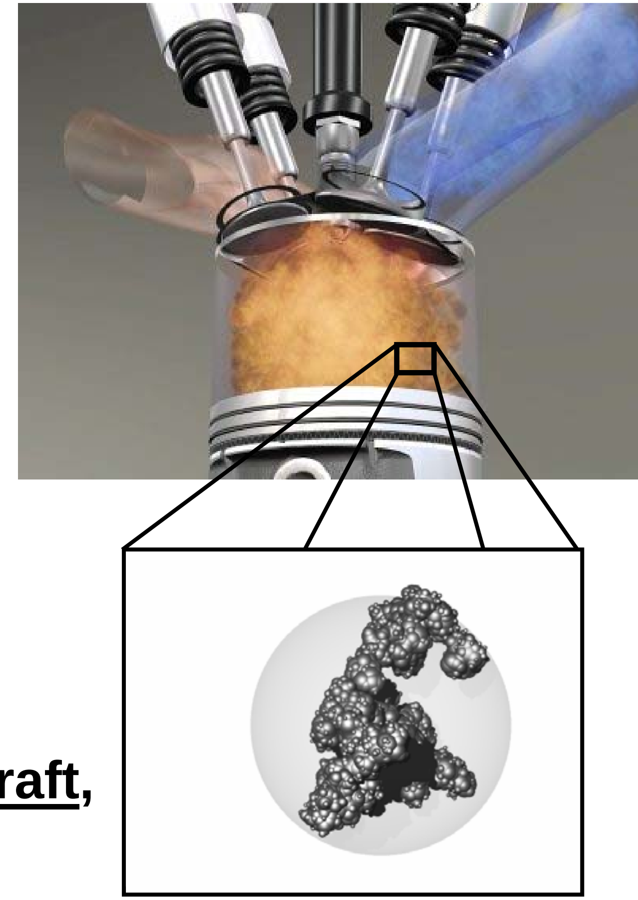
Soot modelling in direct injection spark ignition and diesel engines



Jonathan Etheridge, Sebastian Mosbach, Andreas Braumann, George Brownbridge, Andrew Smallbone, Amit Bhave, Markus Kraft, Hao Wu, Nick Collings

University of Cambridge

Antonis Dris, Robert McDavid

Applied Research Europe, Caterpillar Inc.

Technology Strategy Board

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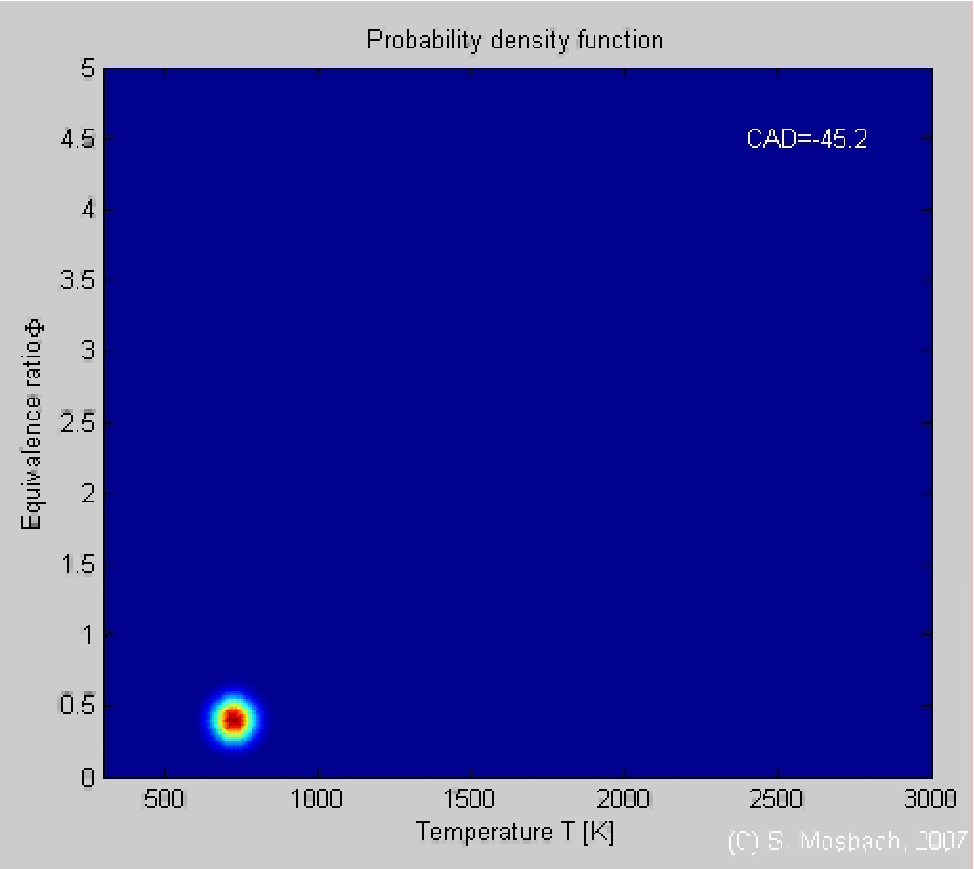
21st May 2010

UNIVERSITY OF CAMBRIDGE

Stochastic Reactor Model (SRM)

- Simulates closed-volume in-cylinder processes.
- Models turbulent mixing, convective heat transfer, direct injection, spark ignition, soot formation.
- Detailed chemical mechanism for PRF + NOx + soot precursors (208 species, 1002 reactions).



Test case:
PFI and DI at 40 CAD BTDC

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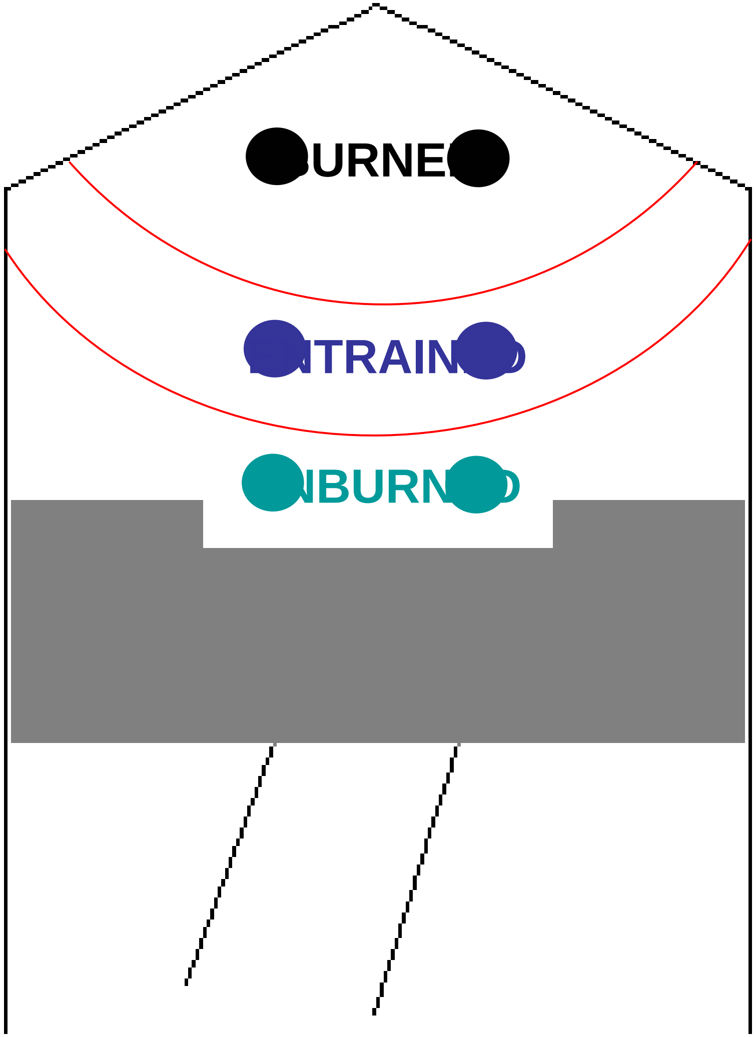
SI model



- The model contains three zones.
- Mixing occurs within each zone but not between zones.

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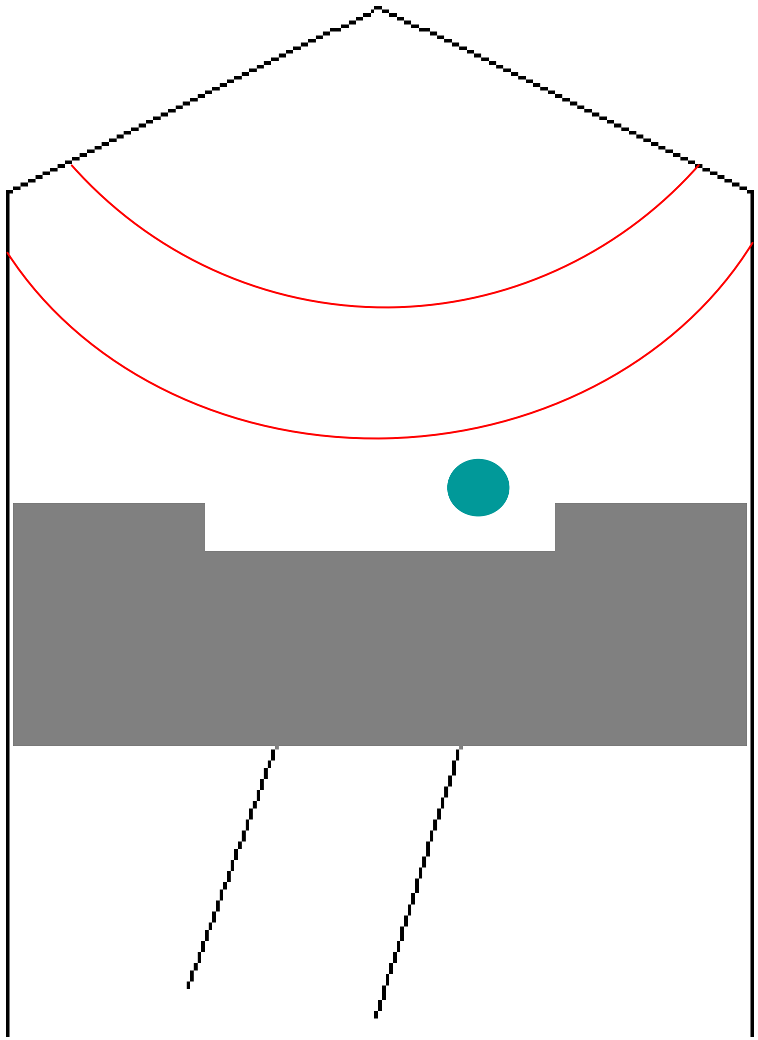

- The turbulent flame speed is used to calculate the new flame radius.
- When the calculated volume is greater than the particles' volume a new particle is added to the entrained zone.

