Optimization of IC Engine Design for Reduced Emissions using Automated Engine Experiments and CFD Modeling

by
Rolf D. Reitz
Engine Research Center
University of Wisconsin-Madison
reitz@engr.wisc.edu

Acknowledgments:

Caterpillar, DOE/Sandia labs
Ford (SRL, FFA), TACOM, ARO
ERC Faculty, students and staff

Motivation and Approach

• Previous studies indicate that significantly improved emissions levels can be achieved with multiple injection strategies and/or engine operating conditions (boost pressure, EGR, etc.)

• However, the number of possible designs is limitless

- develop methodologies for efficient and accurate investigations of new engine design concepts

• Combined experimental/modeling approach

- combination of CFD models and computer optimization
- experimental engine optimization and model validation

• Current status of CPU speed and model development makes multi-dimensional modeling a feasible and valuable tool to engine designers for reducing emissions and fuel consumption

Engine Experiments

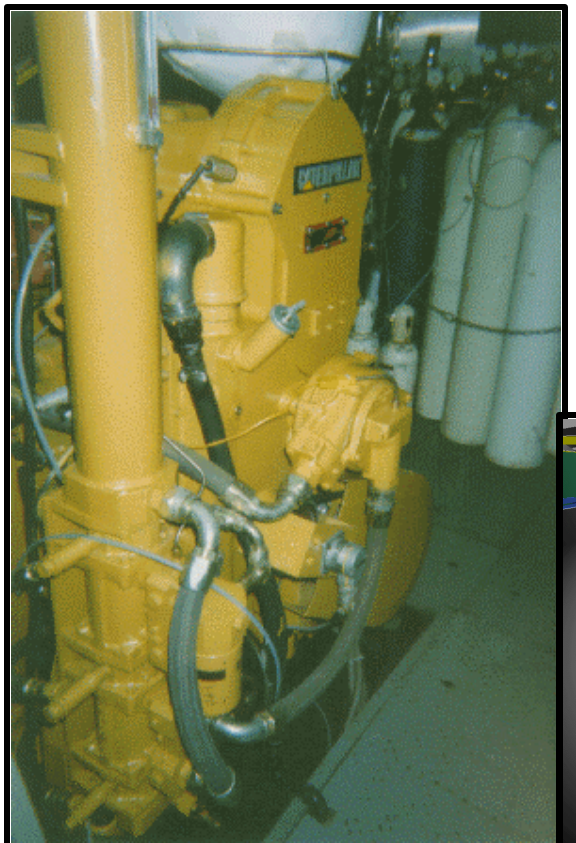
Caterpillar 3401 Engine SCOTE

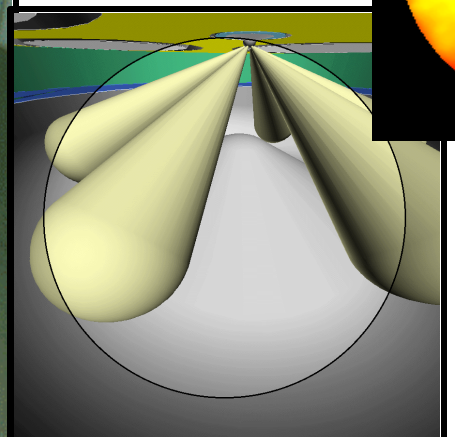
Engine Details

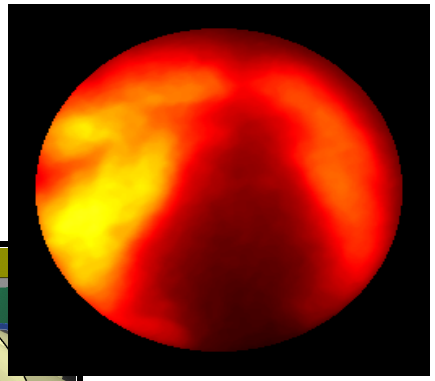
Cylinder Bore	137.2 mm
Stroke	165.1 mm
Compression ratio	15.1
Displacement	2.44 liters
Simulated turbocharge to 4 atm.	
Cooled EGR	0 - 25%

Fuel Injection Systems

- Common Rail (Denso ECD-U2)
  - 6 hole injector, 0.26 mm diameter
  - Injection pressure up to 90 MPa
  - Up to 4 multiple injections
- EUI-2 (Caterpillar prototype, 1999)
  - 6 hole injector, 0.189 mm diameter
  - Injection pressure up to 200 MPa
  - Up to 2 multiple injections







