Adaptive Injection Strategies (AIS) for Ultra-Low Emissions Diesel Engines

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Acknowledgments:

Caterpillar, Inc.

DOE/Sandia National Labs

Diesel Emissions Reduction Consortium (DERC)

DEER 2007 Conference

Detroit, MI

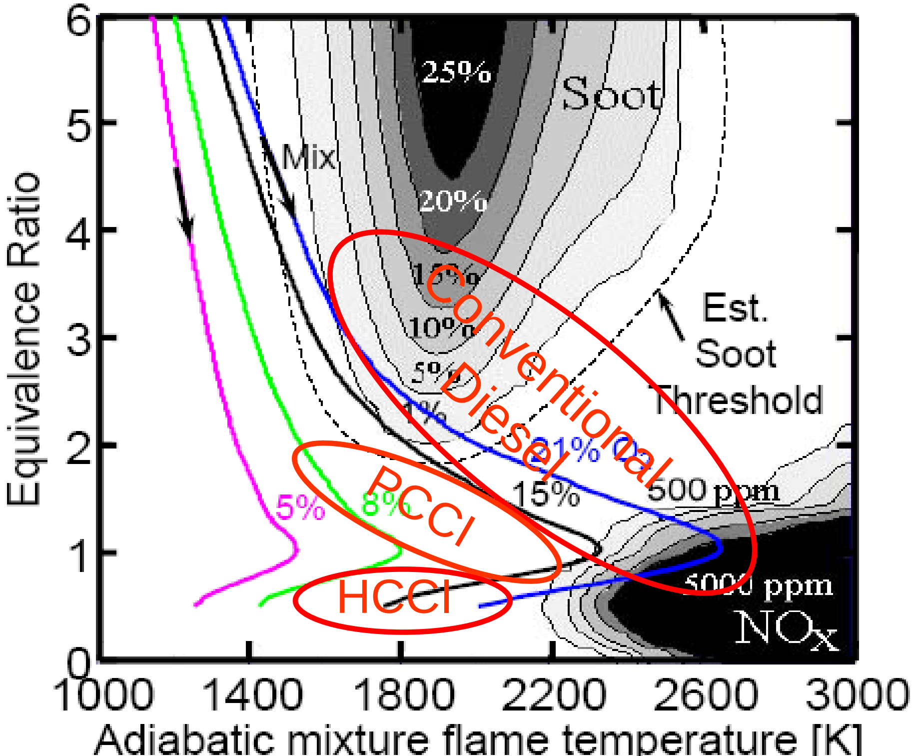
08/16/2007

OUTLINE

- Motivation and background
- Adaptive Injection Strategy (AIS)
- Simulation and optimization
  - Two-Stage Combustion (TSC -- HCCI + Diffusion combustion) optimization using AIS
  - Late injection event optimization
  - Early injection event optimization
- Engine experiments
  - Preliminary experimental results of TSC using AIS
- Conclusions

MOTIVATION AND BACKGROUND

- More and more stringent emission standards
- Low Temperature Combustion (LTC) – low NOx & PM
- Problems in diesel Homogeneous Charge Compression Ignition (HCCI) Combustion

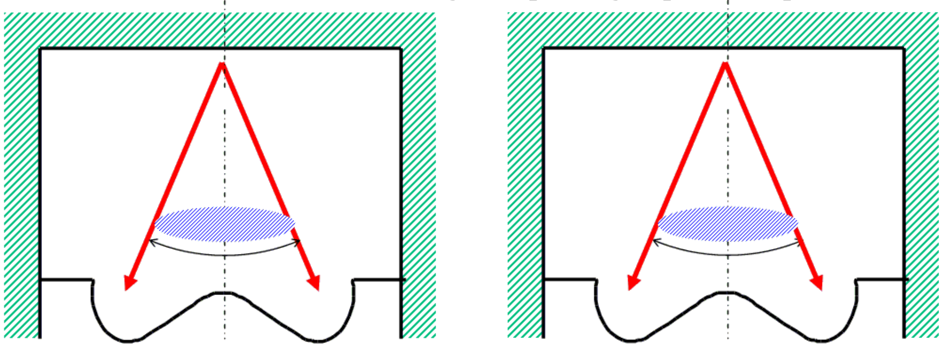


(Kamimoto, Akihama, Pickett)

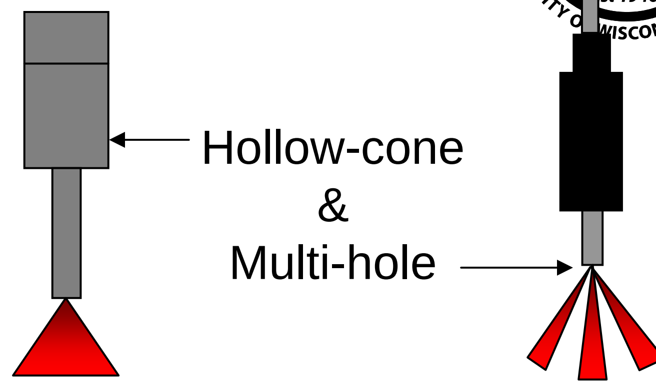
- Early ignition:
  →EGR
  →VVA →VCR
- Evaporation:
  →intake air preheating
  →SMD
- HC & CO
- Spray-wall impingement:
  →Adaptive Injection Strategy (AIS)
  {Variable Geometry Spray (VGS)
  {Variable Injection Pressure (VIP)
- Extension to higher loads:
  →Two-Stage Combustion (TSC)

ADAPTIVE INJECTION STRATEGY (AIS)

