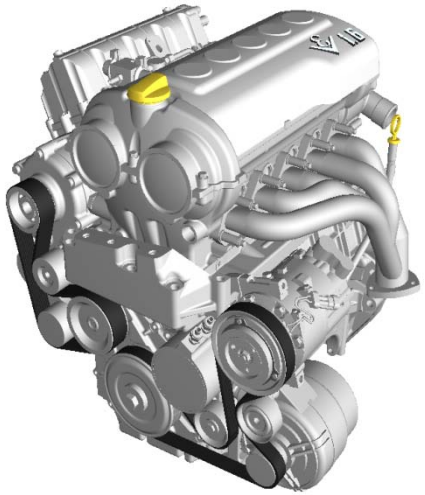
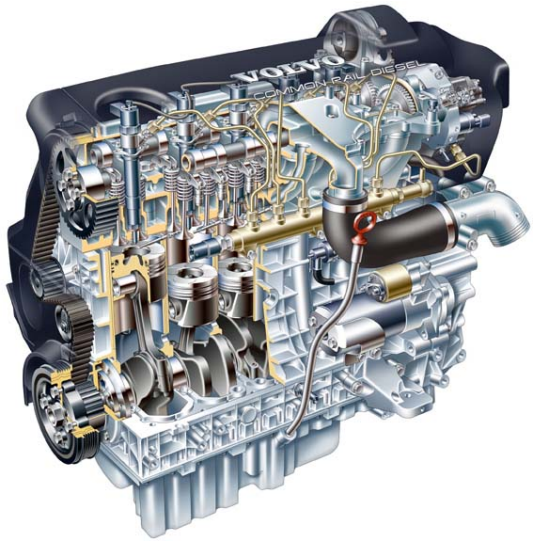
Partially Premixed Combustion, PPC

- from idle to 26 bar IMEP with Euro 6 emissions and 50%+ fuel efficiency

SI → **HCCI** → **PPC**





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Background

Combustion concepts

+ Clean with 3-way Catalyst
- Poor low & part load efficiency

+ High efficiency
- Emissions of NO_x and soot

Spark Ignition (SI) engine (Gasoline, Otto)

Compression Ignition (CI) engine (Diesel)

+ High efficiency
+ Ultra low NO_x

Homogeneous Charge Compression Ignition (HCCI)

-Combustion control
-Power density

Spark Assisted Compression Ignition (SACI) Gasoline HCCI

Partially premixed combustion (PPC) Diesel HCCI

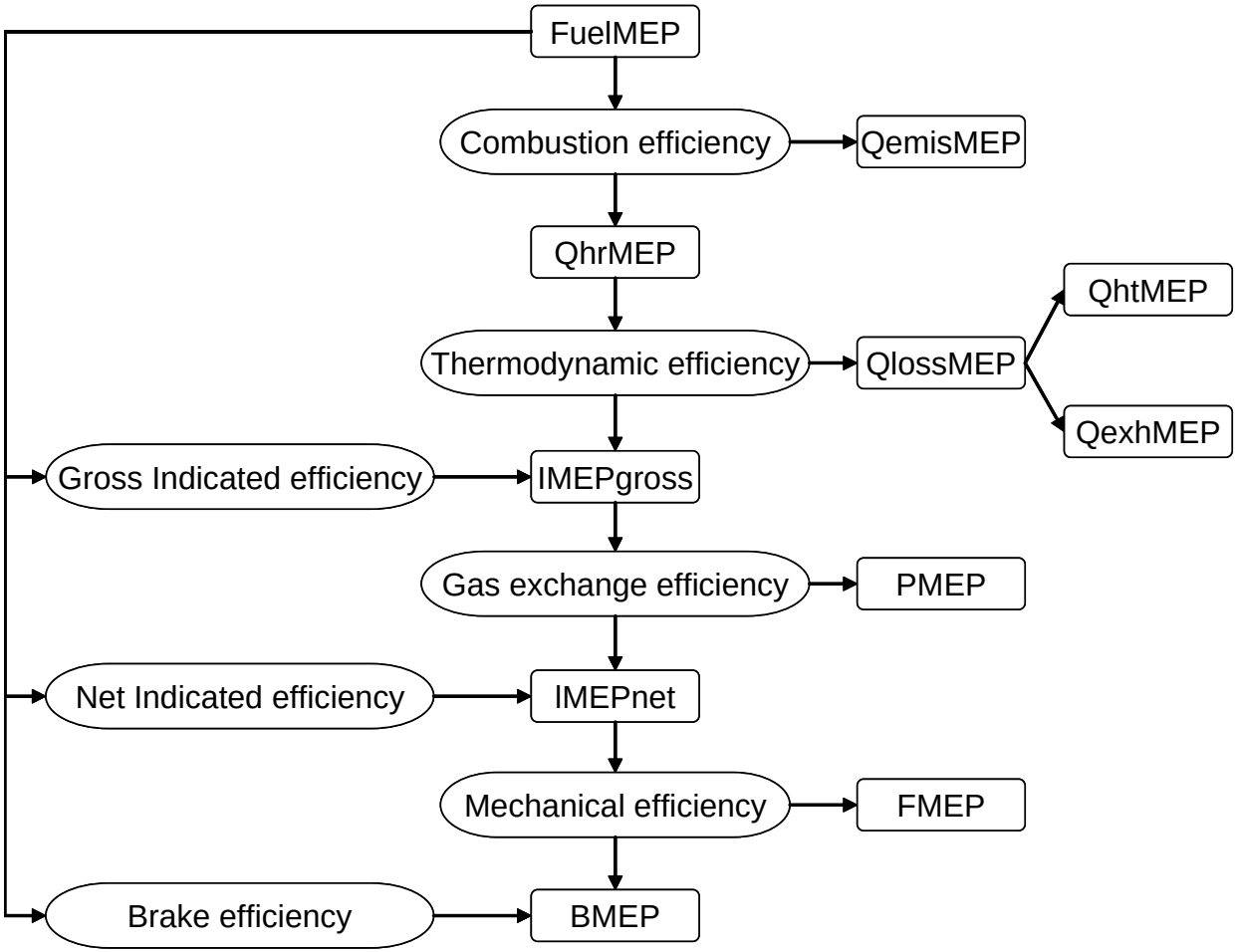
+ Injection controlled
- Less emissions advantage

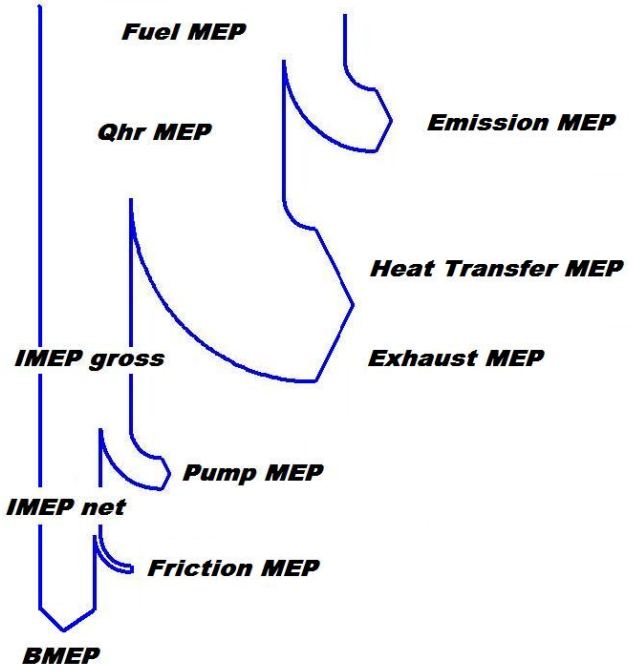
Outline

- Partially premixed combustion, PPC
  - Summary of
    - 56% thermal efficiency in car size engine
    - 57% thermal efficiency in truck size engine
    - Why 55% thermal efficiency is better than 57%
  - Fuel effects in Scania D12 engine
  - How to reach 26 bar IMEP with US10 NOx, PM, HC and CO engine out, Scania D13
  - Fuel effects in Scania D13 engine

Efficiencies?

Energy flow in an IC engine



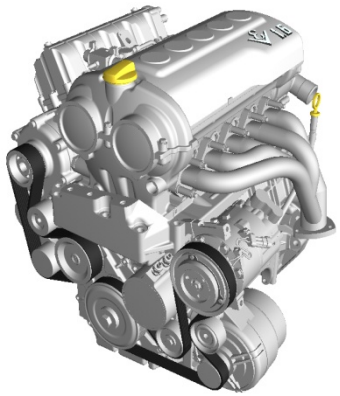


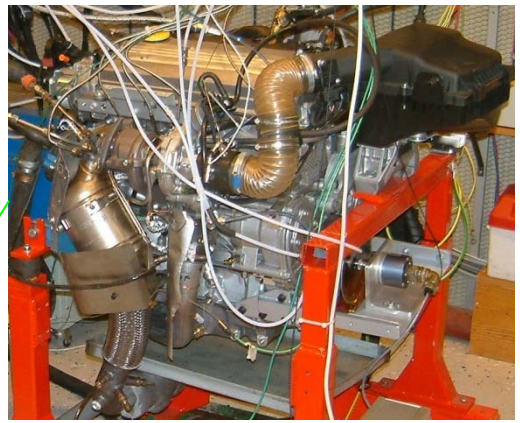
$$\eta_{Brake} = \eta_{Combustion} * \eta_{Thermodynamic} * \eta_{GasExchange} * \eta_{Mechanical}$$

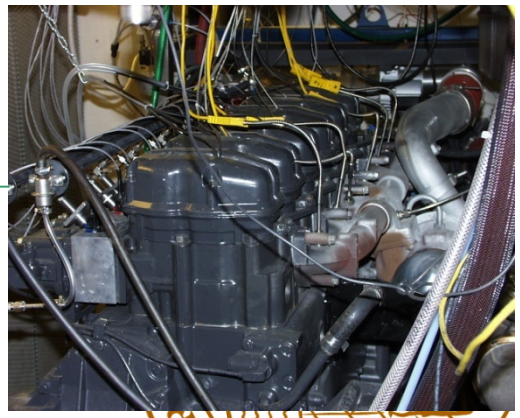
Thermodynamic efficiency

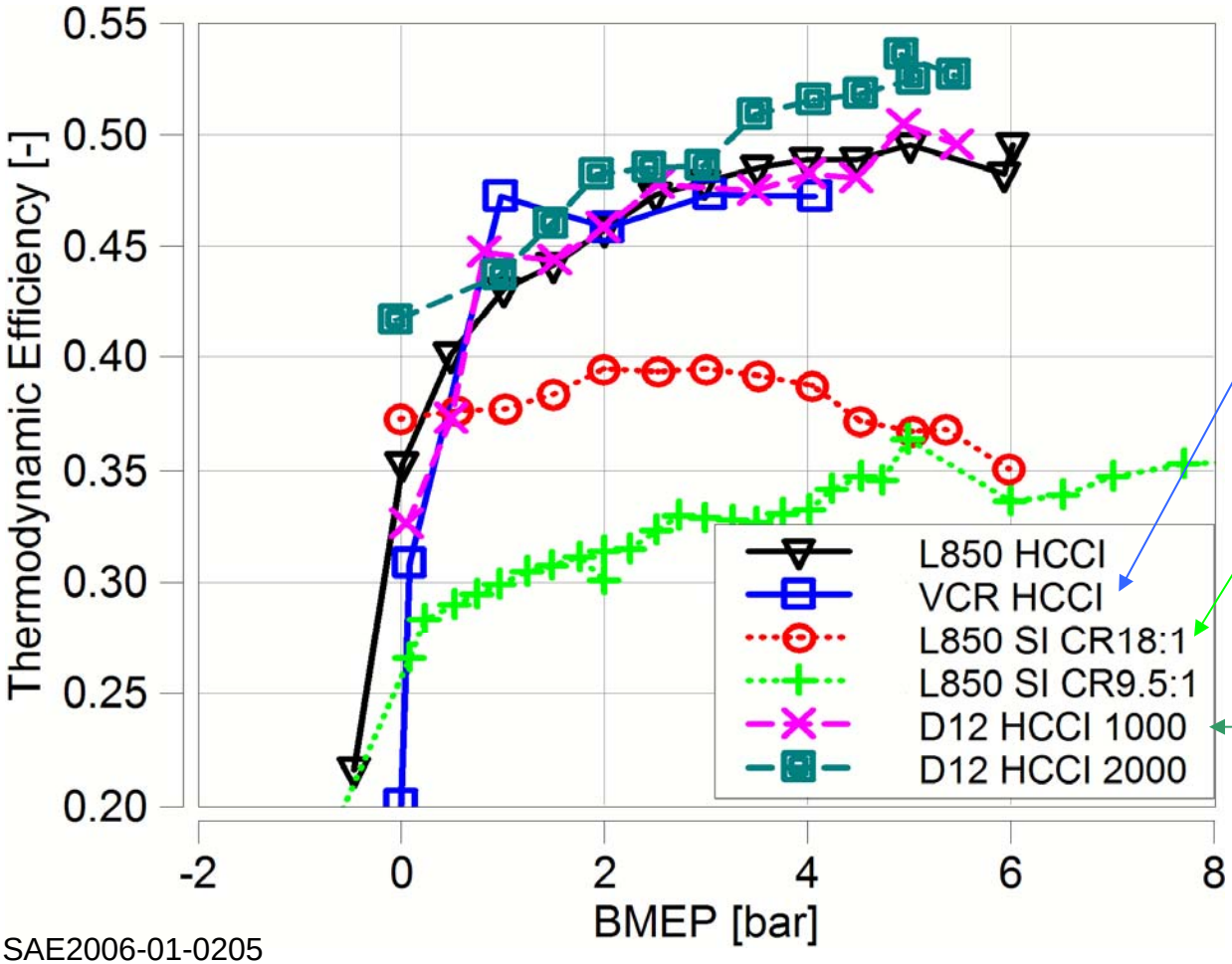
Saab SVC variable compression ratio, VCR, HCCI, Rc=10:1-30:1;
General Motors L850 "World engine", HCCI, Rc=18:1, SI, Rc=18:1, SI, Rc=9.5:1 (std)
Scania D12 Heavy duty diesel engine, HCCI, Rc=18:1;

