Physics-based Control of Residual-Effected HCCI Engines

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Dynamic
Design
Laboratory

Outline

- Challenges/Opportunities for control in HCCI
  - Cyclic coupling
  - Lack of combustion trigger

- Simulation modeling of residual affected HCCI
  - Review of approach: Basic model and ignition criteria
  - Added capabilities: Transients, mode transitions & gasoline

- Control model and controller design
  - Review of approach
  - Added capabilities: direct control of IMEP & phasing

Challenges/Opportunities in HCCI with VVA

- Variable valve actuation
  - Valves are only input: IVO/EVC/IVC
  - Fuel is another input: fixed equivalence ratio in intake
- Cycle-to-cycle coupling through exhaust gas
- No direct initiator of combustion
  - Dependent on kinetics: reactant concentrations, temperature & amount of compression
  - Transients & mode transitions complicate this
- Modeling and control work must account for:
  - Coupling and ignition via kinetics

Our Control Engineering Approach

"Everything should be made as simple as possible, but not simpler."
-Albert Einstein

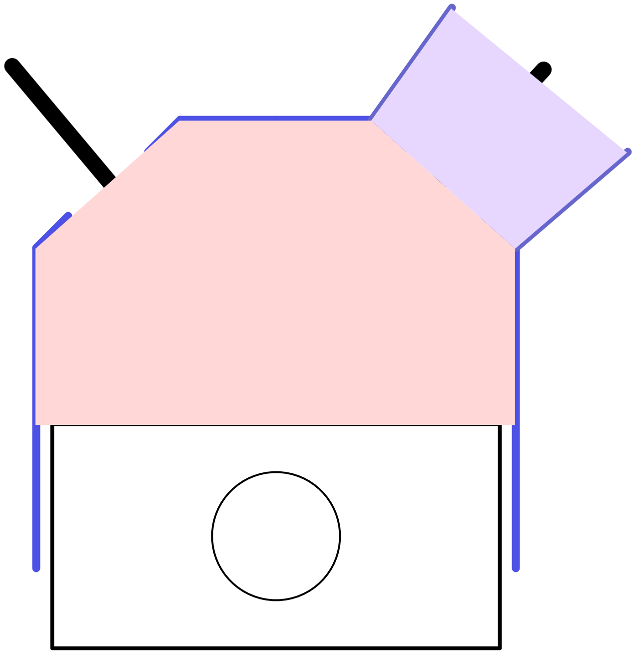
"All models are wrong. Some are useful."
-George E. P. Box

- Objective: Simple physical models and controllers that capture behavior most relevant for control
  - Cyclic coupling
  - Combustion phasing
  - In-cylinder pressure evolution
  - Work output

- Sophistication in proving stability, boundedness, control design, etc.

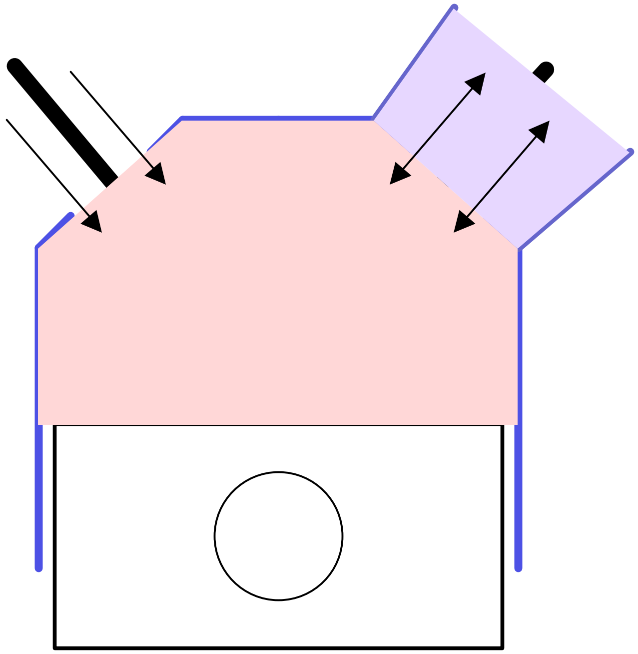
Multi-cycle HCCI Simulation Model

- 1^{st} law analysis of cylinder and exhaust manifold



Multi-cycle HCCI Simulation Model

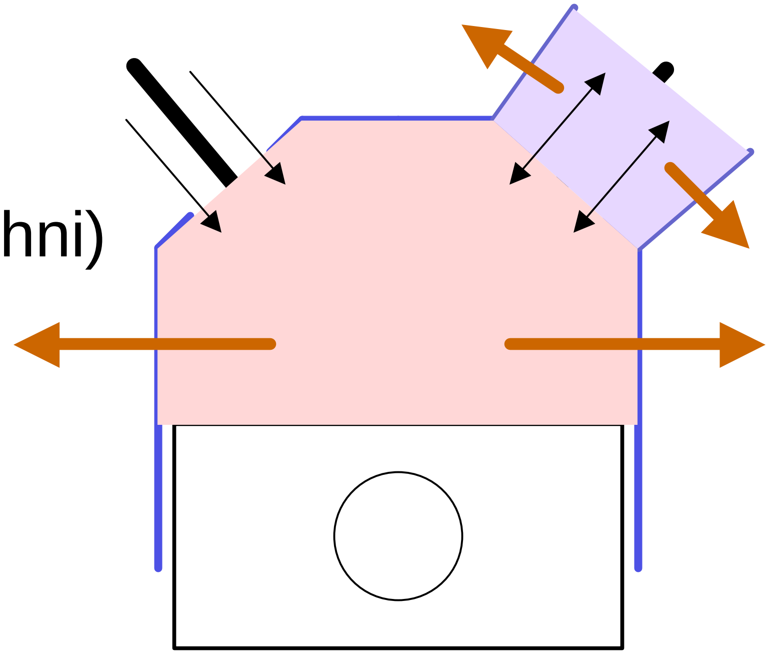
- 1st law analysis of cylinder and exhaust manifold
- Steady state 1D compressible flow relations



Multi-cycle HCCI Simulation Model

- 1^{st} law analysis of cylinder and exhaust manifold
- Steady state 1D compressible flow relations

- Heat transfer
  - In-cylinder (modified Woschni)
    - Ref: Chang et al. 2004
  - Exhaust manifold



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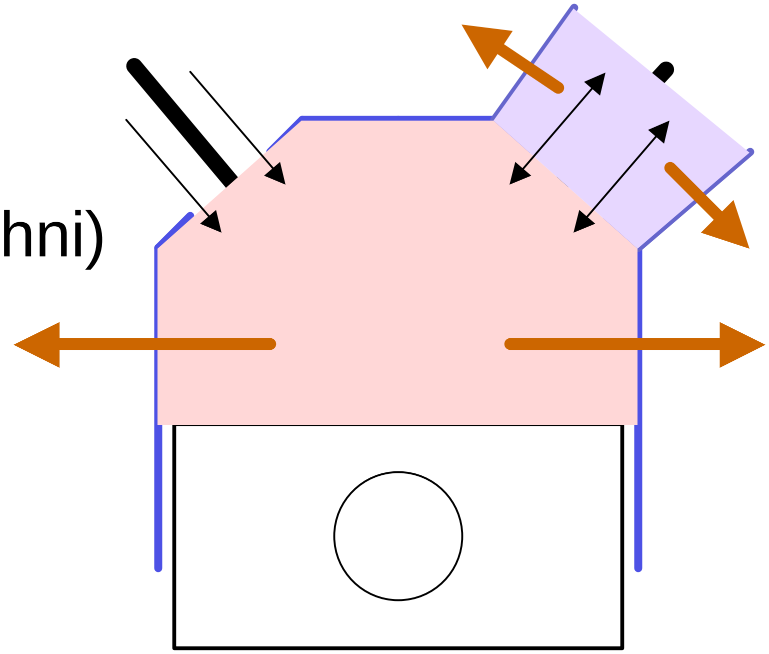


- Combustion model
  - Wiebe function
  - What do we use as a trigger for HCCI combustion?