- **Variable Geometry Spray (VGS)**



Variable Spray Angle



Variable Spray Pattern

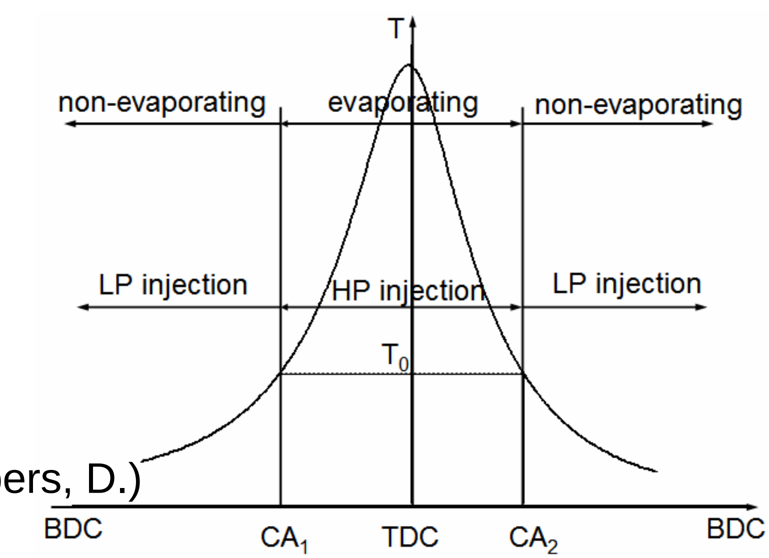
- **Variable Injection Pressure (VIP)**

Liquid penetration of non-evaporating sprays
vapor penetration of evaporating sprays:

$$s = 2.95\left(\frac{\Delta P}{\rho_a}\right)^{1/4}\sqrt{d_0 t} \qquad \text{(Hiroyasu, H.)}$$

Maximum liquid penetration of evaporating sprays:

$$s = \frac{b}{a}\sqrt{\frac{\rho_f}{\rho_a}}\,\frac{\sqrt{\mathrm{Ca}}\cdot d}{\tan(\theta/2)}\sqrt{\left(\frac{2}{B(T_a,P_a,T_f)}+1\right)^2-1} \quad \text{(Siebers, D.)}$$



AIS APPLICATION

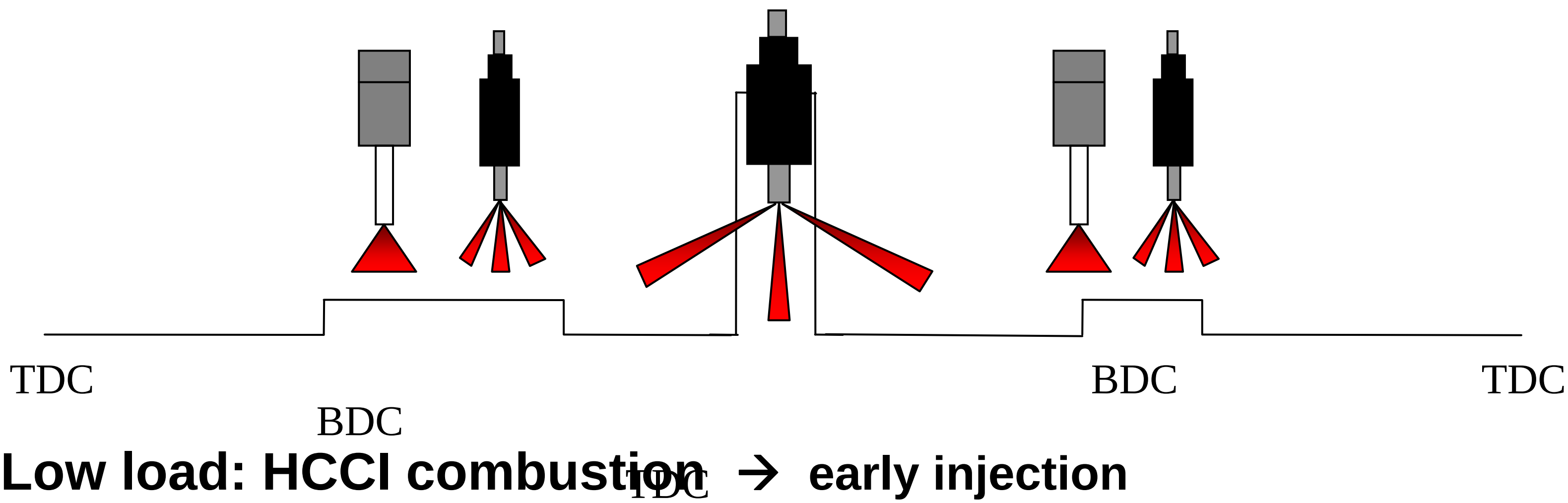
- **Low-pressure (<50MPa, 5~25MPa) narrow-angle injection**

