UserCylinder®:

Hydrogen Combustion

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Why is 0D/1D simulation necessary to develop hydrogen engines?

Hydrogen engines can only be successful when combined with a very well-matched high performance boosting system. This is due to the following reasons:

- Hydrogen combustion has a higher boost pressure demand compared to heavy-duty CI engines, as it is necessary to operate the engine at lambda >= 2 and additional EGR even at high loads (70-100%) in order to manage NO_x emissions. Alternatively, stoichiometric operation would require an operating mode switch, which would place very high demands on the boosting system's transient performance.
- High efficiency and early MFB50 timings of H_2 combustion reduce the available exhaust enthalpy for the turbocharger. At the same time, very high boost pressure are required => challenging situation

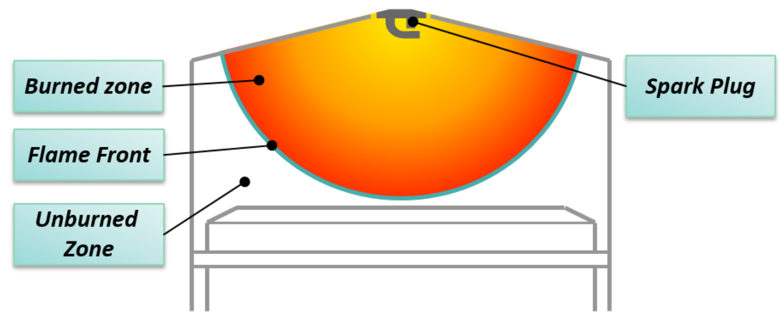
Assessment of turbocharger variants should always be assisted by 0d/1d simulations before and during runs on the engine test bench. This is due to the following reasons:

- It is nearly impossible to draw any meaningful conclusions for full engine design without turbocharger matching. Turbocharger matching can be done even before the engine is on the test bench by means of predictive burn rate models. 1d simulation is always mandatory for turbocharger matching.
- The question if a 1-stage or 2-stage boosting system is more suitable for a heavy-duty H_2 engine can also be investigated beforehand by means of 1d simulation.
- Transient 1d simulations allow to identify critical transient situations in an early stage of development. For instance, if the boost pressure build-up is found to be insufficient, additional electric boost devices can be considered.

Simulation of Hydrogen Combustion

Overview

- The proven, tried and tested models for SI combustion can also be used for hydrogen combustion, but several sub-models have to be adapted:
  - UserCylinder ®:
    - quasidimensional burn rate model
    - variables: flame surface, turbulence, flame wrinkling and laminar flame speed



  - Sub-models that need to be adapted:
    - evaporation
    - calorics
    - auto-Ignition behaviour
    - laminar flame speed

→ **Fuel properties needed** (evaporation, calorics, auto-Ignition behaviour, laminar flame speed)

→ **Model adaptions needed** (calorics, auto-Ignition behaviour, laminar flame speed)

Simulation of Hydrogen Combustion

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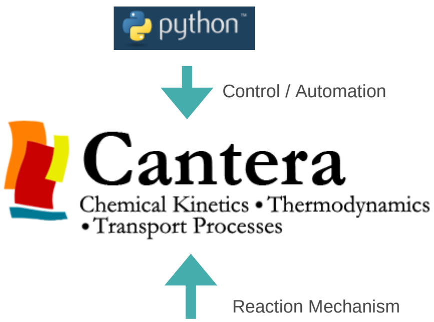
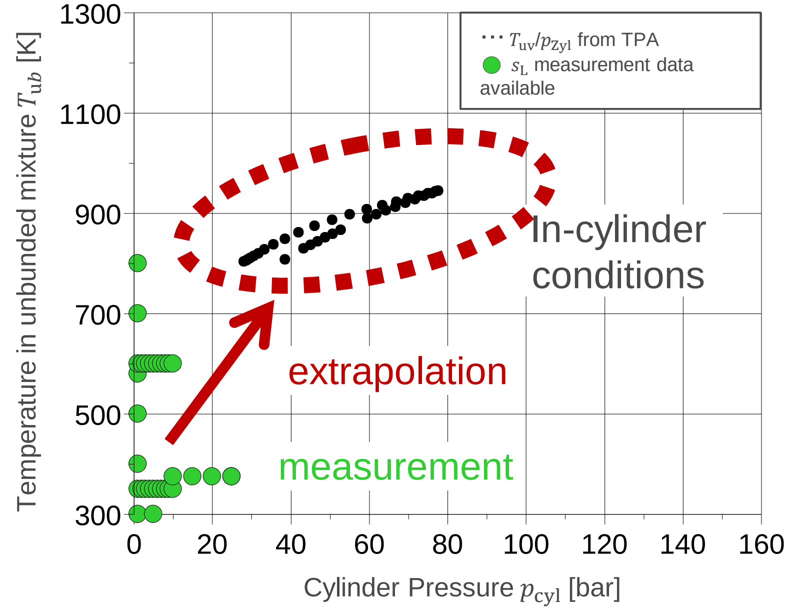
Laminar flame speed and thickness

- no measurement data available for boundary conditions relevant to engine operation
- in the past: extrapolation with huge margins of error
- now: reaction-kinetics-based approach with fuel-specitic mechanism, calculated in a wide range of boundary conditions $s_L = f(p, T, \lambda, y_{egr}, y_{h2o})$





Simulation of Hydrogen Combustion

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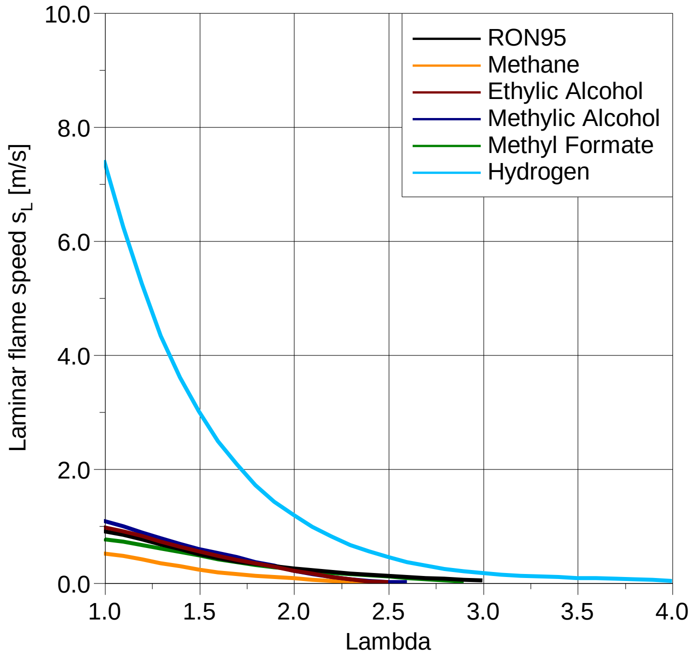
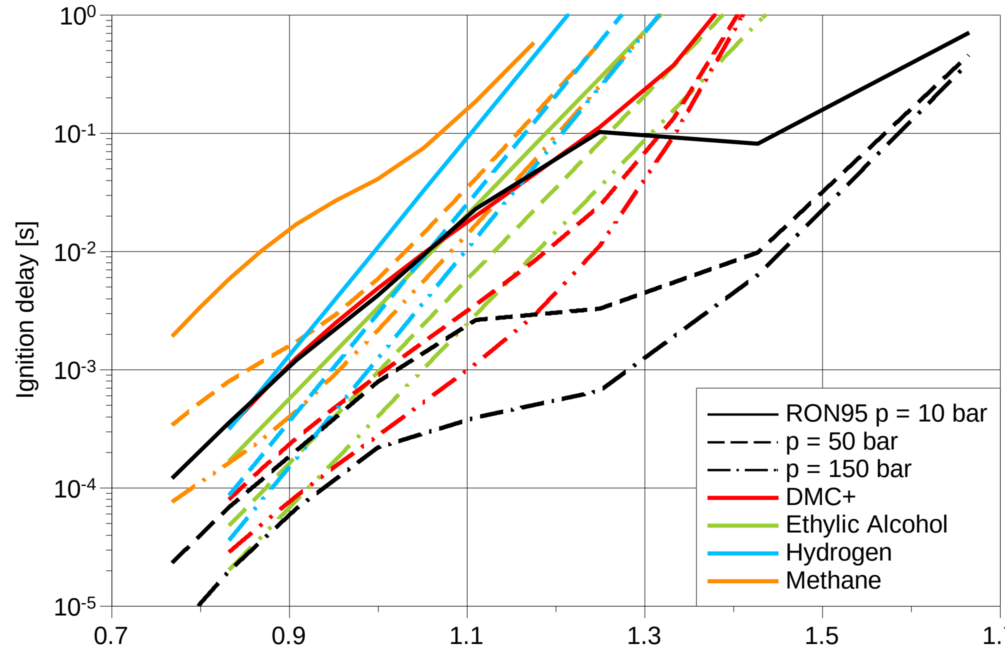
Results from reaction-kinetics calculation