Integrated Arrhenius Rate Equation

- Simple model for start of combustion
  - Integrated Arrhenius rate

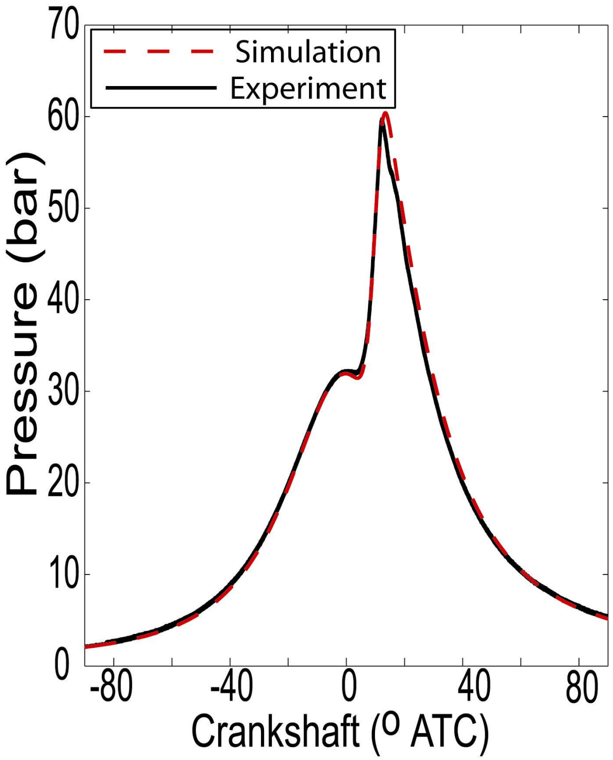
$$threshold = \int_{IVC}^{q_{comb}} A\exp\left(E_a / RT\right)\left[C_3H_8\right]^a \left[O_2\right]^b dq$$

  - Constant threshold
  - *a*, *b* and E_a from published experiments

- Contributions from temperature, compression & concentration captured

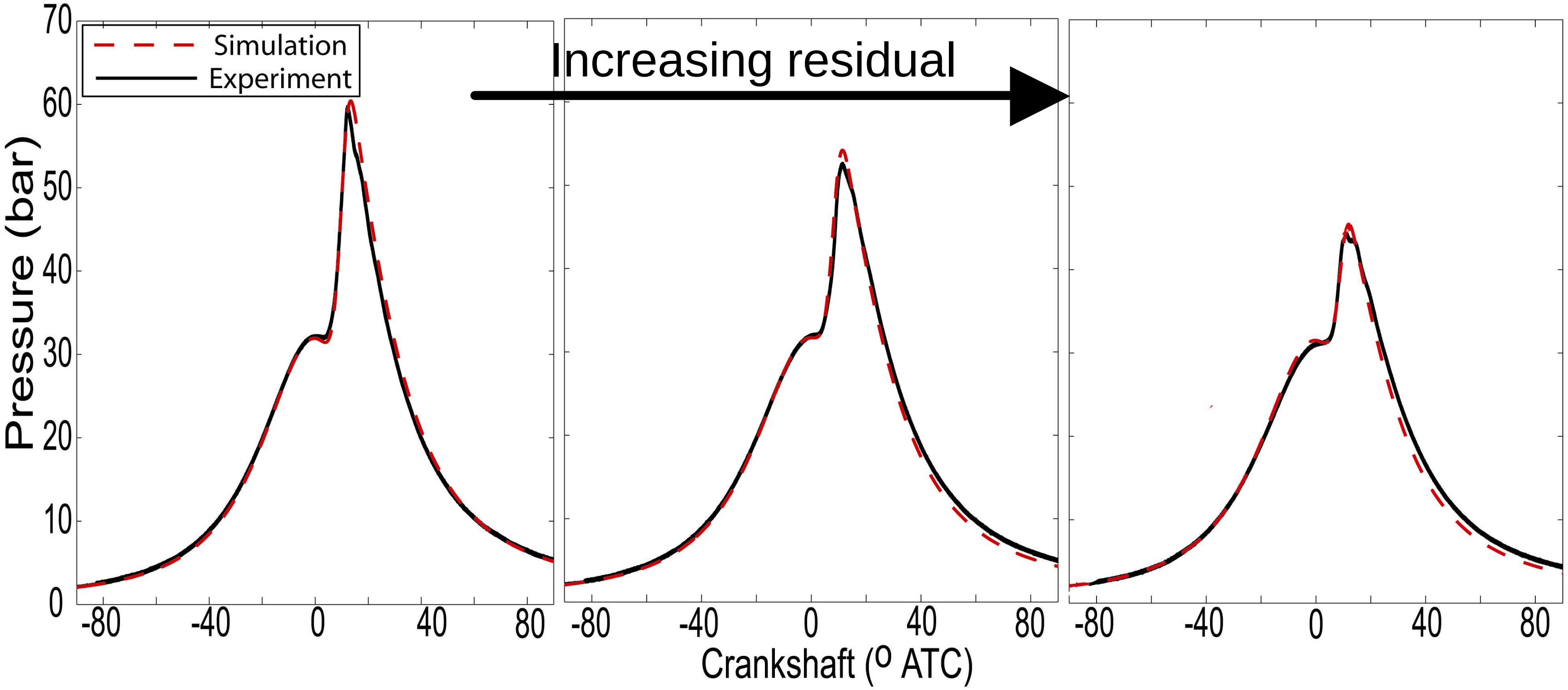
- Different from knock integral:
  - In knock integral $a = b = 0$