  -- 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



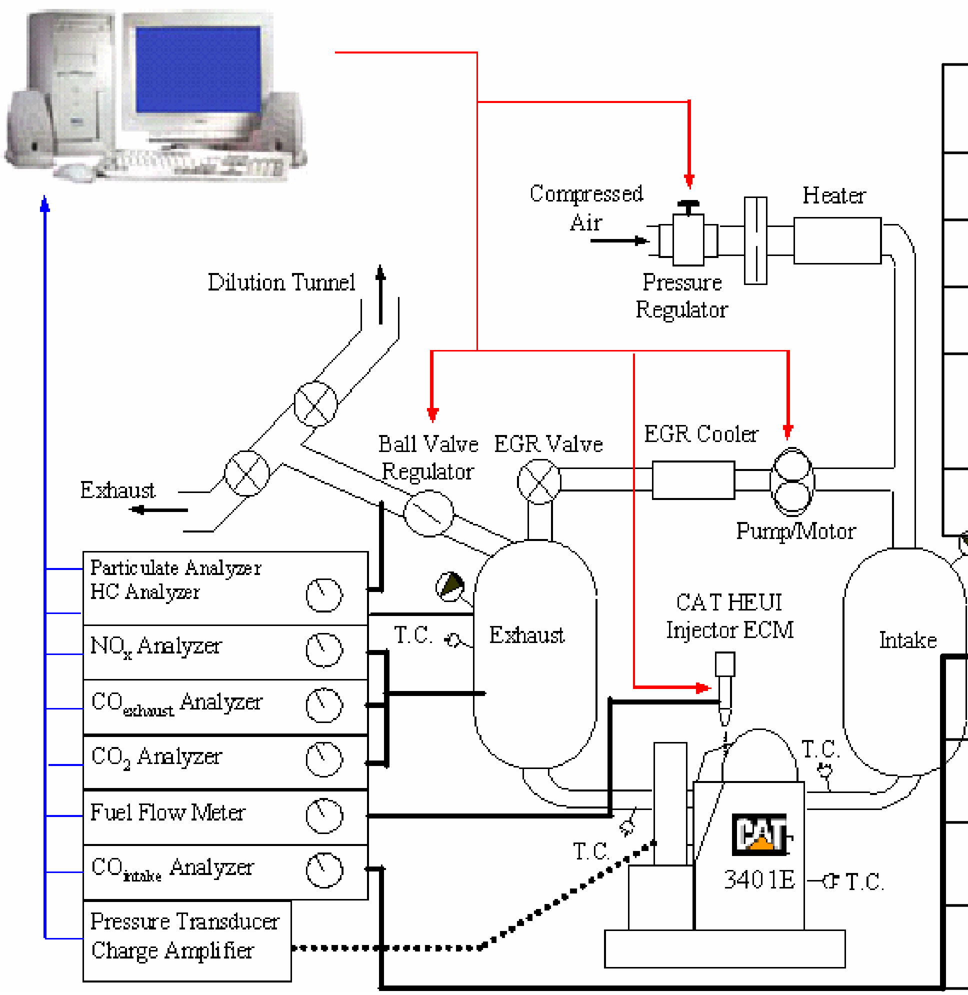
- **Low load: HCCI combustion → early injection**
- **Medium load: Two-Stage Combustion (TSC) → early + late injections**

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

High load: conventional diesel combustion → late injection

(US Patent filed)

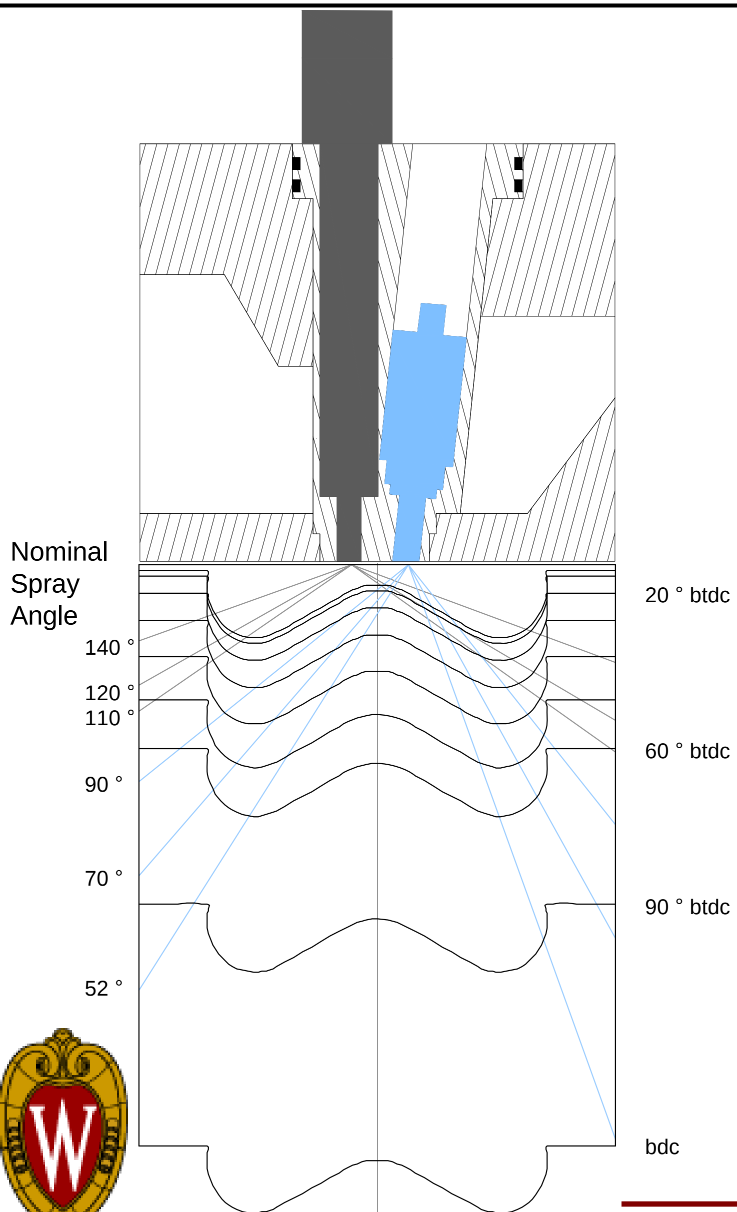
ENGINE SPECIFICATIONS

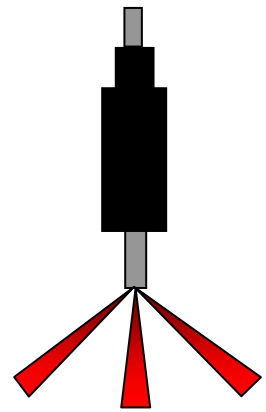


Engine Type	Caterpillar 3401 SCOTE
Bore× Stroke [mm]	137.2 × 165.1
Displacement [L]	2.44
Compression Ratio	16.1:1
Engine valve timing (°CA ATDC)	IVC=-143, EVO=130 EVC=-355, IVO=335
Swirl Ratio	1.0

