Natural Gas Homogeneous Charge Compression Ignition (HCCI) R&D

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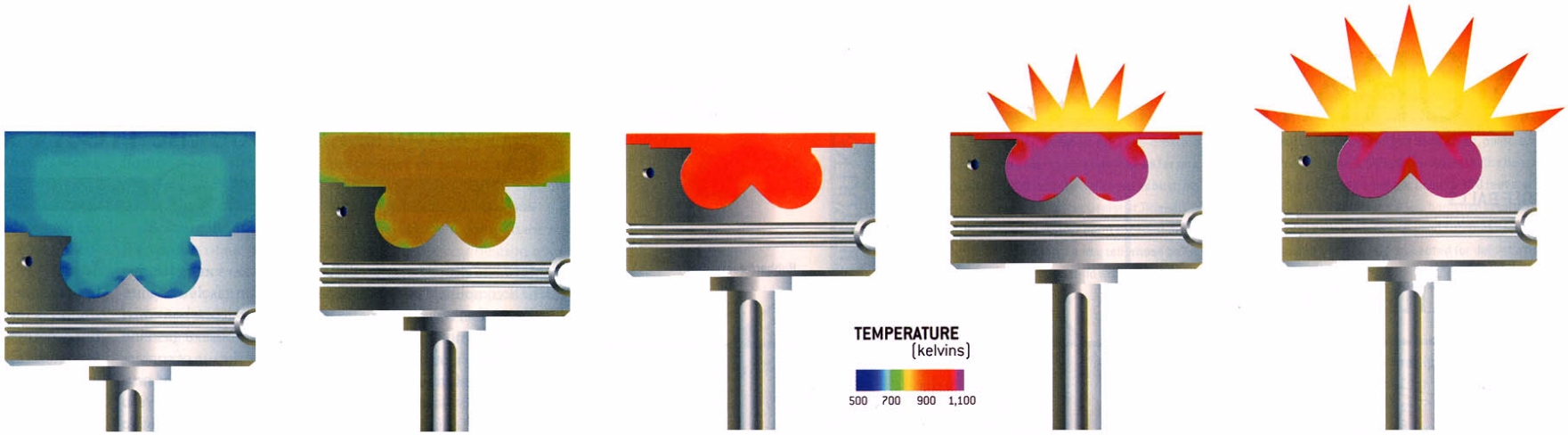
Why study Homogeneous Charge Compression Ignition (HCCI)?



- Diesel engines are unlikely to achieve the NO_x and particulate matter levels required by future legislation

Potential of HCCI Engines

High efficiency
Very low NO_x
Low cost (no need for high pressure injection system, 1/3rd of engine cost)
Low cycle-to-cycle variation
Fuel flexibility
Unthrottled operation

Technical challenges of HCCI

Difficult to control
Difficult to start
High peak heat release and peak pressure
High hydrocarbon and CO emissions

Accomplishments

- **Analysis**
  - **Developed the most advanced simulation capability for modeling HCCI combustion**
    - Multi-zone detailed kinetic simulations predict HCCI combustion with very good accuracy.
    - Procedure has been well validated and extended to long chain hydrocarbons
    - Coupling control model with physics-based engine model to develop optimized performance maps
- **Experiments**
  - **Single and multi-cylinder engine tests providing valuable information on HCCI operation and control**
  - **Generated performance maps in multi-cylinder engine**
    - Maps generated for operation with and without EGR
- **Education**
  - **We are training US graduate students in HCCI combustion though our collaboration with UC Berkeley**

We have published 10 HCCI papers in the SAE literature in the years 2000 and 2001

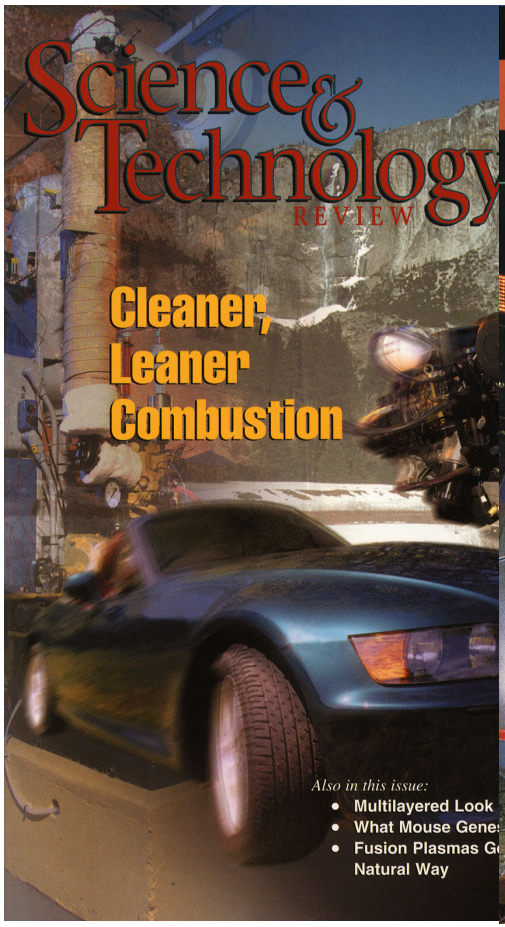
2000-01-0327
2000-01-0328
2000-01-2869
2001-01-1027
2001-01-1894
2001-01-1895
2001-01-2077

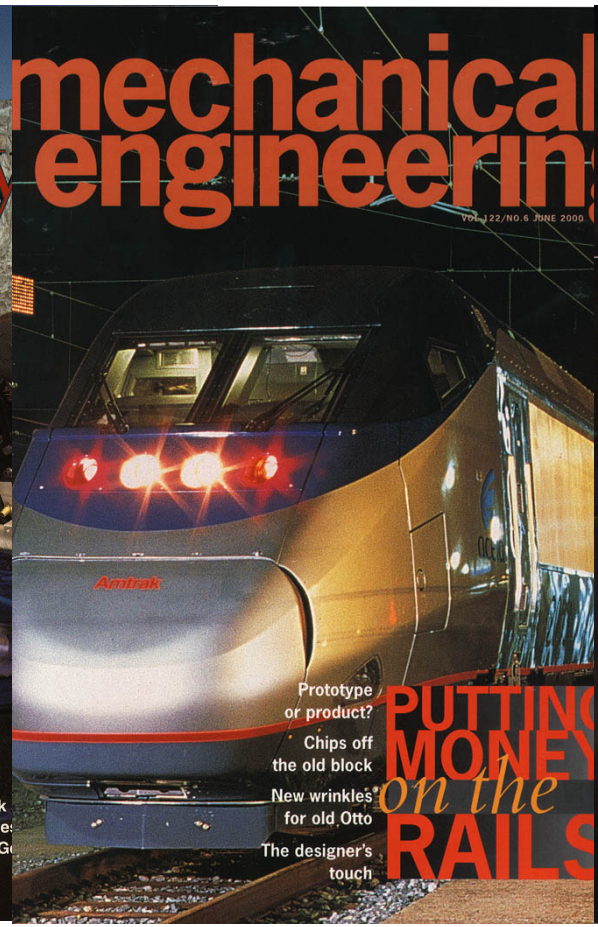
1 paper submitted to the Future Transportation Technologies meeting

2 papers submitted to the Fall Fuels and Lubes meeting

In addition to 2 papers published in ASME Transactions journals

Our contributions to HCCI combustion have appeared in three articles in the popular press