Integrated Arrhenius Rate



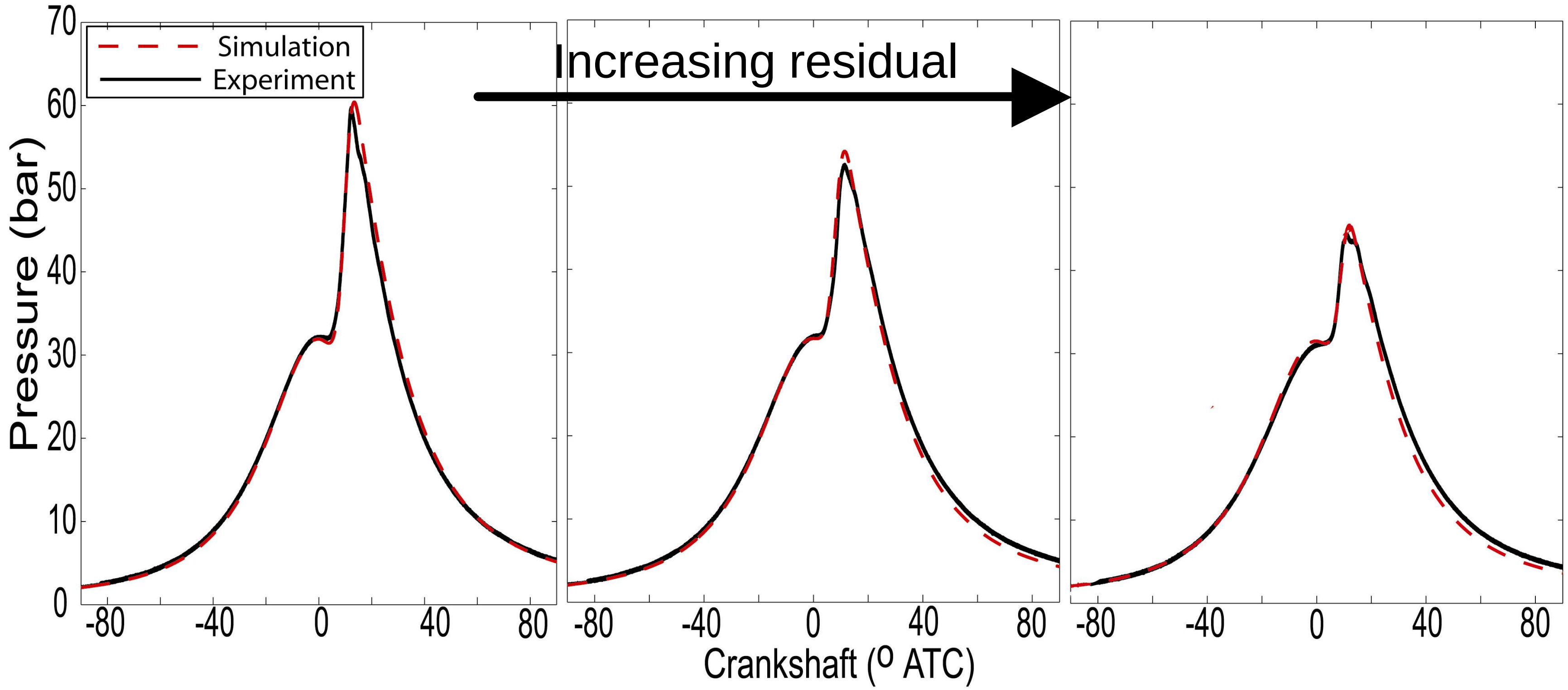
- Set threshold at one operating point…

Simulation Model: Steady State Propane



- Set threshold at one operating point…
  …and pressure, phasing & IMEP at all points is captured

Simulation Model: Steady State Propane

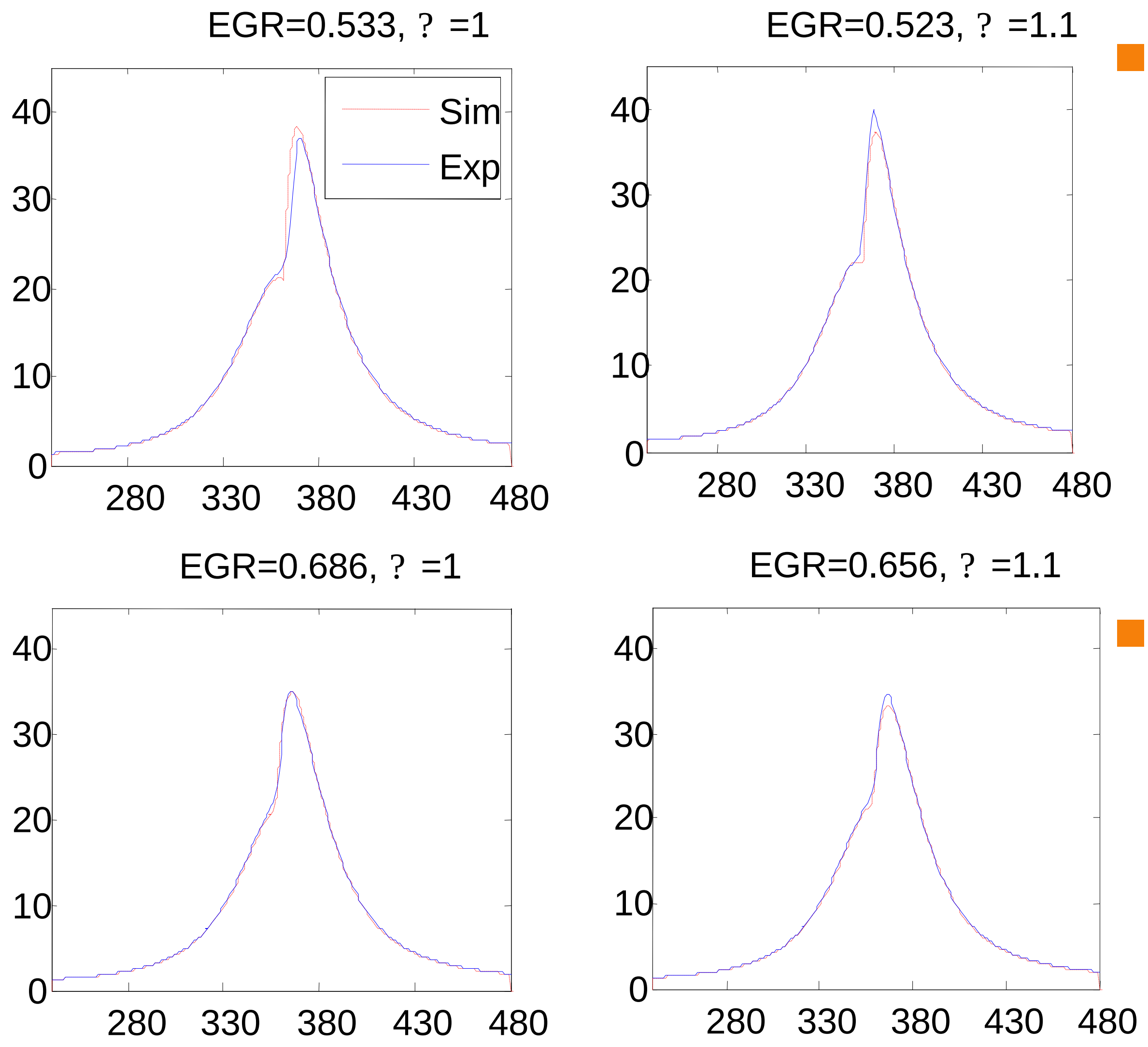


- Note: can vary RMF without much change in phasing
  - Integrated Arrhenius model captures this
  - Can find (IVO/EVC) valve manifold that maintains nearly constant phasing while varying RMF

Simulation Model: Can it be extended?

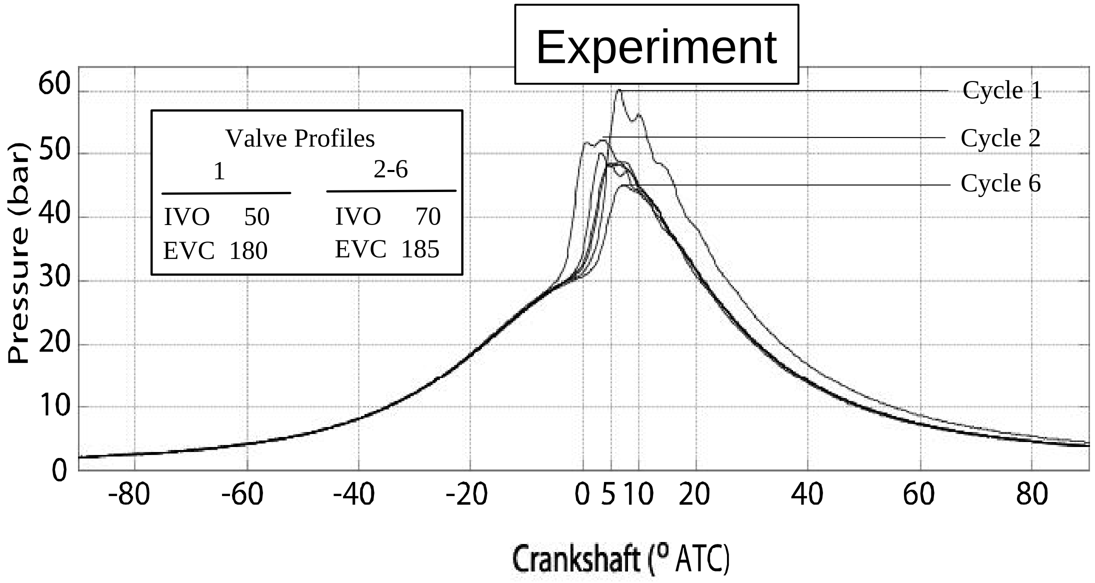
- Steady state behavior with propane captured
- What about:
  - Gasoline
  - Transients
  - SI-to-HCCI mode transitions
- Can modeling approach capture these cases?