Combustion Diagnostics

Cylinder pressure

Bosch rate-of-injection

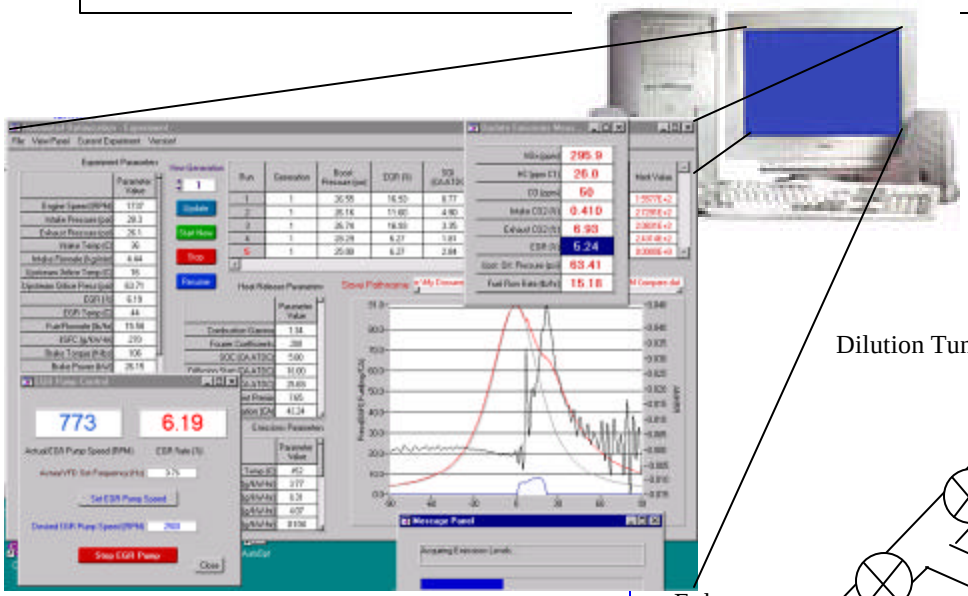
AVL Endoscope

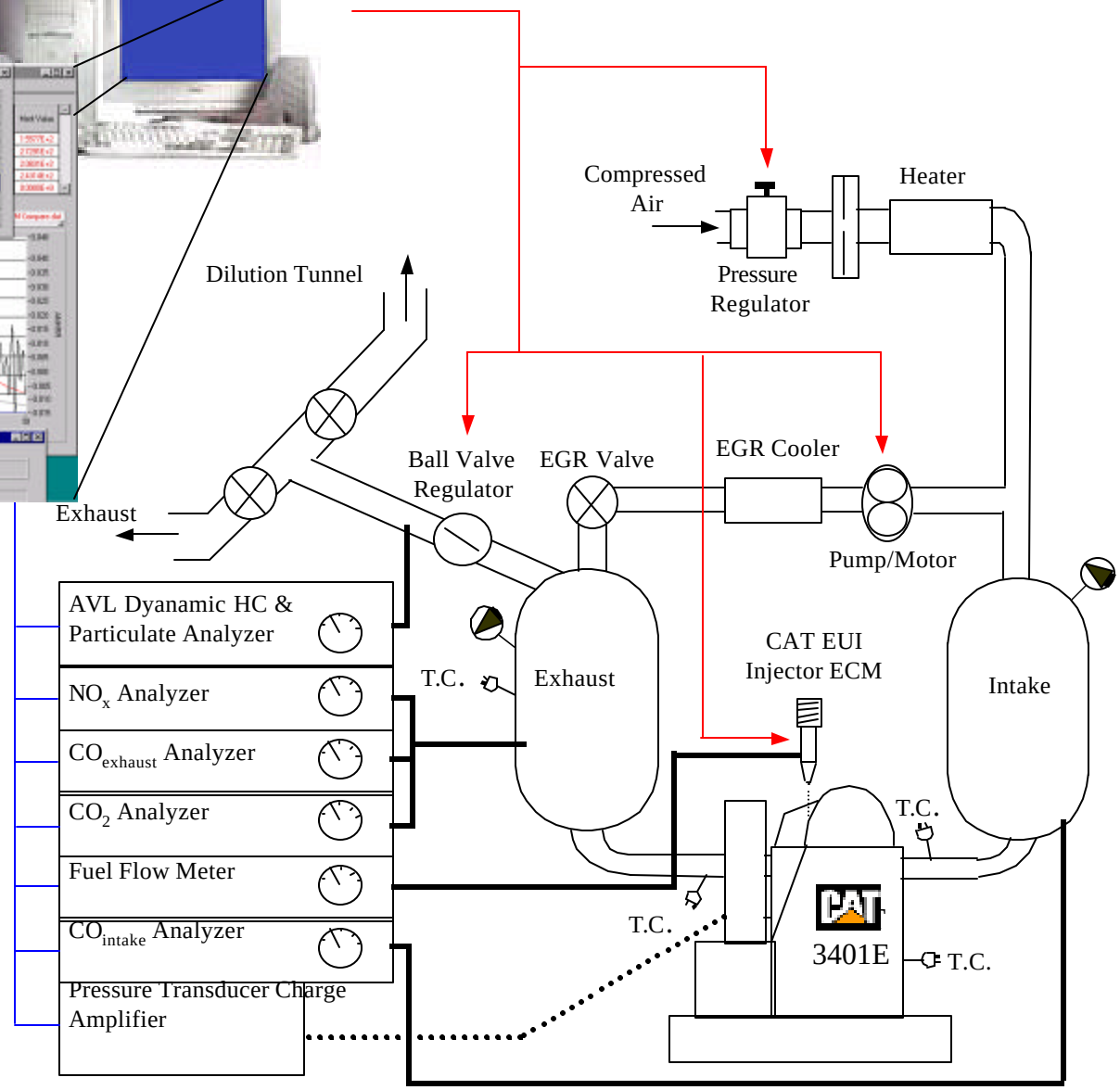
Emissions Instrumentation

Full dilution tunnel

SOF, NOx, CO/CO2, HC

Fully Automated Engine Testing – Thiel MS Thesis 2001

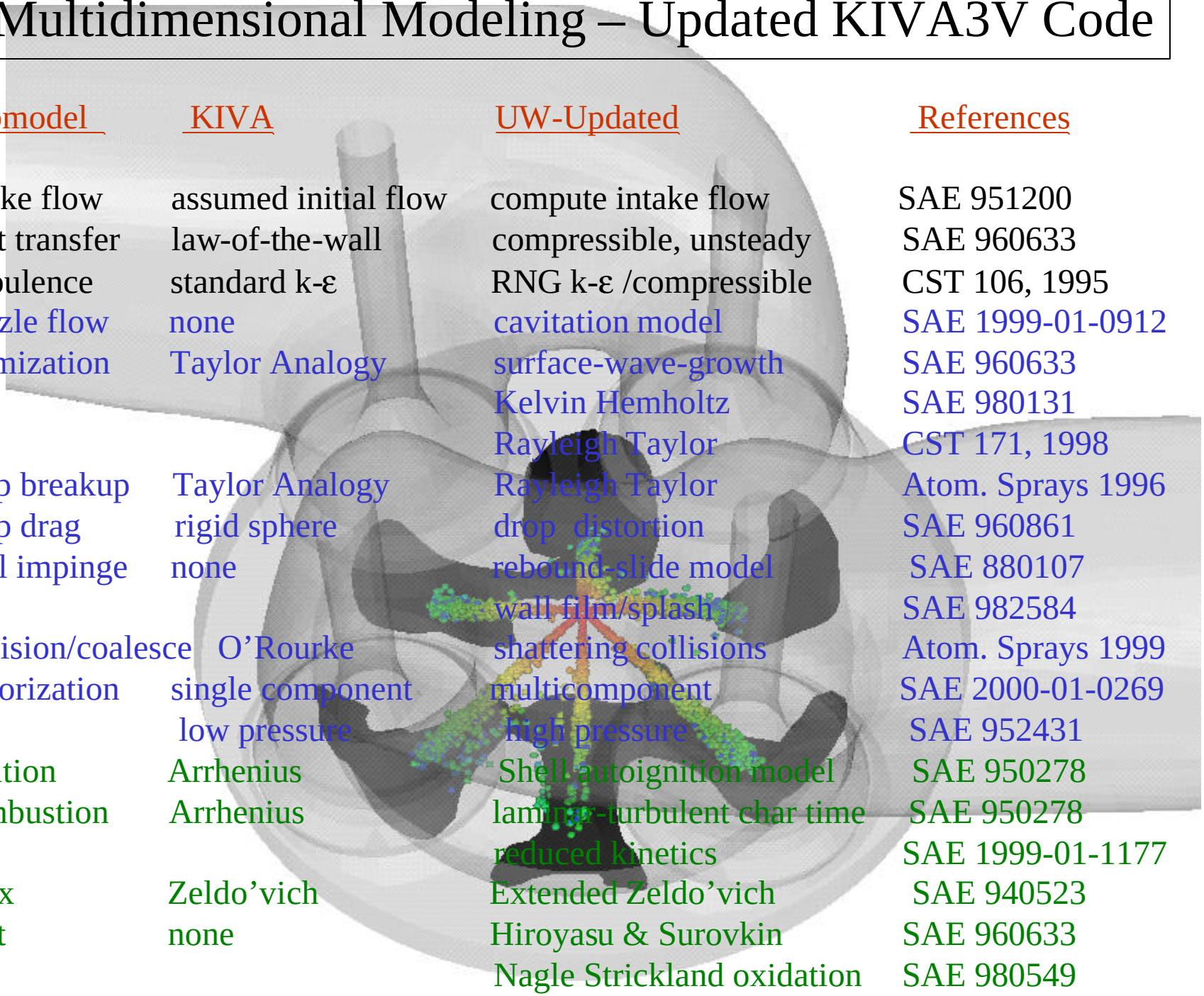




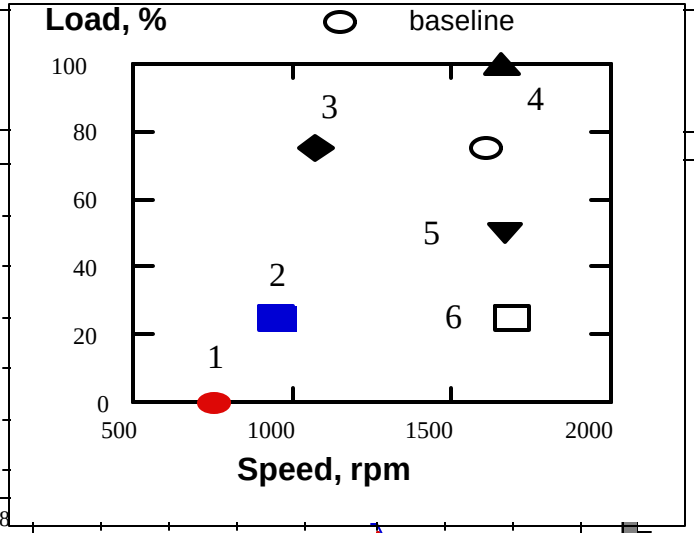
Response Surface Method (RSM) & Genetic Algorithm Optimization

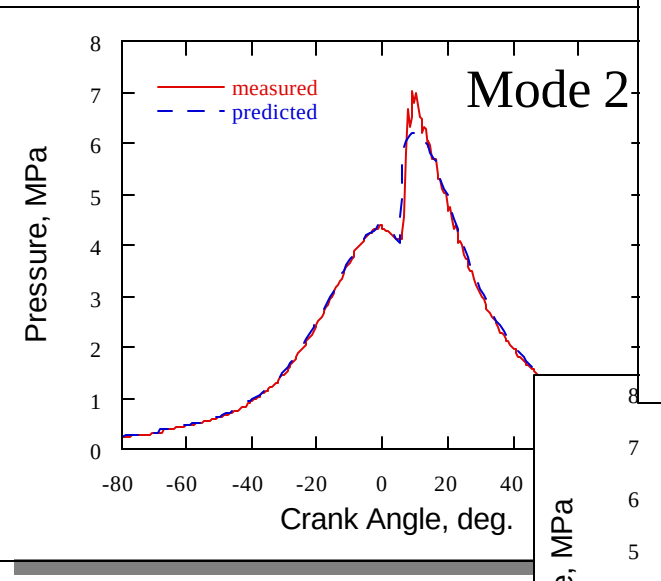
Multidimensional Modeling – Updated KIVA3V Code

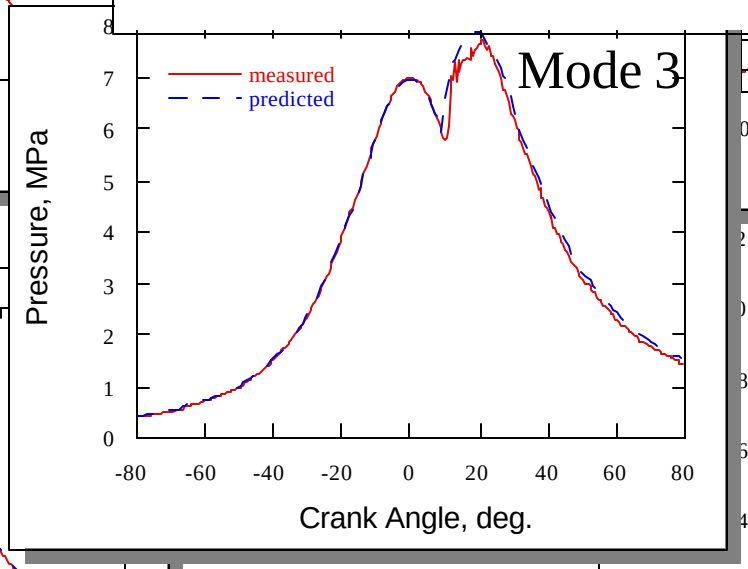
Submodel	KIVA	UW-Updated	References
intake flow	assumed initial flow	compute intake flow	SAE 951200
heat transfer	law-of-the-wall	compressible, unsteady	SAE 960633
turbulence	standard k-ε	RNG k-ε /compressible	CST 106, 1995
nozzle flow	none	cavitation model	SAE 1999-01-0912
atomization	Taylor Analogy	surface-wave-growth	SAE 960633
		Kelvin Hemholtz	SAE 980131
		Rayleigh Taylor	CST 171, 1998
drop breakup	Taylor Analogy	Rayleigh Taylor	Atom. Sprays 1996
drop drag	rigid sphere	drop distortion	SAE 960861
wall impinge	none	rebound-slide model	SAE 880107
		wall film/splash	SAE 982584
collision/coalesce	O'Rourke	shattering collisions	Atom. Sprays 1999
vaporization	single component	multicomponent	SAE 2000-01-0269
	low pressure	high pressure	SAE 952431
ignition	Arrhenius	Shell autoignition model	SAE 950278
combustion	Arrhenius	laminar-turbulent char time	SAE 950278
		reduced kinetics	SAE 1999-01-1177
NOx	Zeldo'vich	Extended Zeldo'vich	SAE 940523
soot	none	Hiroyasu & Surovkin	SAE 960633
		Nagle Strickland oxidation	SAE 980549