Mode	5
Speed [RPM]	1737
Load (%)	57
IVC (°CA ATDC)	-85

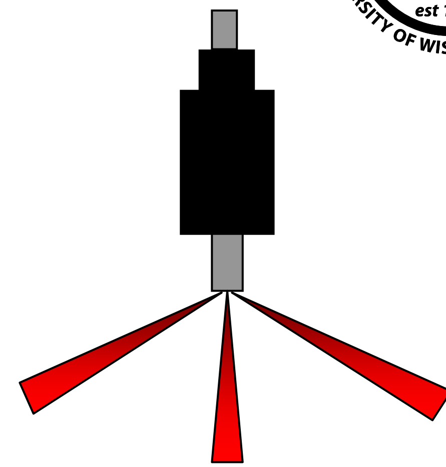
AIS SIMULATION USING TWO INJECTORS





Bosch
10MPa
90°
6-hole
170um

Intake stroke
early compression
stroke



Bosch
150MPa
127°
8-hole
127um

late compression
stroke
around TDC

NUMERICAL ANALYSIS

- KIVA3V R2 (ERC sub-models) -CHEMKIN-GA code
- RNG k-ε turbulence model
- KH-RT break up model -- high-pressure MHN spray
- Recalibrated KH model -- low-pressure MHN spray
- Droplet vaporization, collision and wall-film models
- ERC's reduced n-heptane mechanism (30 species and 65 reactions)
- Reduced NO mechanism, two-step phenomenological soot model
- Genetic Algorithms (GA) -- merit function

$$f = \frac{B}{\left(\frac{NOx}{NOx*}\right)^a + \left(\frac{HC}{HC*}\right)^b + \left(\frac{PM}{PM*}\right)^c + \left(\frac{BSFC}{BSFC*}\right)^d}$$

-- Emission targets are *2010 EPA heavy-duty highway diesel engine emission standards*.

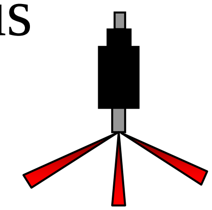
PM: 0.0134 g/kW-hr   NOx: 0.2681 g/kW-hr

HC: 0.1876 g/kW-hr   BSFC: 200 g/kW-hr

-- Penalty functions based on the physical constraints of the engine

LATE INJECTION EVENT OPTIMIZATION

- Genetic Algorithm (GA) was used to optimize four engine operating parameters at mode 5 (homogeneous assumption for the early injection)



- Range of parameters explored

Parameter	Lower Limit	Upper Limit
IVC (°CA)	-143	-83
SOLI (°CA)	-10	21
Premixed fraction (-)	0.2	0.9
EGR ratio (%)	0	60

- Merit function

$$f = \frac{100}{\left(\frac{NOx}{NOx*}\right)^2 + \left(\frac{HC}{HC*}\right) + \left(\frac{PM}{PM*}\right) + \left(\frac{BSFC}{BSFC*}\right)^{10}}$$