Simulation Model: Gasoline



- Simple model captures behavior most relevant for control
  - In-cylinder pressure evolution
  - Combustion phasing
  - Work output
- This is not a big surprise:
  - Ignition delay models of complex fuels have same form as integrated Arrhenius (He et al. 2003)

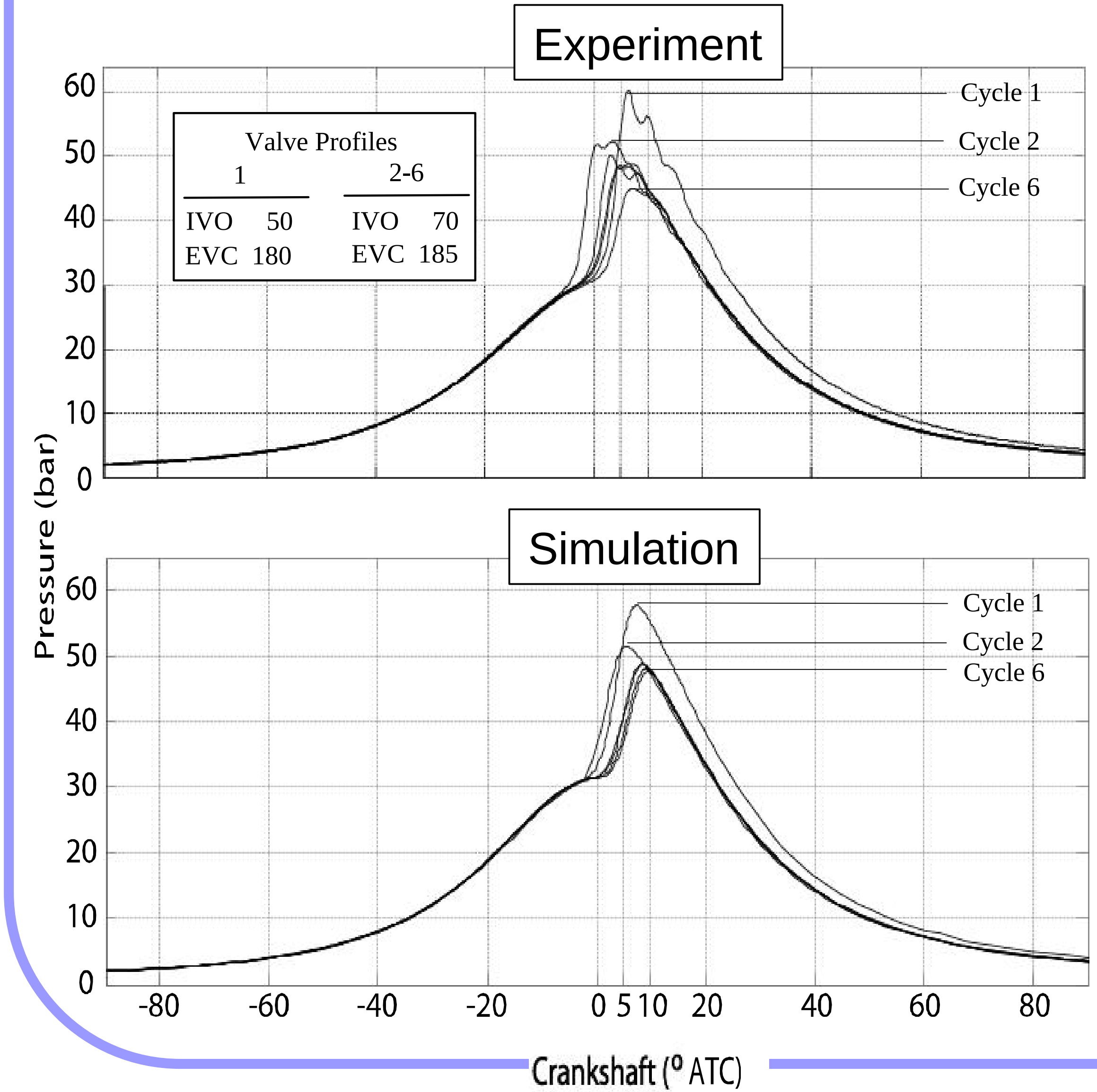
Simulation Model: Transients



Experiment

- 1st operating point has higher steady state temperature than 2nd
- The elevated exhaust temperature advances combustion process during transition
- As exhaust temperature decreases, behavior reaches new steady state

Simulation Model: Transients

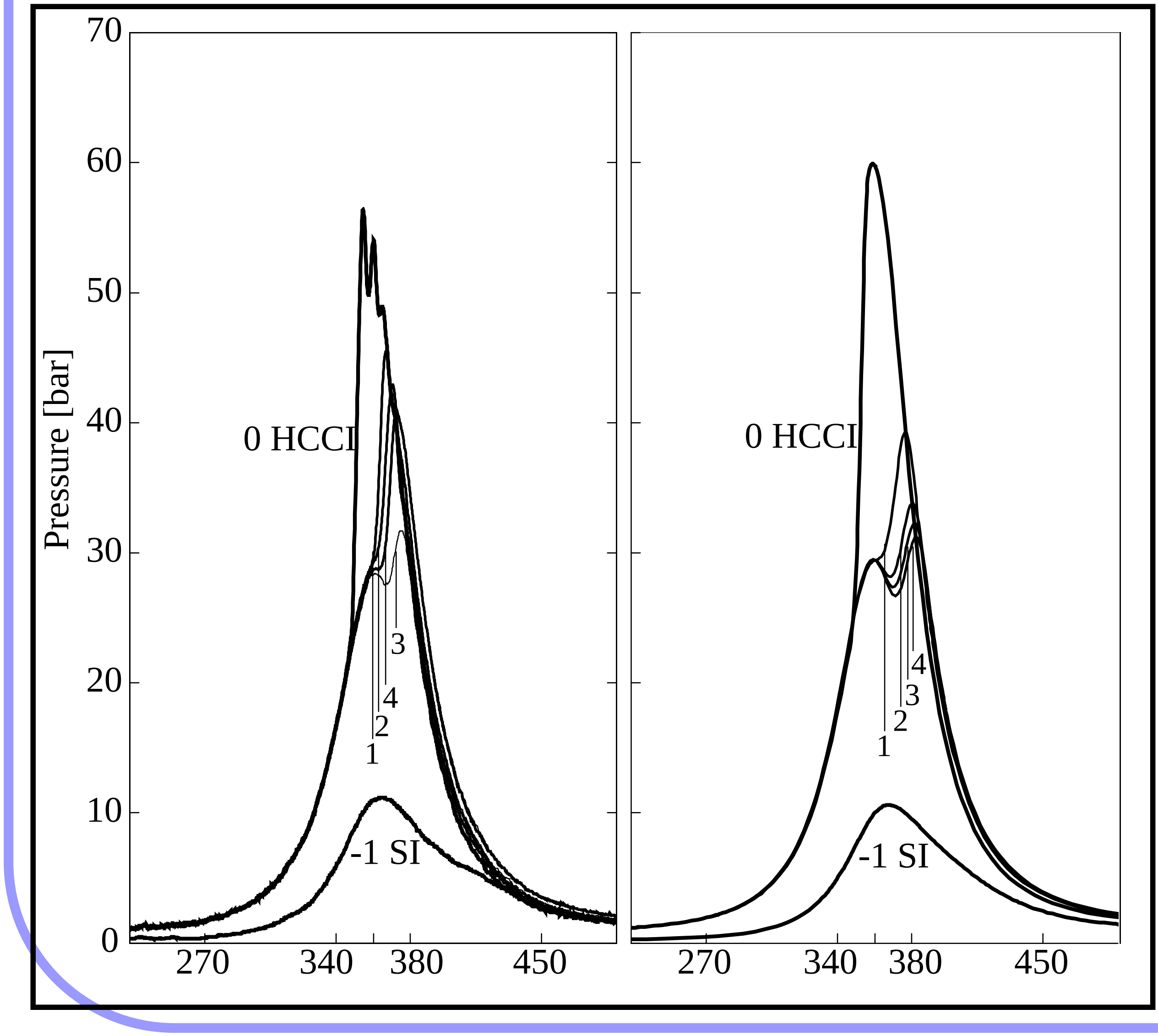


- Simple model captures the coupling and ignition behavior during transition
- As ΔT_{exht} increases, effect increases

