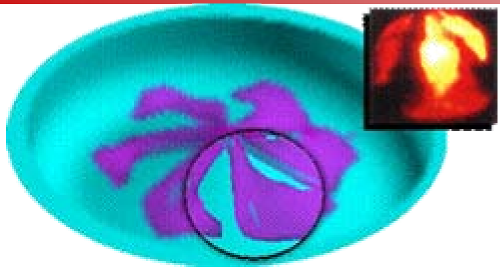

Experiments and Modeling of Two-Stage Combustion in Low-Emissions Diesel Engines

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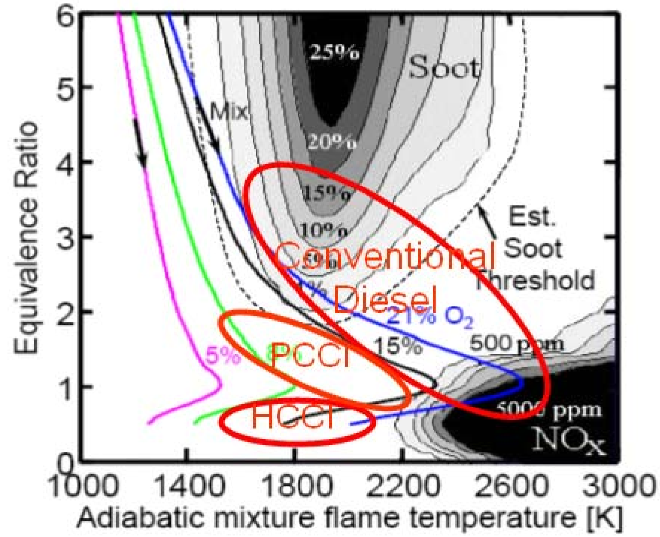
Presentation Outline

- Motivation and background
- Numerical models and validation
- Simulation results and discussion
- Experimental setup
- Experimental results and discussion
- Conclusions

Motivation and Background

- Emissions standards are becoming more and more stringent
- A focus on the reduction of greenhouse gases has driven a need for increased efficiency
- HCCI can yield high efficiency, low NOx & PM
- Y. Sun used the TSC concept to expand operating range of HCCI combustion in a heavy-duty engine (SAE 2008-01-0058)
- HCCI problems and solutions
  - Ignition control
    - EGR & VVA
  - Excessive pressure rise rates
    - Two-stage combustion (TSC)
  - Spray-wall impingement resulting from early injection
    - Adaptive injection strategies (AIS)



(Kamimoto, Akihama, Pickett)

AIS (Yong Sun SAE 2008-01-0058)

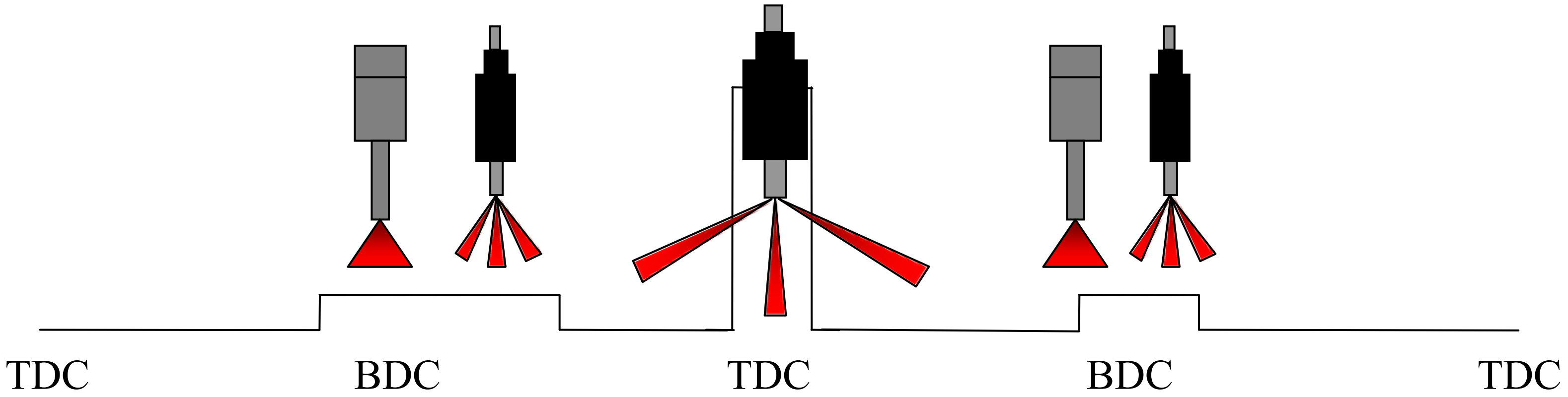
- **Low-pressure (<50MPa, 5~25MPa) narrow-angle injection**