Fuel: US regular Gasoline



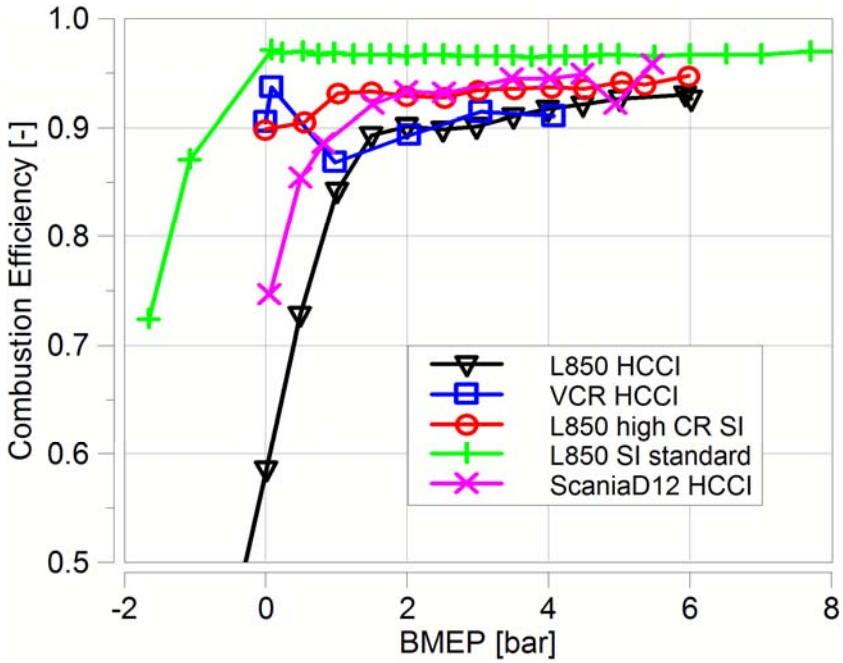


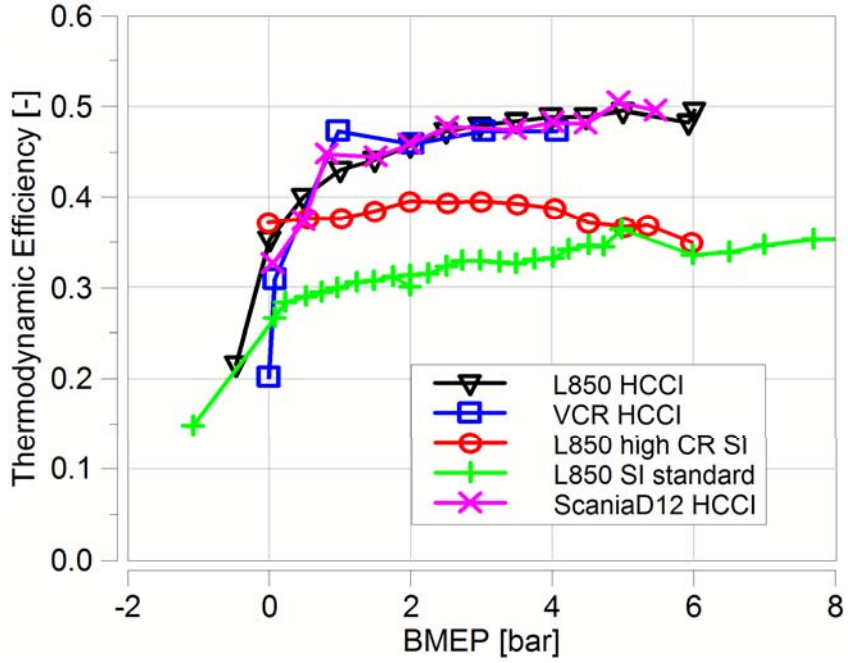


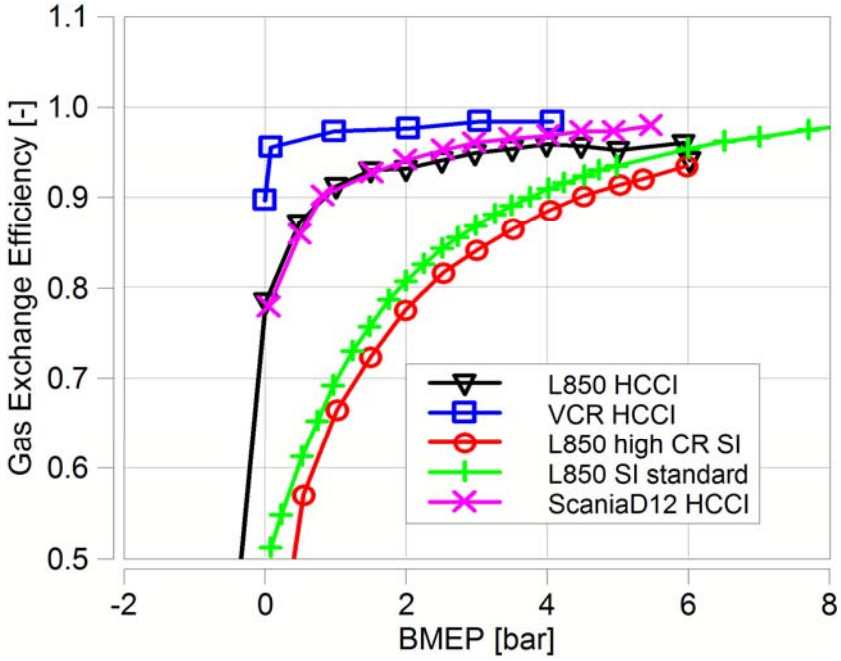


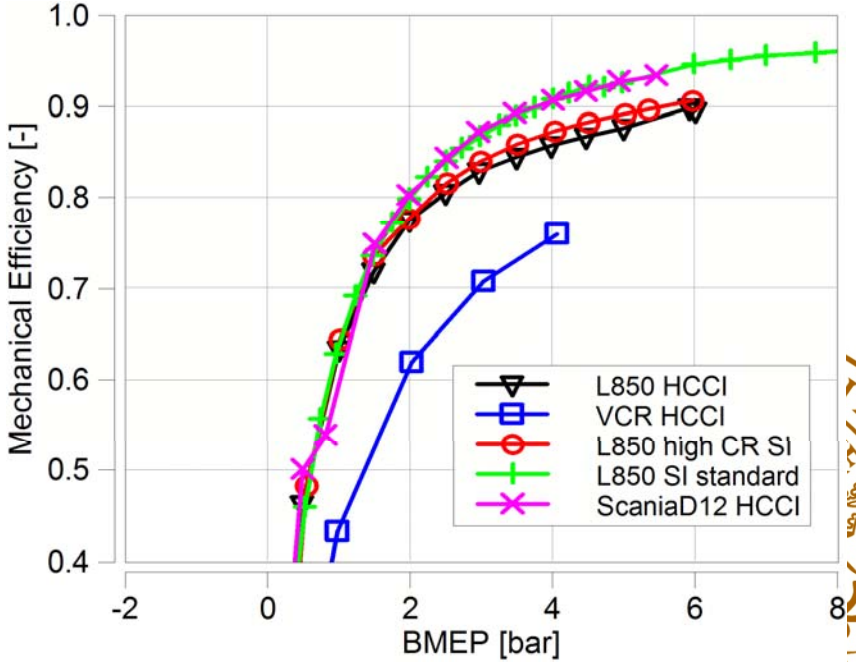
SAE2006-01-0205

All four efficiencies

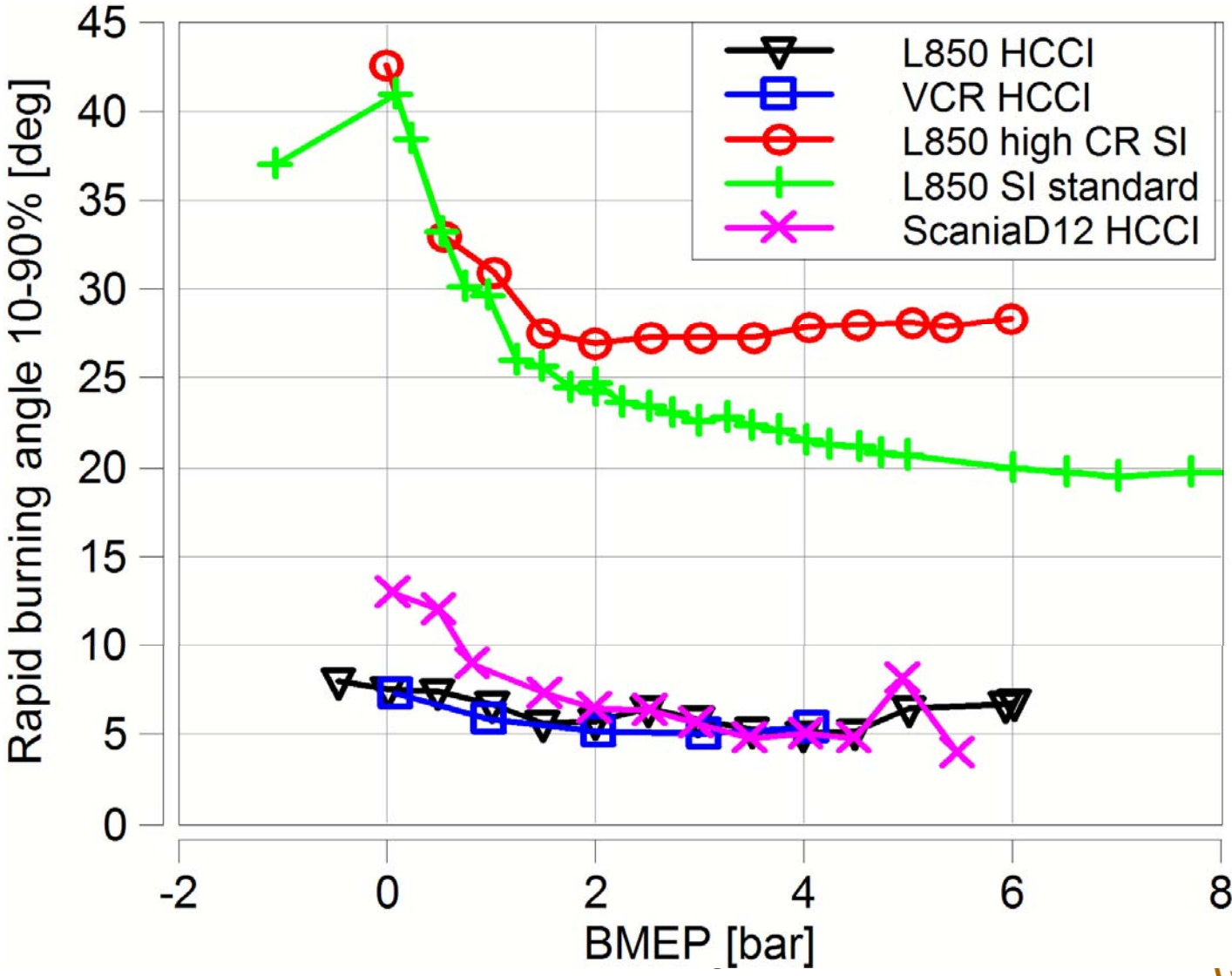




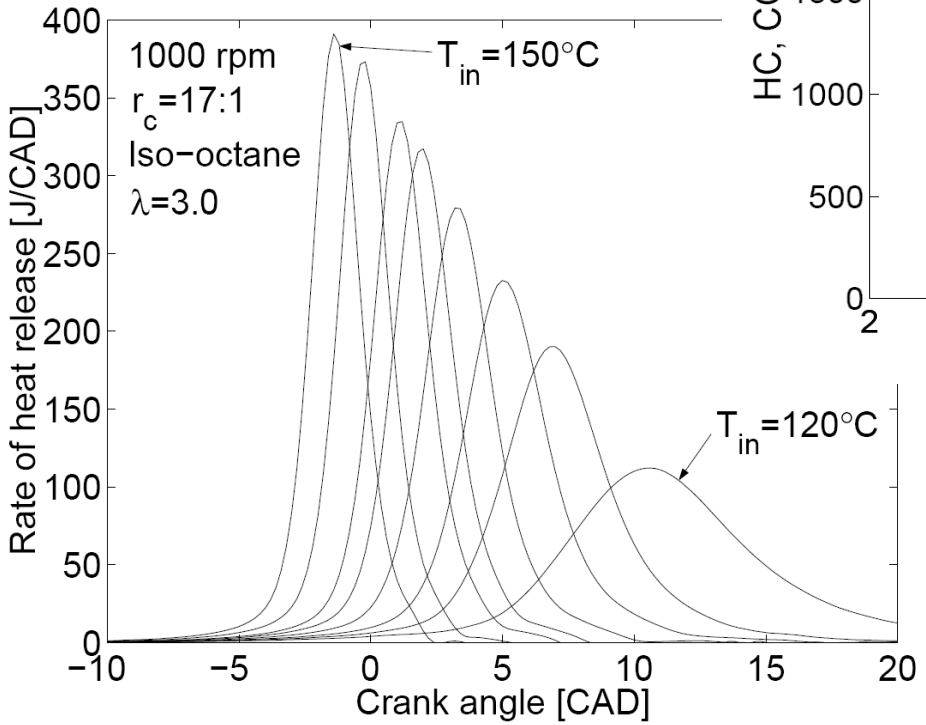


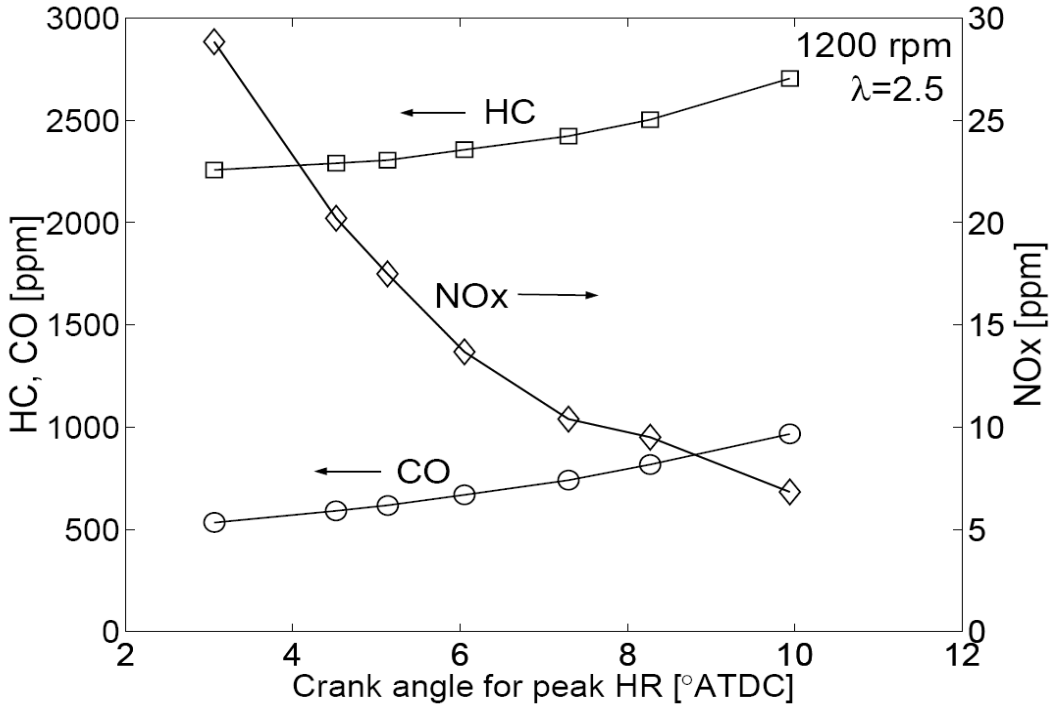


Problem with HCCI: Too fast combustion



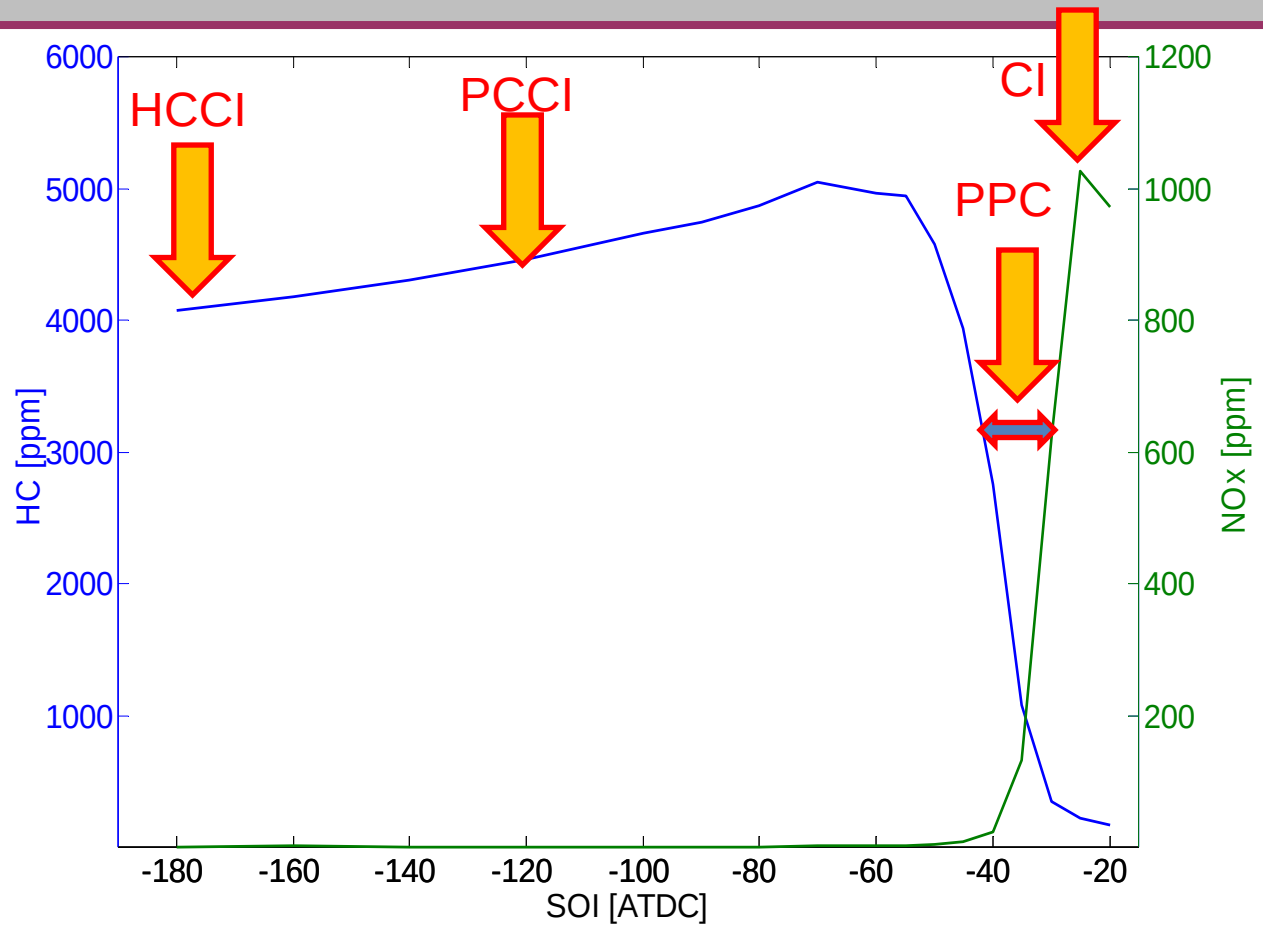
Phasing HCCI combustion late helps burn rate but reduce η_C





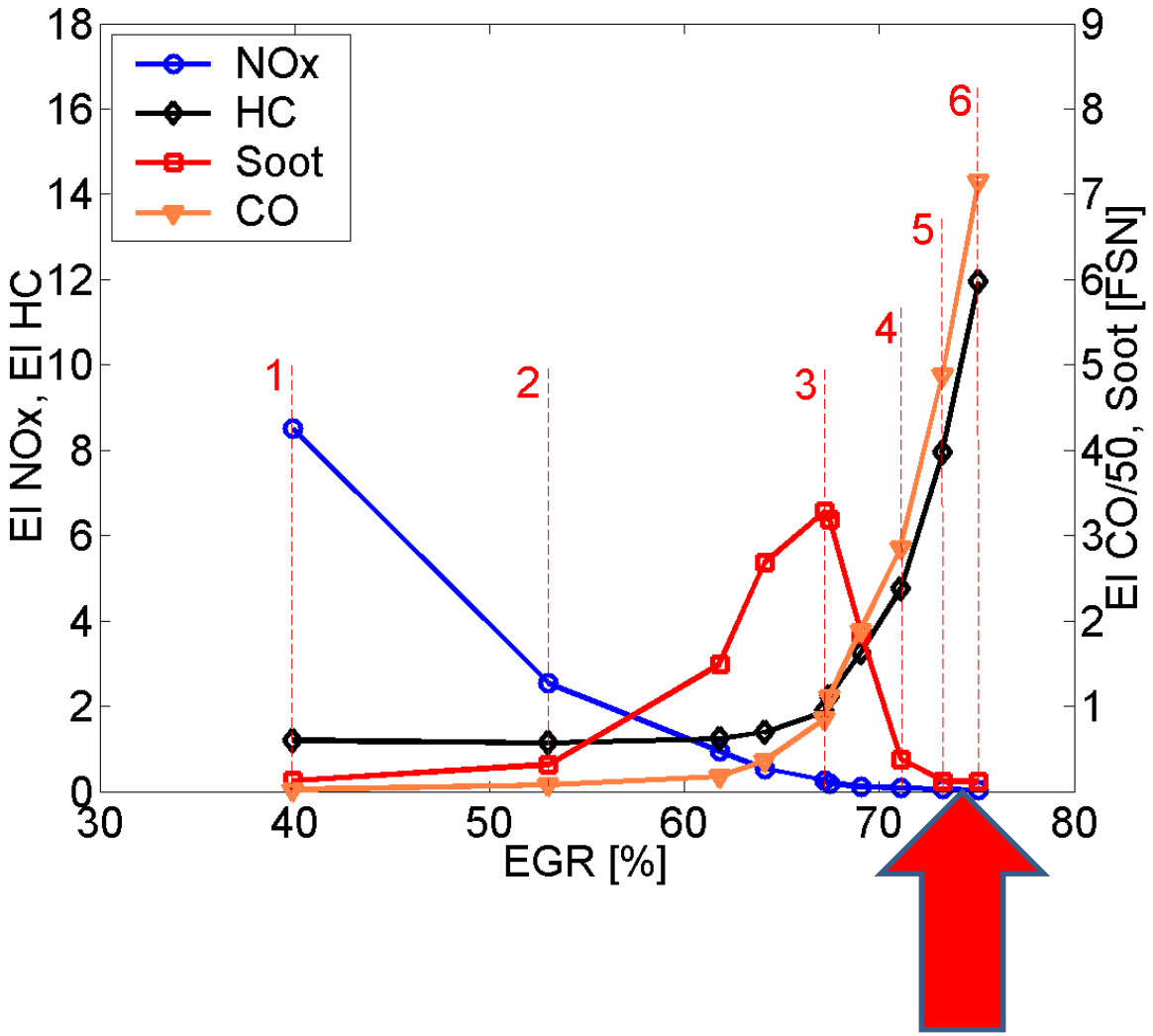
Magnus Christensen Ph.D. thesis 2002

Partially Premixed Combustion, PPC



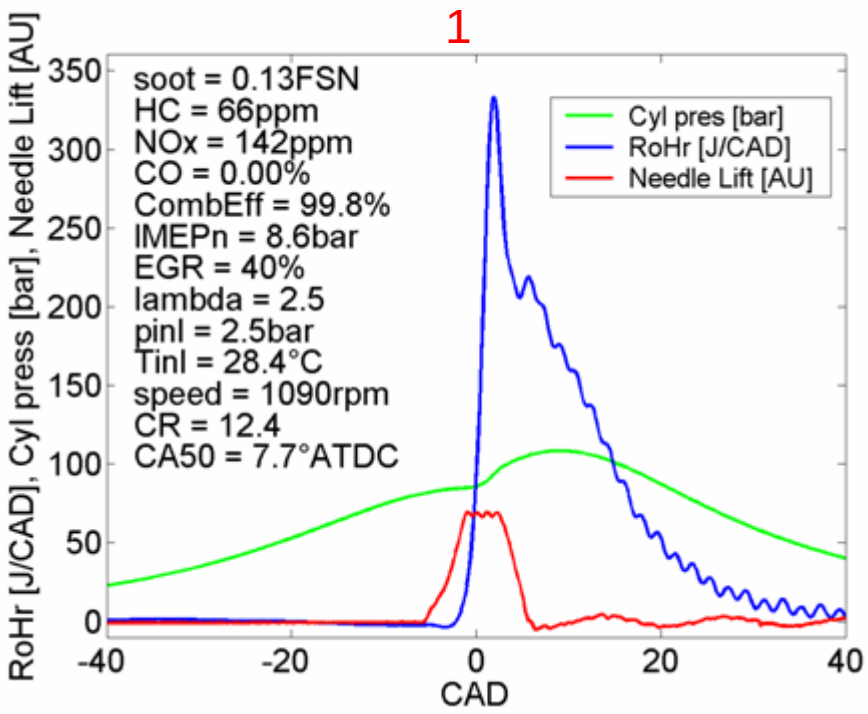
Def: region between truly homogeneous combustion, HCCI, and diffusion controlled combustion, diesel

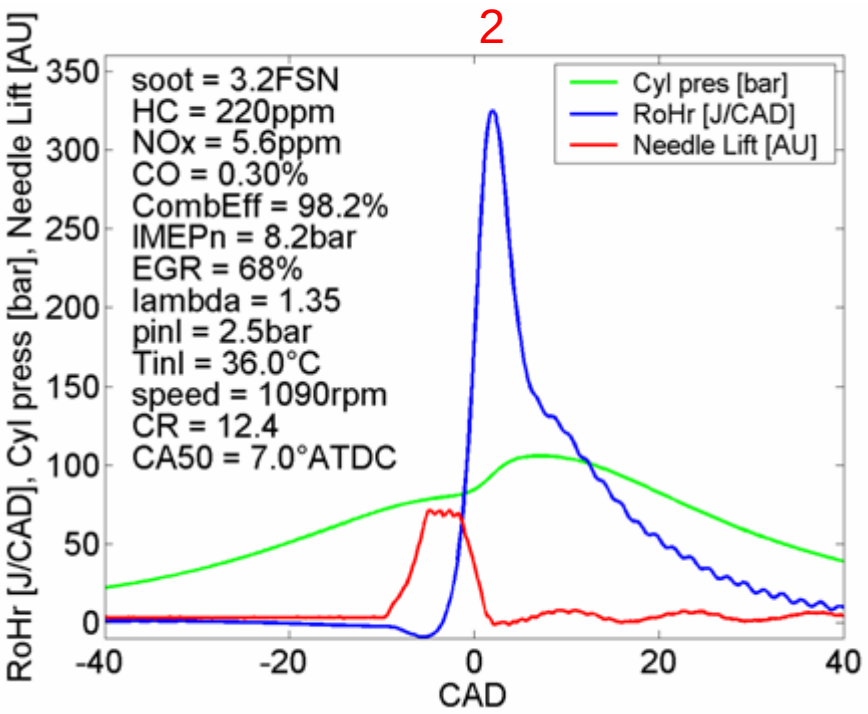
PPC: Effect of EGR with diesel fuel

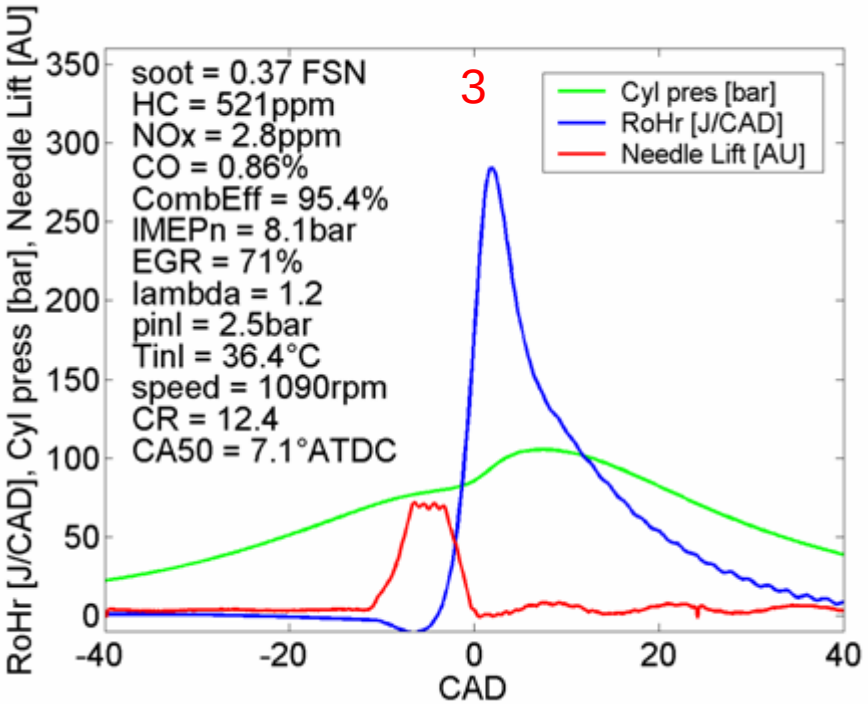


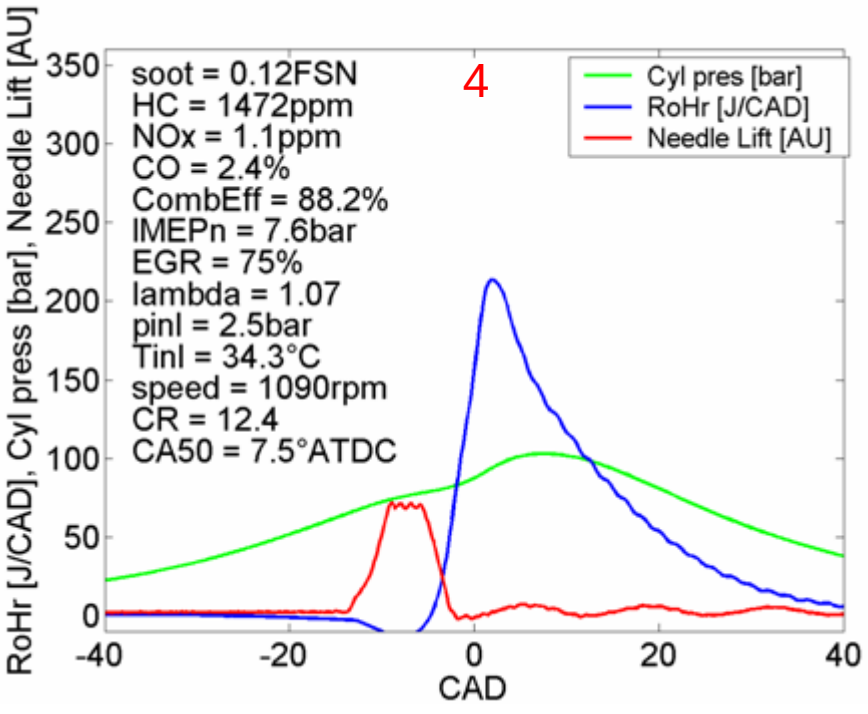
Load	8 bar IMEP
Abs. Inlet Pressure	2.5 bar
Engine Speed	1090 rpm
Swirl Ratio	1.7
Compression Ratio	**12.4:1 (Low)**

Scania D12 single cylinder


1
soot = 0.13FSN
HC = 66ppm
NOx = 142ppm
CO = 0.00%
CombEff = 99.8%
IMEPn = 8.6bar
EGR = 40%
lambda = 2.5
pinl = 2.5bar
Tinl = 28.4°C
speed = 1090rpm
CR = 12.4
CA50 = 7.7°ATDC
Cyl pres [bar]
RoHr [J/CAD]
Needle Lift [AU]
RoHr [J/CAD], Cyl press [bar], Needle Lift [AU]
CAD

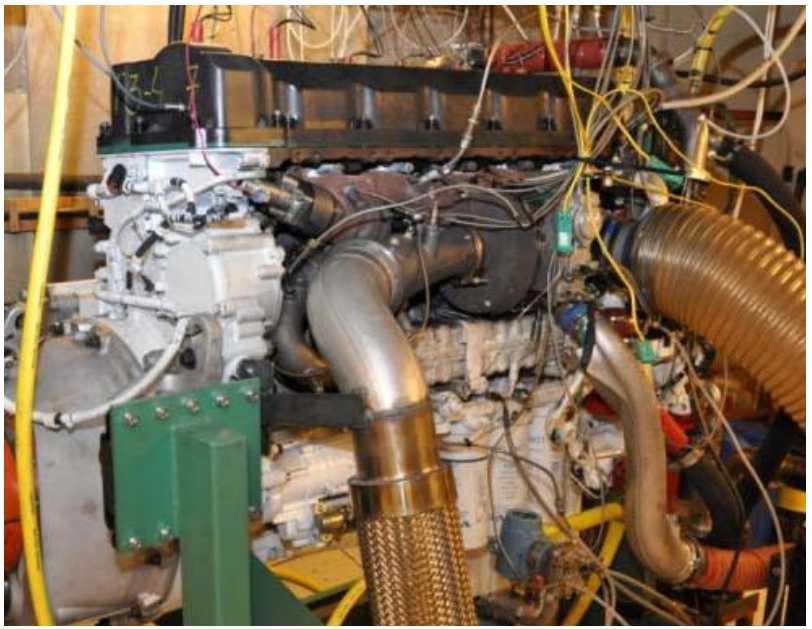

2
soot = 3.2FSN
HC = 220ppm
NOx = 5.6ppm
CO = 0.30%
CombEff = 98.2%
IMEPn = 8.2bar
EGR = 68%
lambda = 1.35
pinl = 2.5bar
Tinl = 36.0°C
speed = 1090rpm
CR = 12.4
CA50 = 7.0°ATDC
Cyl pres [bar]
RoHr [J/CAD]
Needle Lift [AU]
RoHr [J/CAD], Cyl press [bar], Needle Lift [AU]
CAD

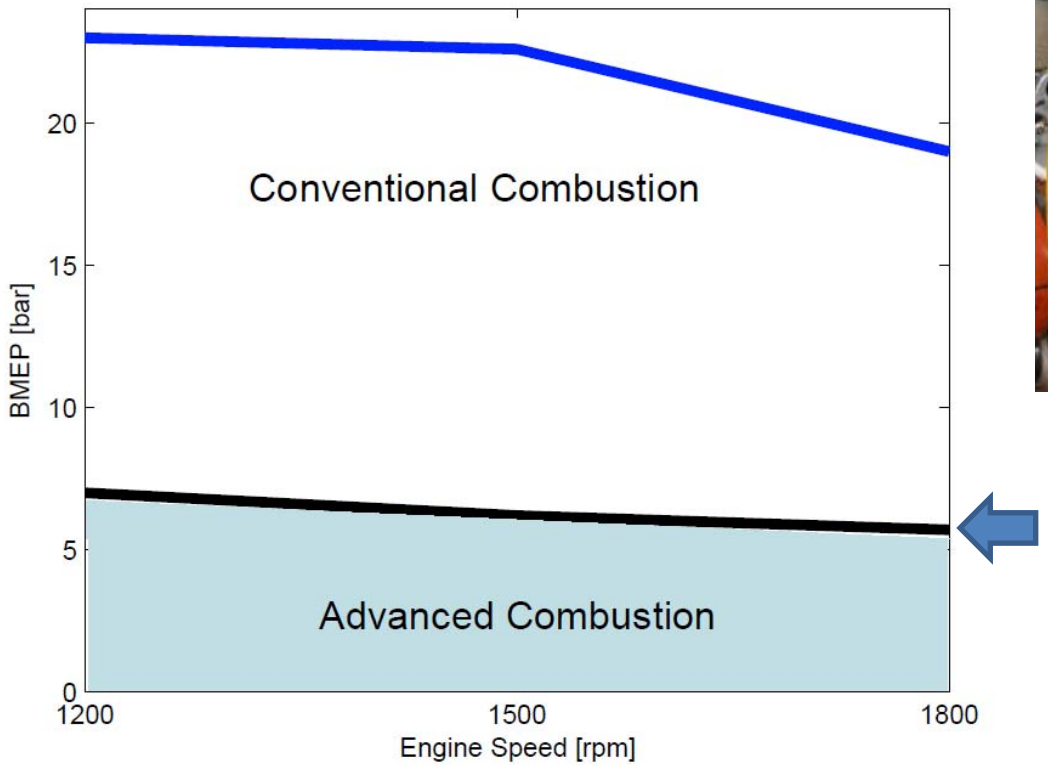

3
soot = 0.37 FSN
HC = 521ppm
NOx = 2.8ppm
CO = 0.86%
CombEff = 95.4%
IMEPn = 8.1bar
EGR = 71%
lambda = 1.2
pinl = 2.5bar
Tinl = 36.4°C
speed = 1090rpm
CR = 12.4
CA50 = 7.1°ATDC
Cyl pres [bar]
RoHr [J/CAD]
Needle Lift [AU]
RoHr [J/CAD], Cyl press [bar], Needle Lift [AU]
CAD


4
soot = 0.12FSN
HC = 1472ppm
NOx = 1.1ppm
CO = 2.4%
CombEff = 88.2%
IMEPn = 7.6bar
EGR = 75%
lambda = 1.07
pinl = 2.5bar
Tinl = 34.3°C
speed = 1090rpm
CR = 12.4
CA50 = 7.5°ATDC
Cyl pres [bar]
RoHr [J/CAD]
Needle Lift [AU]
RoHr [J/CAD], Cyl press [bar], Needle Lift [AU]
CAD

Delphi/Lund/Volvo PPC Project

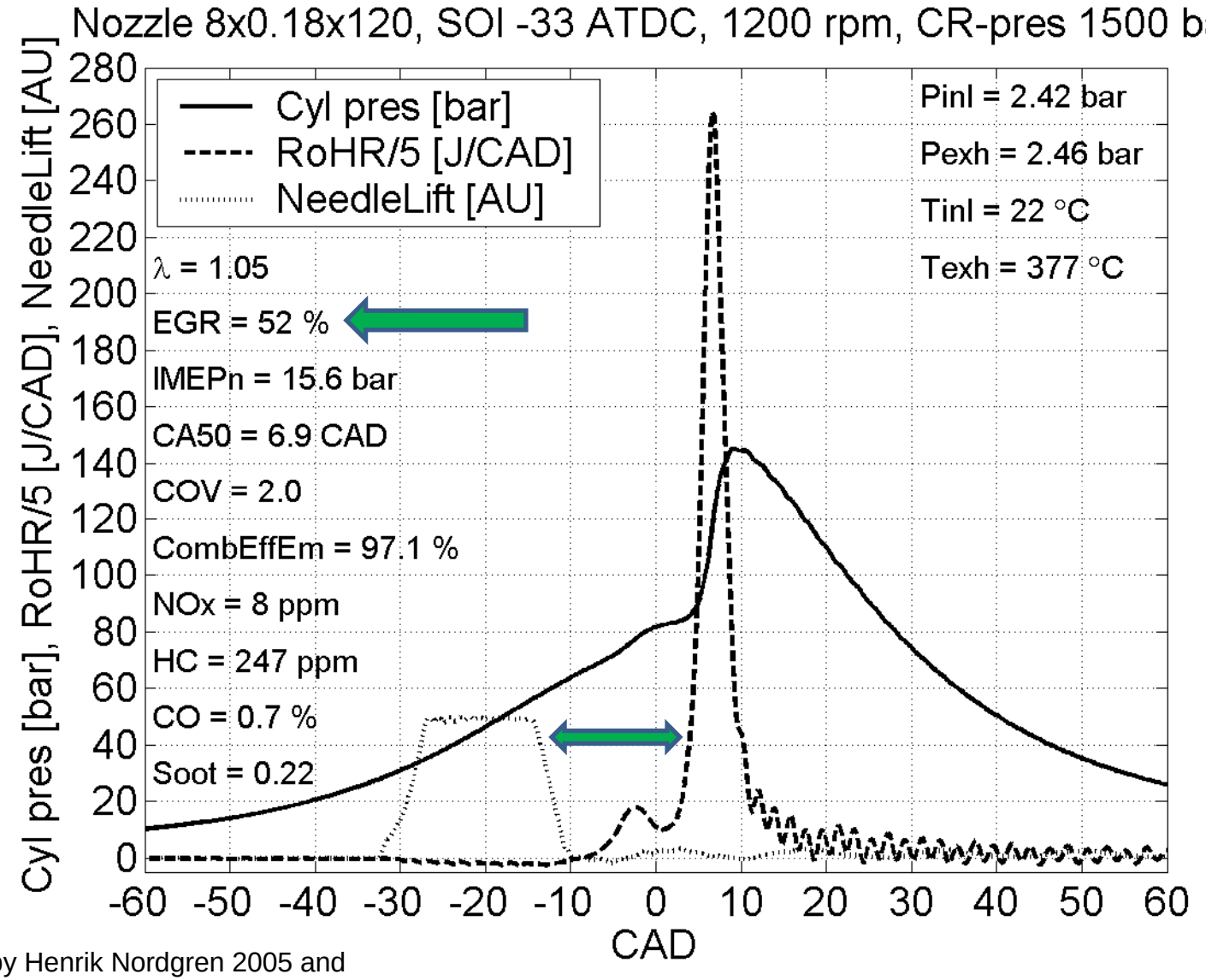
Volvo D13 US07 EGR base engine





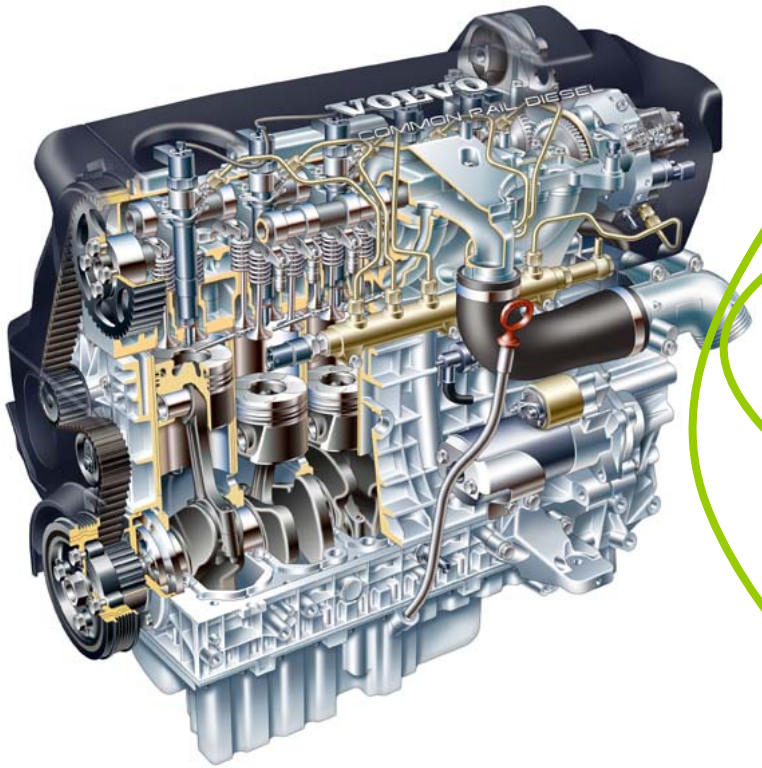
NOx <0.3 g/kWh
PM < 2 FSN
using
Swedish MK1 **diesel** fuel