Mode Transition

- What will happen during a SI-to-HCCI mode transition?
- SI exhaust temperature are typically substantially higher than HCCI
- We would expect to see a more pronounced effect

SI to HCCI Mode Transition Simulation



- Mode transition captured
- Coupling same: natural extension of HCCI coupling

Results from Simulation modeling

- Aspects most relevant for control captured with simple simulation model:
  - Cyclic coupling
  - Combustion phasing
  - Work output & in-cylinder pressure evolution

- Approach can handle:
  - Steady-state behavior w/ propane and gasoline
  - Transients
  - SI-to-HCCI mode transitions

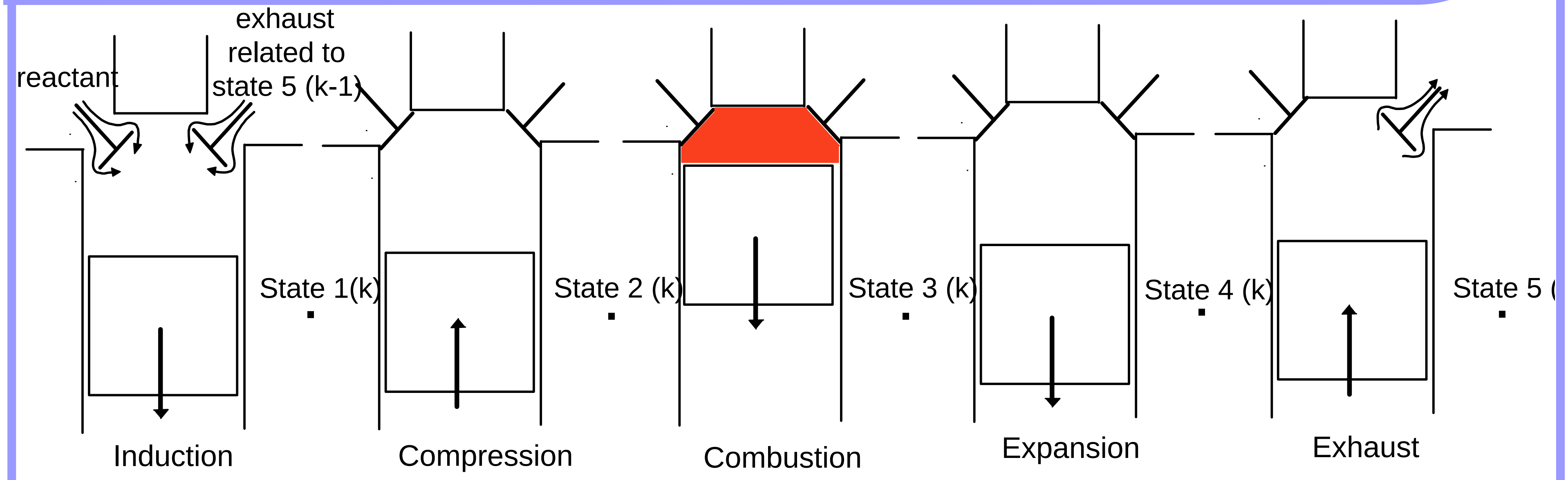
A Simple Control Strategy

- Intuition gained from simulation work: can use VVA to independently:
  - Vary inducted composition (via IVO and EVC)
  - Vary effective compression ratio (via IVC)

- Control model:
  - Input: $\alpha = N_p / N_r$ (composition)
  - Input: IVC (amount of compression)
  - Output: peak pressure or load
  - Output: combustion phasing

- Step through process to determine model

Control Model



- Assumptions:
  - Induction: atmospheric pressure
  - Full mixing
  - Isentropic compression & expansion
  - HCCI is fast: constant volume combustion
  - In-cylinder heat transfer (in cylinder): % of LHV
  - Exhaust manifold Heat transfer: convective

Control Model

- The control model takes the form:

$$P_k = f\,(a_k, a_{k-1}, P_{k-1}, q_k, q_{k-1}, IVC_k, IVC_{k-1})$$

$$threshold = \int_{IVC}^{q_{comb}} A\exp\left(E_a / RT\right)\left[C_3H_8\right]^a\left[O_2\right]^b dq$$

  - P- peak pressure
  - θ – crank angle at combustion
  - α – composition (VVA controllable input)
  - IVC (VVA controllable input)
  - All constants derived from physical values
- Control model still captures
  - Cyclic coupling
  - Ignition via kinetics