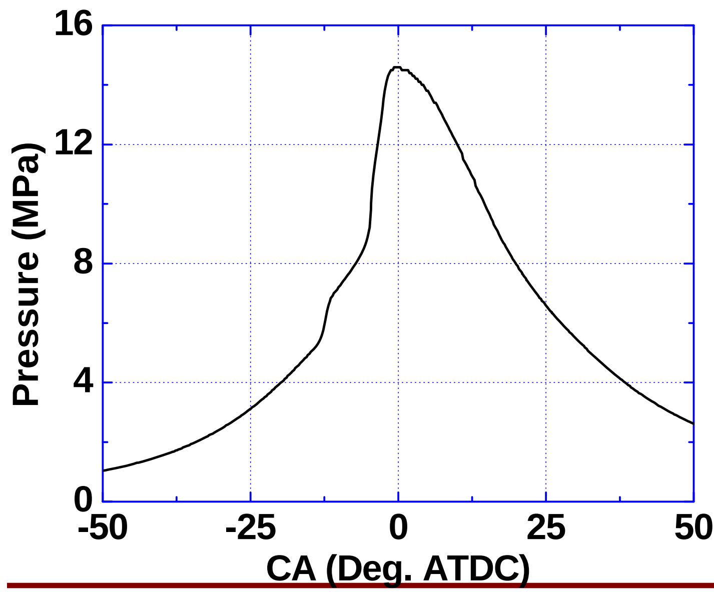
HCCI + LATE INJECTION OPTIMUM

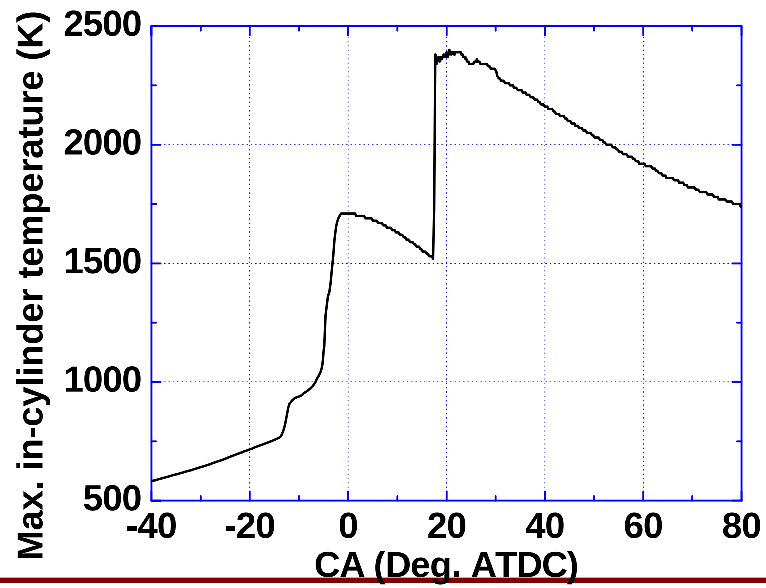
Best case after 100 generations

IVC (°CA)	SOLI (°CA)	EGR (%)	Premixed fraction
-95	17	28	0.7

Results of the best case so far

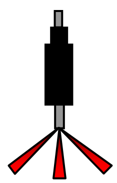
(g/kW-hr)	BSFC	Soot	NOx	HC	CO
Optimum	211.4	0.017	0.174	0.014	0.123
Target	200	0.0134	0.2681	0.1876	