  -- Early injection: intake or early compression stroke →HCCI, PCCI combustion

  -- Post injection: late expansion or exhaust stroke → DPF, LNT regeneration

- **High-pressure (>50MPa, above 100MPa) wide-angle injection**

  -- Late injection: late compression or early expansion stroke → conventional diesel, PCCI combustion



- **Low load: HCCI combustion → early injection**
- **Medium load: Two-Stage Combustion (TSC) → early + late injections**

  -- Sun, Y., SAE 2006-01-0027

High load: conventional diesel combustion → late injection

Specifications

Engine Specifications

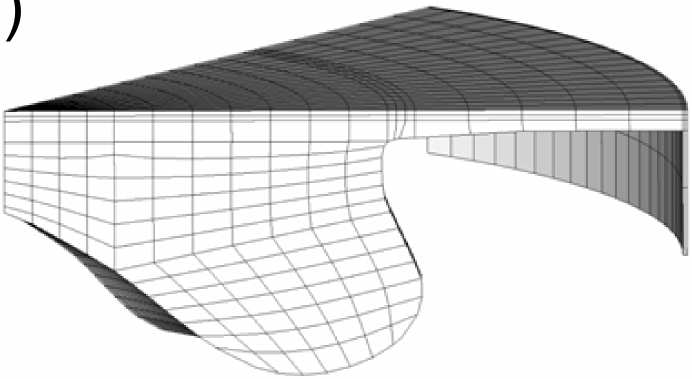
Base engine type	GM1.9 L
Bore	8.2 cm
Stroke	9.04 cm
Connecting Rod Length	16.1 cm
Squish height	0.0617 cm
Displacement	0.4774 L
Compression ratio	16.5:1
Swirl ratio	2.2
Bowl type	re-entrant
Intake valve opening	344º ATDC Firing
Intake valve closing	-132º ATDC Firing
Exhaust valve opening	112º ATDC Firing
Exhaust valve closing	388º ATDC Firing

Injector Specifications

Injector type	High-pressure solid-cone
Manufacturer	Bosch
Injection pressure	860 bar
Included angle	155°
Number of holes	7
Nozzle hole diameter	141 μm

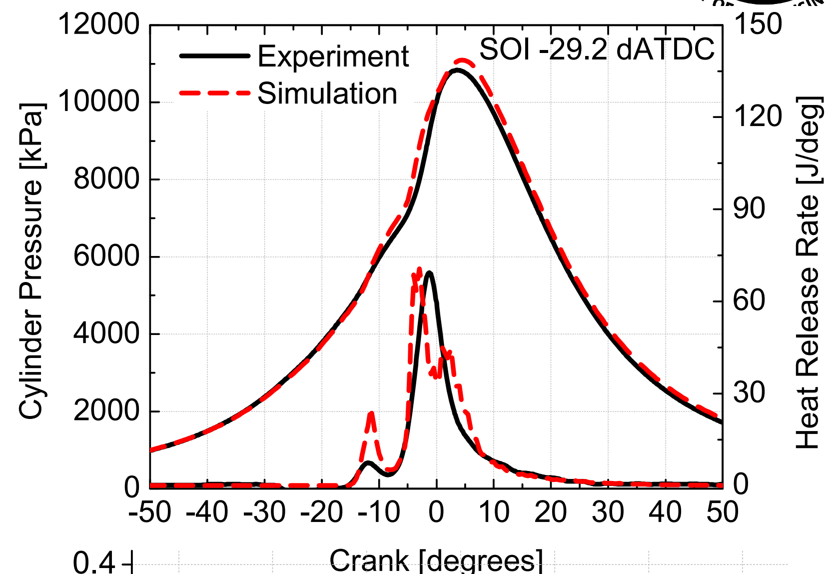
Numerical Models

- KIVA-3V Release 2 code coupled with CHEMKIN II
  - 39 species and 131 reaction n-heptane mechanism
- RNG k- ε turbulence model
- Gasjet theory used to model near nozzle droplet/gas relative velocity (SAE 2008-01-0970)
- KH-RT break up model
- Unsteady droplet vaporization
- Drop collision and coalescence
- Multi-objective genetic algorithm (MOGA) optimization

