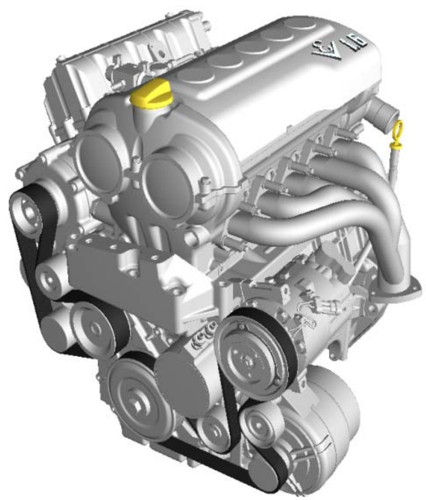
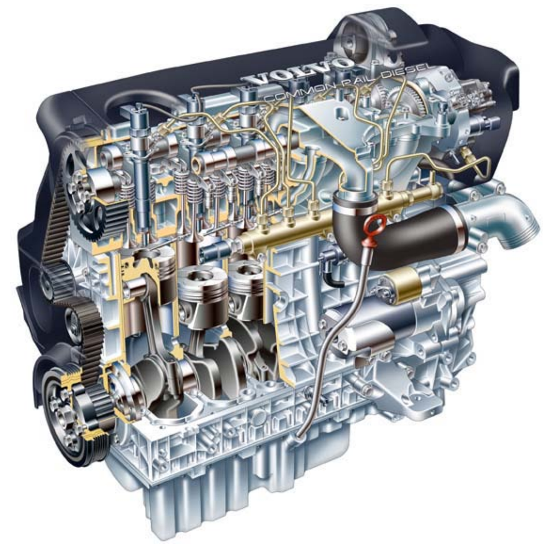
Path to High Efficiency Gasoline Engine

SI → **HCCI** → **PPC**



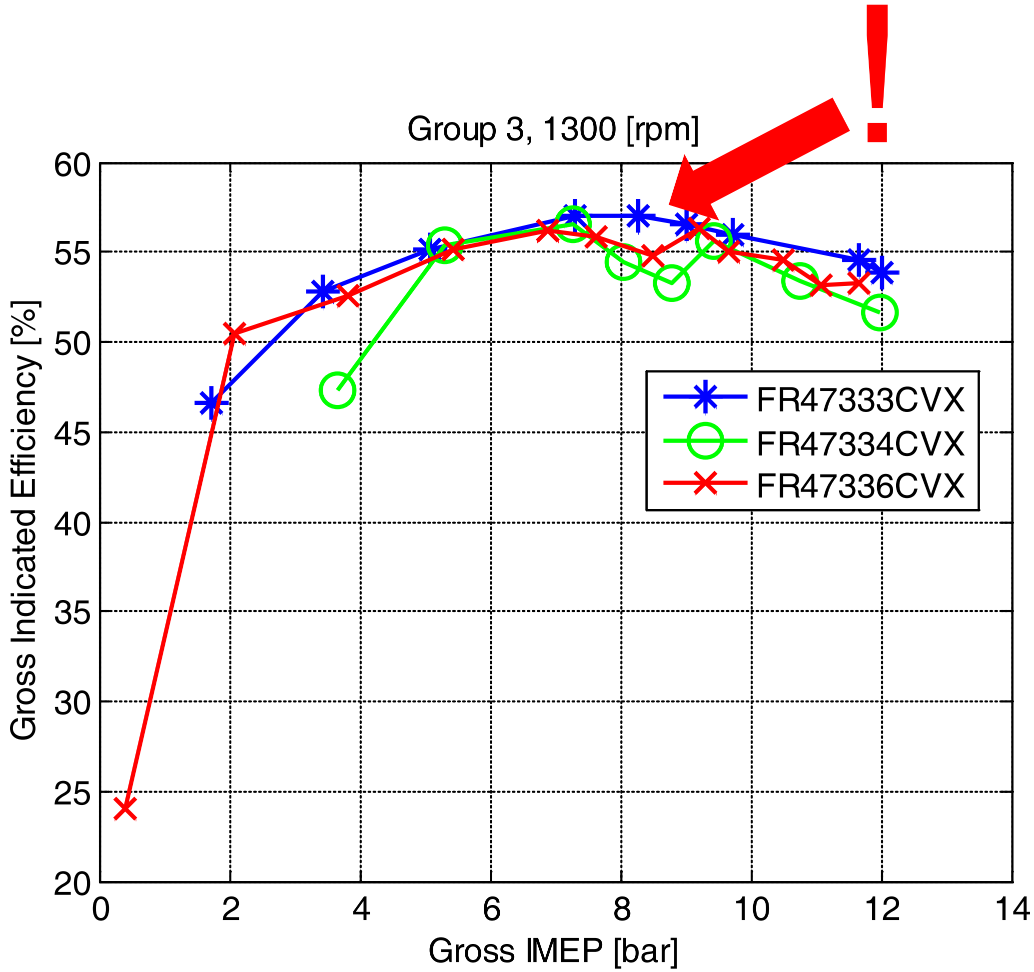


Prof. Bengt Johansson

Division of Combustion Engines
Department of Energy Sciences

Lund University

Scania diesel engine running on gasoline



η_i=57% ⟺ Isfc =147 g/kWh (@43 MJ/kg heating value)

Outline

- HCCI and fuel efficiency
  - 50% thermal efficiency
- Partially premixed combustion, PPC
  - Background
  - Why gasoline is the best diesel engine fuel
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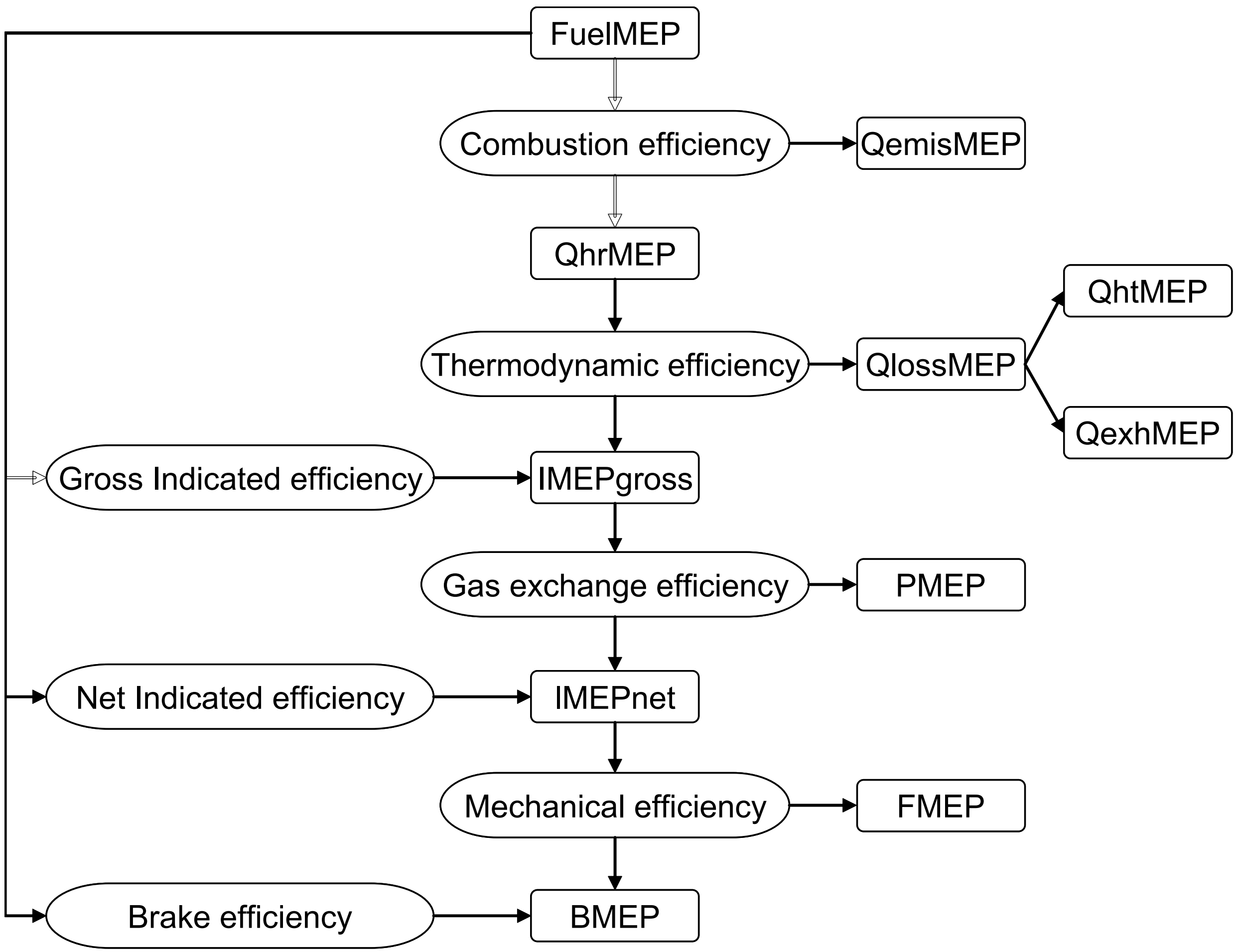
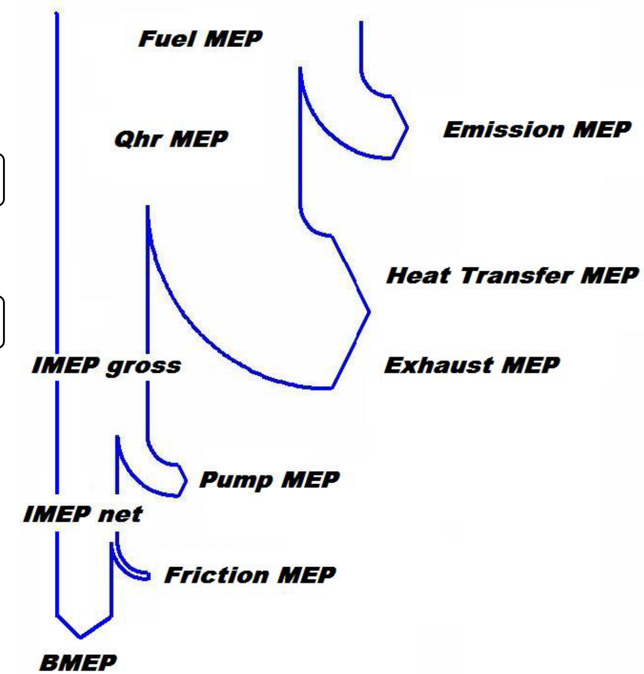
Efficiencies?

Energy flow in an IC engine



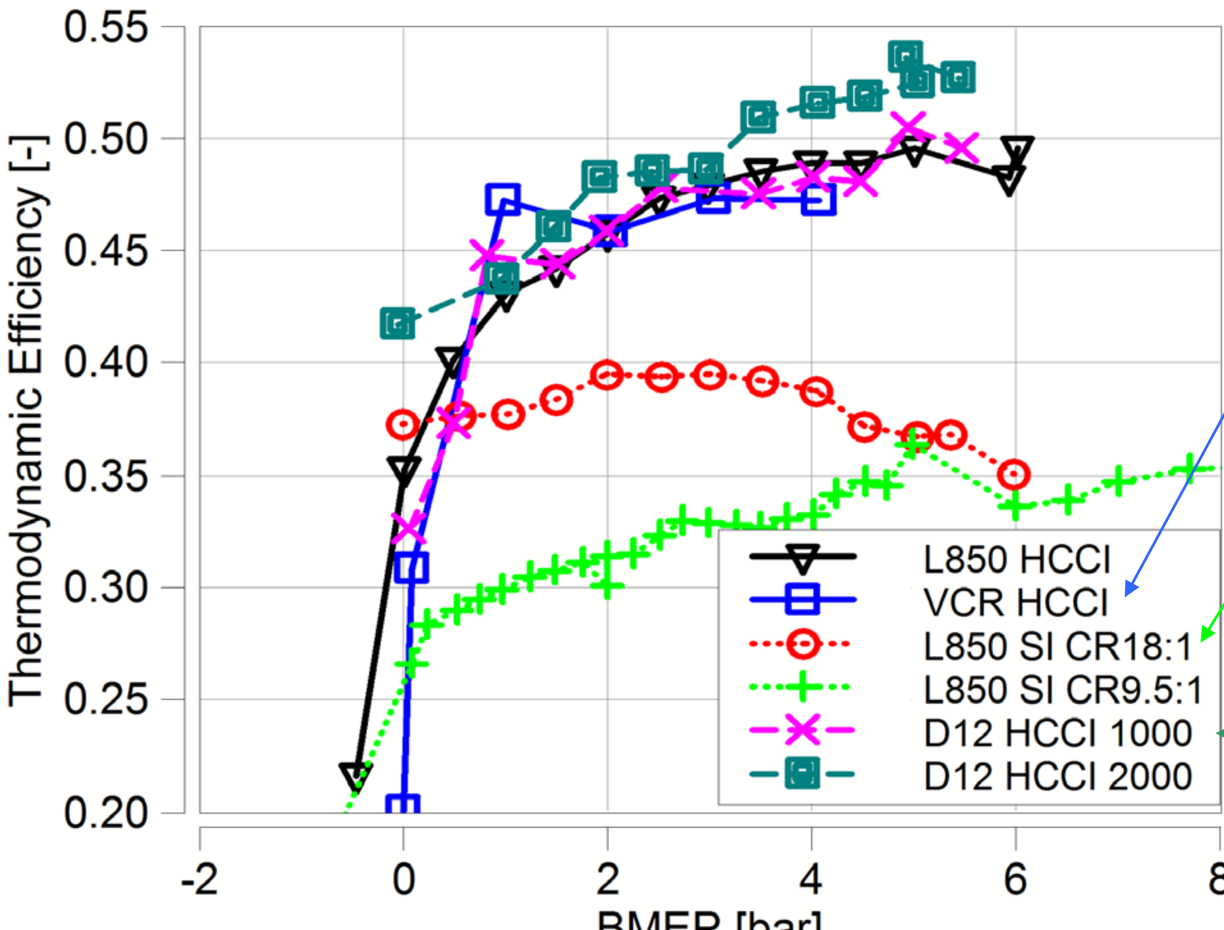


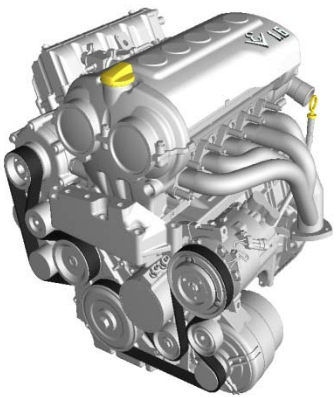
$$\eta_{Brake} = \eta_{Combustion} * \eta_{Thermodynamic} * \eta_{GasExchange} * \eta_{Mechanical}$$

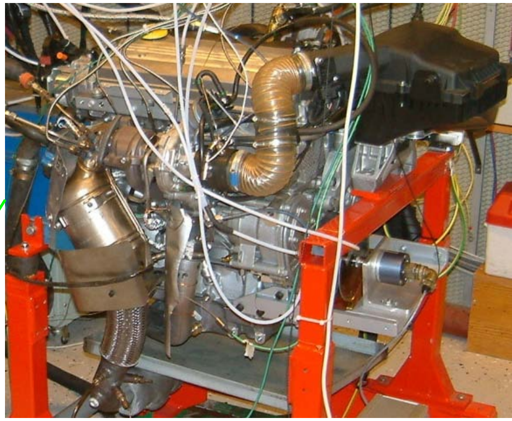
Thermodynamic efficiency

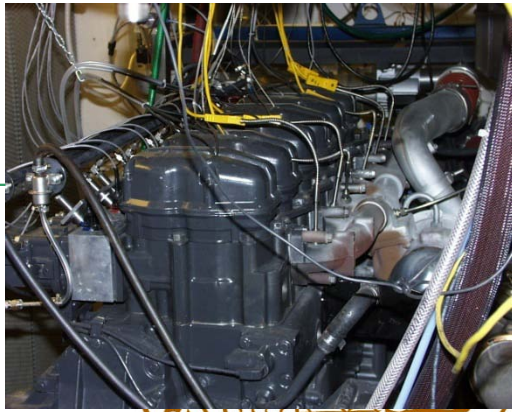
Saab SVC variable compression ratio, VCR, HCCI, Rc=10:1-30:1;
General Motors L850 "World engine", HCCI, Rc=18:1, SI, Rc=18:1, SI, Rc=9.5:1 (std)
Scania D12 Heavy duty diesel engine, HCCI, Rc=18:1;