Simulation of Alternative Fuels

Huge gain in predictive capability due to new modelling approach

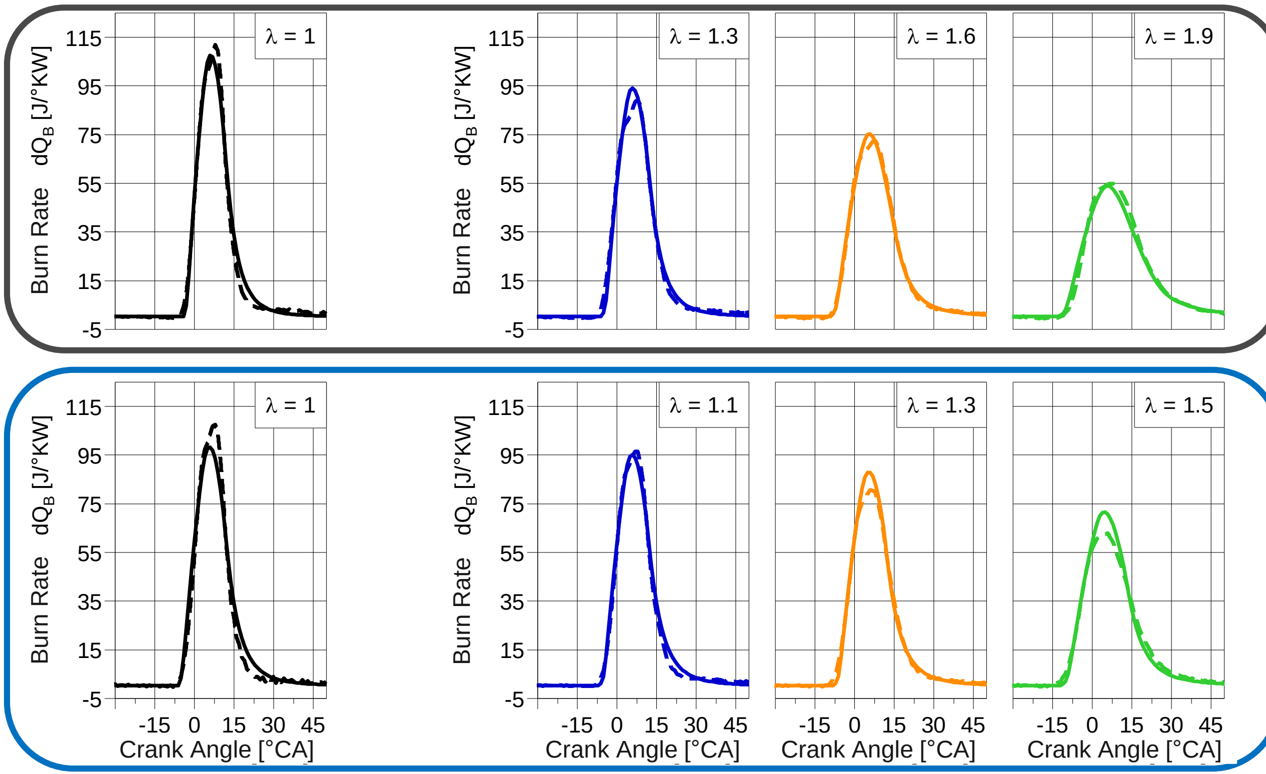
calibration:
RON 98
$\lambda = 1$

prediction
fuel change
$\lambda \uparrow$

prediction:
methanol
$\lambda \geq 1$

prediction
fuel change
$\lambda \uparrow$

prediction:
methyl formate
$\lambda \geq 1$



Measurement Data

Overview

Measurement data

- single-cylinder engine based on MTU BR2000
- flat bowl piston
- central spark plug position
- 79 operating points
- 2 different loads (approx. 7 bar and 11 bar) at the same engine speed (1200 rpm)
- includes ignition timing and EGR variations
- most other parameters are nearly constant (e.g. lambda)

Stoke x Bore	130 x 150 mm
Displacement	1991 cm³
Connecting Rod Length	273 mm
Compresion Ratio	11,5 :1
Number of Valves	4
Max. Torque	350 Nm
Max. Engine Speed	1800 rpm
Max. Boost Pressure	5,0 bar
Max. Cylinder Pressure	180 bar

Calibration UserCylinder®

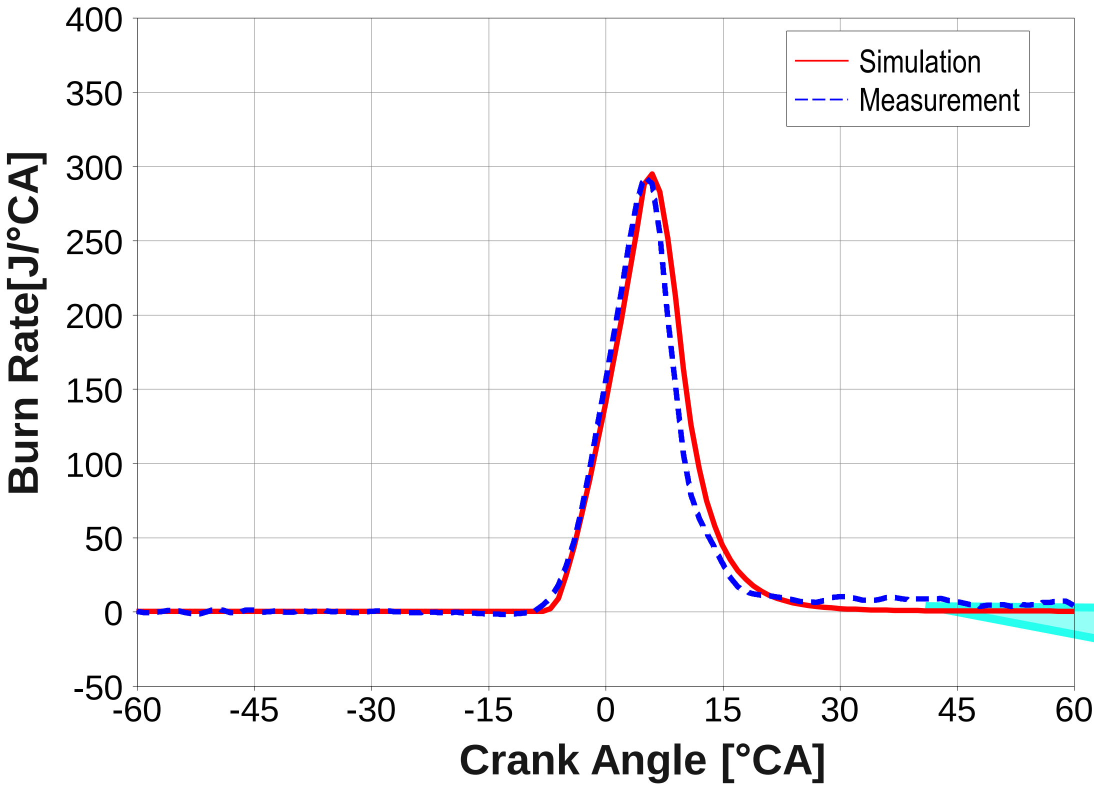
Calibration Procedure

Burn rate model

- (random) choice of **one single** operating point
- Automated optimisation of **one single** tuning parameter (defining the turbulence level)
- MFB50 from TPA is adopted by internal MFB50 controller

Calibrated operating point

Comparison of measurement and simulation



Engine Speed [rpm]	1200
IMEP [bar]	6.7
λ [-]	1.83
Ignition timing [°CA BFTDC]	12

Deviation on the falling edge is mainly due to implausible behaviour of measurement (measured burn rate never becomes zero).

