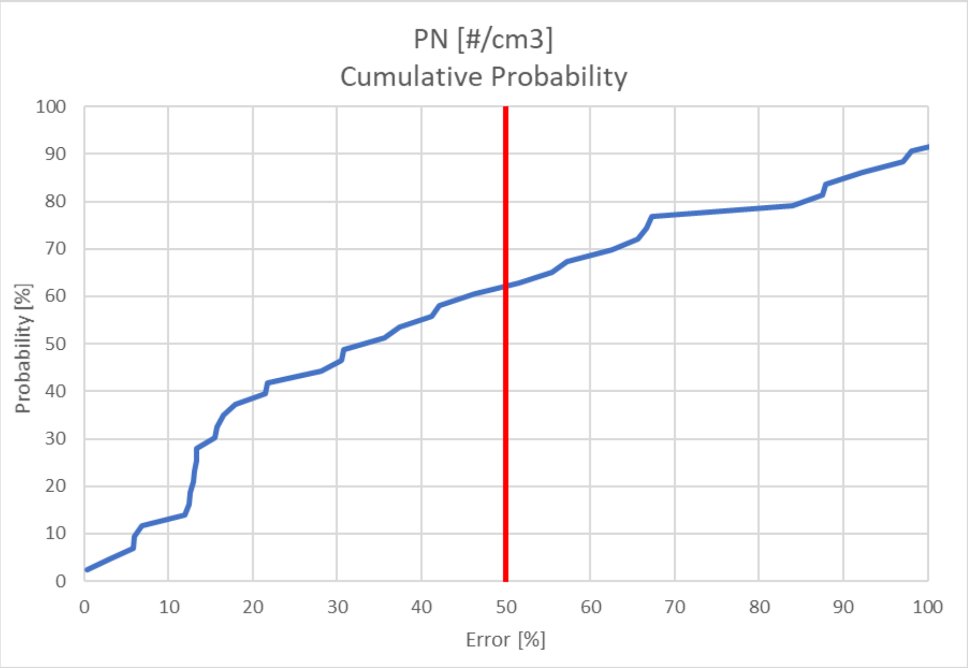


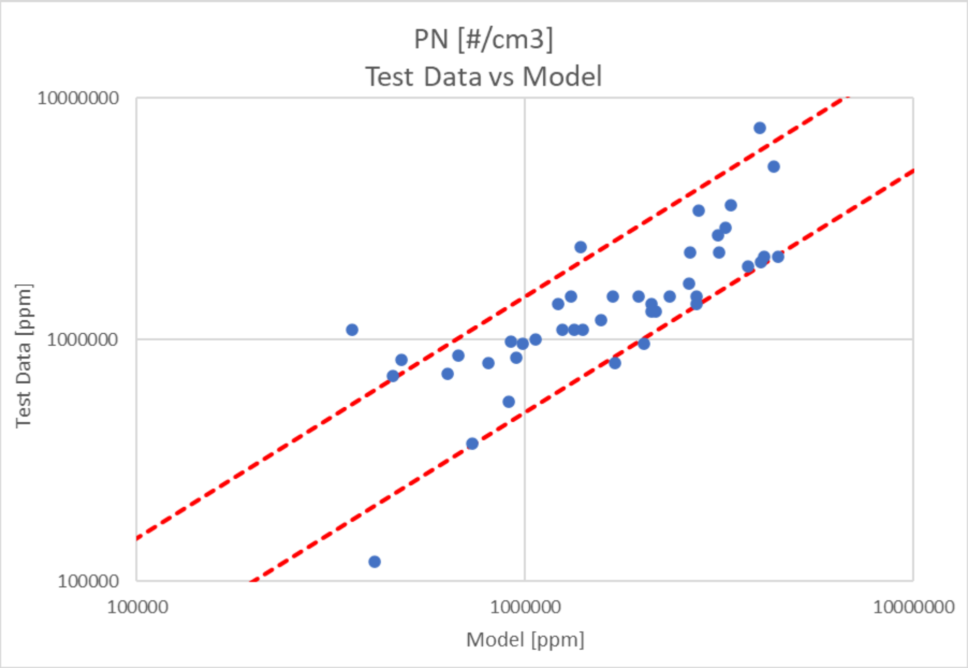
- This section compares the soot and PN emissions from the model validation (blind test) results against the measurement data