Fuel: US regular Gasoline



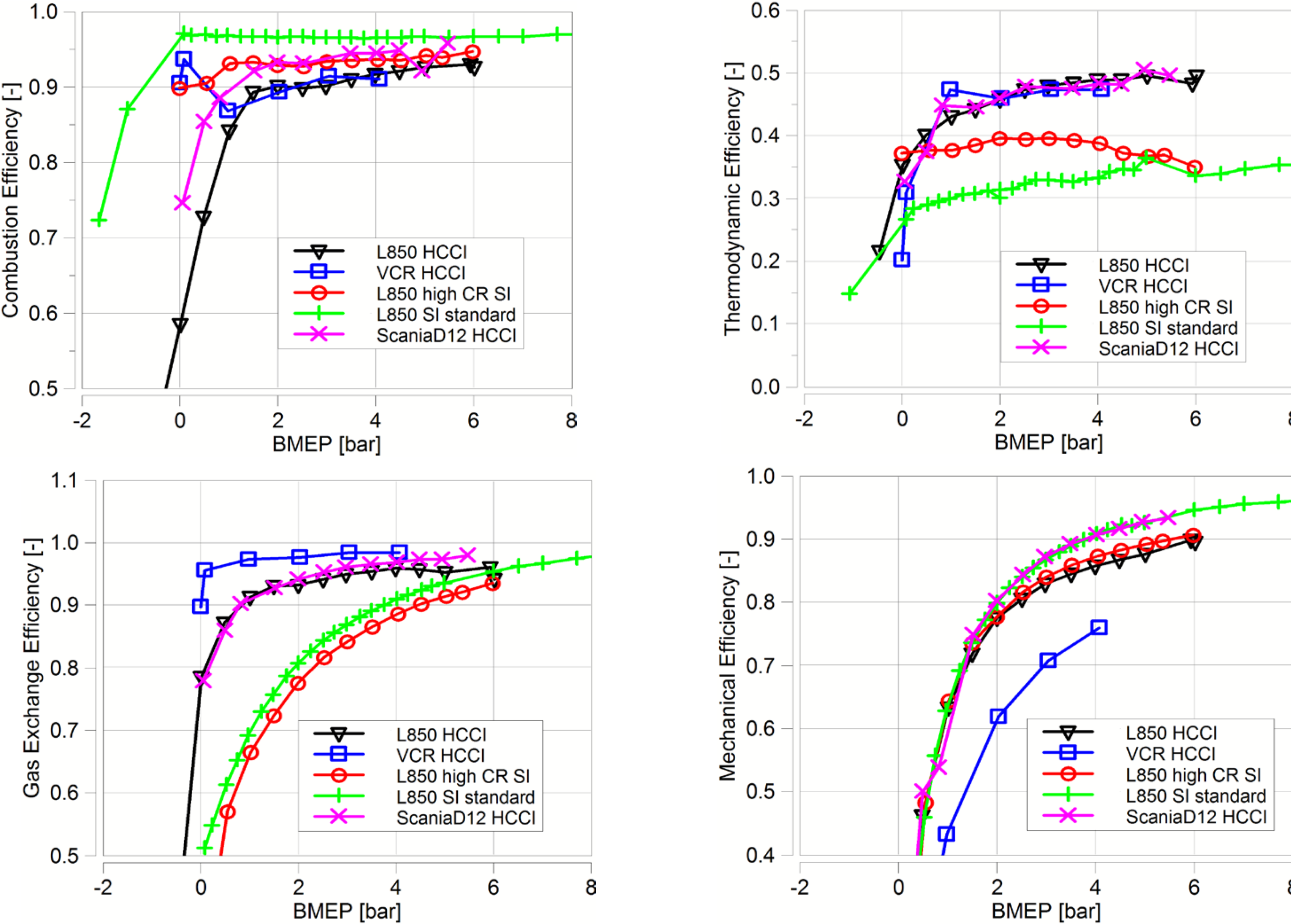




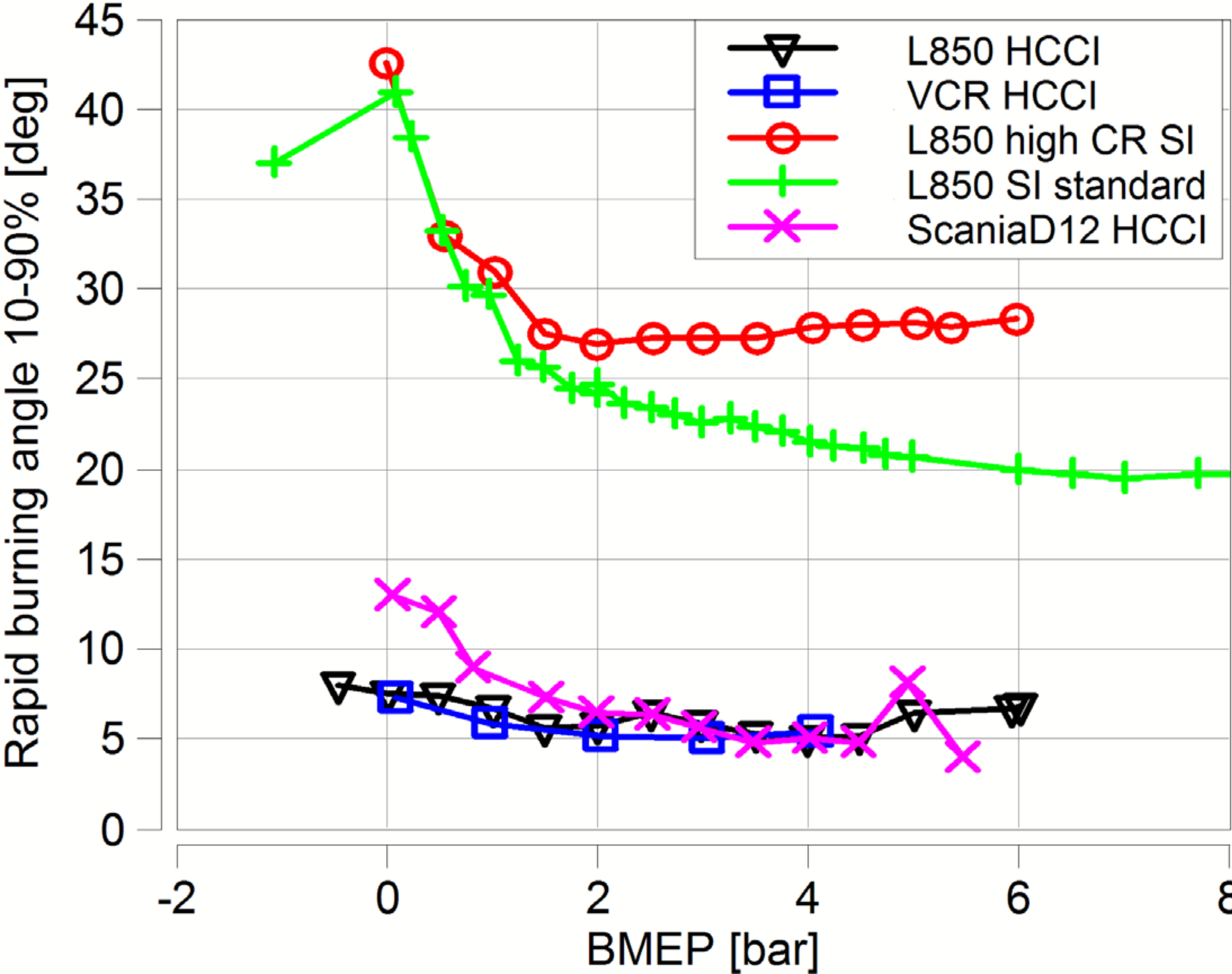


SAE2006-01-0205

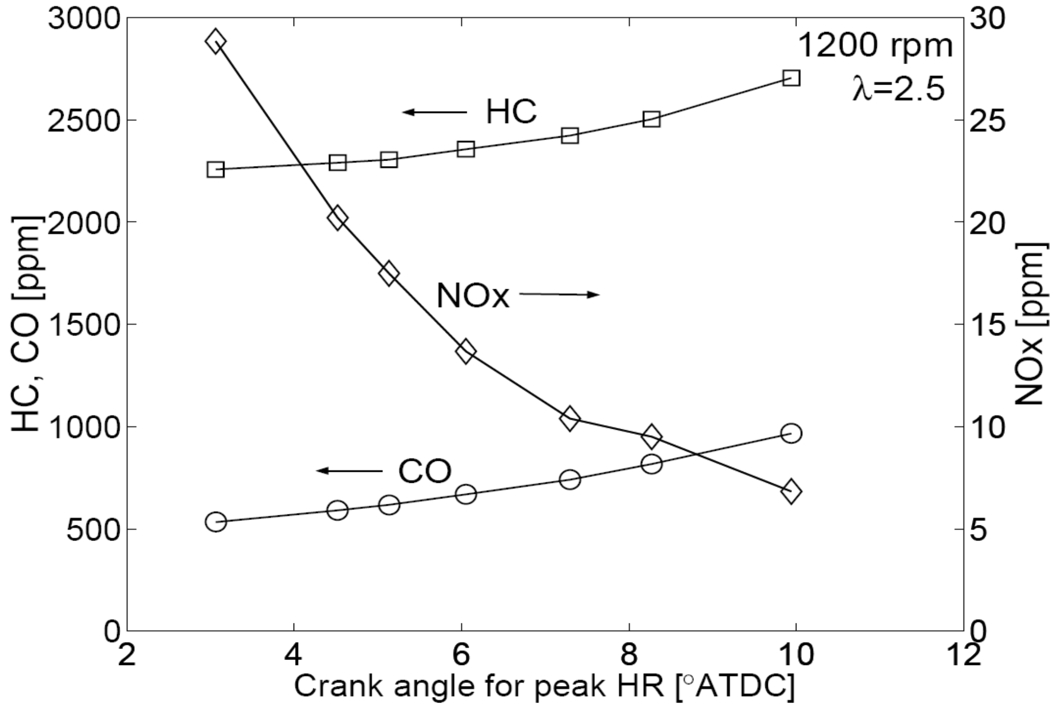
All four efficiencies

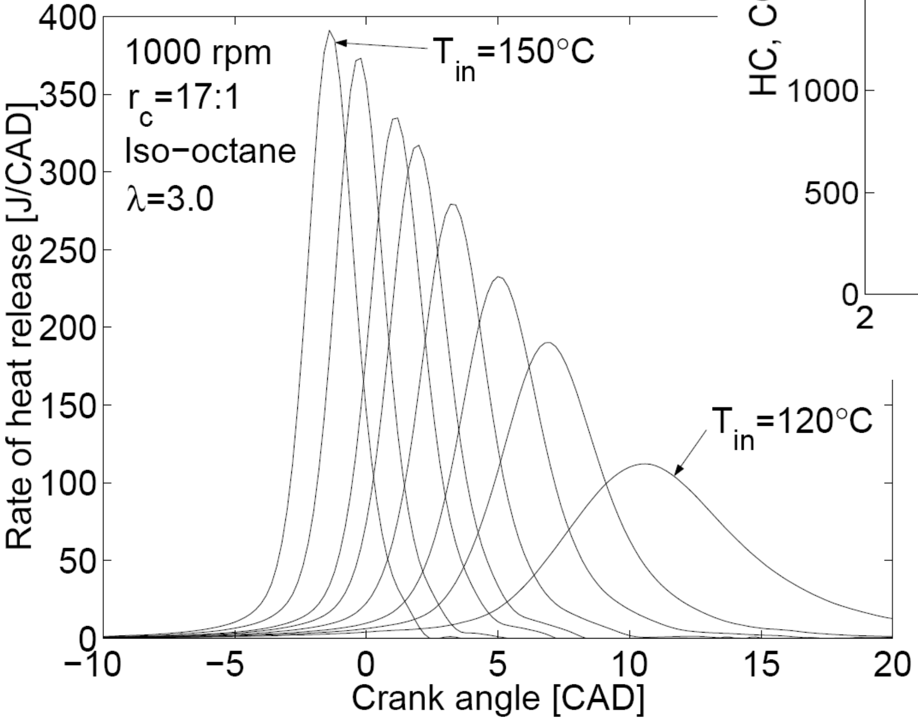


Problem with HCCI: Too fast combustion



Phasing HCCI combustion late helps burn rate but reduce η_c





Magnus Christensen Ph.D. thesis 2002

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Background

Combustion concepts

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

Spark Ignition (SI) engine (Gasoline, Otto)

+ High efficiency
- Emissions of NO_x and soot

Compression Ignition (CI) engine (Diesel)

Homogeneous Charge Compression Ignition (HCCI)

+ High efficiency
+ Ultra low NO_x

-Combustion control

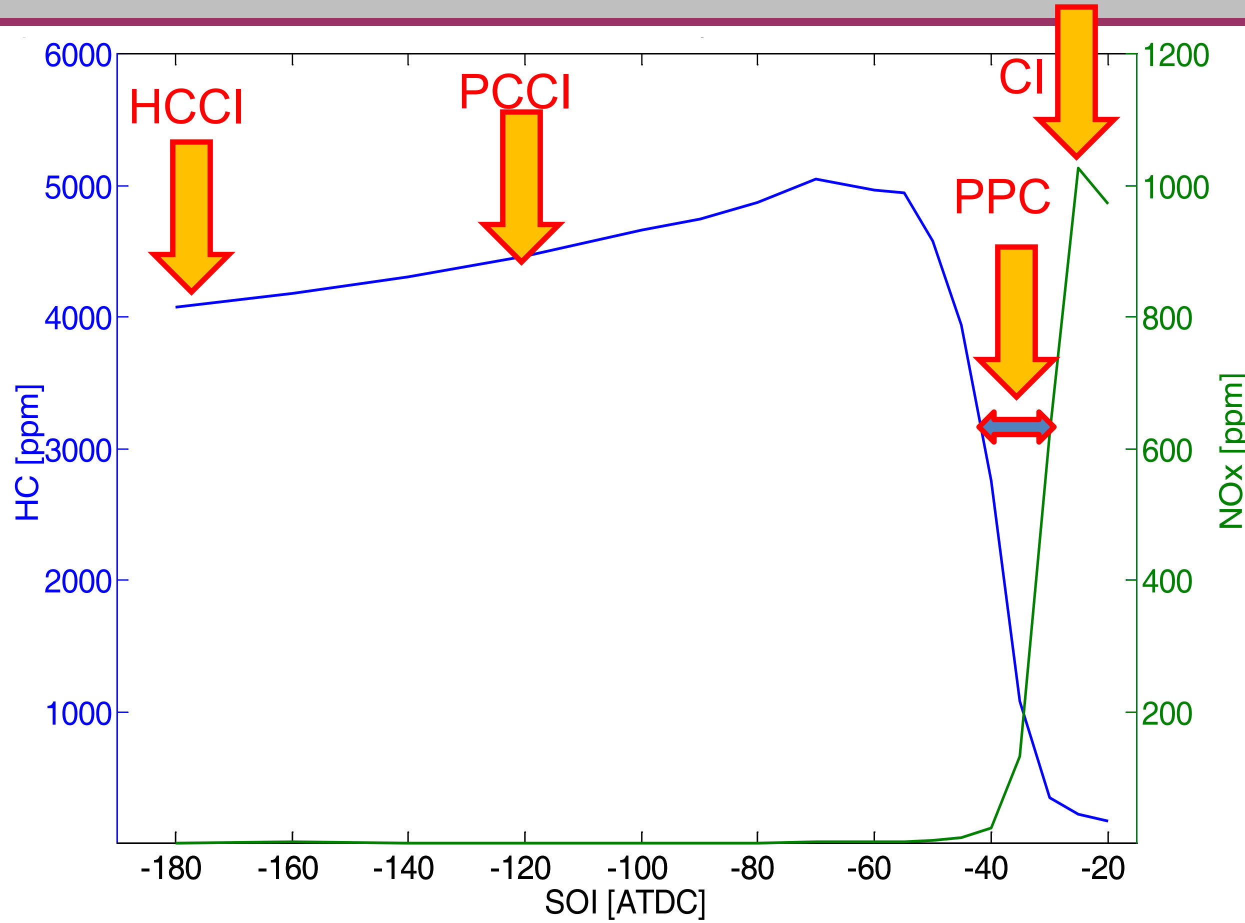
-Power density

Spark Assisted Compression Ignition (SACI) Gasoline HCCI

Partially premixed combustion (PPC) Diesel HCCI

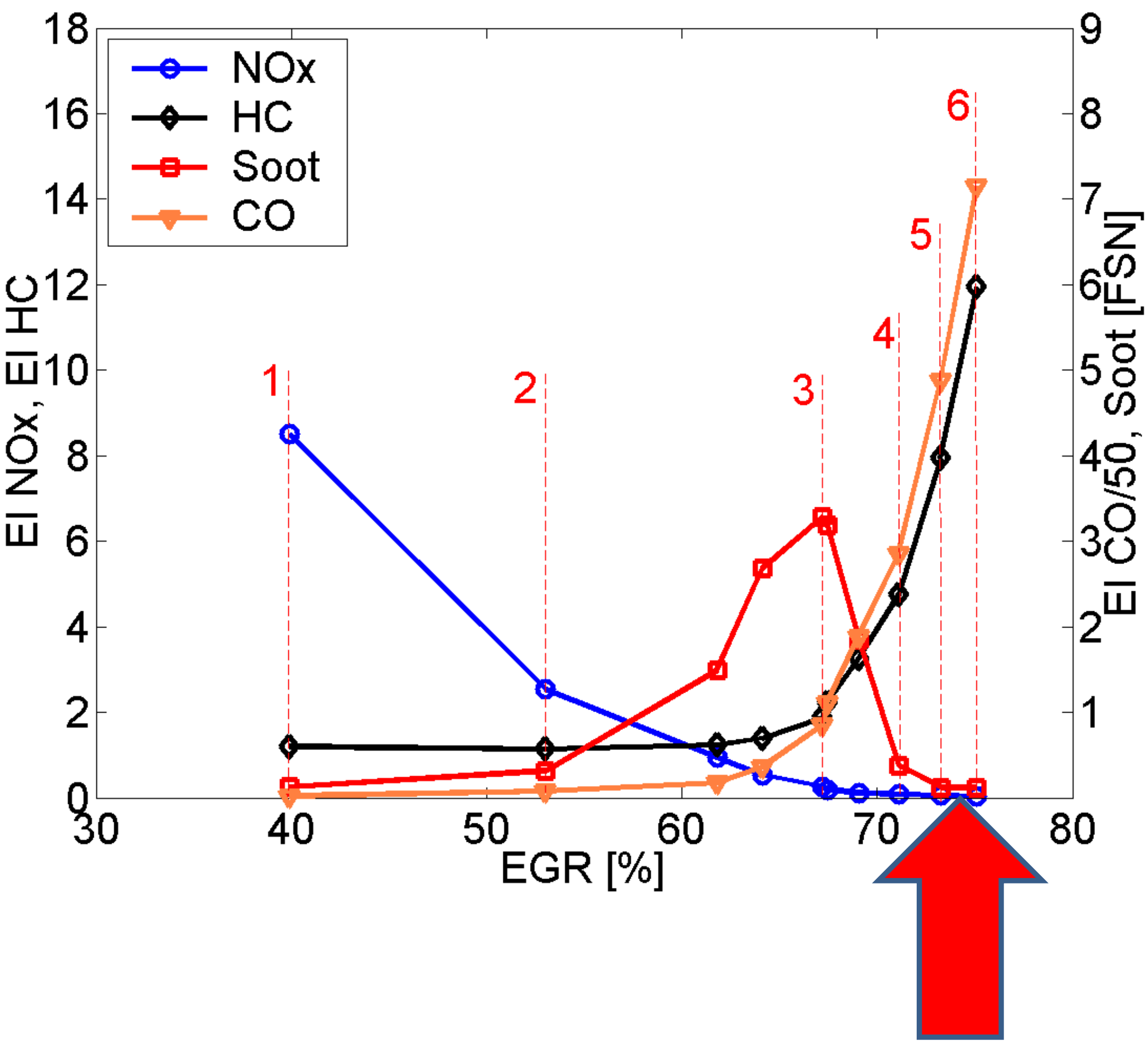
+ Injection controlled
- Less emissions advantage

Partially Premixed Combustion, PPC



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

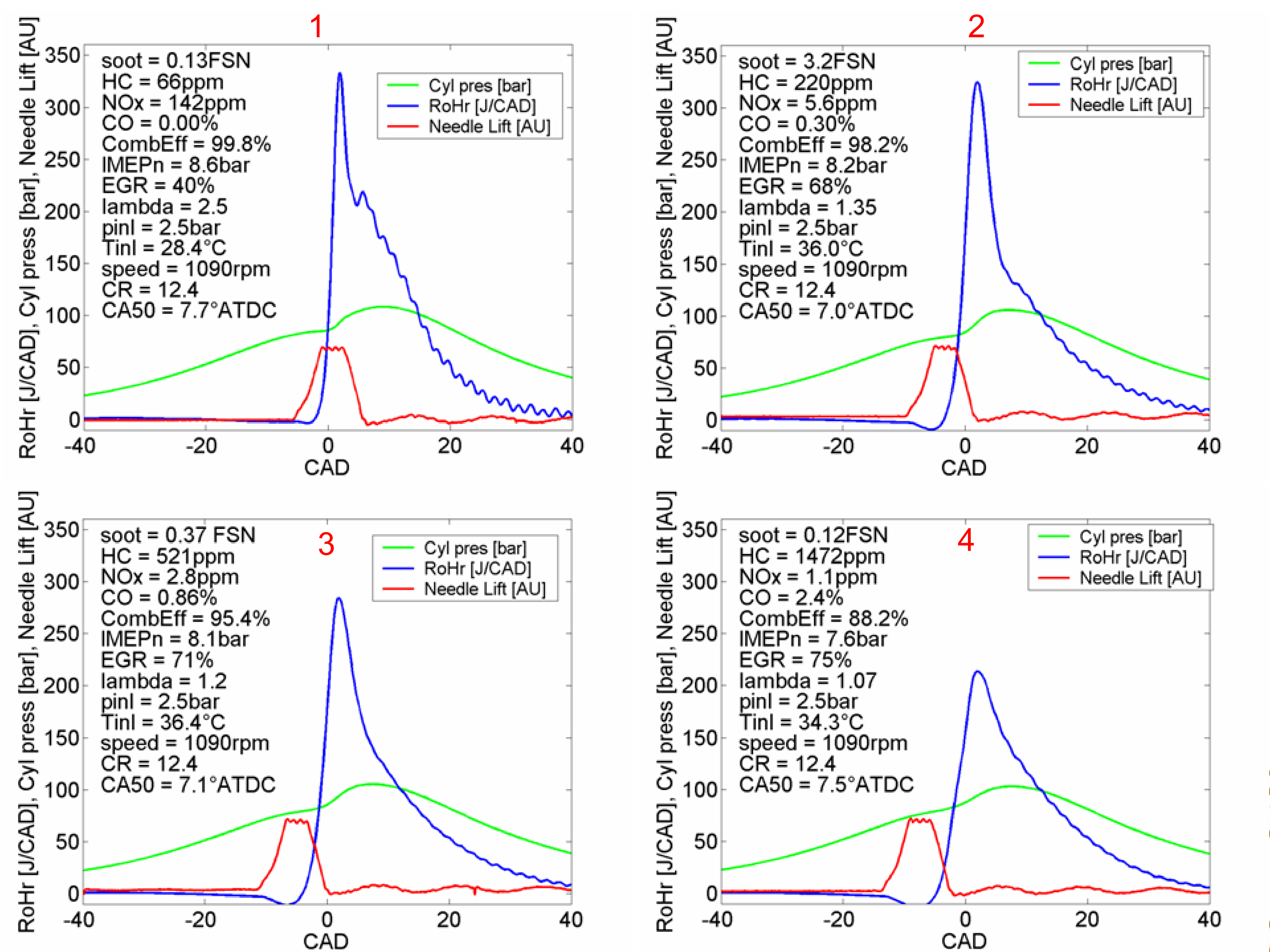
PPC: Effect of EGR with diesel fuel



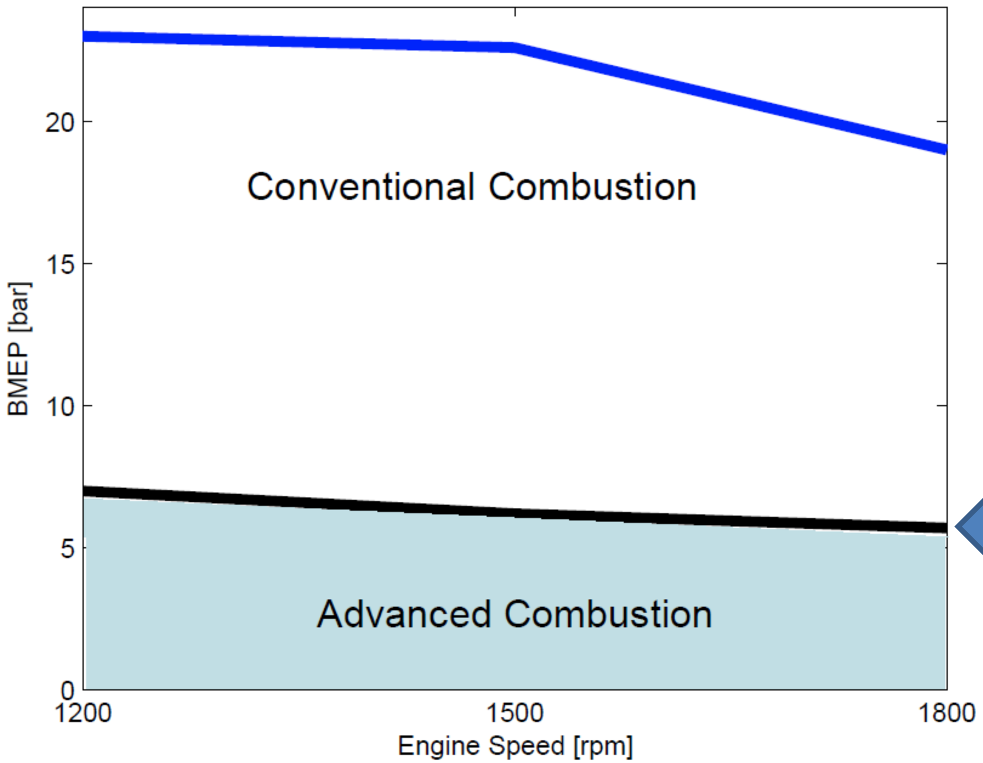
Load	8 bar IMEP
Abs. Inlet Pressure	2.5 bar
Engine Speed	1090 rpm
Swirl Ratio	1.7
Compression Ratio	**12.4:1 (Low)**

Scania D12 single cylinder

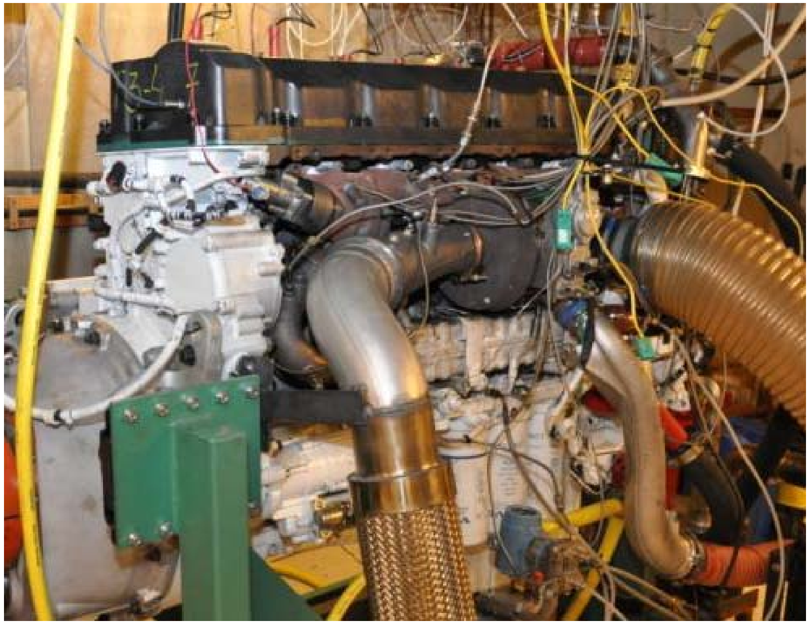
DEER2005


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
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
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

Lund/Delphi/Volvo PPC Project



Volvo D13 Multi-cylinder engine



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

Adapted from
SAE paper 2009-01-1127

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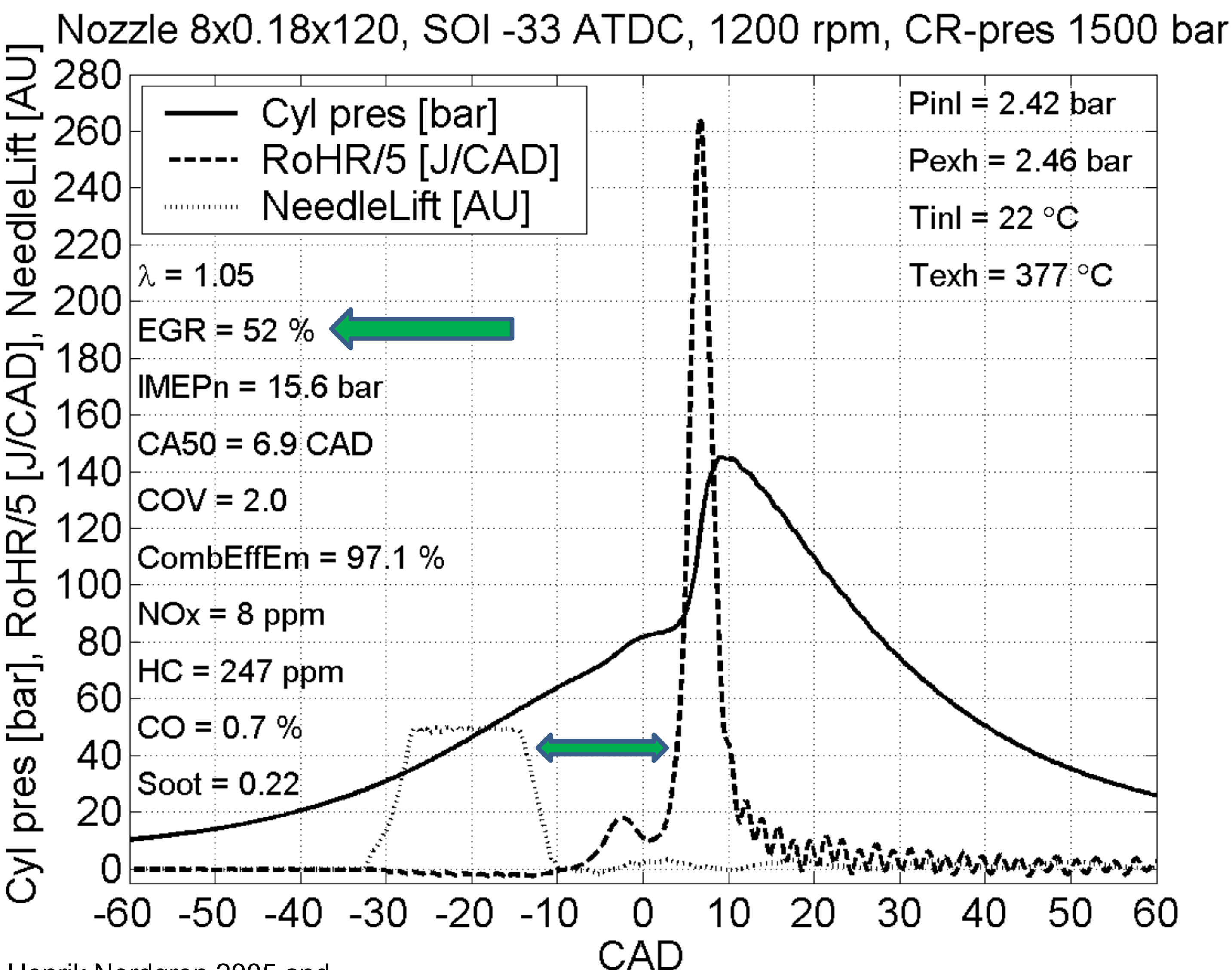
PPC with low cetane diesel