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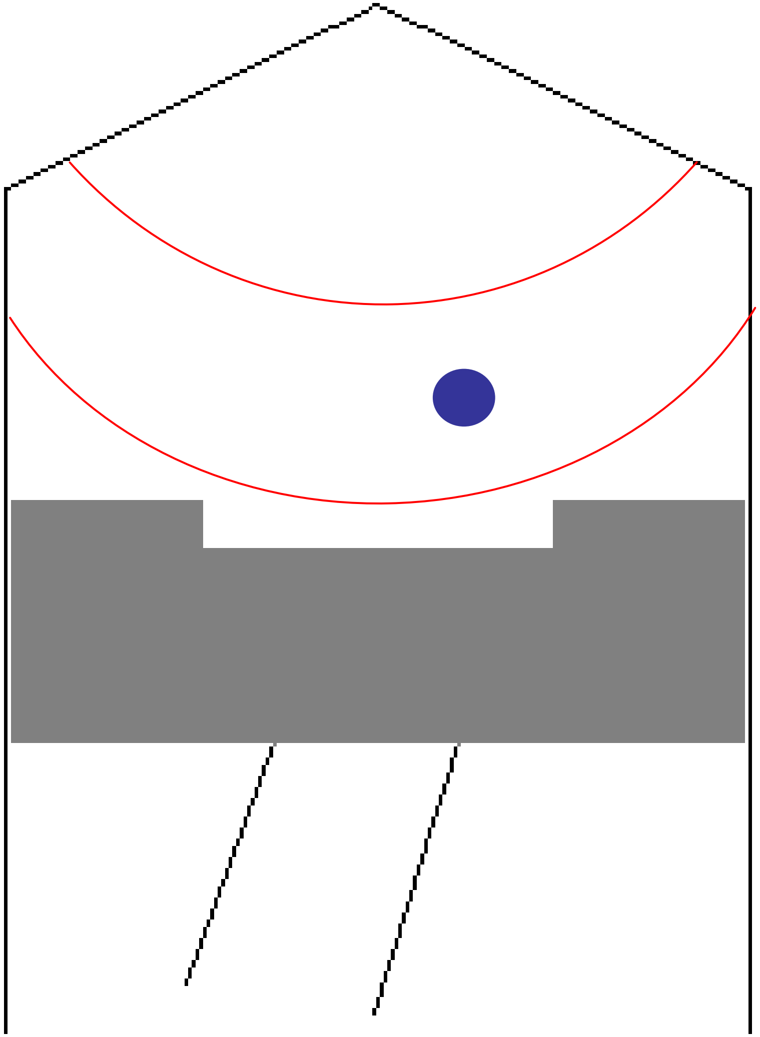
SI model



- Particles move from entrained to burned zone once heat release rate goes above then drops below a certain value.

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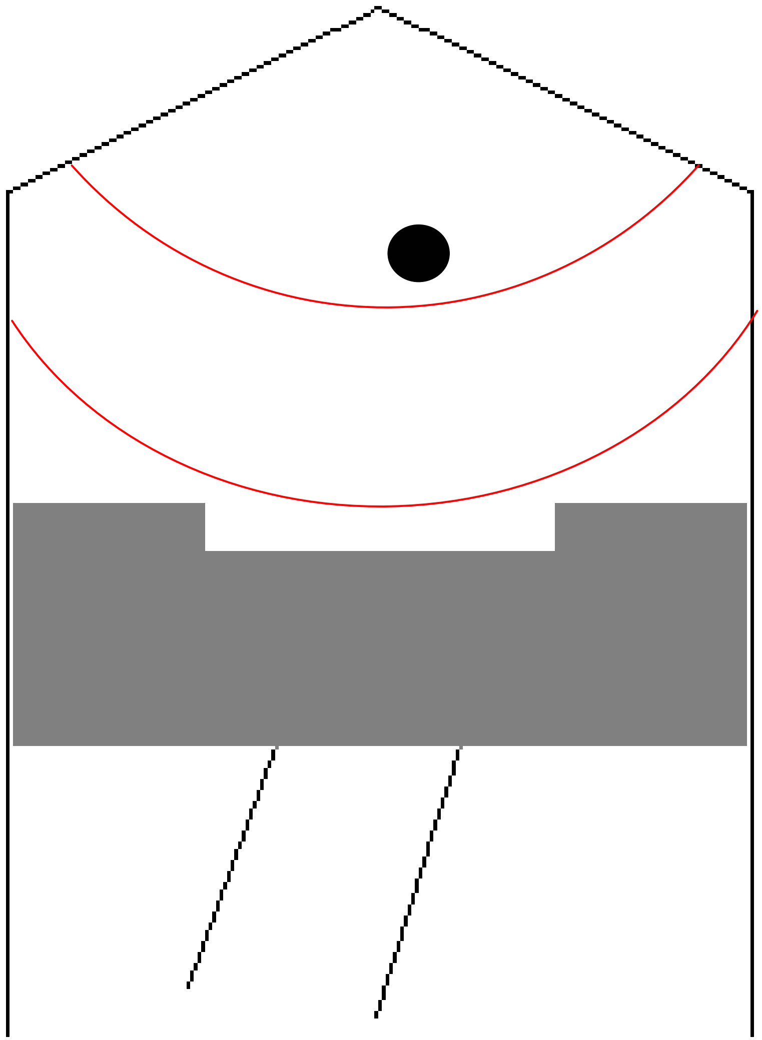
SI model



- The chemistry within each particle is calculated at each time step with the detailed mechanism.

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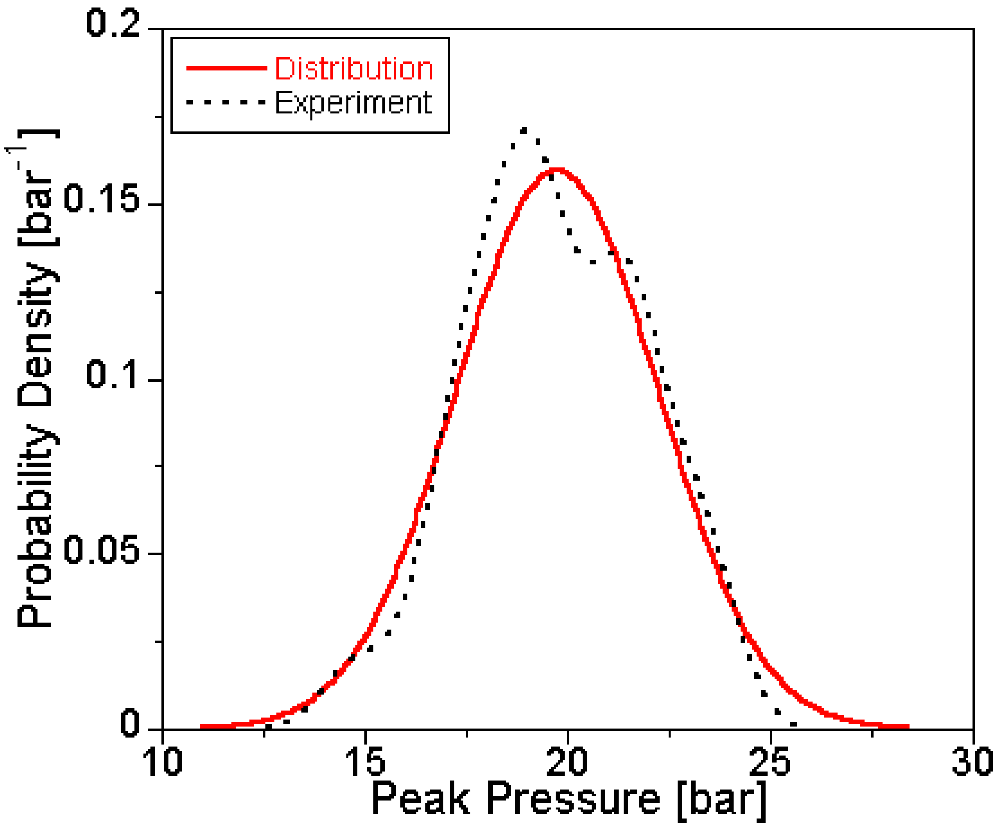
SI engine CCV

Cycle-to-cycle variation (CCV)



Fuel	gasoline
Bore	87.5 mm
Stroke	83.0 mm
Con. rod length	146.3 mm
Disp. volume	499 cm^3
CR	12.0
Speed	1500 RPM
Air/fuel equiv. ratio	1.0
EGR	28.8%

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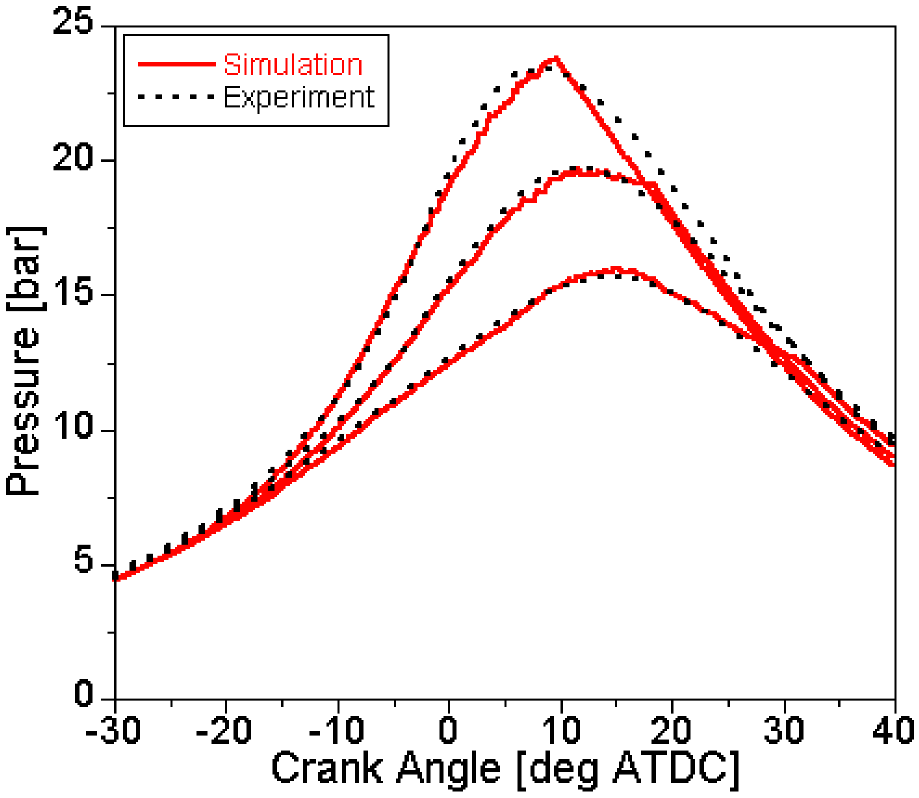
SI model calibration



- Characteristic flame speed obtained from:

$$u_T = 0.08 C \bar{u}_i \left(\frac{\rho_u}{\rho_i} \right)^{1/2}$$

- Constant, C, calibrated to match representative slow, medium and fast cycles.