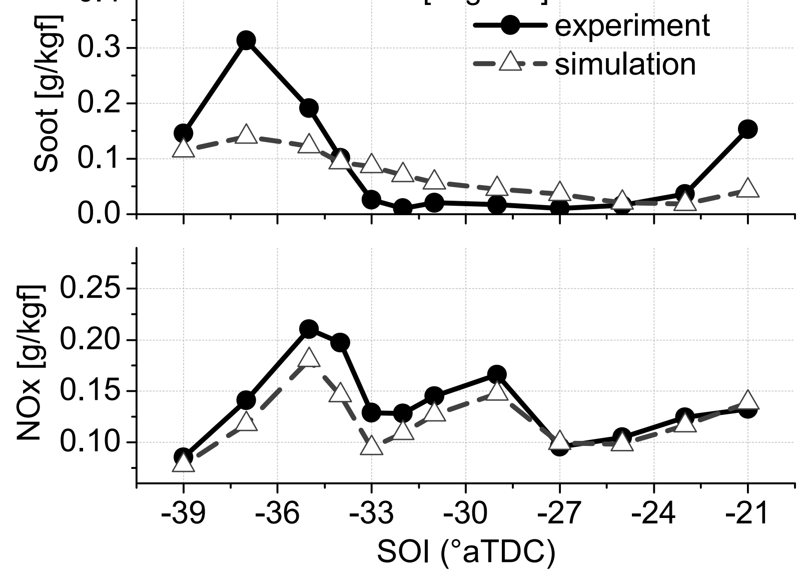


Model Validation

- Validation was performed against PCCI experiments of Opat et al. (SAE 2007-01-0193)
- Engine was operated at the F4 condition



Engine speed (rev/min)	2000
Nominal IMEP (bar)	5.5
Fuel flow rate (kg/hr)	0.895
EGR rate (%)	65
IVC Temperature (K)	350
IVC Pressure (bar)	1.91
SOI (ºATDC)	-16.2 to -34.2