- For soot emissions:
  - 40% of the points simulated are situated within the 20% error relative to the measurement data
  - 80% of the points simulated are situated within the 50% error relative to the measurement data

- For PN emissions:
  - 62% of the points simulated are situated within the 50% error relative to the measurement data
  - 92% of the points simulated are situated within the 100% error relative to the measurement data

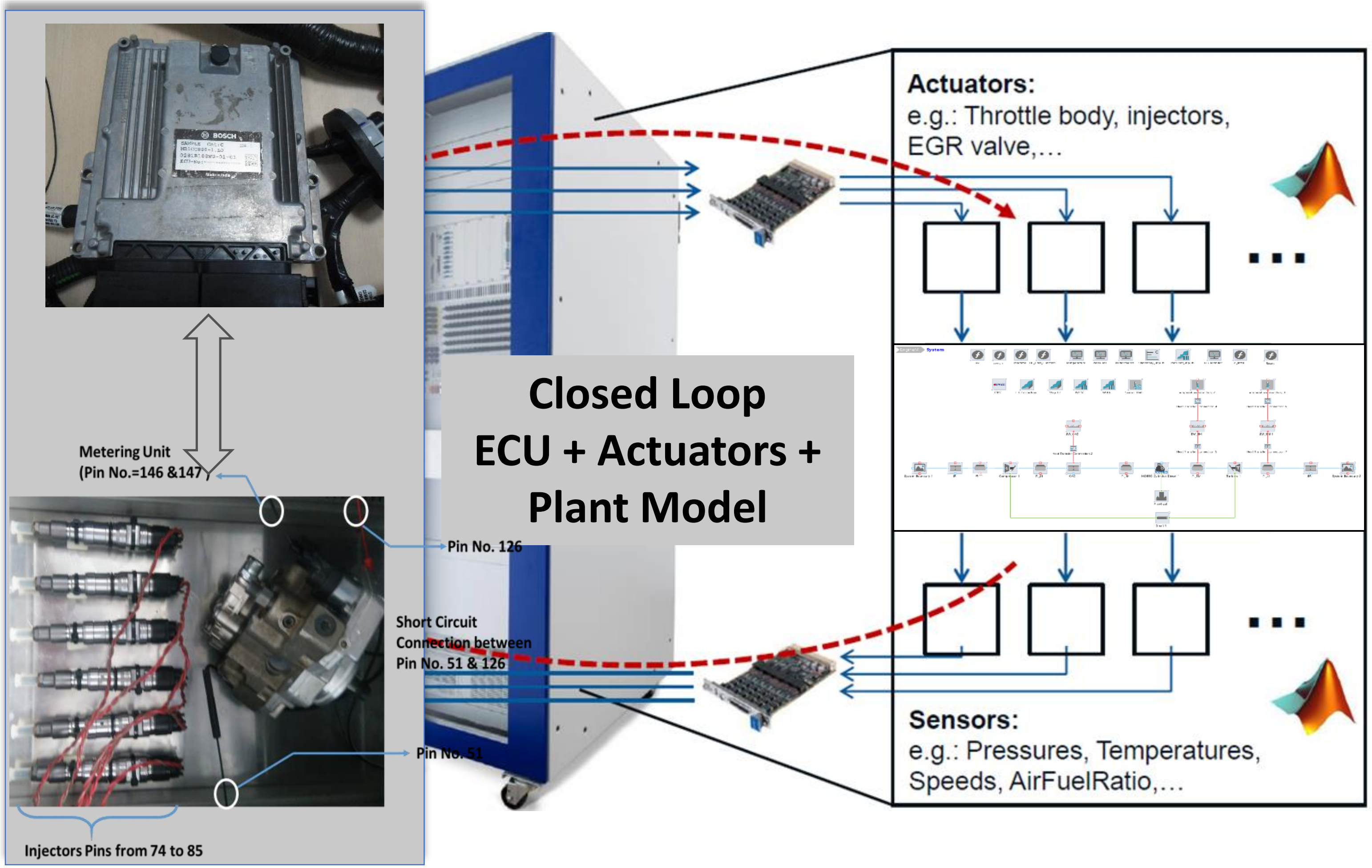
Results





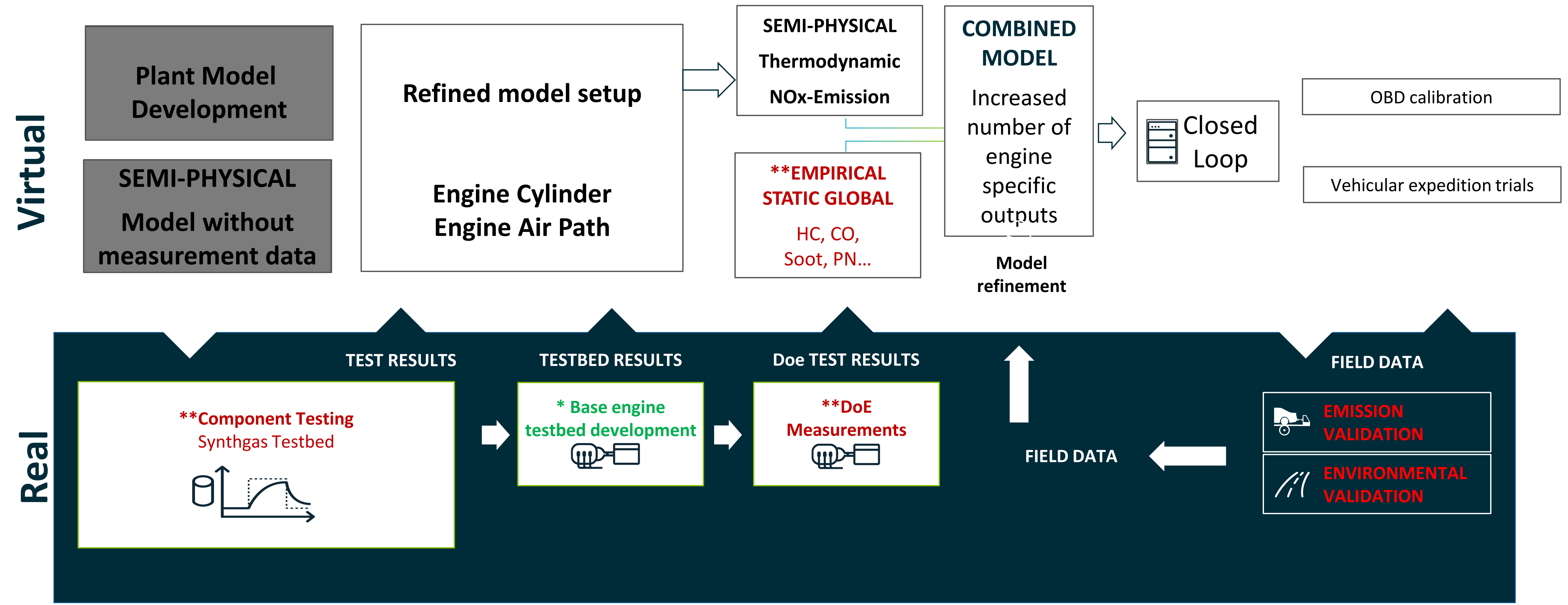
- The figure on the left shows the cumulative probability distribution with respect to the absolute error
- The figure on the right compares the simulation results against the test data
  - The red dotted lines indicate the ±50% error boundary
- It can be observed that the majority of operating points simulated are situated within the 50% error
  - 62% of the points simulated are situated within the 50% error relative to the test data
  - 92% of the points simulated are situated within the 100% error relative to the test data
  - The maximum error is 242% at one operating point

Virtual test setup preparation



- ECU in loop with RT plant model
- Feedbacks to ECU from plant model
- Steady state and transient operation

Virtual calibration: workflow



Conclusion

- This work demonstrated capabilities of PN estimation workflow for Heavy duty Diesel engines
- General trends for gas phase and particulate emissions at all operating points across entire operating window are very well predicted
- Detailed understanding on physics involved in generation and evolution of particles, sensitive parameters etc. was established
- This workflow approach with extended measurements with respect to variation in EGR, Fuelling parameters, altitude and ambient conditions demonstrate a cost reduction potential of calibration for upcoming emission norms

Future Work

Steady State/Transient Estimation

- Engine Out vs Tail Pipe
- WHSC/WHTC comparison

Vehicle level estimation

- Surrogate Model
- Integration with existing vehicle model

RDE estimation

- Extrapolation capability

ARAI
Progress through Research

Automotive Research Association of India

Establishment : 1966
Location : Pune, INDIA (150 km from Mumbai)
Manpower : 750+
Facilities : Corporate office, Pune
HTC-Chakan; FID- Chakan