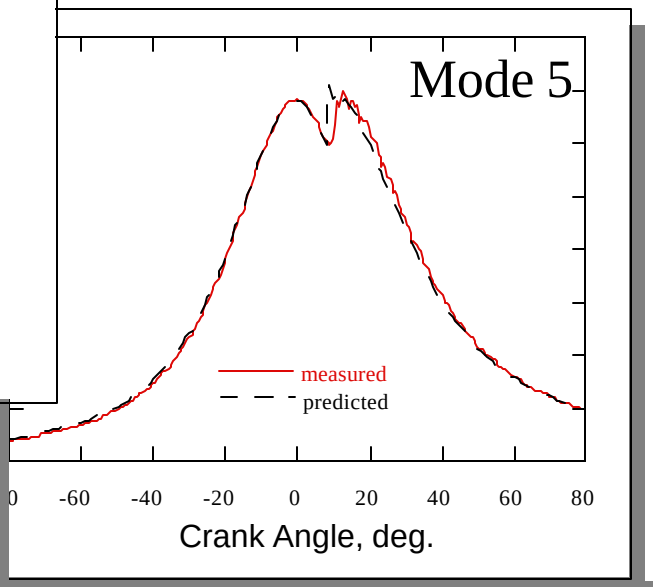


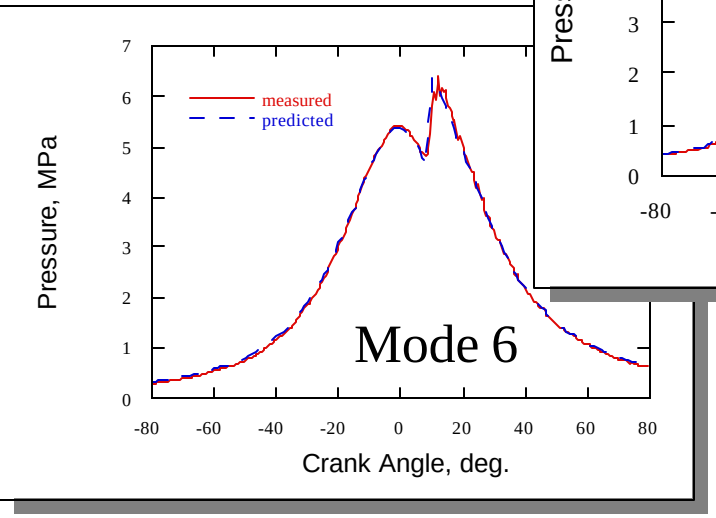
Spray & Combustion Model Validation

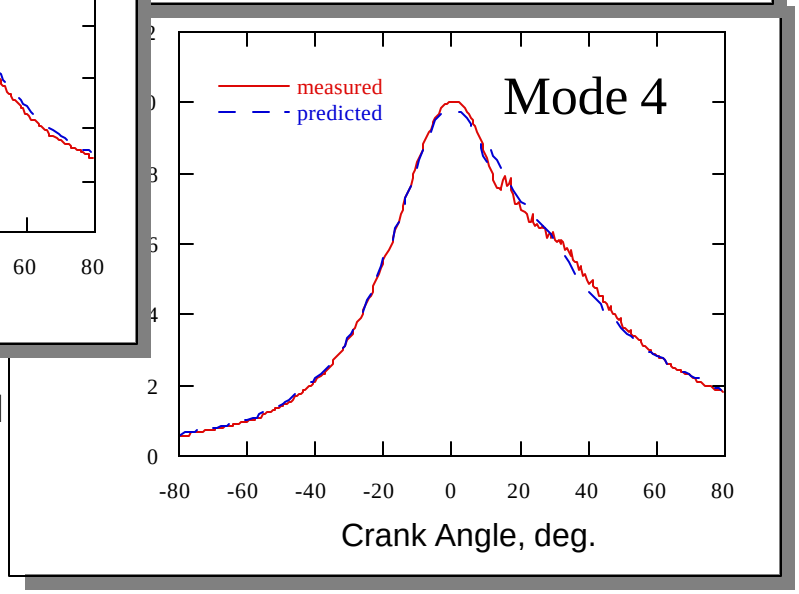










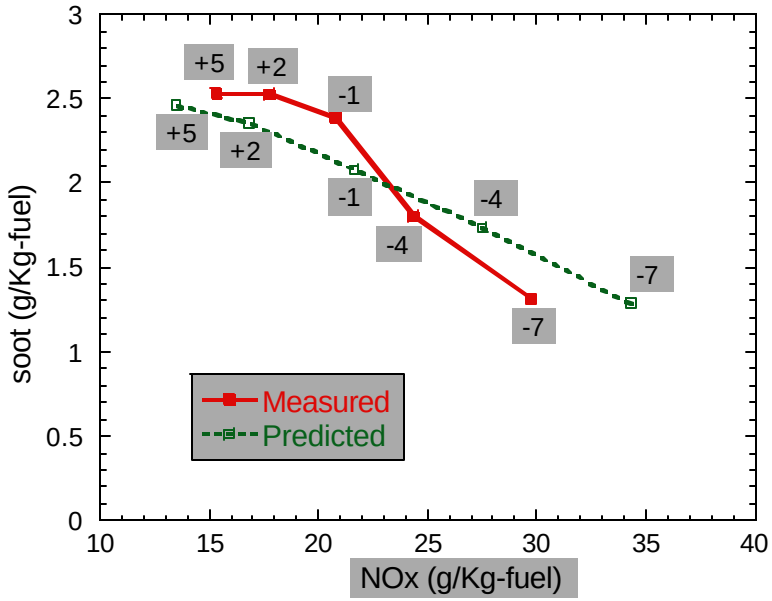


Combustion predicted - empiricism is at submodel level

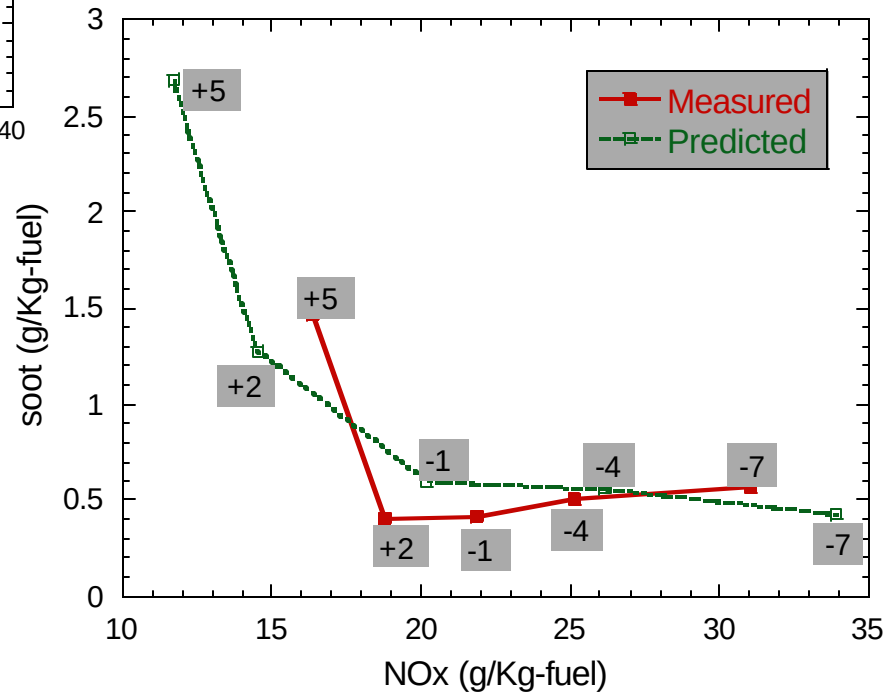
Emissions Model Validation

- Single Injection

Baseline: 1600 rev/min 75% Load



- Split Injection



Split injection: →
Significant particulate reduction explained by computer modeling
- Han et al. SAE960633

Overview of Optimization Techniques

- Enumerative or exhaustive
- Calculus or gradient-based

  "local" methods - search in neighborhood of current design point
- Univariate (one-factor-at-a-time)
- Design of Experiments (DOE)
  - Two-level factorial designs (main & interaction effects)
  - Response surface methods (RSM)
  - Statistical model building
- Random