Worst Case Operating Points

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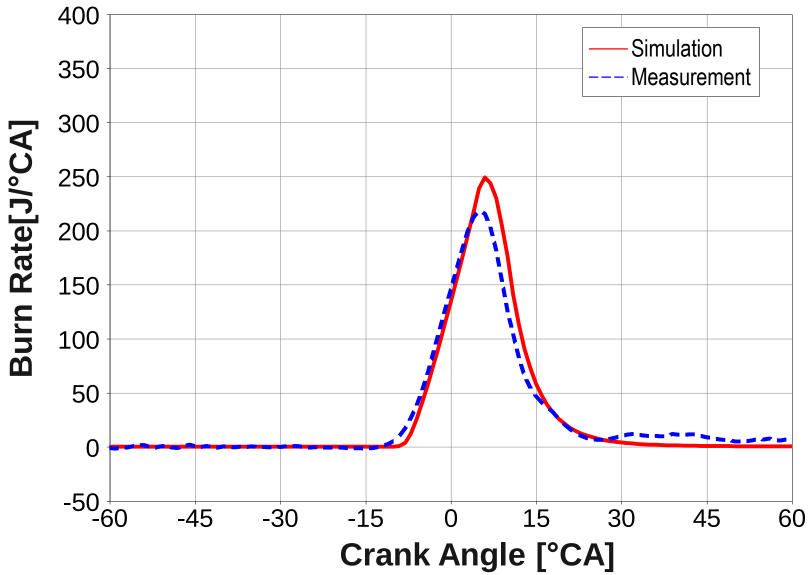
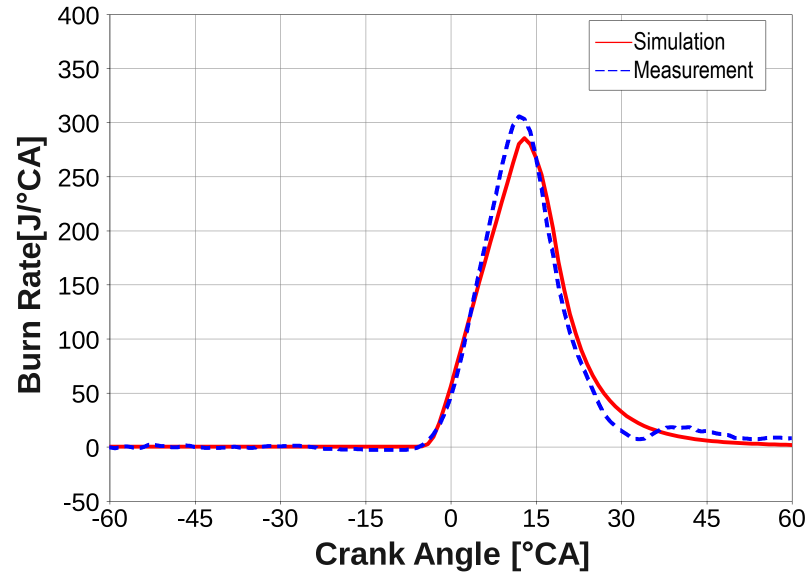
Comparison of measurement and simulation

Engine Speed [rpm]	1200	λ [-]	1.84
IMEP [bar]	6.8	IP [°CA BFTDC]	16



Resulting IMEP deviation: **0.22 bar**
Resulting peak pressure deviation: **2.30 bar**

Engine Speed [rpm]	1200	λ [-]	1.85
IMEP [bar]	10.4	IP [°CA BFTDC]	9



Resulting IMEP deviation: **0.18 bar**
Resulting peak pressure deviation: **0.20 bar**

Overview Model Performance

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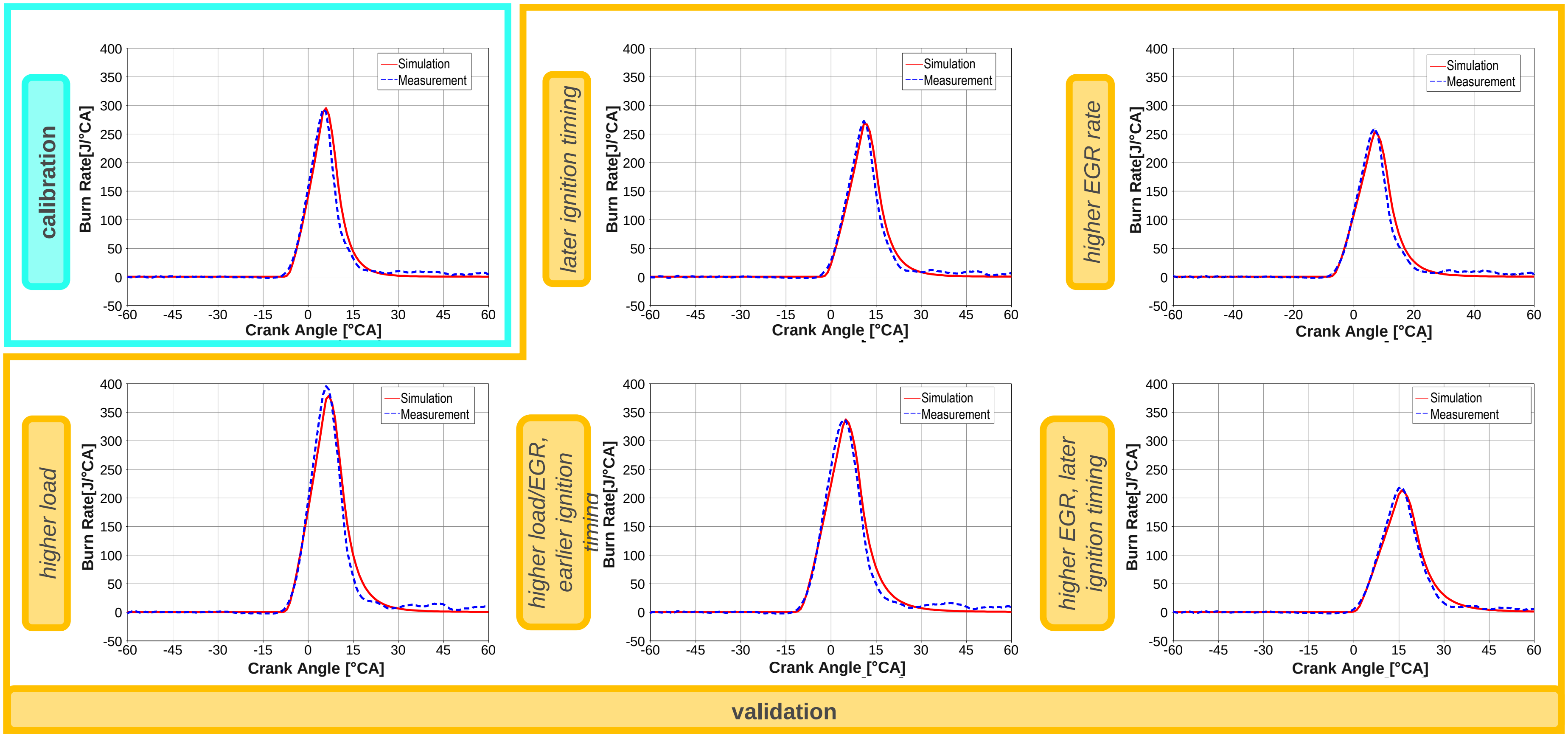
Validation based on variations, examples from approx. 80 operating points