Laboratories – Powertrain, Emissions, Safety & Homologation, Passive Safety, Vehicle Evaluation, Materials, Automotive Electronics, NVH, CAE, Structural Dynamics, Calibration, Environmental Research, Centre of excel Emobility, Fatigue & Materials Centre of Excellence, Centre of Excellence Powertrain, Transmission & Gear Test Centre, Academy,

Reginal Office, Chennai

Affiliates : China and South Korea
Investments : 110 MUSD
Accreditations : ISO 9001, 14001, 27001
OHSAS 18001 &
NABL (ISO/IEC 17025)

CMCL Innovations

Virtual Calibration Centre
your Partner from Concept to Reality. . .

Problem space

- Complex engineering systems
- High-dimensional and dynamic
- Data and information silos
- Lack of distributed regulation
- Lack of interoperability
- Bespoke linking not scalable

Motivation: solution space

- Digital Engineering
- Combining physico-chemical and statistical algorithms
- Interoperability across domains
- IIoT: Industrial Internet of Things
- IoS: Internet of Services/ Senses

Computational Modelling Cambridge Ltd (CMCL)

- Research-driven business spun out of Cambridge University over a decade ago
- Diverse team of dedicated, technical specialists
- Computational Modelling Pirmasens GmbH – to be founded in Germany shortly
- Established distributor network covering China, India, Korea and Turkey
- Markets: Automotive, materials, chemicals, energy, environment, infrastructure

Dynamic Knowledge Graph technology

- Account for dynamic nature of data and information
- Interoperability between heterogeneous data and software
- Live representation of the aspects of real world to aid scenario analysis and cross-domain decision support
- Digital twins and interactions between them say, via smart contracts
- Knowledge management, accounting for the context of the data

Software

MoDS | kinetics | SRM Engine Suite | CMCL Explorer

Consulting

- Experience in problem-solving with customers including governments, industry and academia

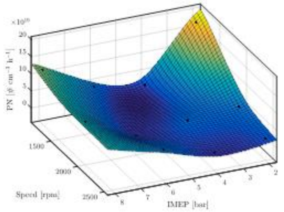
Training

- Specialised technical training services offered online, on-site, and at client-site

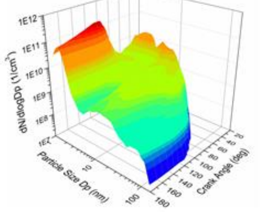
Use cases: within and across domains

Automotive: Vehicle emissions in RDE

PN emissions

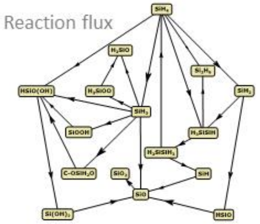


Particle size distribution

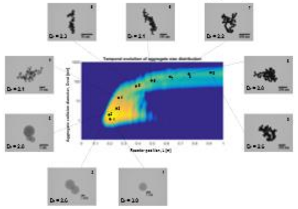


Chemicals: Nanomaterial production

Reaction flux

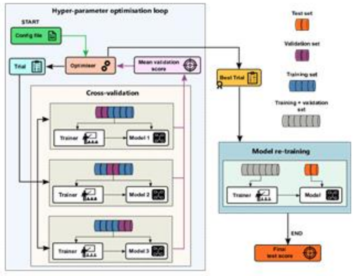


Fractal dimension of aggregates

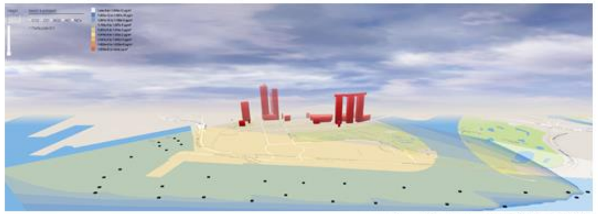


Renewables: Organic solar photovoltaics

Machine Learning	HOPV15 dataset		
	MSE	R^2	r
BiLSTM	3.935	0.188	0.467
Simple GNN	2.410	0.470	0.698
SVR	2.846	0.423	0.668
HDMR	3.185	0.350	0.623



Air quality: Virtual sensors



Collaboration: CoMo GROUP CAMBRIDGE CARES

Thank You