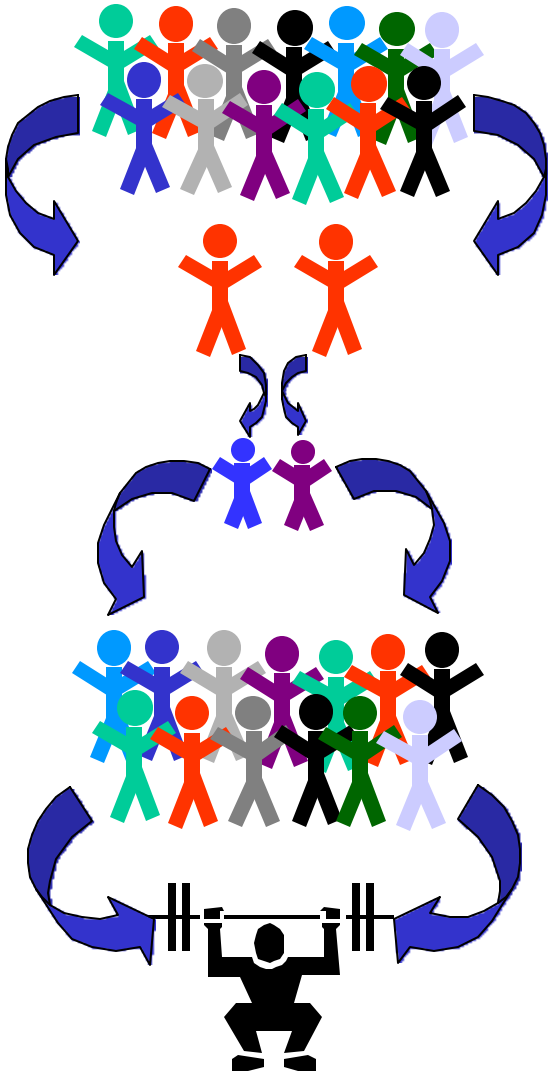
  "global" methods such as genetic algorithms (GA) which typically converge on a global optimum

<u>Parameters:</u>

Multiple injection
  Number pulses, % fuel, dwell
Boost pressure
EGR rate
SOI
Injection pressure
Rate-shape
Chamber geometry
…….

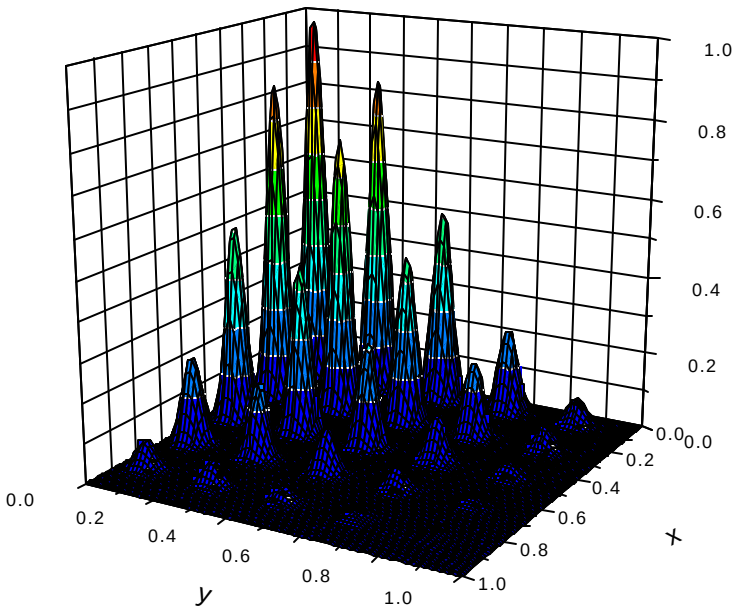
Engine Optimization - Genetic Algorithms

- "Individuals" are generated through random selection and a "population" is produced
- Fitness of each individual evaluated (BSFC, Emissions)
- The fittest individuals are allowed to "reproduce"
- A new "generation" is formed - "mutations" are allowed through random changes
- The fitness criteria thins out the population and the most fit solution is achieved over successive generations



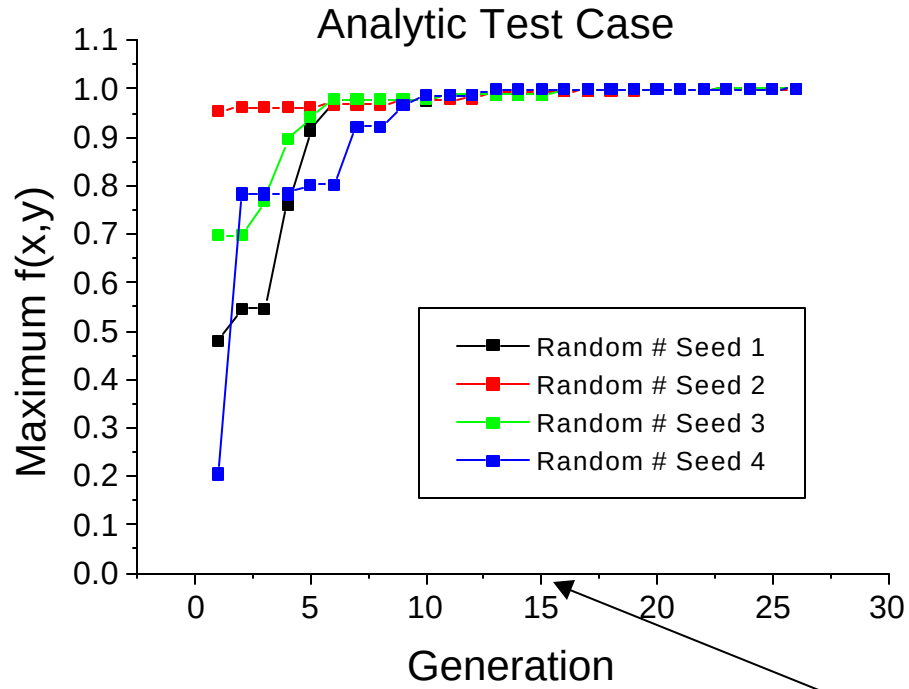
Simple and Micro GA (4-12 members)

Optimization Test Case



Maximum of 1.0 at (x,y)=(0.0667,0.0667)

Effect of Random Number Seed



$$f(x,y) = f_{1,x} f_{2,x} f_{1,y} f_{2,y}$$

$$f_{1.x} = [\sin(5.1px + 0.5)]^6 \qquad f_{1,y} = [\sin(5.1py + 0.5)]^6$$

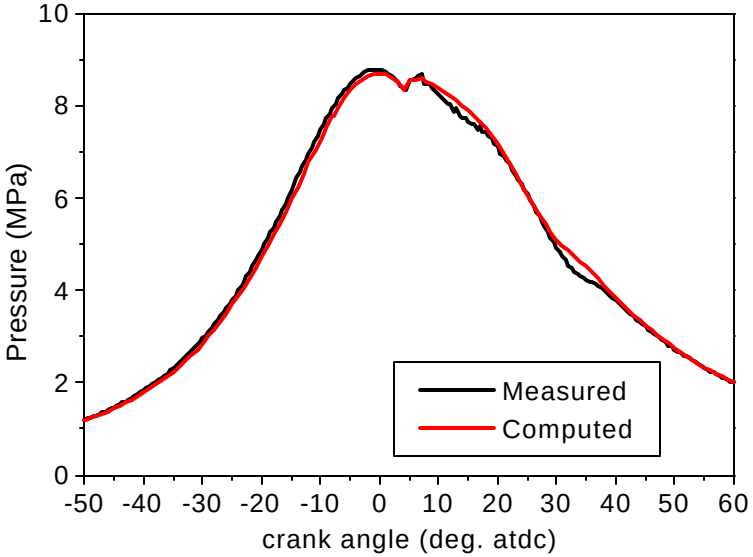
$$f_{2,x} = \exp\left[-4\ln(2)\frac{(x-0.0667)^2}{0.64}\right] \qquad f_{2,y} = \exp\left[-4\ln(2)\frac{(y-0.0667)^2}{0.64}\right]$$

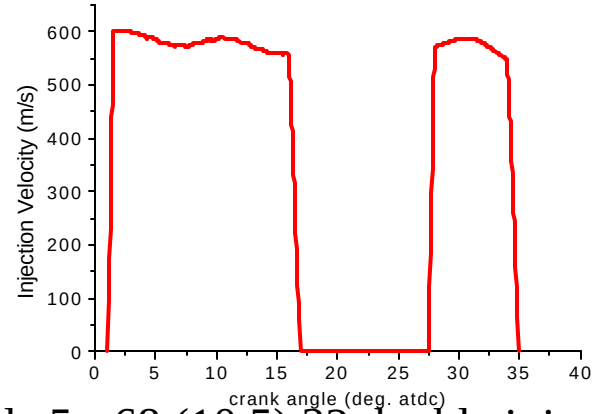
Convergence in 10-15 generations (40-60 runs)

$$\mathrm{d}x = \mathrm{d}y \approx 3\times10^{-5} \Rightarrow 1\times10^{9} \text{ possible solutions}$$