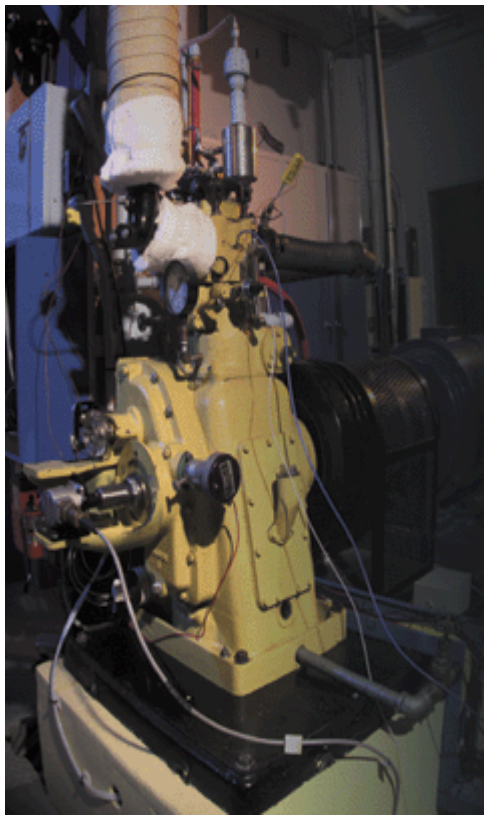


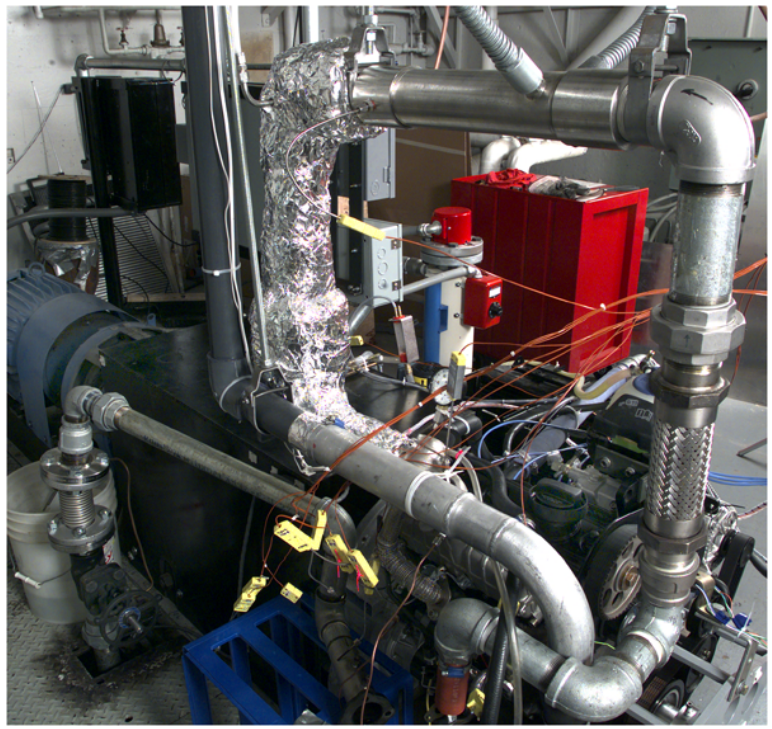


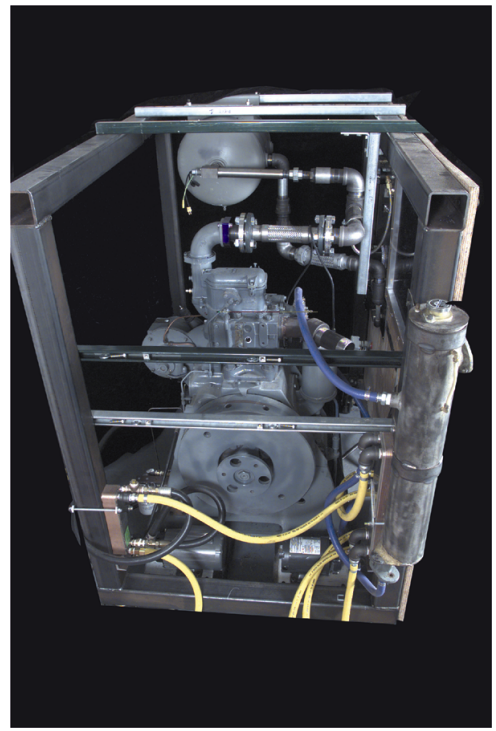
We are collaborating with multiple industrial and academic partners

- **Cummins**
  - 2-year long CRADA, 2 joint papers
  - working on establishing a new CRADA
- **Caterpillar**
  - donated experimental engine 3401
- **Ford**
  - donated engine
  - plans for collaboration on HCCI combustion analysis
- **Lund Institute of Technology**
  - 1 joint paper, collaboration on analysis
- **University of Wisconsin**
  - joint work on KIVA analysis
  - 2 joint papers
- **UC Berkeley**
  - joint experimental and numerical work, 10 joint papers
  - four graduate students obtaining degrees on HCCI

We have operated three different engines in HCCI mode







CFR engine

First experimental prototype

SAE 2000-01-0328

Volkswagen TDI engine

High-speed, 4-cylinder small displacement engine

Running in HCCI mode for 1 ½ years

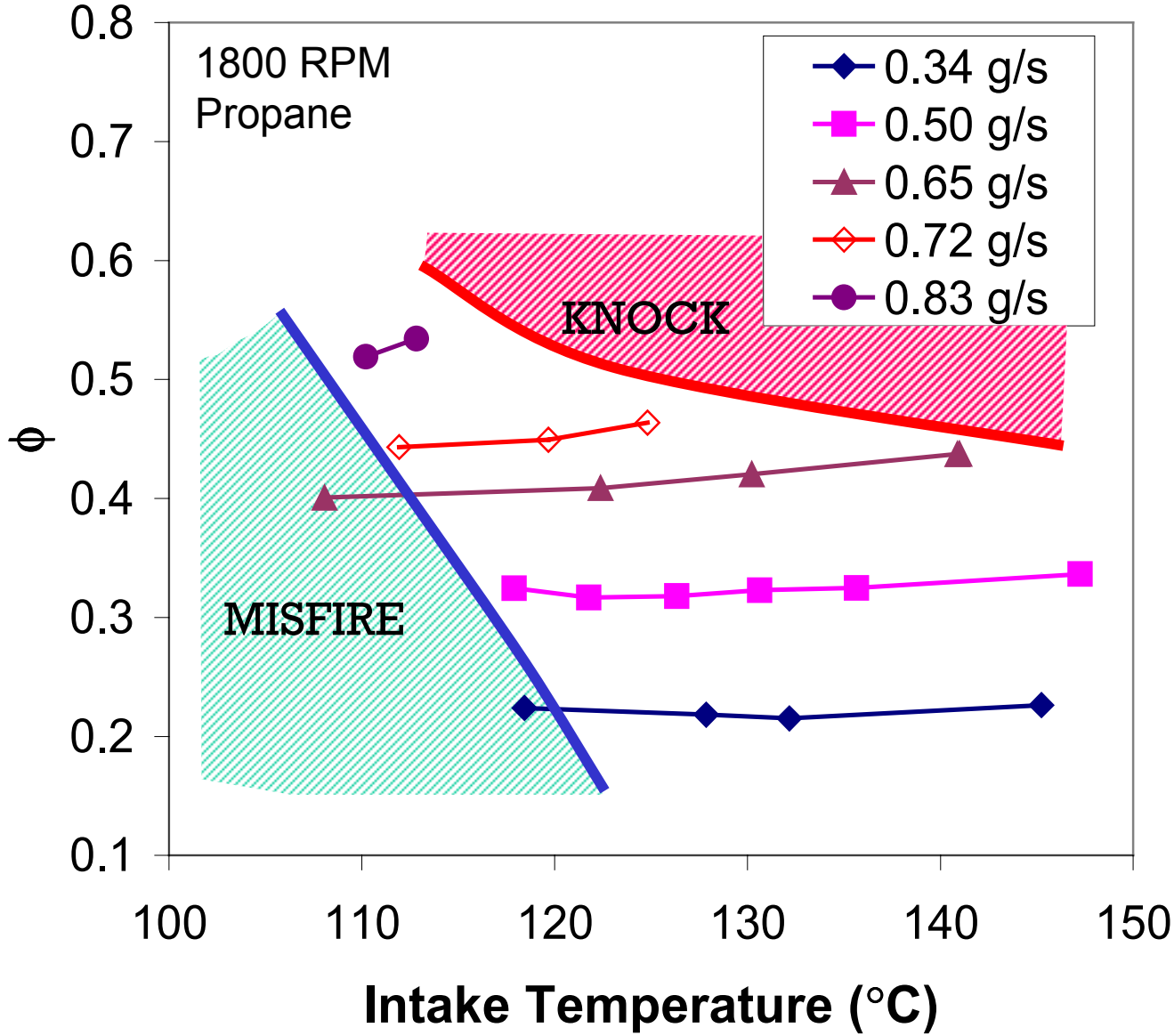
SAE 2001-01-1894 and 1895

Caterpillar 3401 engine

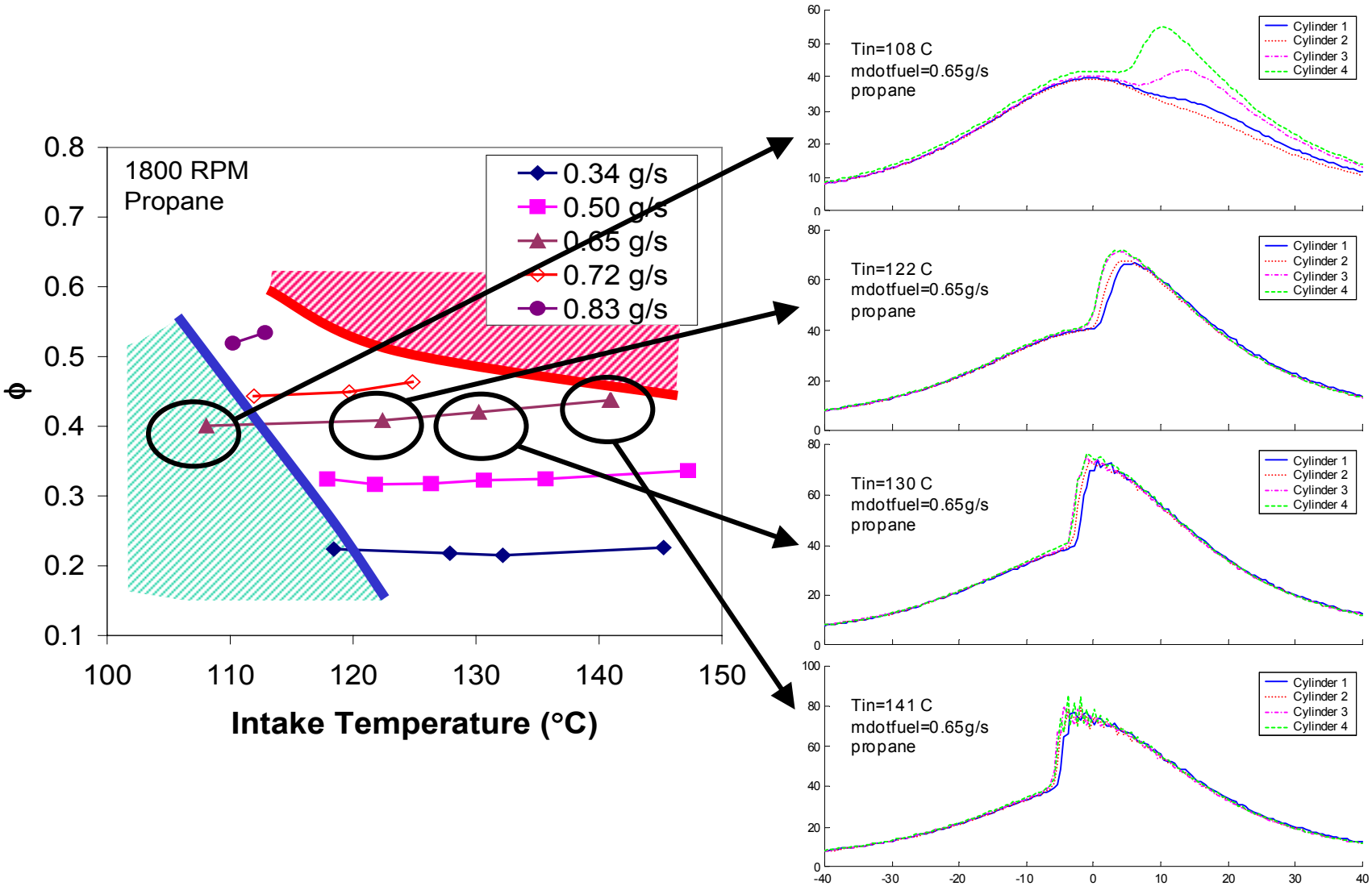
Representative of heavy-duty diesel engines