Ignition Timing Variation

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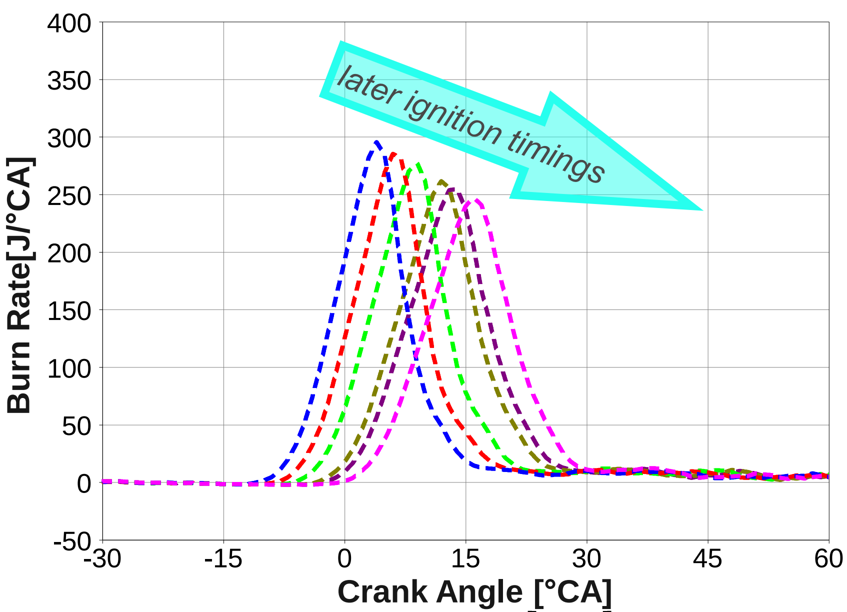
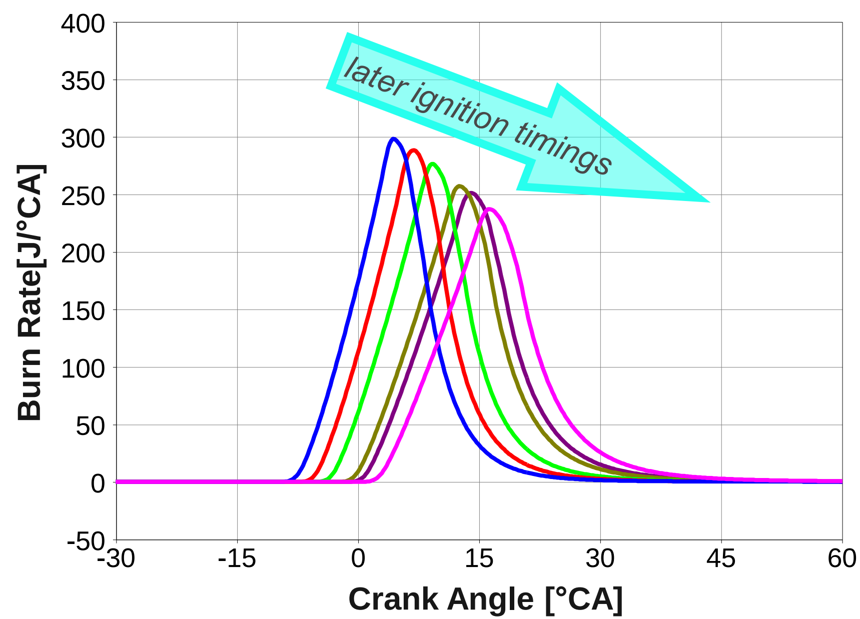
Measurement

Simulation

Engine Speed [rpm]	1200	λ [-]	1.83	IMEP [bar]	6.7	IP [°CA BFTDC]	Var.