Engine Optimization

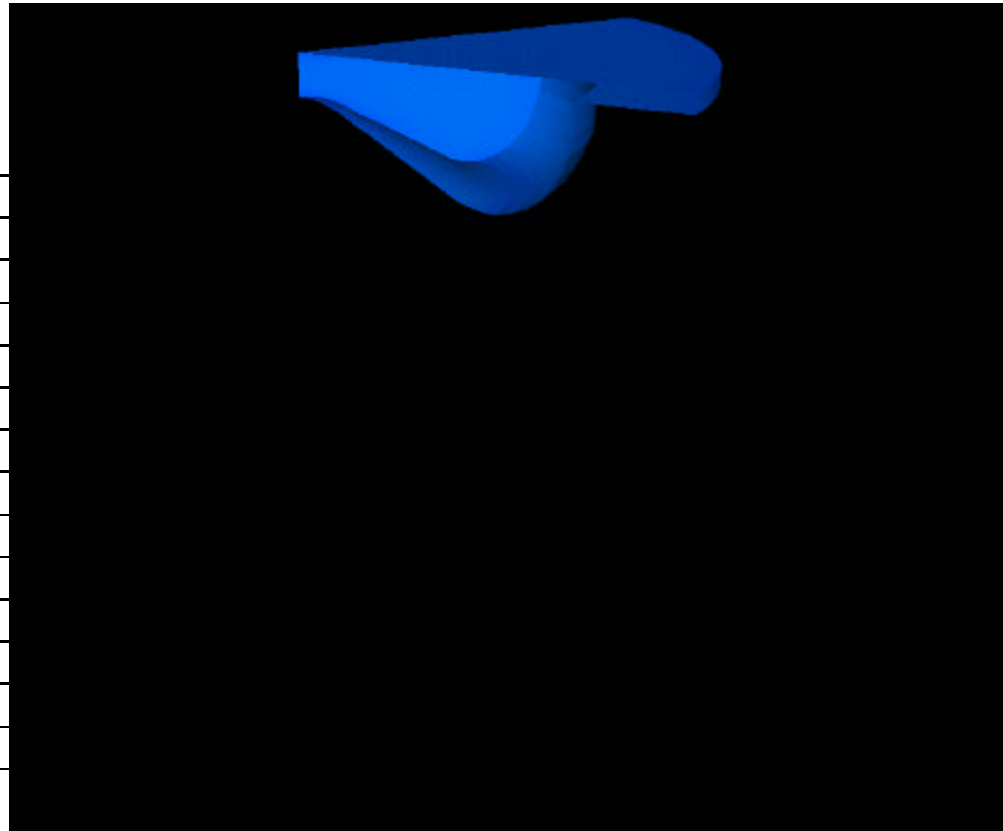
Baseline Design and Operating Condition





Mode 5 - 68 (10.5) 32 double injection

Bore	13.72 cm
Stroke	16.51 cm
Displacement	2.44 L
Compression ratio	16.1:1
Intake pressure	184 kPa
Intake surge tank temperature	309 K
Exhaust pressure	181 kPa
Intake valve closure	-144 deg. atdc
Injection Pressure	150 MPa
Start of Injection	+1 deg. atdc
EGR level	12 %
Swirl ratio (nominal)	1.0
% of Maximum Load	57
Engine speed	1737 rpm



Engine Design Parameters for GA Optimization

- Parameters of Interest and Ranges of Variation
  - Boost Pressure (kPa) 165 ➡ 284
  - EGR (%) 0 ➡ 25/50
  - SOI (CA deg. atdc) -10 ➡ +10
  - Injection Pressure (MPa) 100 ➡ 200
  - Mass in First Pulse (%) 10 ➡ 90
  - Dwell (CA deg.) 5 ➡ 15
- Physical Constraints on the Engine
  - Maximum Exhaust Temperature of 1023 K
  - Maximum Peak Pressure of ~ 15 MPa

Reference Goals EPA 2002/4

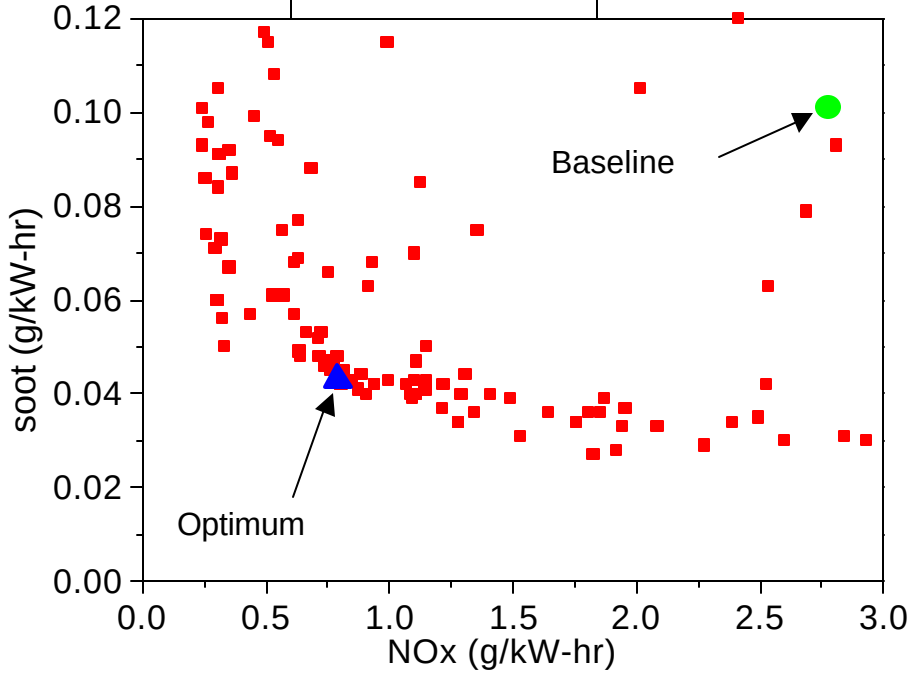
$$(NOx + HC)_m = 3.35 g/kW-hr$$
$$PM_m = 0.13 g/kW-hr$$
$$BSFC_0 = 215 g/kW-hr$$
$$W_1 = W_2 = 0.8$$

- Define objective function $f(\mathbf{X})$, where $\mathbf{X} = (X_1, X_2, X_3, \ldots, X_k)$ which maximizes $f(\mathbf{X})$ subject to constraints on the system

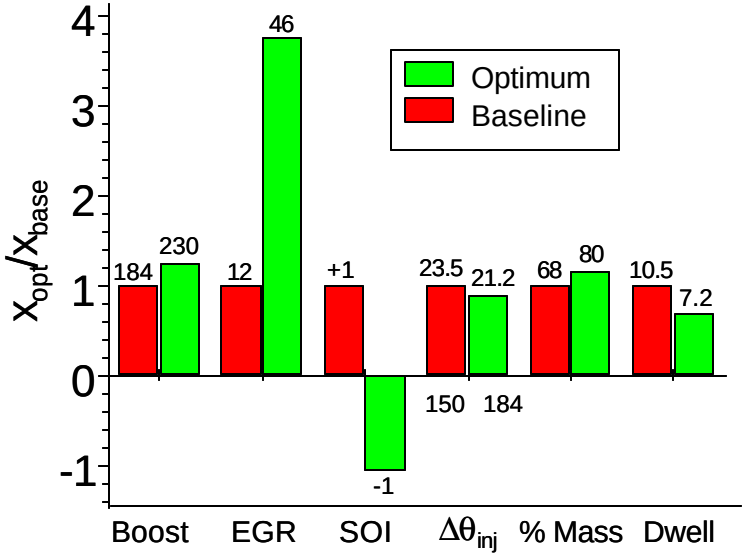
$$f(X) = \frac{1000}{\left(\frac{NOx + HC}{W_1 \times (NOx + HC)_m}\right)^2 + \left(\frac{PM}{W_2 \times PM_m}\right)^2 + \frac{BSFC}{BSFC_0}}$$