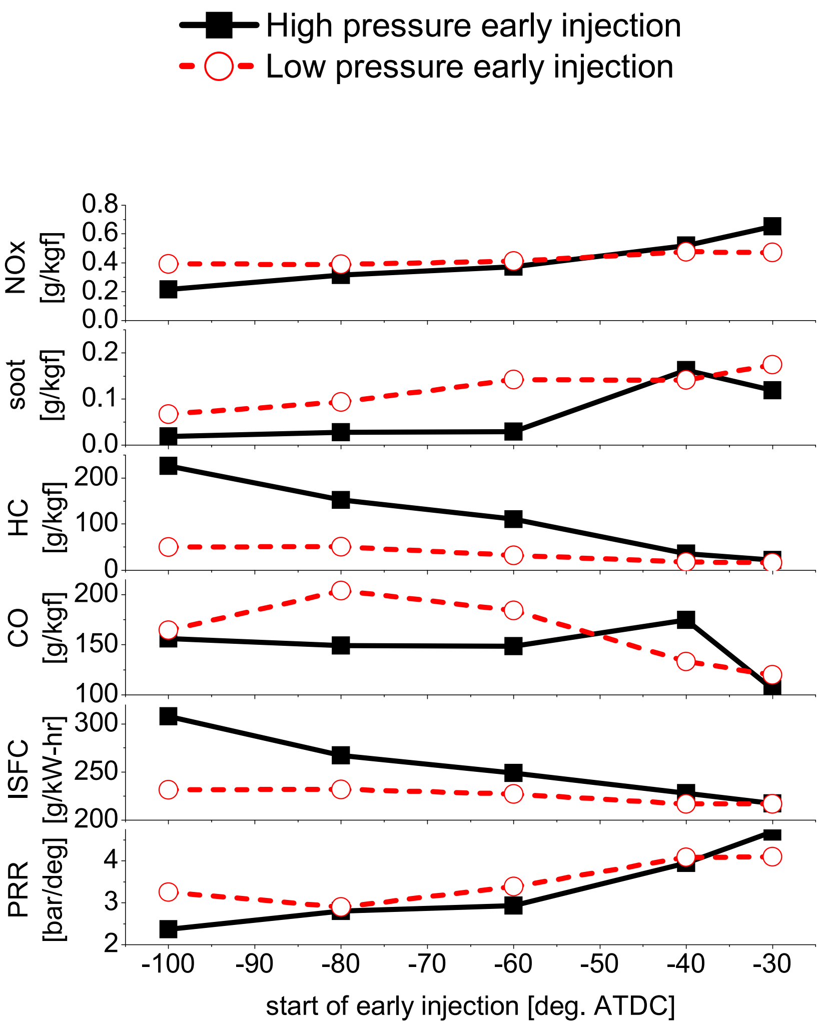


Simulation Results & Discussion

Preliminary investigation

- Fixed parameters to those of TSC case found by Kokjohn and Reitz (2008-01-2412)
- Swept early injection timing at two injection pressures
  - 100 bar and 860 bar
- Low pressure early injection showed a significant reduction in spray-wall impingement

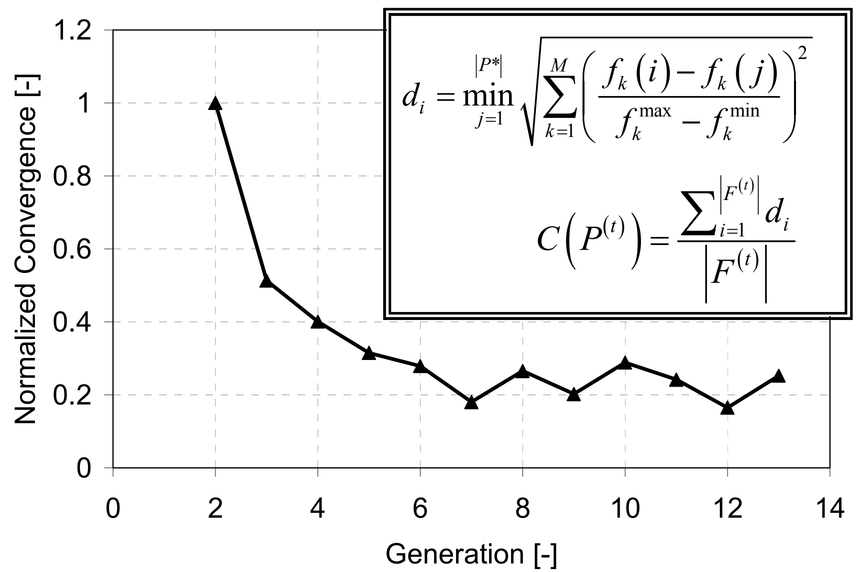
IVC Pressure (bar)	1.74
EGR rate (%)	54
SOLI timing (ºATDC)	2.9
Late injection pressure (bar)	860
Early injection fueling (mg)	5.36
Late injection fueling (mg)	9.54



AIS Optimization

- Multi-Objective Genetic Algorithm (MOGA)
- Seven optimization parameters
- Minimize six objectives
  - NOx, soot, HC, CO, ISFC, and PRR
- 13 generations with a population size of 24
  - 20 hours/case on 3.0 GHz AMD Athalon™ processor
  - Monitored convergence by comparing location of current generation Pareto front to the location of all other Pareto solutions

Early inj. pressure	100 ~ 1500 bar
Late inj. pressure	600 ~ 1500 bar
Early inj. timing	IVC ~ (SOLI-30) ºATDC
Late inj. timing	-10 ~ 25 ºATDC
IVC pressure	1.67 ~ 3.0 bar
Fuel split	10 ~ 90 % total fuel
EGR rate	0 ~ 65 %