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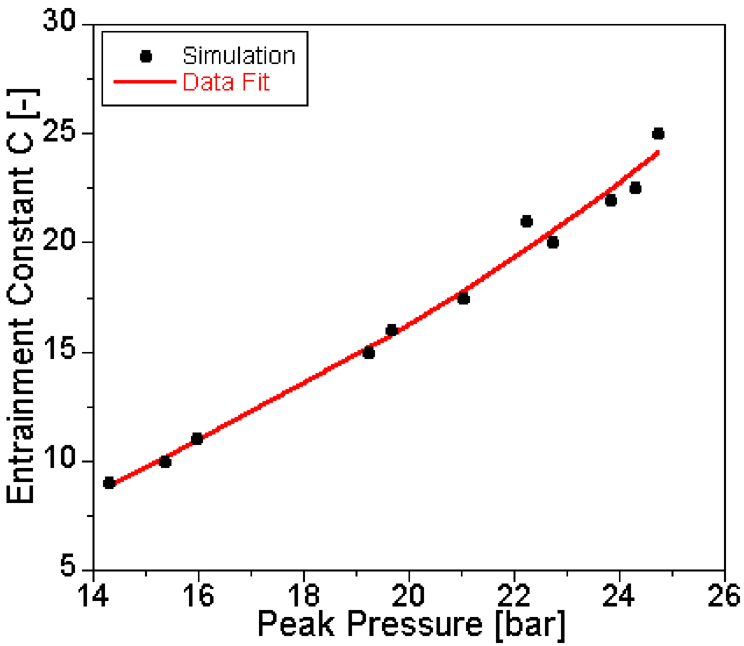
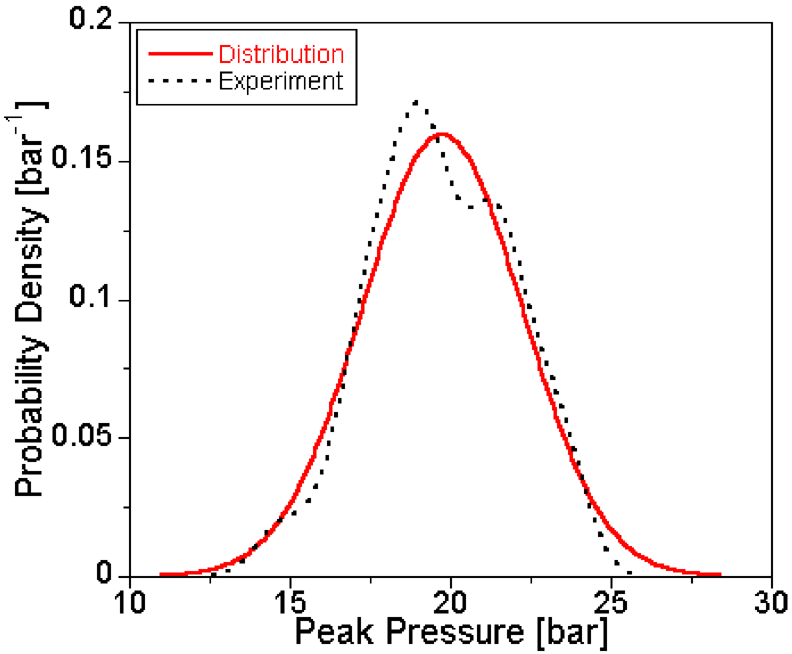
SI model calibration

- Relation between C and the peak pressure obtained.
- Used with peak pressure distribution to provide C during each cycle of a multi-cycle simulation.





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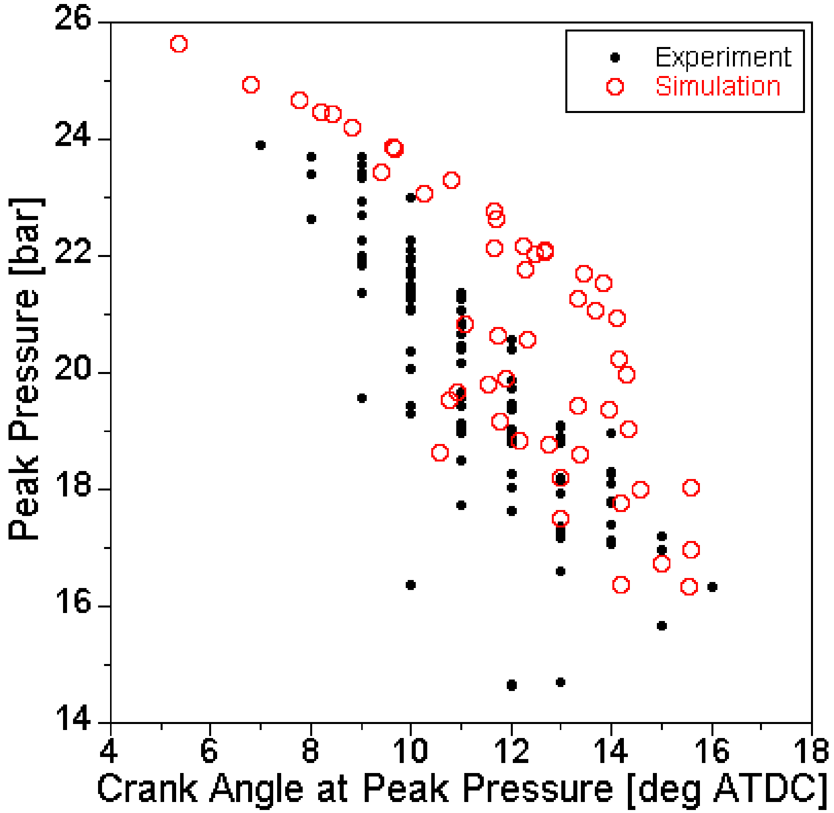
Multi-cycle SI simulation



- Model coupled to GT-Power for multi-cycle simulation.
- 50 simulated and 96 experimental cycles.
- NO_x emissions:
  - 790 ppm simulation
  - 530 ppm experiment

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DISI engine

Image from www.engineforall.com

- Late injection produces stratified mixture.
- Fuel rich regions close to spark gap.

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DISI engine experiments

- Data from Maricq *et al.*, SAE 1999-01-1530.
- Fuel comprised of 60% paraffin and 40% aromatic compounds.
- Fuel modelled as 60% iso-octane and 40% toluene.
- Exhaust measurements for various injection timings.

Cylinders	4
Bore [mm]	81.0
Stroke [mm]	89.0
Disp. volume [cm^3/cyl]	457.5
Compression Ratio	12

1500 RPM, Φ=0.58 (global)

Case	1	2	3	4	5
EOI [CAD ATDC]	-50	-60	-70	-75	-80
Spark Timing [CAD ATDC]	-19	-19	-19	-23	-31

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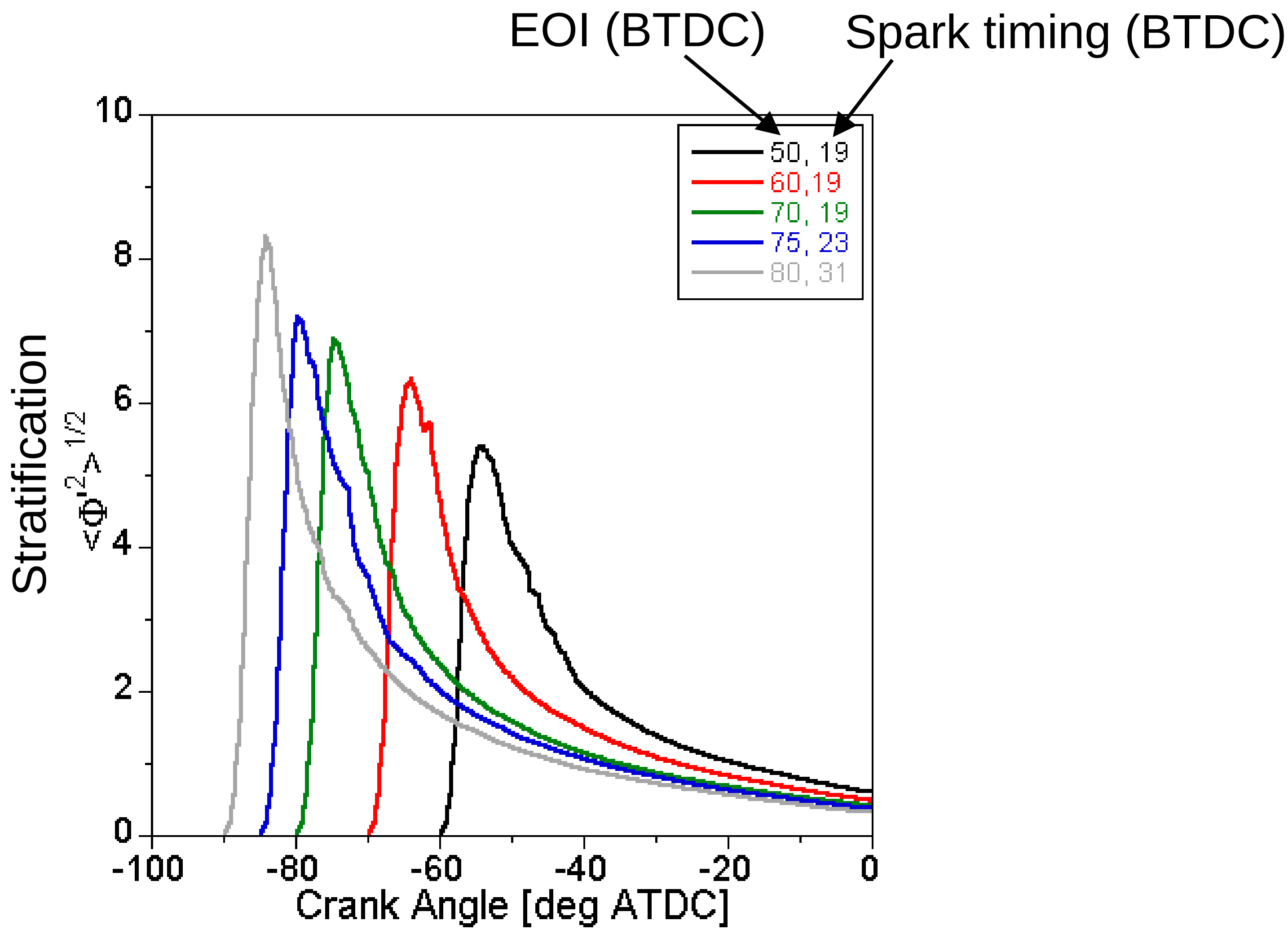
DISI engine simulation results