Lic. Thesis by Henrik Nordgren 2005 and presented at DEER2005

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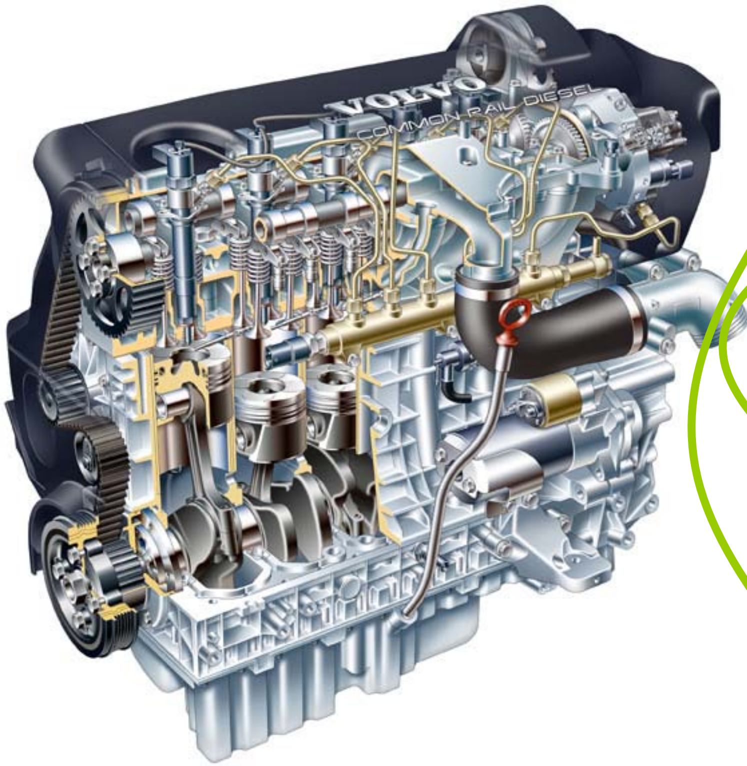
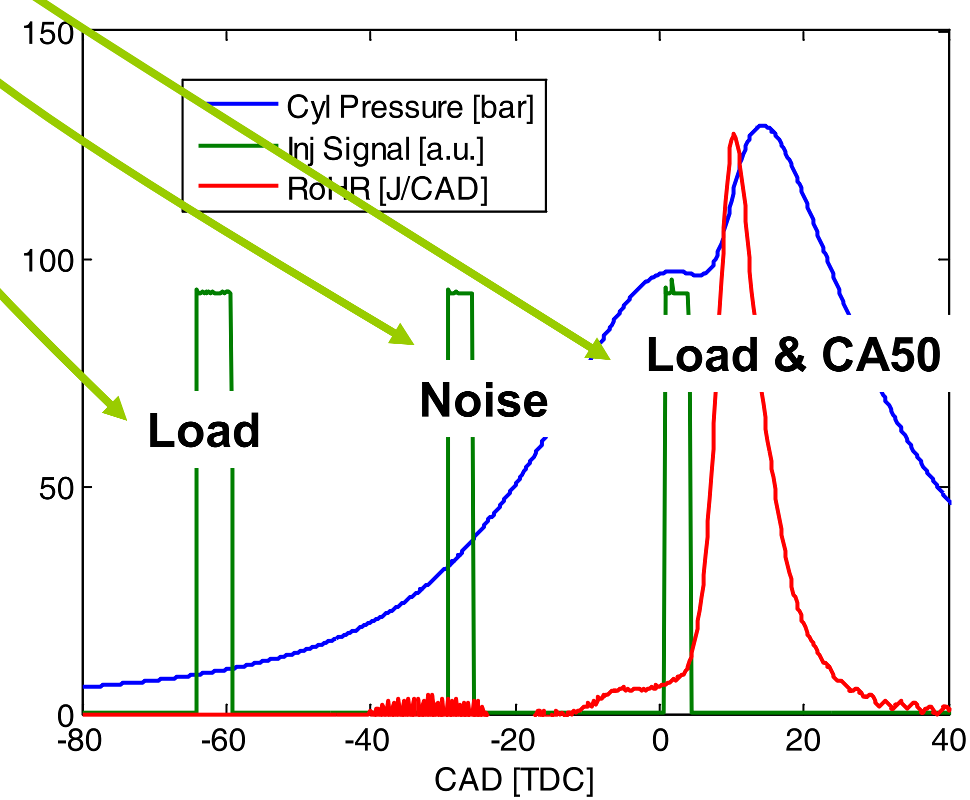
VOLVO D5 with Gasoline

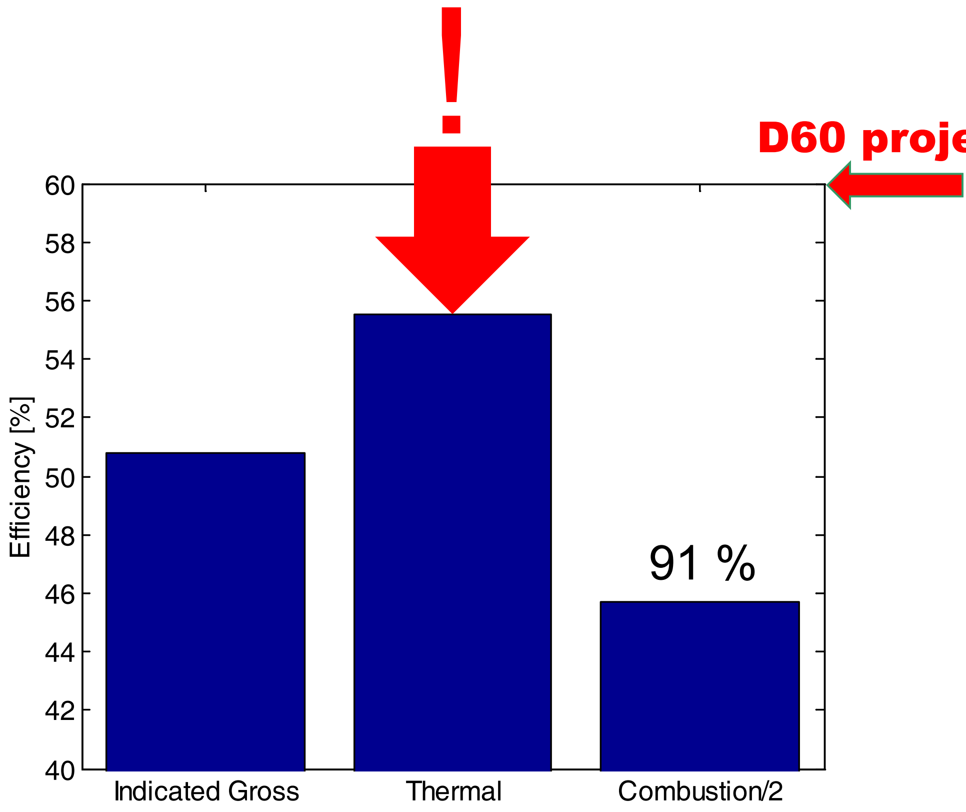


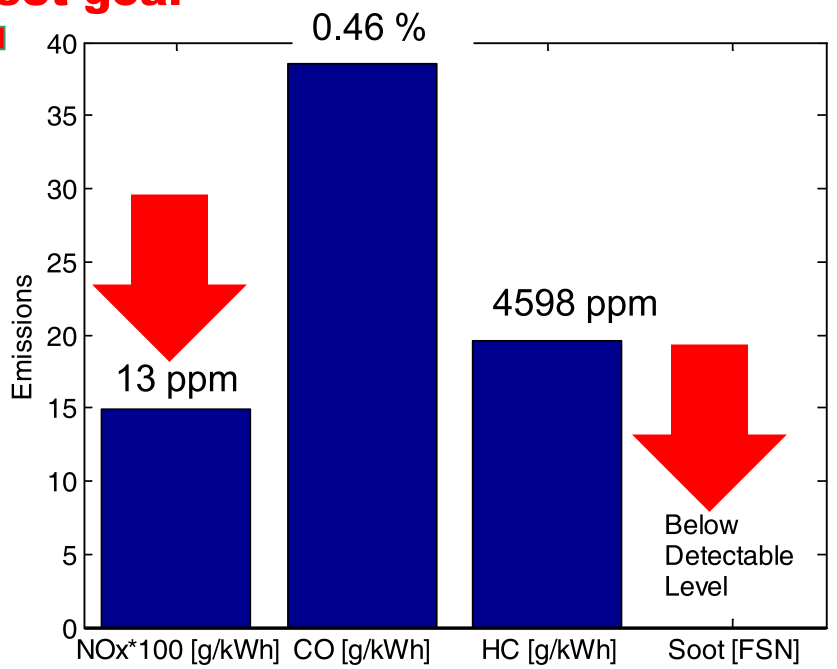
Injection	SOI [TDC]	Fuel MEP [bar]	Percentage [%]
1	-64.00	10.88	41.28
2	-29.20	7.74	29.36
3	0.80	7.74	29.36



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

Efficiencies & Emissions



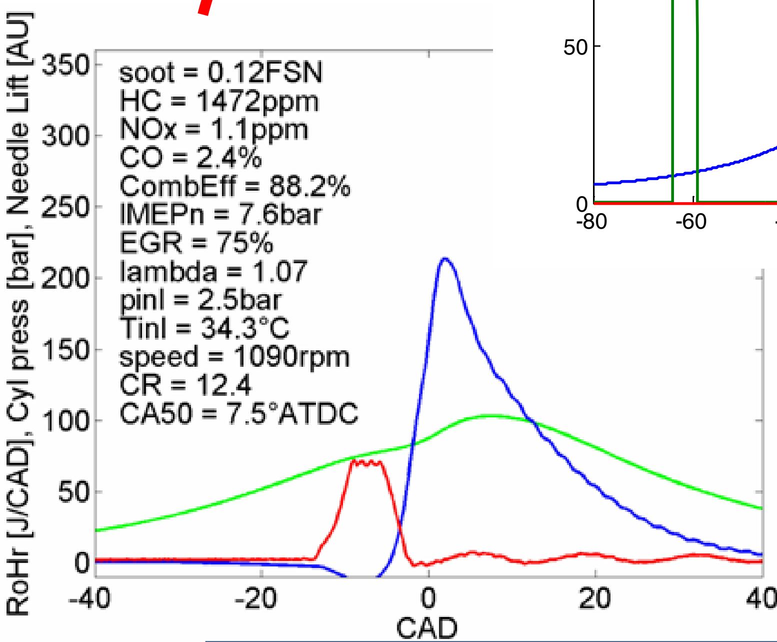


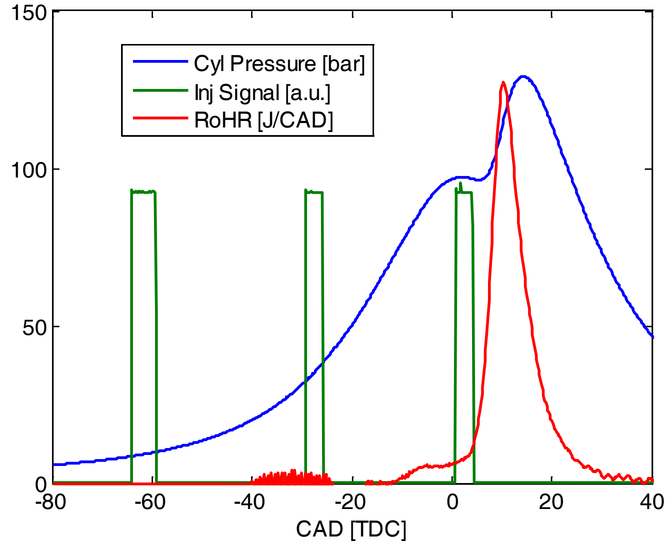
dPmax	7.20	[bar/CAD]
CA5	3.40	[TDC]
ID	-1.00	[CAD]
CA50	11.35	[TDC]
CA90-10	13.00	[CAD]

Burn rate and η_T

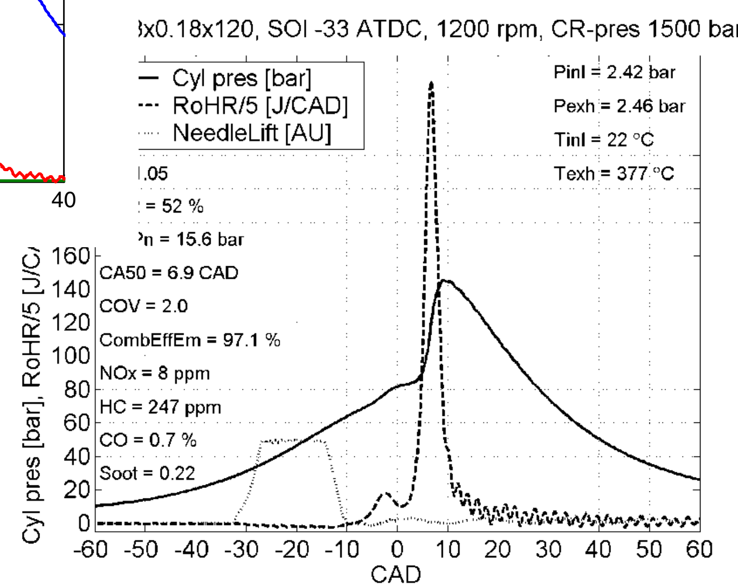
Optimum Thermodynamic efficiency

Low effective expansion ratio





High heat losses



Premixedness

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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

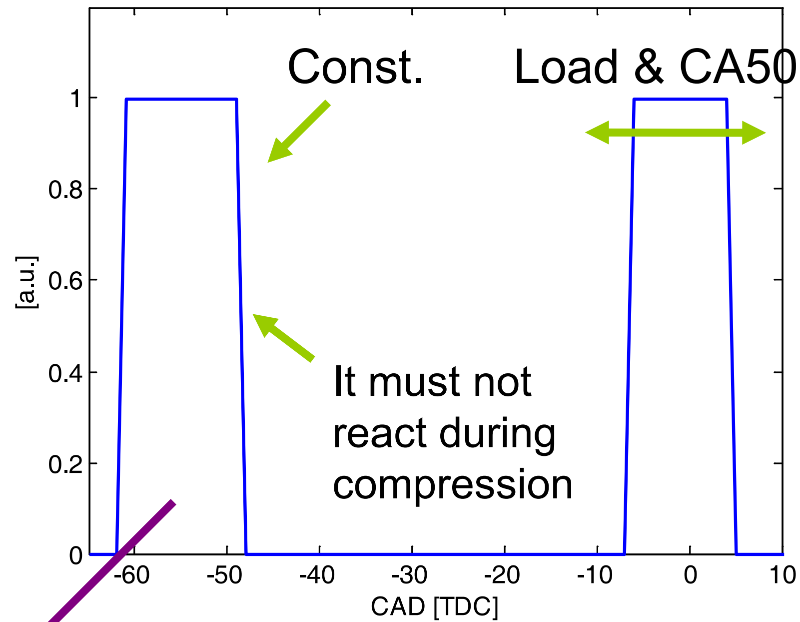
Two Test Series: High & Low Compression Ratio

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.

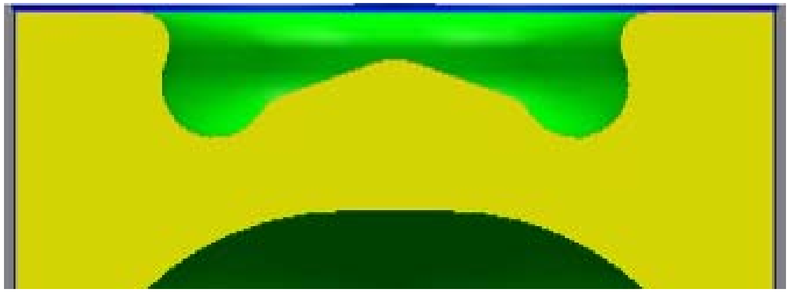


Fuel amount in the pilot is a function of:

1. rc
2. RON/MON
3. EGR

SAE 2009-01-0944

High Compression Ratio PPC



IMEP sweep @ 1300 [rpm]

EGR ~ const throughout the sweep, 40-50 [%]

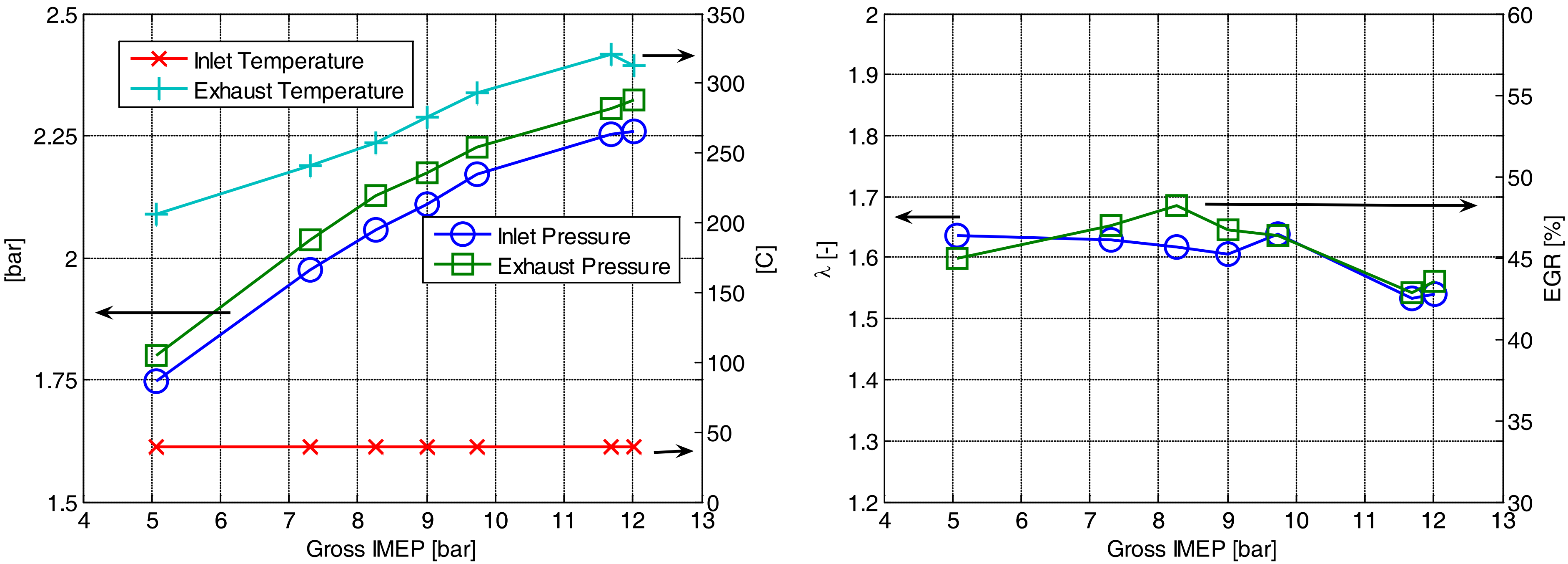
λ~ const throughout the sweep, 1.5-1.6 [-]

Tin = 308 [K]