Peak Pressure Control w/ Constant Phasing

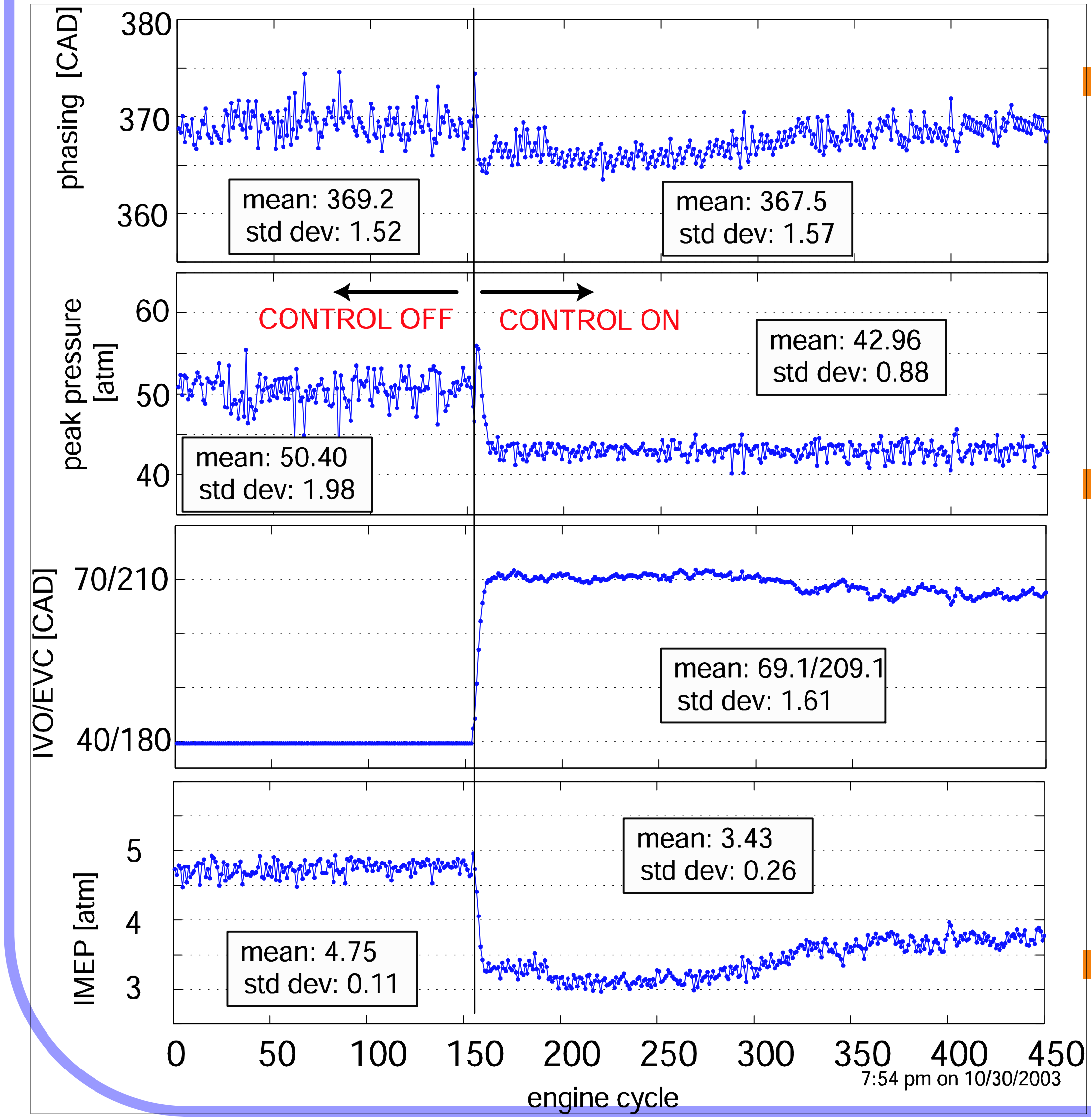
- Fix IVC

- pick IVO/EVC manifold to vary α, with:
  - ~ constant phasing (a “static” approach to treating phasing)

$$\boxed{\begin{aligned} &P_k = f(a_k, a_{k-1}, P_{k-1}, q_k, q_{k-1}, IVC_k, IVC_{k-1}) \\ &threshold = \int_{IVC}^{q_{comb}} A\exp\left(E_a / RT\right)[C_3H_8]^a[O_2]^b\, dq \end{aligned}} \longrightarrow \boxed{P_k = f(a_k, a_{k-1}, P_{k-1})}$$

  - Can then linearize model and synthesis controller

Experimental Control of Peak Pressure



- Accurate control of peak pressure
  - Mean tracking
  - Dispersion reduction
- Little change in phase
  - Fast transient
    - Residual temperature
  - Slow transient
    - Wall temperatures
- What about direct control of IMEP?

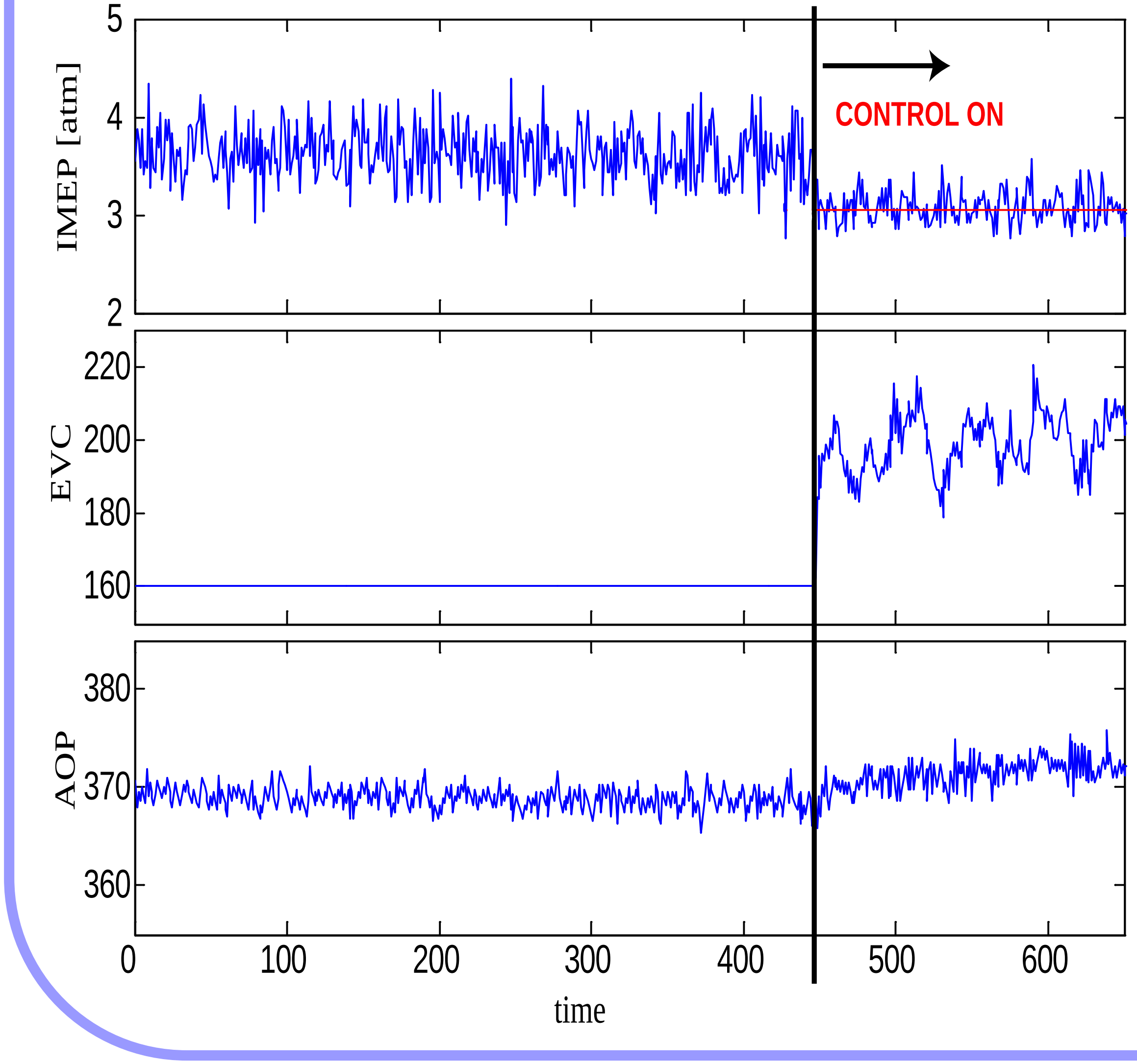
Direct IMEP Control

- A very simple model for IMEP can be formulated

$$IMEP = \frac{P_{atm} V_{IVC}^{g}\left(V_{TDC}^{1-g} - V_{IVC}^{1-g}\right) + \mathrm{P}_{\mathrm{pk}} V_{pk}^{g}\left(V_{EVO}^{1-g} - V_{pk}^{1-g}\right)}{1-g}$$

- With IVC and phasing fixed, IMEP is linearly dependent on peak pressure
  - So: IMEP control is extension of peak pressure control
  - Can use similar control strategy

Experimental IMEP Control



- Rapid tracking & dispersion reduction
- Manageable valve movements
- We can control IMEP, while keeping phasing roughly constant

Comments on Experiments

- Simple physics-based controller works well
  - Mean tracking & dispersion reduction:
    - peak pressure
    - IMEP
  - Phasing fairly constant
  - Implementation is straightforward

- What about independent control of IMEP & phasing?