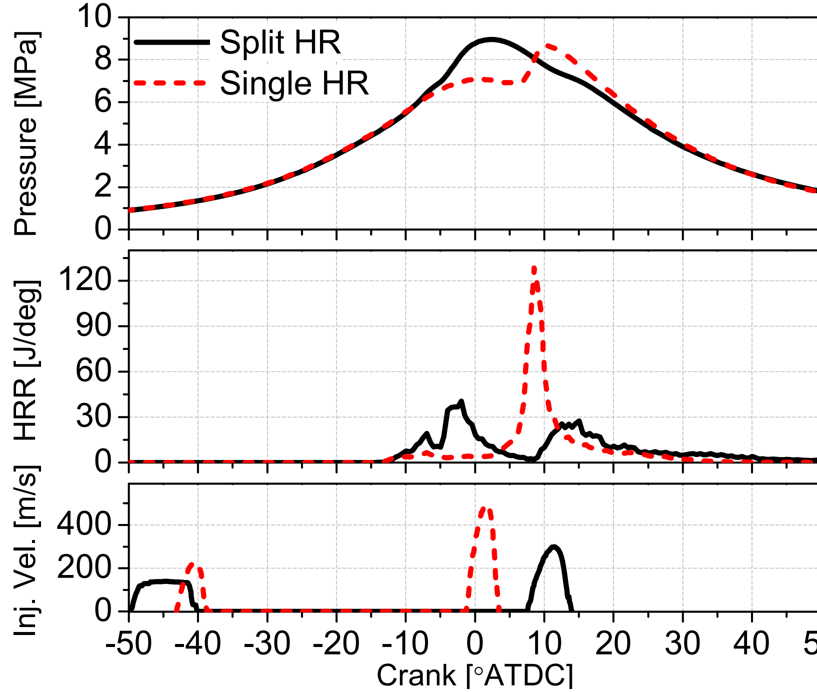
$$d_i = \min_{j=1}^{|P^*|} \sqrt{\sum_{k=1}^{M} \left(\frac{f_k(i) - f_k(j)}{f_k^{\max} - f_k^{\min}} \right)^2}$$

$$C\left(P^{(t)}\right) = \frac{\sum_{i=1}^{|F^{(t)}|} d_i}{|F^{(t)}|}$$

AIS Optimization

- Two promising types of combustion strategies found by GA optimization
- Both strategies utilize low pressure early injections

1) Split Heat Release
   - ~50% fuel split
   - Moderate EGR (43%)
   - Very retarded second injection
2) Single Heat Release
   - 30% fuel injected early
   - Second injection near TDC
   - Similar to UNIBUS strategy



	Parameters								Objectives					
	Early Inj. Pres.	Late Inj. Pres	SOEI	SOLI	IVC Press.	frac	EGR	IVC	Max PRR	Net ISFC	soot	NOx	CO	HC
	bar	bar	°ATDC	°ATDC	bar	-	%	°ATDC	bar/deg	g/kW-hr				
Split HR	110	774	-49.7	7.5	2.5	0.5	43	-100	**4.8**	**194**	0.68	0.1	45	7.0
Single HR	563	1384	-43.1	-1.3	2.4	0.3	54	-104	6.7	**196**	0.21	0.1	23	8.4
Baseline-LTC	860	NA	-28.2	NA	1.91	1	65	-132	5.5	199	0.004	0.004	46	9.0

Adaptation of AIS for Experiments

Engine Specifications

Base engine type	GM1.9 L
Bore	8.2 cm
Stroke	9.04 cm
Connecting Rod Length	16.1 cm
Squish height	**0.11 cm**
Displacement	0.4774 L
Compression ratio	**15.5:1**
Swirl ratio	2.2
Bowl type	**Mexican-hat**
Intake valve opening	344º ATDC Firing
Intake valve closing	-132º ATDC Firing
Exhaust valve opening	112º ATDC Firing
Exhaust valve closing	388º ATDC Firing