Engine Optimization Results

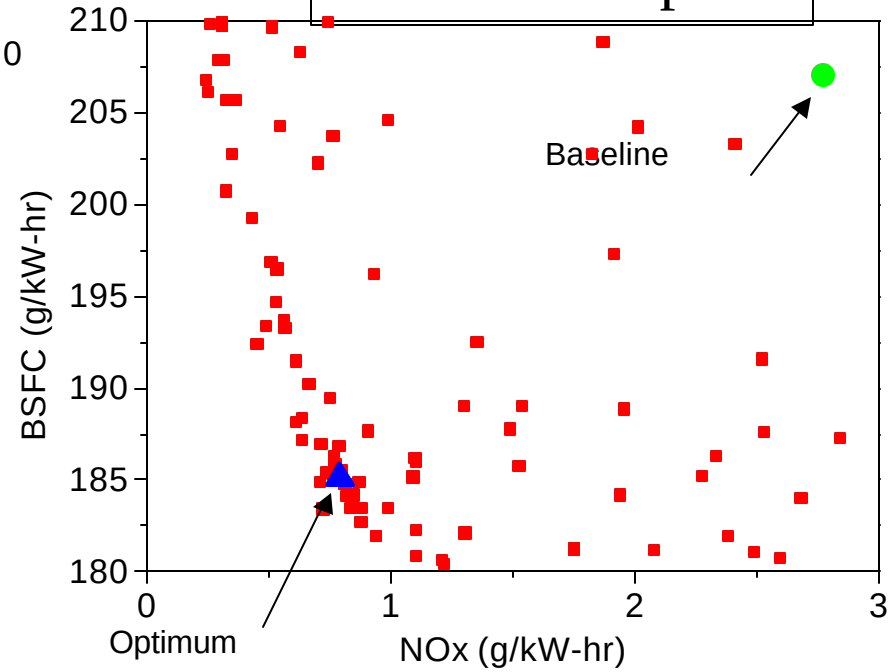
Emissions



Convergence in
250 simulations
SGI Origin 4xCPU
= 12 days



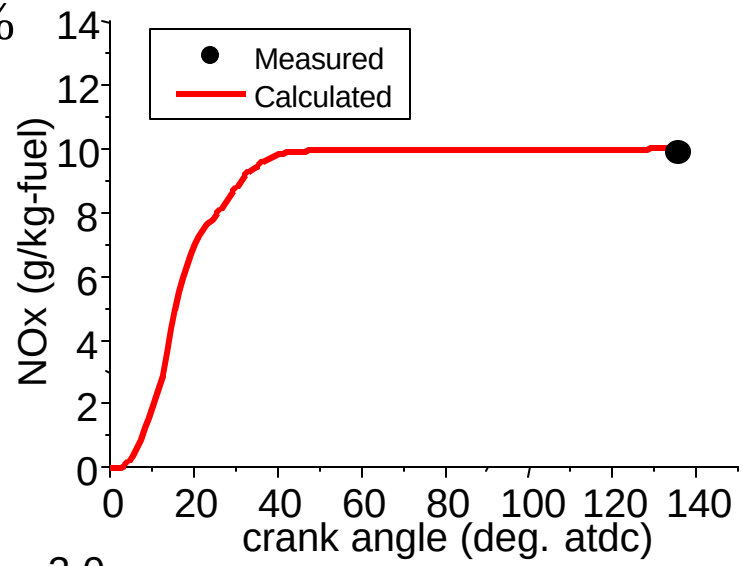
Fuel consumption

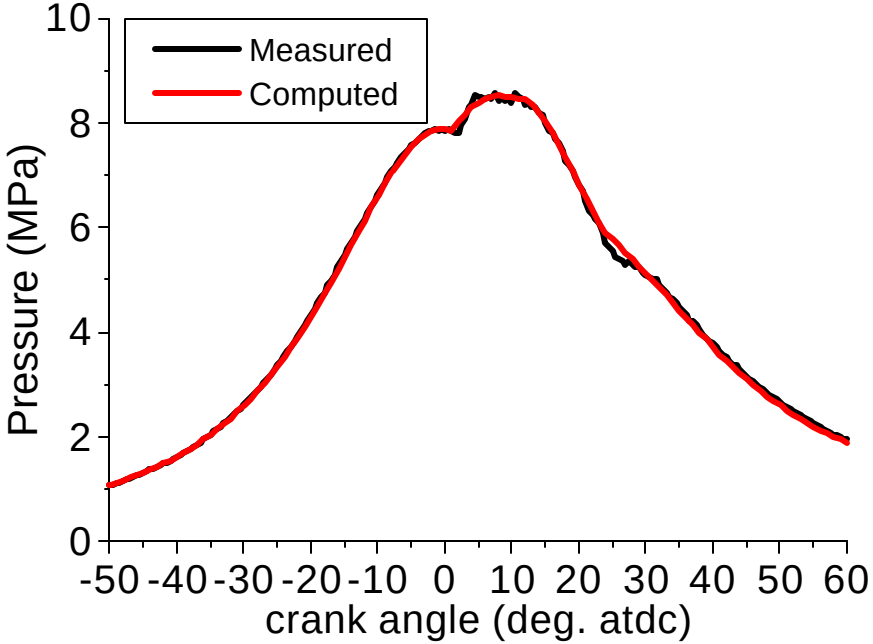


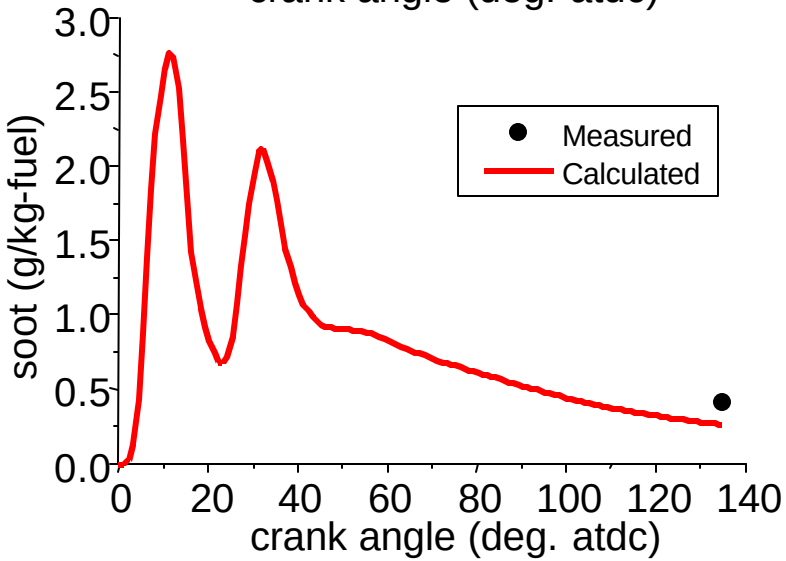
A Posteriori Experimental Validation of Design Parameters

Comparison with GA Optimum EGR 0-25%

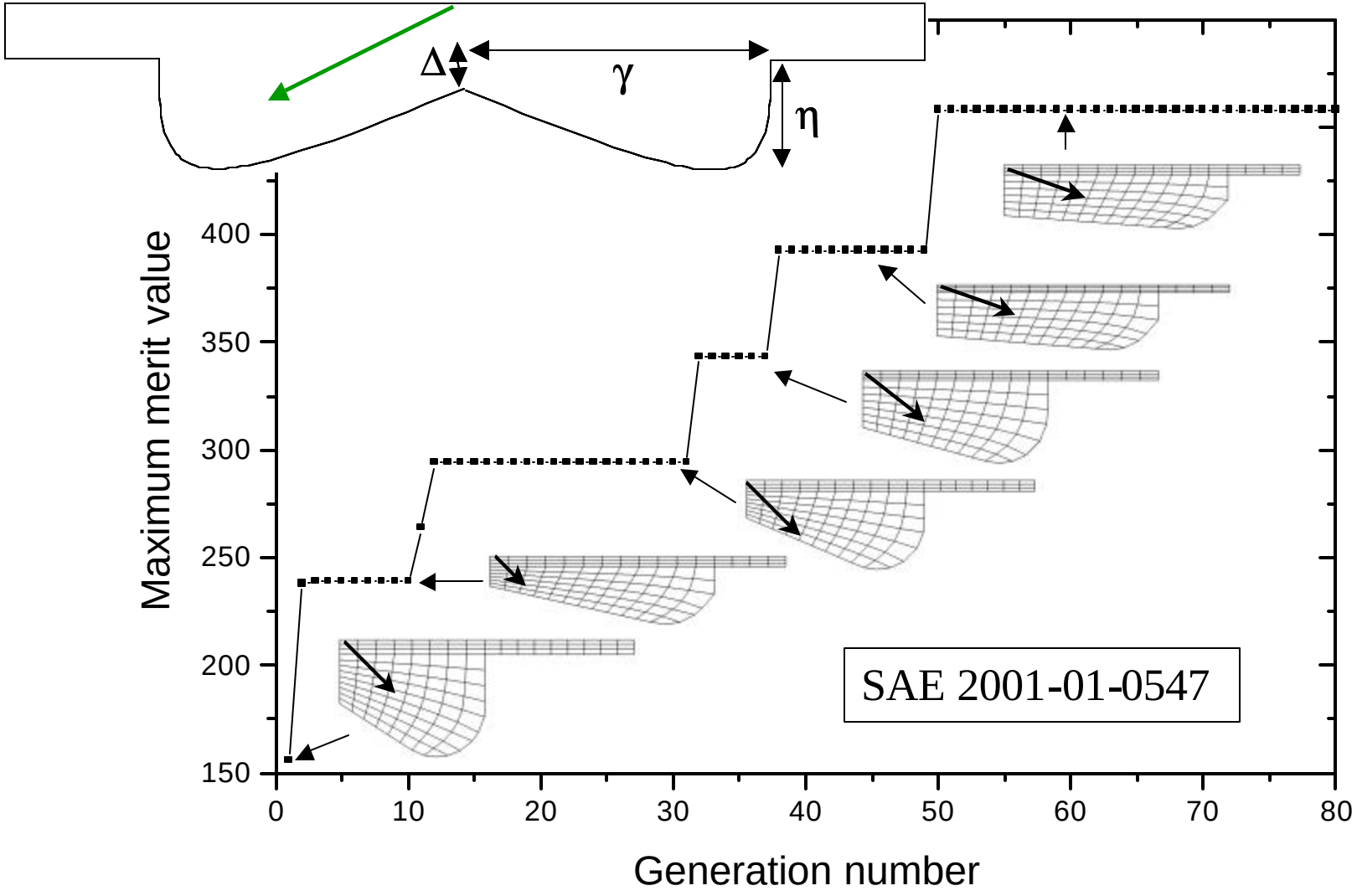
Injection Pressure:	200 MPa
EGR:	21 %
Boost Pressure:	169 kPa
SOI:	4.5 deg. atdc
First Pulse:	57 %
Dwell:	10 deg.