Now running in HCCI mode

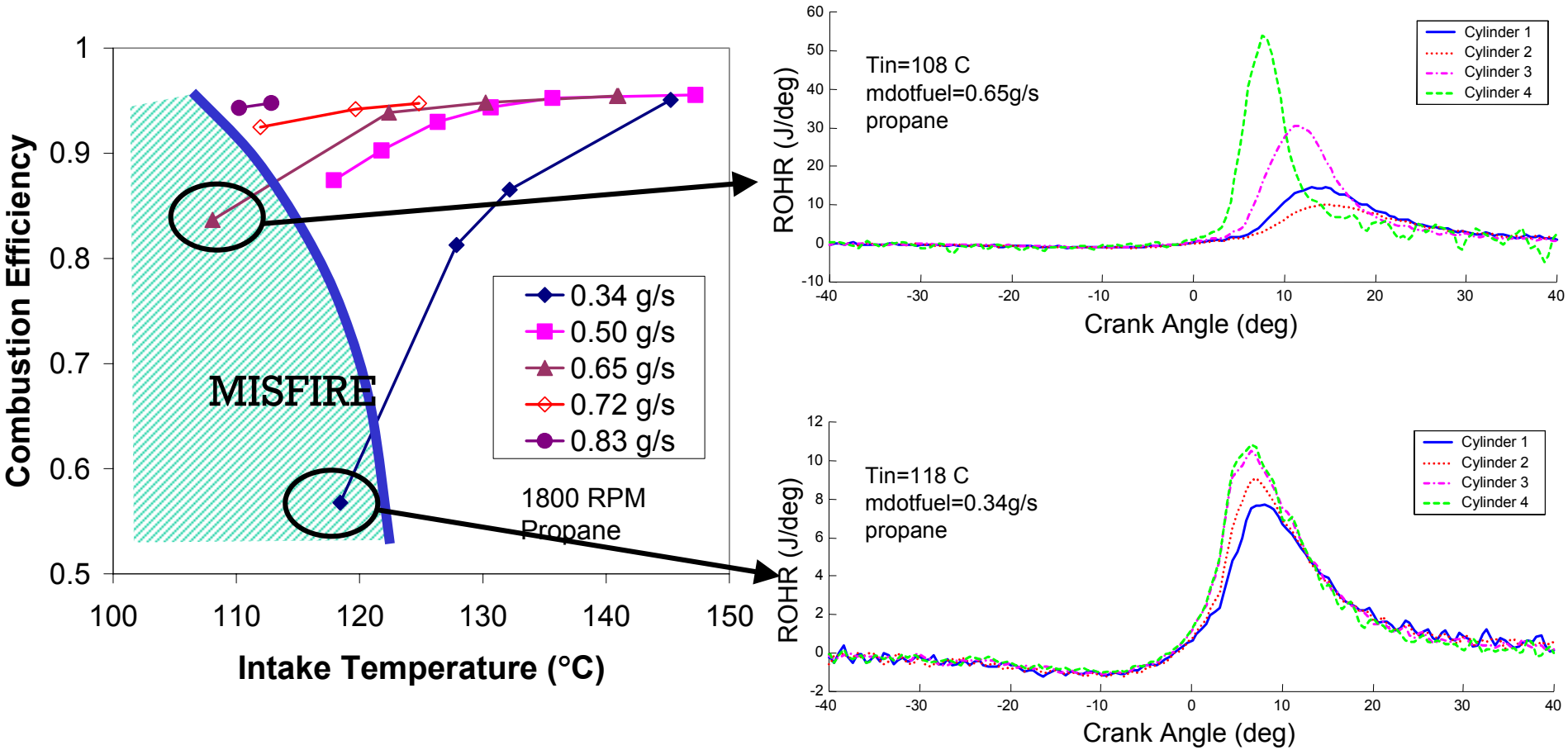
We have generated a full performance map for the 4-cylinder Volkswagen TDI engine (SAE 2001-01-1894)



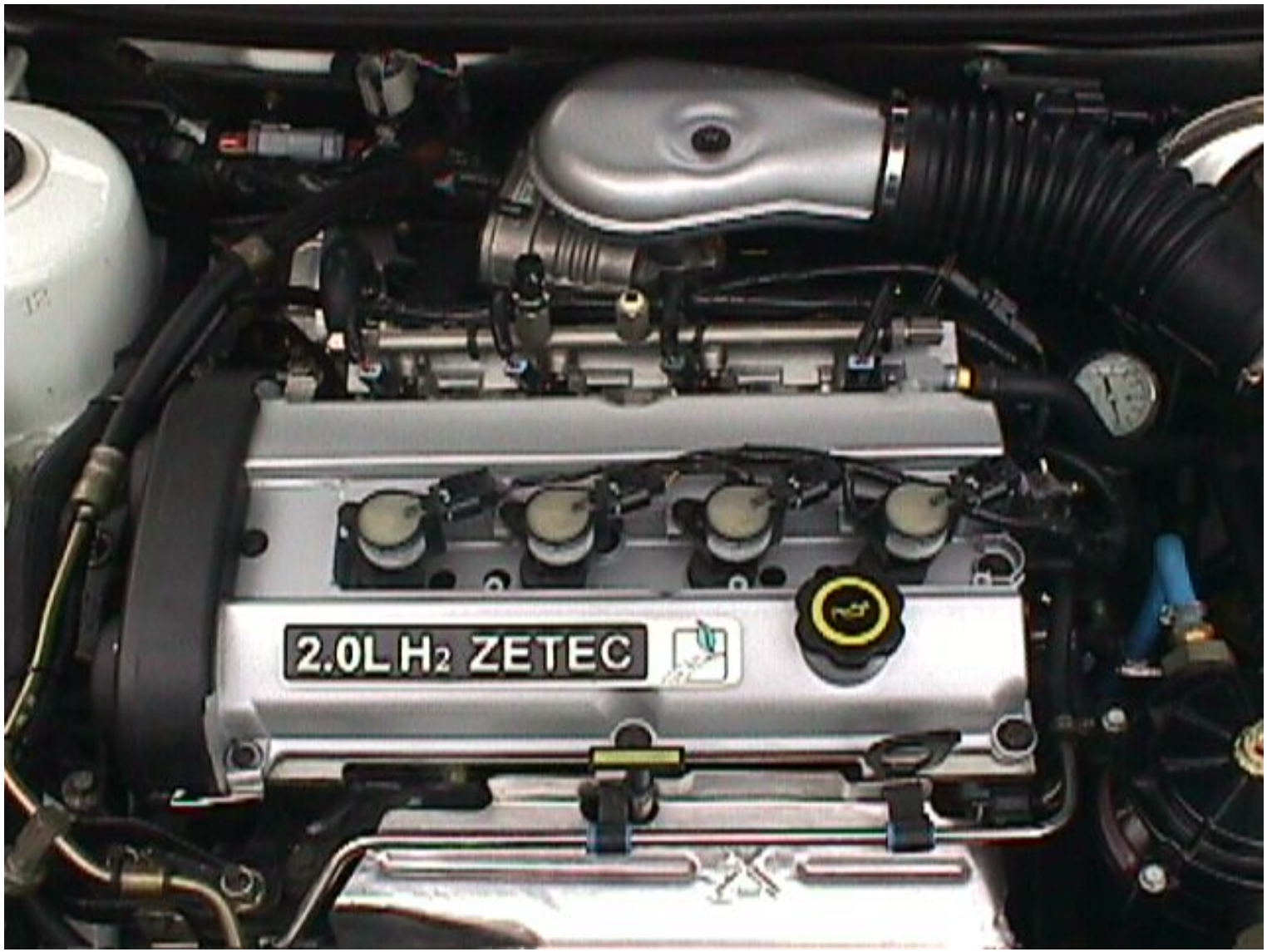
Pressure traces show transition from misfire to knock as the inlet temperature is increased