Peak Pressure and Phasing Control

- Recall: control model

$$P_k = f(a_k, a_{k-1}, P_{k-1}, q_k, q_{k-1}, IVC_k, IVC_{k-1})$$

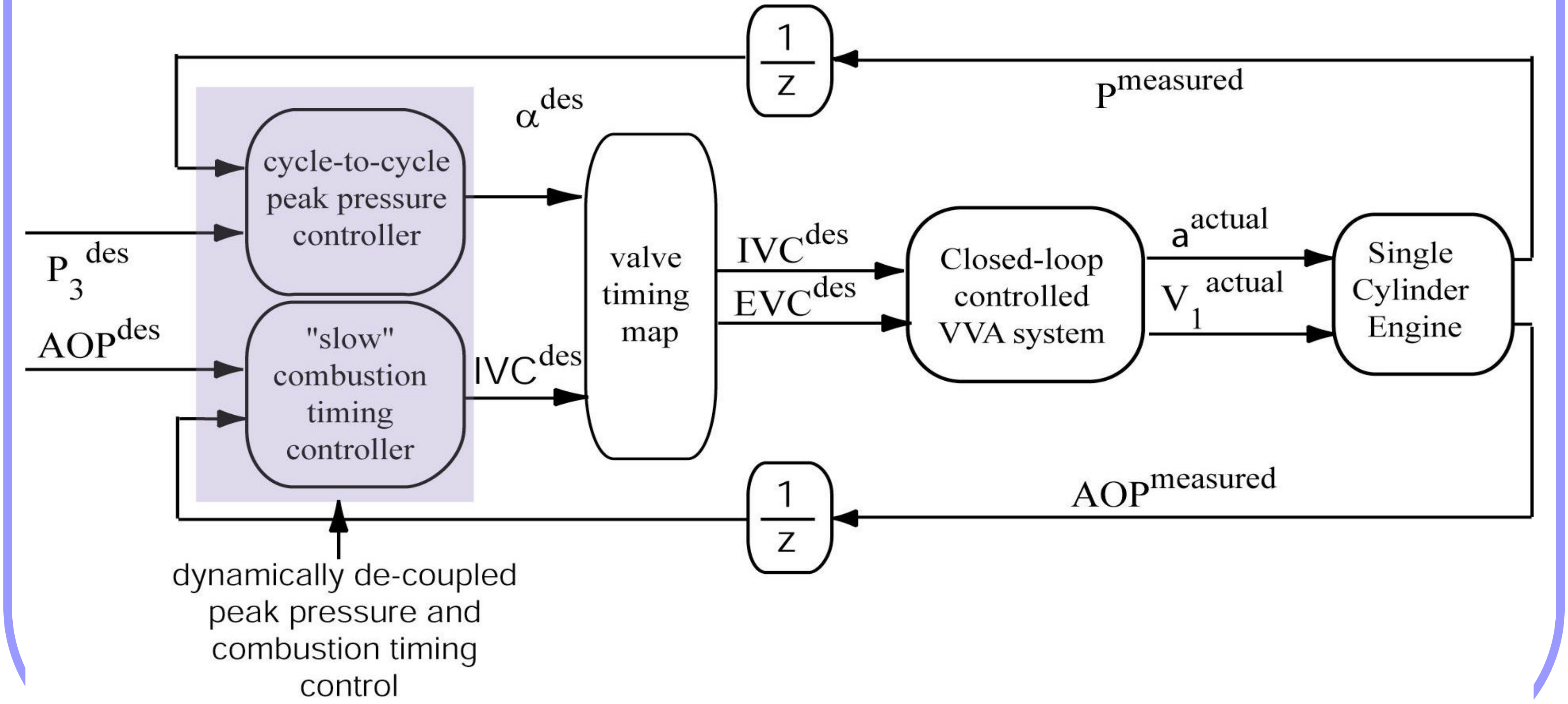
$$threshold = \int_{IVC}^{q_{comb}} A\exp\left(E_a / RT\right)\left[C_3H_8\right]^a \left[O_2\right]^b dq$$

- Add a control input: IVC (effective comp. ratio)

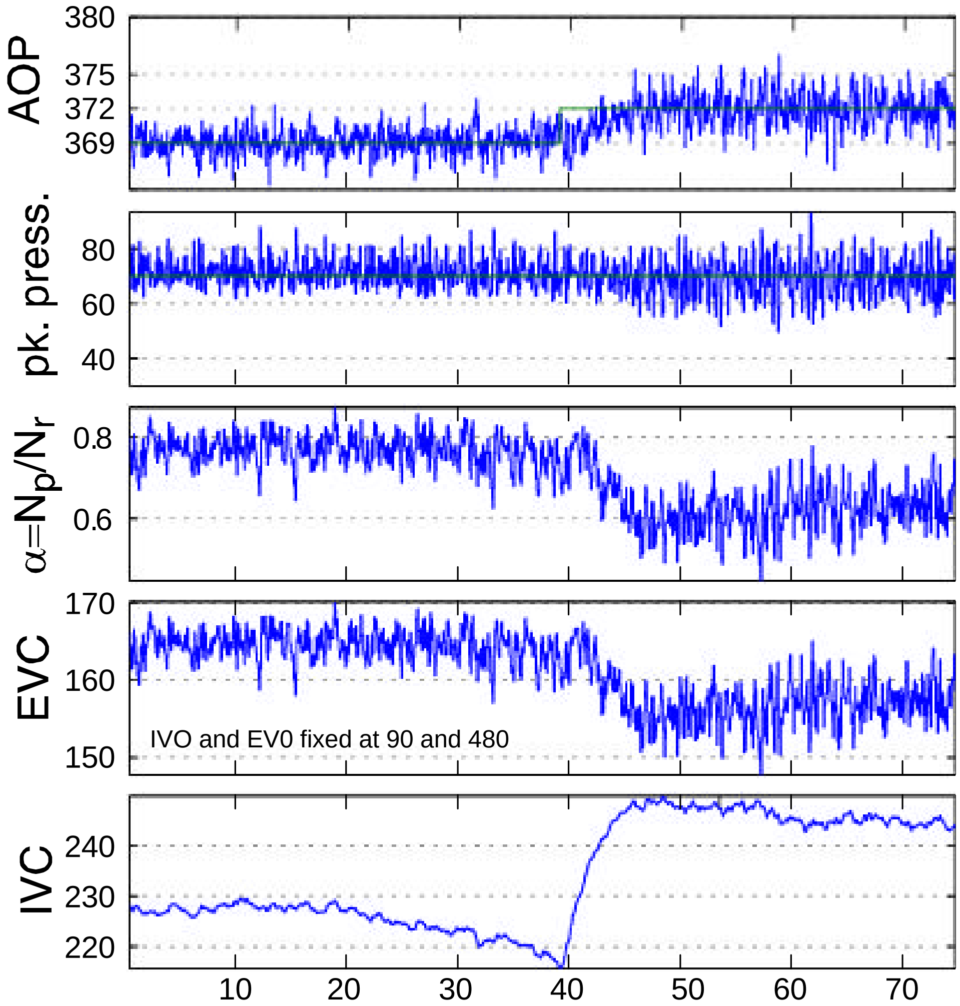
- Two different approaches
  - Separate linear controllers for peak pressure and phasing
  - Solve two nonlinear equations simultaneously
    - Dynamic Feedback Linearization