Combustion Chamber Geometry Optimization



- Automated mesh generation – applied to a small-bore and large-bore diesel engine

Emissions with optimized piston geometry

<u>9 Parameters</u>

Δ

γ

η

DOI

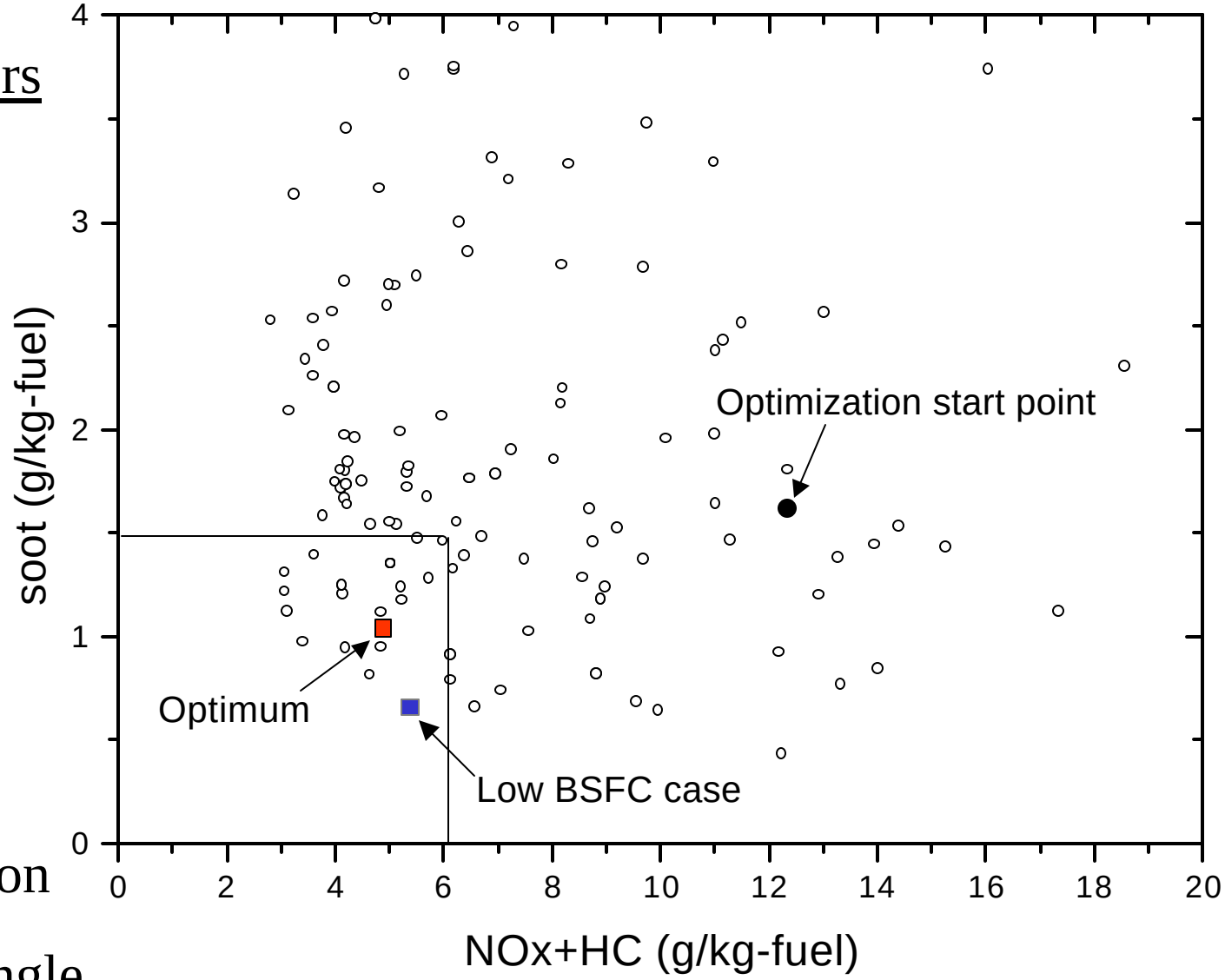
SOI

Hole size

Swirl ratio

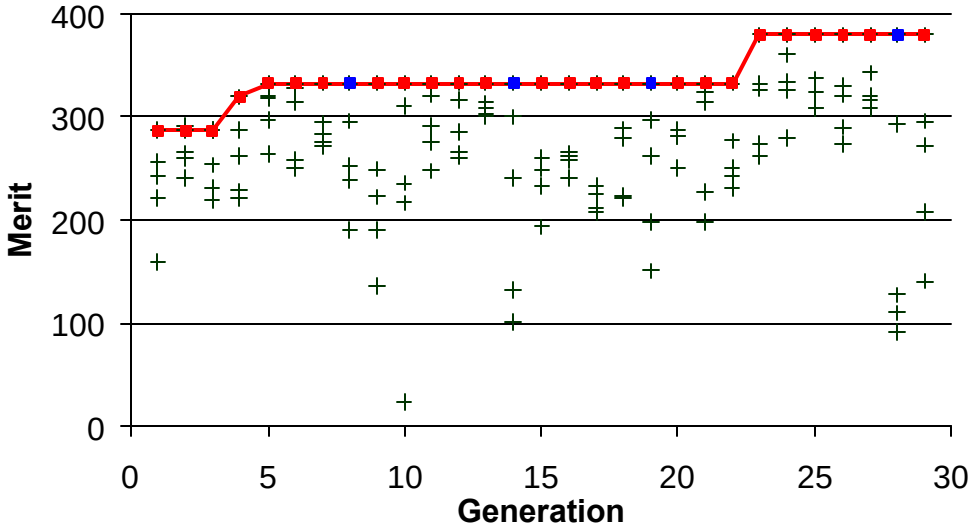
EGR fraction

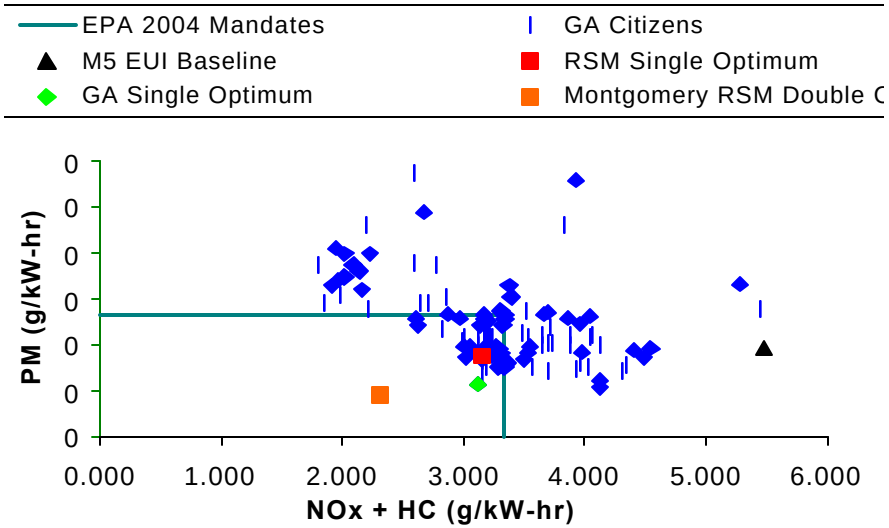
Injection angle



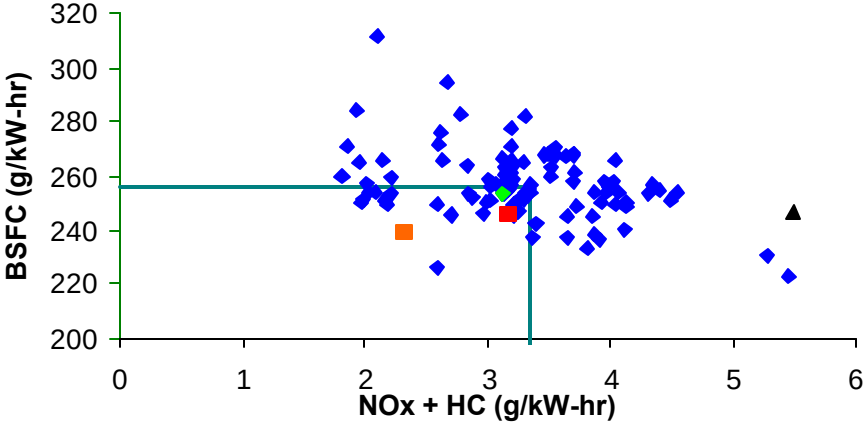
Automated Engine Experiments GA vs. RSM

Mode 5 EUI Single Injection

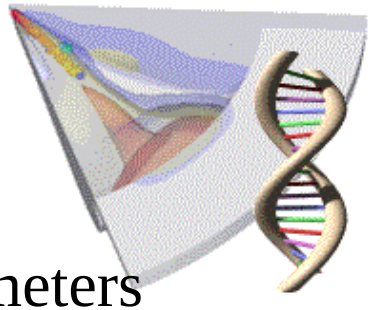




Factor/Emissions	GA Opt	RSM Opt
EGR (%)	9.5	10.0
Boost (psi)	29.3	28.1
Centroid (CA-ATDC)	28.1	28.3
NOx+HC (g/kW-hr)	3.12	3.16
PM-AVL (g/kW-hr)	0.058	0.089
BSFC (g/kW-hr)	253	246
Merit	379	329



Summary and Conclusions



- Efficient methodologies formulated for automated optimization of engines with a large number of parameters
- Validation experiments with fully instrumented single-cylinder heavy-duty truck engine with electronically controlled ultra-high pressure unit injector with simulated turbo-charging and EGR
- Results show further significant NOx and particulate emissions reductions, together with improved fuel economy can be achieved
- Current work

  Genetic Algorithm & RSM optimization with laboratory engines

  KIVA-GA model used to optimize HD diesel injection rate-shape

  GA used to optimize submodels (select model constants)

  KIVA-GA model and automated engine experiments used to optimize HSDI, GDI, HCCI engines

Department of Energy Invests Over $85 Million in Energy Efficient Science and Technology

HCCI Engine Optimization and Control

DOE Proposal $4M - 9/1/01 to 8/31/04

Engine Research Center UW-Madison

SUBCONTRACTOR(S)/COLLABORATOR(S):

(ERC): Profs. P. Farrell, D. Foster, J. Ghandhi, K. Hoag, C. Rutland and R. Reitz (PI)