PPC with low cetane diesel



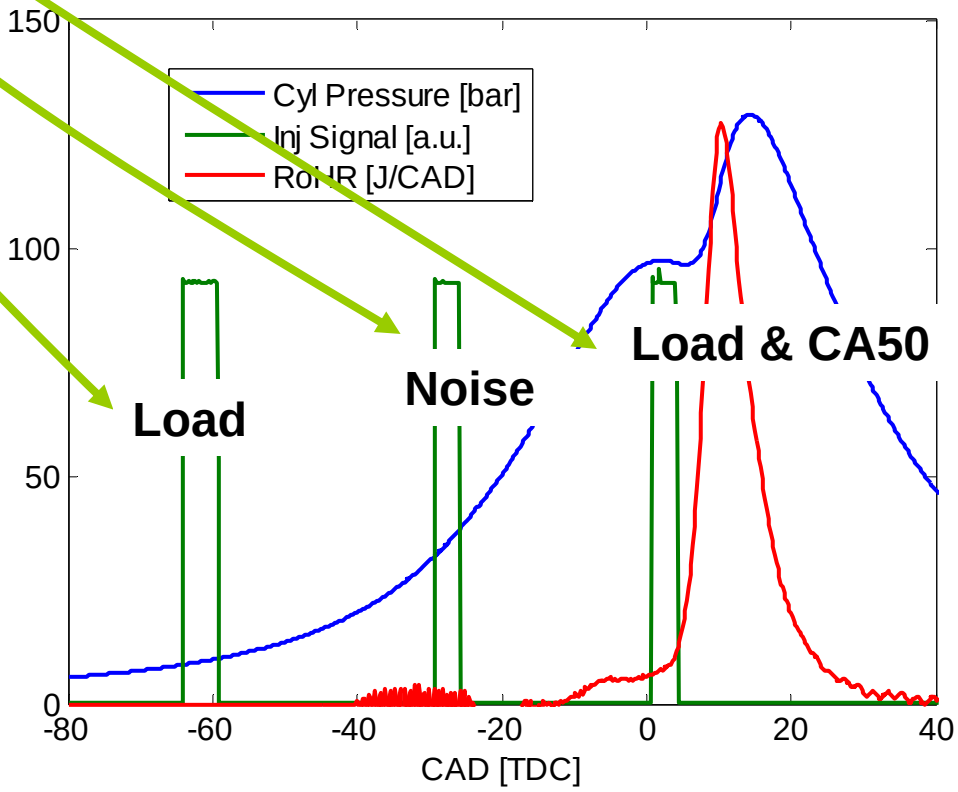
Lic. Thesis by Henrik Nordgren 2005 and presented at DEER2005

VOLVO D5 with Gasoline

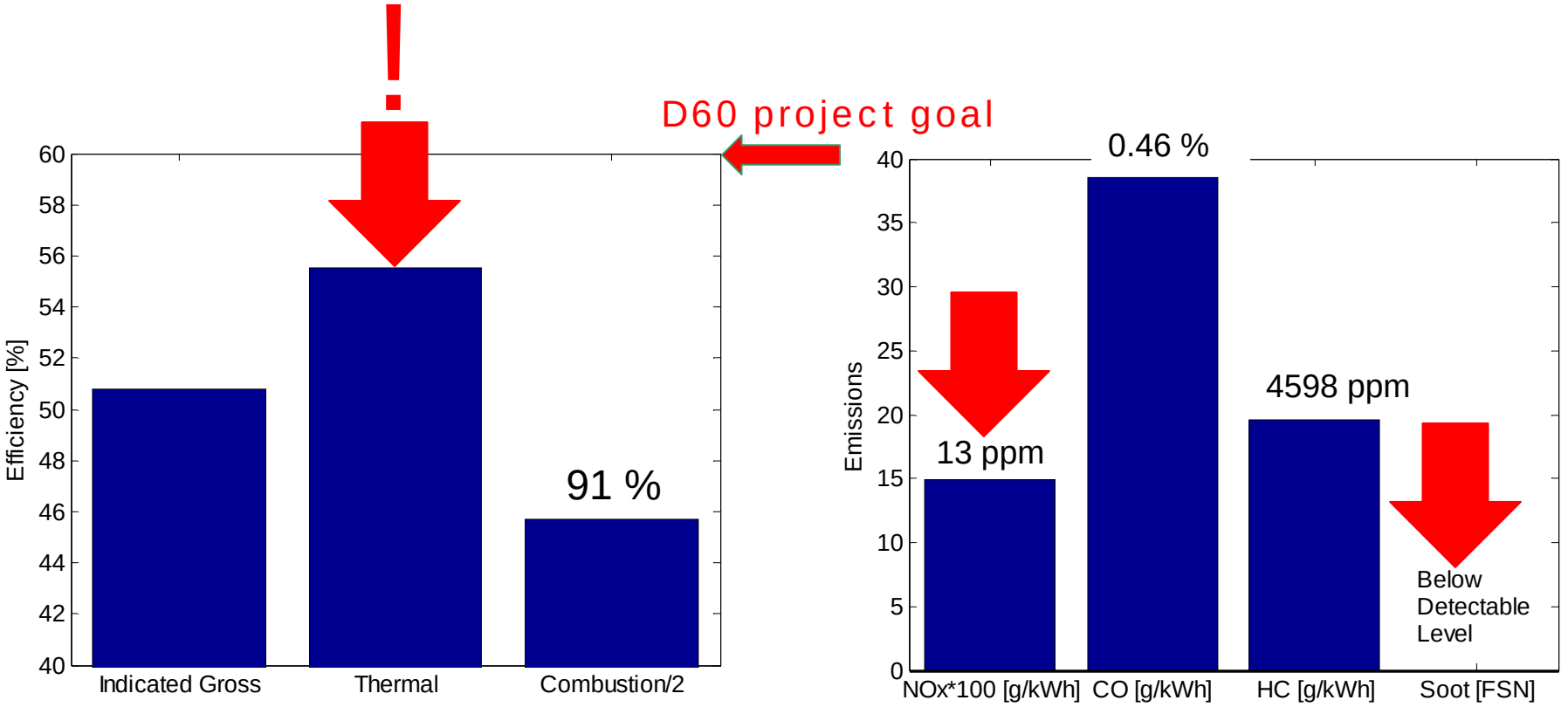


Injection	SOI [TDC]	Fuel MEP [bar]	Percentage [%]
1	-64.00	10.88	41.28
2	-29.20	7.74	29.36
3	0.80	7.74	29.36

N	2000	[rpm]
IMEPg	13.38	[bar]
Pin	2.57	[bar]
Tin	354	[K]
EGR	39	[%]
lambda	1.75	[-]



Efficiencies & Emissions



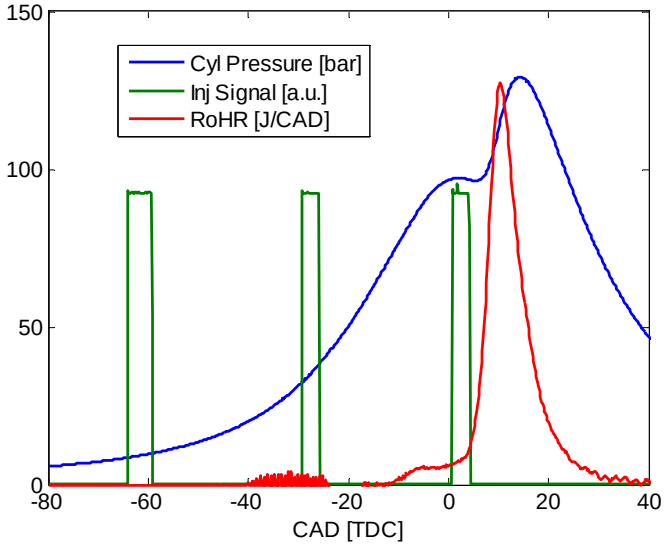
dPmax	7.20	[bar/CAD]
CA5	3.40	[TDC]
ID	-1.00	[CAD]
CA50	11.35	[TDC]
CA90-10	13.00	[CAD]

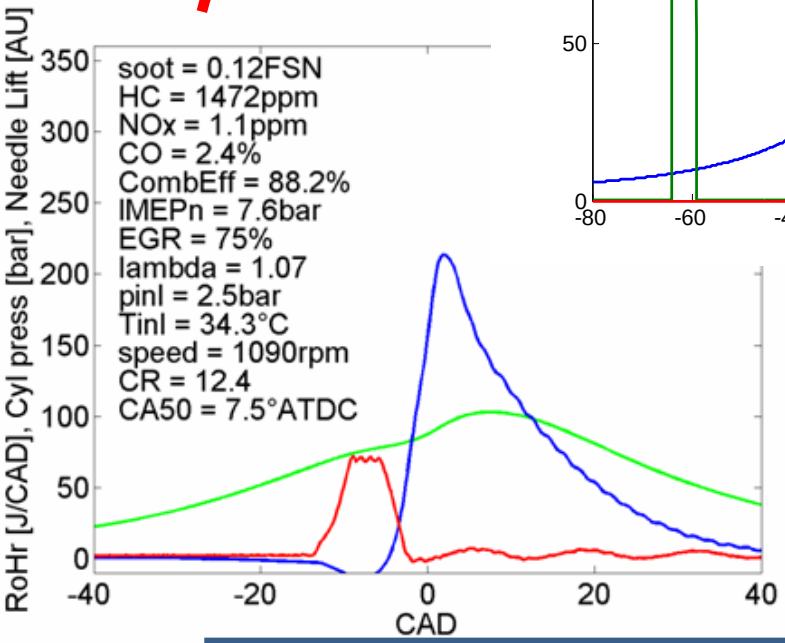
Burn rate and η_T

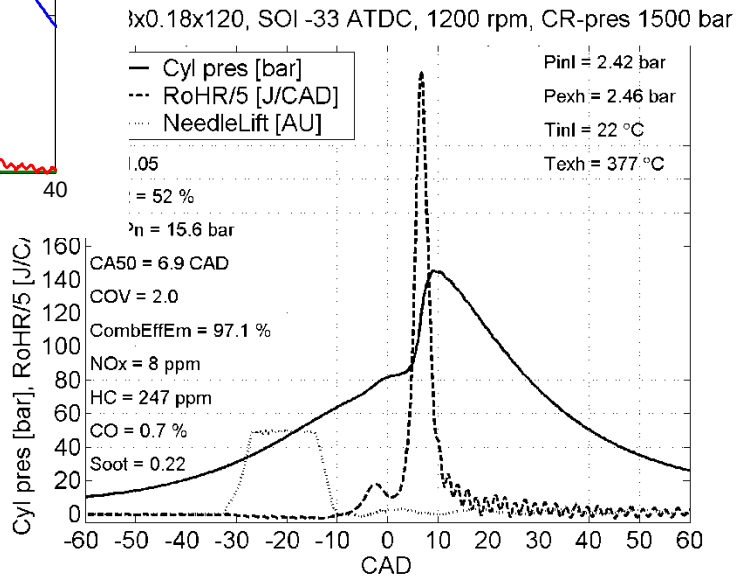
Optimum Thermodynamic efficiency

Low effective expansion ratio

High heat losses







Premixedness

Experimental setup, Scania D12

Bosch Common Rail		
$Prail_{max}$	1600	[bar]
Orifices	8	[-]
Orifice Diameter	0.18	[mm]
Umbrella Angle	120	[deg]
Engine / Dyno Spec		
BMEPmax	15	[bar]
Vd	1951	[cm3]
Swirl ratio	2.9	[-]

Fuel: Gasoline or Ethanol

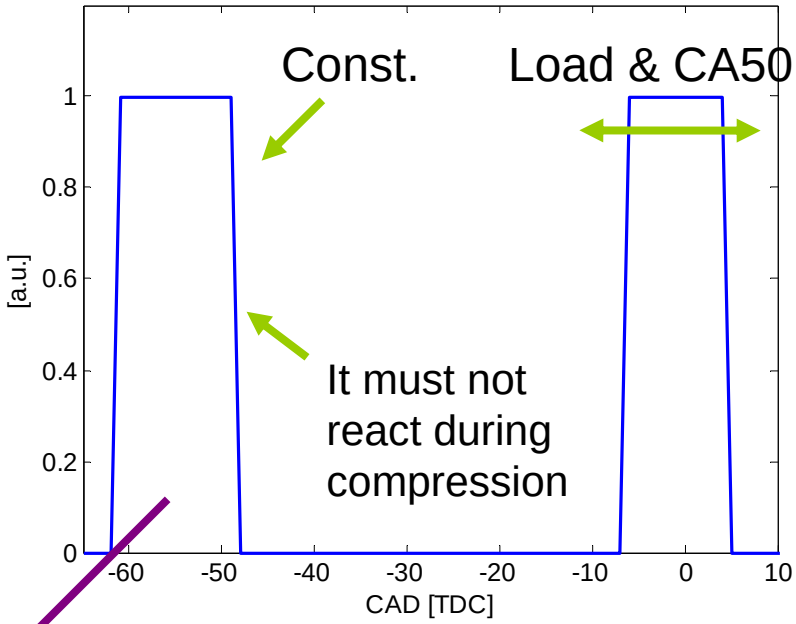
Two Test Series: High & Low Compression Ratio

Low Compression Ratio PPC

High Compression Ratio PPC

Injection Strategy

It consists of two injections. The first one is placed @ -60 TDC to create a homogeneous mixture while the second around TDC. The stratification created by the second injection triggers the combustion. The first injection must not react during the compression stroke, this is achieved by using EGR.



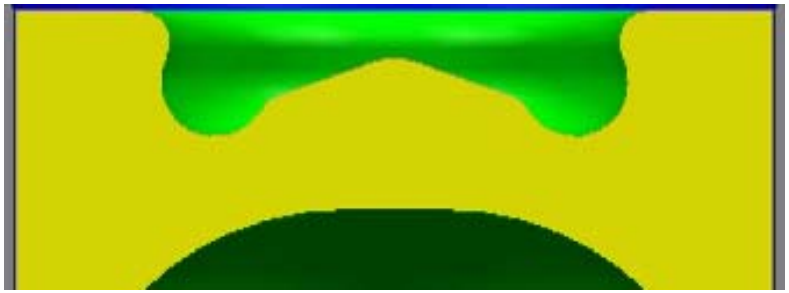
Fuel amount in the pilot is a function of:

1.rc

2.RON/MON

3.EGR

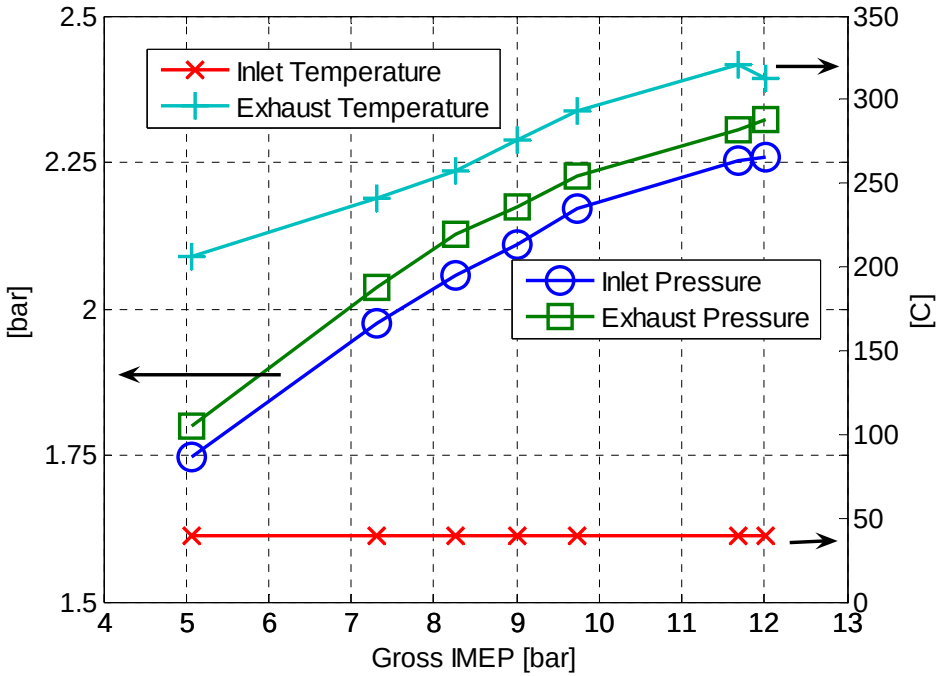
High Compression Ratio PPC

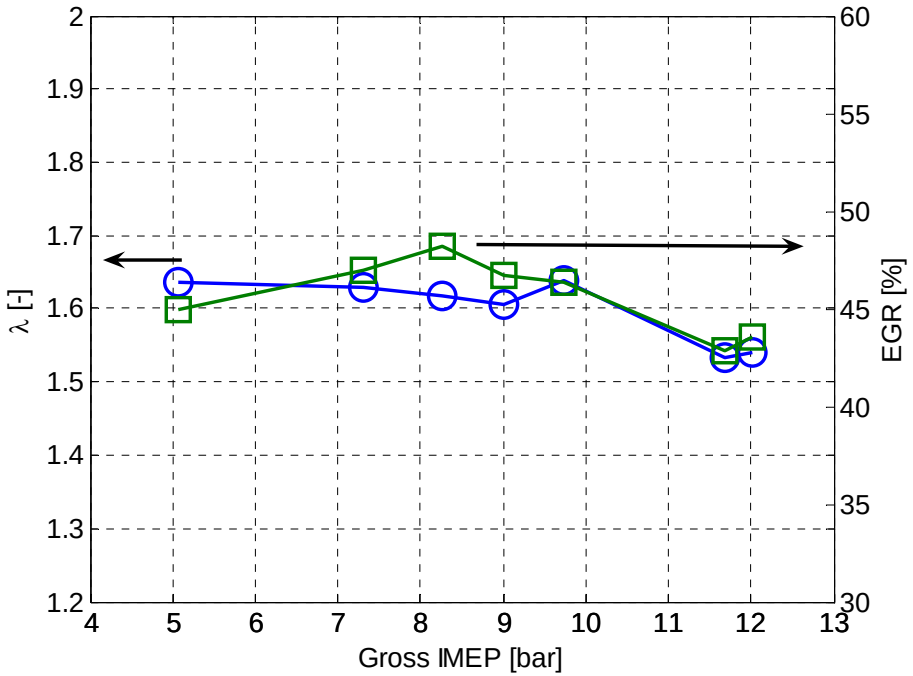


IMEP sweep @ 1300 [rpm]
EGR ~ const throughout the sweep, 40-50 [%]
λ~ const throughout the sweep, 1.5-1.6 [-]
Tin = 308 [K]