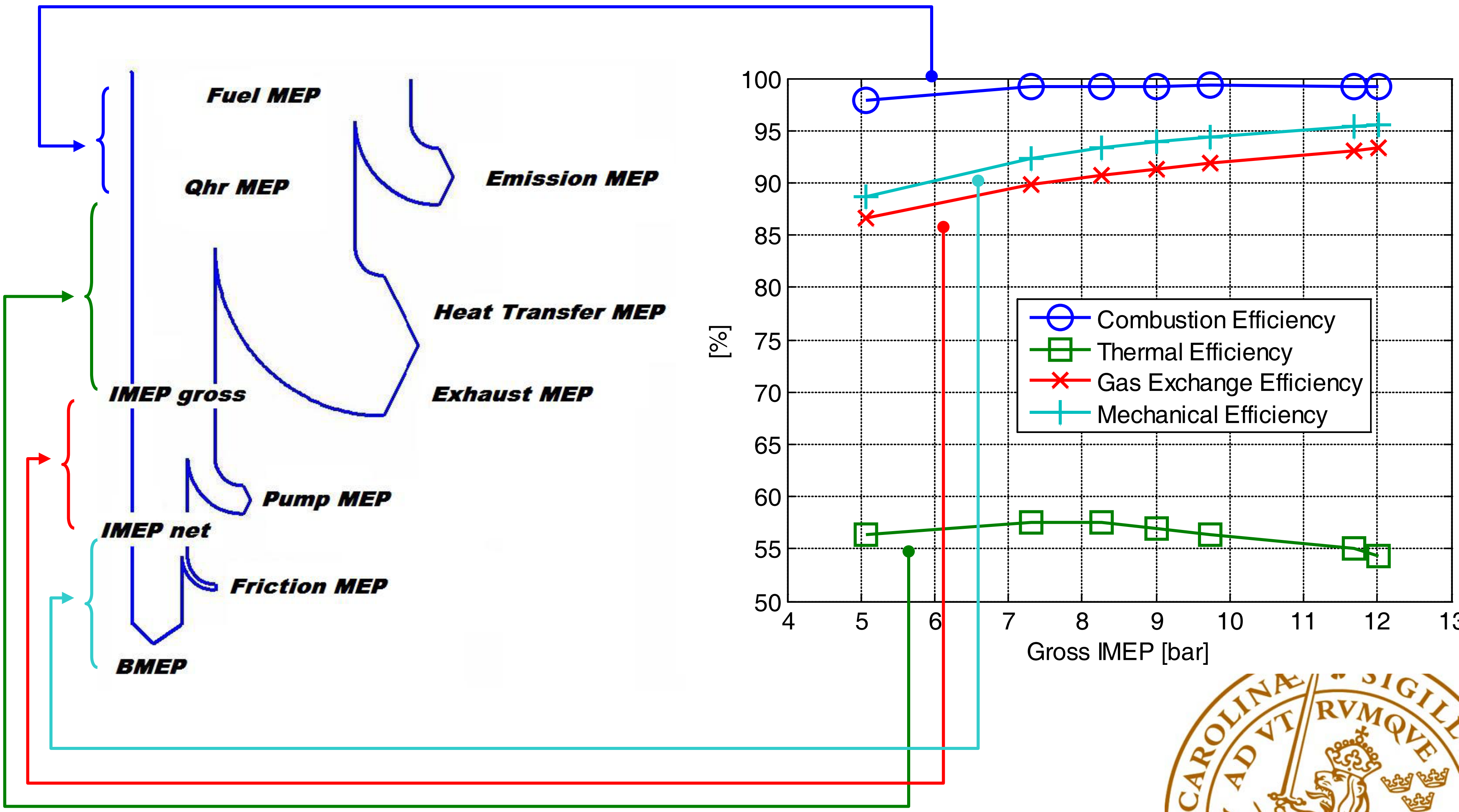
Standard piston bowl, rc: 17:1

SAE 2009-01-2668

Running Conditions



Efficiencies

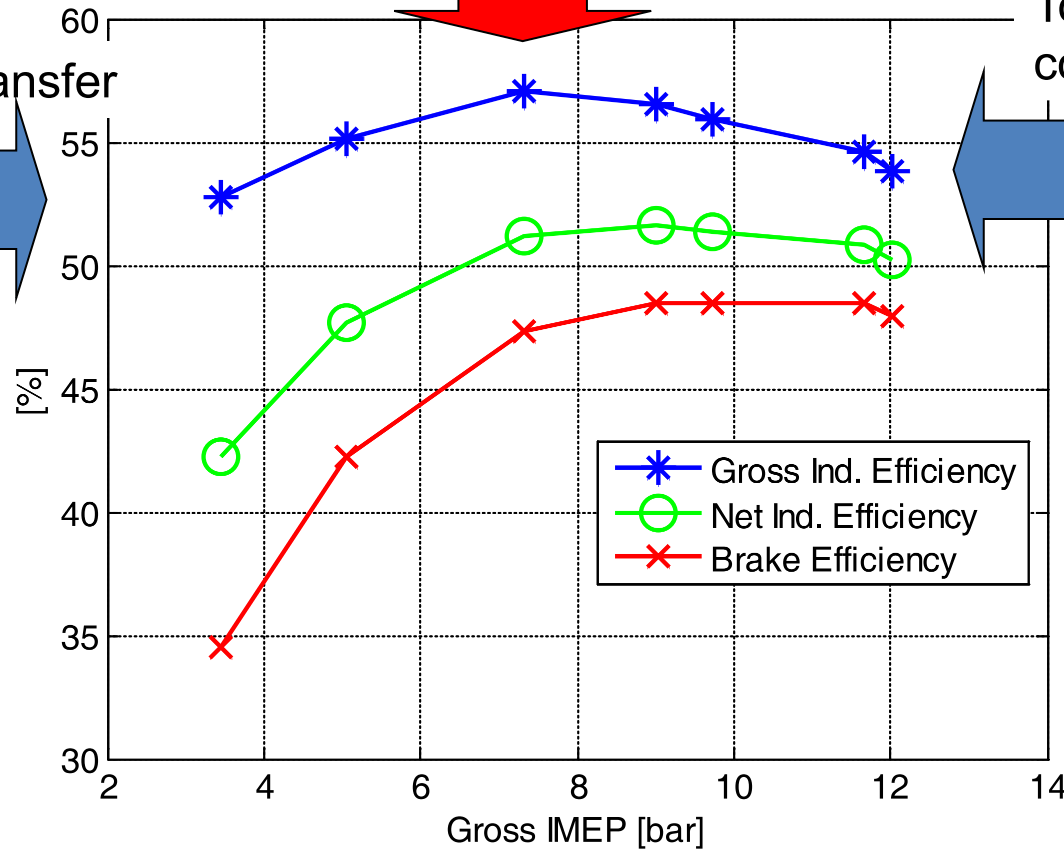


Efficiency

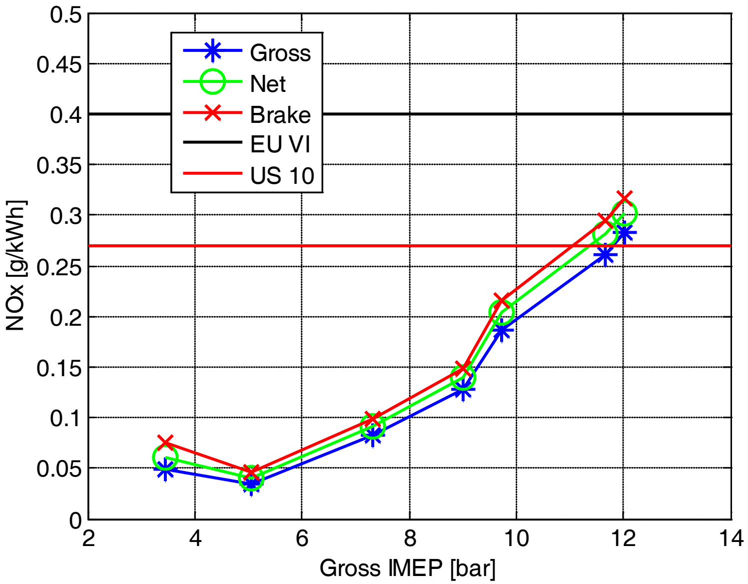
57%

Too much heat transfer

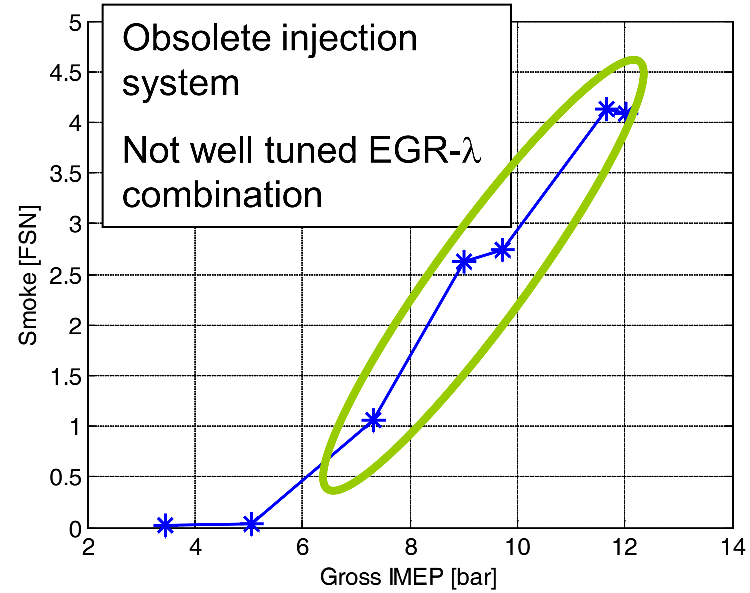
Too much rate controlled combustion



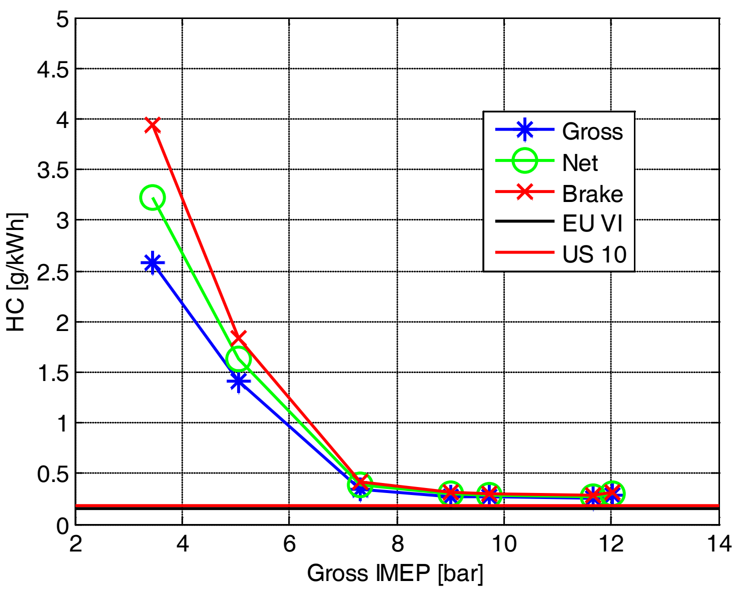
Emissions



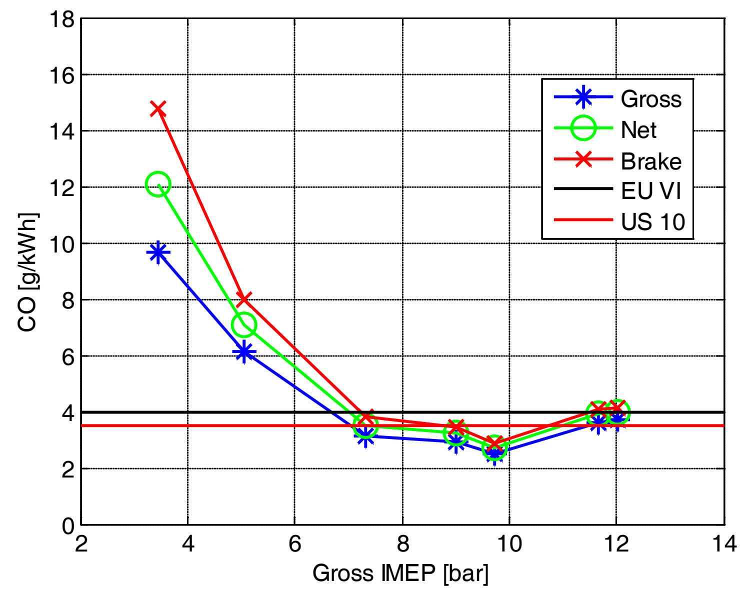
Gross
Net
Brake
EU VI
US 10
NOx [g/kWh]
Gross IMEP [bar]



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]

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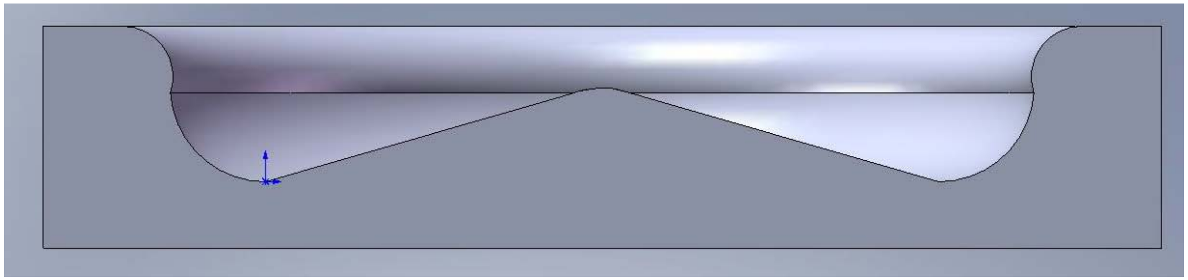
Low Compression Ratio PPC

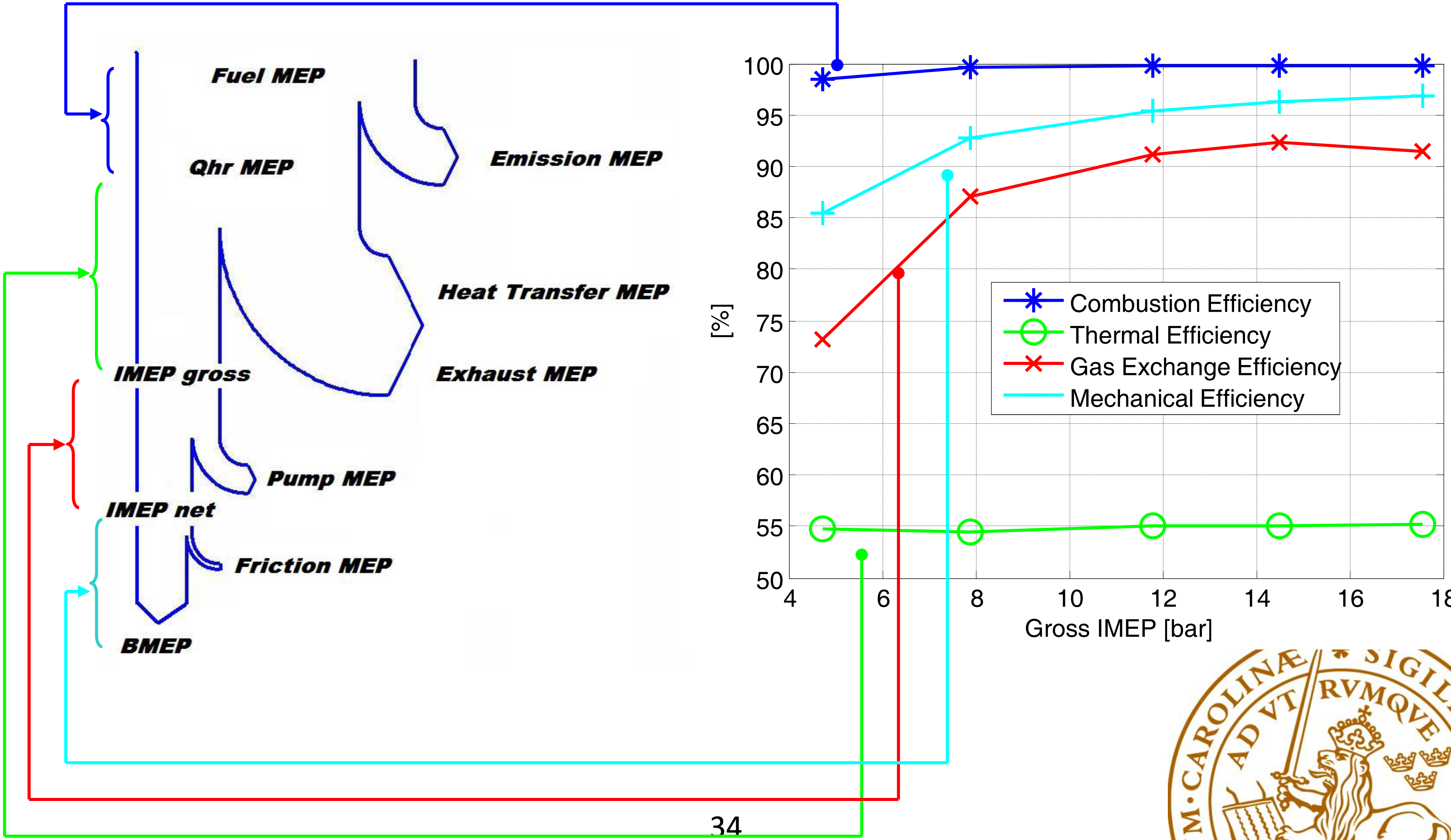


IMEP sweep @ 1300 [rpm]
EGR ~ const throughout the sweep, 40-50 [%]
λ~ const throughout the sweep, 1.5-1.6 [-]
Tin = 308 [K]

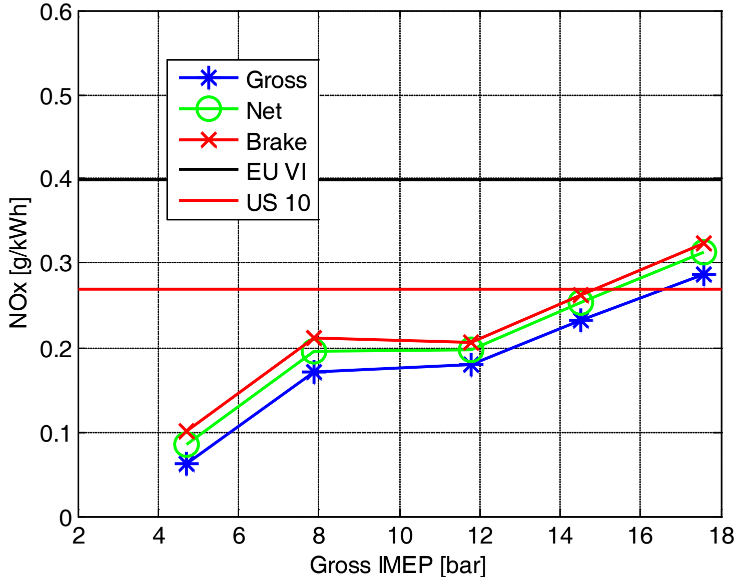
Custom piston bowl, rc: 14.3:1

SAE 2010-01-0871

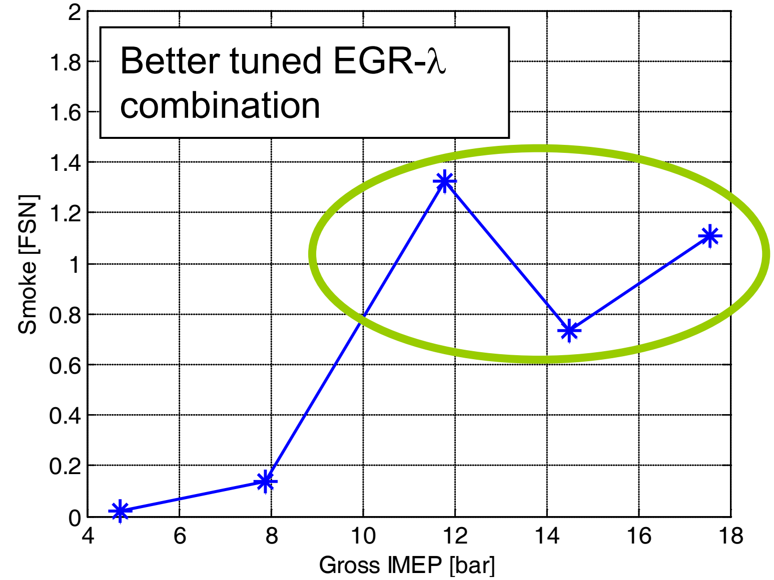
Efficiencies



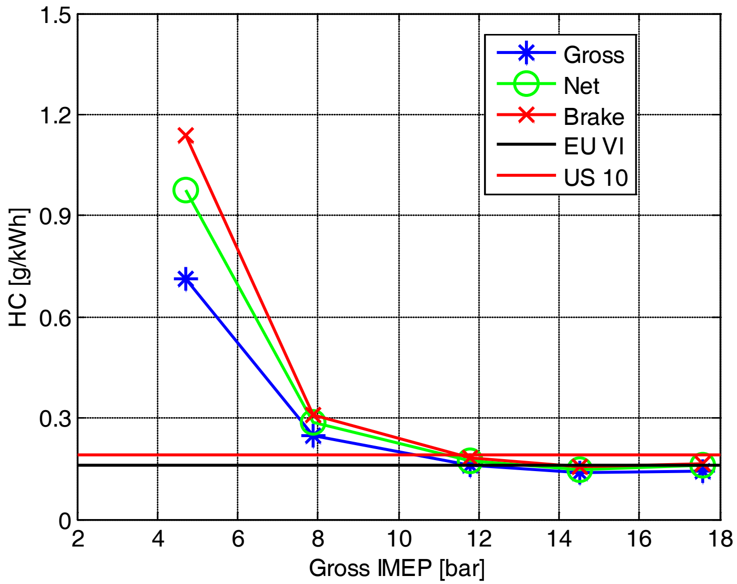
Emissions



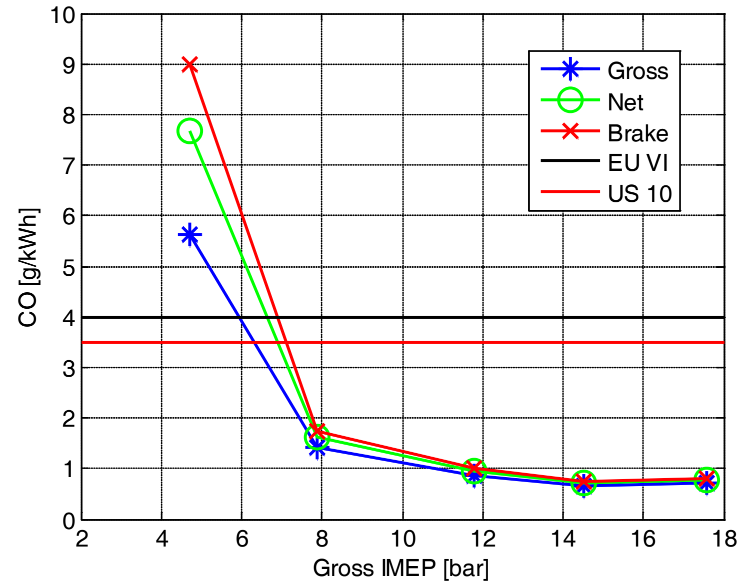
NOx [g/kWh]
Gross IMEP [bar]
Gross
Net
Brake
EU VI
US 10



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

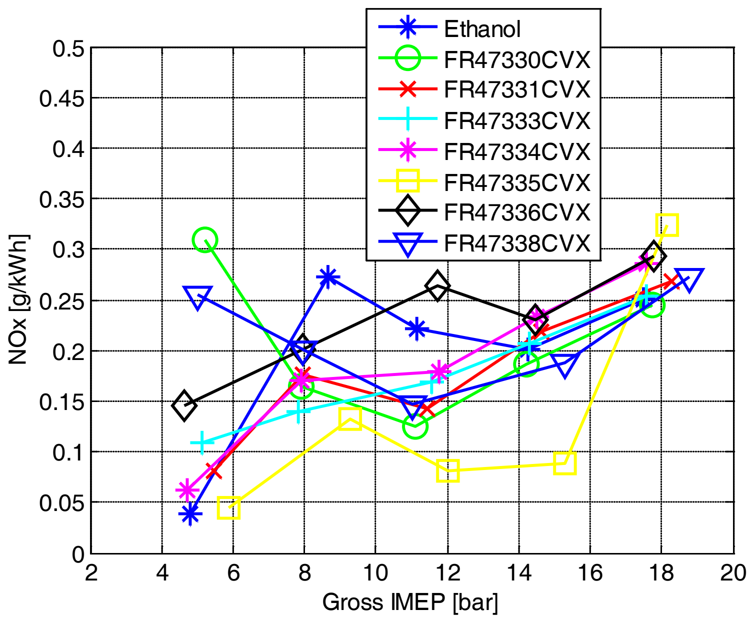


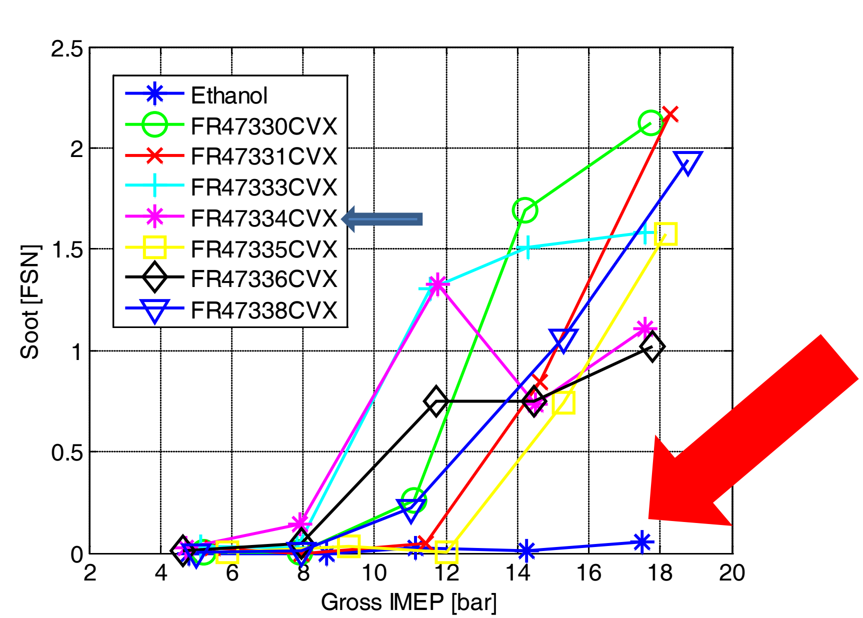
HC [g/kWh]
Gross IMEP [bar]
Gross
Net
Brake
EU VI
US 10

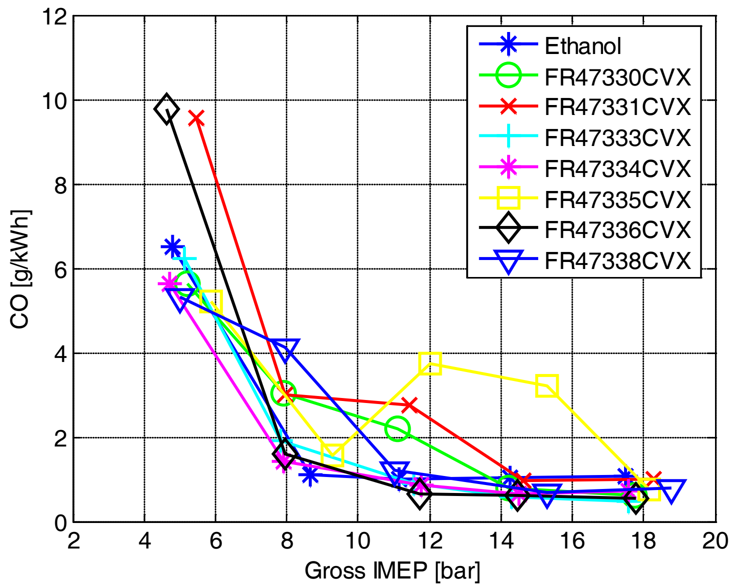


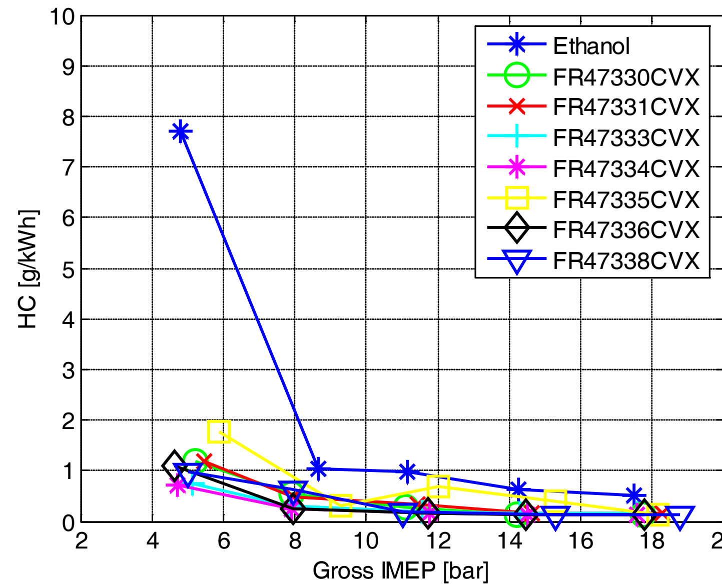
CO [g/kWh]
Gross IMEP [bar]
Gross
Net
Brake
EU VI
US 10