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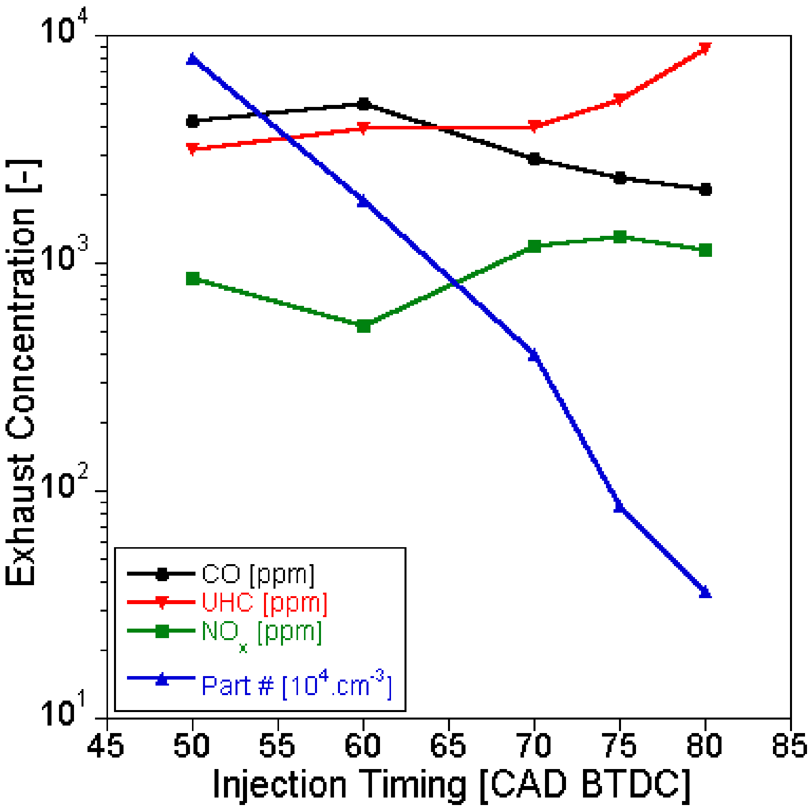
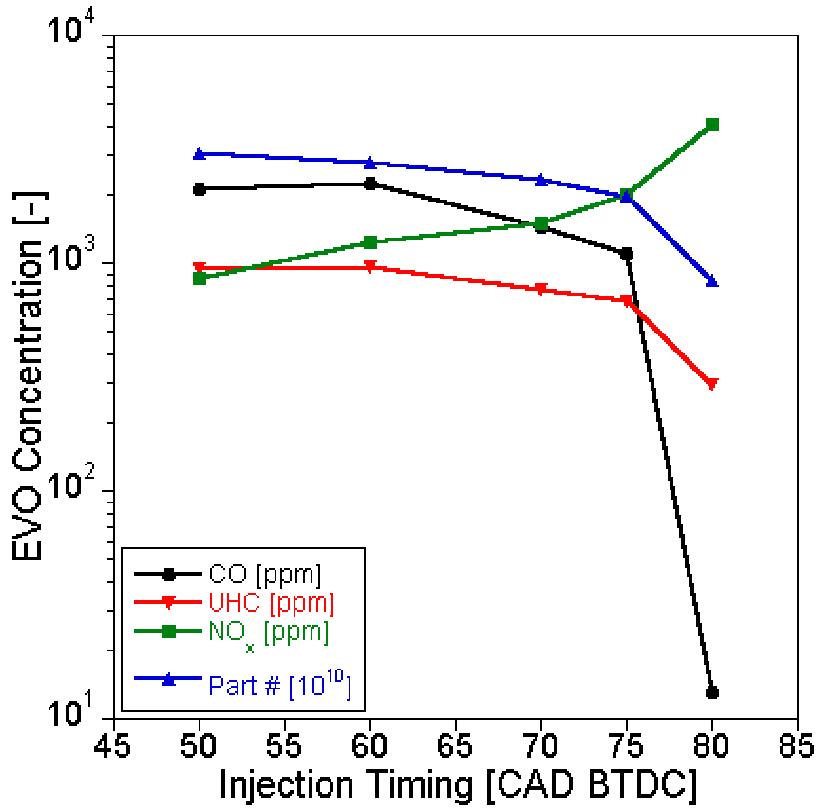
DISI engine emissions

Experiment



Simulation



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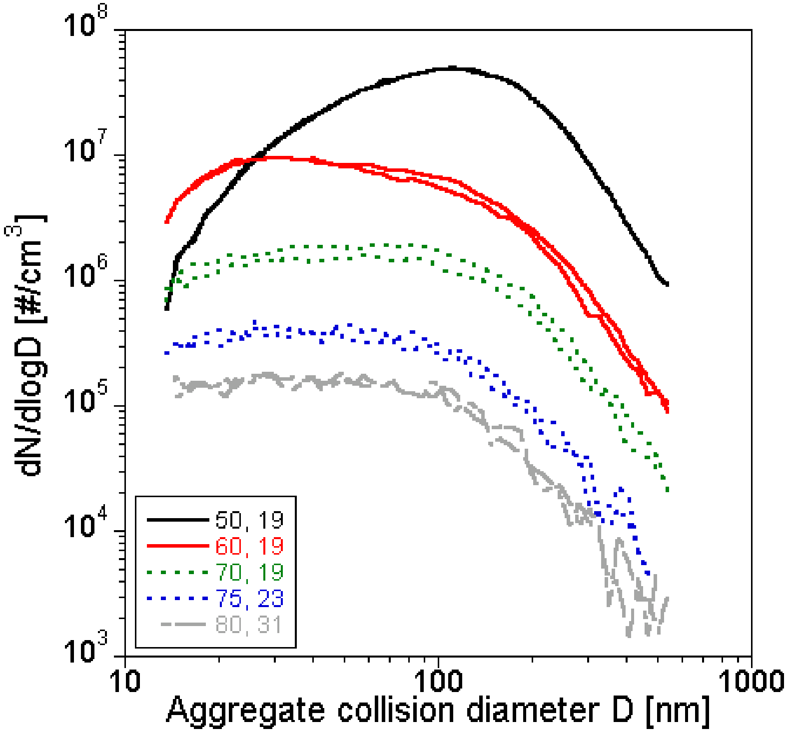
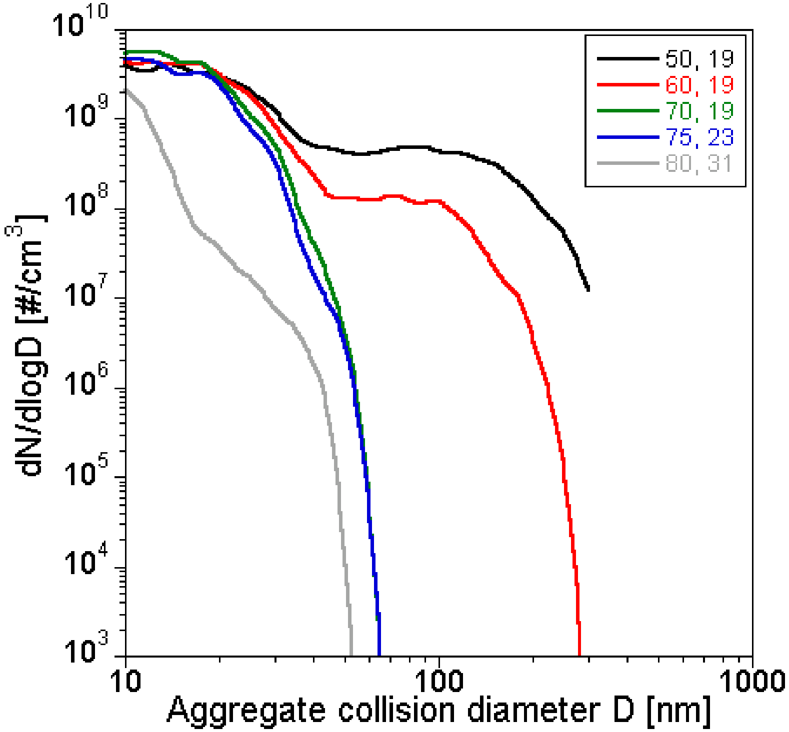
Particle size distributions

Experiment



Simulation



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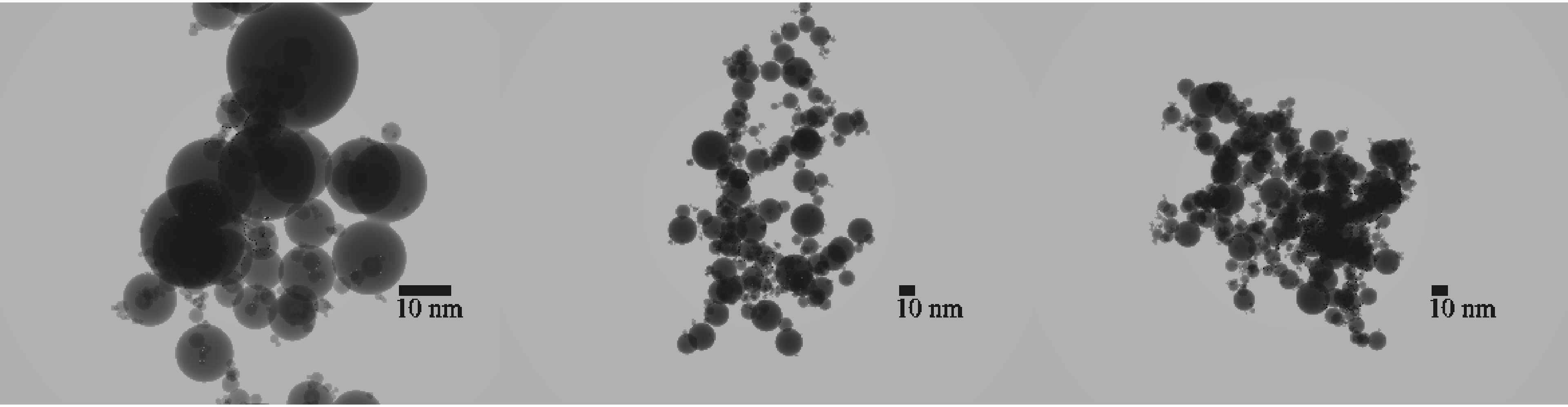
Soot in DISI engine

2.6 CAD ATDC | 12.6 CAD ATDC | 32.6 CAD ATDC



CAD [deg ATDC]	2.6	12.6	32.6
No. Primaries	492	1315	2083
Coll. Diam [nm]	70	108	137