Decoupled Peak Pressure and Phase Control

- Maintain cycle-to-cycle peak pressure controller, vary phase more slowly



Experiments with Load and Phase



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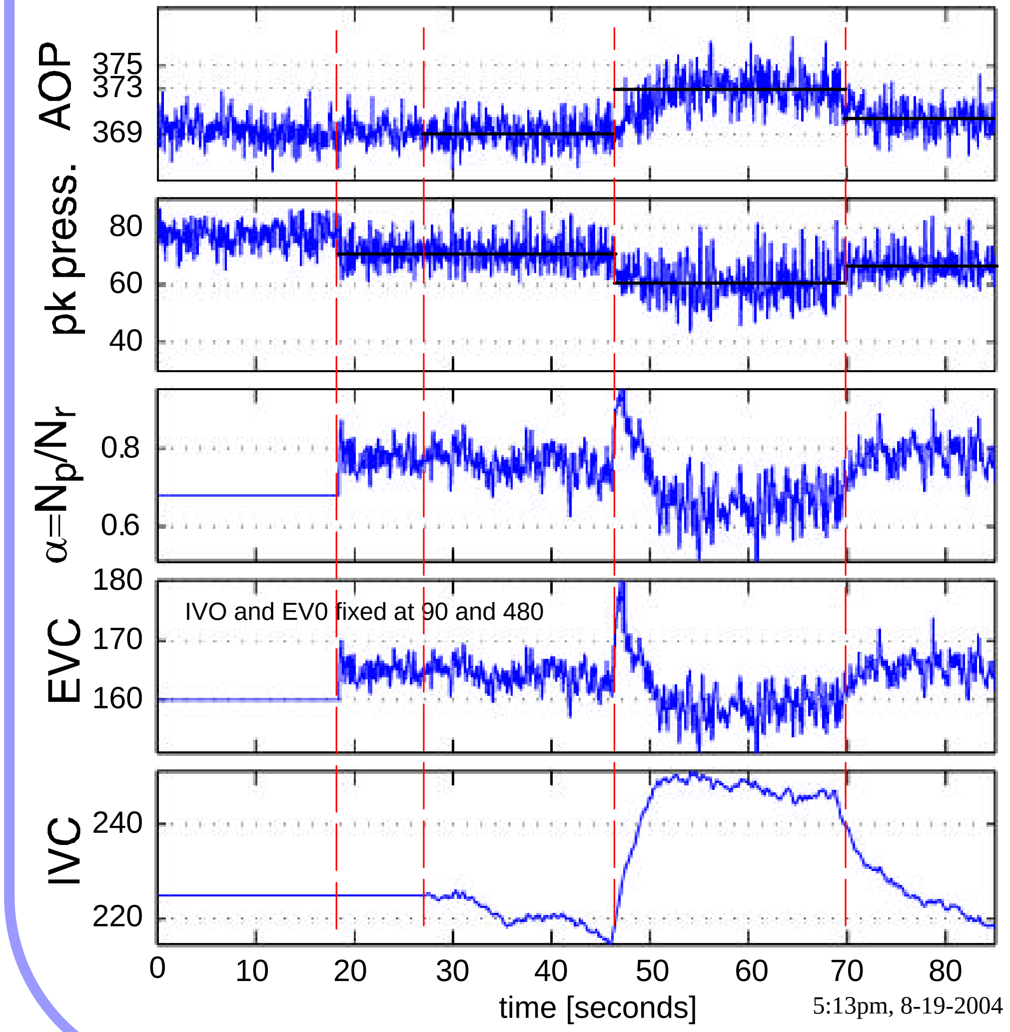
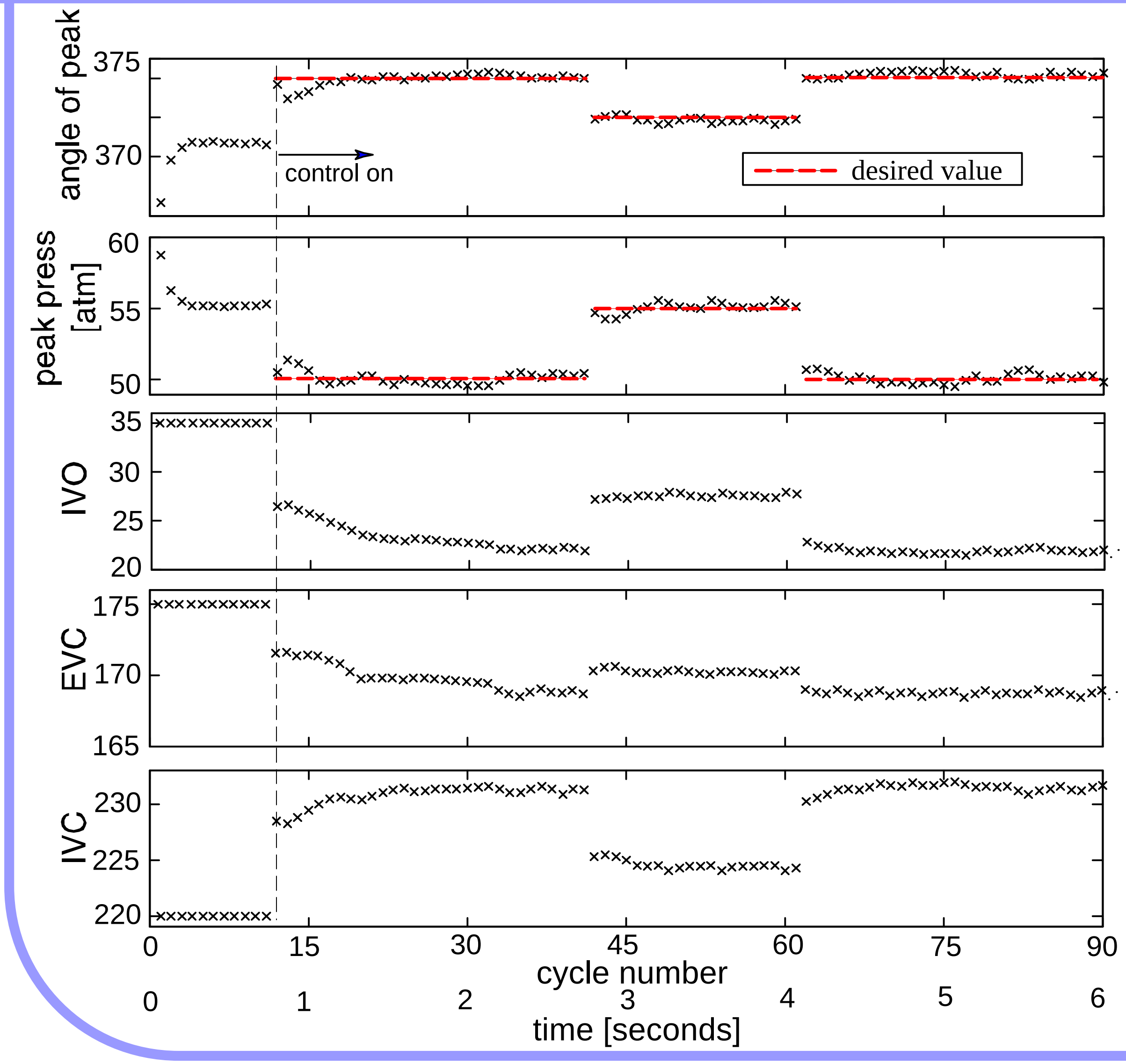
- Approach works
- Step change
  - Phasing
- Change in dispersion
  - Variation higher at later phase

Experiments with Decoupled Control



- Approach works
- Simultaneous step changes
  - Phasing and peak pressure
- 4 degree change in phase
  - ~ 30 degree change in IVC

Dynamic Feedback Linearization



- Simulation results
  - Fast cycle-to-cycle response
- Drawback
  - Computation time
- Future work:
  - Finding appropriate balance between complexity & capability

Conclusion

- Key behaviors captured in both simulation and control:
  - Cyclic coupling through the exhaust gas temperature
  - Ignition via chemical kinetics:
    - reactant concentration
    - temperature
    - effective compression ratio
- Simulation modeling extended to handle:
  - Gasoline
  - HCCI transients
  - SI-to-HCCI mode transitions
- Physics-based control of:
  - Peak pressure
  - IMEP
  - Peak pressure and phasing

Future Work

- Extension of techniques to independent control of IMEP and phasing on cycle-to-cycle basis
- Control of SI-to-HCCI transitions
- Investigate use of variable lift strategies for control