Emissions – different fuels









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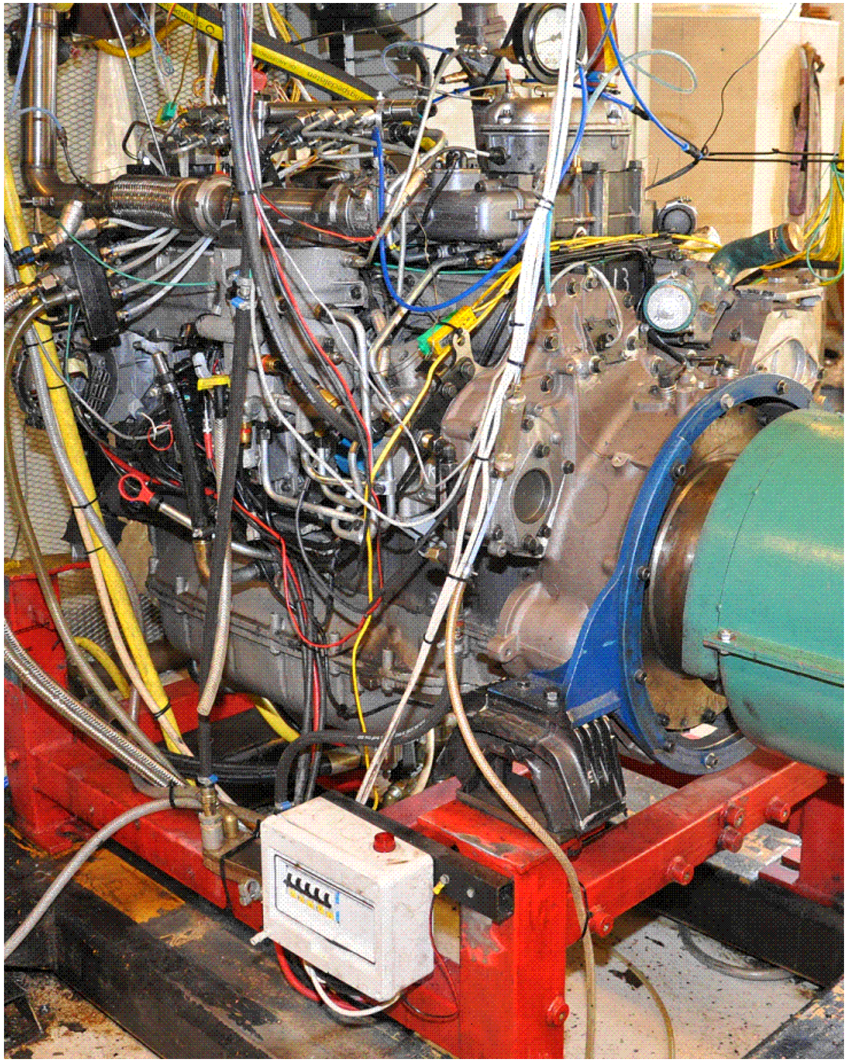
Experimental Apparatus, Scania D13

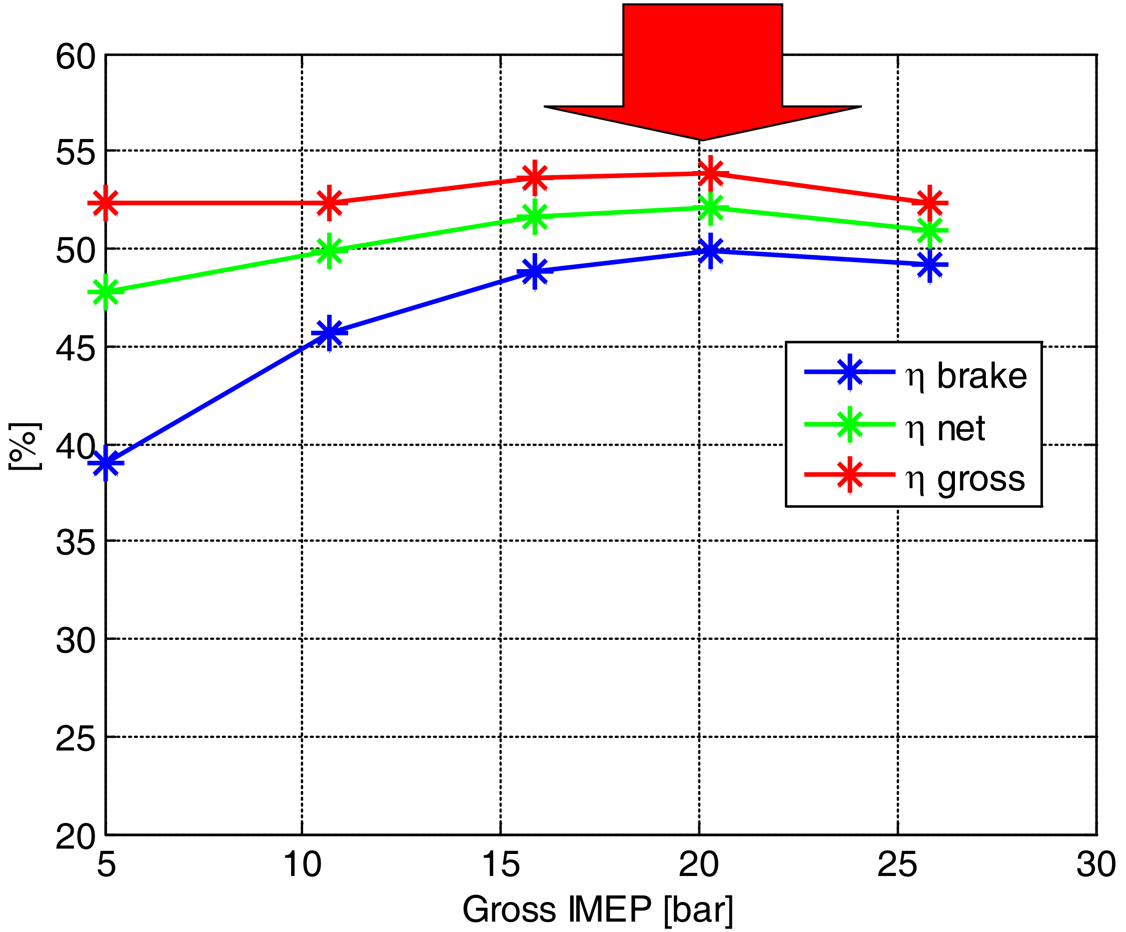


XPI Common Rail		
Orifices	8	[-]
Orifice Diameter	0.19	[mm]
Umbrella Angle	148	[deg]
Engine / Dyno Spec		
BMEPmax	25	[bar]
Vd	2124	[cm3]
Swirl ratio	2.095	[-]

Standard piston bowl, rc: 17.3:1

Efficiency

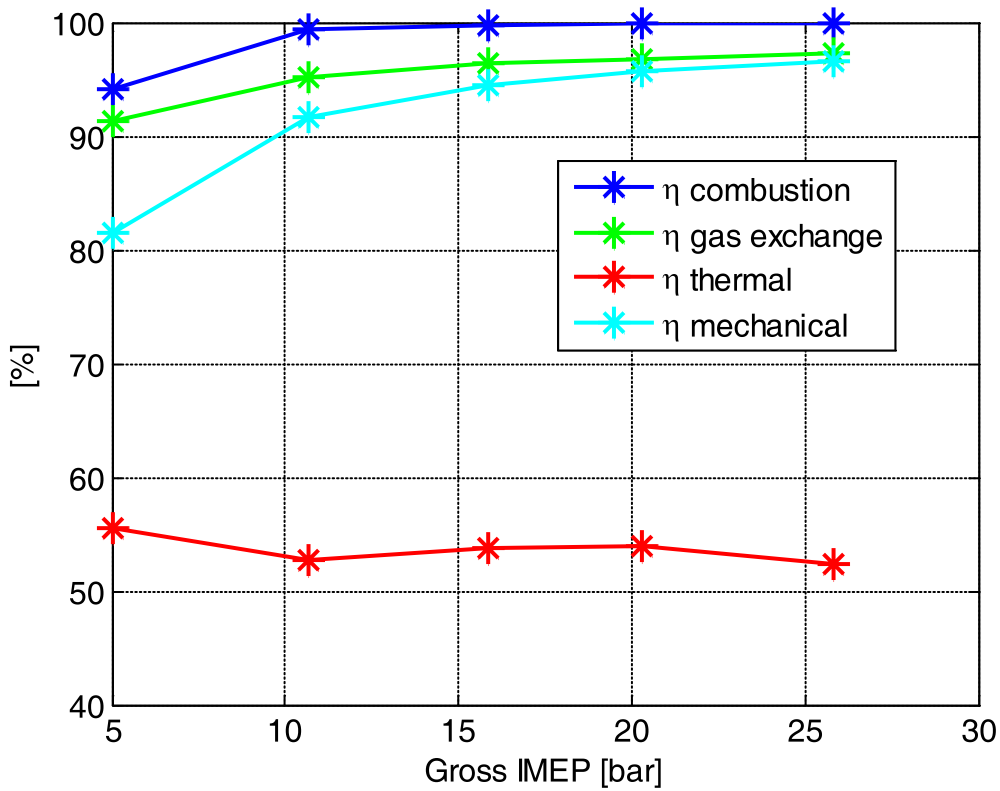
50% brake efficiency seems viable!!!



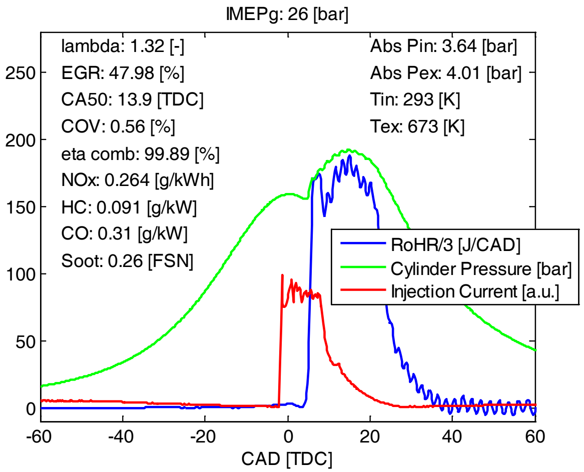
Efficiency

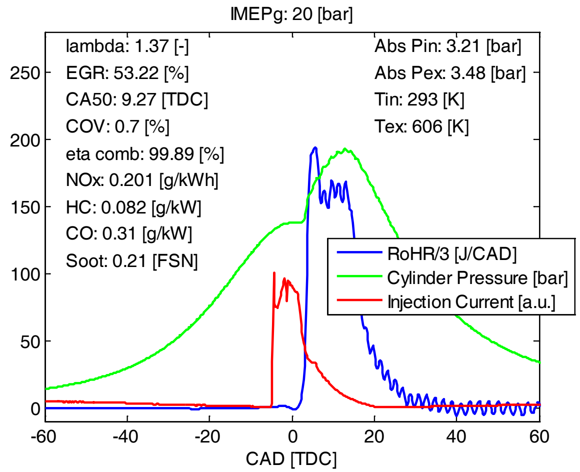
50% brake efficiency ➔ maximization of all intermediate efficiencies

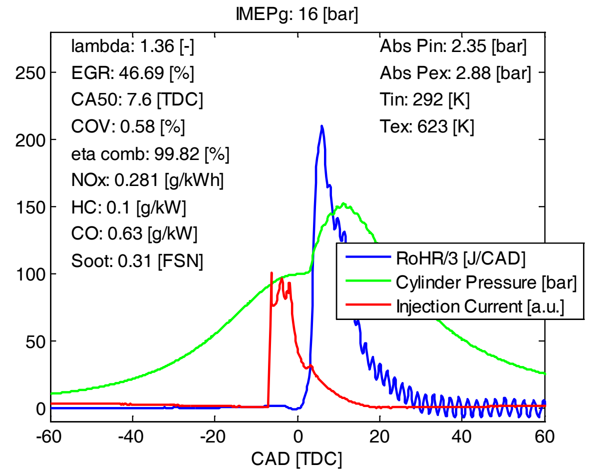
$$\eta_{Brake} = \eta_{Combustion} \cdot \eta_{Thermodynamic} \cdot \eta_{GasExchange} \cdot \eta_{Mechanical}$$

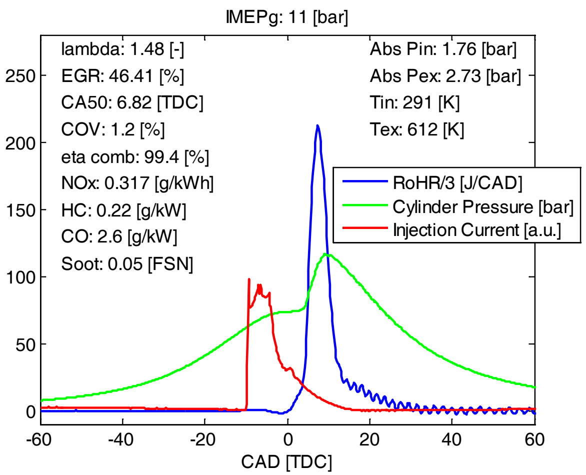


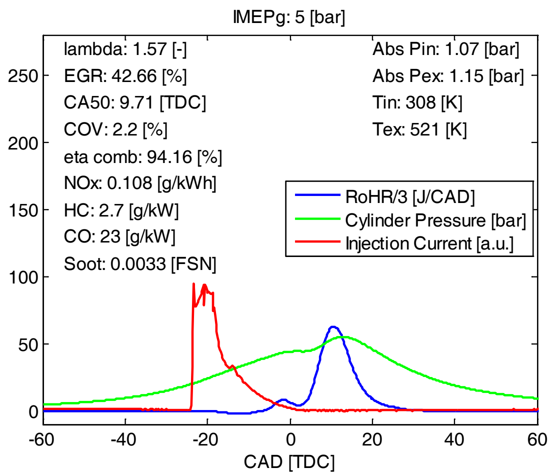
RoHR, Cylinder Pressure & Injection Signal



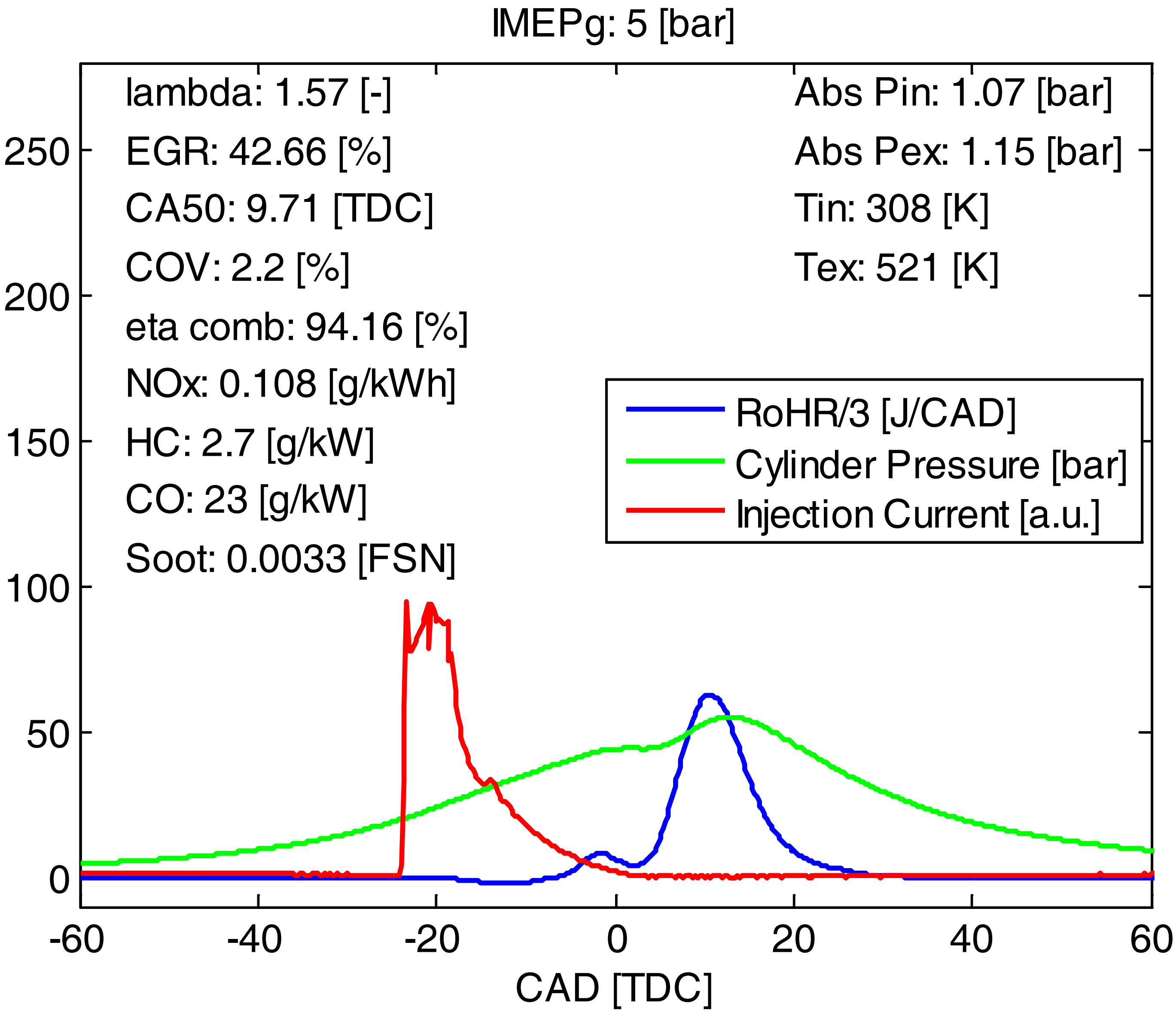




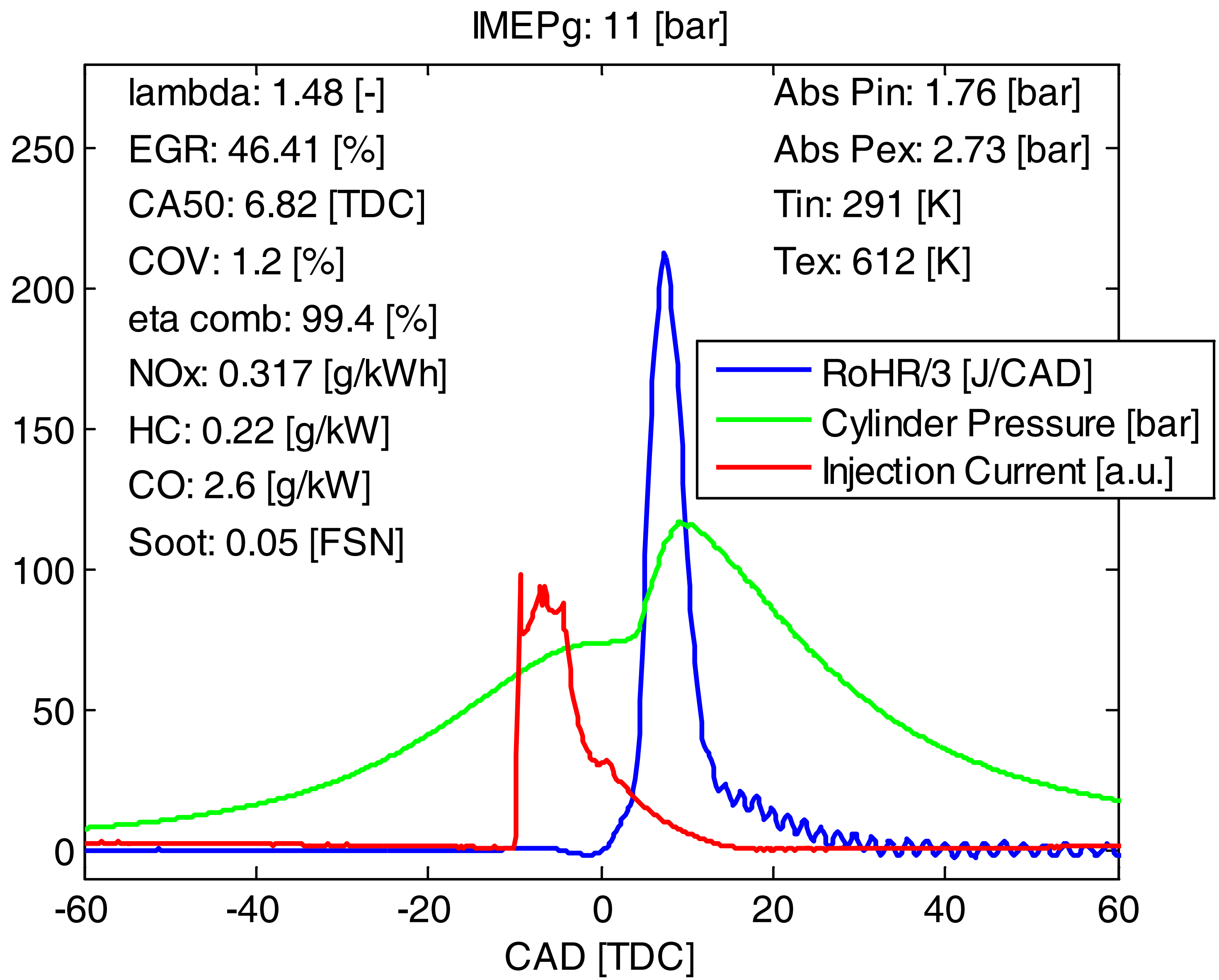




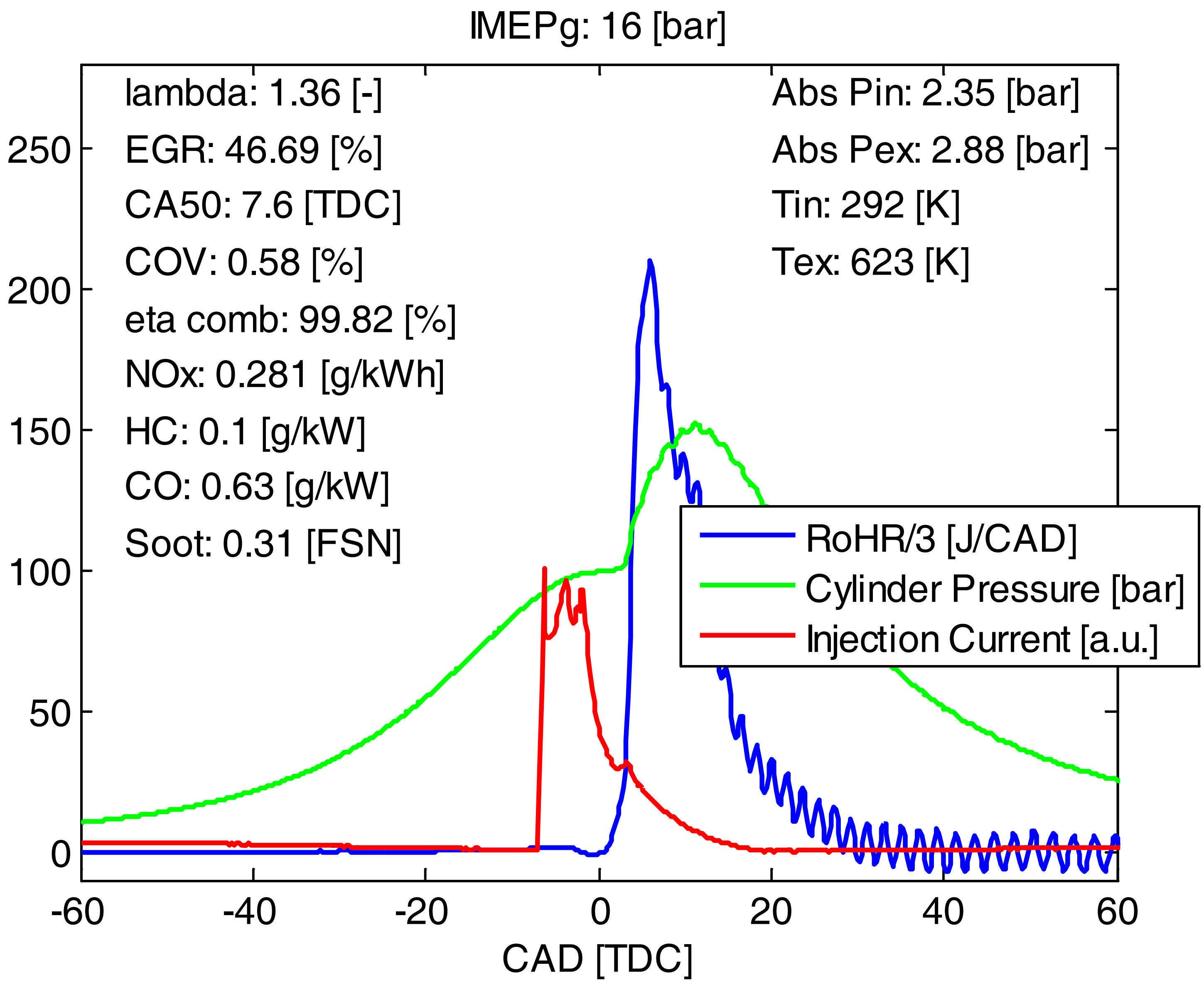
RoHR, Cylinder Pressure & Injection Signal