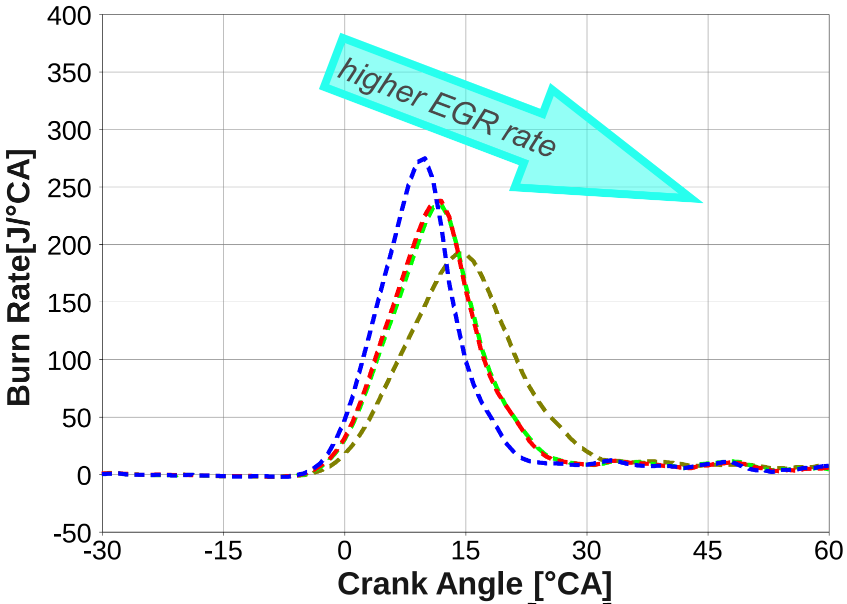


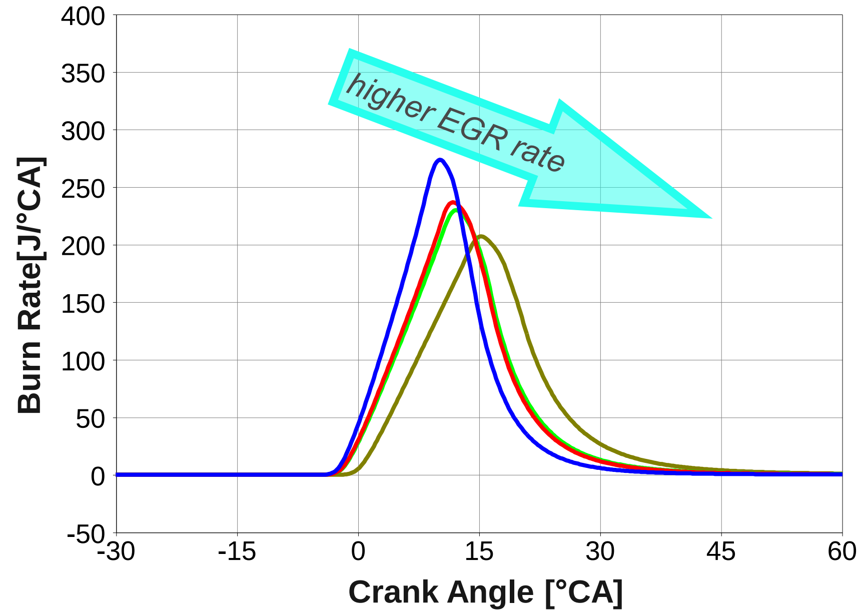
AGR-Variation

Messung

Simulation

Engine Speed [rpm]	1200	λ [-]	1.82	IMEP [bar]	6.7	IP [°CA BFTDC]	13



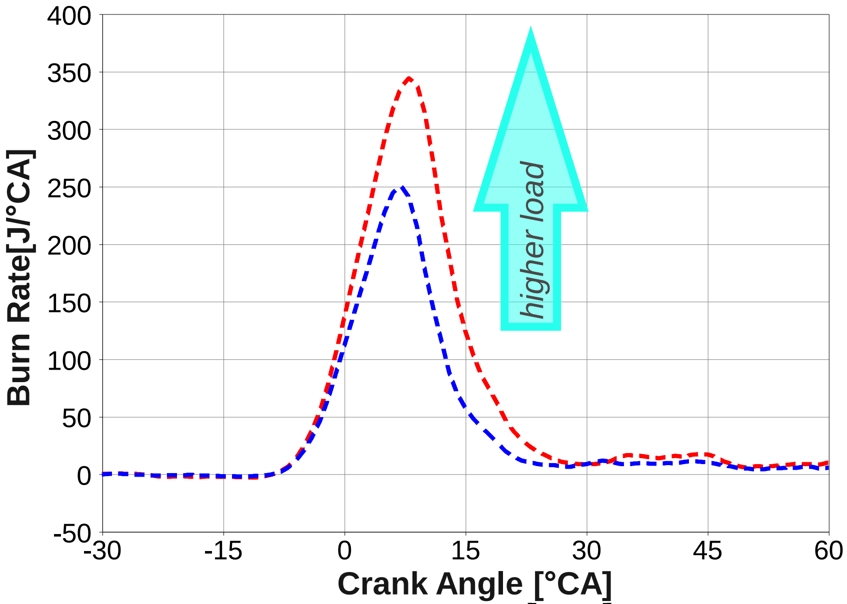


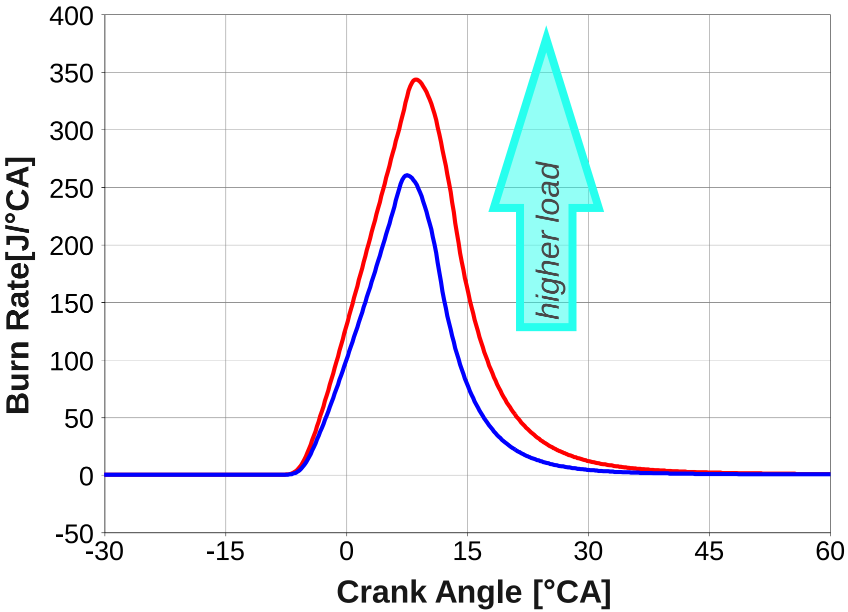
Load Variaiton

Measurement

Simulation

Engine Speed [rpm]	1200	λ [-]	1.86	IMEP [bar]	7-11	IP [°CA BFTDC]	12





Integral Values

Comparison measurement/simulation for all investigated operating points

- From left to right:
  - 1st measurement series (OP1-12): Ignition timing variation, no EGR, lower load
  - 2nd measurement series (OP13-24): Ignition timing variation, low EGR, lower load
  - 3rd measurement series (OP25-36): Ignition timing variation, middle EGR, lower load
  - 4th measurement series (OP37-50): Ignition timing variation, high EGR, lower load
  - 5th measurement series (OP51-57): Ignition timing variation, no EGR, higher load
  - 6th measurement series (OP58-68): Ignition timing variation, middle EGR, higher load
  - 7th measurement series (OP69-79): Ignition timing variation, high EGR, higher load

Comparison Measurement – Simulation

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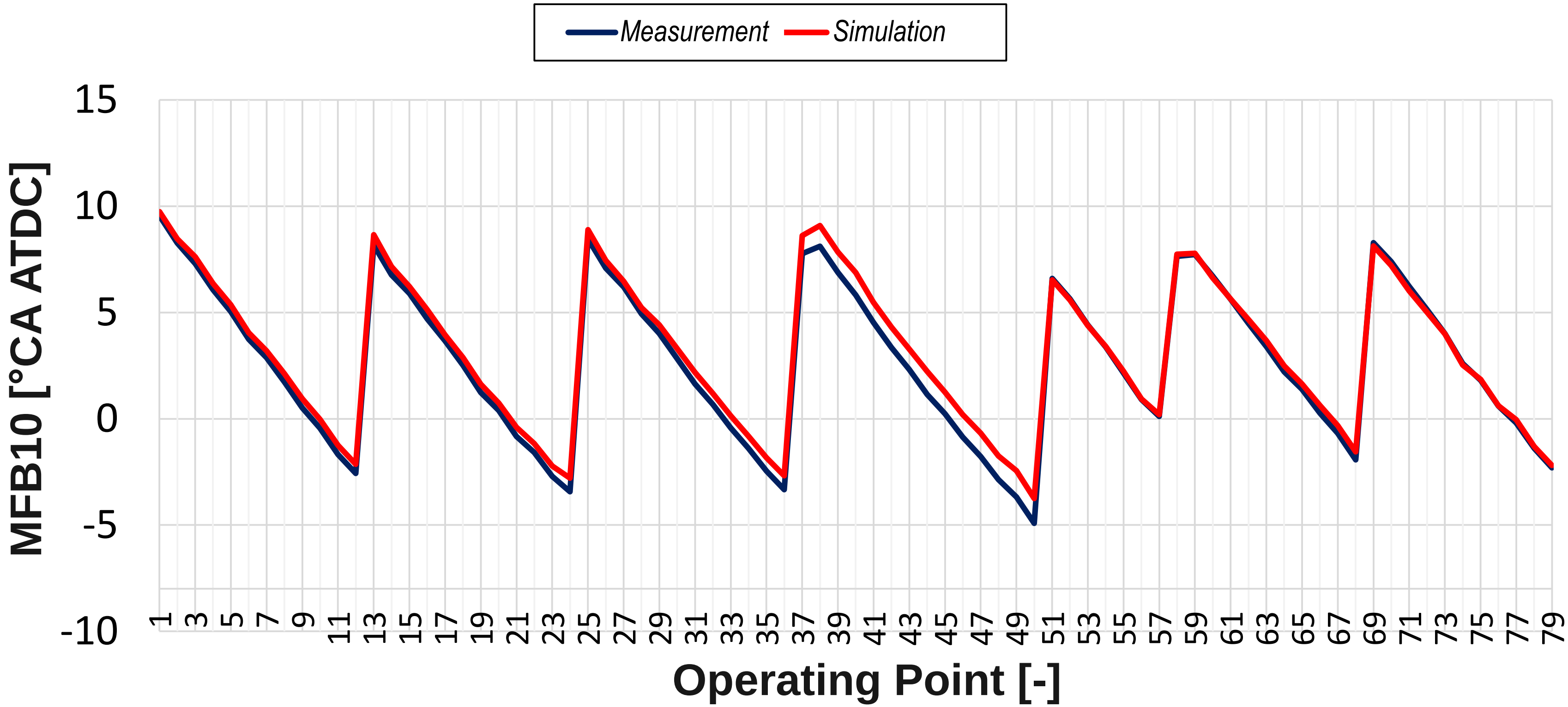
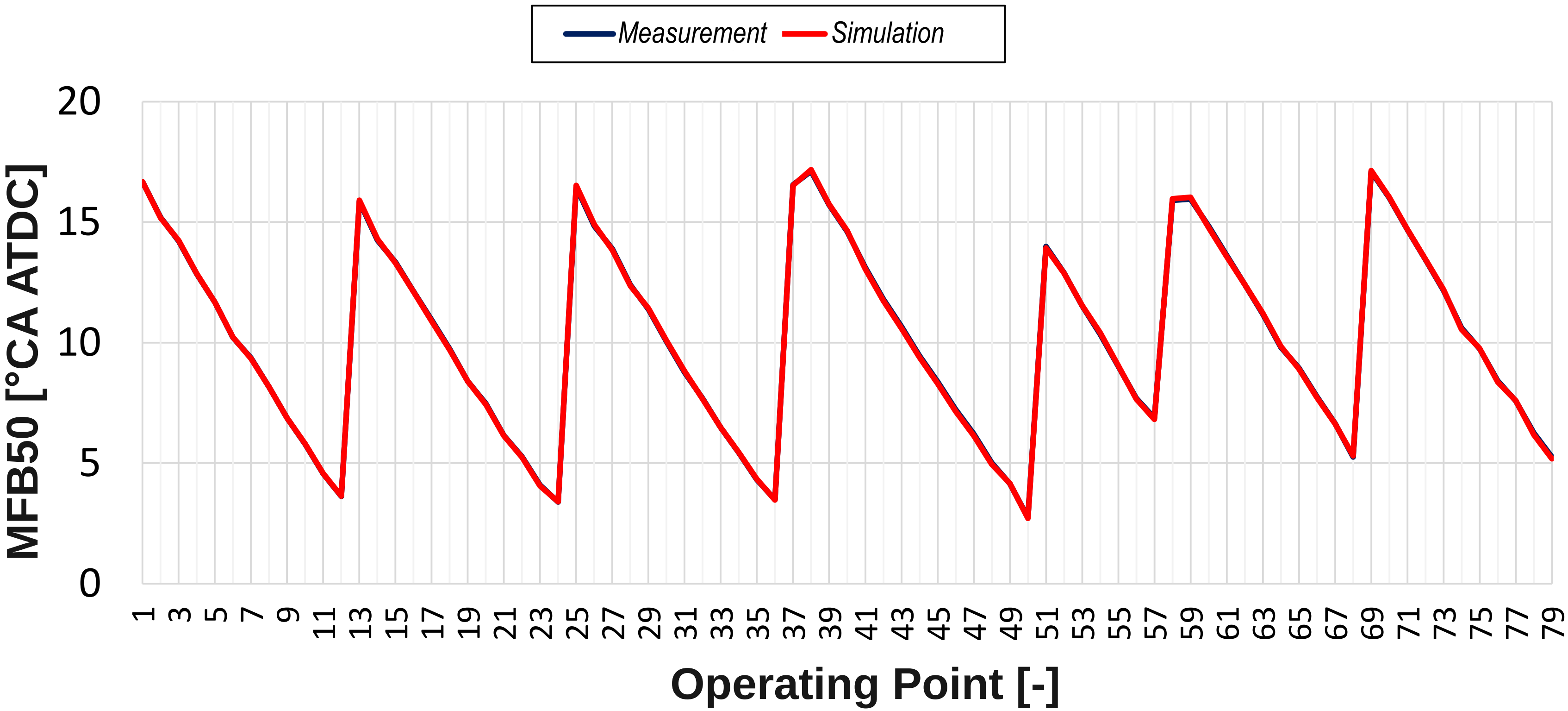
Mass of fuel burned 10%