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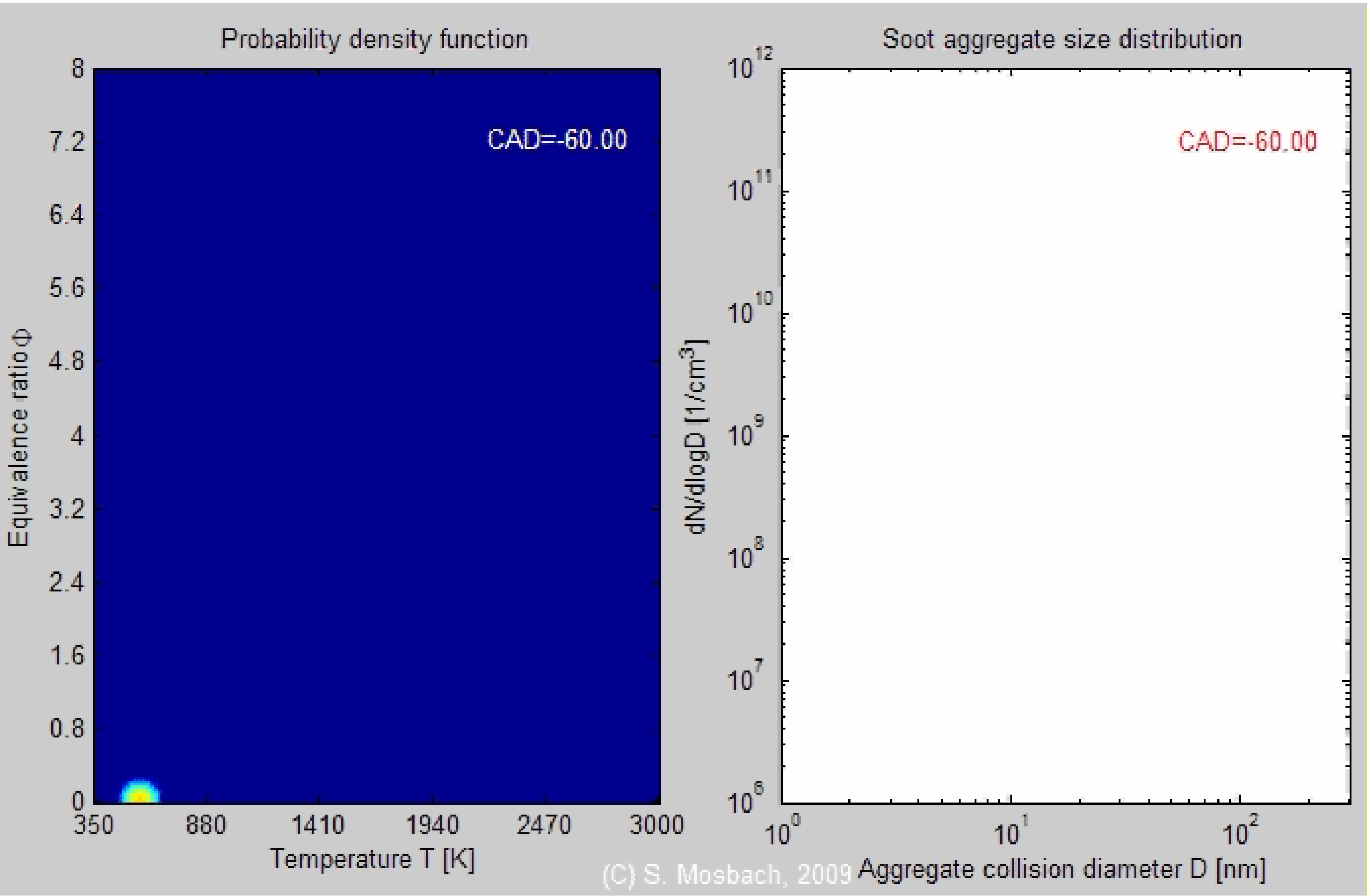
Temporal evolution (late injection)



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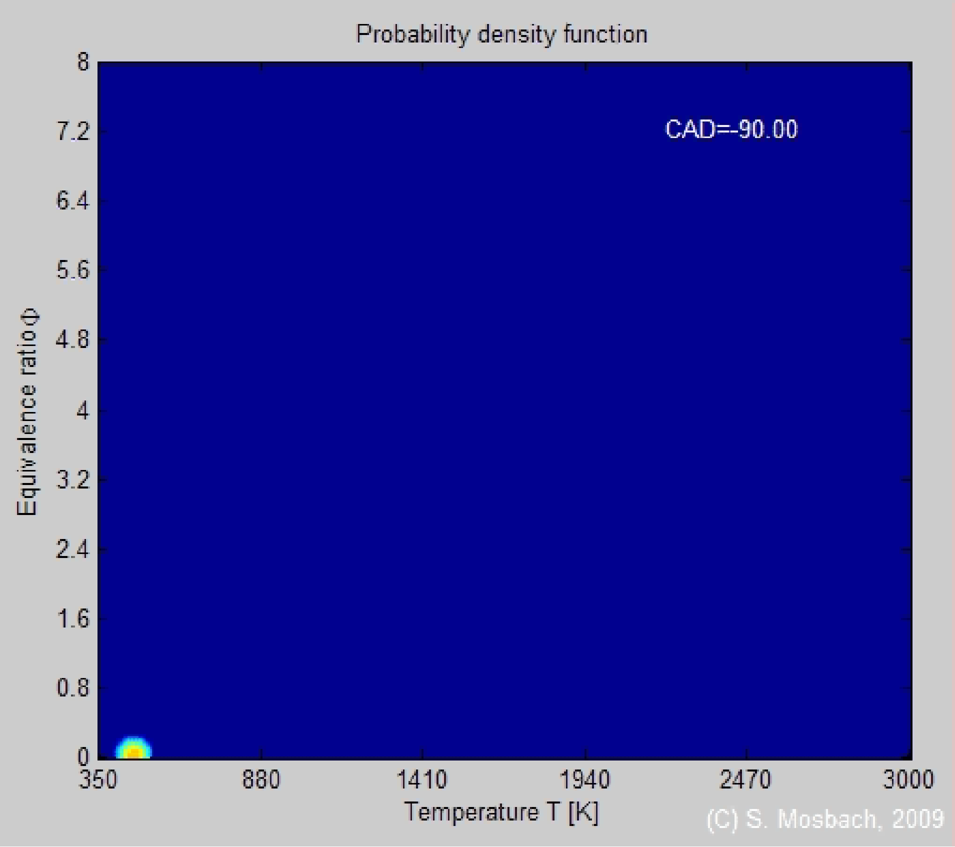
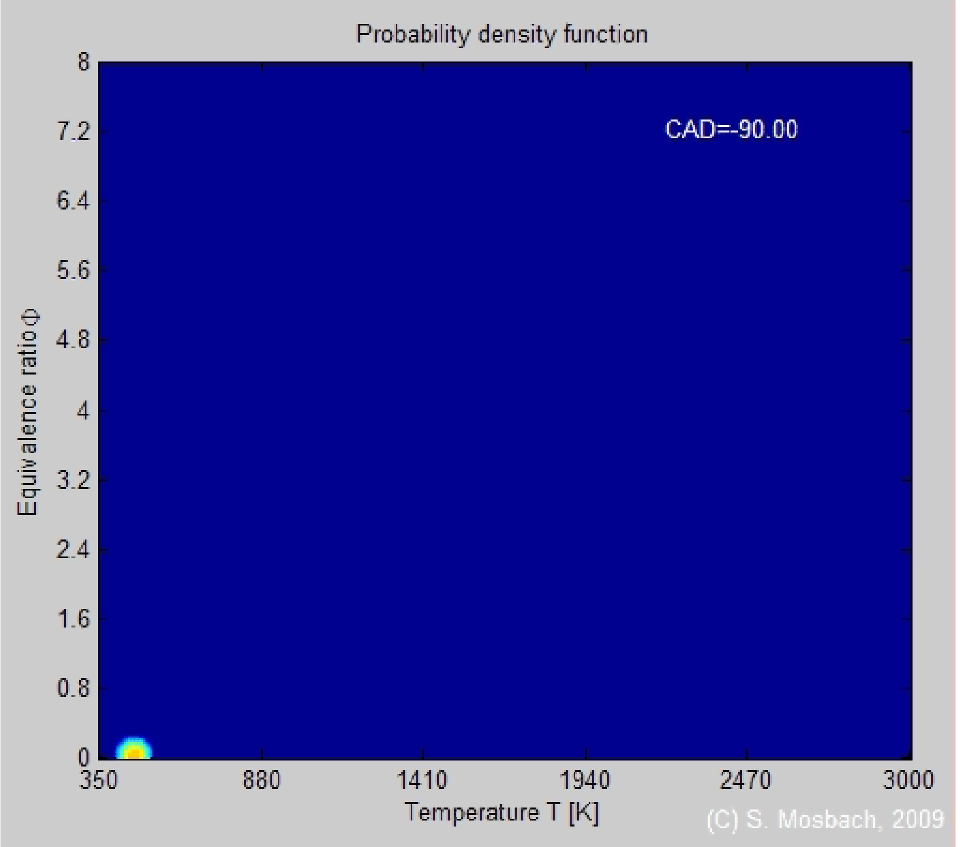
Comparison early/late injection

EOI -80 CAD ATDC
Spark -31 CAD ATDC



EOI -50 CAD ATDC
Spark -19 CAD ATDC



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Problem

Current engine model development

- Experimental data in a variety of formats, sometimes largely unstructured, often incomplete
- Uncertainties/errors associated with experimental data typically unknown or unavailable
- Too many models and “tuneable”/unknown model parameters
- How “good” (or not) is a particular model?