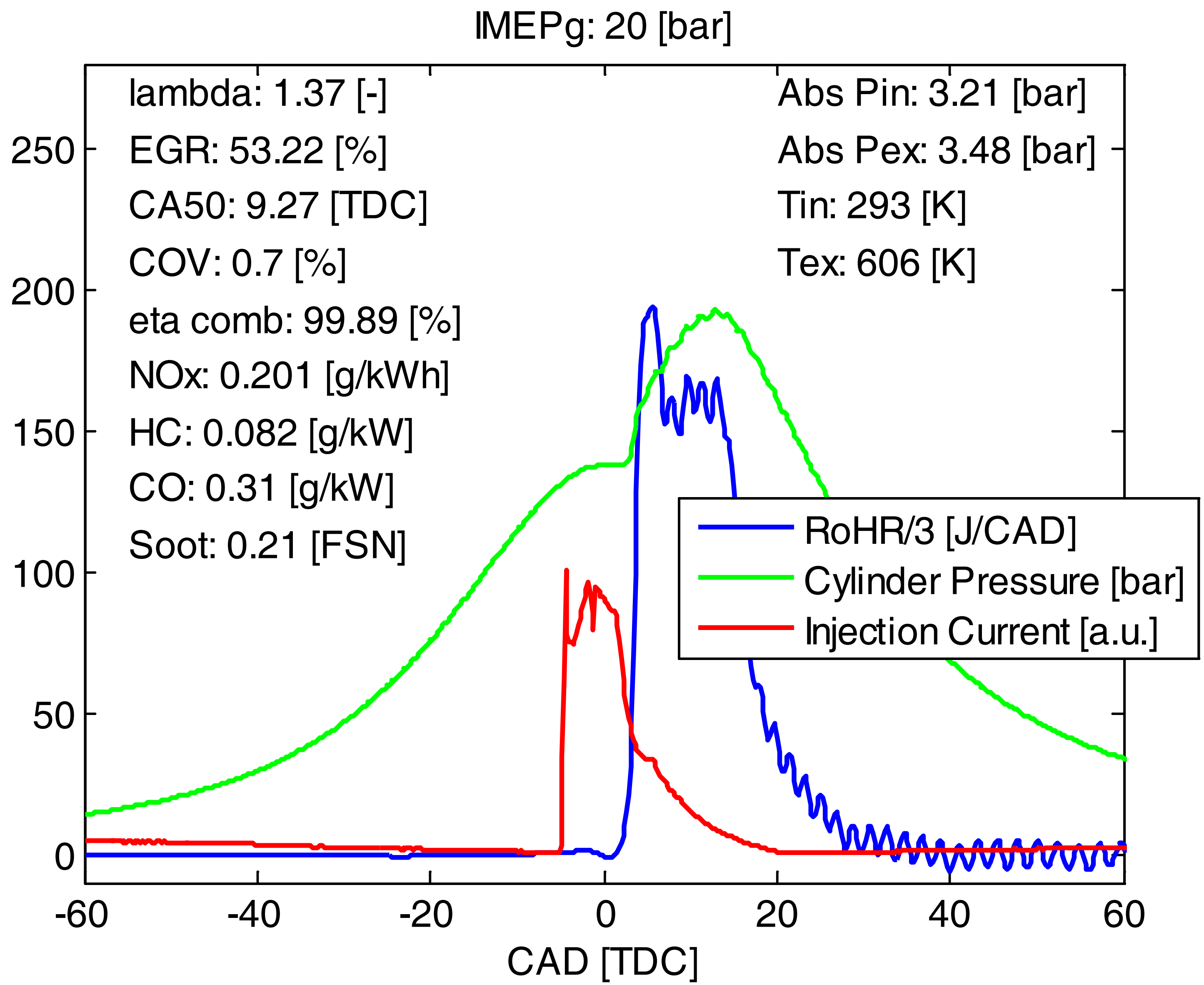
RoHR, Cylinder Pressure & Injection Signal



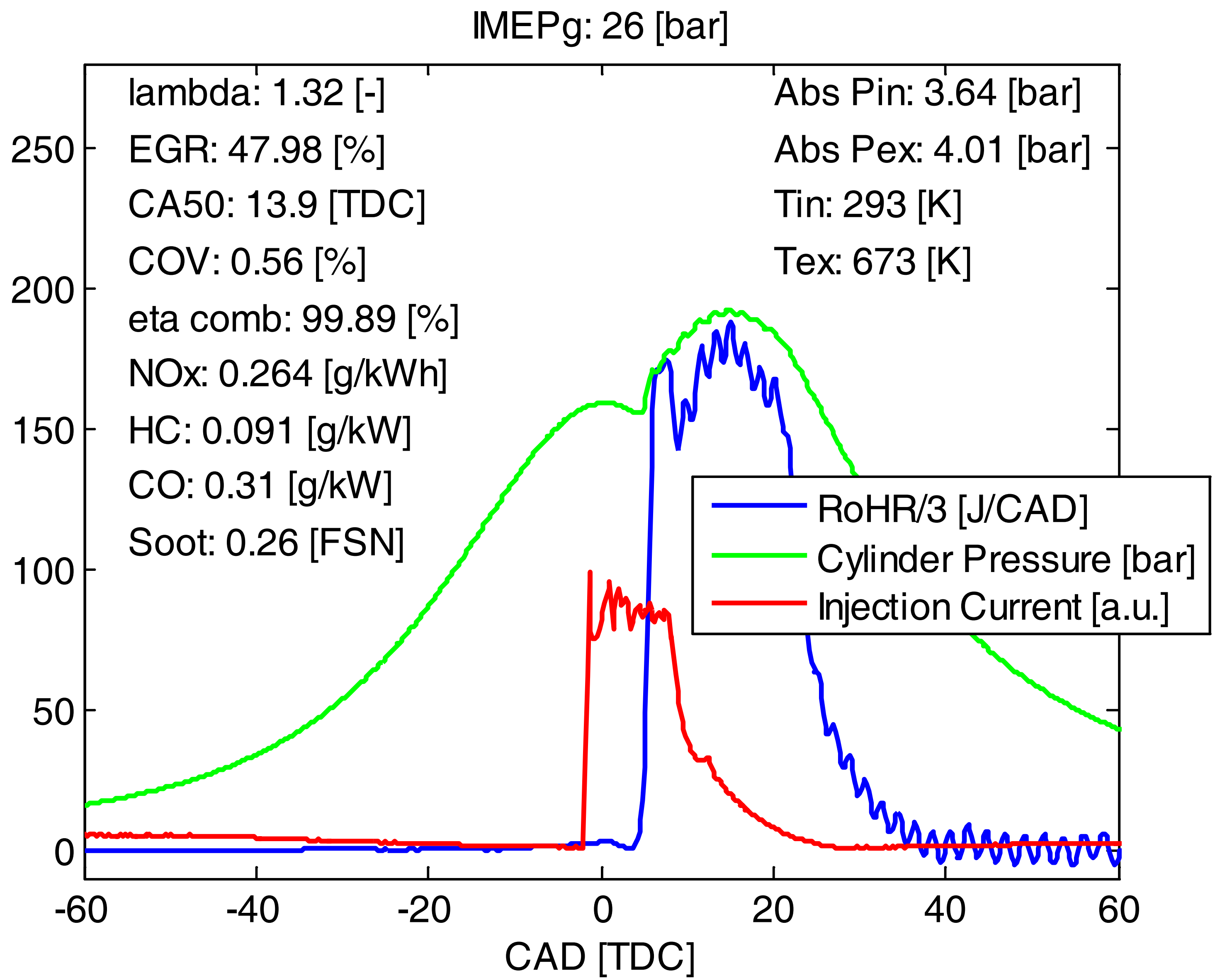
RoHR, Cylinder Pressure & Injection Signal



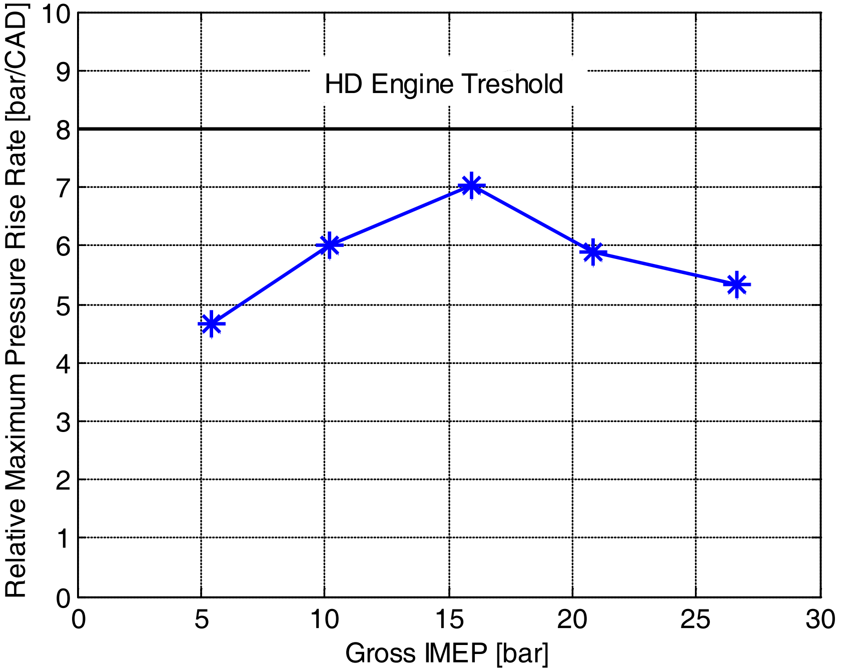
RoHR, Cylinder Pressure & Injection Signal

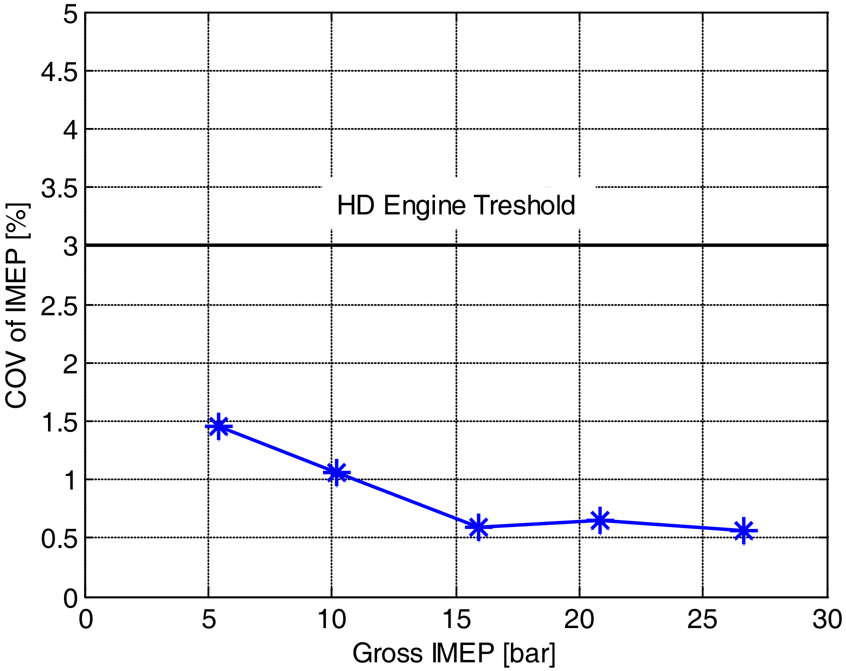


RoHR, Cylinder Pressure & Injection Signal

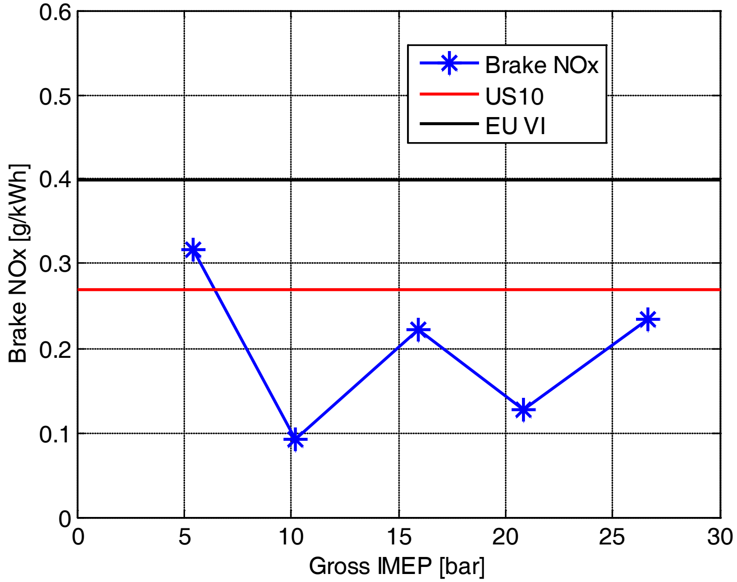


Combustion Noise & Stability

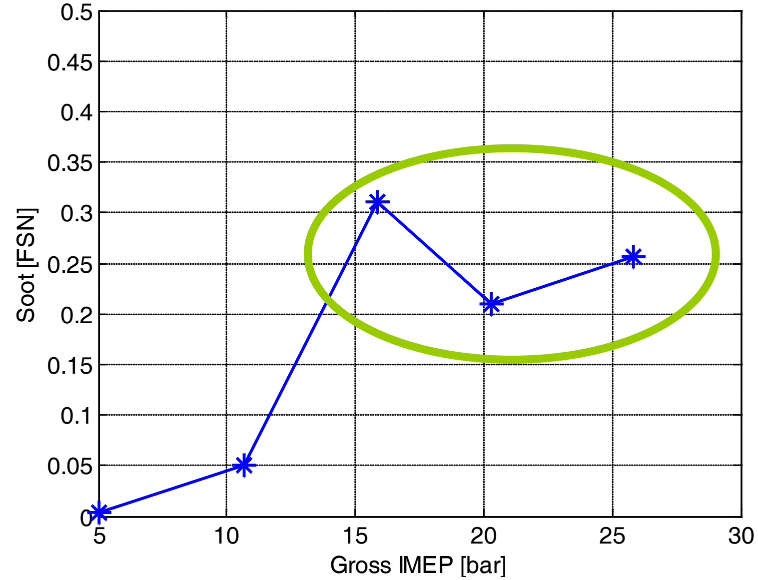




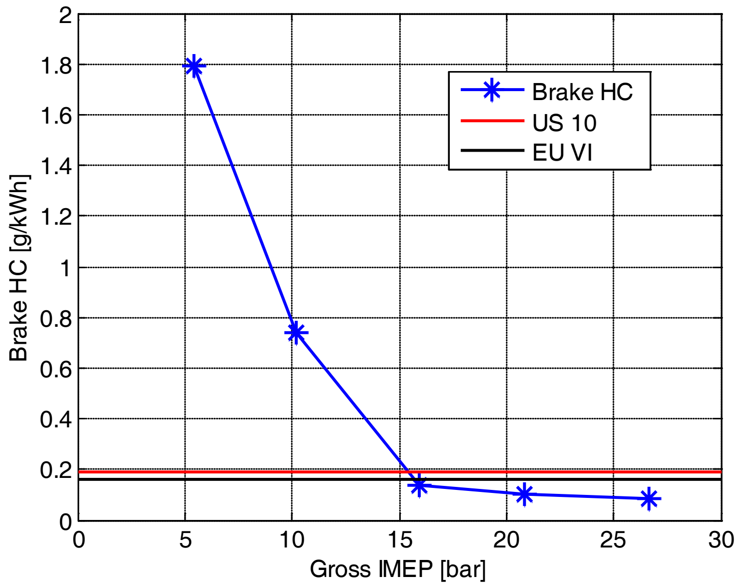
Emissions



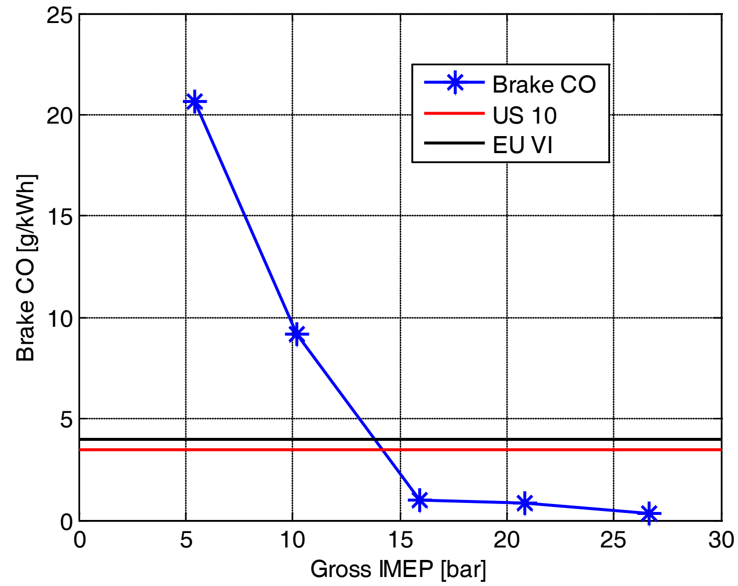
Brake NOx
US10
EU VI
Brake NOx [g/kWh]
Gross IMEP [bar]
0
0.1
0.2
0.3
0.4
0.5
0.6
0
5
10
15
20
25
30



Soot [FSN]
Gross IMEP [bar]
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
5
10
15
20
25
30



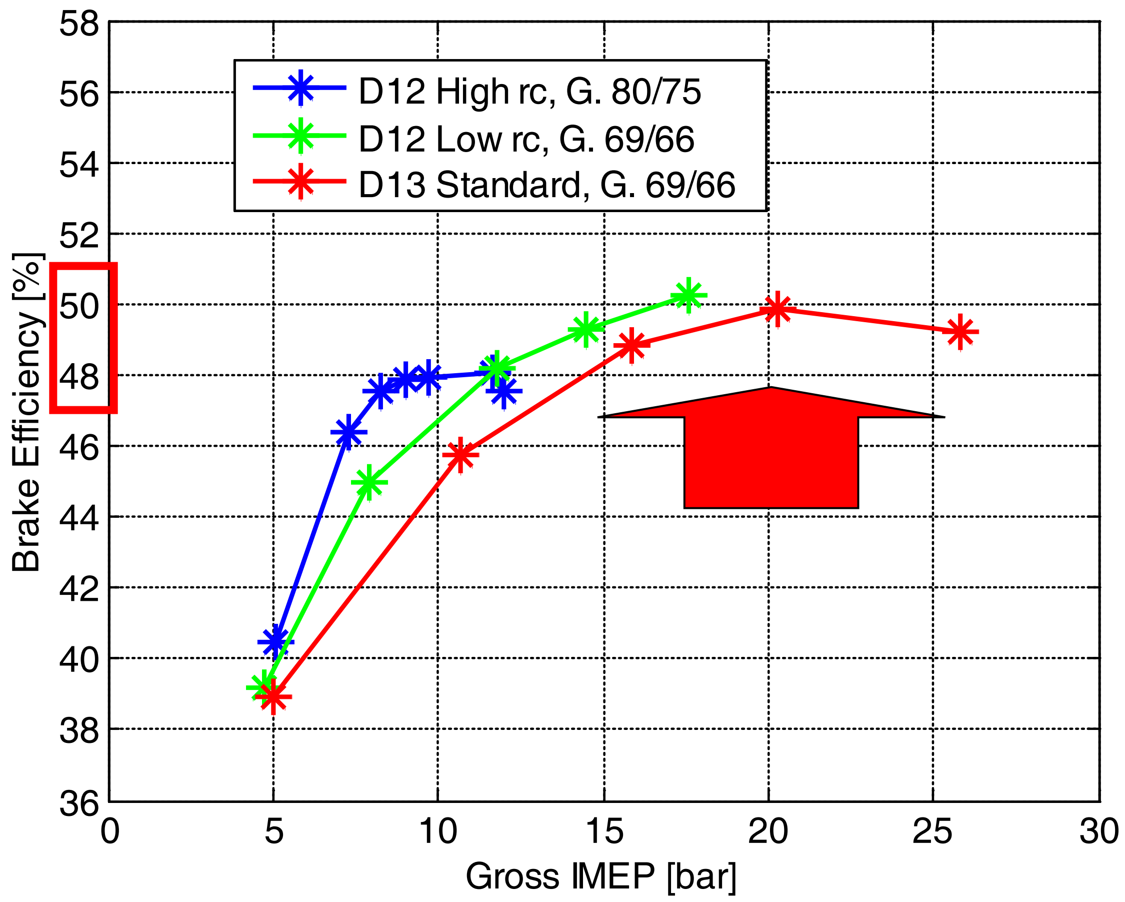
Brake HC
US 10
EU VI
Brake HC [g/kWh]
Gross IMEP [bar]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
5
10
15
20
25
30



Brake CO
US 10
EU VI
Brake CO [g/kWh]
Gross IMEP [bar]
0
5
10
15
20
25
0
5
10
15
20
25
30