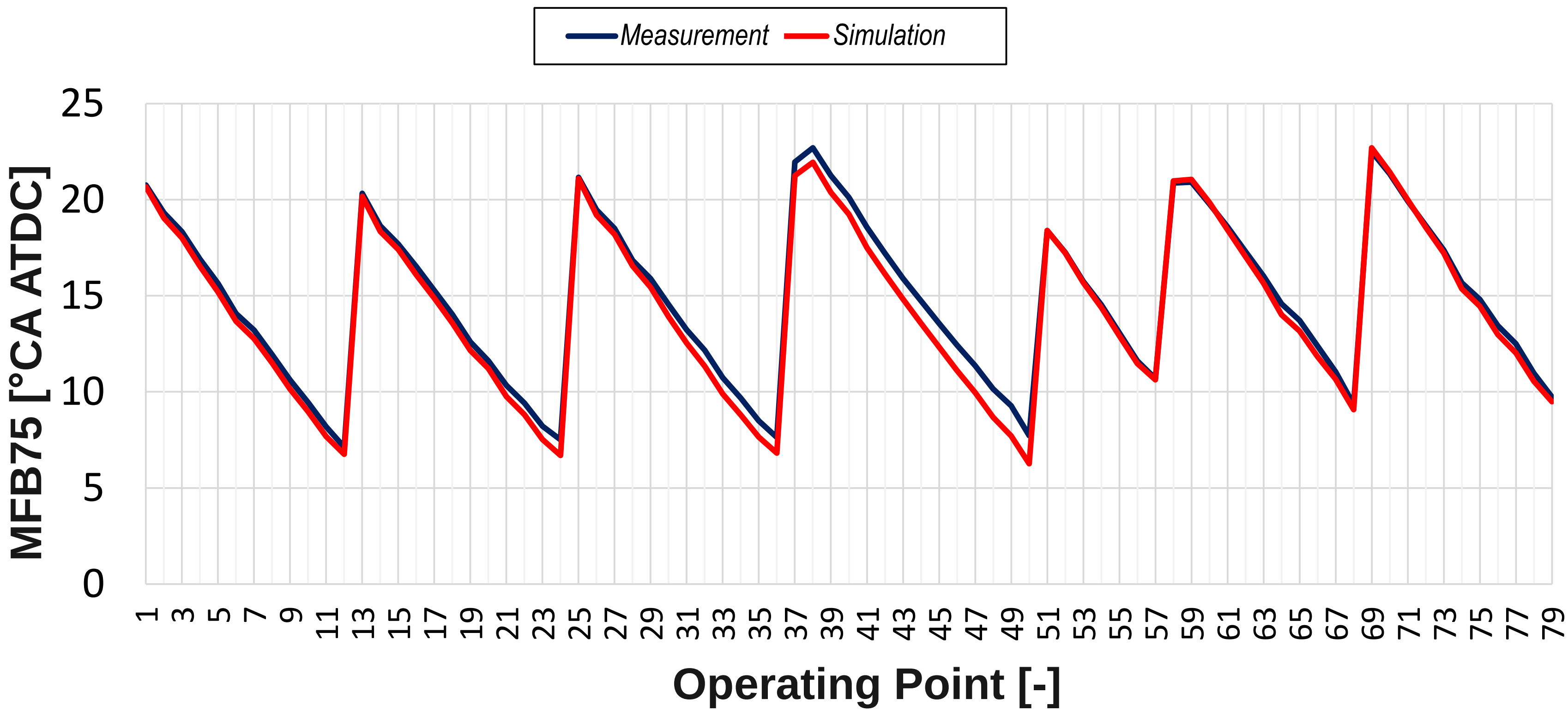
Comparison Measurement – Simulation

Mass of fuel burned 50%



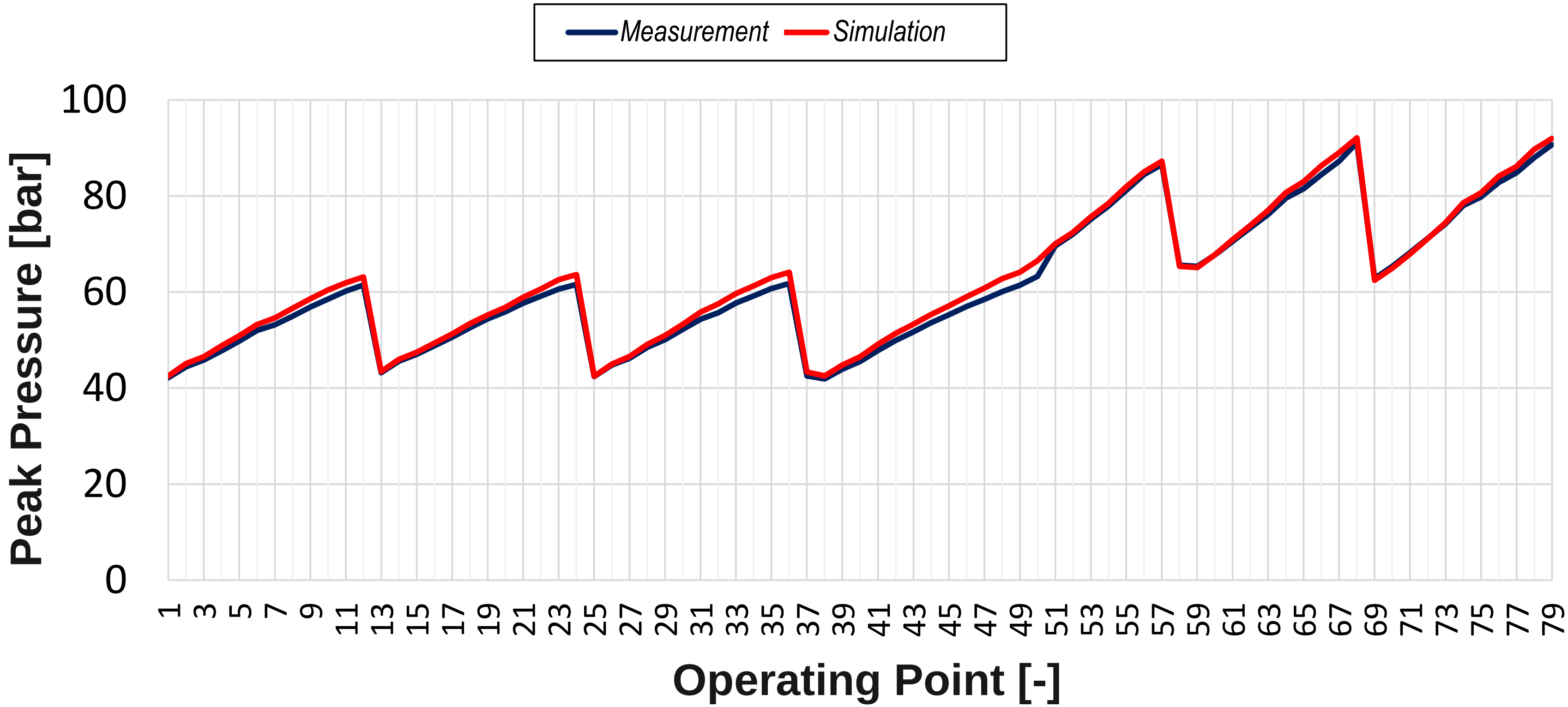
Comparison Measurement – Simulation

Mass of fuel burned 75%



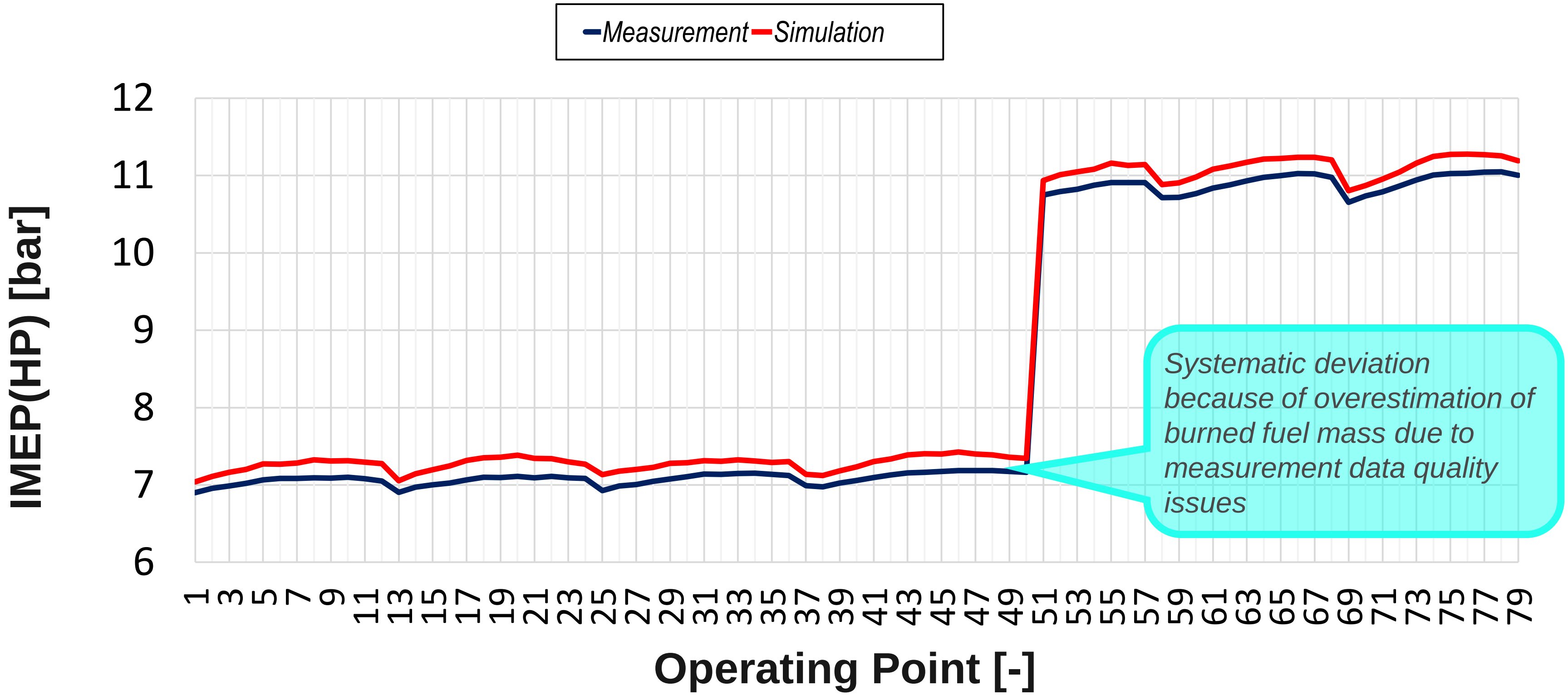
Comparison Measurement – Simulation