=> Ad hoc, fragmented, short-term approach

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Solution: Process Informatics

We need a robust **integrated methodology** to help us work systematically and efficiently:

- Effective use of cost-intensive experimental data through **data standardisation**
- Systematic and robust model development through **systematic optimisation**, taking into account **uncertainties**
- Suggesting “useful” future experiments

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A data model: engineML

Consistent format

- point data (e.g. rpm, CO, u_l)
- time resolved data (p-CA)
- apparatus (production engine, research engine)
- errors
- data type (consistent units)
- raw or processed
- experimental or model

eXtensible Markup Language (XML)

- machine and human readable, tagged with metadata
- highly structured (tree), easily queried
- can be validated against schema

Easily accessible database

- read by model code
- data stored consistently
- old data never “lost”

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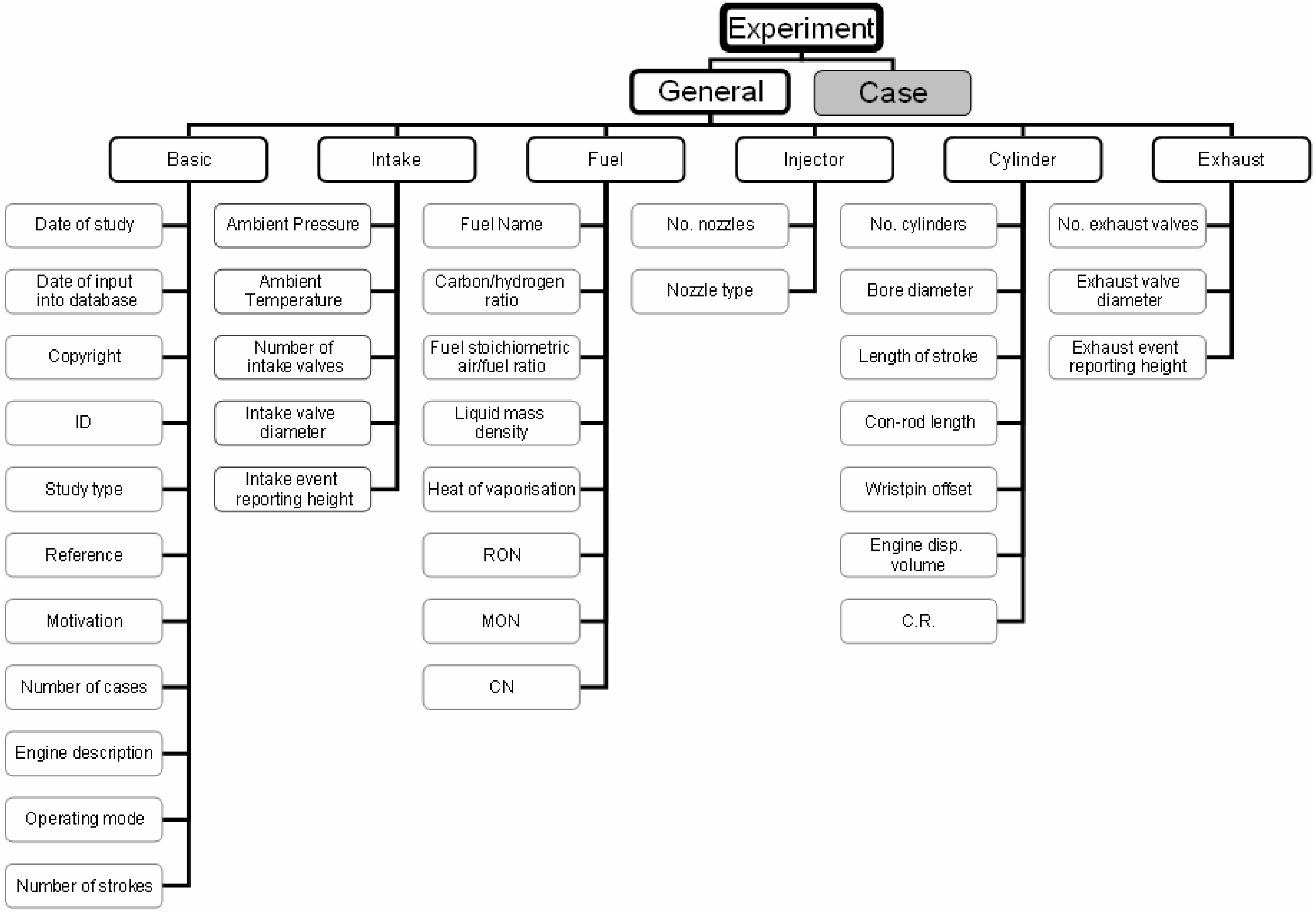
General data



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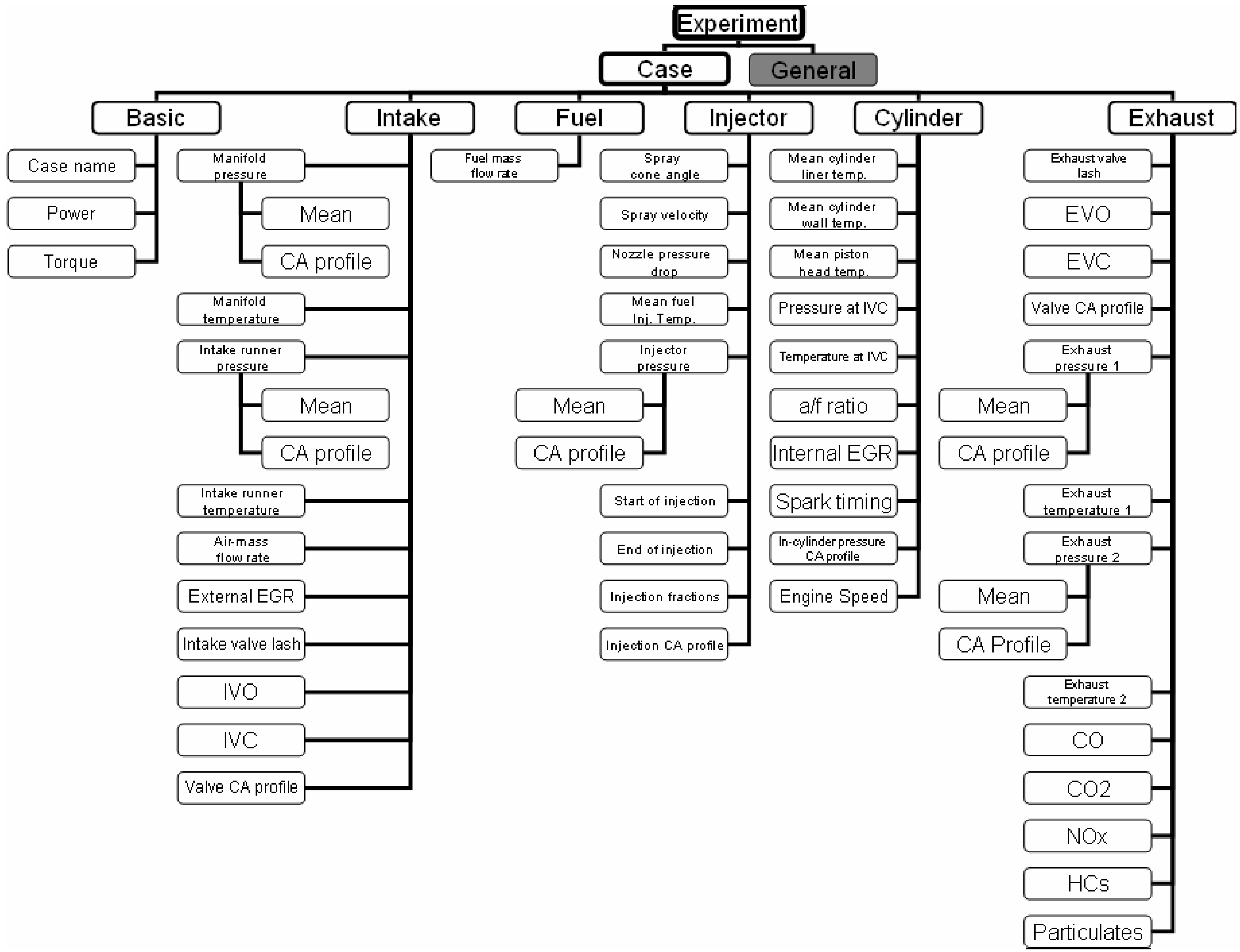
Case data



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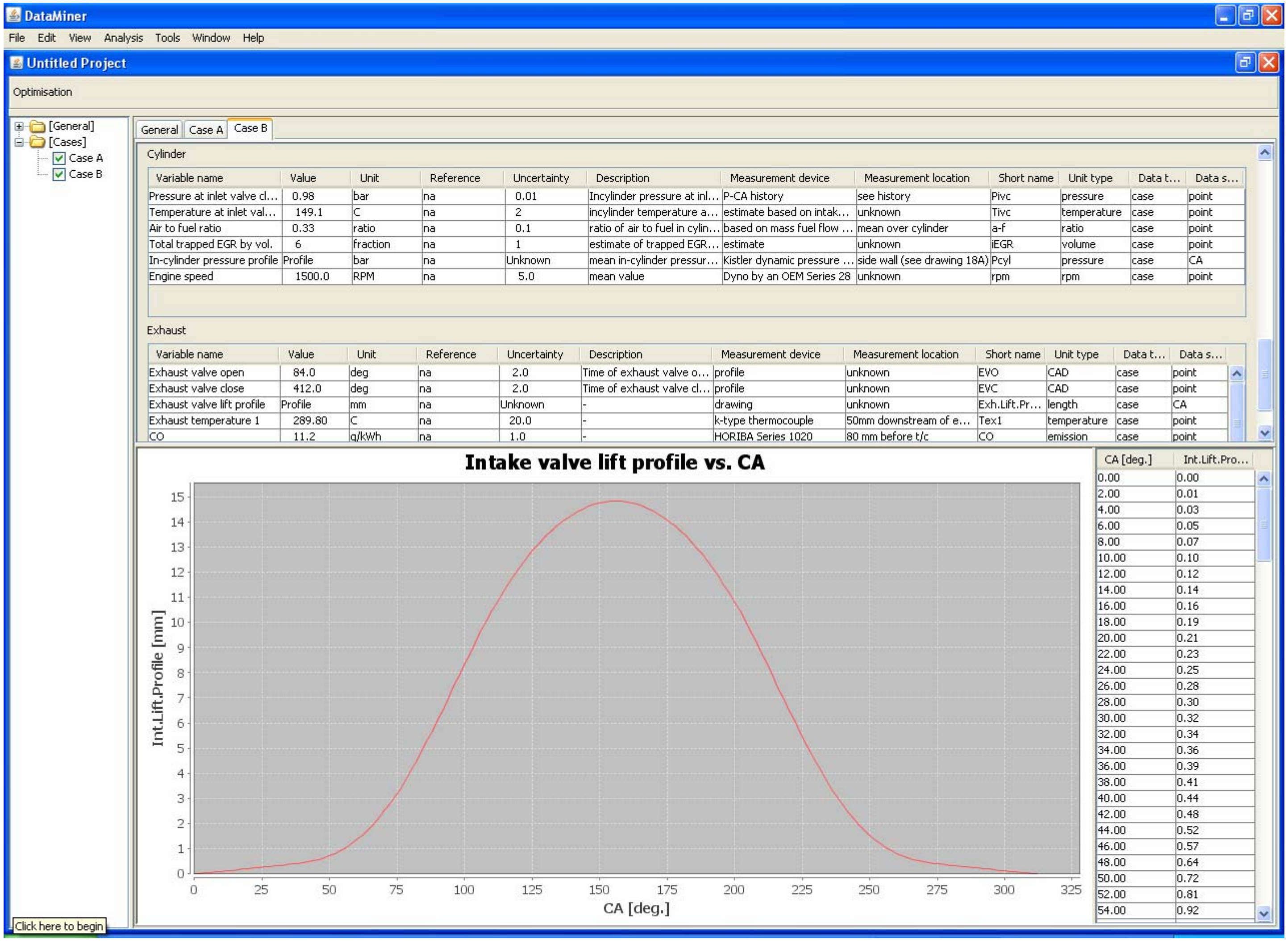
Data visualisation



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Model parameter optimisation

We must accept that model parameters exist and have to be tuned to experimental data!