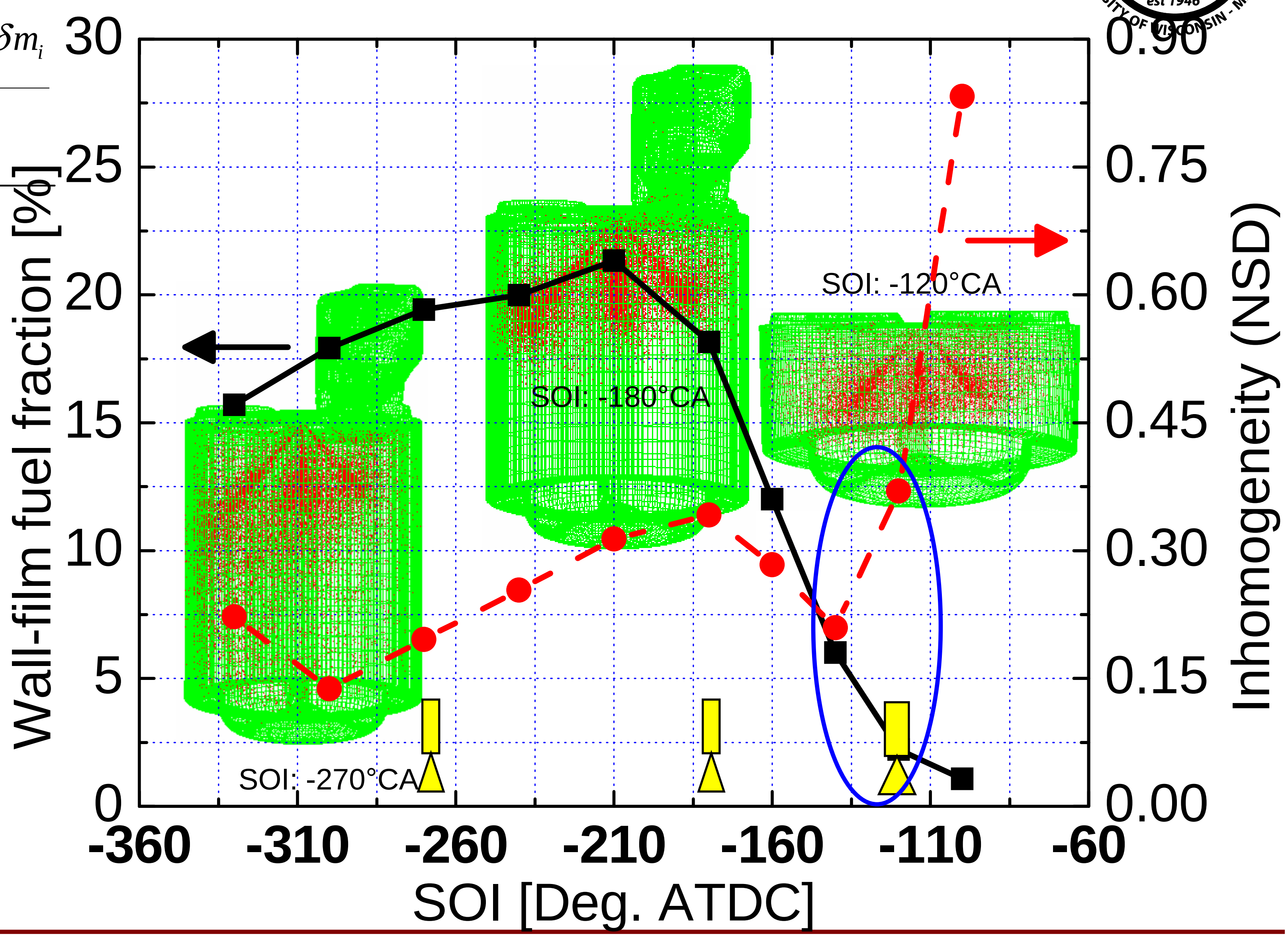




EARLY INJECTION OPTIMIZATION

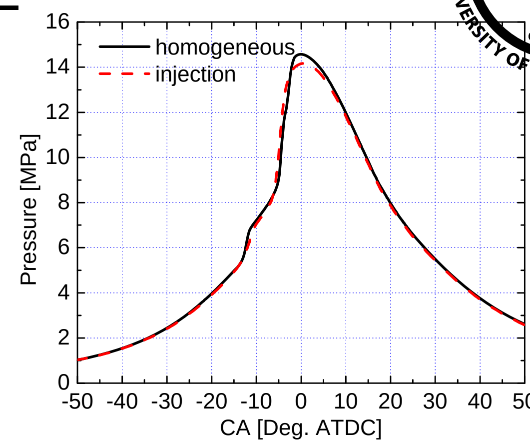
$$\frac{\sqrt{\dfrac{\sum_{i}^{\#cells}(\Phi_i-\bar{\Phi})^2\,\delta m_i}{\sum_{i}^{\#cells}\delta m_i}}}{\Phi}$$





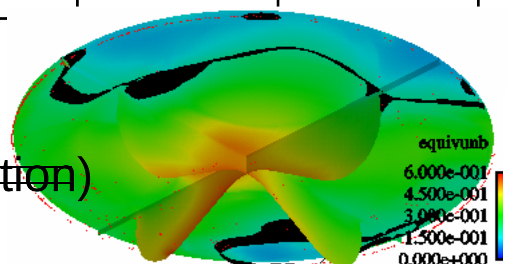
TSC USING AIS

(g/kW-hr)	Soot	NOx	HC	CO
Injection	0.033	0.181	2.040	12.889
Homogeneous	0.017	0.174	0.014	0.123
Target	0.0134	0.2681	0.1876	

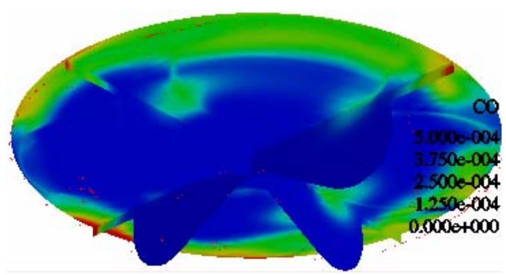


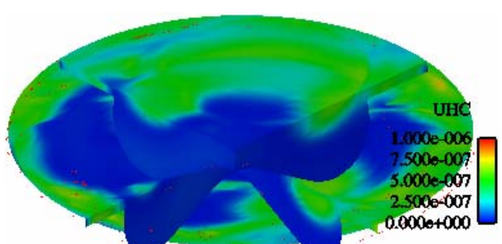
~~(homogeneous assumption)~~

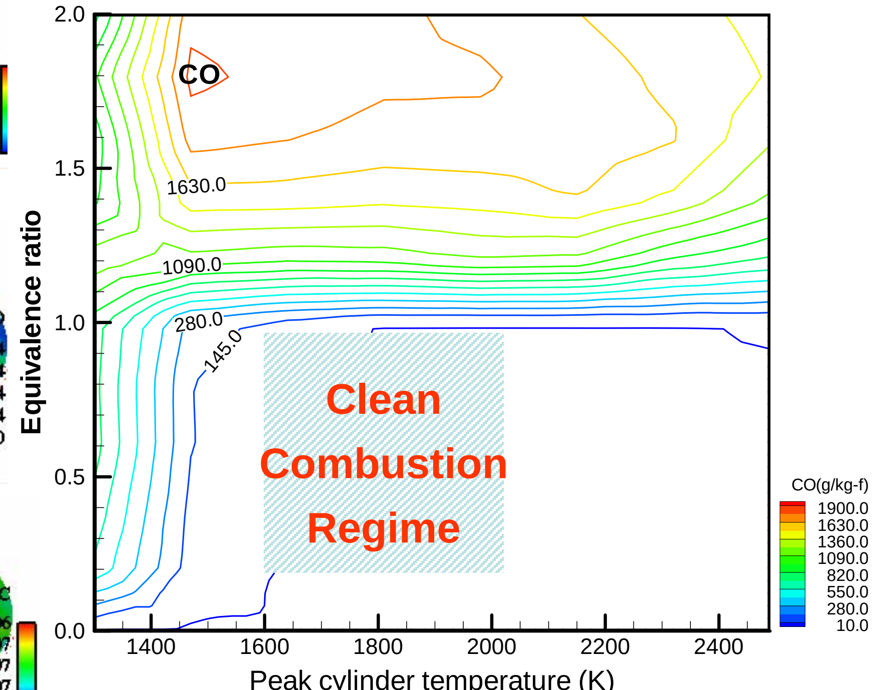
- IVC: -95°CA
- EGR: 28%
- HCCI: 70%
- Diffusion: 30%
- SOLI: 17°CA
- SOEL: -120°CA



(iso-surface: phi=0.2)







(Sung Wook Park, ERC, UW-Madison)

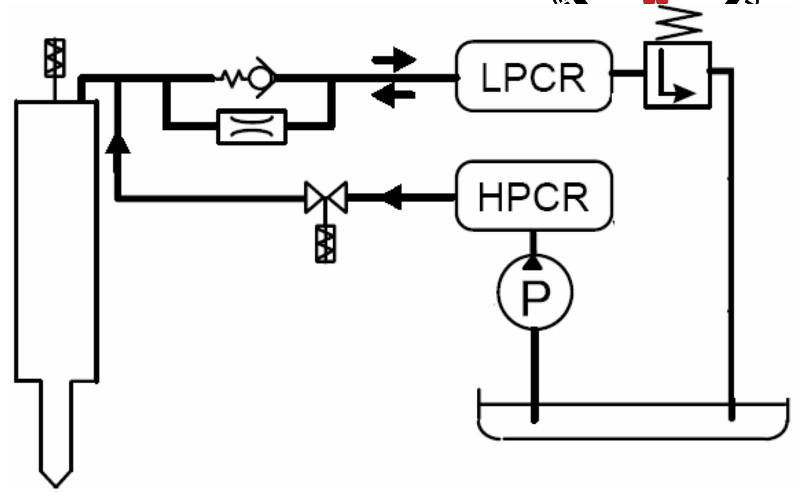
TSC & AIS USING ONE INJECTOR

- Wide angle (130°) w/ VIP
  - — Incompatibility w/ HCCI operation
  - — Later SOI, larger fueling rate