Princeton University: Prof. F. Dryer

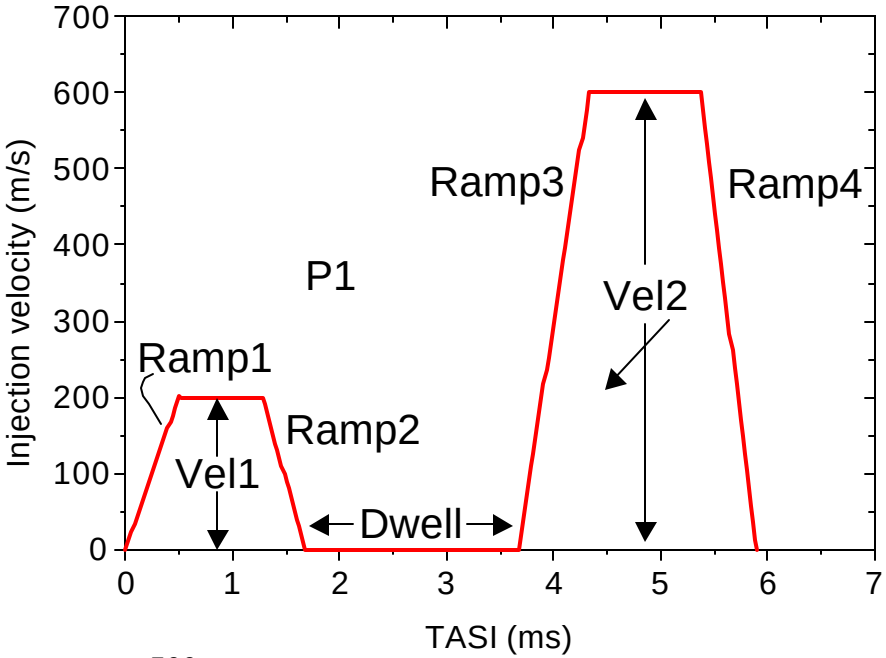
Penn State University: Prof. D. Haworth

Stanford University: Prof. C. Edwards

University of Illinois Urbana-Champaign: Prof. C.-F. Lee

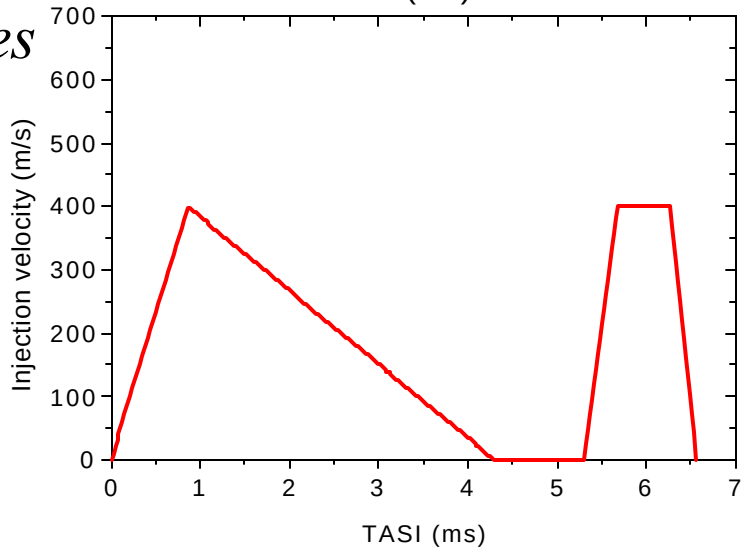
Level 1:		Level 2:
Caterpillar	DOE National Laboratories	Cummins
Delphi	Sandia	DaimlerChrysler
General Motors Research	Lawrence Livermore	Detroit Diesel
Mercury Marine	Los Alamos	Ford Motor Company
Ricardo North America		International (Navistar)
Yamaha		

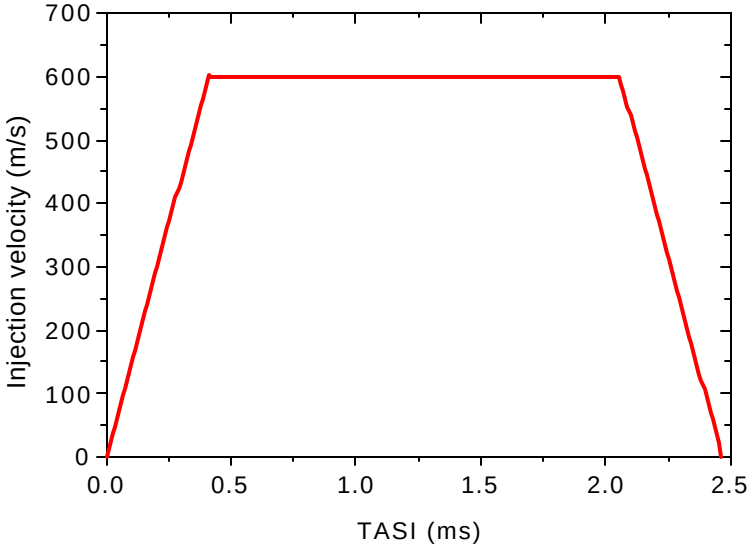
Injection Rate-Shape



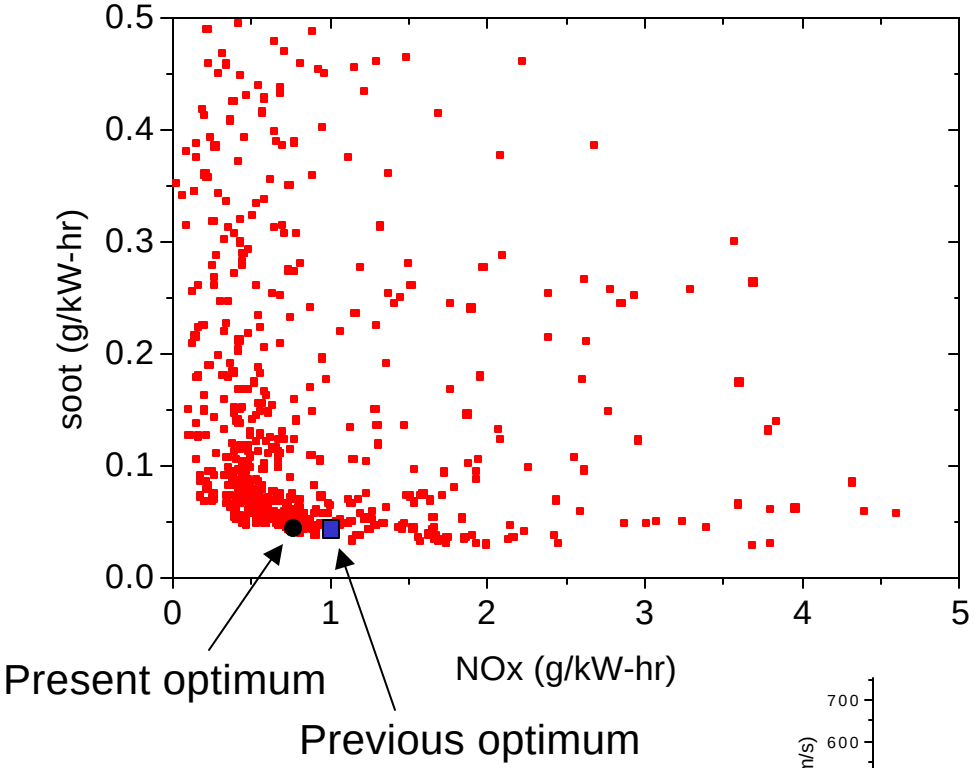
•Boost (kPa)	165	284
•EGR	0	50
•SOI (atdc)	-10	+10
•Vel1 (m/s)	100	700
•Vel2 (m/s)	100	700
•P1 (%)	10	90
•Ramp1 (%)	0	100
•Ramp2 (%)	0	100
•Ramp3 (%)	0	100
•Ramp4 (%)	0	100
•Dwell (deg.)	0	15

Examples





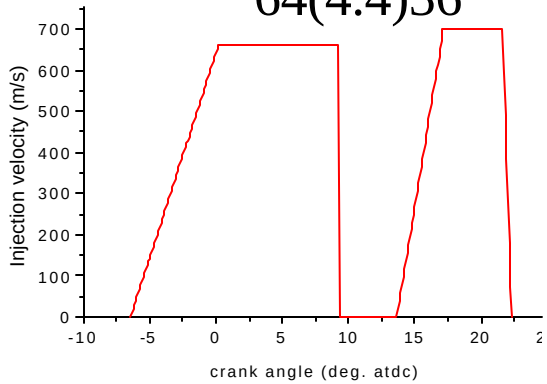
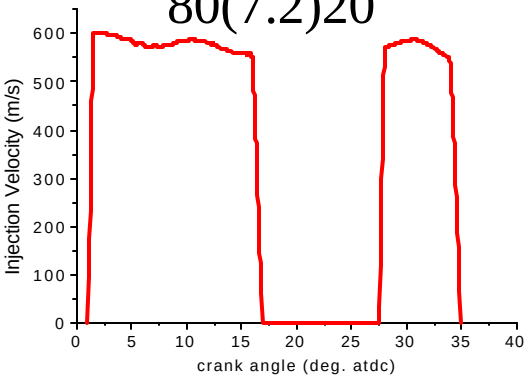
Improvement over Previous Optimum



SAE 2000-01-1890

	Present	Previous
soot (g/kW-hr)	0.04	0.04
NOx (g/kW-hr)	0.77	1.0
BSFC (g/kW-hr)	197	212
Boost (kPa)	216	230
EGR (%)	46	44
SOI (deg. ATDC)	-6.5	-1

64(4.4)36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