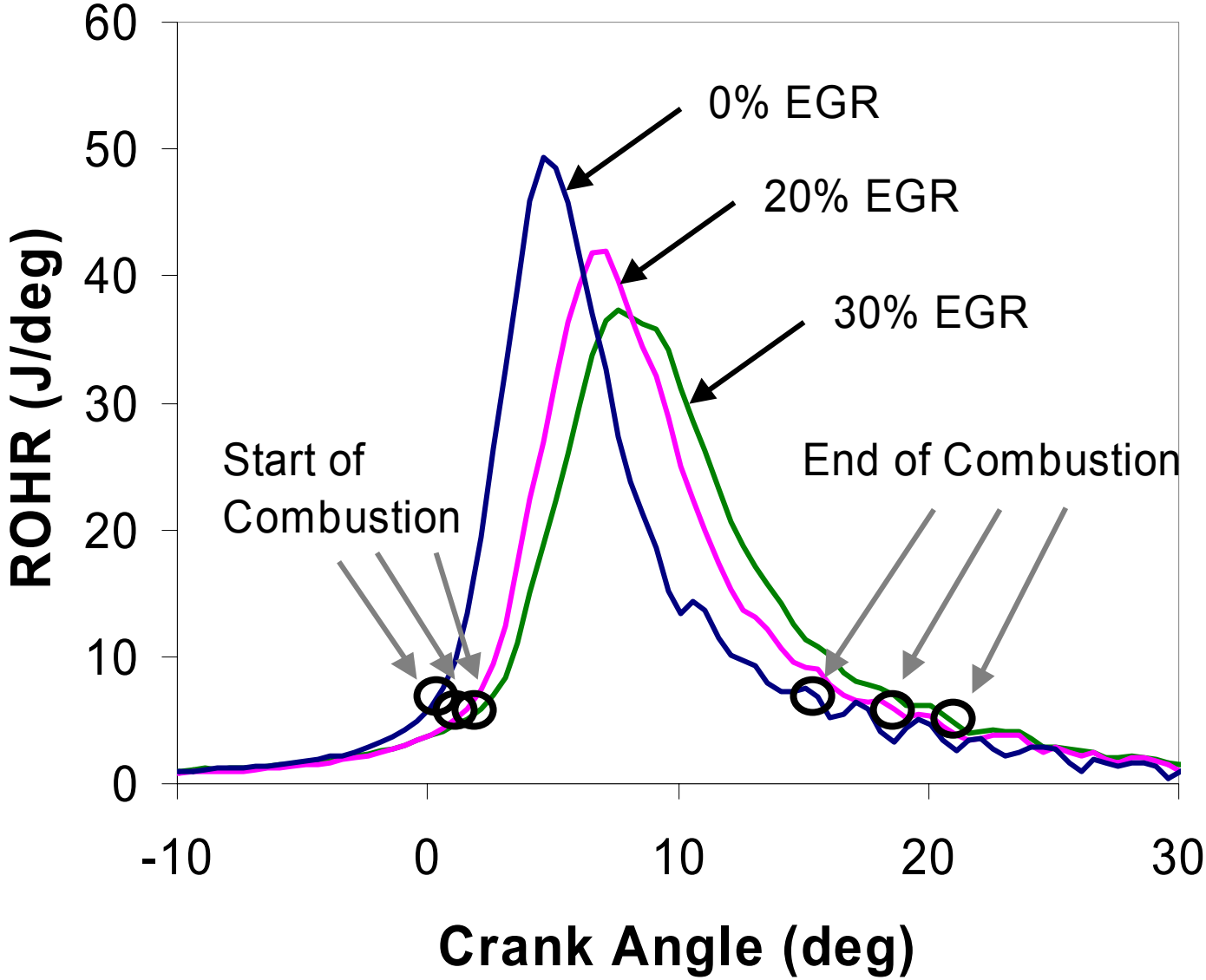
Modes of misfire can be global or cylinder-by-cylinder



Ford has recently donated an engine for conversion to HCCI operation

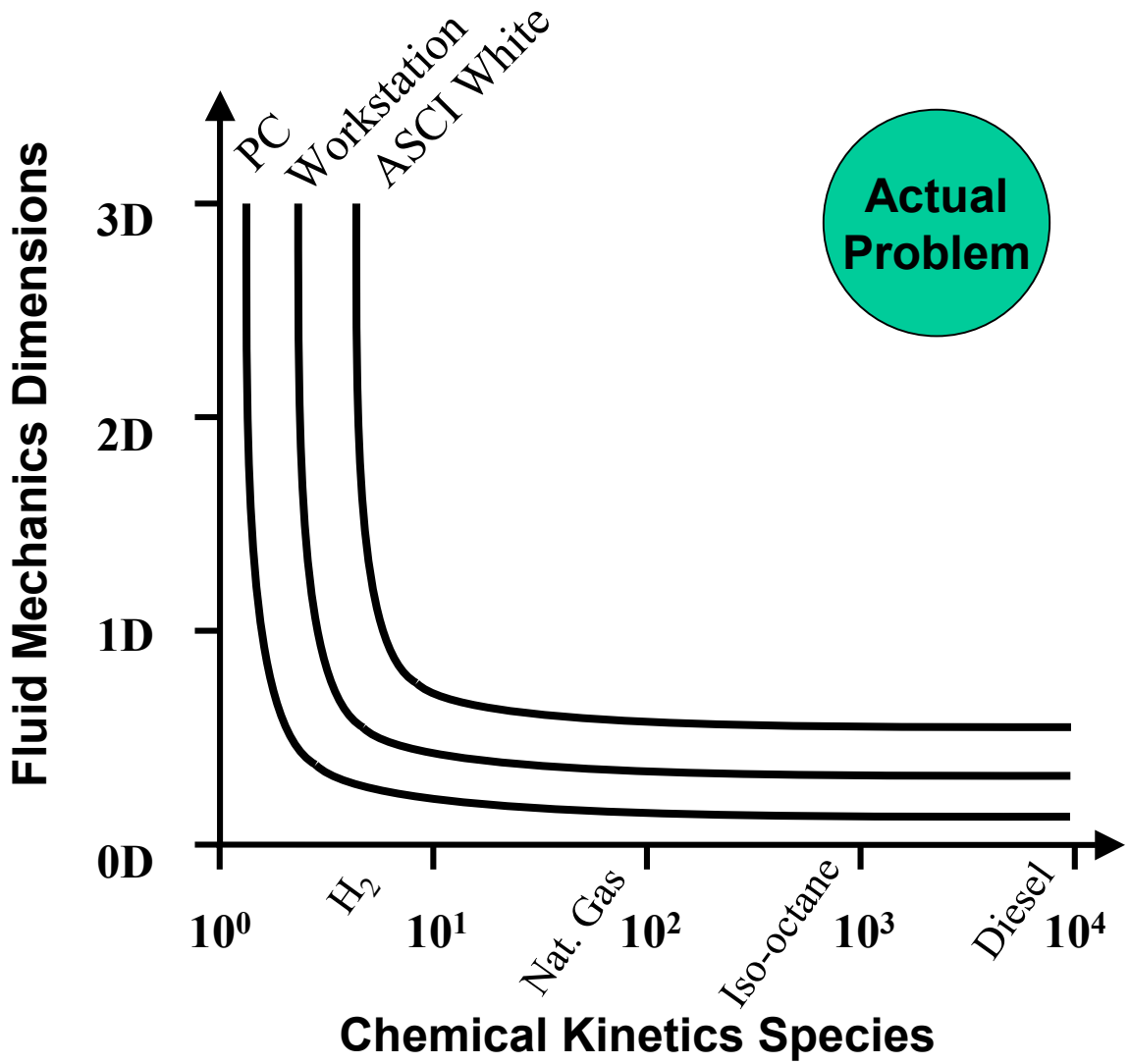


We have characterized the effect of EGR on HCCI combustion with propane and butane in the TDI engine

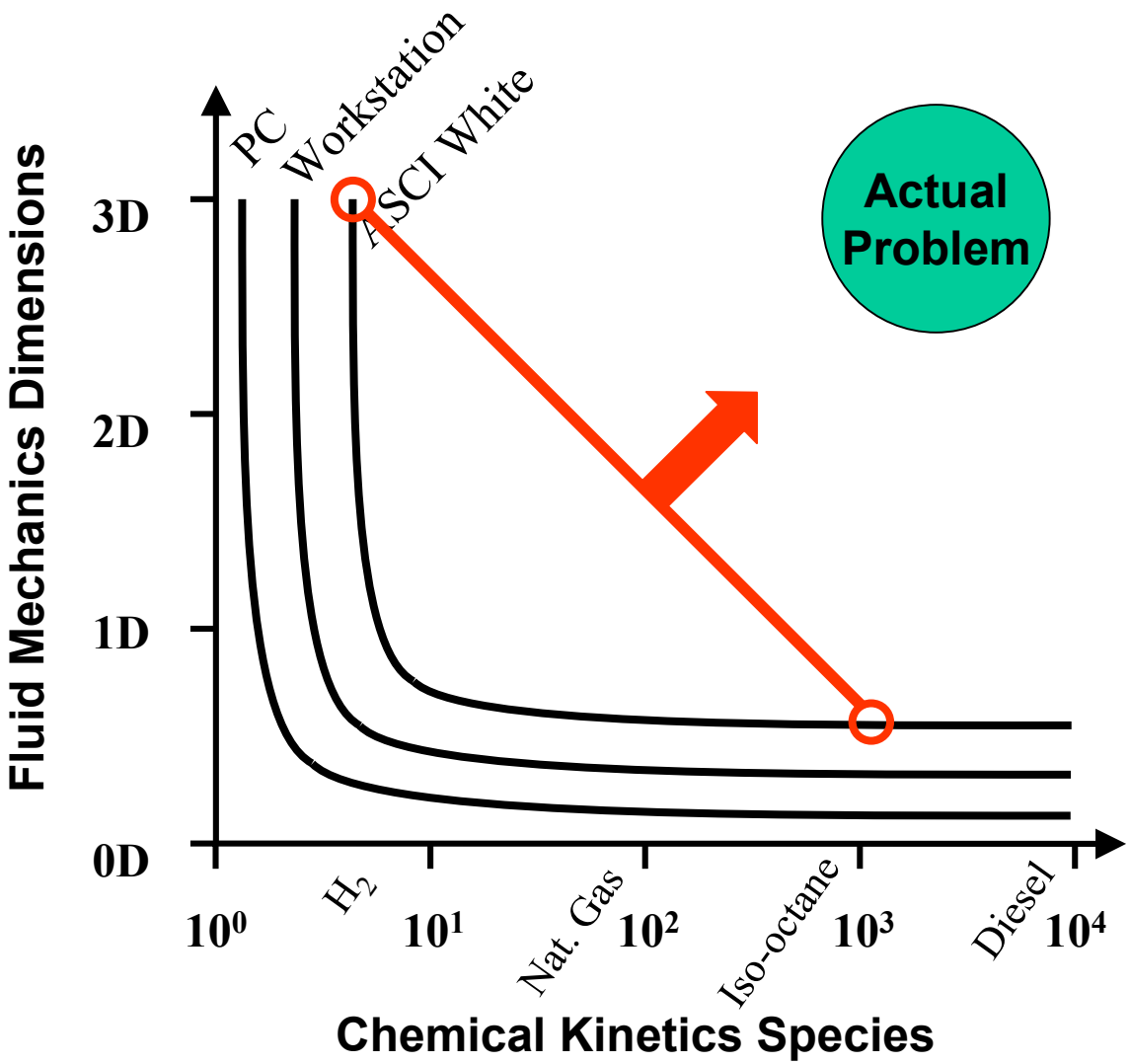


SAE 2001-01-1895

Problems of combined fluid mechanics and combustion require extremely high computational resources