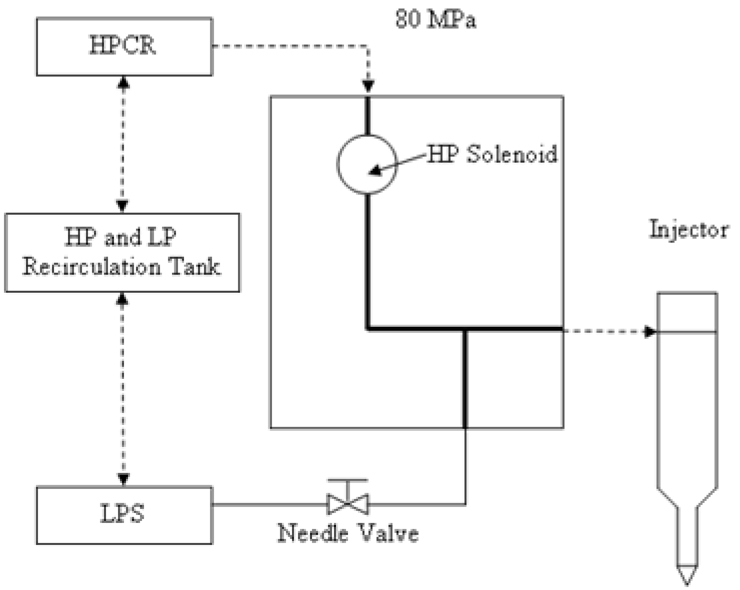
Injector Specifications

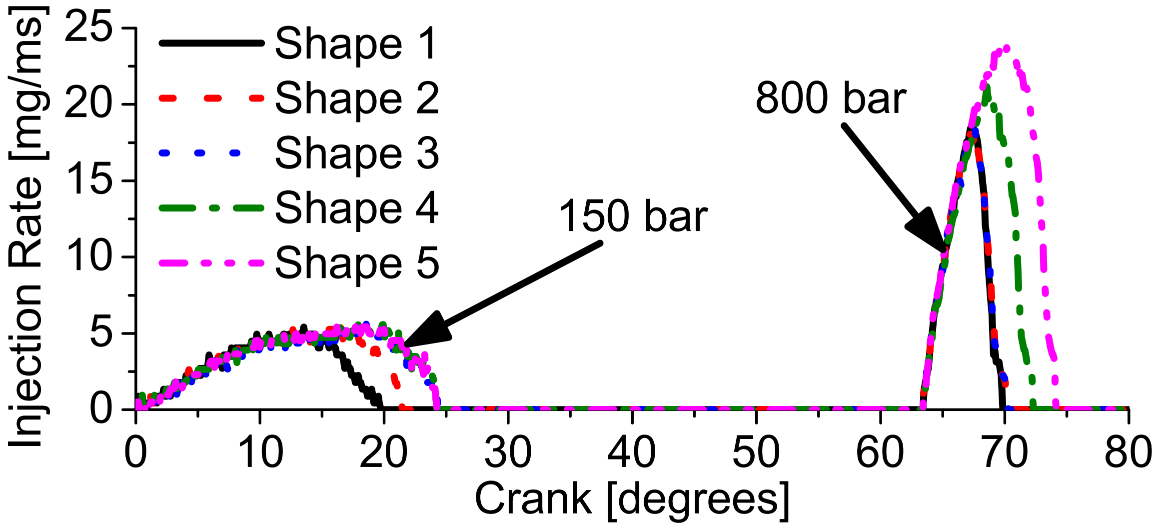
Injector type	High-pressure solid-cone
Manufacturer	**Denso**
Included angle	155°
Number of holes	**8**
Nozzle hole diameter	**128 μm**

- Hardware limitations prohibited use of VVA
- Lower compression ratio
- Mexican-hat combustion chamber
- 8 hole Denso injector

Variable Pressure Pulse System

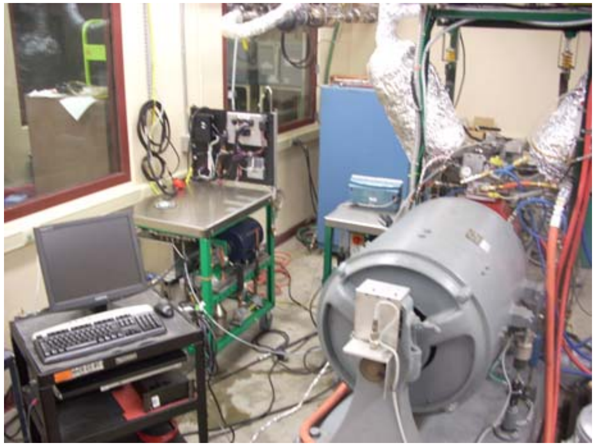
- Low pressure early injection and high pressure secondary injection
- Achieved by switching between a low and high pressure system