Peak Pressure



Comparison Measurement – Simulation

IMEP high pressure part



Final Combustion Phase

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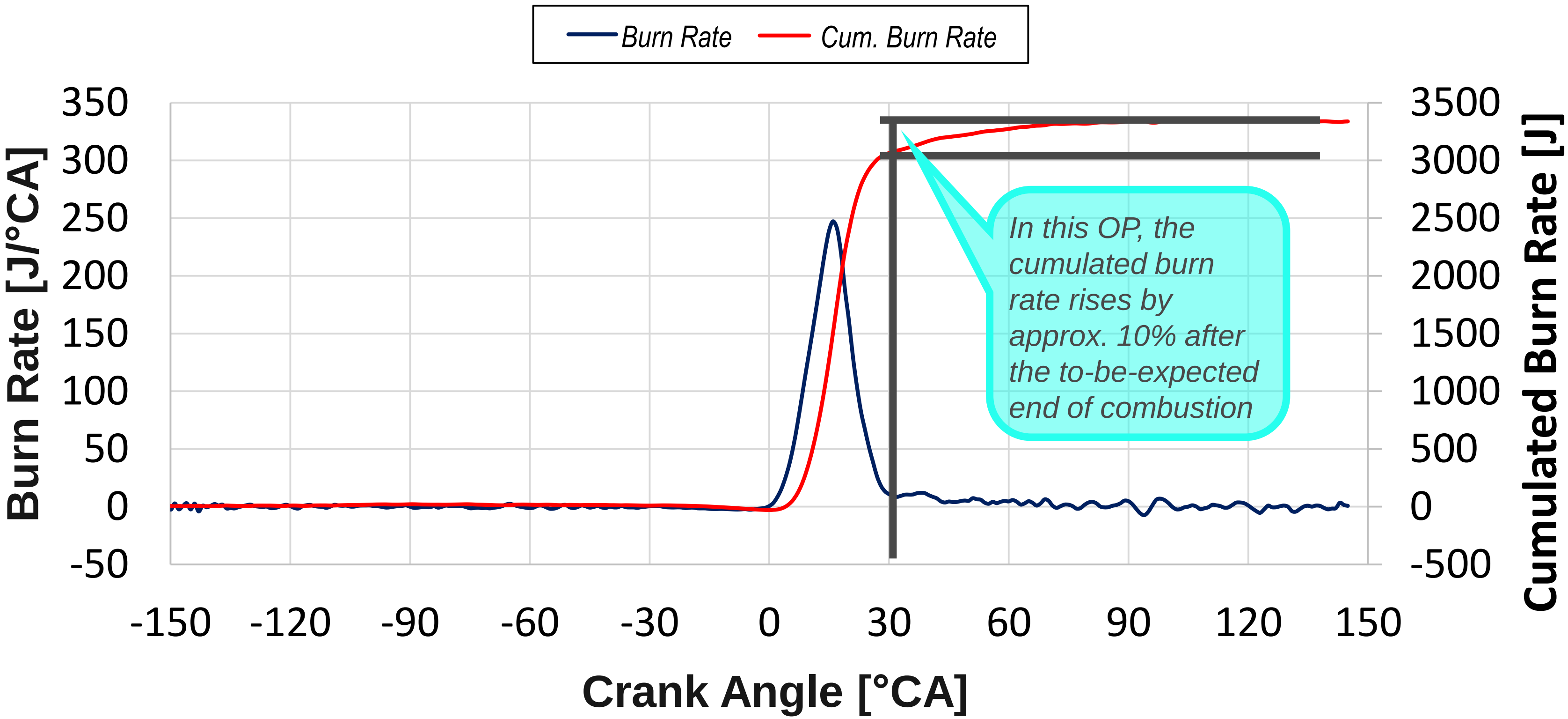
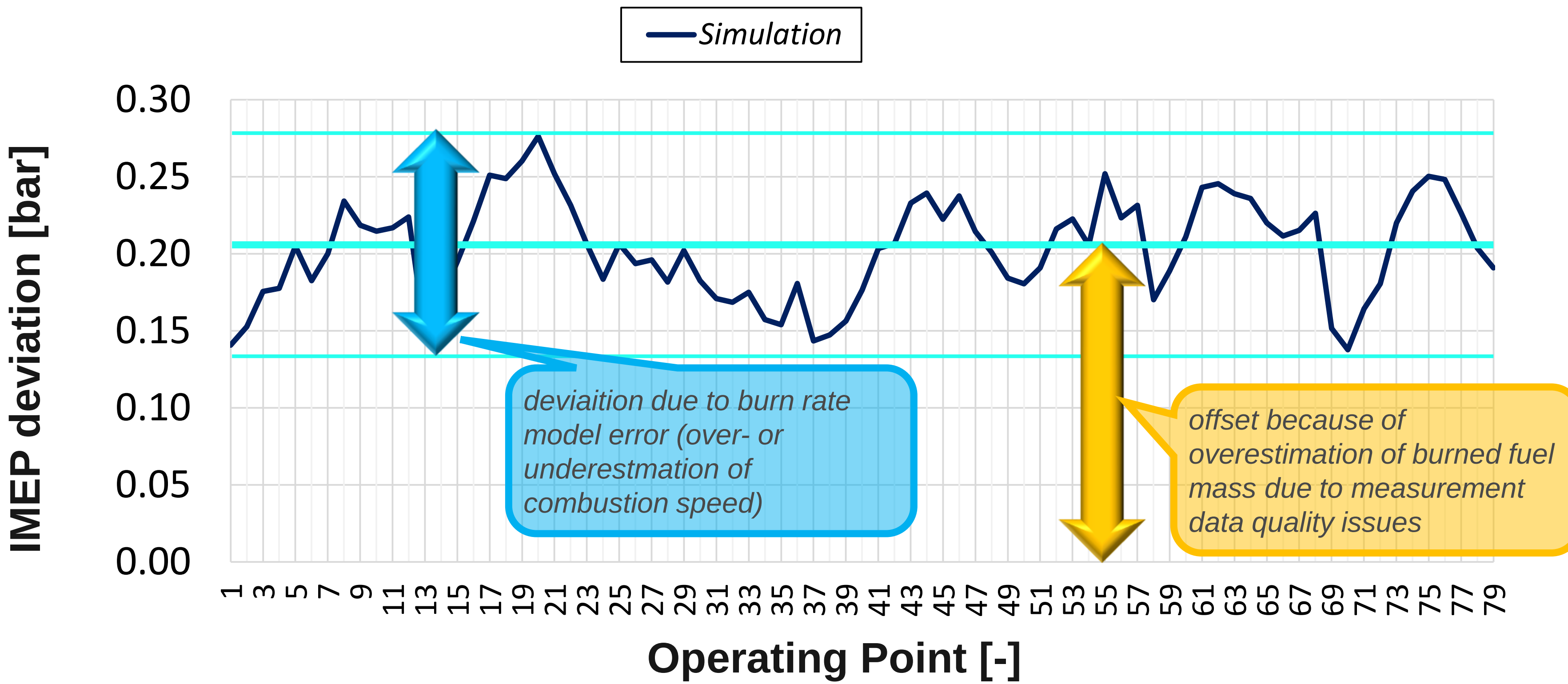
Problematic measurement data