What is the best way to fit these parameters?

- As many data points as possible
- Uncertainties in experimental data as well as model parameters must be accounted for
- Use experimental data to reduce model parameter uncertainties
- Use experimental and model uncertainties to identify possible outliers in the data, or model shortcomings

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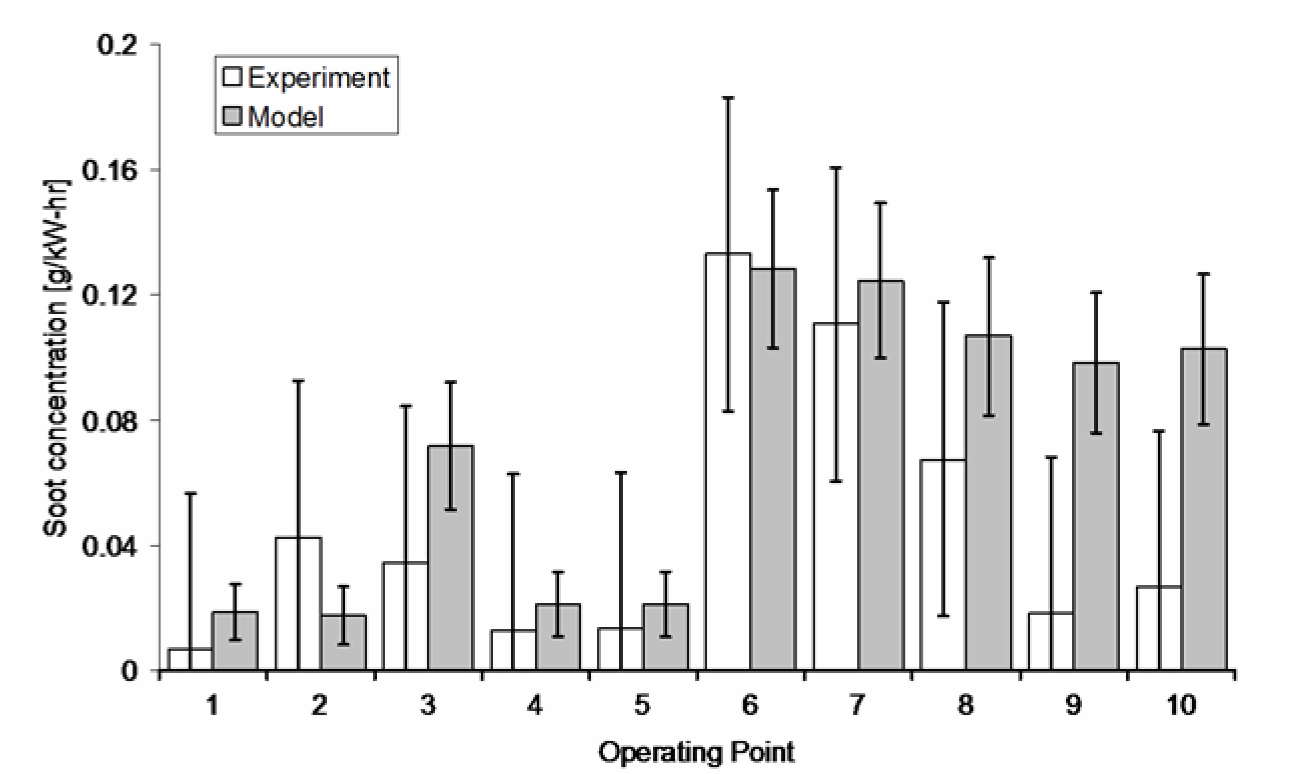
Application: Diesel soot

Empirical soot model (Plee):

$$soot[g] = A \cdot mps^B \cdot phi^C \cdot \exp\left(\frac{D}{T_f}\right)$$

Optimised parameters A, B, C, D, against database of 503 operating points from 7 engines



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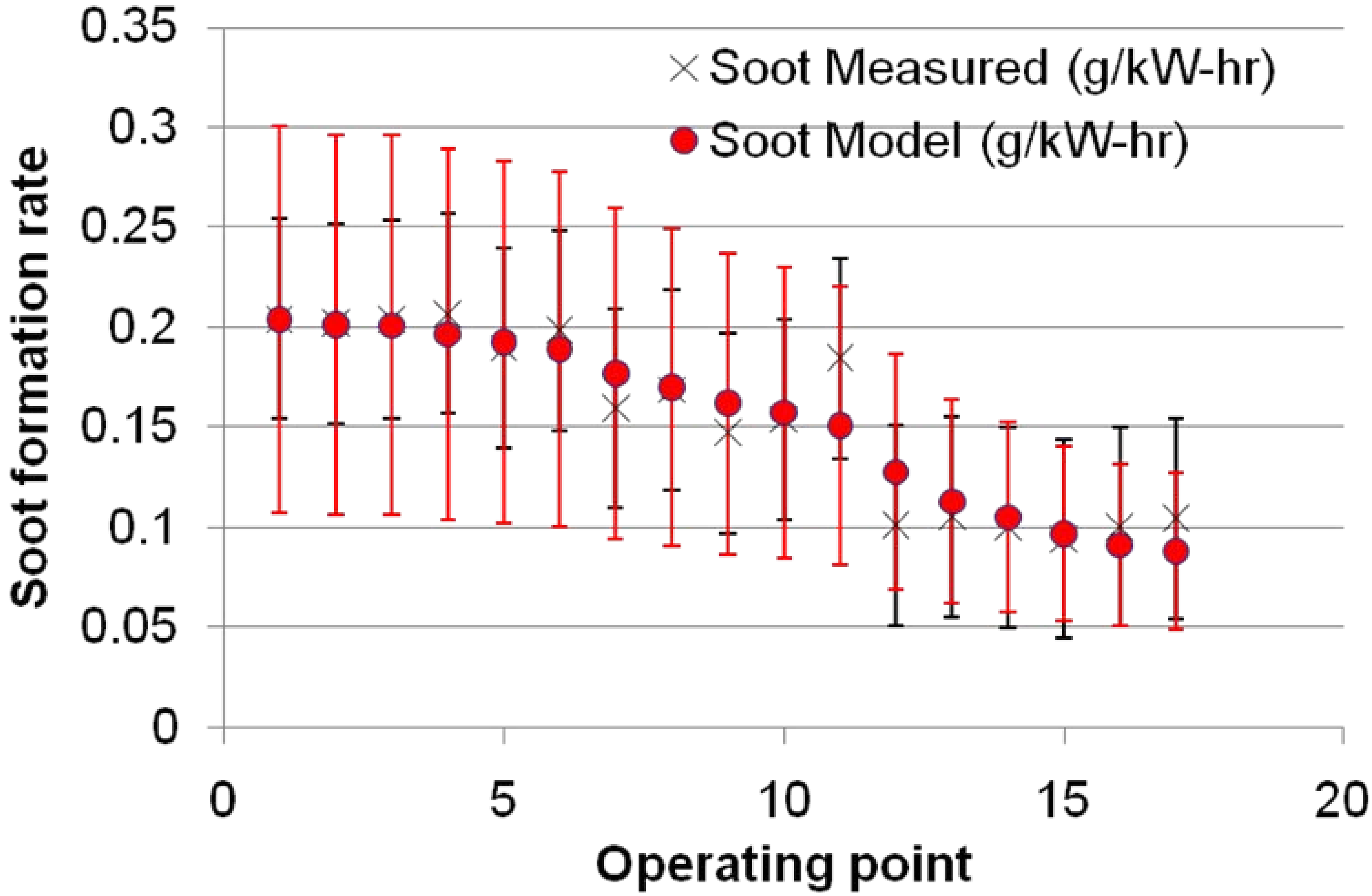
Example engine



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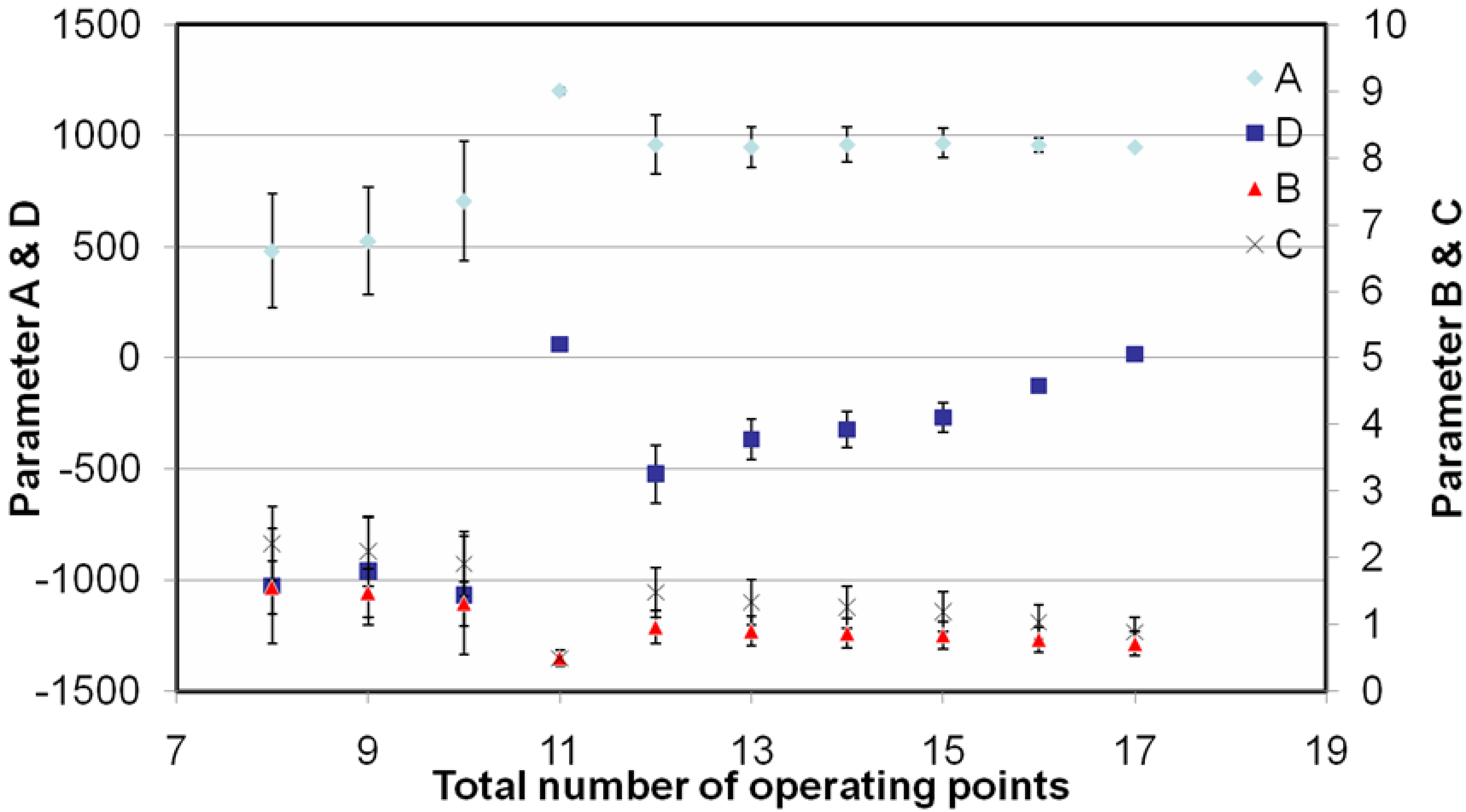
Parameter optimisation