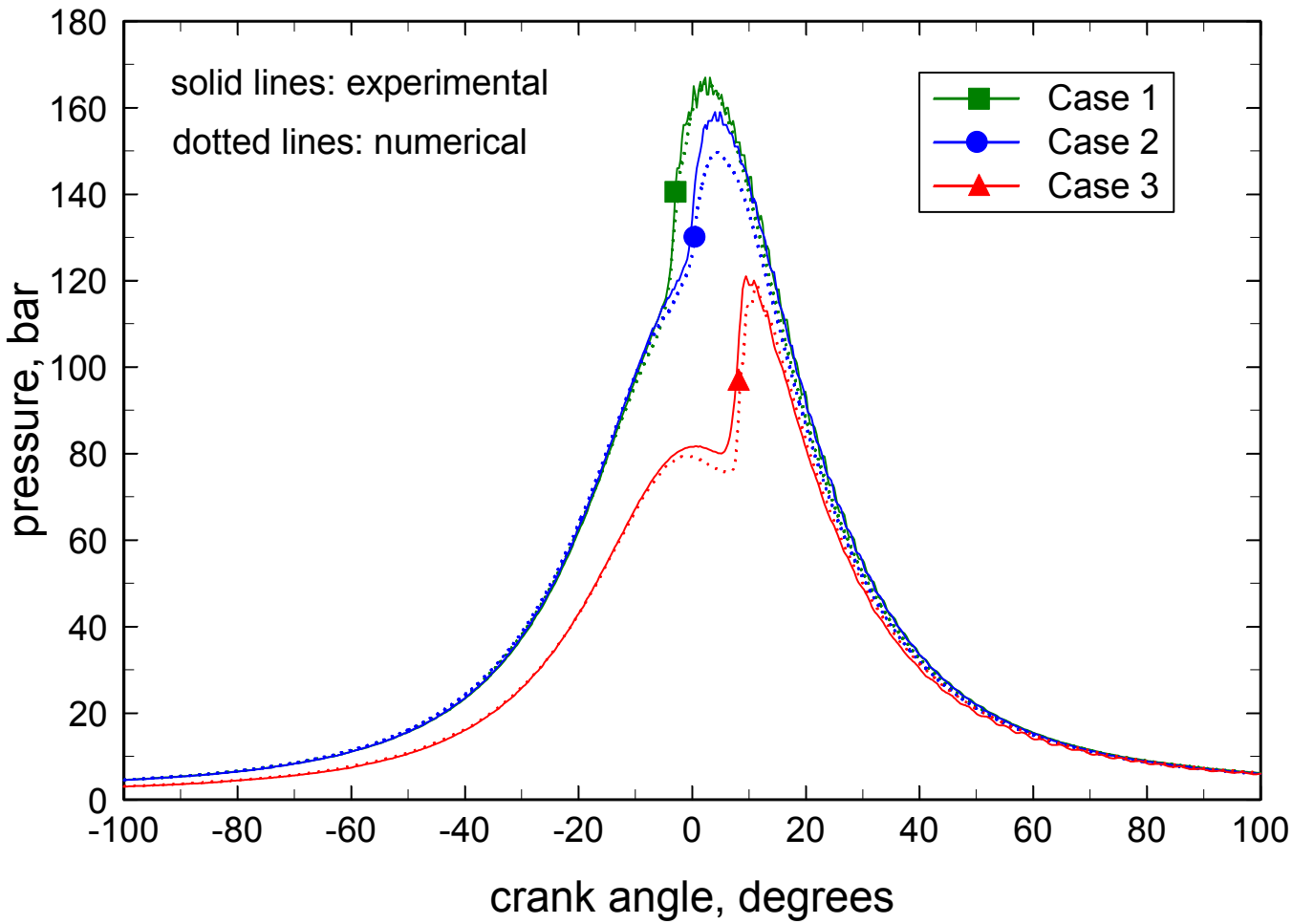
Our methodology takes advantage of the uncoupled nature of fluid mechanics and chemical kinetics in HCCI combustion



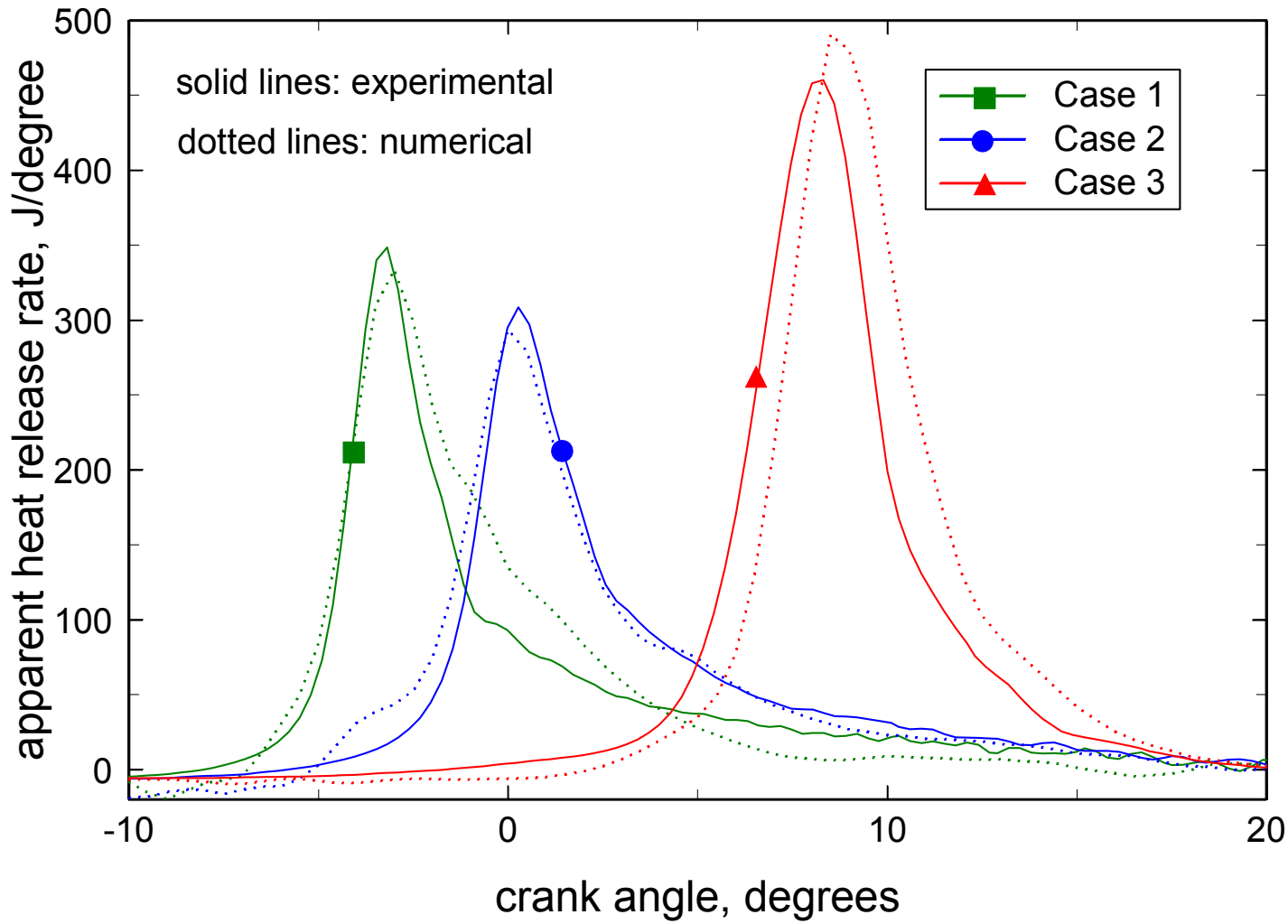
And produces accurate results with a much reduced computational time

We have validated our multi-zone model with Cummins data for propane (SAE 2001-01-1027)

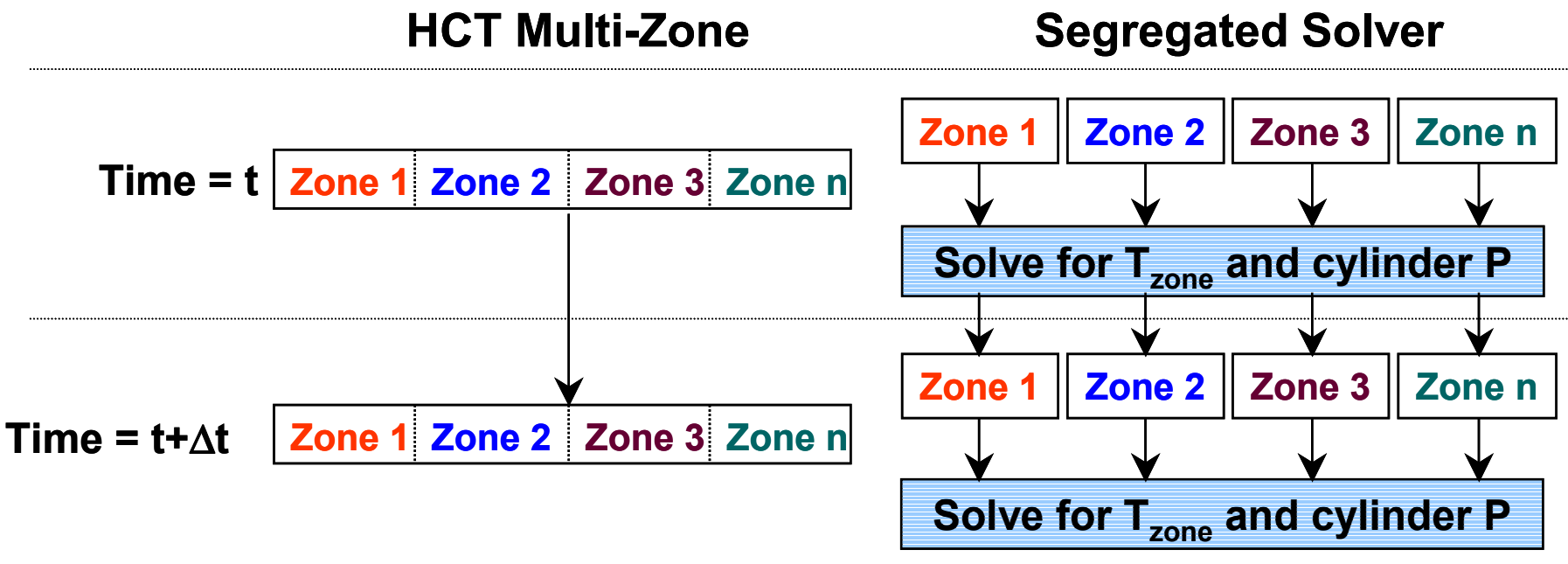
Case 1: 1002 rpm, ϕ=0.17, P_{in}=2.72 bar, T_{in}=352 K
Case 2: 1001 rpm, ϕ=0.17, P_{in}=2.75 bar, T_{in}=340 K
Case 3: 1800 rpm, ϕ=0.36, P_{in}=1.88 bar, T_{in}=342 K