Included angle: 90° → 130°

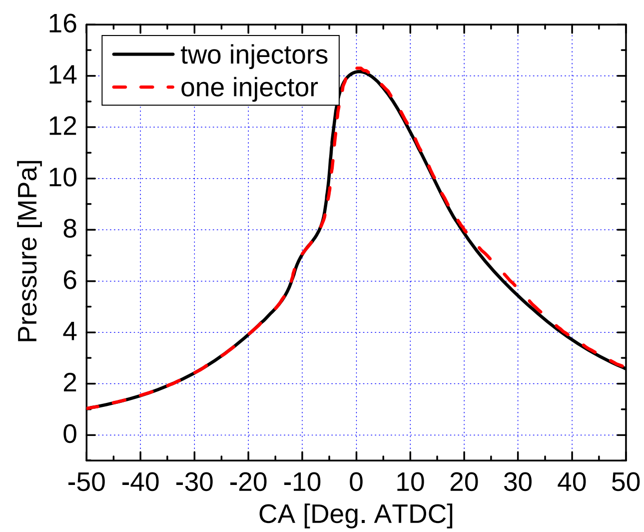
SOEL: -120°CA → -100°CA

Injector: 6-hole → 8-hole

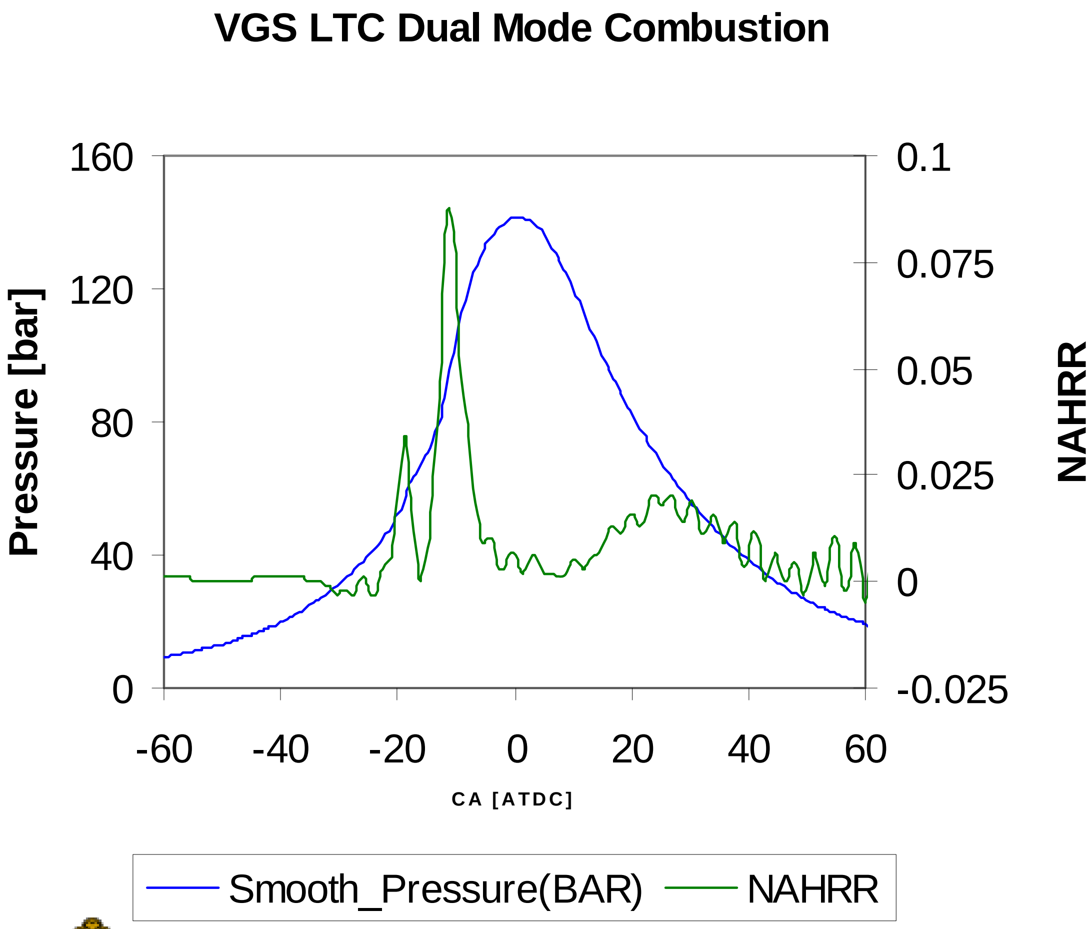


(Tanabe, K., SAE 2005-01-007)

(g/kW-hr)	Soot	NOx	HC	CO
two injectors	0.033	0.181	2.040	12.889
one injector	0.030	0.229	3.376	9.895
Target	0.0134	0.2681	0.1876	



Preliminary TSC Experimental Results



Experimental Conditions

First injection:

100 deg. BTDC

70% of fuel

Injection pressure 10MPa.