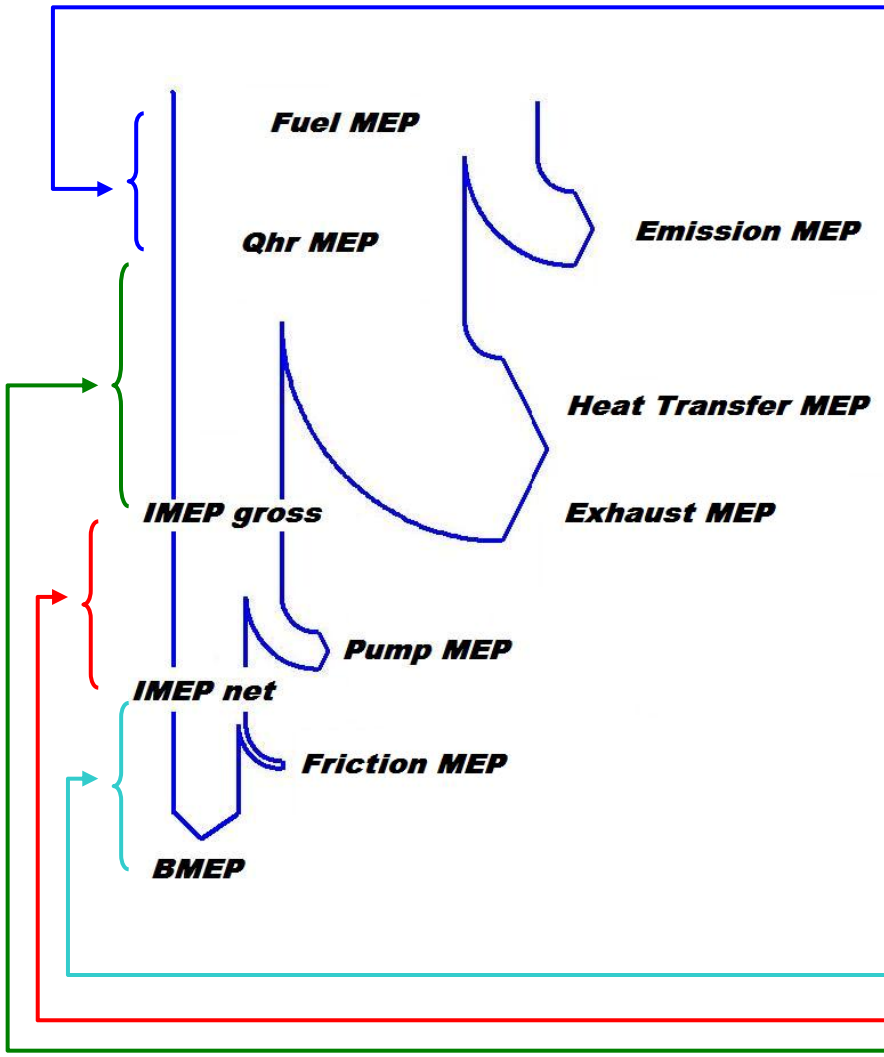
Standard piston bowl, rc: 17:1

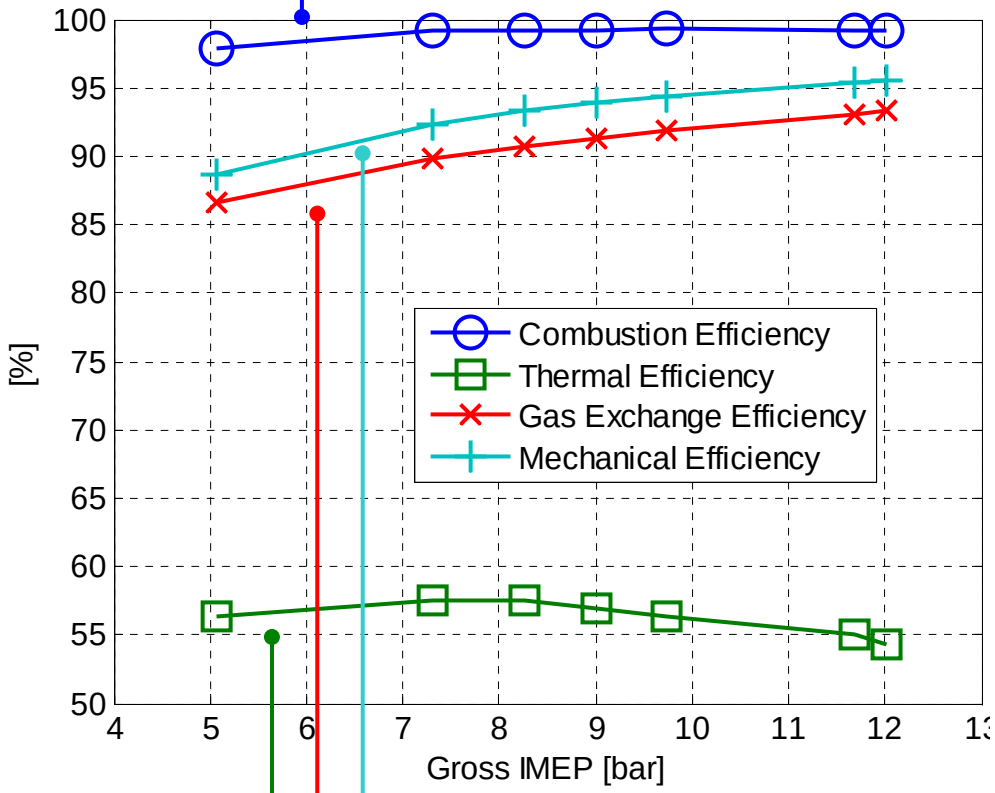
Running Conditions



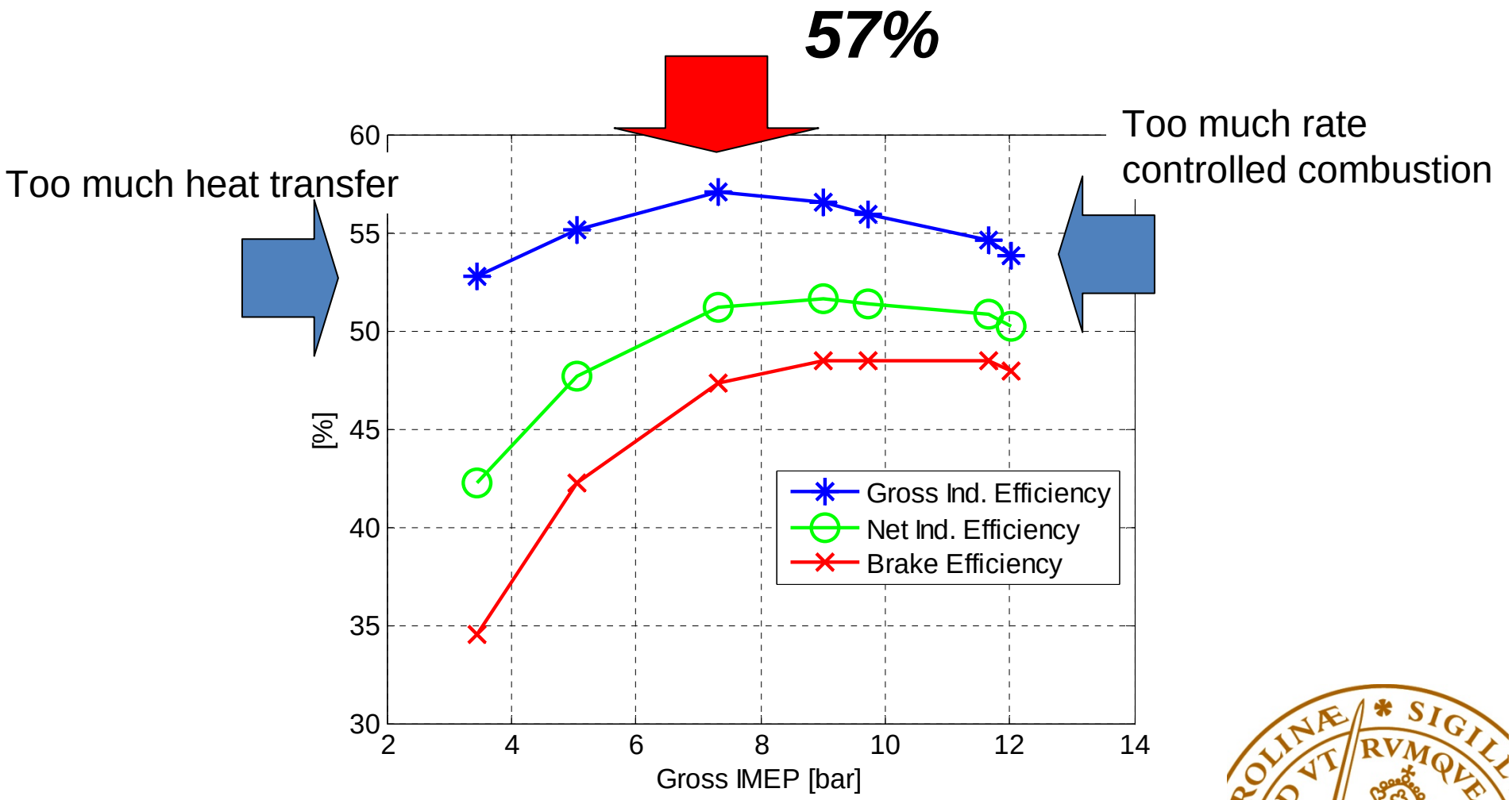


Efficiencies

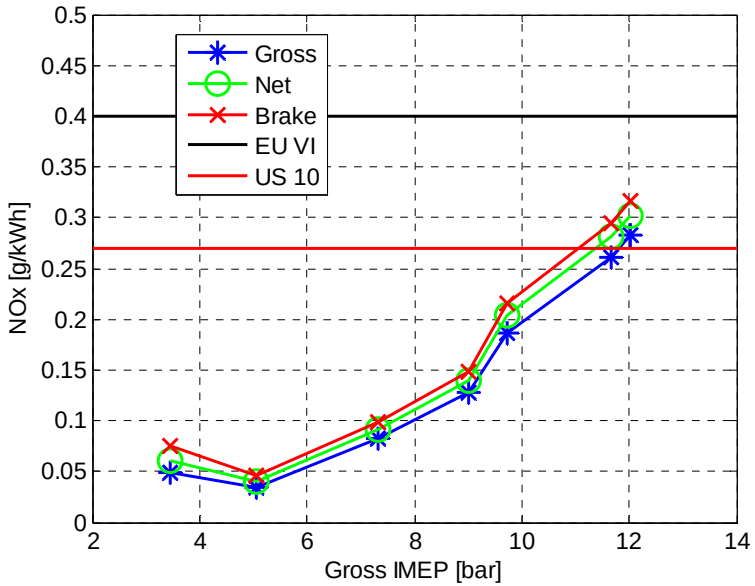


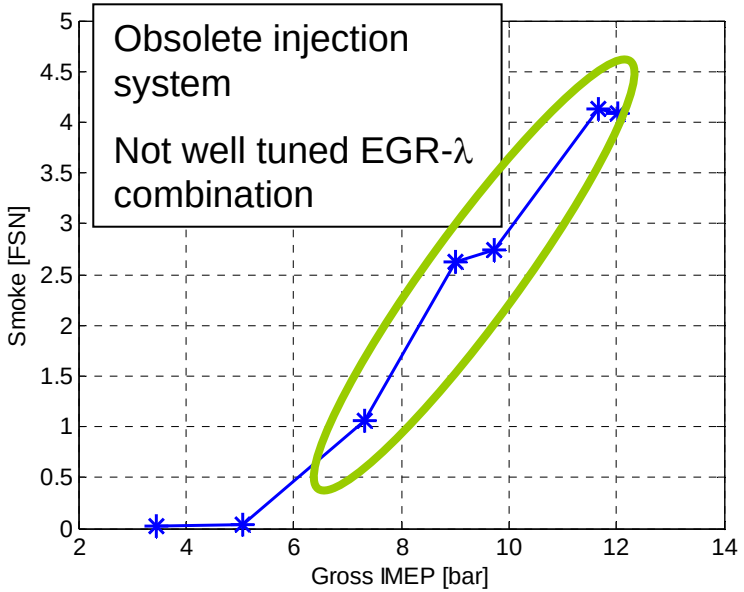


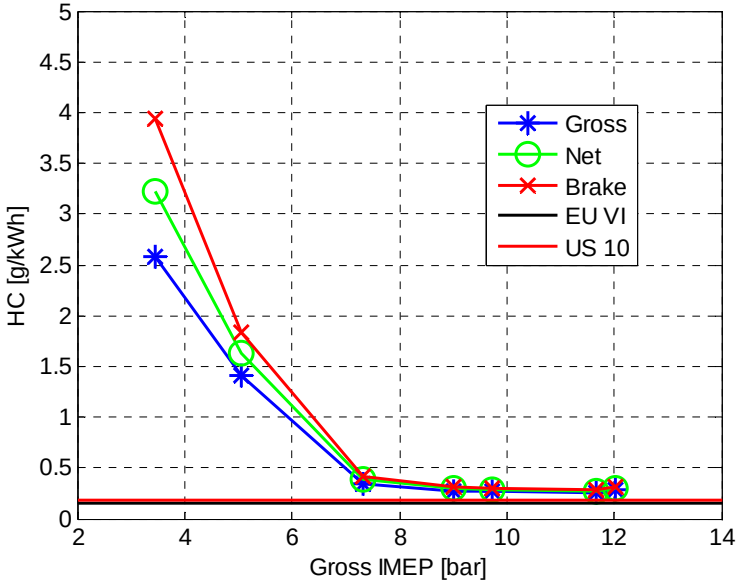
Efficiency

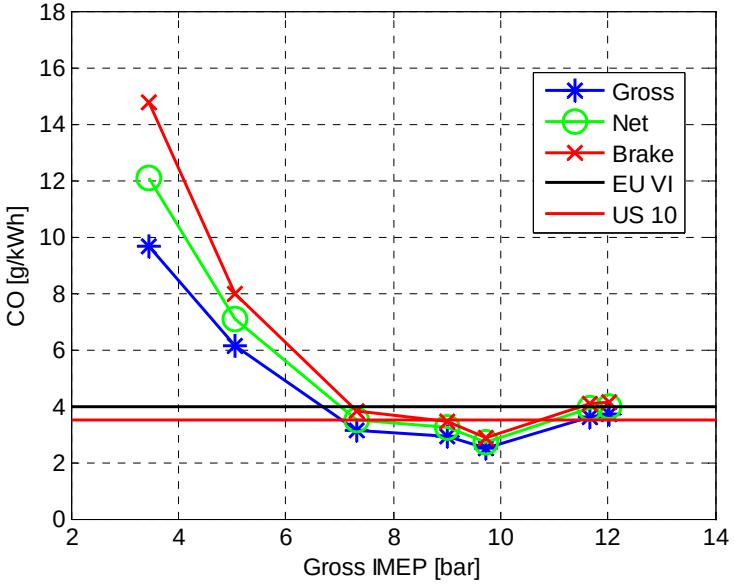

57%
Too much heat transfer
Too much rate controlled combustion
60
55
50
45
40
35
30
[%]
2
4
6
8
10
12
14
Gross IMEP [bar]
Gross Ind. Efficiency
Net Ind. Efficiency
Brake Efficiency

Emissions

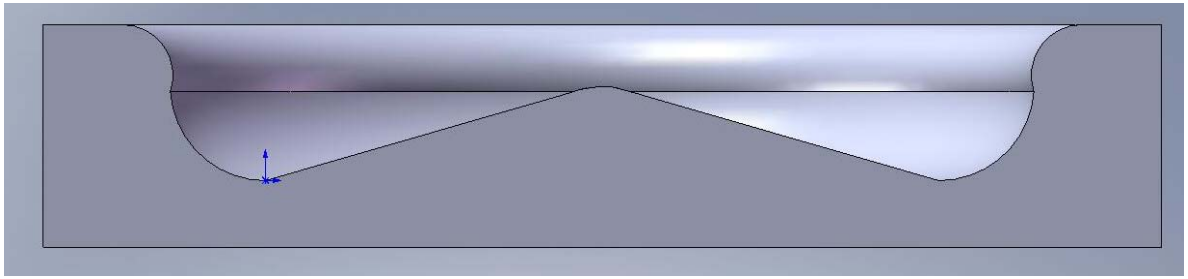

Gross
Net
Brake
EU VI
US 10
NOx [g/kWh]
Gross IMEP [bar]


Obsolete injection system
Not well tuned EGR-λ combination
Smoke [FSN]
Gross IMEP [bar]


Gross
Net
Brake
EU VI
US 10
HC [g/kWh]
Gross IMEP [bar]


Gross
Net
Brake
EU VI
US 10
CO [g/kWh]
Gross IMEP [bar]

Low Compression Ratio PPC

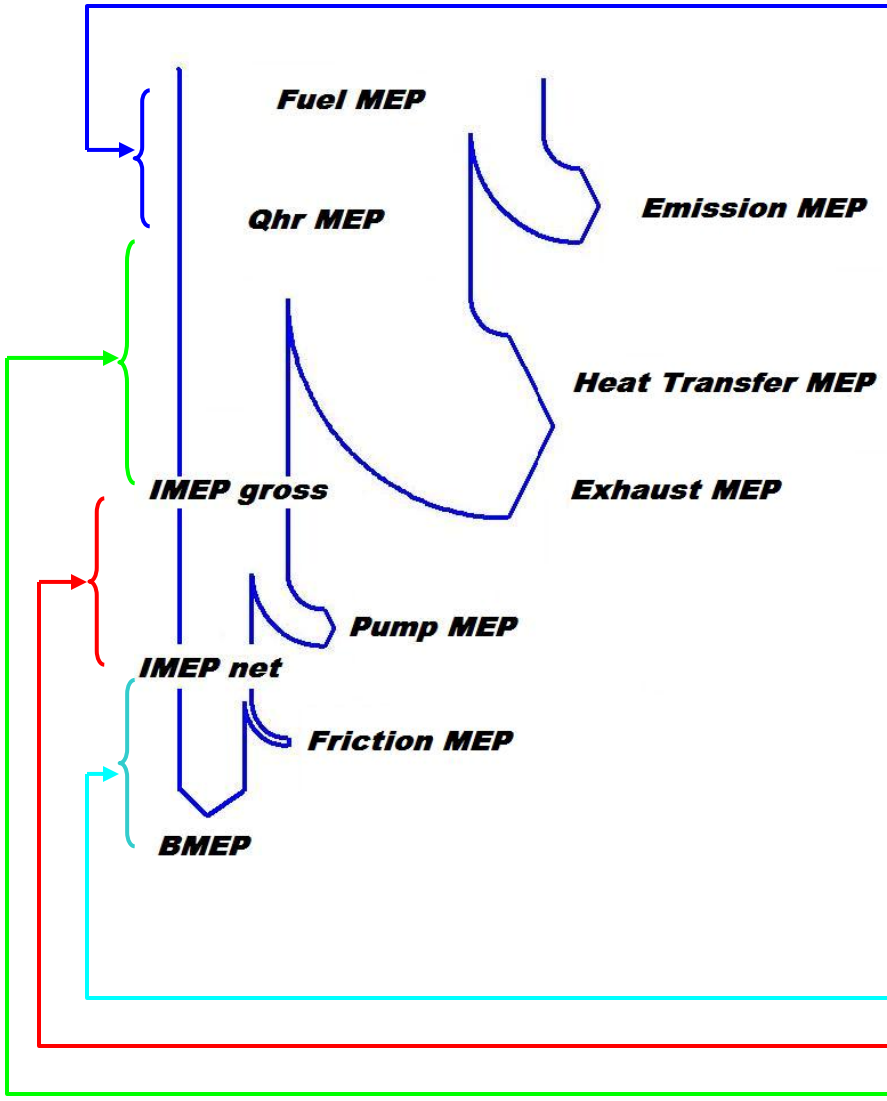


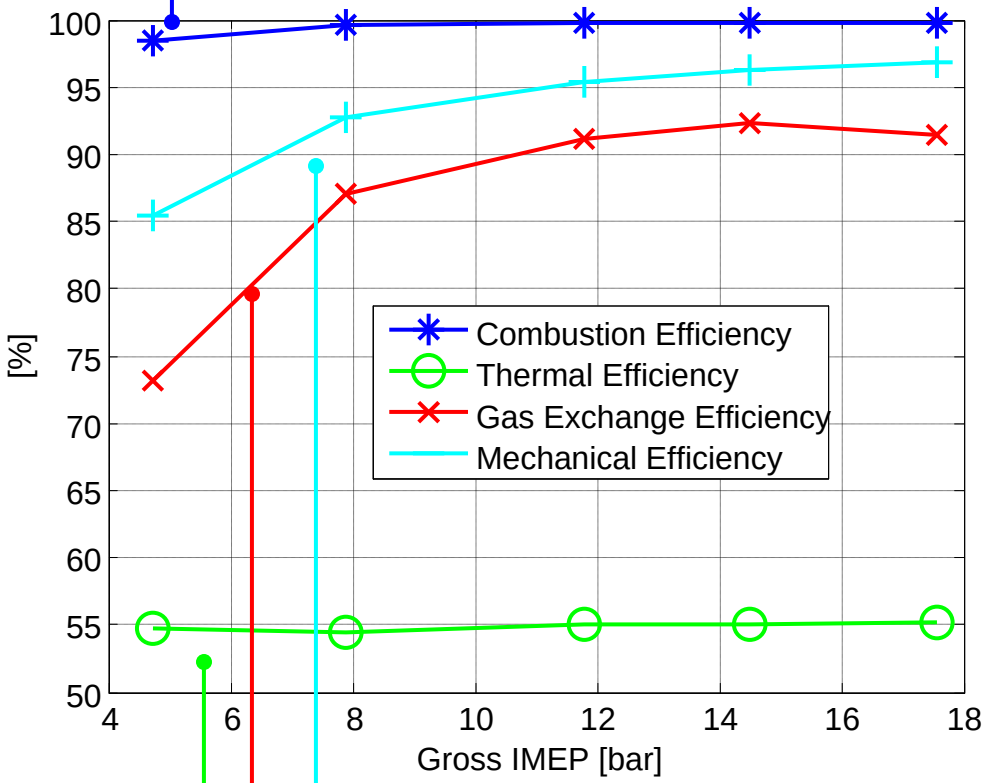
IMEP sweep @ 1300 [rpm]
EGR ~ const throughout the sweep, 40-50 [%]
λ~ const throughout the sweep, 1.5-1.6 [-]
Tin = 308 [K]

Custom piston bowl, rc: 14.3:1

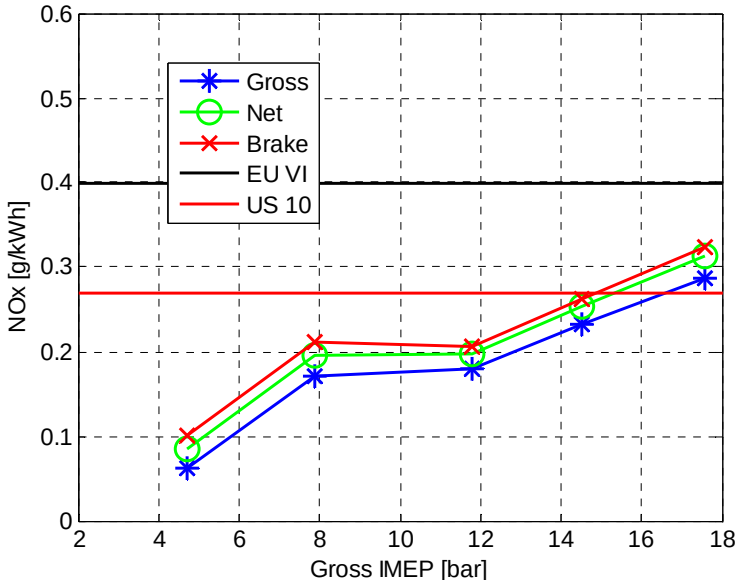
SAE 2010-01-0871

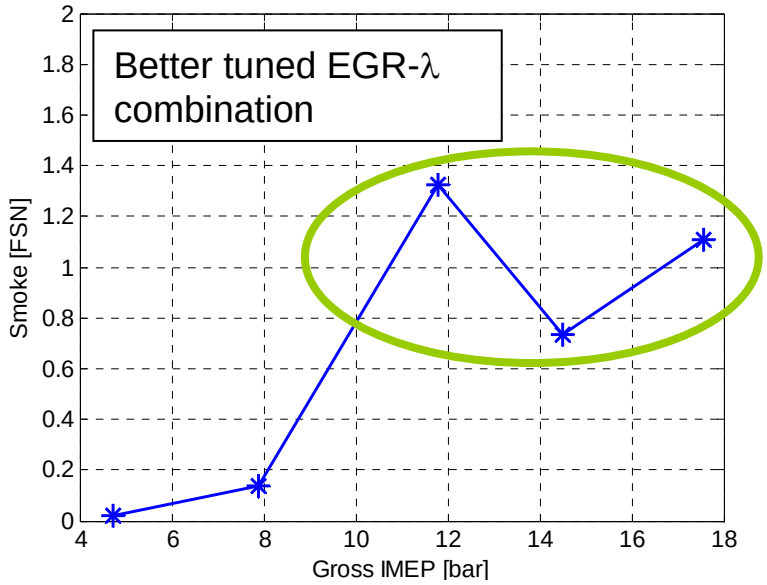
Efficiencies

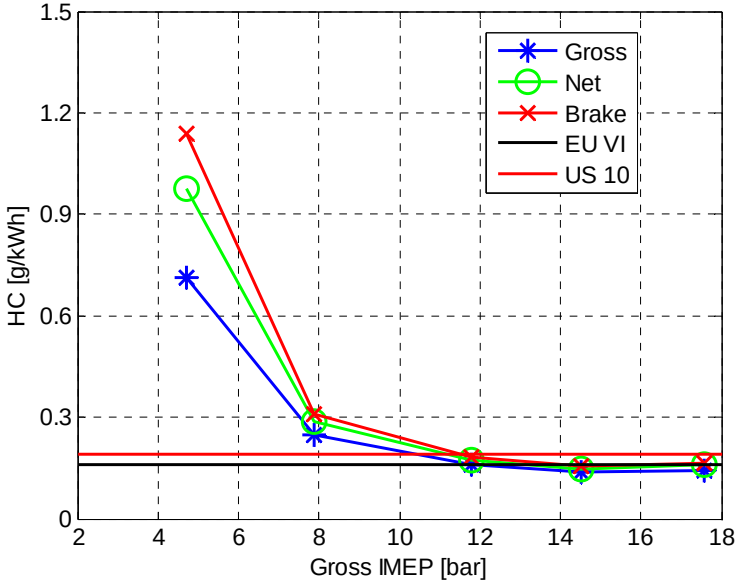


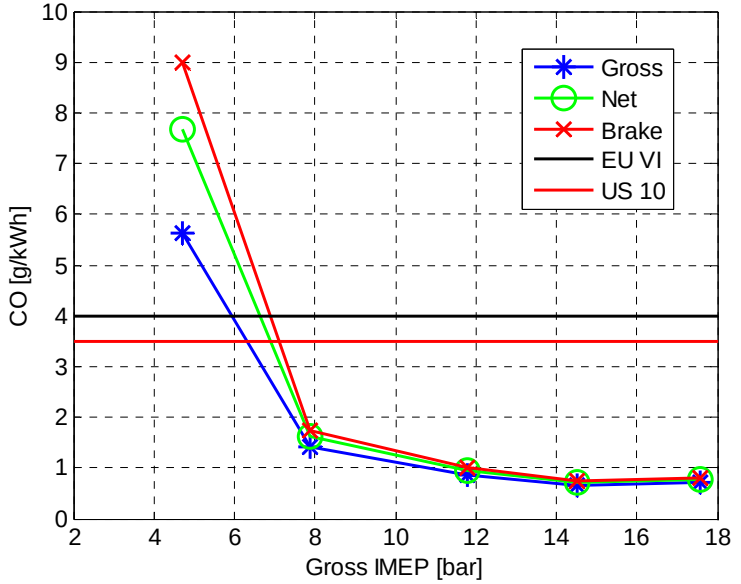


Emissions


Gross
Net
Brake
EU VI
US 10
NOx [g/kWh]
Gross IMEP [bar]


Better tuned EGR-λ combination
Smoke [FSN]
Gross IMEP [bar]


Gross
Net
Brake
EU VI
US 10
HC [g/kWh]
Gross IMEP [bar]


Gross
Net
Brake
EU VI
US 10
CO [g/kWh]
Gross IMEP [bar]

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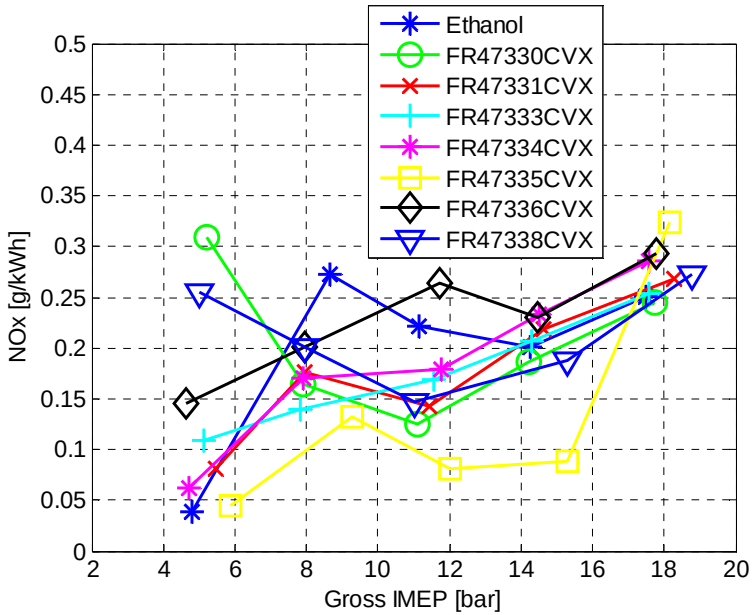
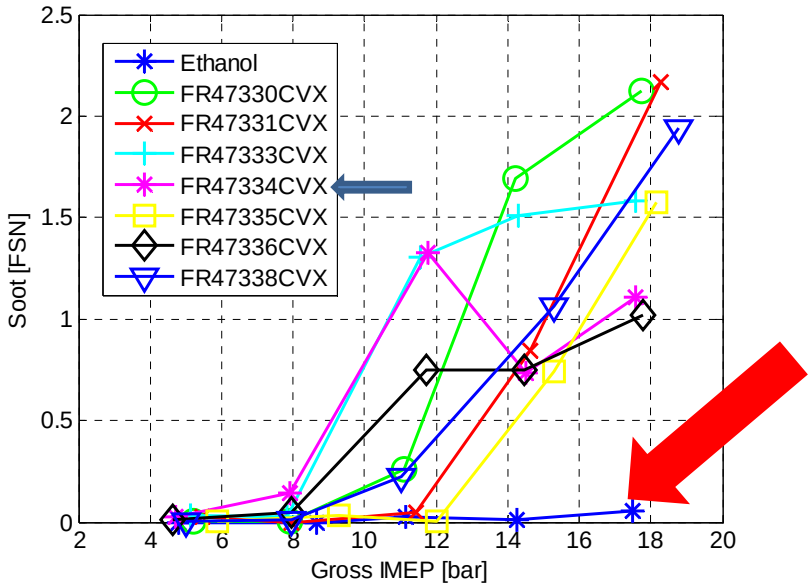
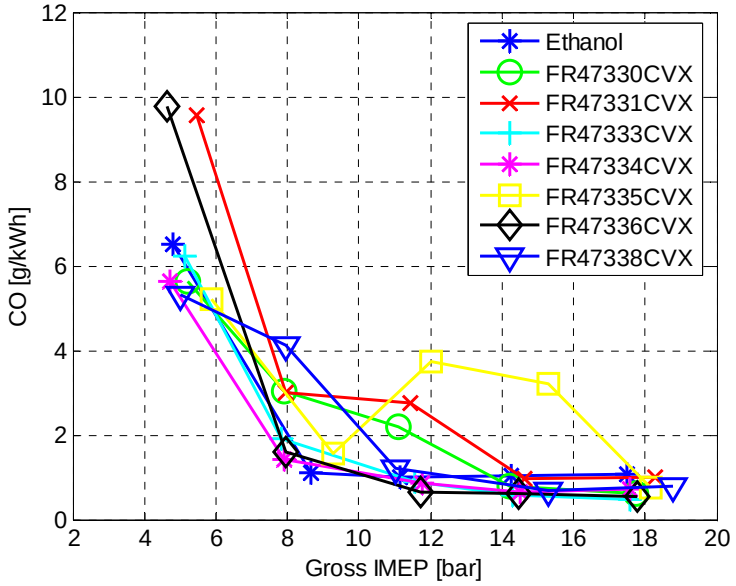
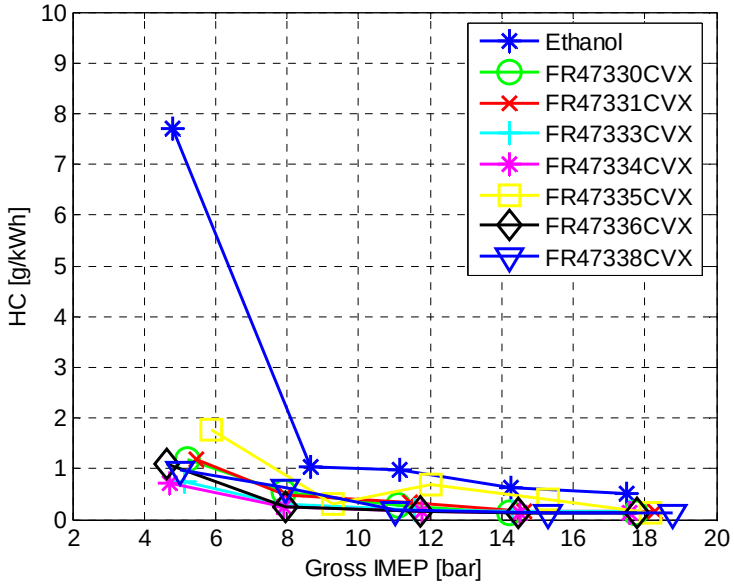
  - Fuel effects in Scania D13 engine