Our multi-zone model predicts heat release rates with good accuracy (SAE 2001-01-1027)



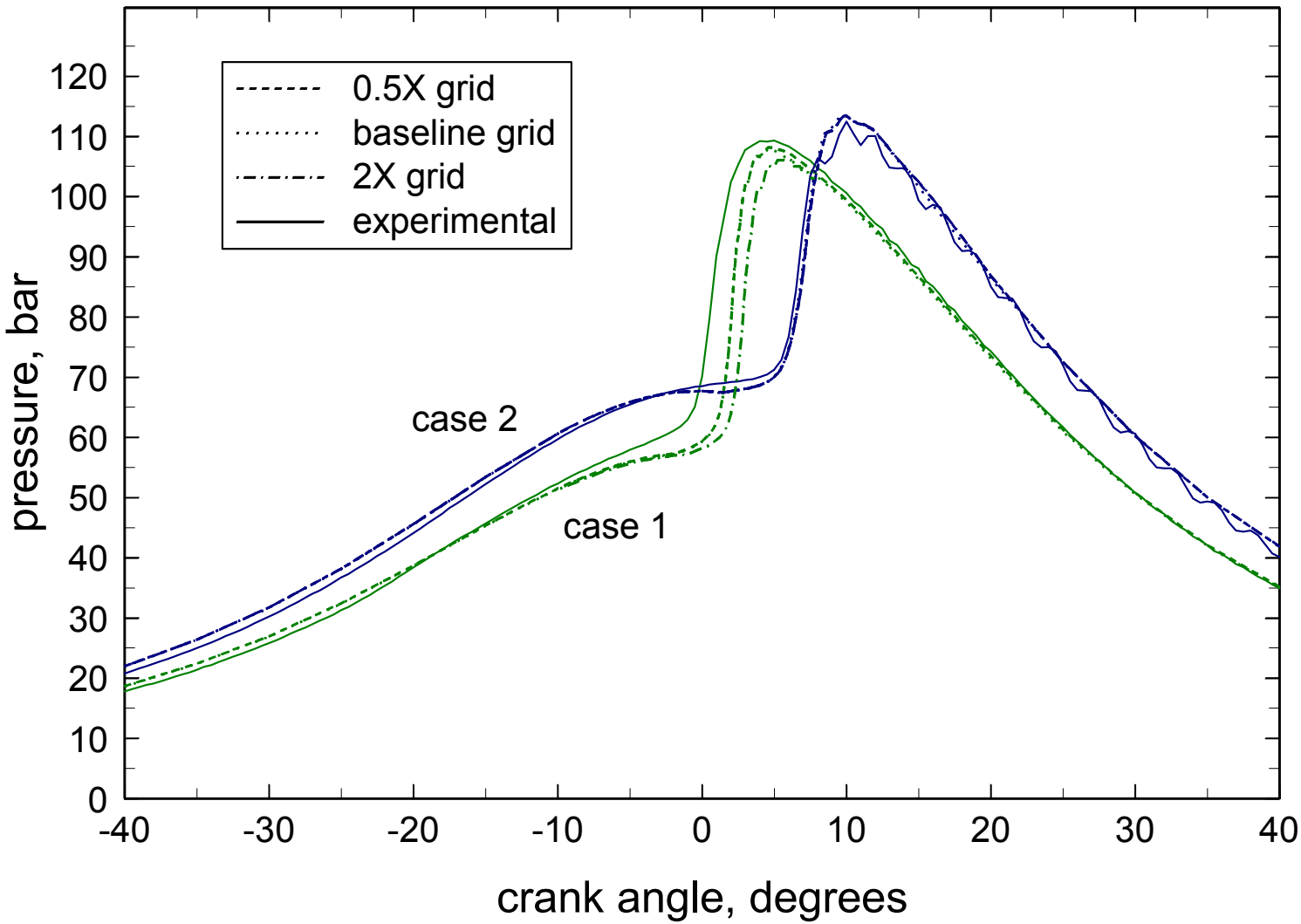
We have developed a segregated solver to analyze HCCI combustion of long-chain hydrocarbons



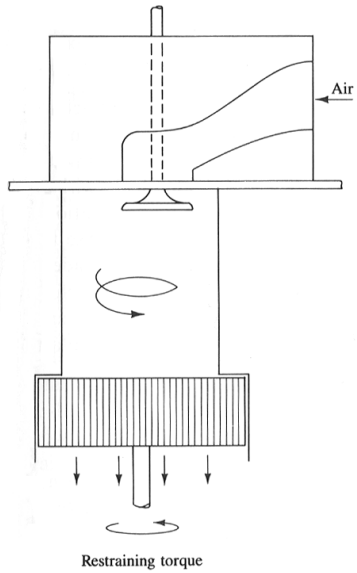
10X faster

Our model can predict with good accuracy Cummins experiments of iso-octane HCCI combustion

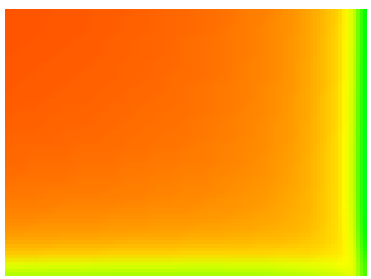
Case 1: 1010 rpm, ϕ=0.346, P_{in}=2.41 bar, T_{in}=381 K
Case 2: 2007 rpm, ϕ=0.348, P_{in}=3.11 bar, T_{in}=413 K



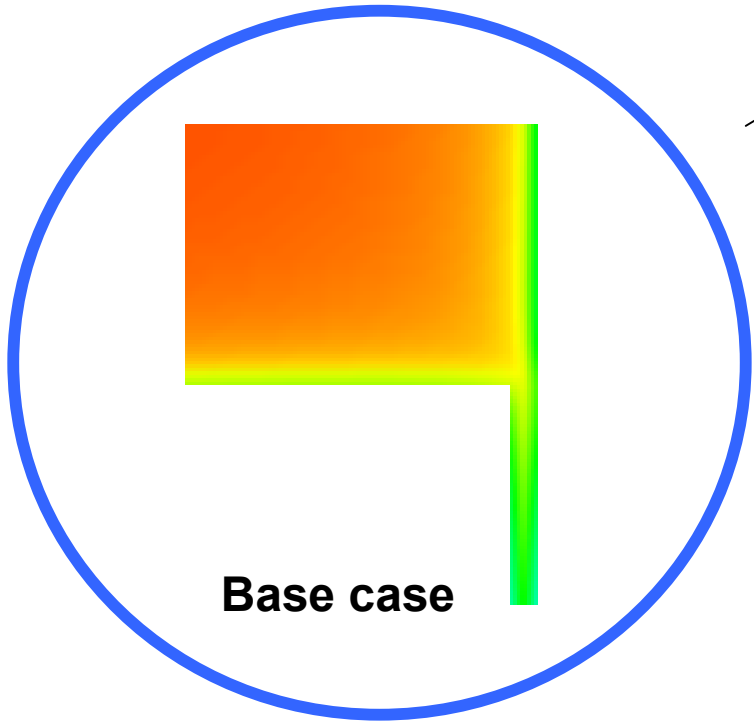
Multi-zone methodology is applied to four engine designs to evaluate their effect on emissions



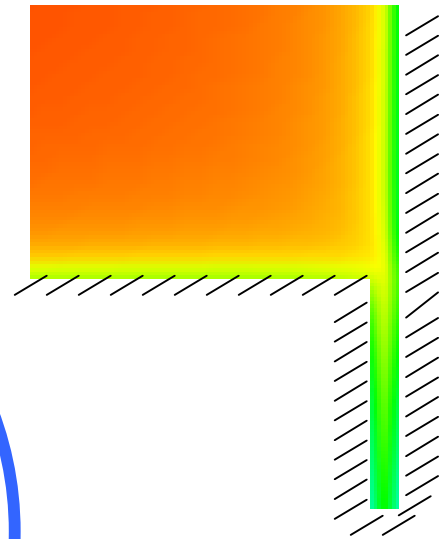
Low swirl
(0.43 vs. 4.3)