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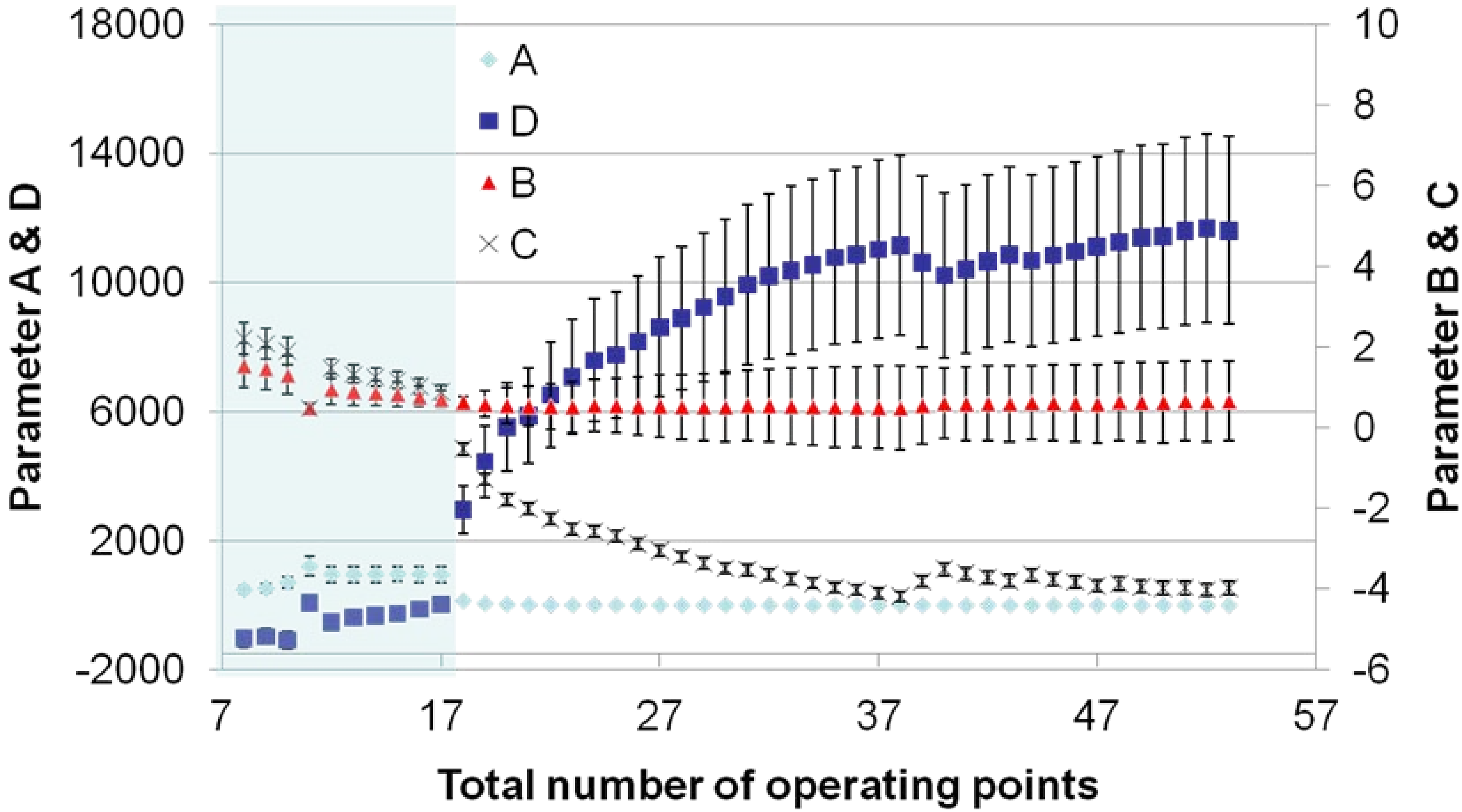
Add data from second engine



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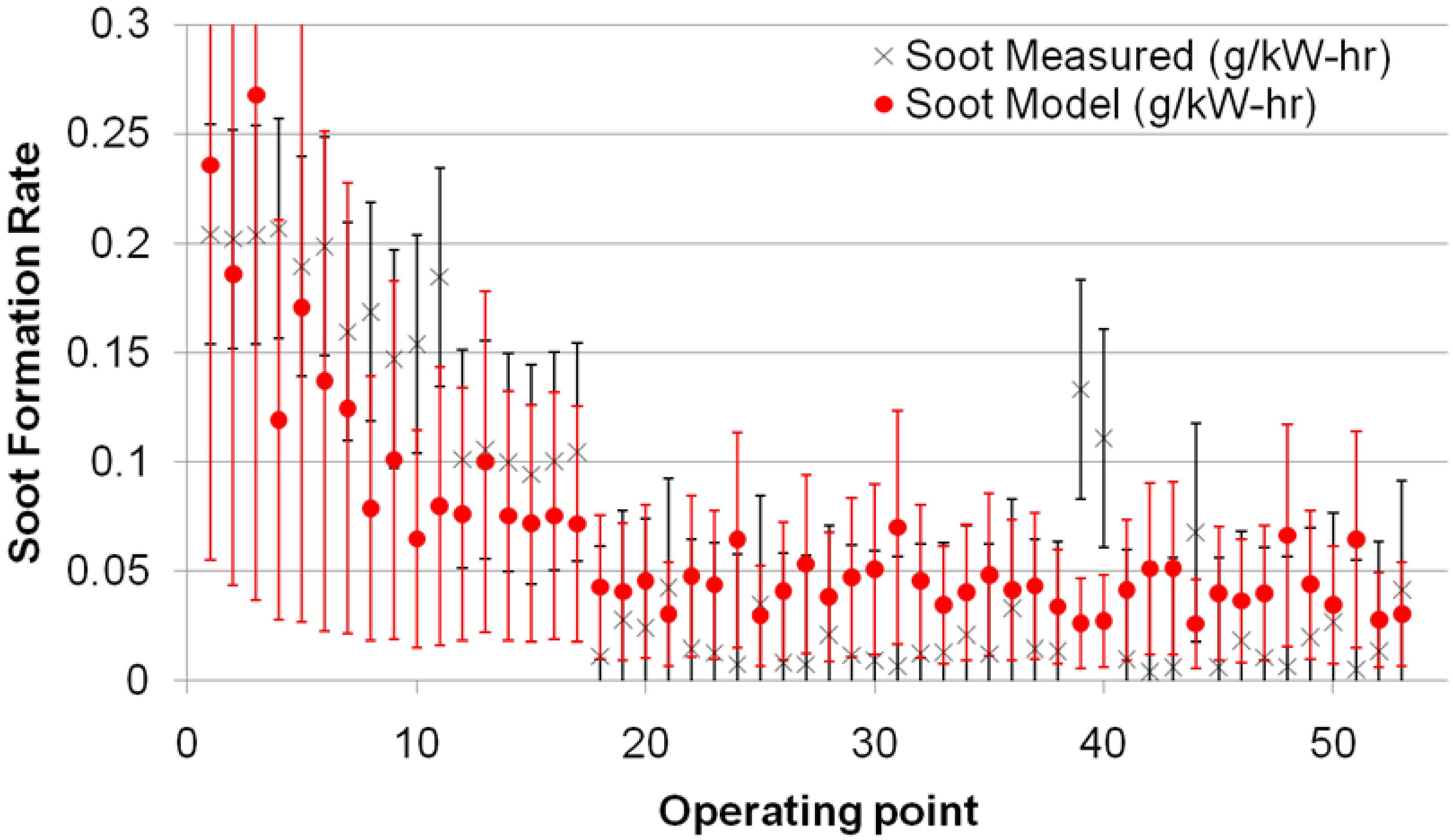
Add data from second engine



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Summary

- Initial results of detailed soot modelling in a DISI engine have been presented, though, with room for improvement.
- A Process Informatics based methodology has been proposed for robust engine model development.
- A standardised, machine-readable format, engineML, has been presented.
- Optimisation results including model parameter and experimental uncertainties have been presented for an empirical diesel soot model.

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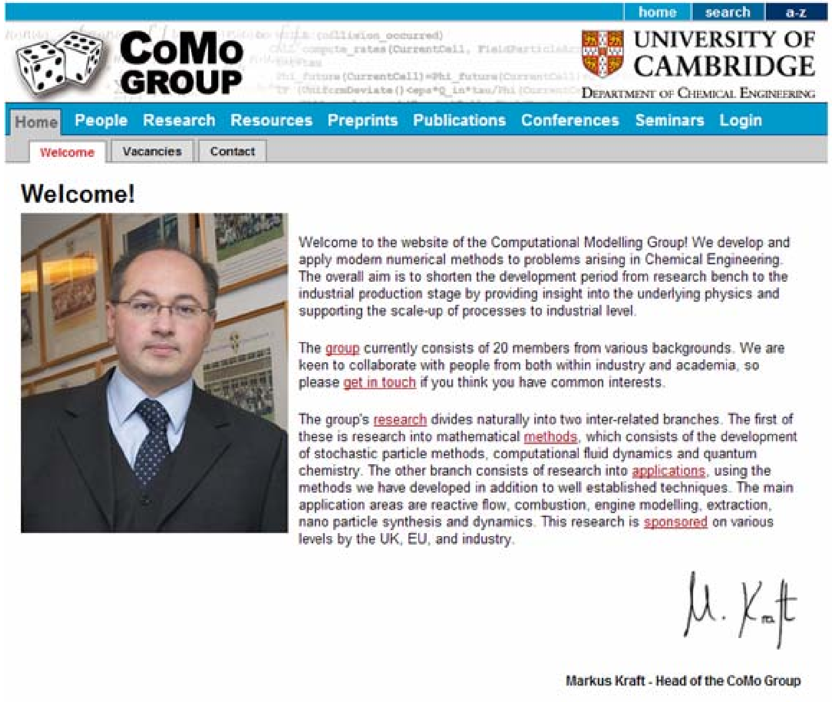
Thank you!

Please visit our website:



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