Emissions – 8 different fuels









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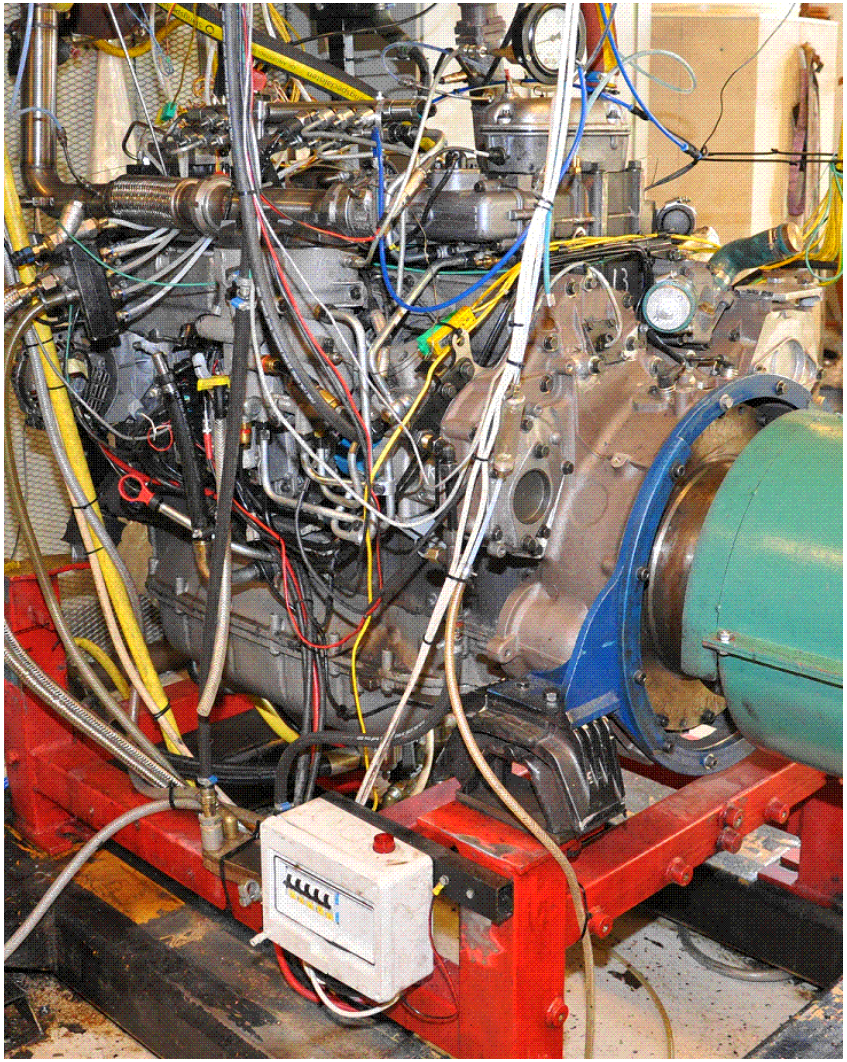
Experimental Apparatus, Scania D13

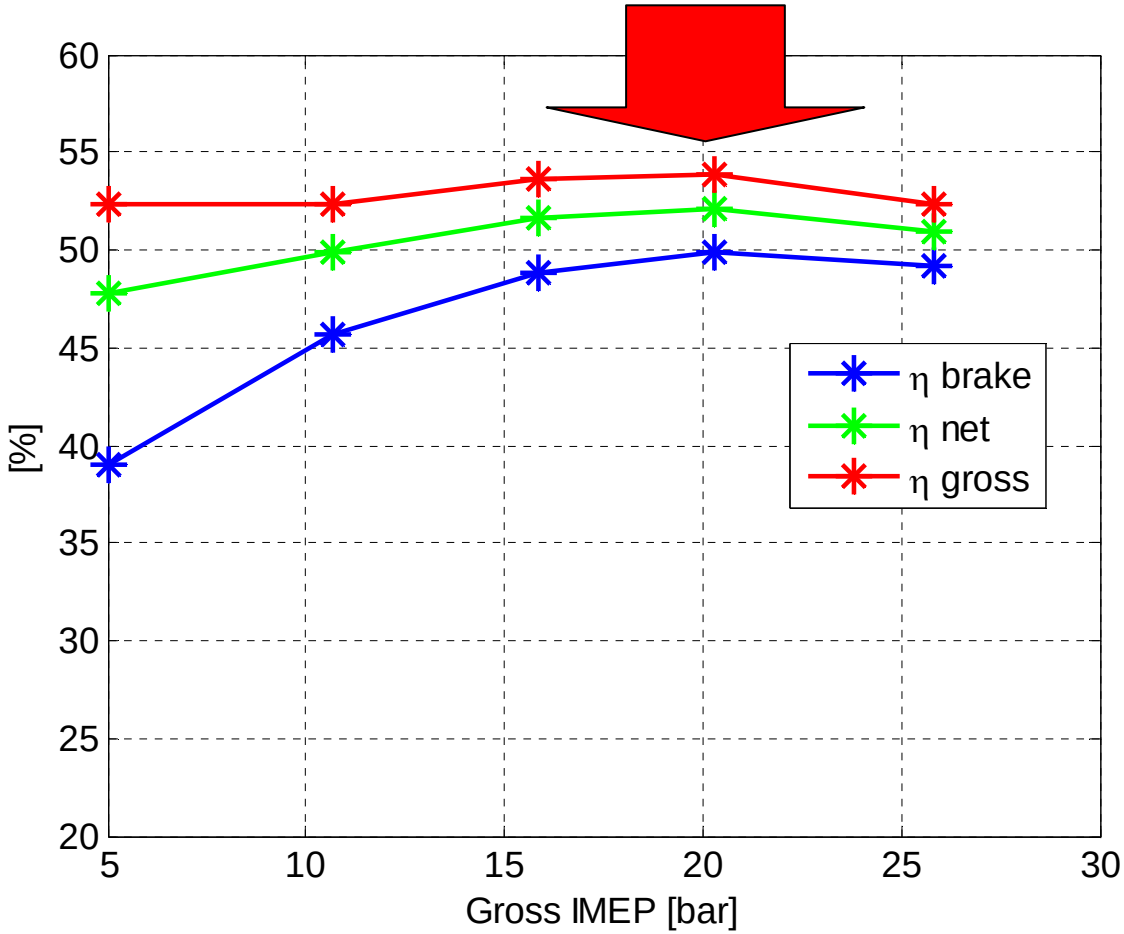


XPI Common Rail		
Orifices	8	[-]
Orifice Diameter	0.19	[mm]
Umbrella Angle	148	[deg]
Engine / Dyno Spec		
BMEPmax	25	[bar]
Vd	2124	[cm3]
Swirl ratio	2.095	[-]

Standard piston bowl, rc: 17.3:1

Efficiency

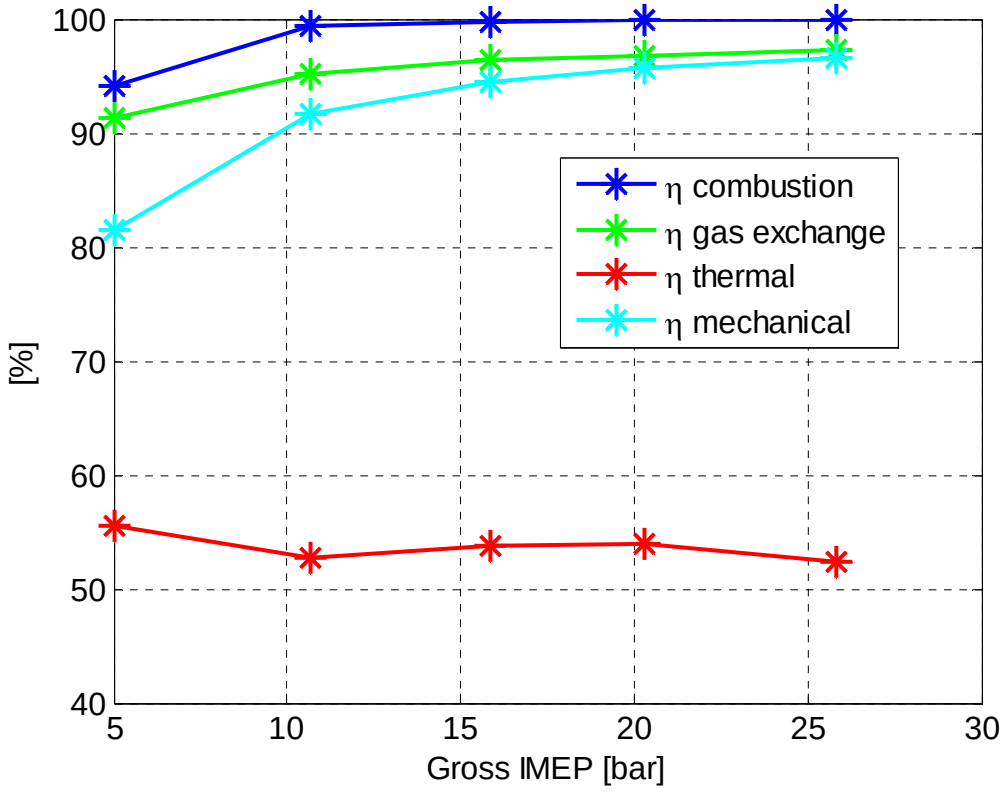
50% brake efficiency seems viable!!!



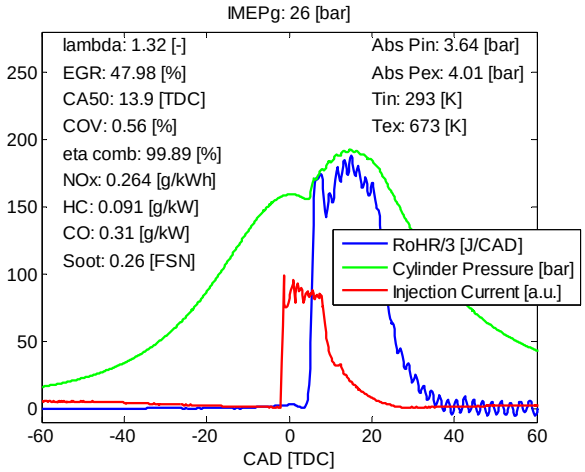
Efficiency

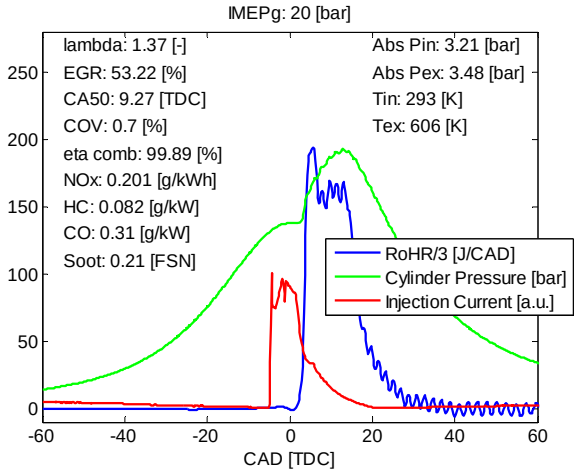
50% brake efficiency ➔ maximization of all intermediate efficiencies

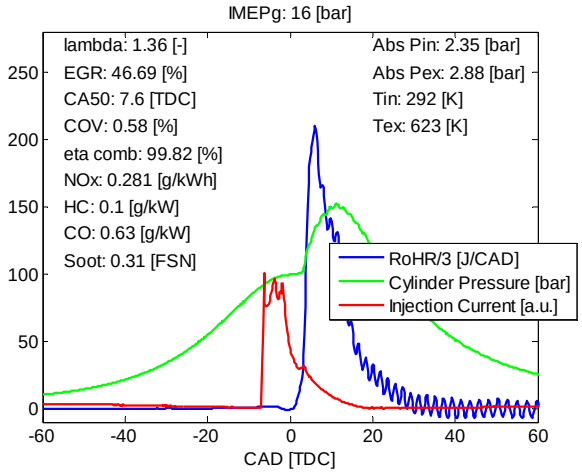
$$\eta_{Brake} = \eta_{Combustion} \cdot \eta_{Thermodynamic} \cdot \eta_{GasExchange} \cdot \eta_{Mechanical}$$

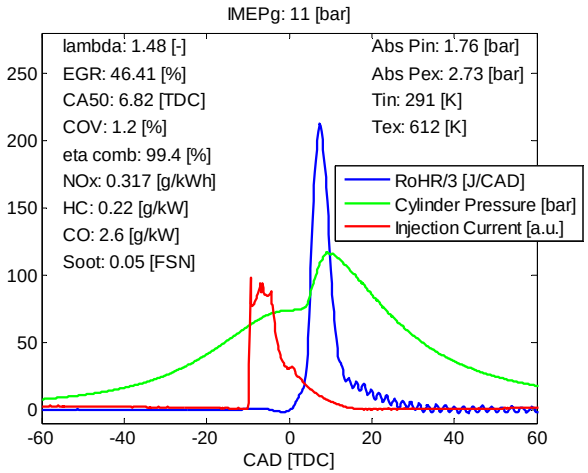


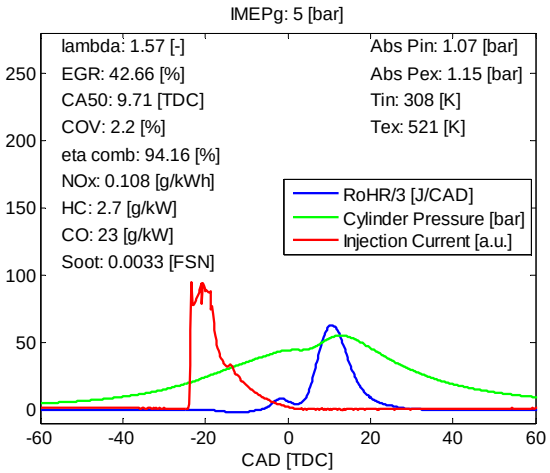
RoHR, Cylinder Pressure & Injection Signal



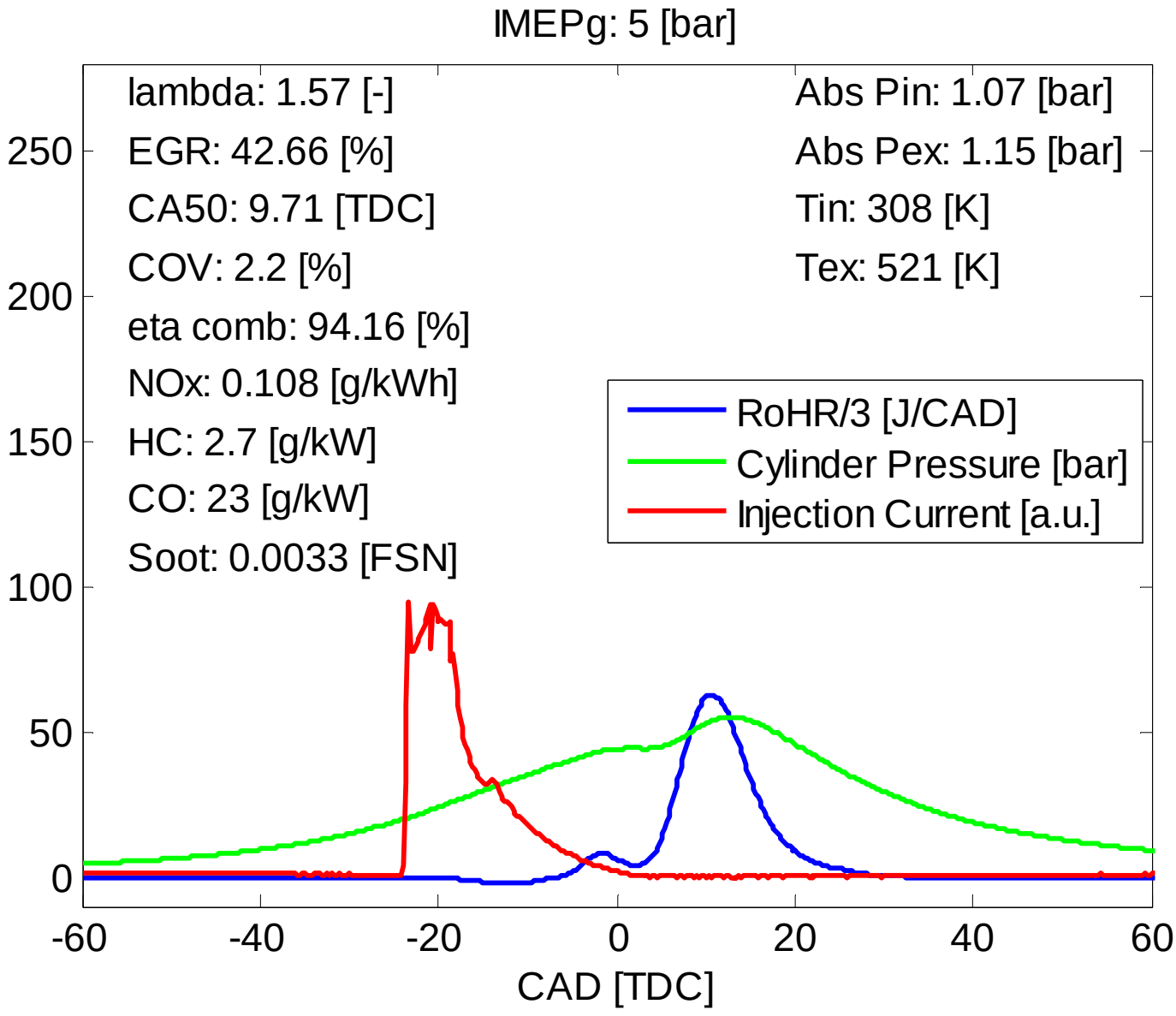




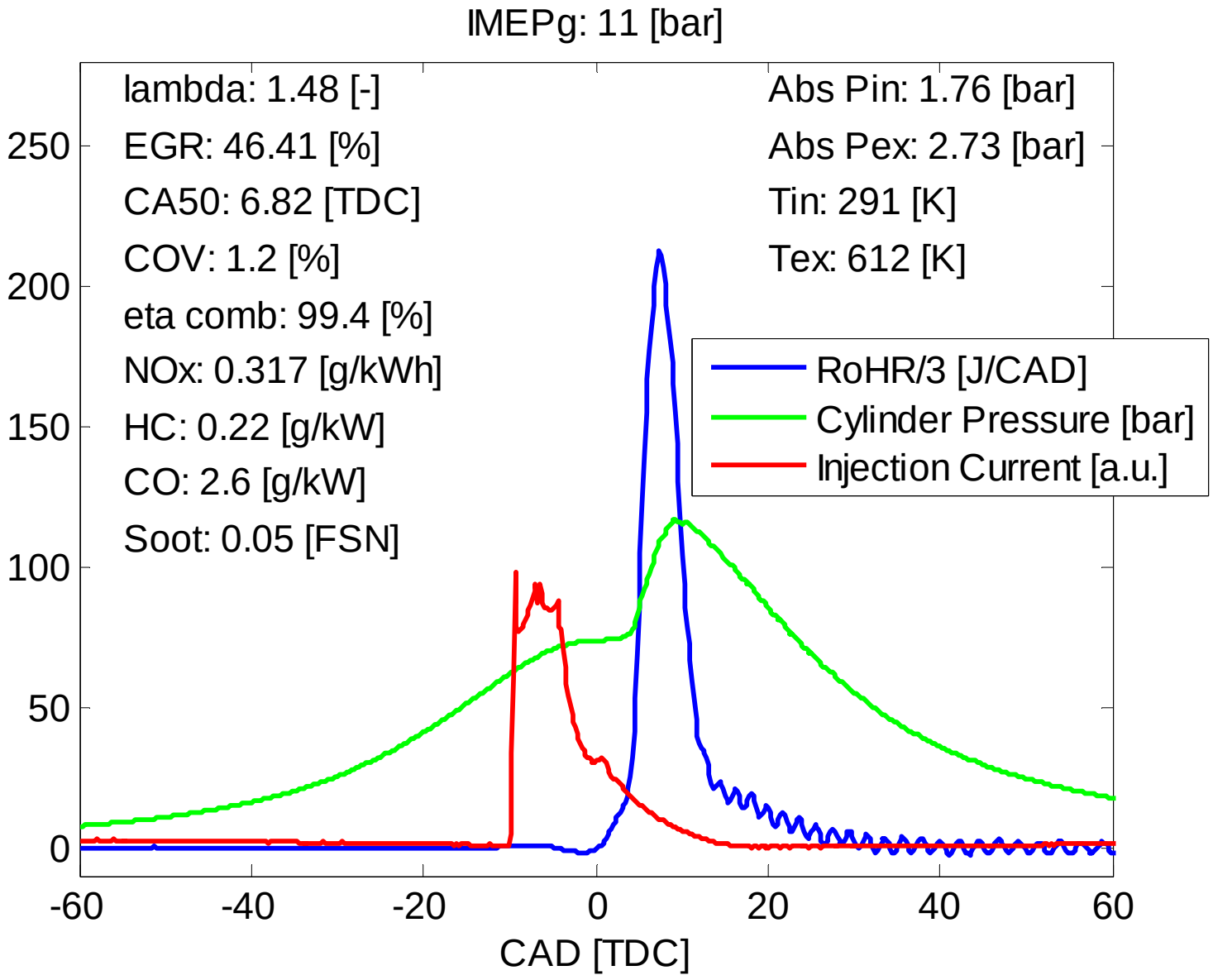




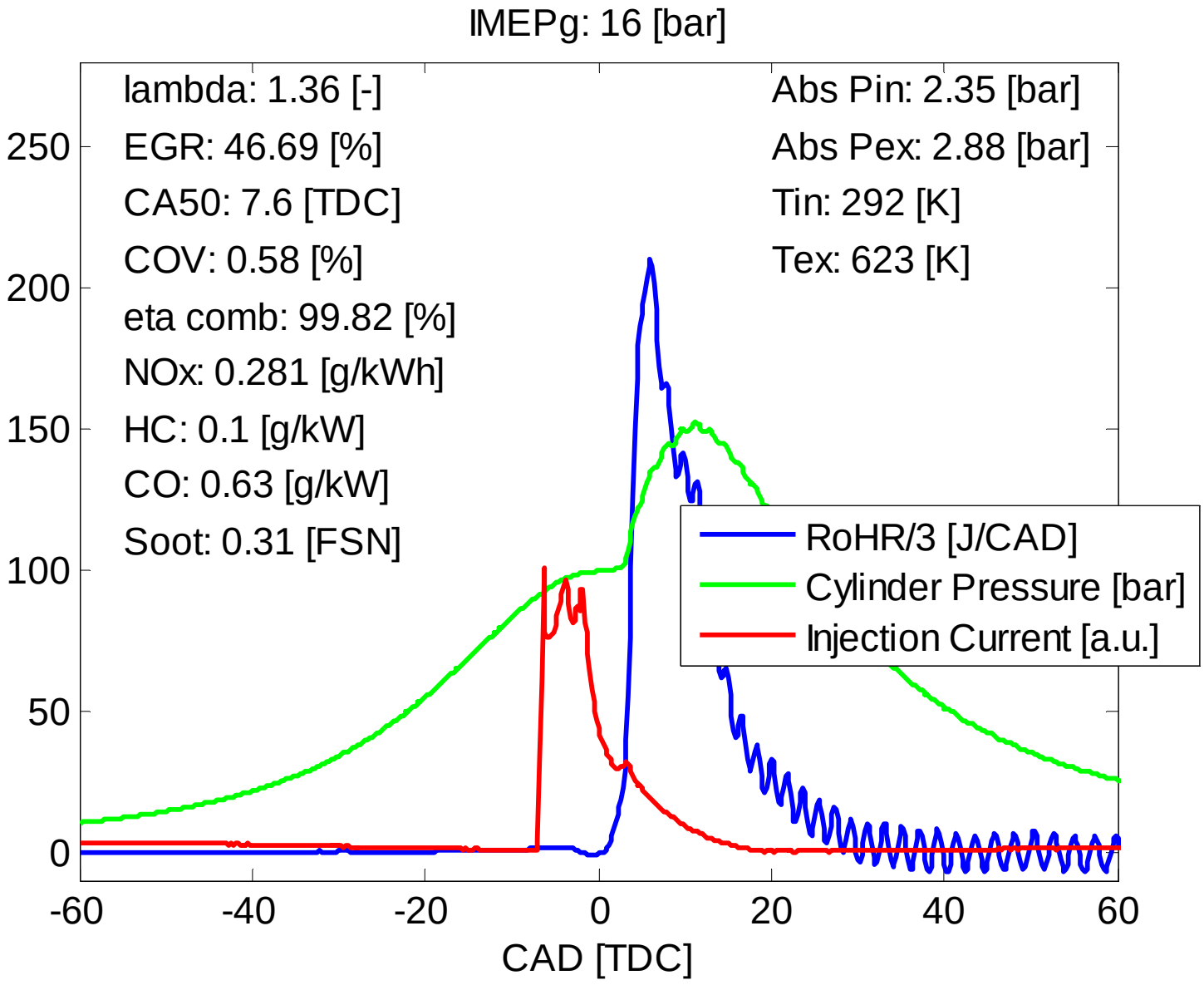
RoHR, Cylinder Pressure & Injection Signal



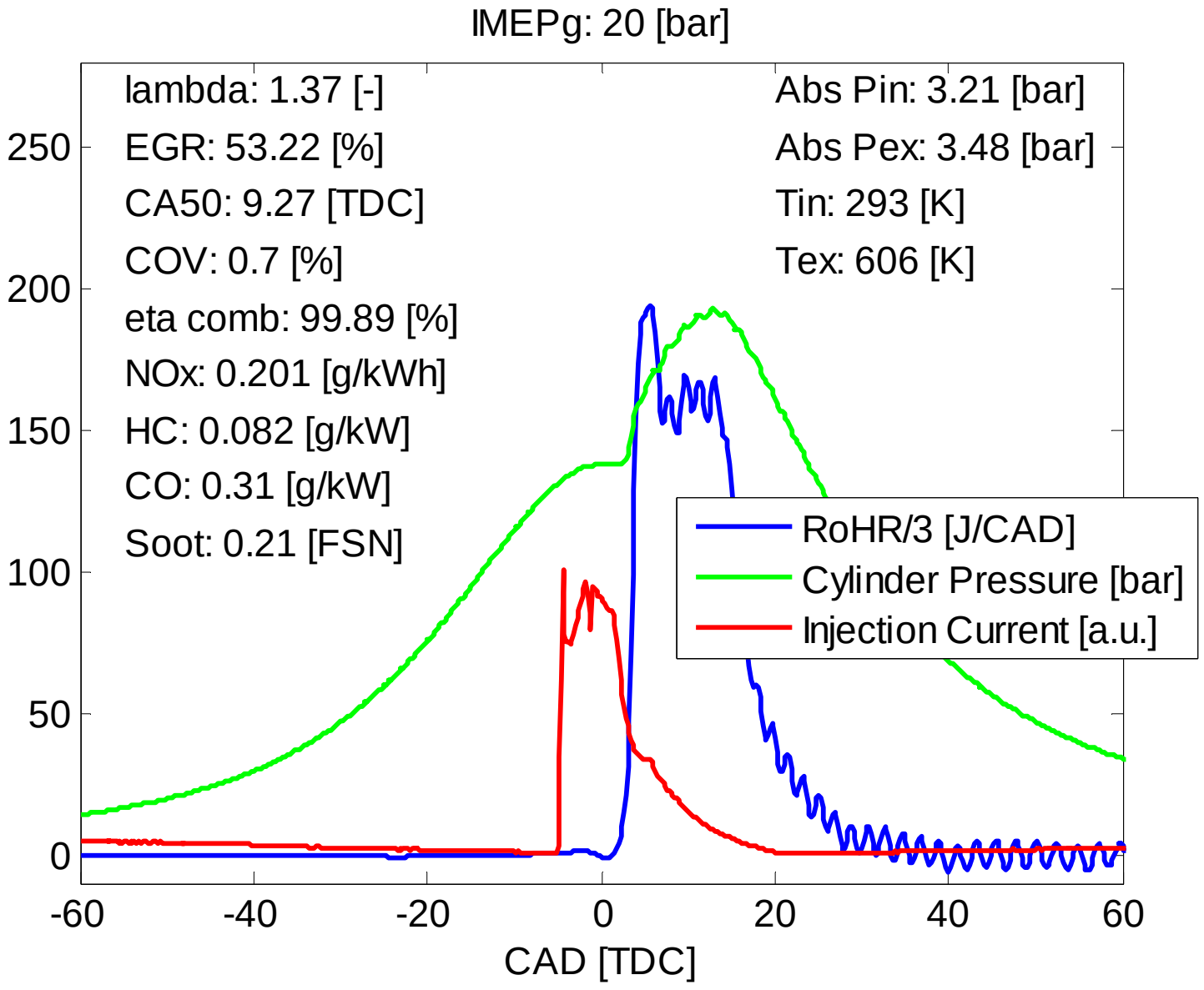
RoHR, Cylinder Pressure & Injection Signal