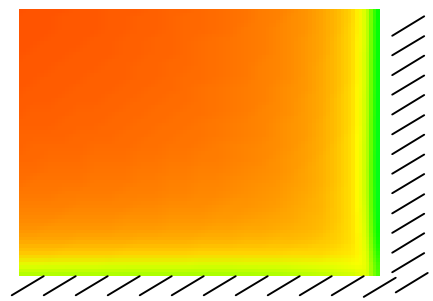
No crevice



Base case

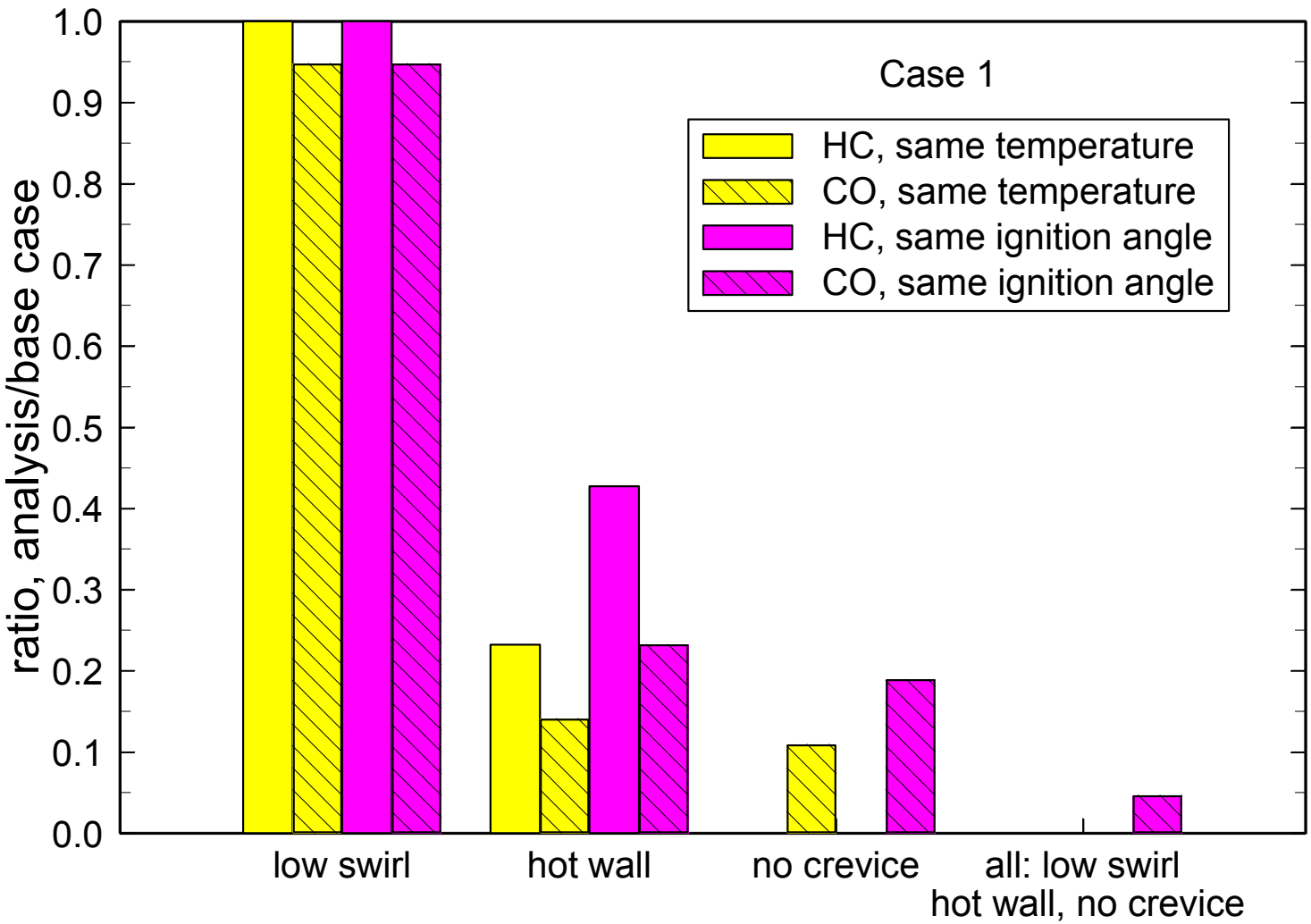


Hot wall (600K)



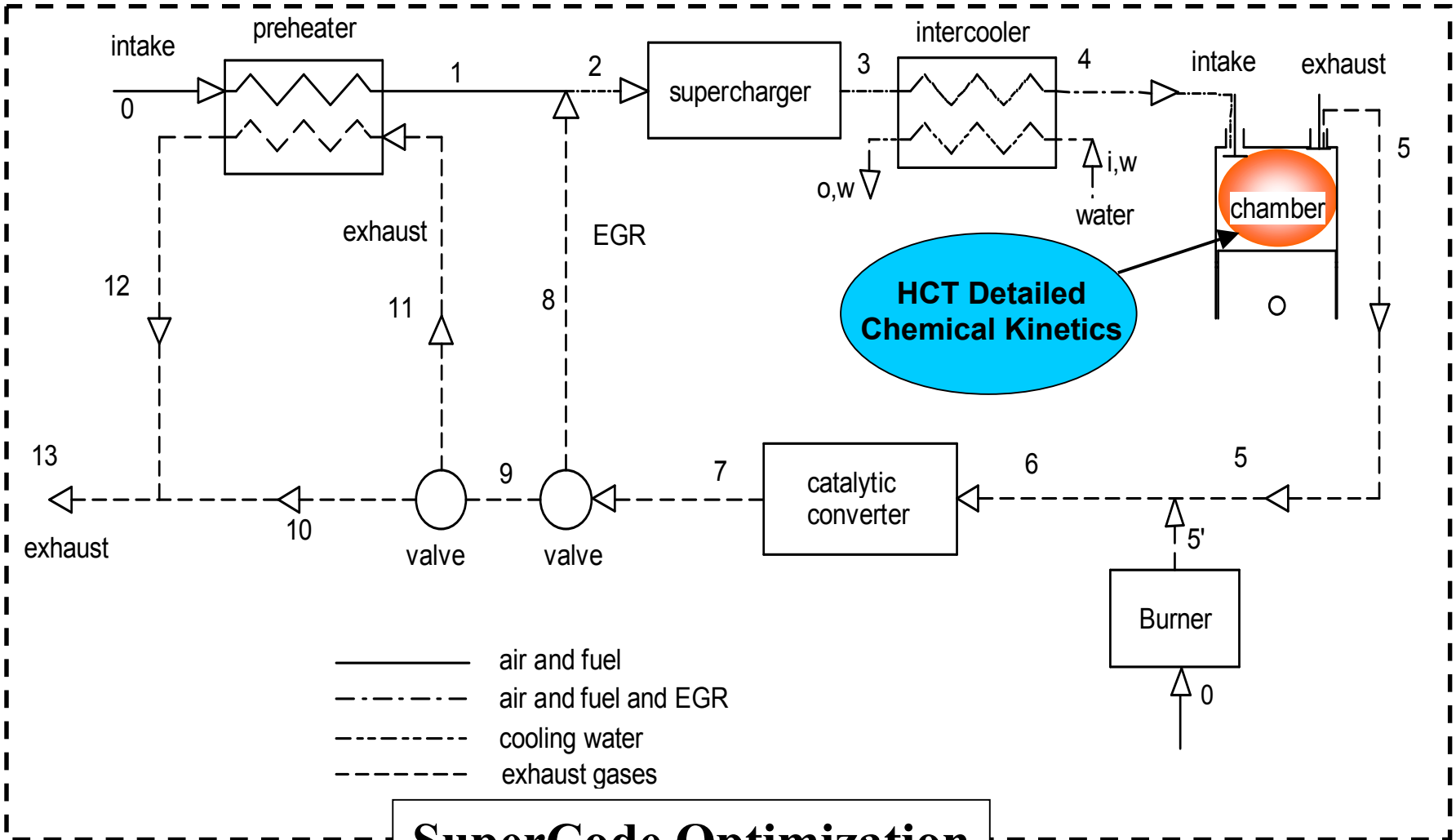
All — Low swirl, hot wall, no crevice

Hot walls and crevice size reduction are effective in reducing engine HC and CO emissions



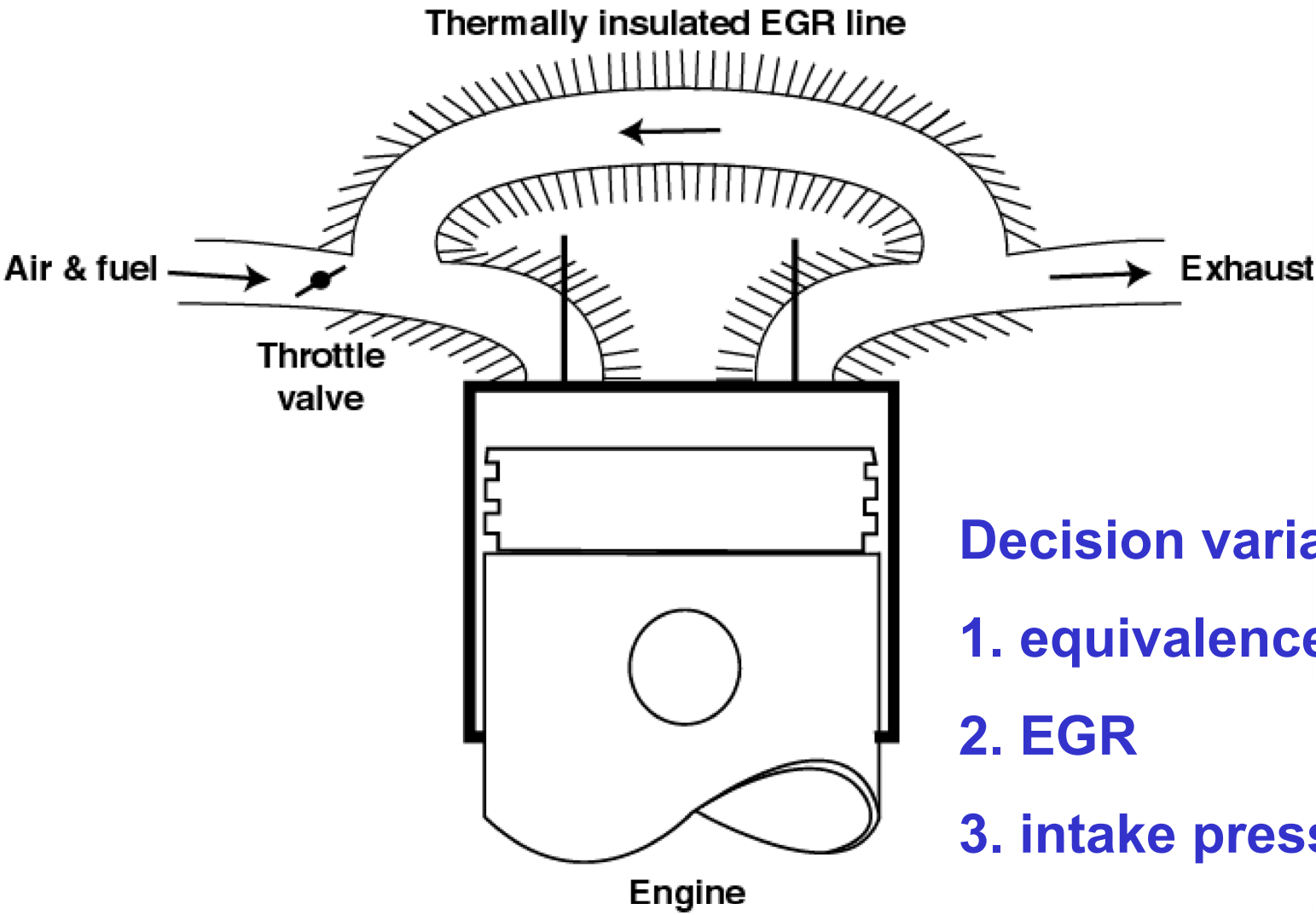
We have developed an HCCI engine system simulation and optimization tool (SAE 2000-01-2869)