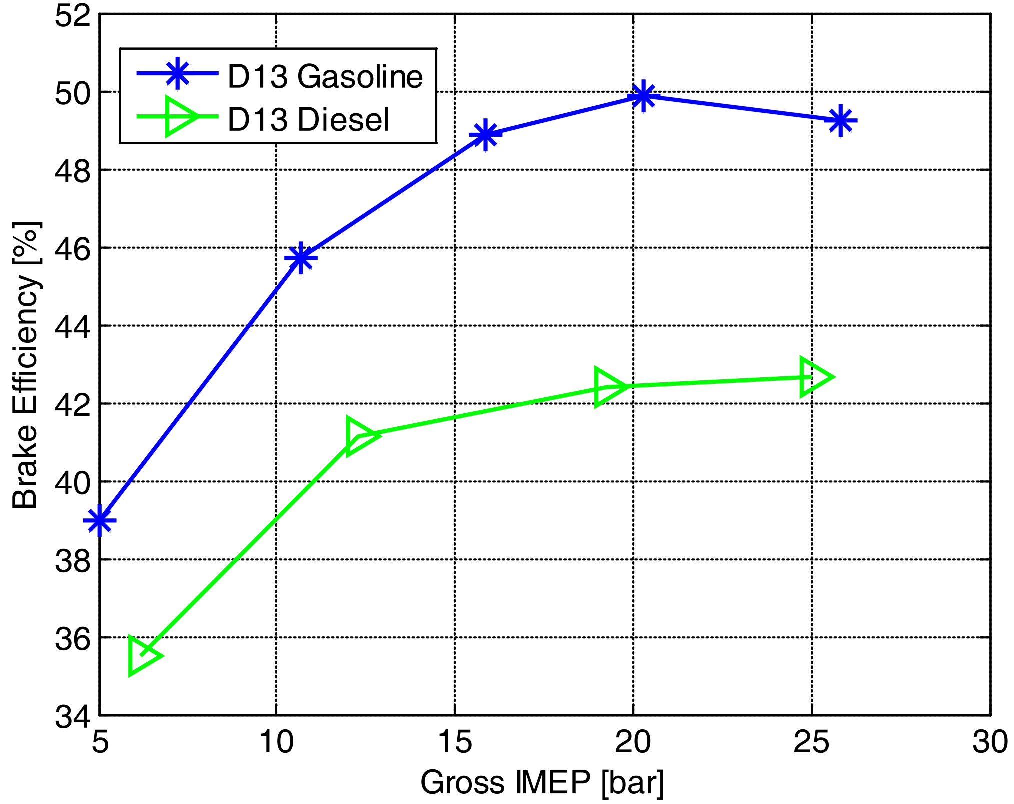
Summary

Brake Efficiency



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

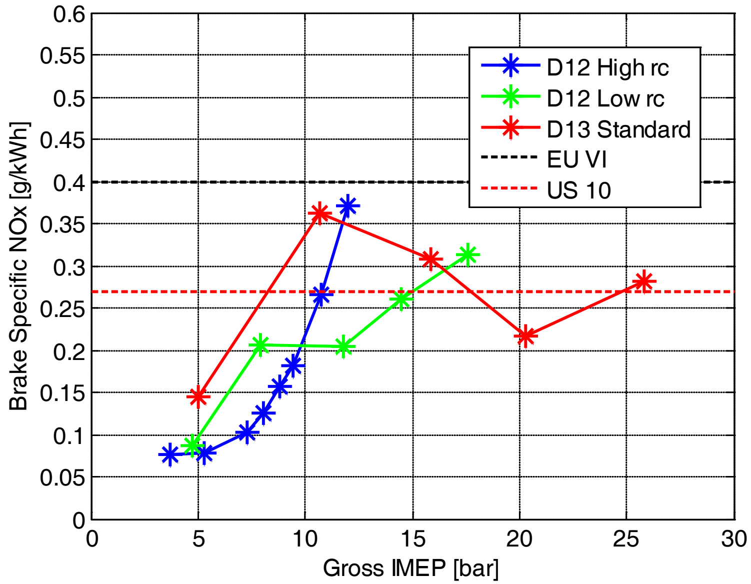
D13 Running on Diesel & Gasoline

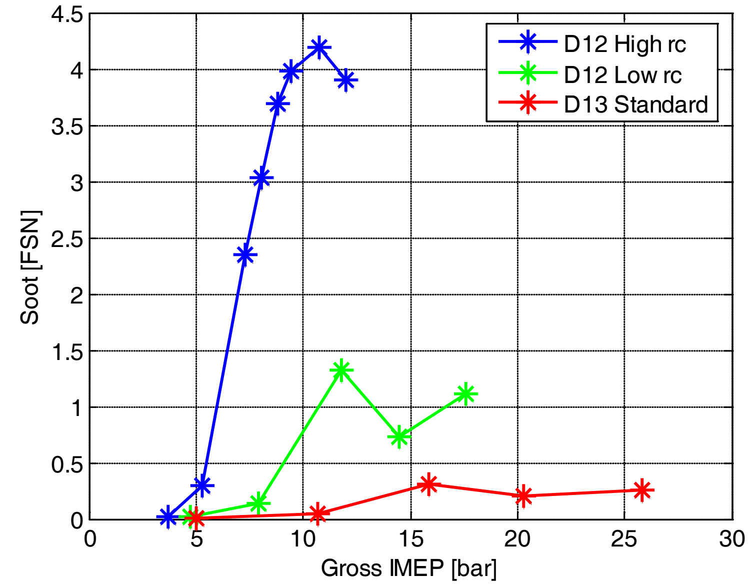


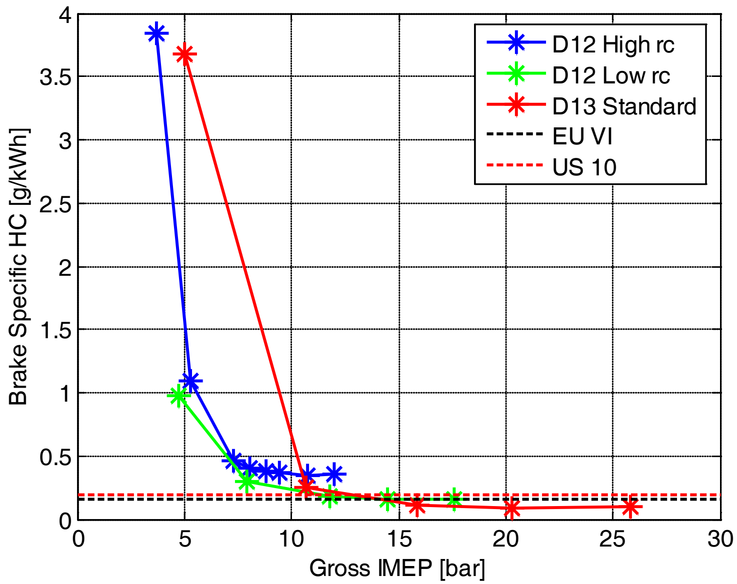
D13 Diesel was calibrated by Scania and the calibration was done to meet EU V legislation.

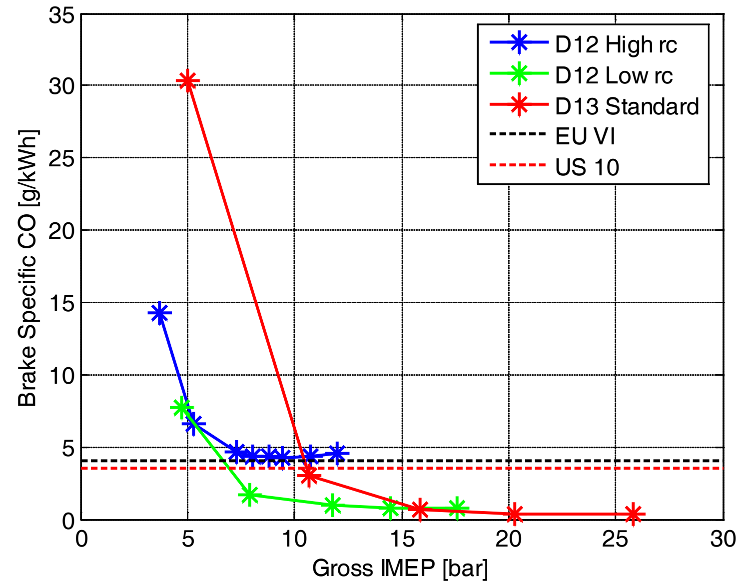
Average improvement of 16.6% points @ high load!!!

Brake Emissions

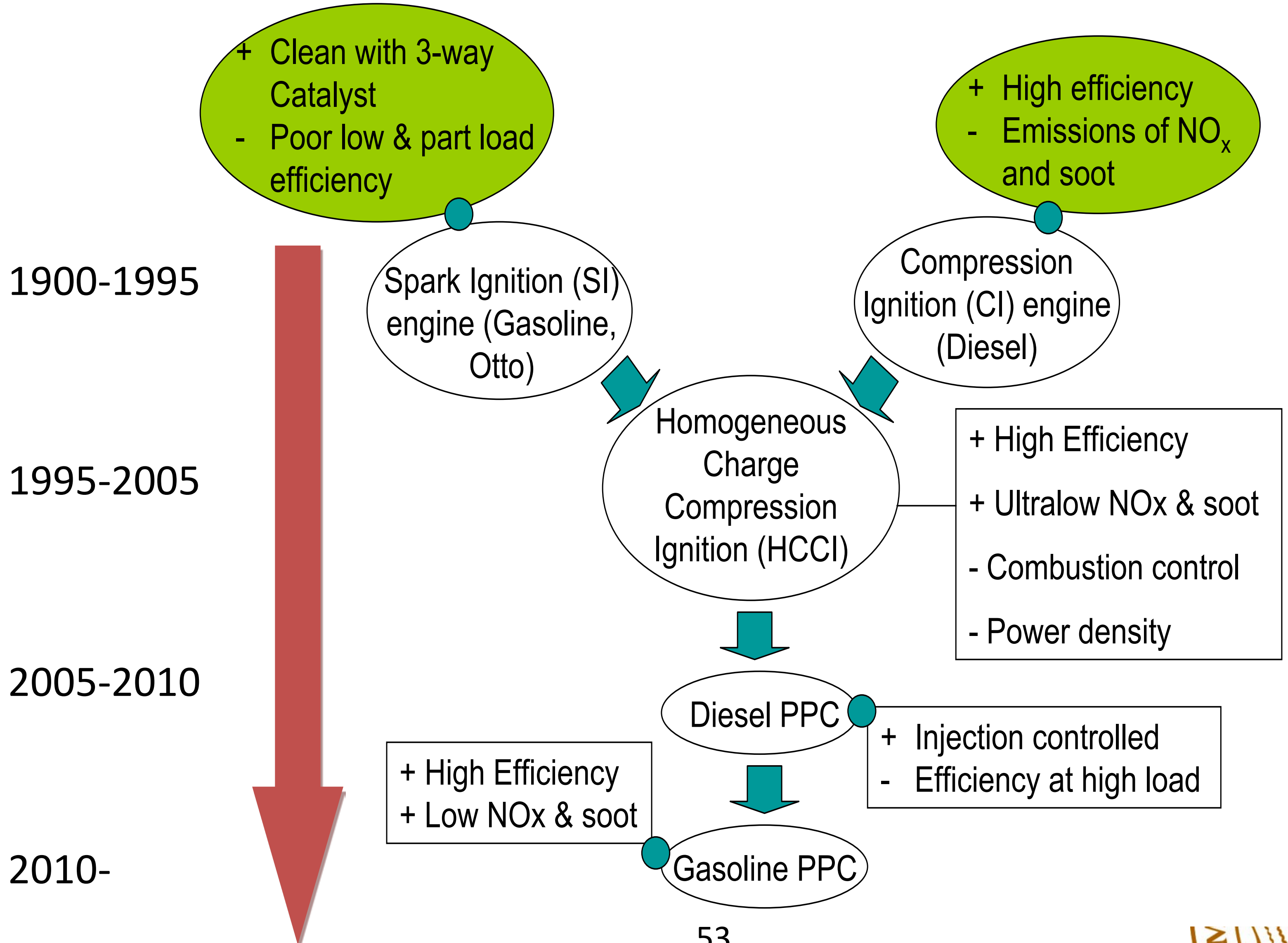








Engine combustion - direction

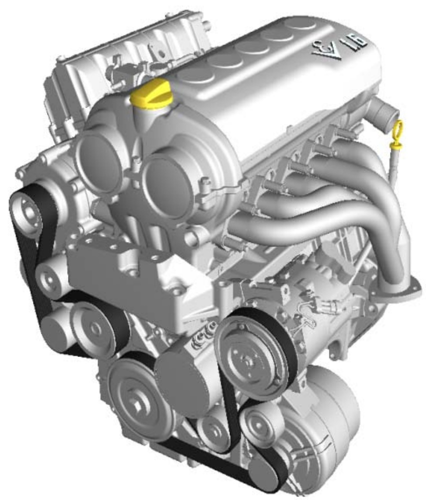


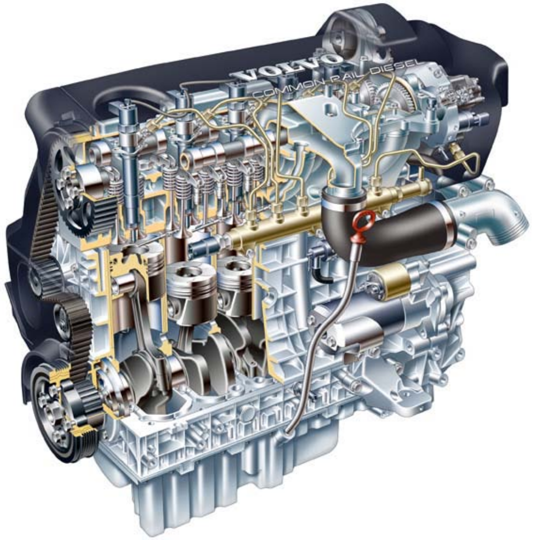
The End

Thank you

Path to High Efficiency Gasoline Engine

SI → **HCCI** → **PPC**





Prof. Bengt Johansson

Division of Combustion Engines
Department of Energy Sciences

Lund University

Outline

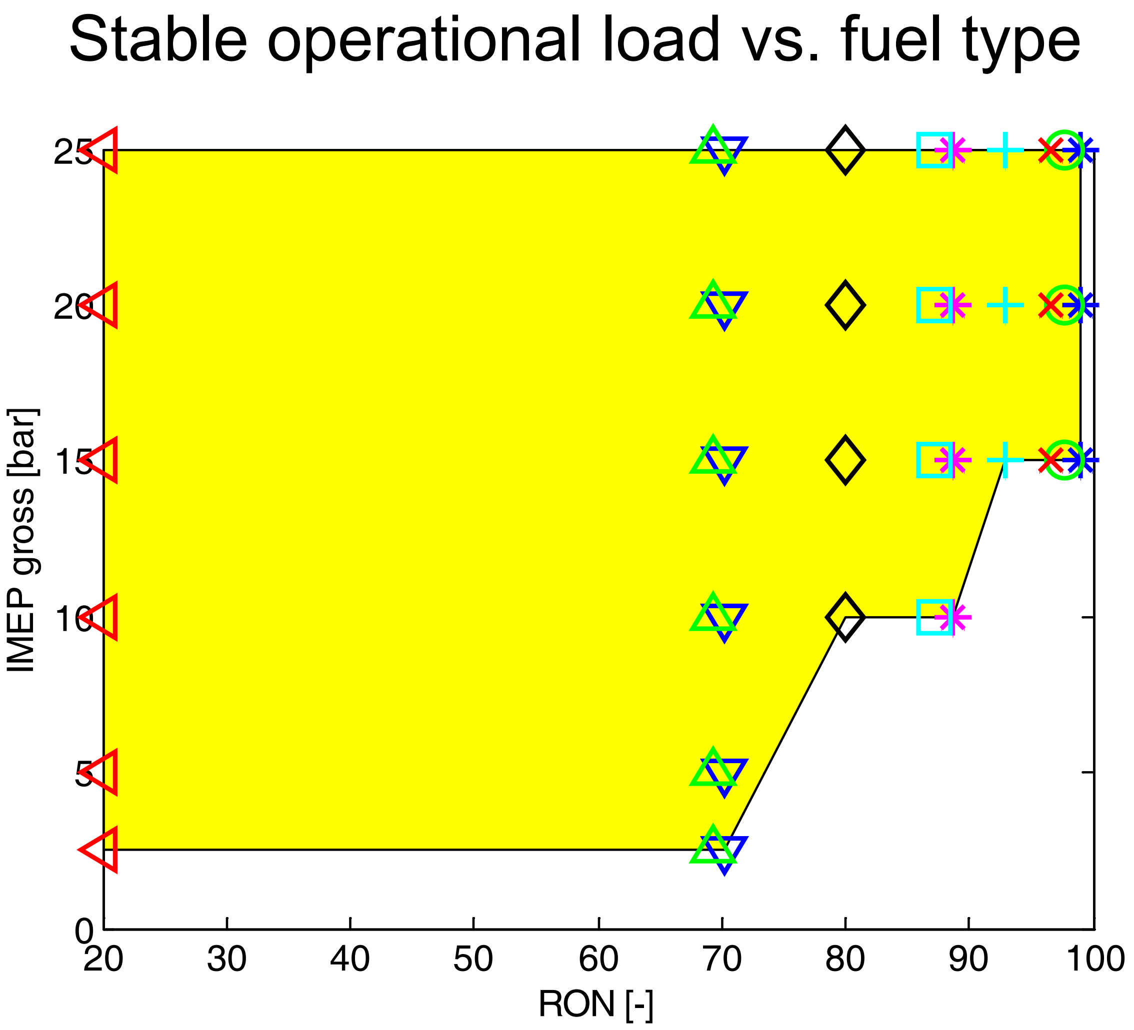
- Partially premixed combustion, PPC
  - Summary of
    - 56% thermal efficiency in car size engine
    - 57% thermal efficiency in truck size engine
    - Why 55% thermal efficiency is better than 57%
  - Fuel effects in Scania D12 engine
  - How to reach 26 bar IMEP with US10 NOx, PM, HC and CO engine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

Fuel Matrix

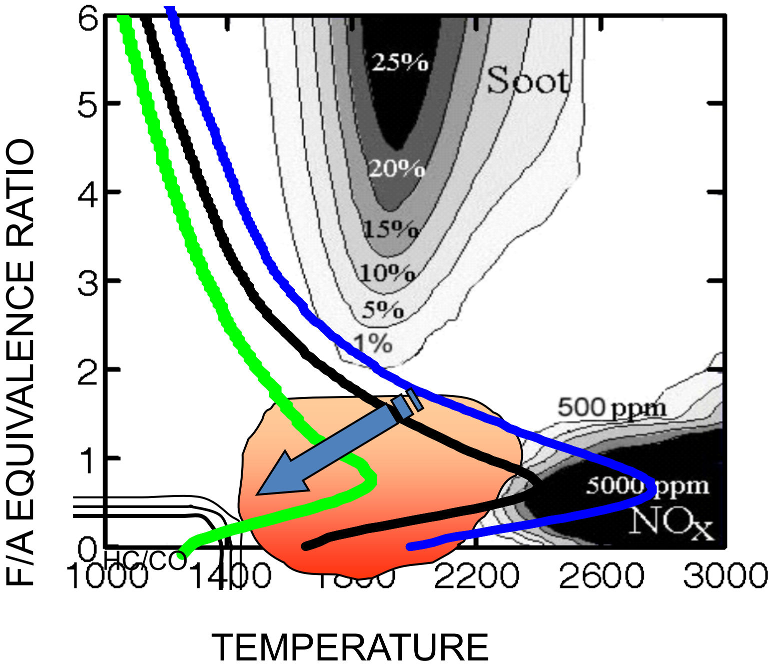
		RON	MON	C	H/C	O/C	LHV [MJ/kg]	A/F stoich
Group 1	**FR47335CVX**	99.0	96.9	7.04	2.28	0.00	44.30	15.10
	FR47332CVX	97.7	87.5	6.61	2.06	0.07	39.70	13.44
	FR47337CVX	96.5	86.1	7.53	1.53	0.00	42.10	14.03
Group 2	**FR47338CVX**	88.6	79.5	7.21	1.88	0.00	43.50	14.53
	FR47330CVX	87.1	80.5	7.20	1.92	0.00	43.50	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

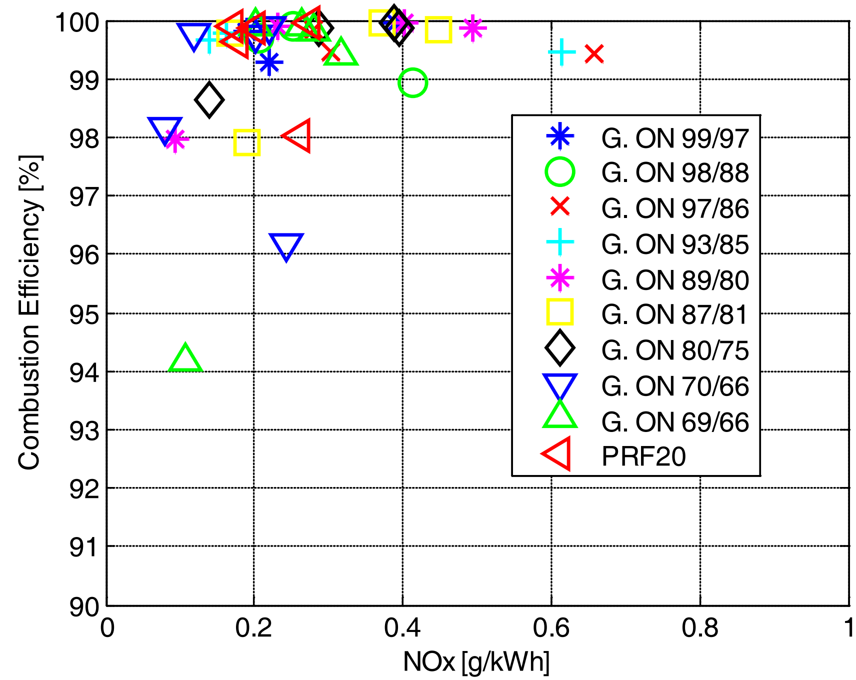
Results

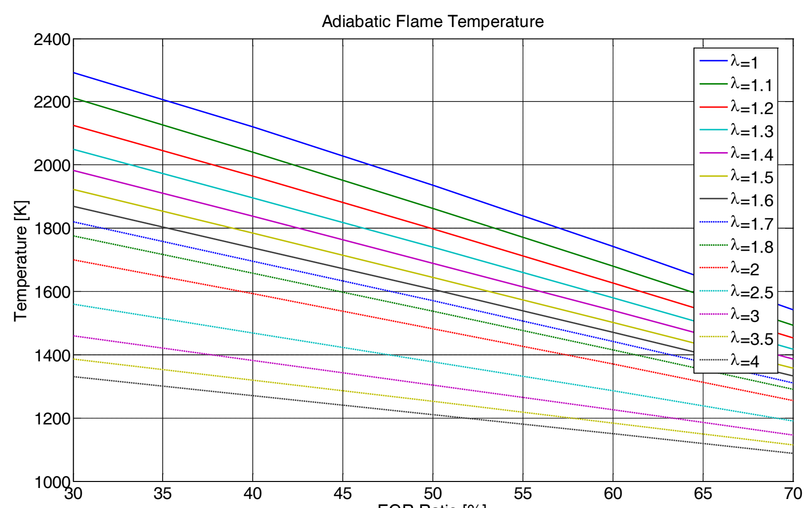
Tested Load Area



NOx - η_{comb} Trade – Off Solution

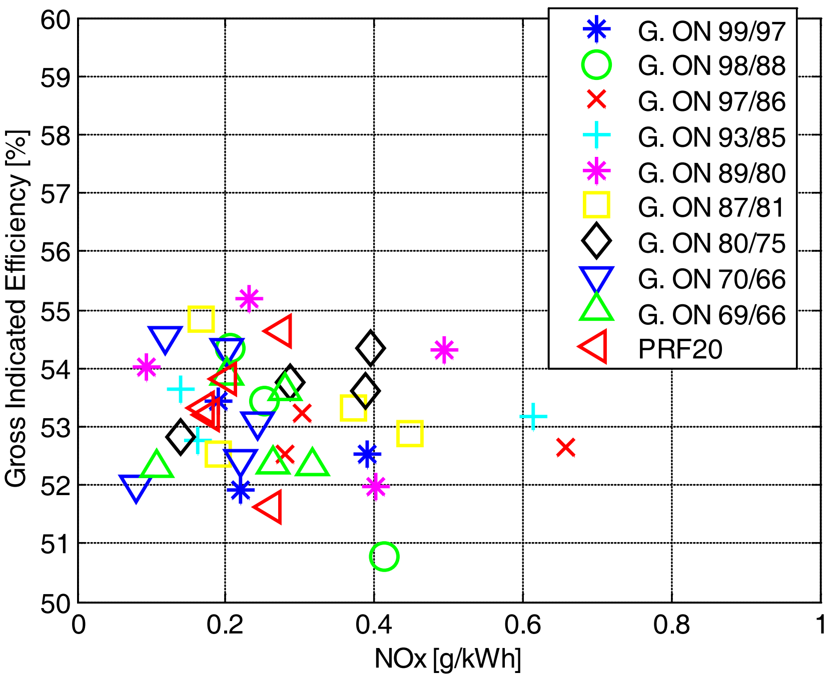


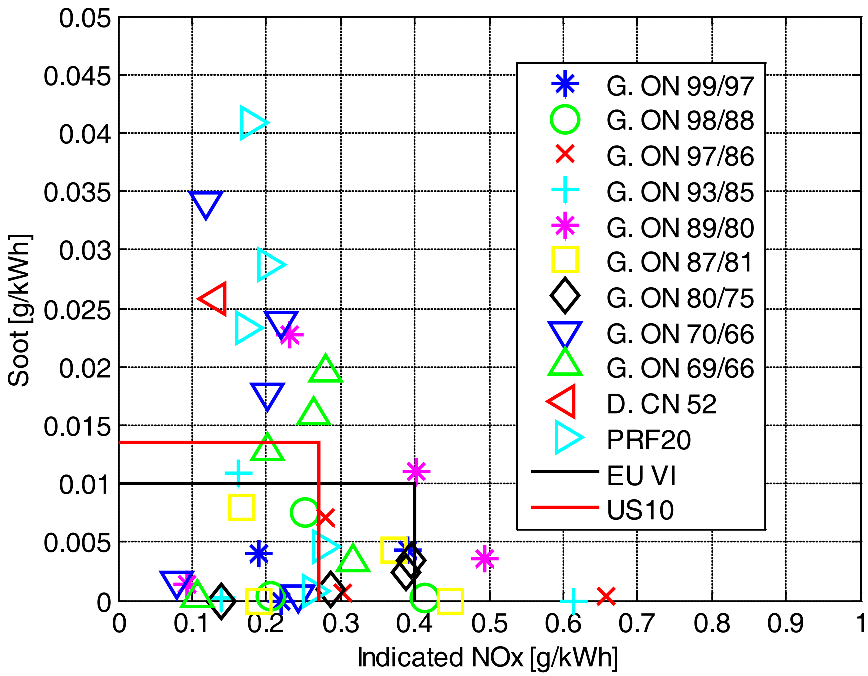




It is possible to achieve low NOx and still keep high combustion efficiency in the whole load range!