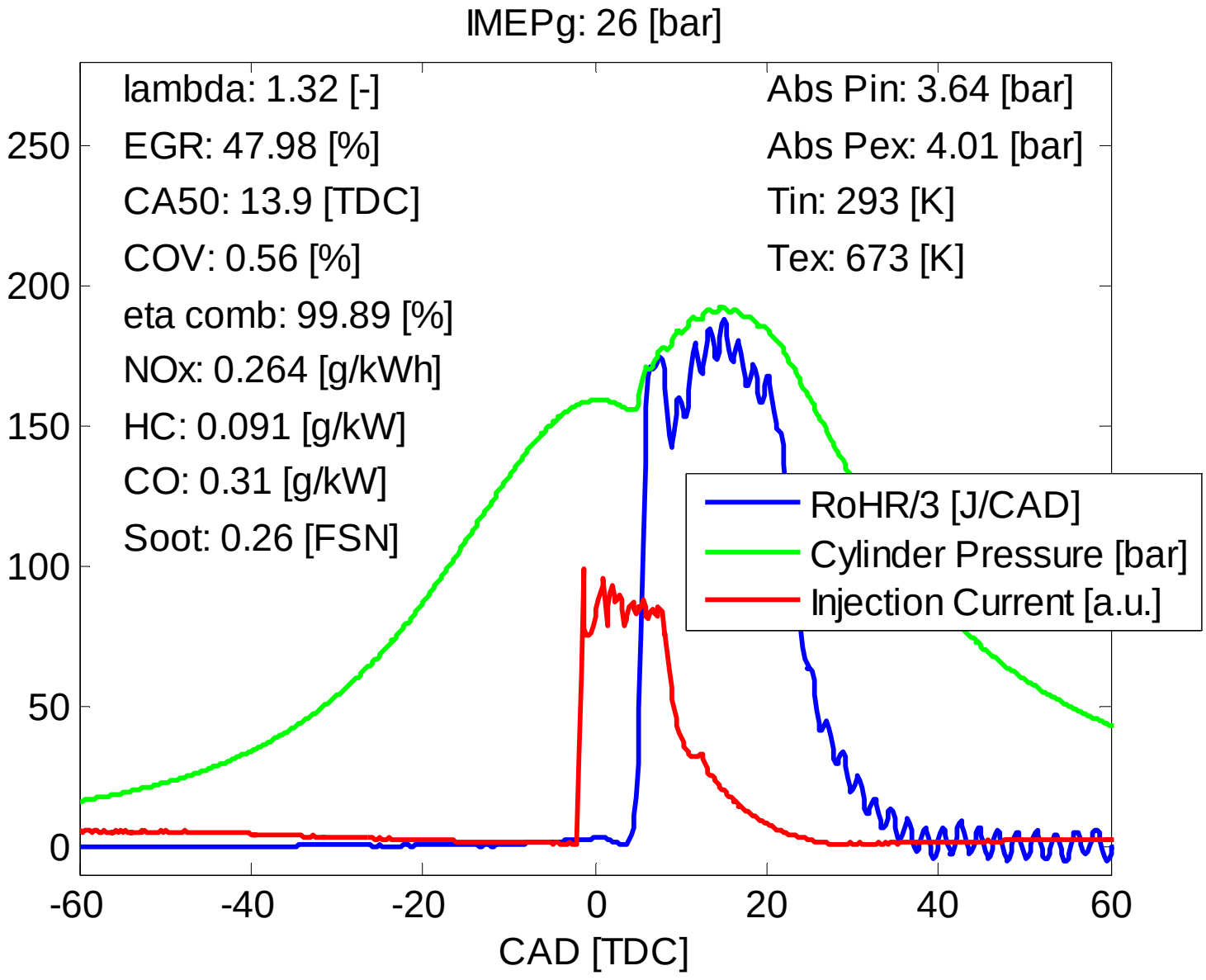
RoHR, Cylinder Pressure & Injection Signal



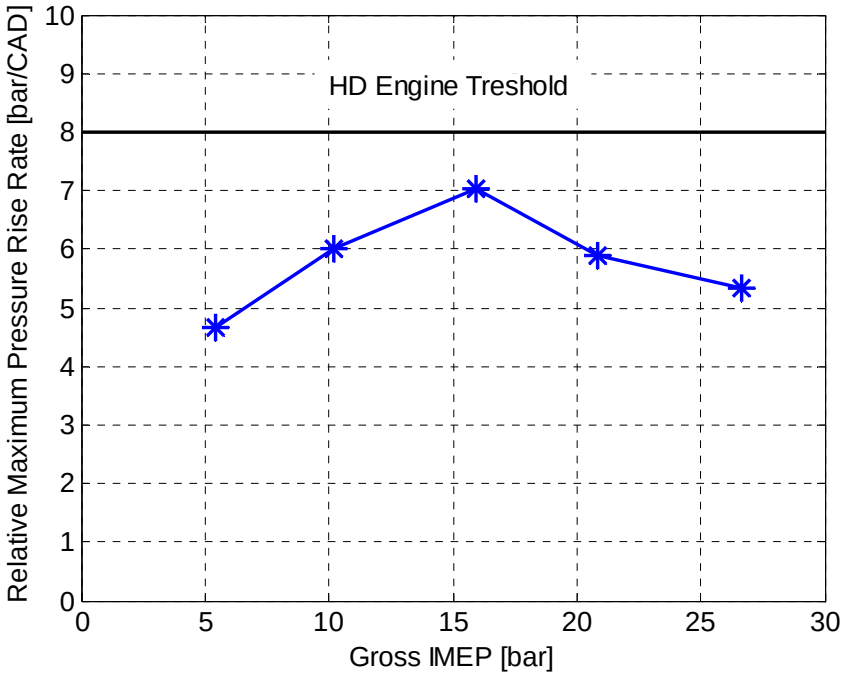
RoHR, Cylinder Pressure & Injection Signal

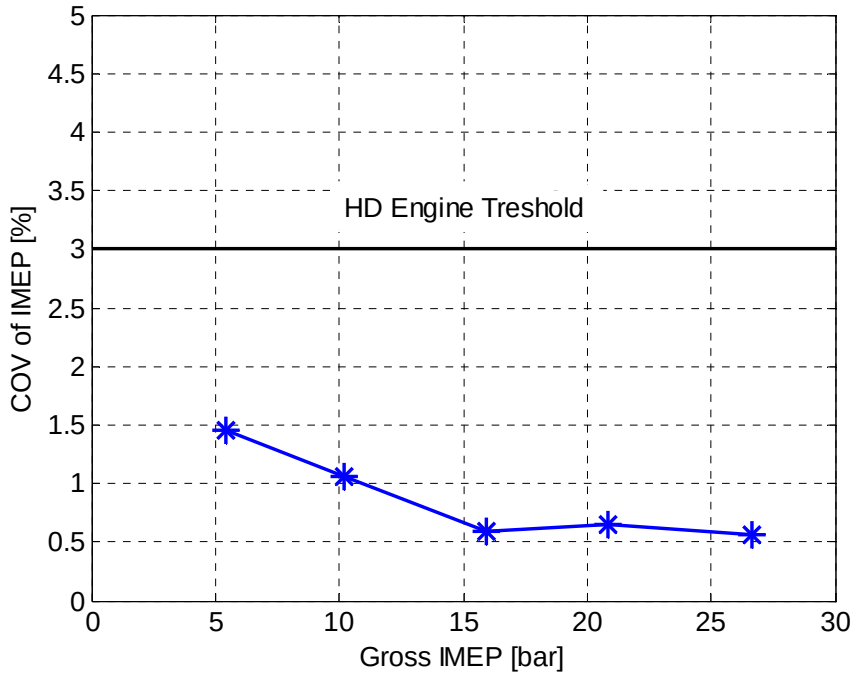


RoHR, Cylinder Pressure & Injection Signal

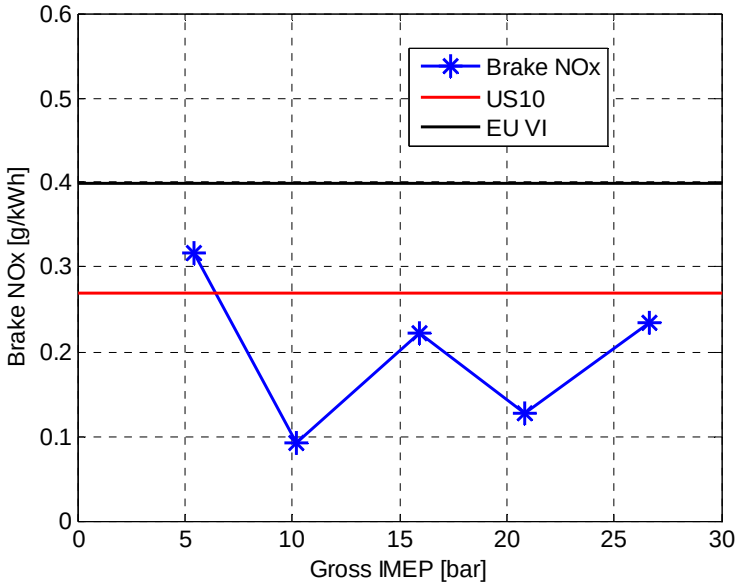


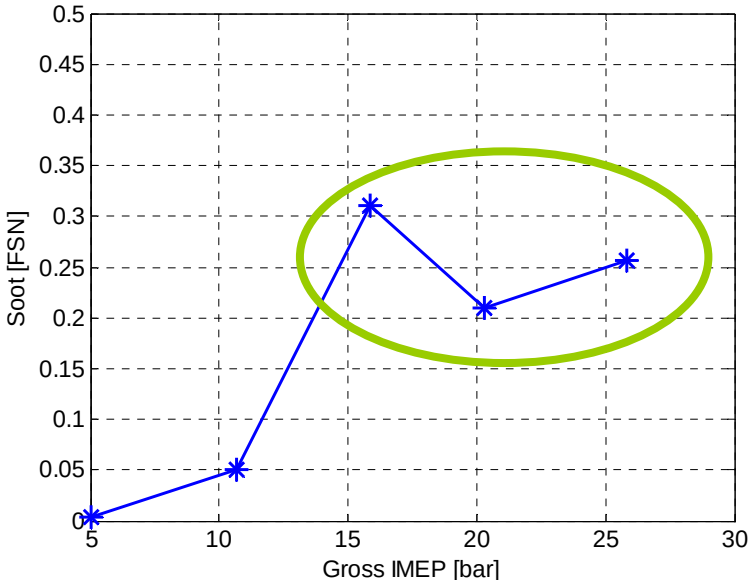
Combustion Noise & Stability

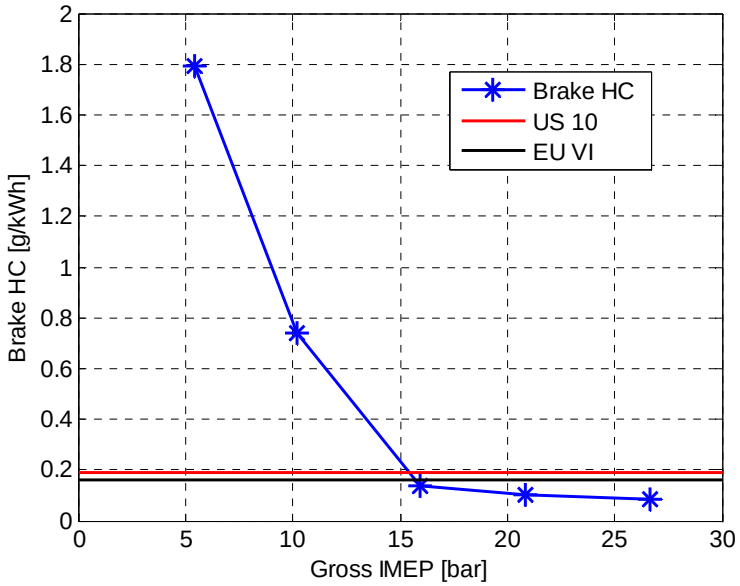


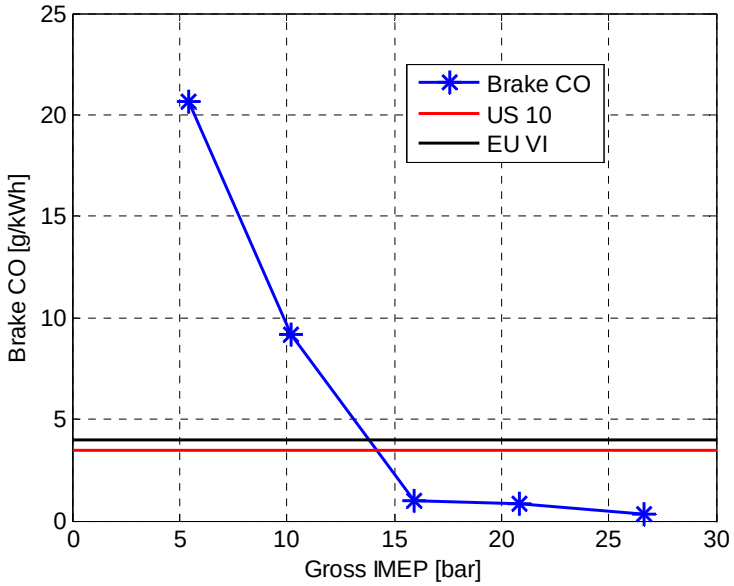


Emissions


Brake NOx
US10
EU VI
Brake NOx [g/kWh]
Gross IMEP [bar]


Soot [FSN]
Gross IMEP [bar]


Brake HC
US 10
EU VI
Brake HC [g/kWh]
Gross IMEP [bar]


Brake CO
US 10
EU VI
Brake CO [g/kWh]
Gross IMEP [bar]

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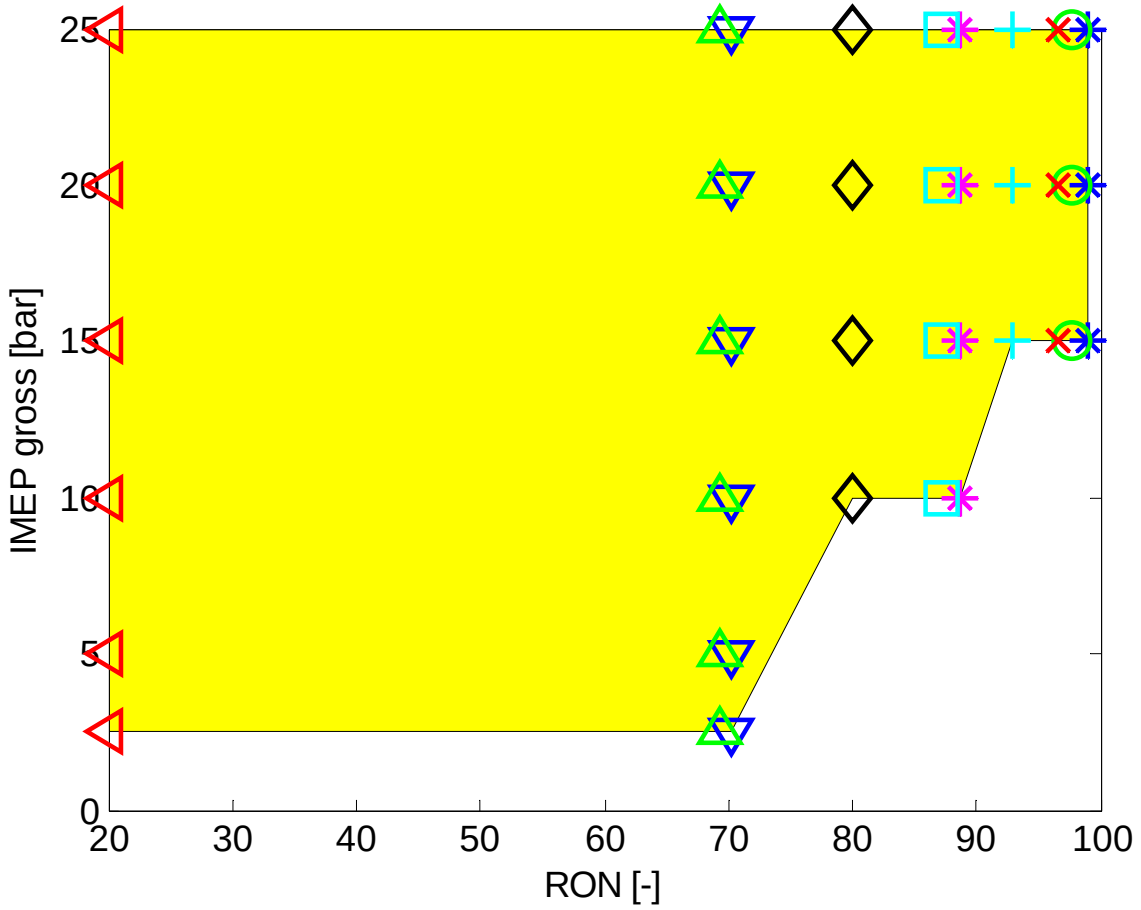
Fuel Matrix

		RON	MON	C	H/C	O/C	LHV [MJ/kg]	A/F stoich
Group 1	FR47335CVX	99.0	96.9	7.04	2.28	0.00	44.30	15.10
	FR47332CVX	97.7	87.5	6.61	2.06	0.07	39.70	13.44
	FR47337CVX	96.5	86.1	7.53	1.53	0.00	42.10	14.03
Group 2	FR47338CVX	88.6	79.5	7.21	1.88	0.00	43.50	14.53
	FR47330CVX	87.1	80.5	7.20	1.92	0.00	43.50	14.60
	FR47331CVX	92.9	84.7	6.90	1.99	0.03	41.60	14.02
Group 3	FR47336CVX	70.3	65.9	7.10	2.08	0.00	43.80	14.83
	FR47334CVX	69.4	66.1	7.11	1.98	0.00	43.80	14.68
	FR47333CVX	80.0	75.0	7.16	1.97	0.00	43.70	14.65
Group 4	PRF20	20	20	7.2	2.28	0	44.51	15.07
	MK1	n.a.	20	16	1.87	0	43.15	14.9

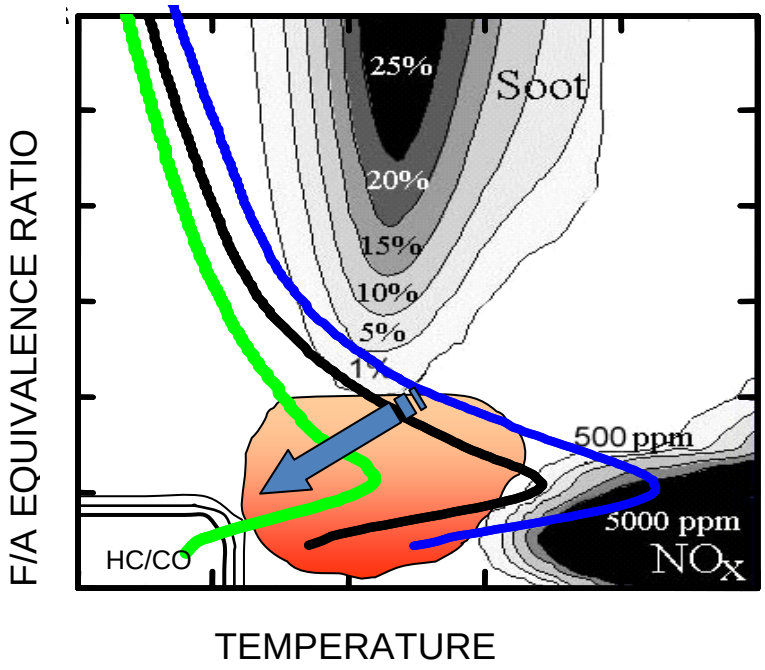
Results

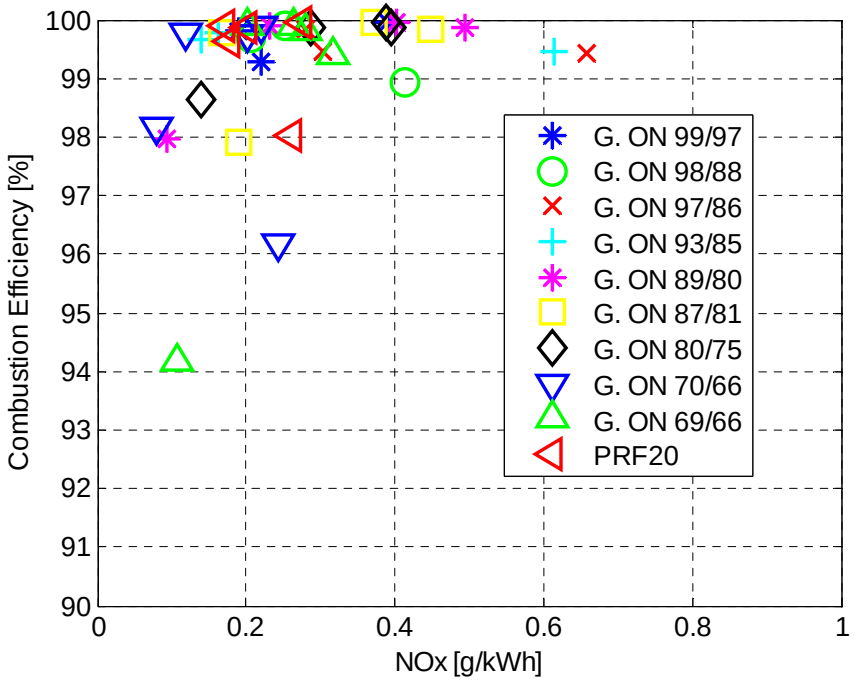
Tested Load Area

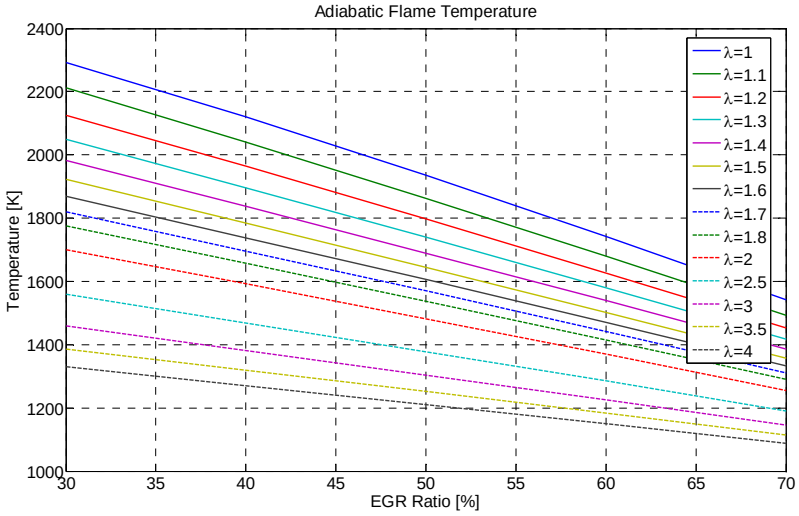
Stable operational load vs. fuel type



NOx - η_{comb} Trade – Off Solution

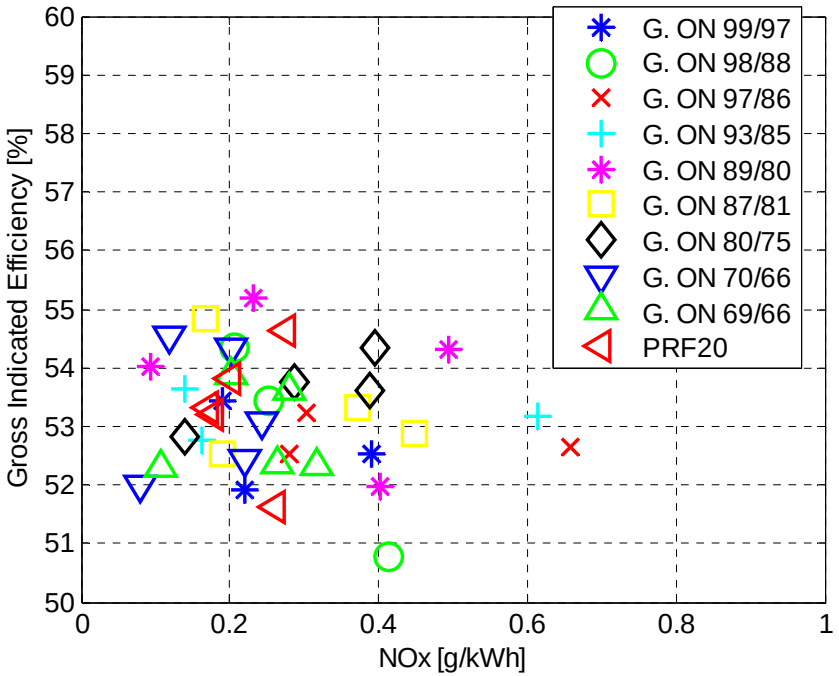


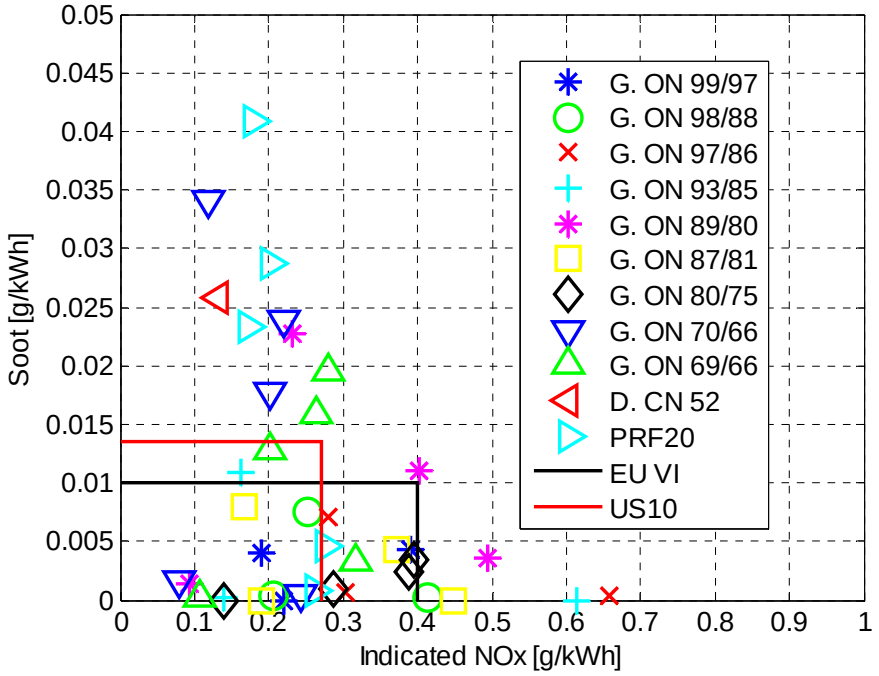




It is possible to achieve low NOx and still keep high combustion efficiency in the whole load range!