Comparison Measurement – Simulation

IMEP deviation



Comparison Measurement – Simulation

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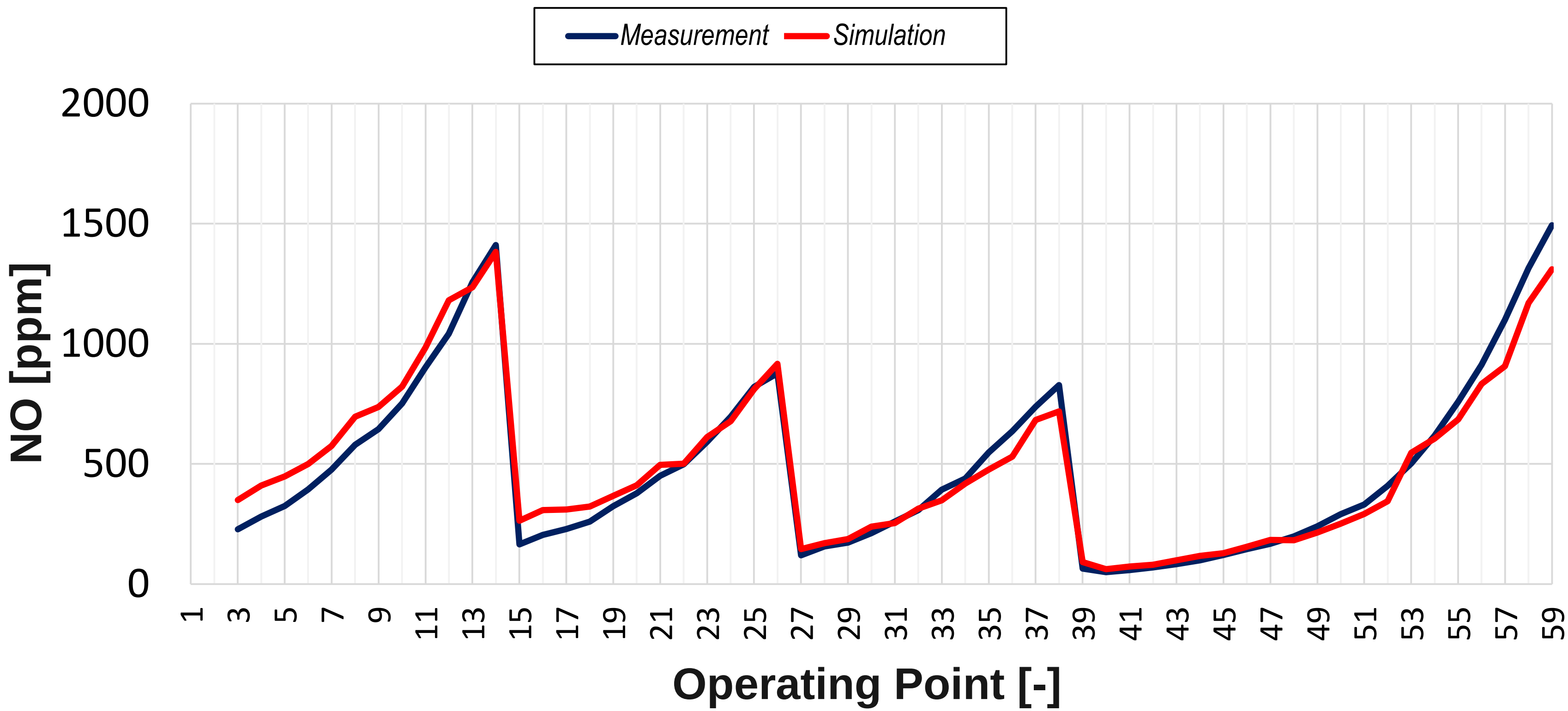
NO_x model



Conclusion

Overall Assessment

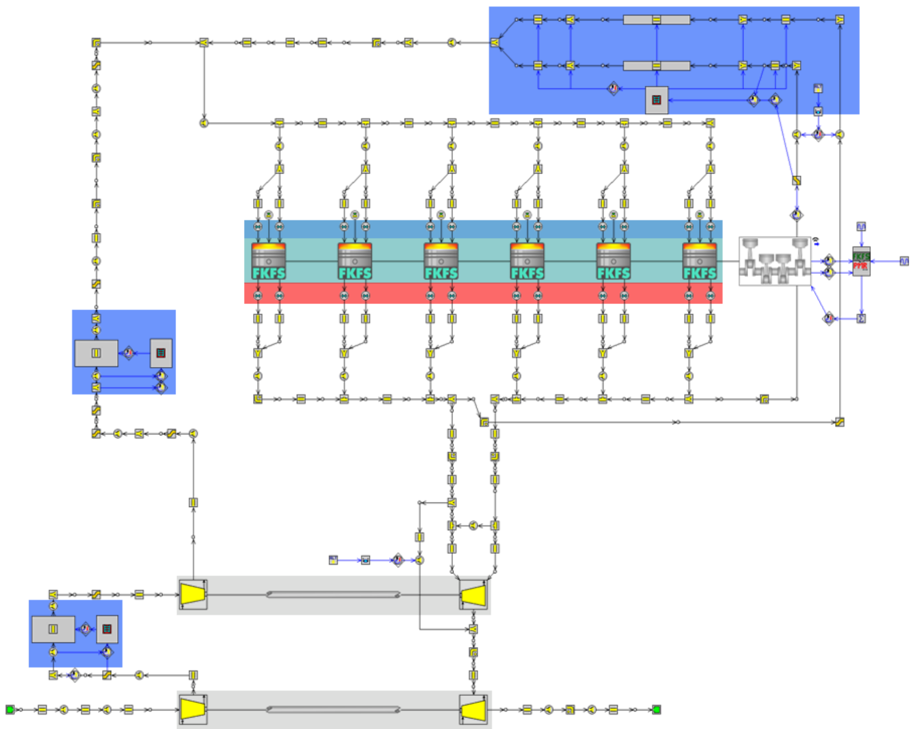
Model quality

- Calibrating **one single** operating point using **one single** tuning parameter that is kept constant is sufficient to get an excellent match between measured and simulated burn rates
- The model reacts correctly to any changes in control parameters (both from a quantitative and a qualitative point of view)
- IMEP deviation are very low in spite of measurement data quality issues that lead to a systematic overestimation of ÍMEP; simulated peak pressure is in very good agreement with measurement as well.
- The *shape* of the burn rate can be reproduced very well as well; the remaining, very minor deviations that can be observed in the calibration point are mainly due to the problematic measurement data showing implausible behaviour in the final phase of combustion.
- The NO_x model is in good agreement with measurement as well
- **Basic configuration for investigation of hydrogen combustion is ready to use**

Coming Up Soon

Virtual development engine

- The calibration shown in this presentation will be integrated for use in a heavy-duty engine model (MAN D2676) by FKFS.
- **This model can be used for concept studies and virtual engine development.**



Thank you very much.

Dr.-Ing.

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Simulation 0D/1D

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