Example of thermal control system



SuperCode Optimization

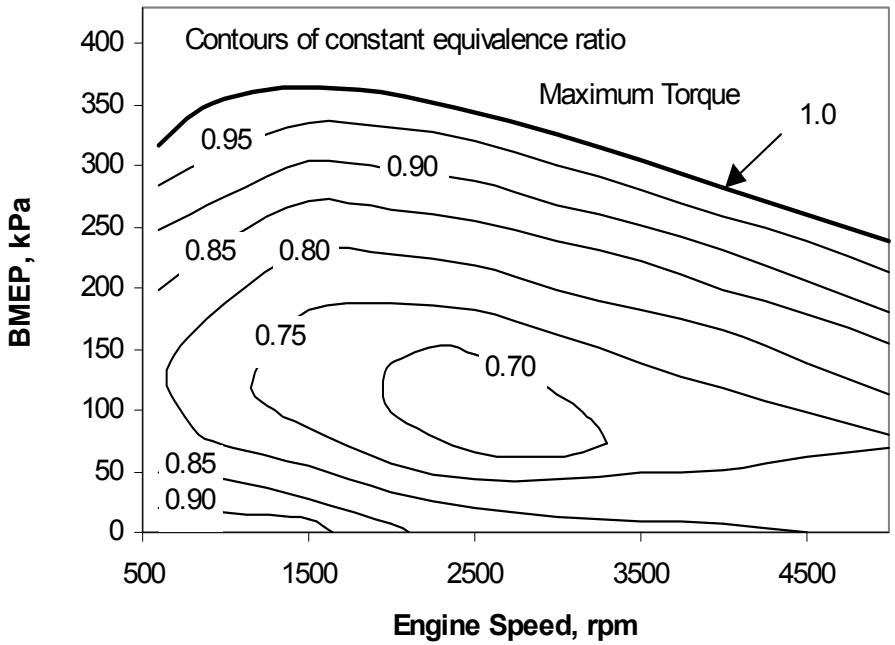
We have applied the system simulation and optimization tool to evaluate an equivalence ratio-EGR control for HCCI

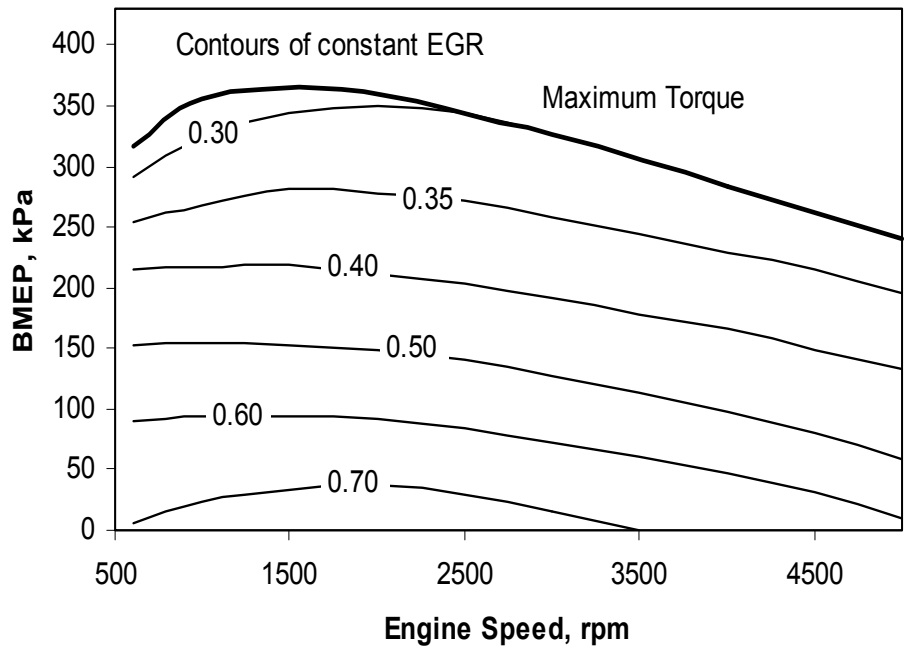


Decision variables:

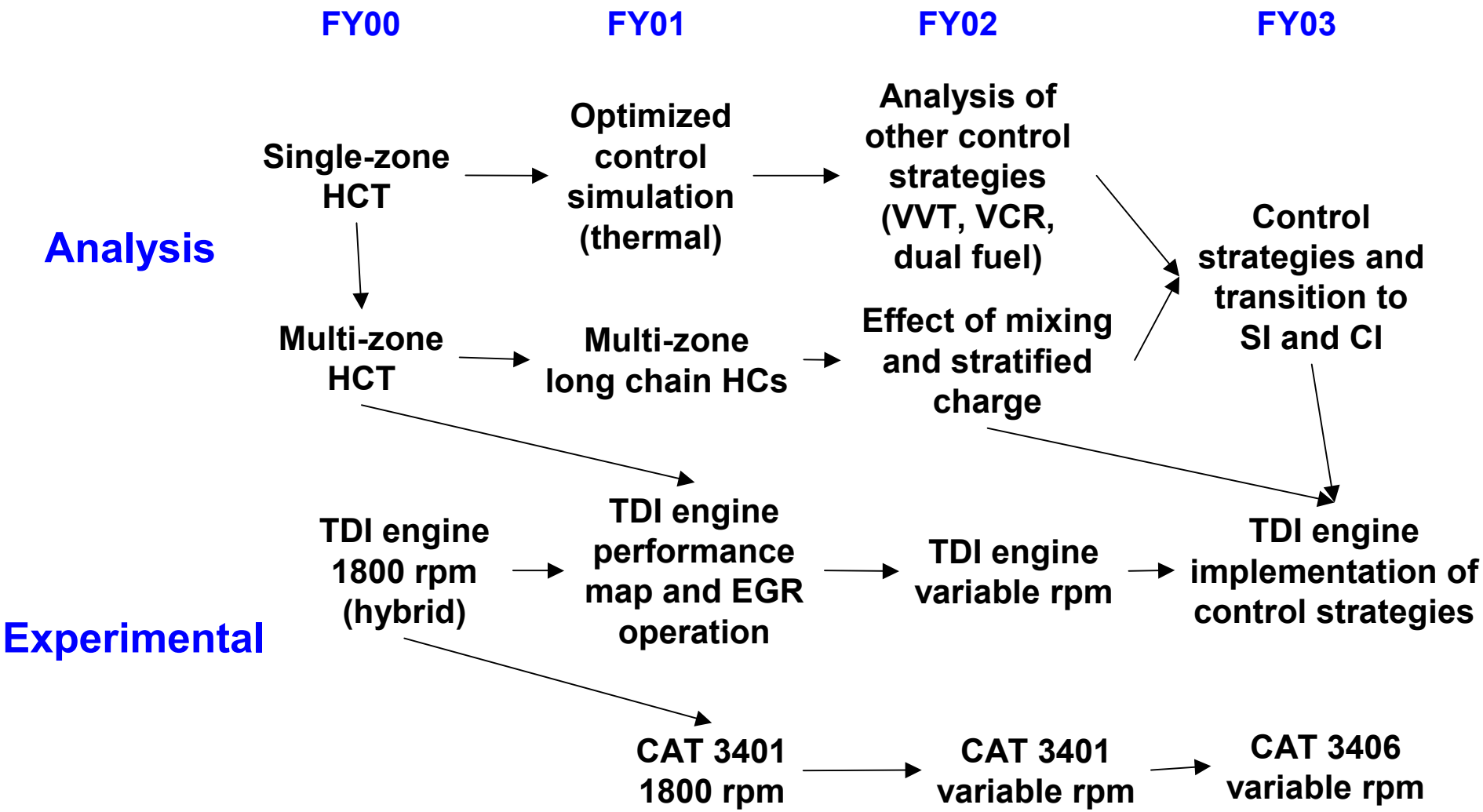
1. equivalence ratio
2. EGR
3. intake pressure

SuperCode generates optimum ϕ and EGR performance maps and optimizes conditions for transition to SI operation





Map of optimum equivalence ratio

Map of optimum EGR

HCCI roadmap