Second injection:

17 deg. ATDC

30% of fuel,

Injection pressure 130MPa

EGR (%)	21.83
BSFC (g/kW-hr)	245.2833
NOx (g/kW-hr)	0.5667
HC (g/kW-hr)	6.1953
NOx + HC (g/kWhr)	6.7621
PM (g/kW-hr)	0.1426
CO (g/kw-hr)	13.899

CONCLUSIONS

- Use of Adaptive Injection Strategies (AIS) is an effective way to minimize diesel spay-wall wetting and to enable advanced combustion strategies.
- Low-pressure injection is superior to conventional high-pressure injection for HCCI charge preparation.
- A low-pressure early injection, followed by a high-pressure late injection provides Two-Stage Combustion (TSC) that shows great potential to achieve low engine-out emissions (2010 levels) and fuel consumption at medium engine load when engine operating parameters are optimized.
- One injector with VIP and a fixed spray included angle can be used for practical implementation of the TSC concept - (patent applied for).
- Further work is in progress to explore AIS/TSC concepts at other speed/load conditions, and for different engine displacements.

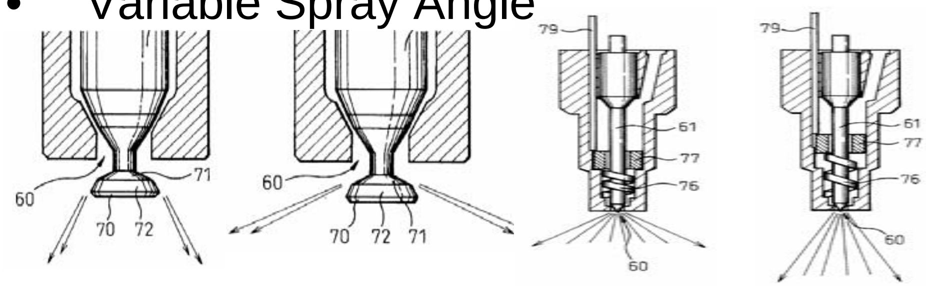
Thank you for your attention !

Questions or Comments

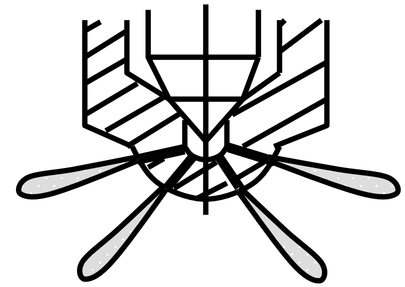
Backup Slides

AIS IMPLEMENTATION

- **Variable Geometry Spray (VGS)**
  - Variable Spray Angle

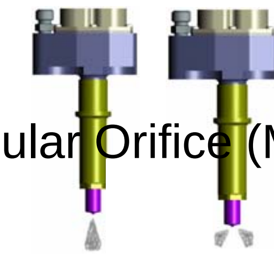


Hollow-cone spray (Kawaguchi, A.)

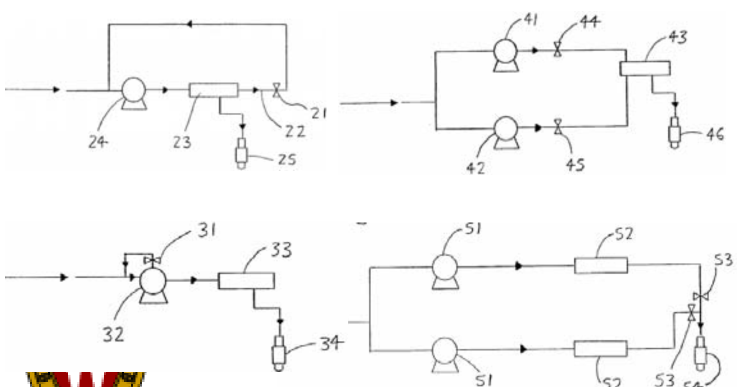


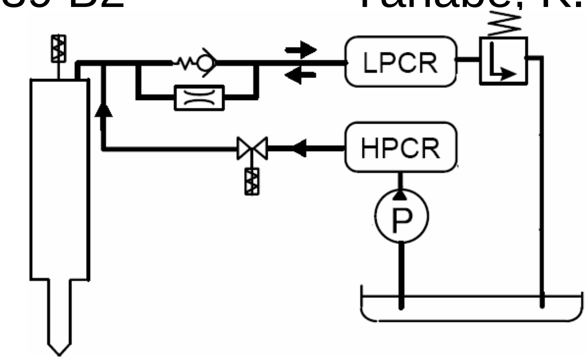
Multi-hole Nozzle (MHN) spray

  - Variable Spray Pattern
    – Caterpillar Inc., mixed mode injector (DEER 2004)
    -- Hou et al., SAE 2007-01-0249, Micro-Variable Circular Orifice (MVCO) injector

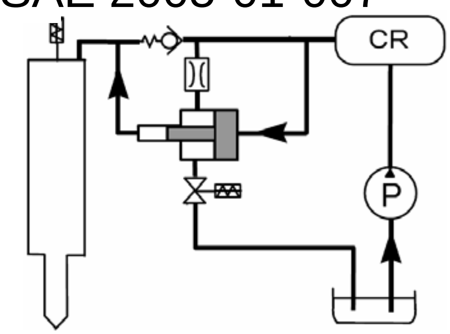


- **Variable Injection Pressure (VIP)**
  - Reitz et al., US Patent: 6,526,939 B2
  - Tanabe, K., SAE 2005-01-007





dual rail type CRS



pressure intensifier type CRS