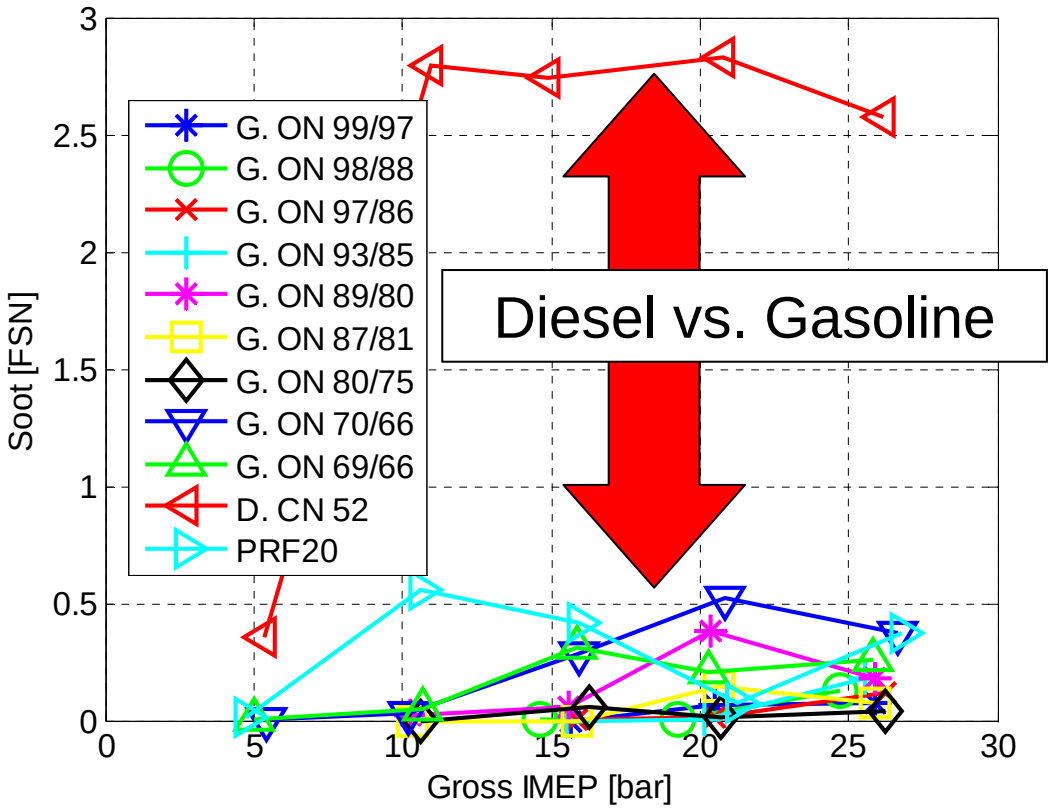
Efficiency & Emissions



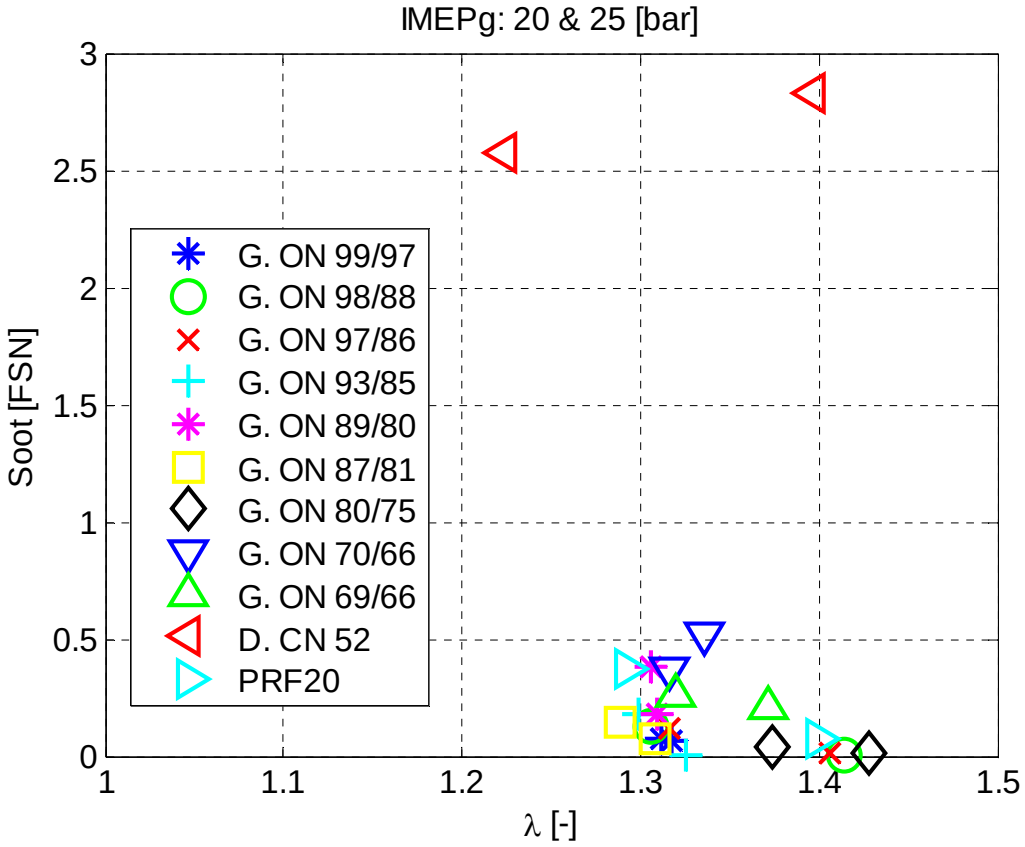


In certain operating range, some fuels are capable to comply EU VI & US10 legislations and still keep high efficiency without compromising the efficiency!

Soot Emissions

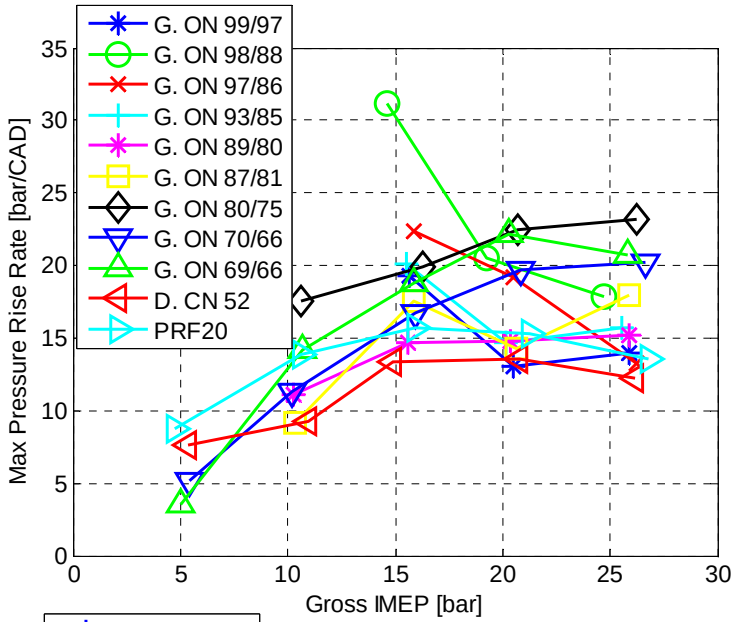


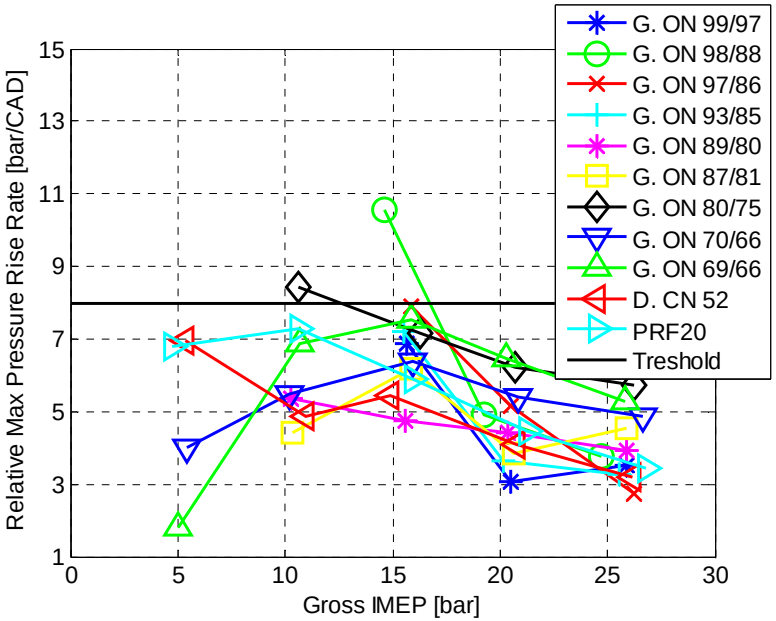
Higher Power Density

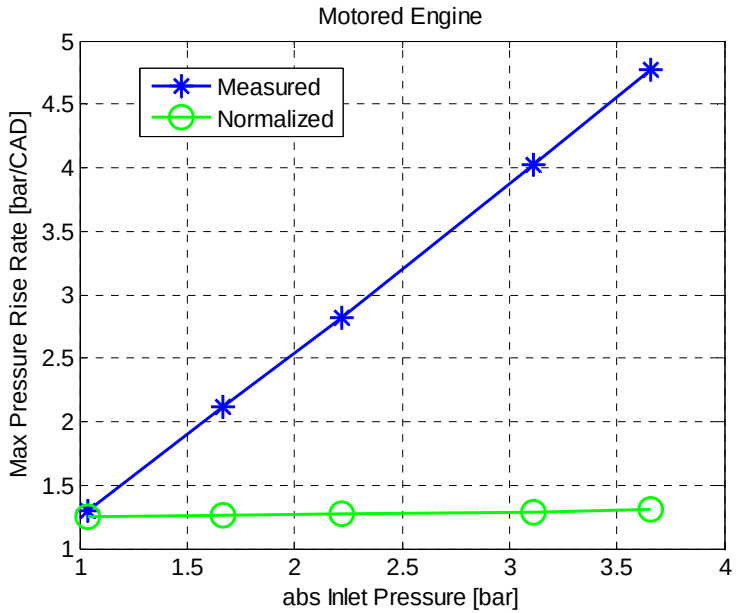


Low soot even @ λ 1.3 ➔ higher power density without producing smoke!

Acoustic Noise

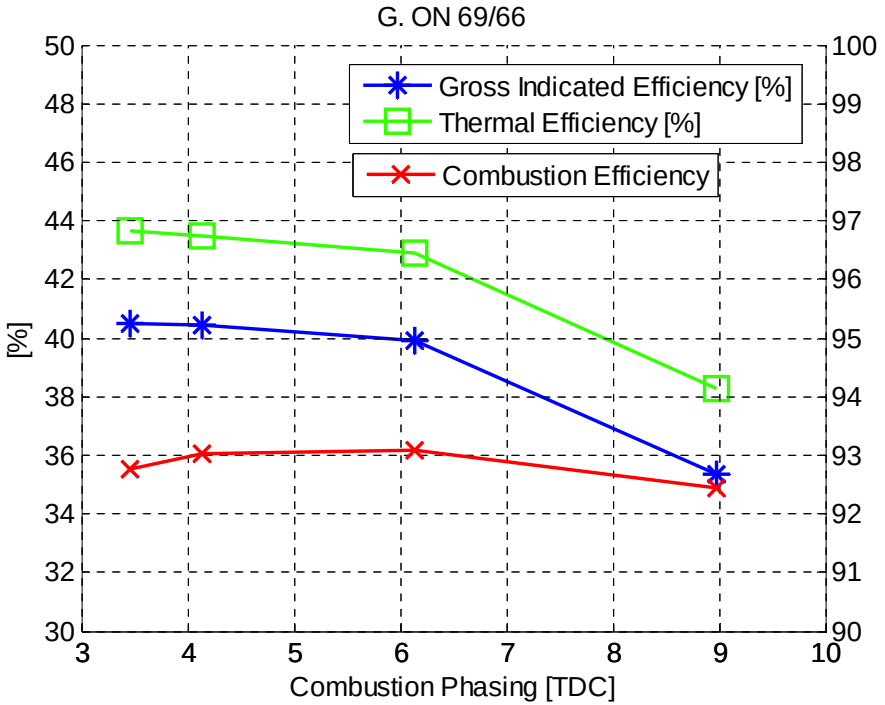


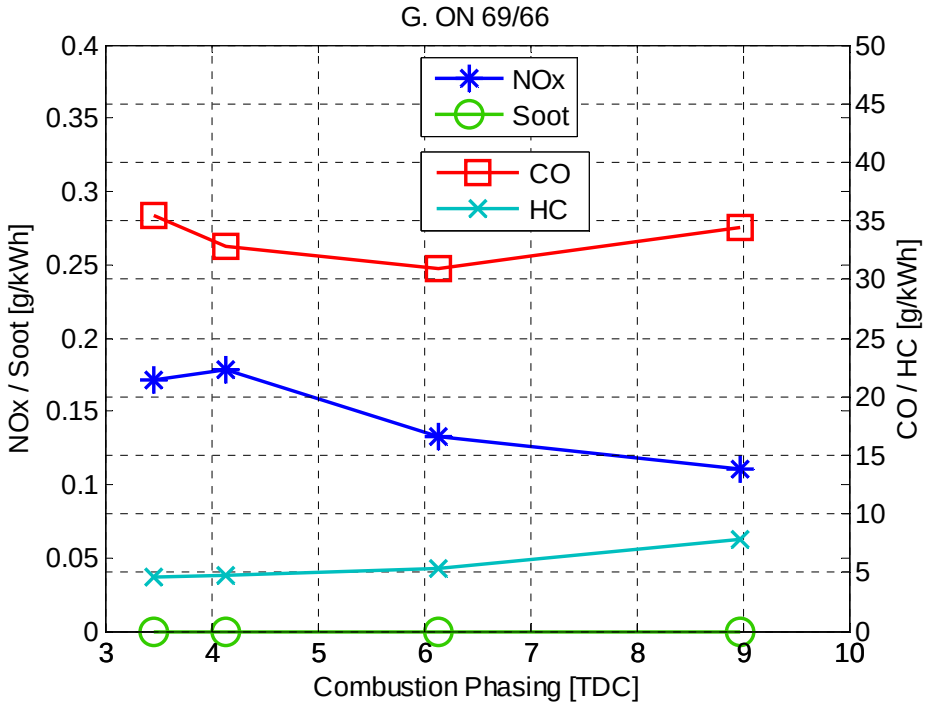




Idle

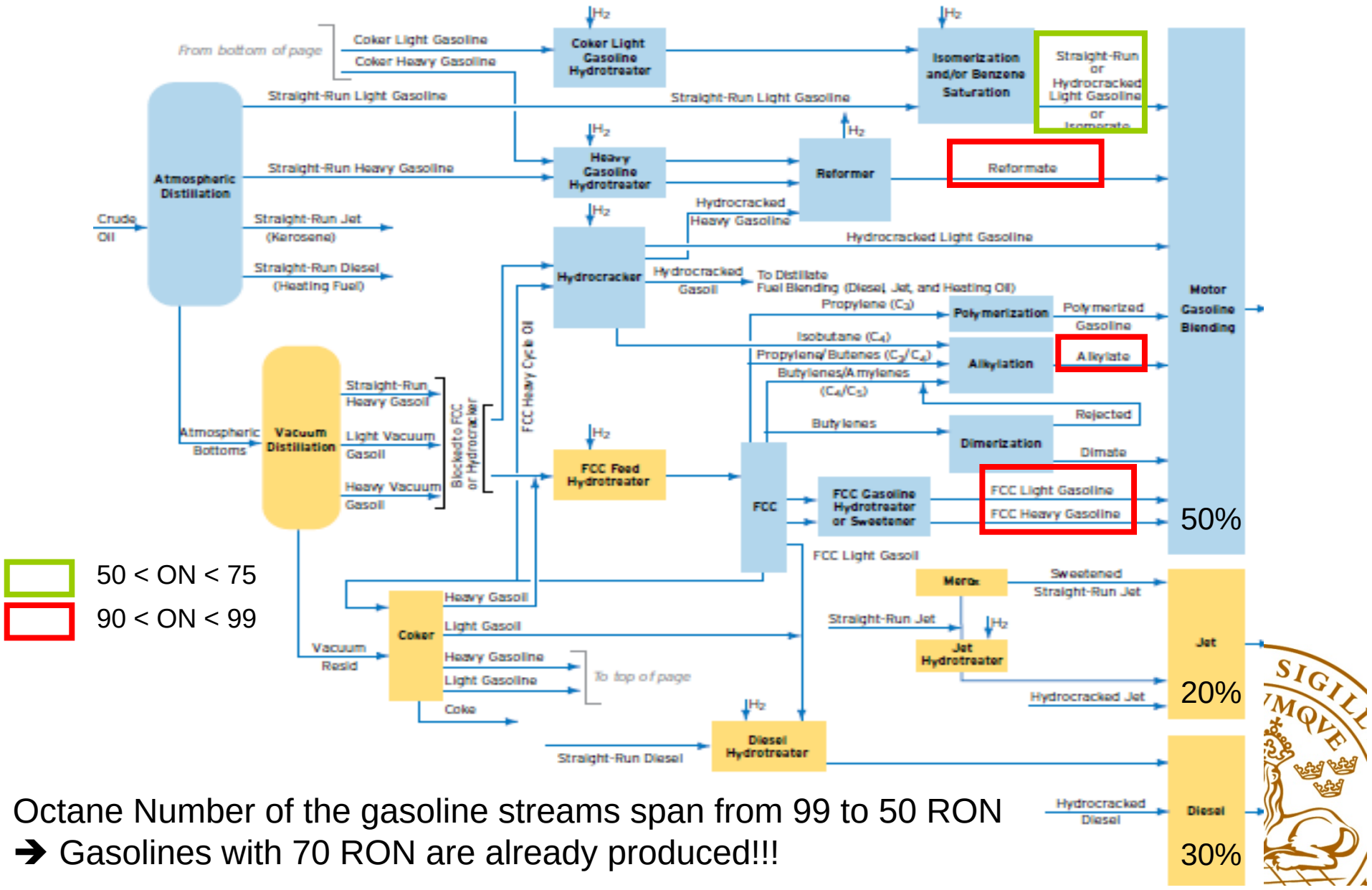
Efficiencies & Emissions





Viability of Low ON Gasolines for PPC?

Oil Refineries Production Layout



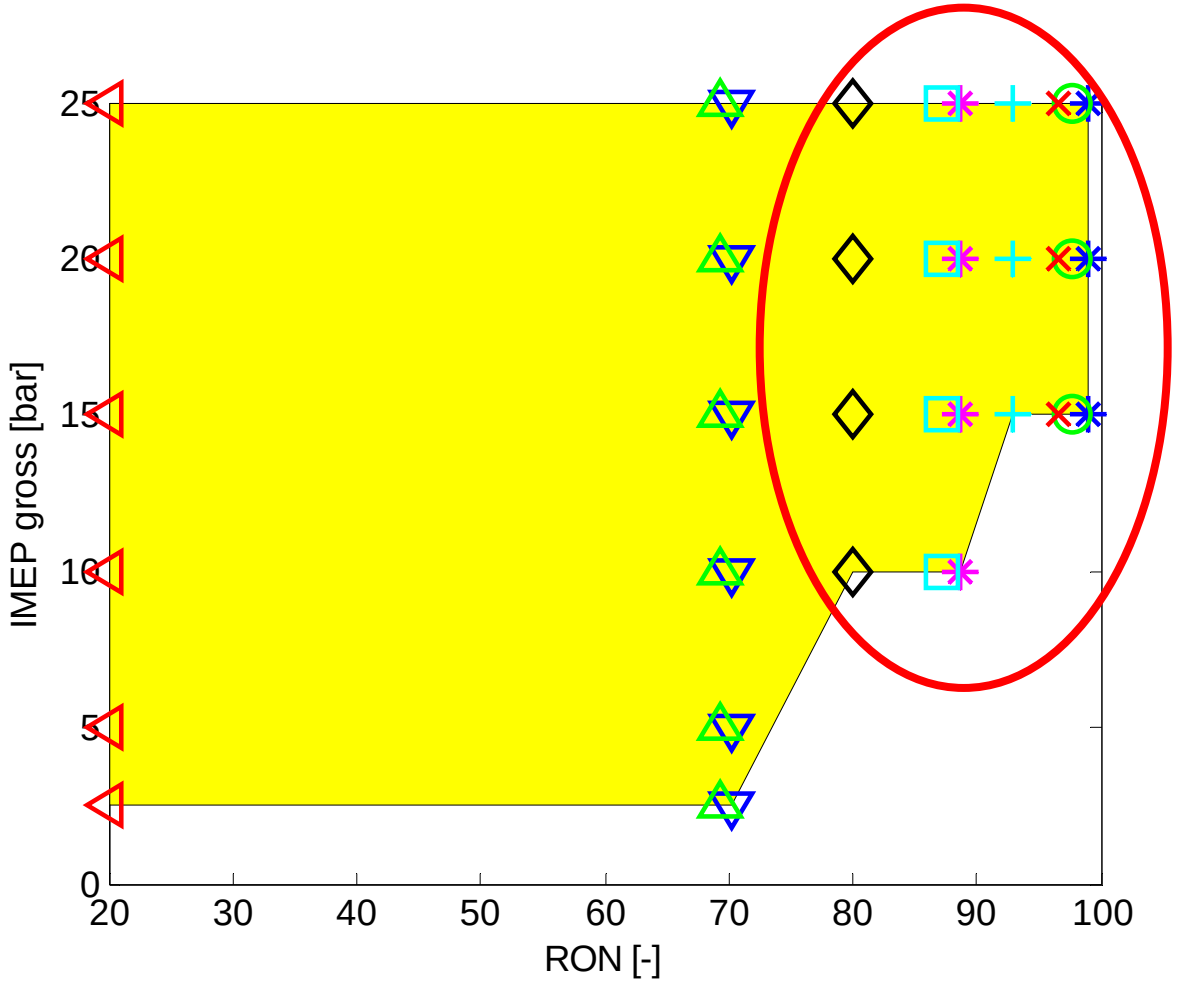
Octane Number of the gasoline streams span from 99 to 50 RON

➔ Gasolines with 70 RON are already produced!!!

Oil Refineries Perspectives

Oil refineries are a very stiff system and their kerosene, diesel and gasoline production can not be easily varied without major investments ➔ we need to build highly efficient vehicles with the available fuels…

High ON Gasolines in Scania D13

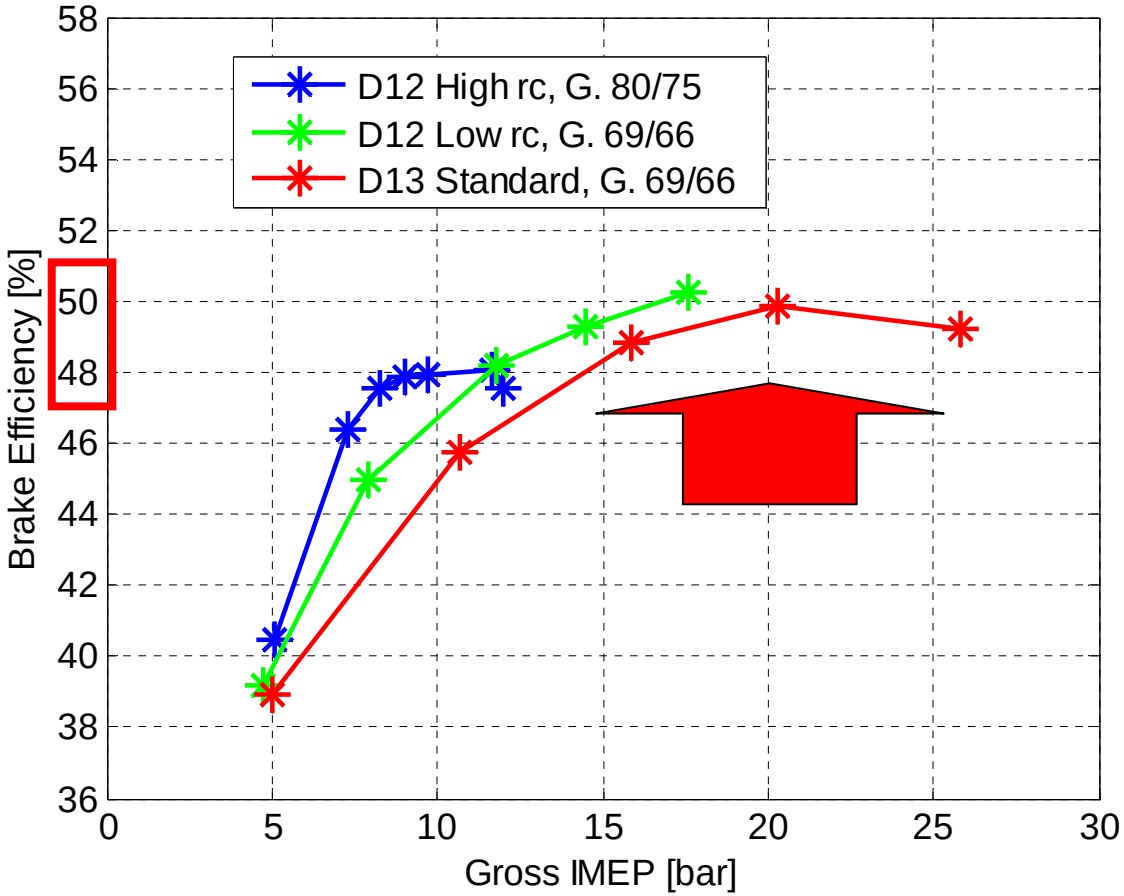


What to do with these fuels?!

Still to be used in SI engines?!

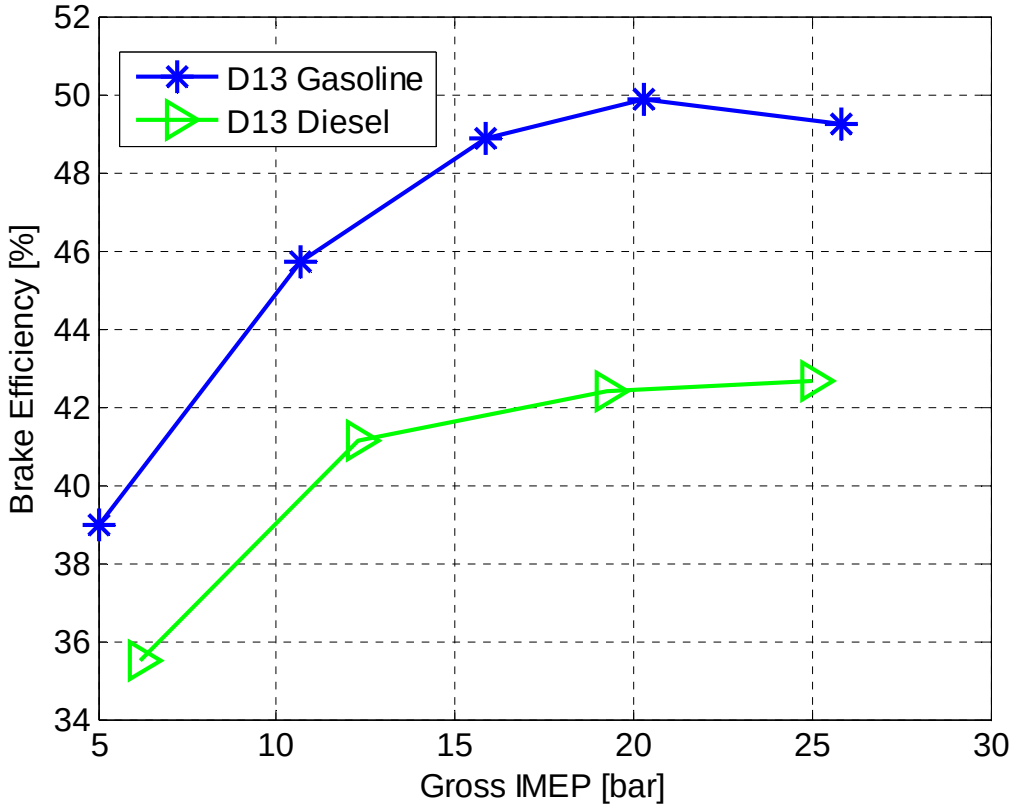
Summary

Brake Efficiency



Brake efficiency in the range of 48-50% seems to be viable between 12.5 and 26 bar gross IMEP.