Variable Pressure Pulse System

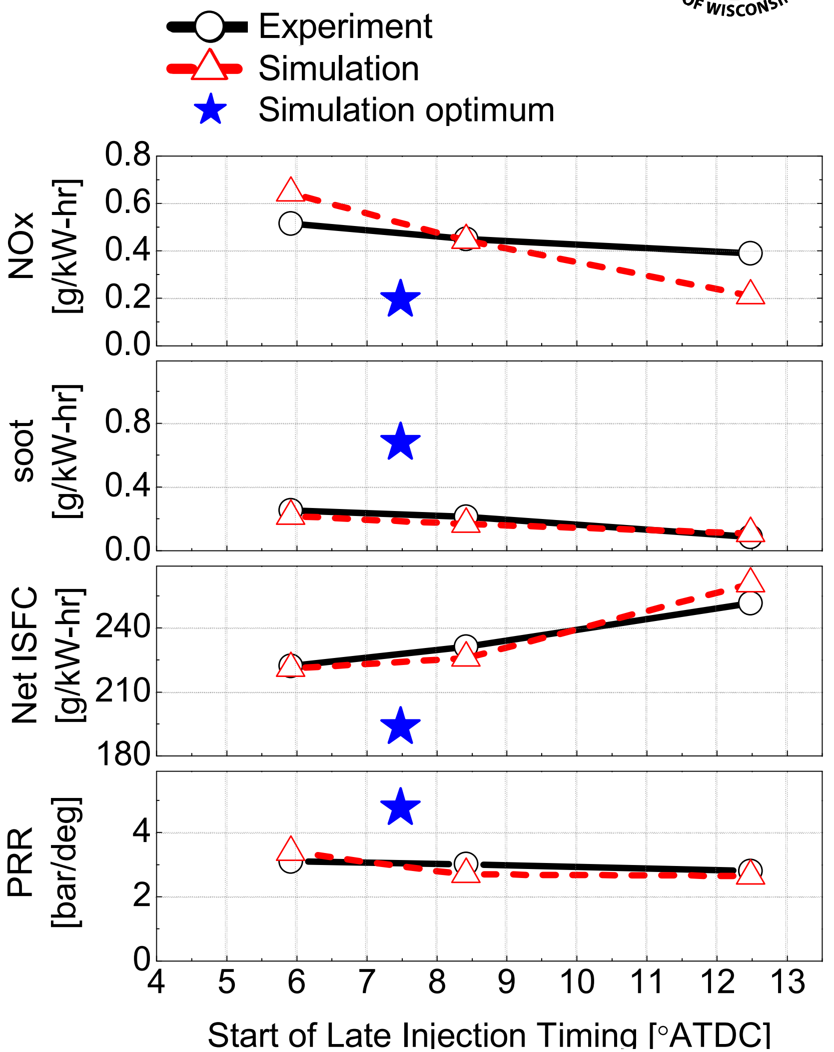
- Consists of:
  - High Pressure Common Rail
  - Low Pressure Fuel System
  - Switching Solenoid
  - Needle Valve
  - Relief Orifice
  - PFIM controller
    - Synchronize the solenoid and injector



AIS Experimental Results

Split Heat Release Cases

	Experiments/ Simulations	GA Optimum Split Heat Rel.
Early inj. pressure	150 bar	110 bar
Late inj. pressure	800 bar	740 bar
Early inj. timing	-53 ºATDC	-49 ºATDC
Late inj. timing	5.8 ~ 12.8 ºATDC	7.5 ºATDC
Boost	1.55 bar	2.35 bar
IVC timing	-132 ºATDC	-100 ºATDC
Total Fuel	13 mg/stroke	14.9 mg/stroke
Early Inj. Fuel	40 %	50 %
EGR rate	47 %	43 %
Nominal IMEP	4.3 bar	5.5 bar