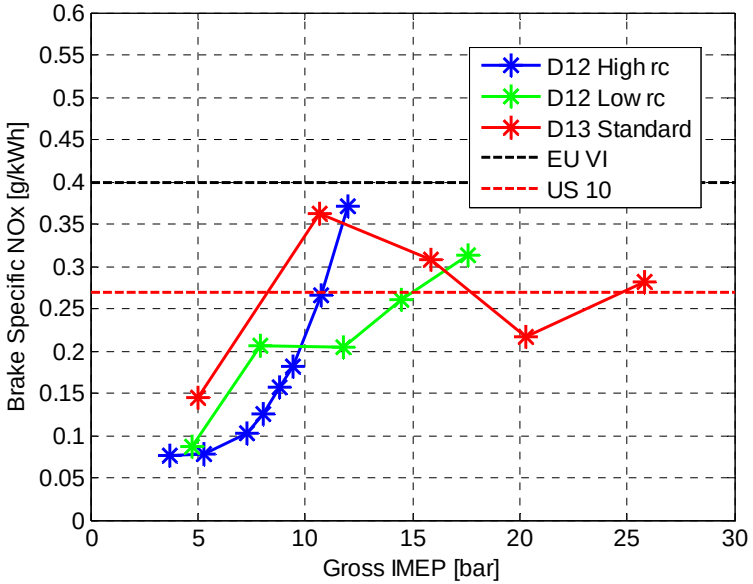
D13 Running on Diesel & Gasoline

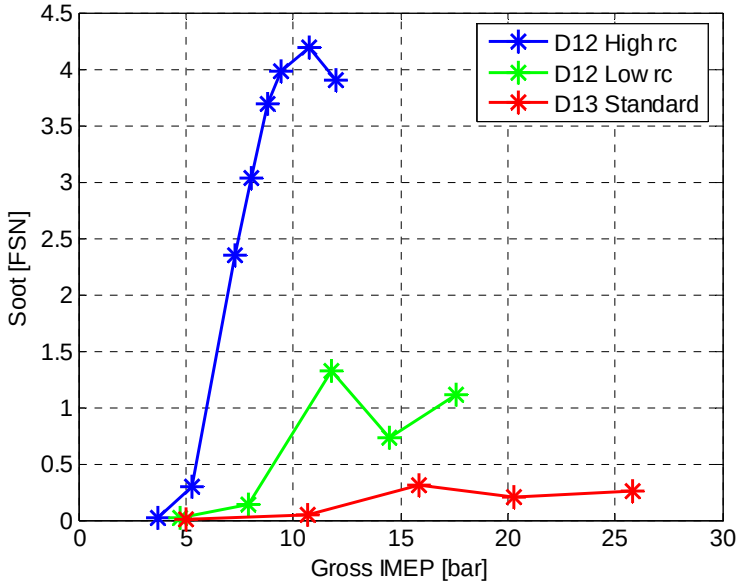


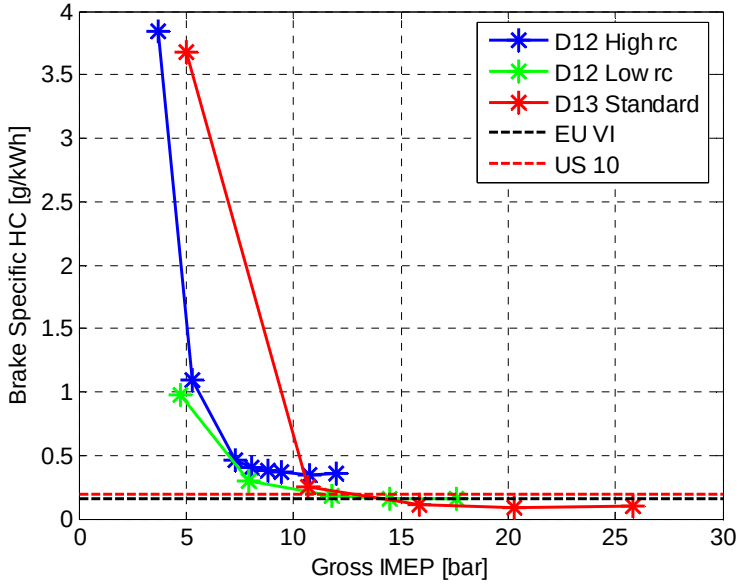
D13 Diesel was calibrated by Scania and the calibration was done to meet EU V legislation.

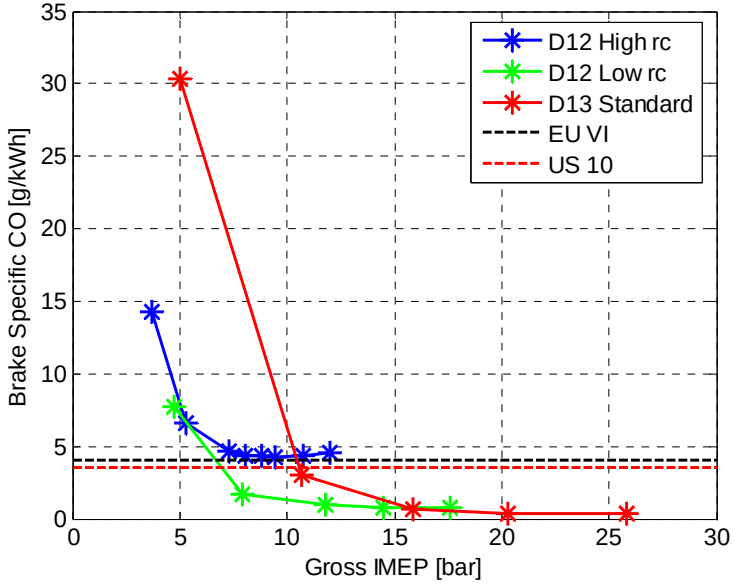
Average improvement of 16.6% points @ high load!!!

Brake Emissions

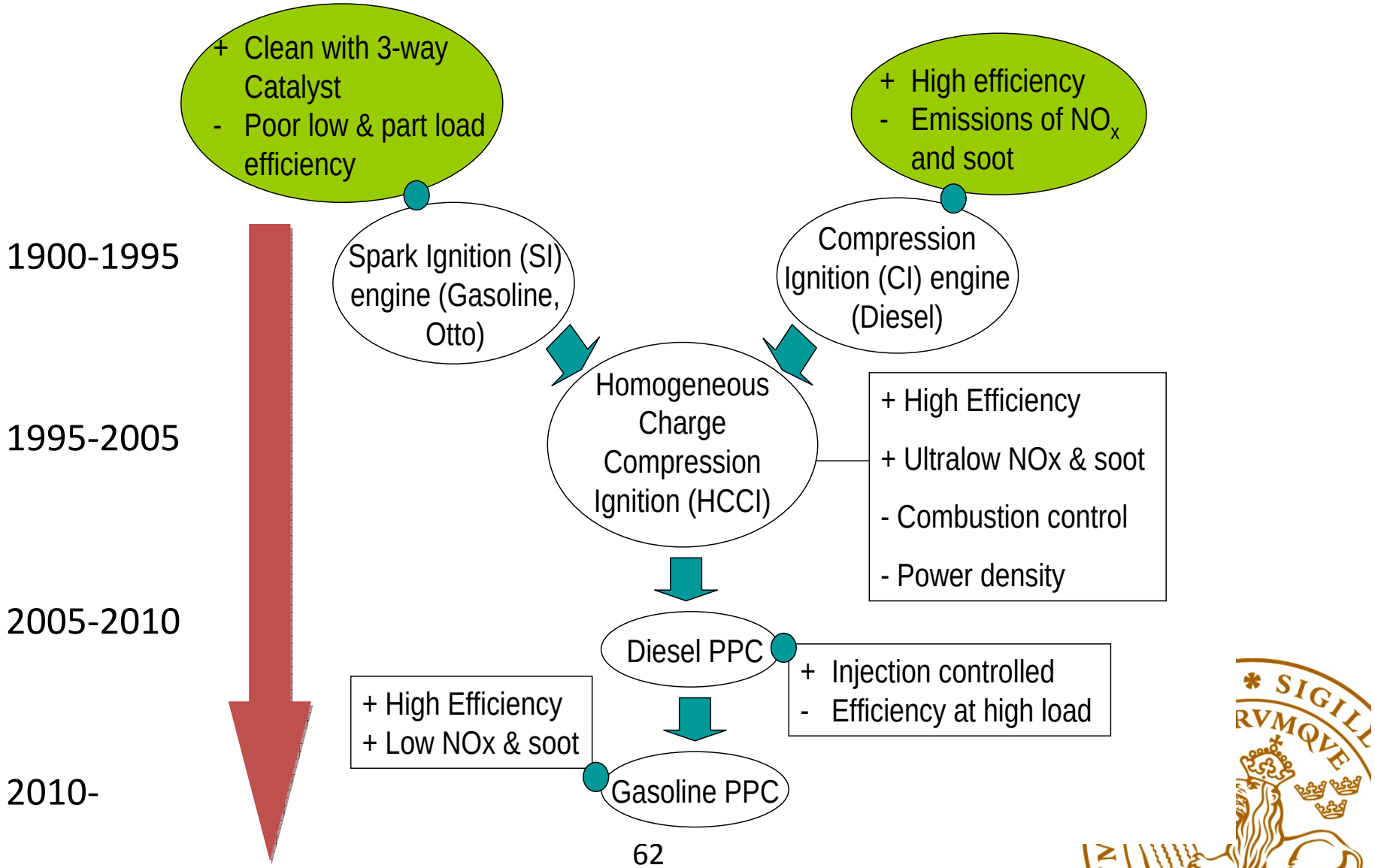








Engine combustion - direction



The End

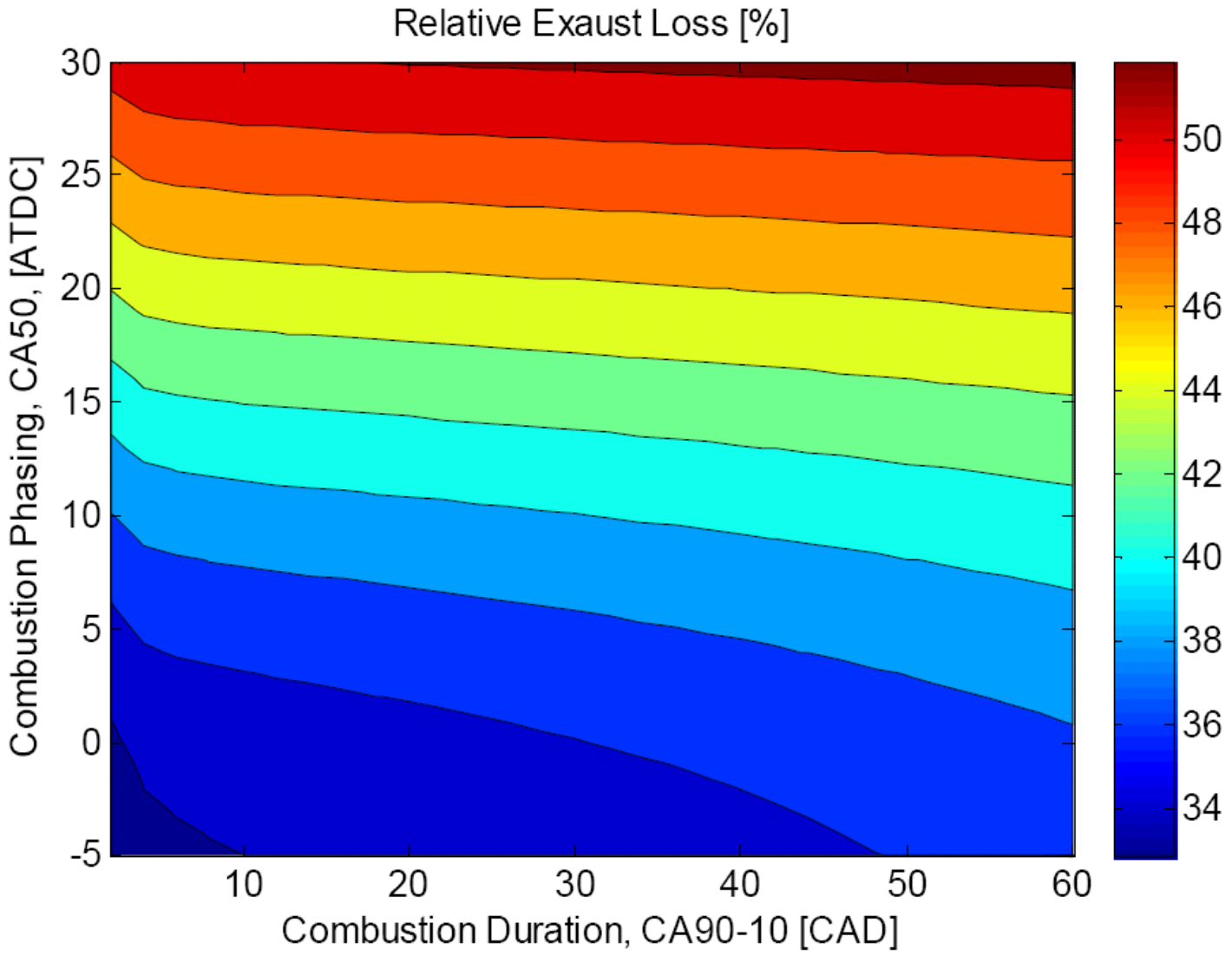
Thank you

Ideal burn rate?

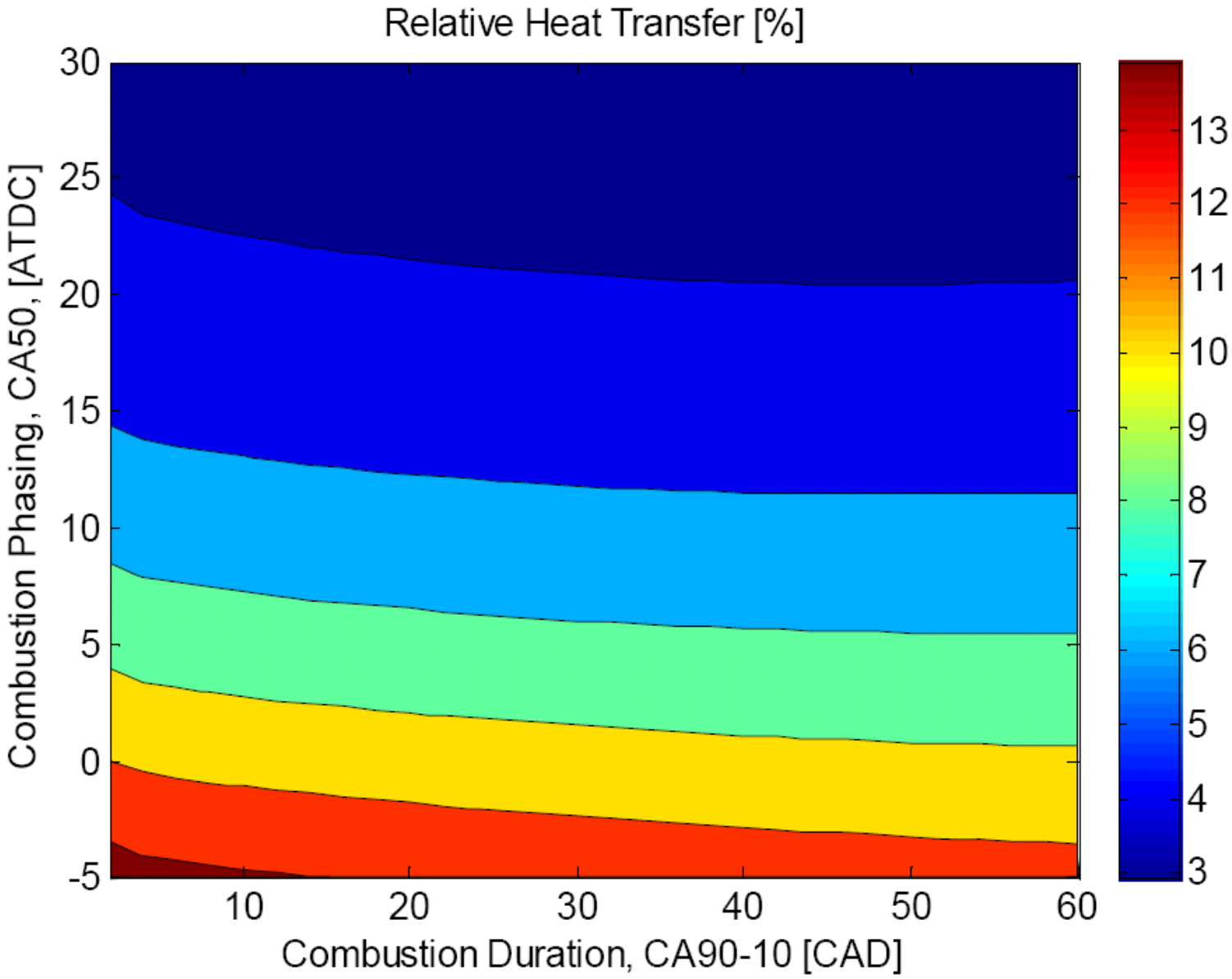
Conditions:

1. CA50: 8 [ATDC].
2. CA90-10: 15 [CAD].
3. Engine geometry: custom Scania D13.
4. Inlet temperature: 303 [K].
5. Reference temperature: 298 [K].
6. Engine speed: 1250 [rpm].
7. Differential pressure exhaust minus inlet: 0.25 [bar].
8. Cylinder wall temperature: 450 [K].
9. **Heat transferred modeled with the Woschni equation** and tuned to match the experimental results
10. **The rate of heat release has been approximated with a Wiebe function**.
11. EGR is added in order to have 1.35 as λ. If the inlet pressure was not enough to have λ without EGR higher than 1.35, EGR was set to zero.
12. The combustion efficiency was assumed to be 100%.
13. Lower heating value 43.8 MJ/kg, stoichiometric air fuel ratio 14.68.

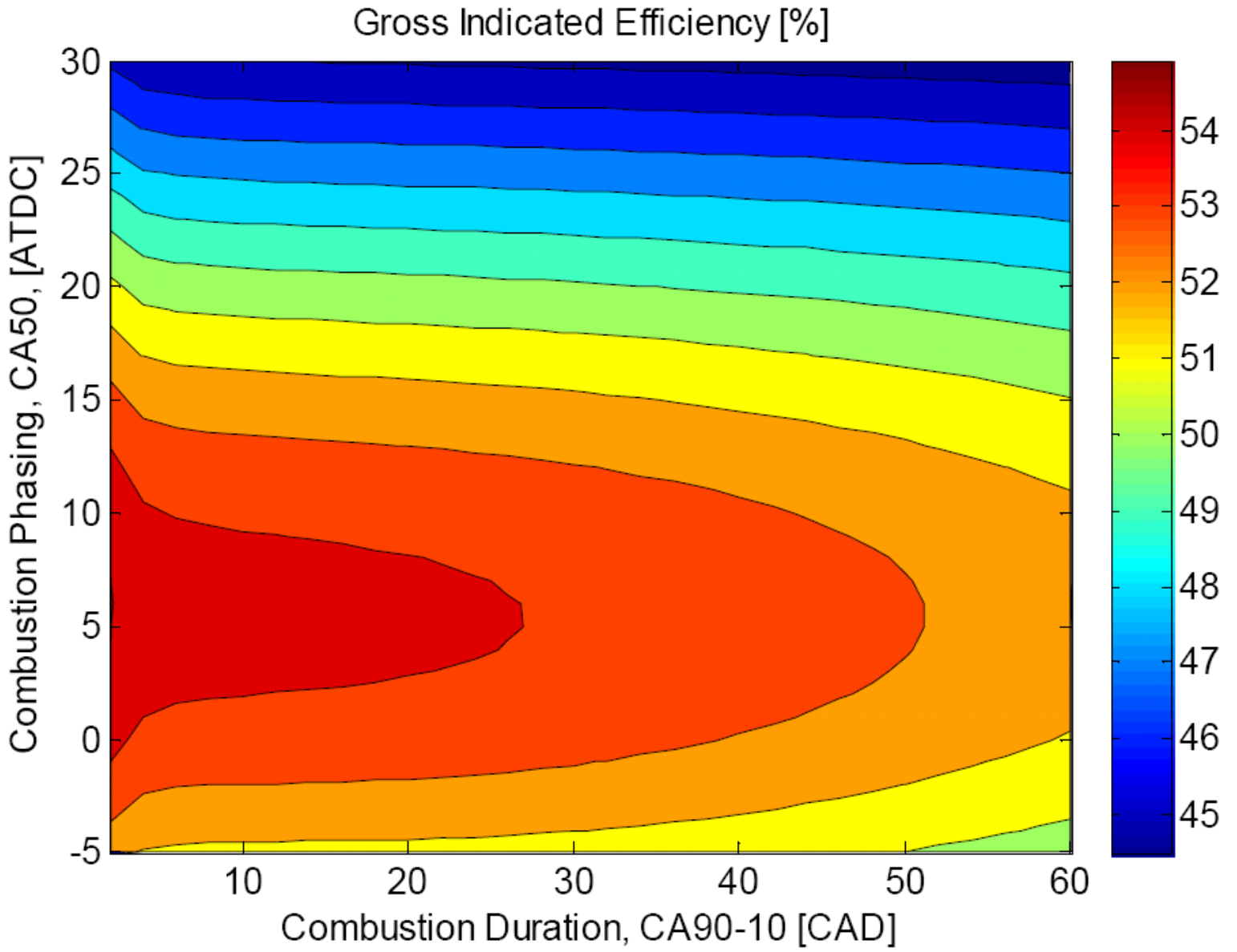
Exhaust Loss



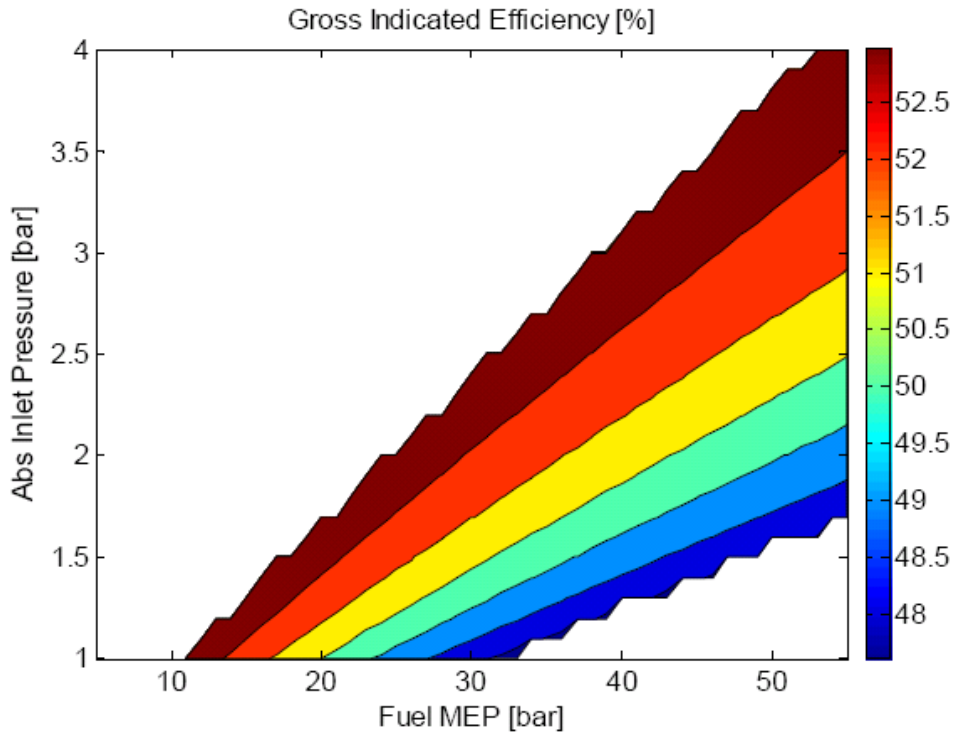
Heat transfer loss

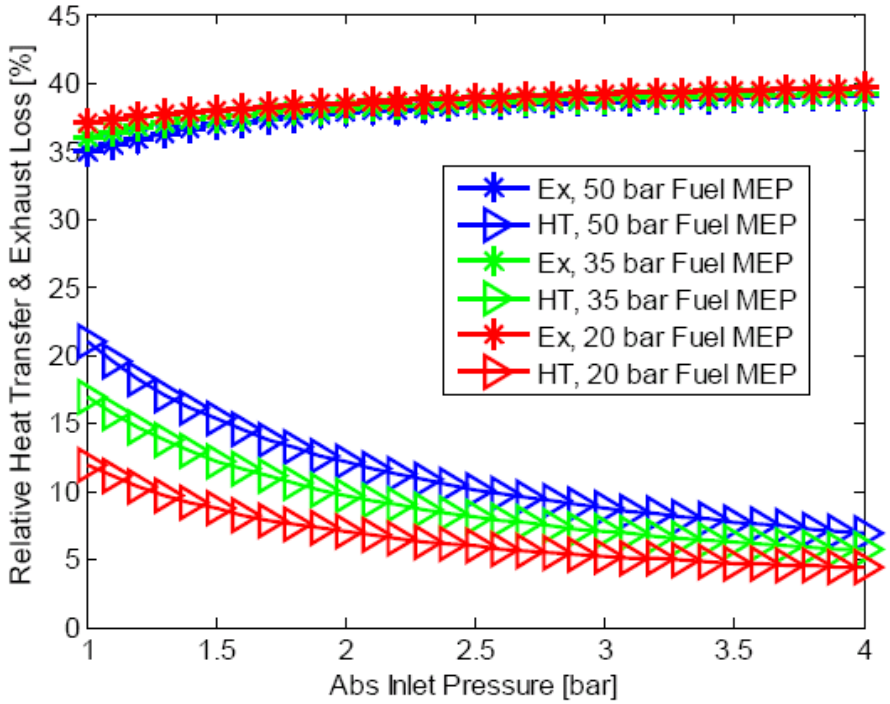


The rest (useful work)



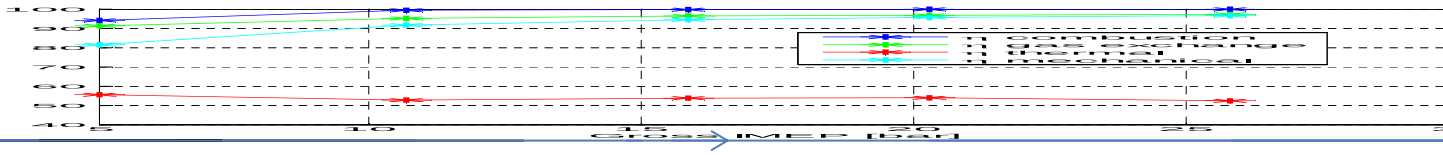
Boosting reduce heat losses





Rc: 14.3:1

13 diesel engine running on gasol



Diesel vs. Gasoline