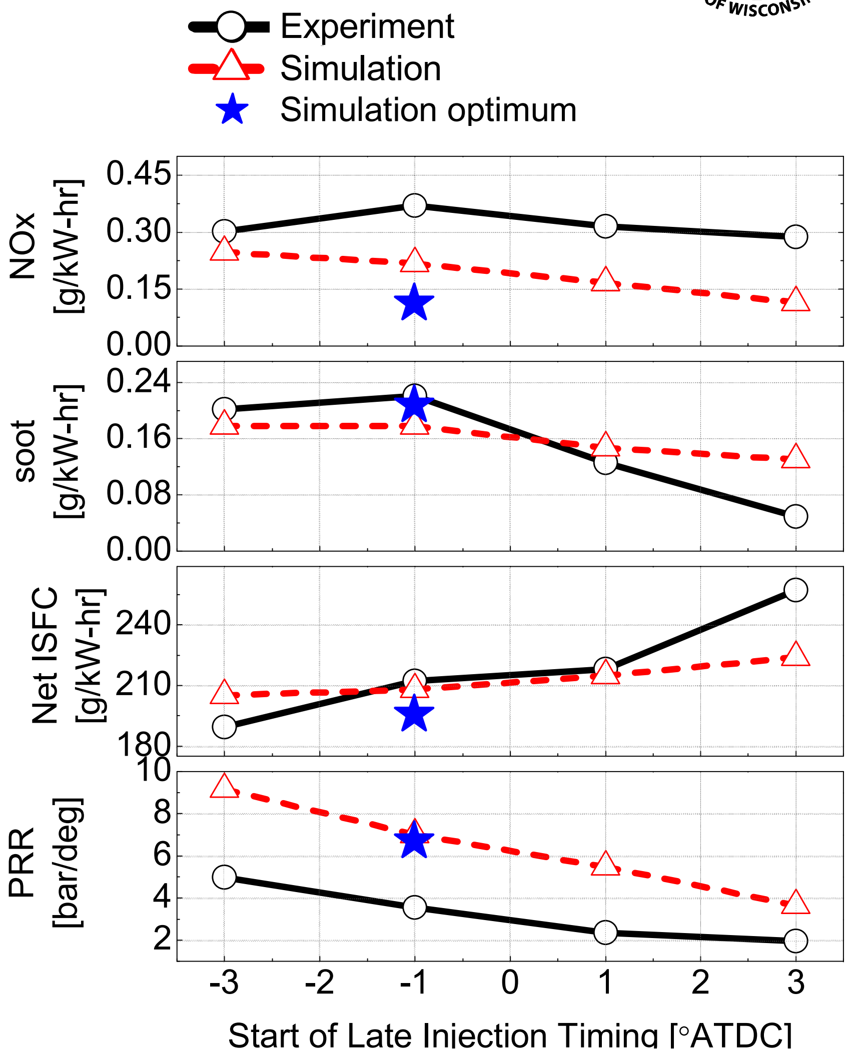
- Simulations capture emissions trends and magnitudes very well
- GA optimum shows that significant improvements in NOx and ISFC are possible with higher boost and early fueling

AIS Experimental Results

Single Heat Release Cases

	Experiments/ Simulations	GA Optimum Single Heat Rel.
Early inj. pressure	150 bar	560 bar
Late inj. pressure	1000 bar	1400 bar
Early inj. timing	-53 ºATDC	-43 ºATDC
Late inj. timing	-3 ~ 3 ºATDC	-1 ºATDC
Boost	1.62 bar	2.32 bar
IVC timing	-132 ºATDC	-104 ºATDC
Total Fuel	14.9 mg/stroke	14.9 mg/stroke
Early Inj. Fuel	10 %	30 %
EGR rate	57 %	54 %
Nominal IMEP	5.5 bar	5.5 bar

- Emissions trends are captured, but simulations over predict peak PRR and under predict NOx
- GA optimum shows that significant improvements in NOx and ISFC are possible with higher boost and early fueling



Summary and Conclusions

- Significant reductions in ISFC and NOx were observed through the use of low-pressure early injection and high boost pressure
  - Net ISFC ~ 194 g/kW-hr and NOx ~ 0.1 g/kW-hr
- VVA has been shown to provide a means for premixed combustion phasing control
- A split heat release strategy (TSC) was used control pressure rise rate and reduce engine noise
  - Peak PRR ~ 4 bar/deg
- Low pressure early injections were shown to reduce spray-wall impingement, resulting in improved ISFC and HC emissions
- A variable injection pressure system was developed and used to validate the AIS/TSC computational results
- Future work will include validation of GA optimum points when VVA system is available