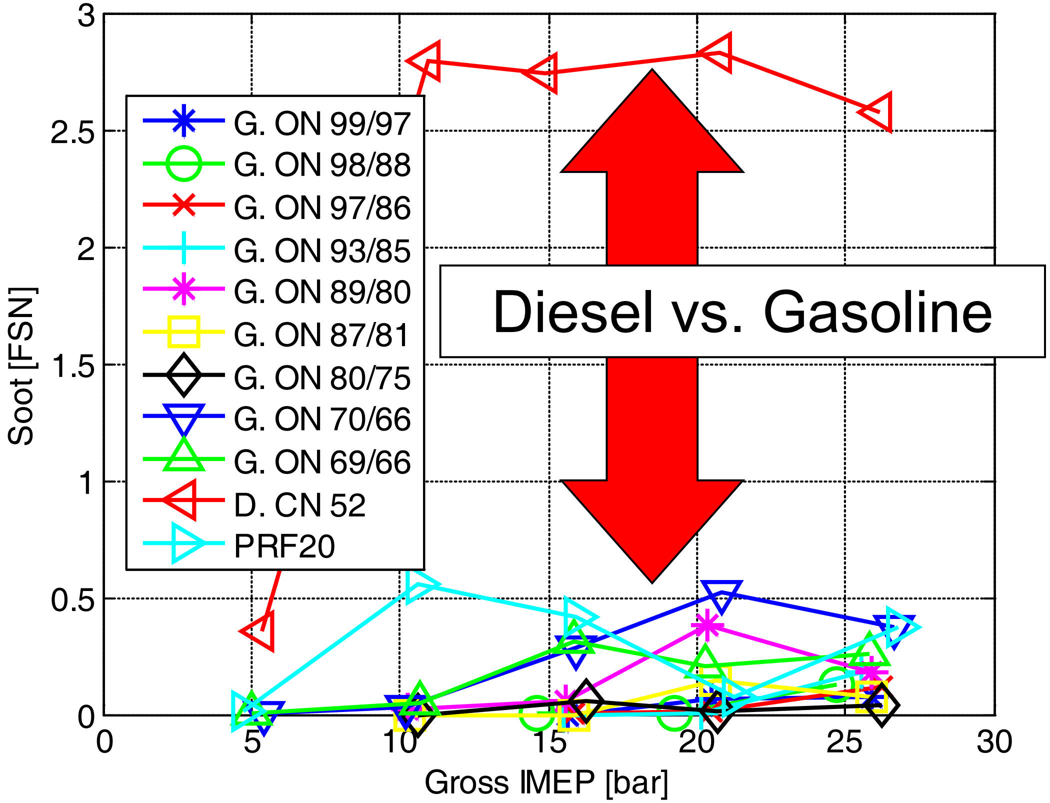
Efficiency & Emissions



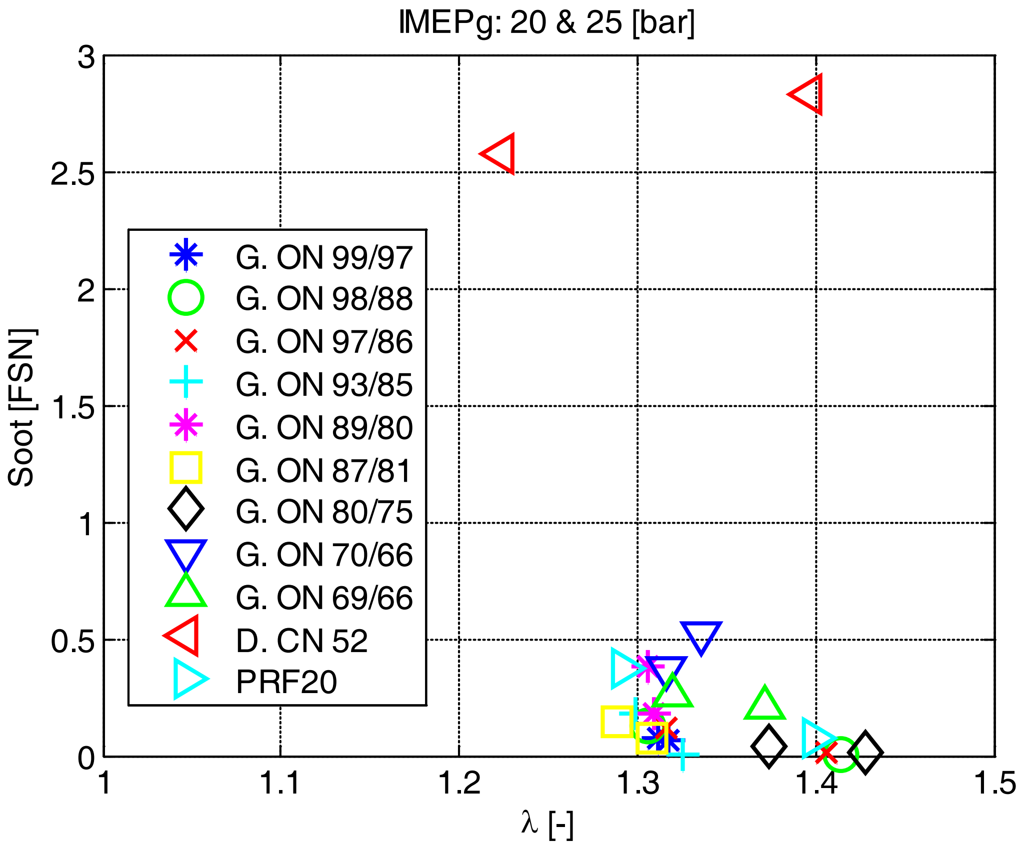


In certain operating range, some fuels are capable to comply EU VI & US10 legislations and still keep high efficiency without compromising the efficiency!

Soot Emissions

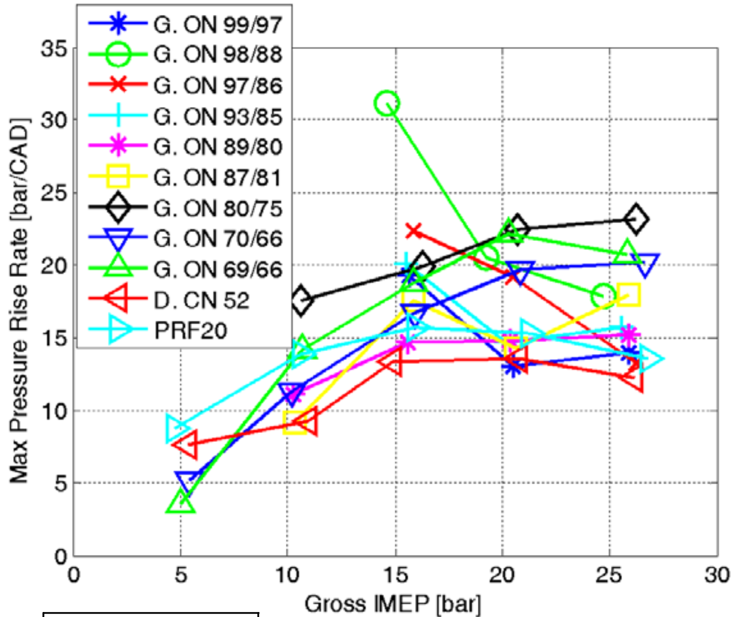


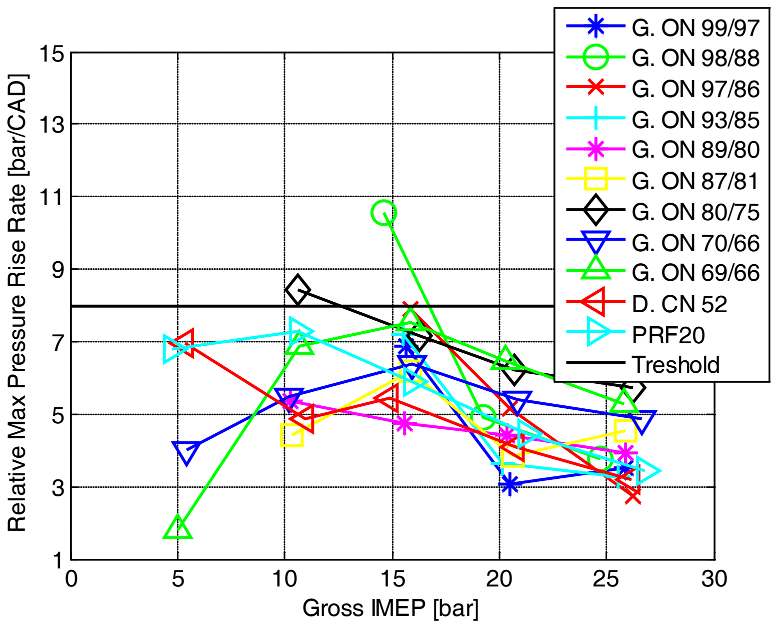
Higher Power Density

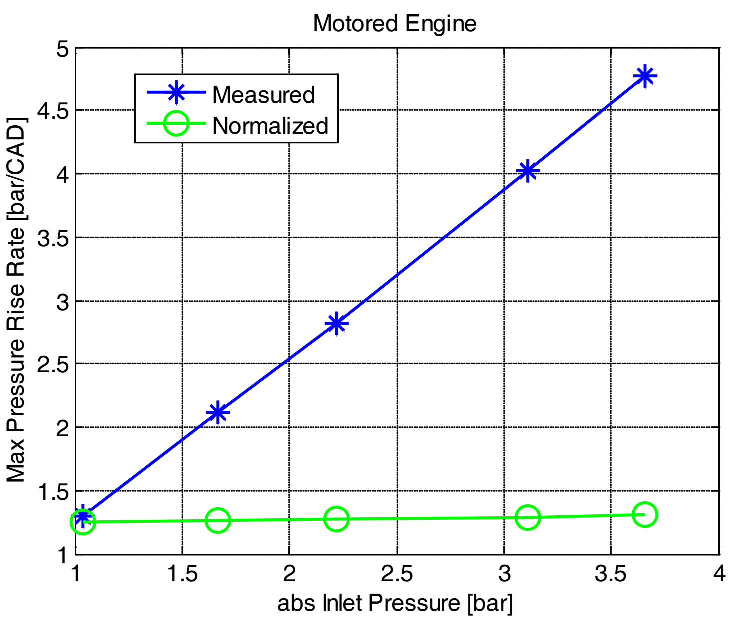


Low soot even @ λ 1.3 ➔ higher power density without producing smoke!

Acoustic Noise

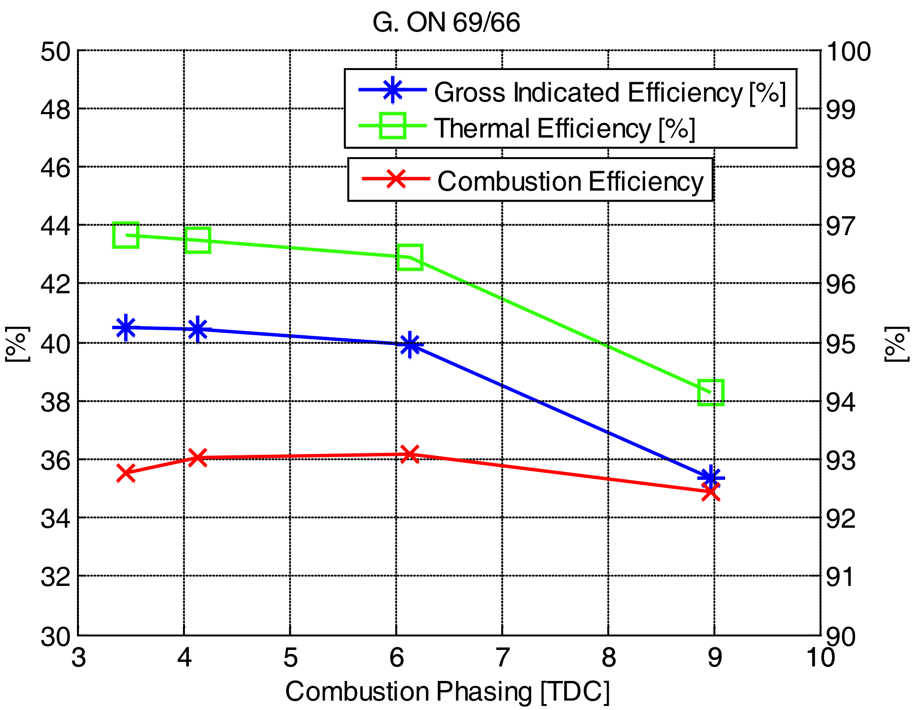


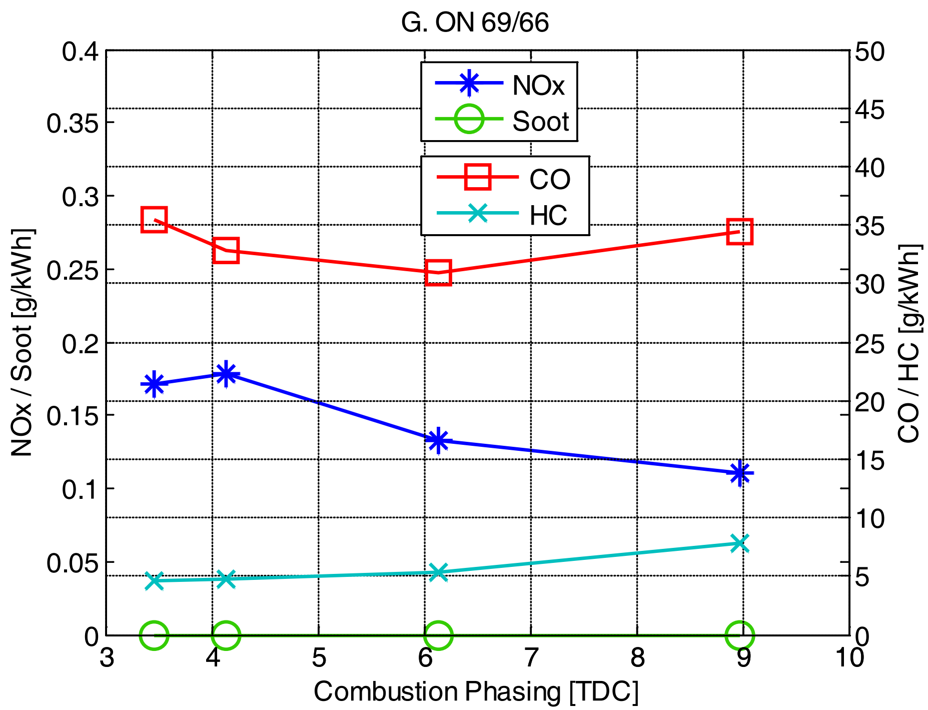




Idle

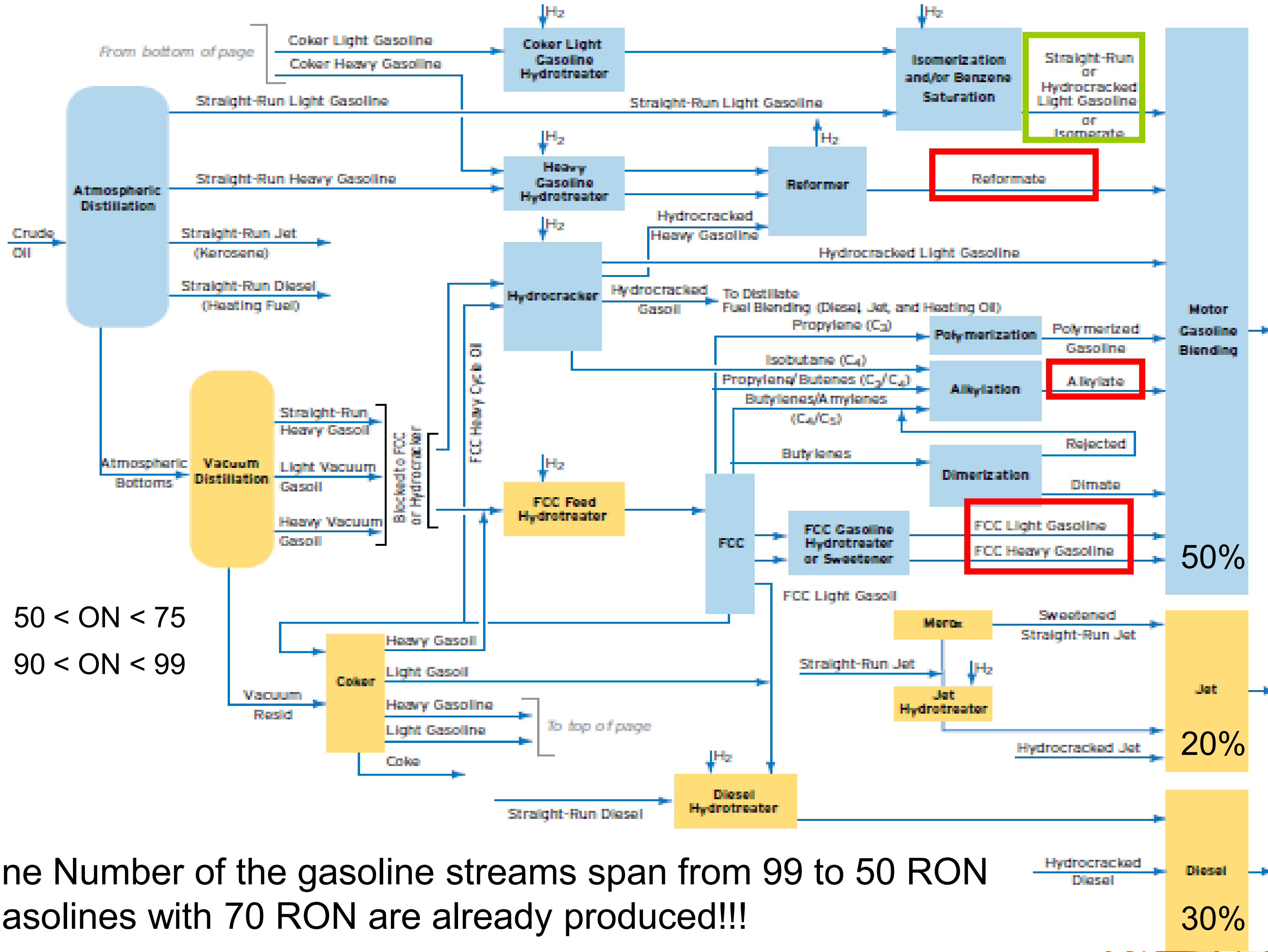
Efficiencies & Emissions





Viability of Low ON Gasolines for PPC?

Oil Refineries Production Layout



50 < ON < 75

90 < ON < 99

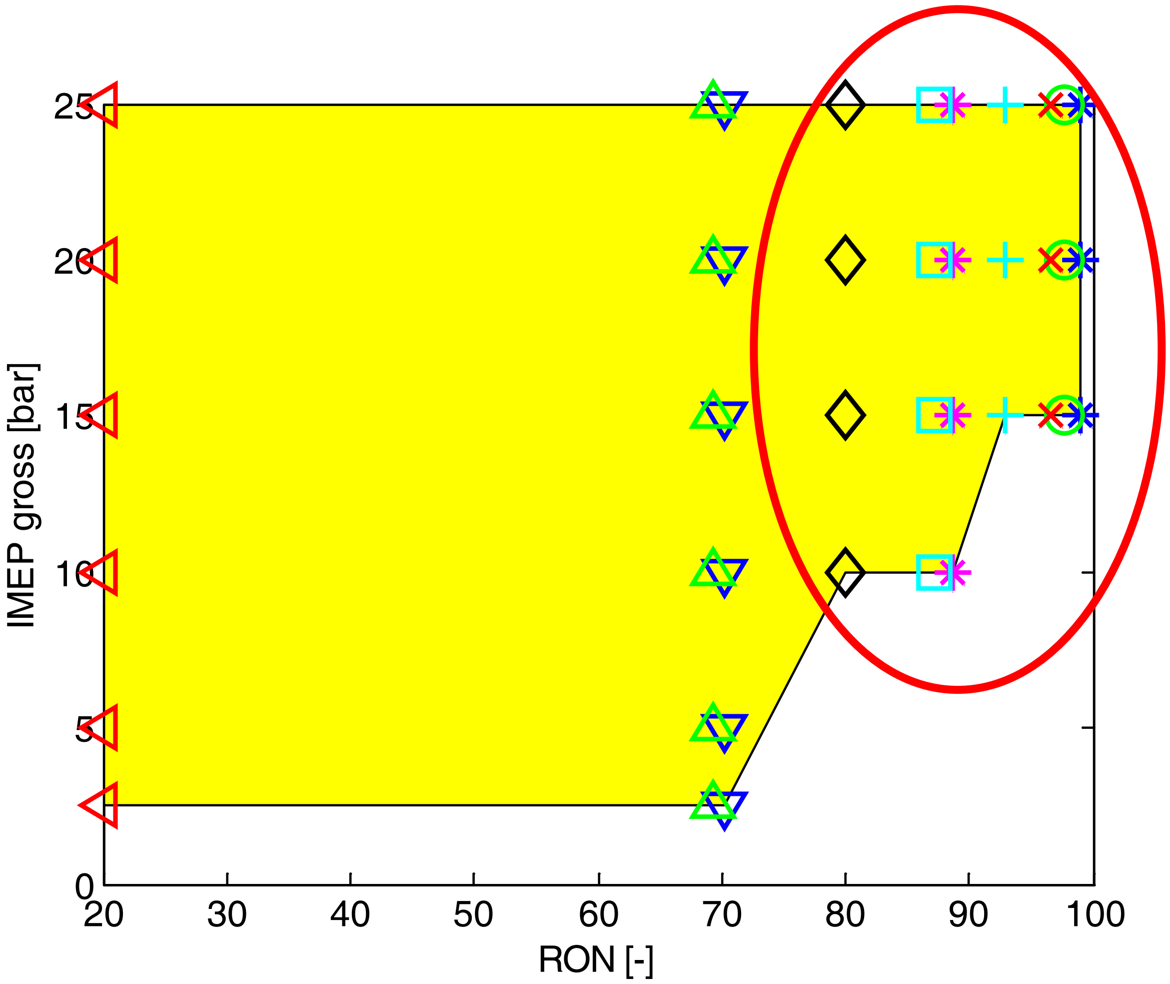
Octane Number of the gasoline streams span from 99 to 50 RON

➔ 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



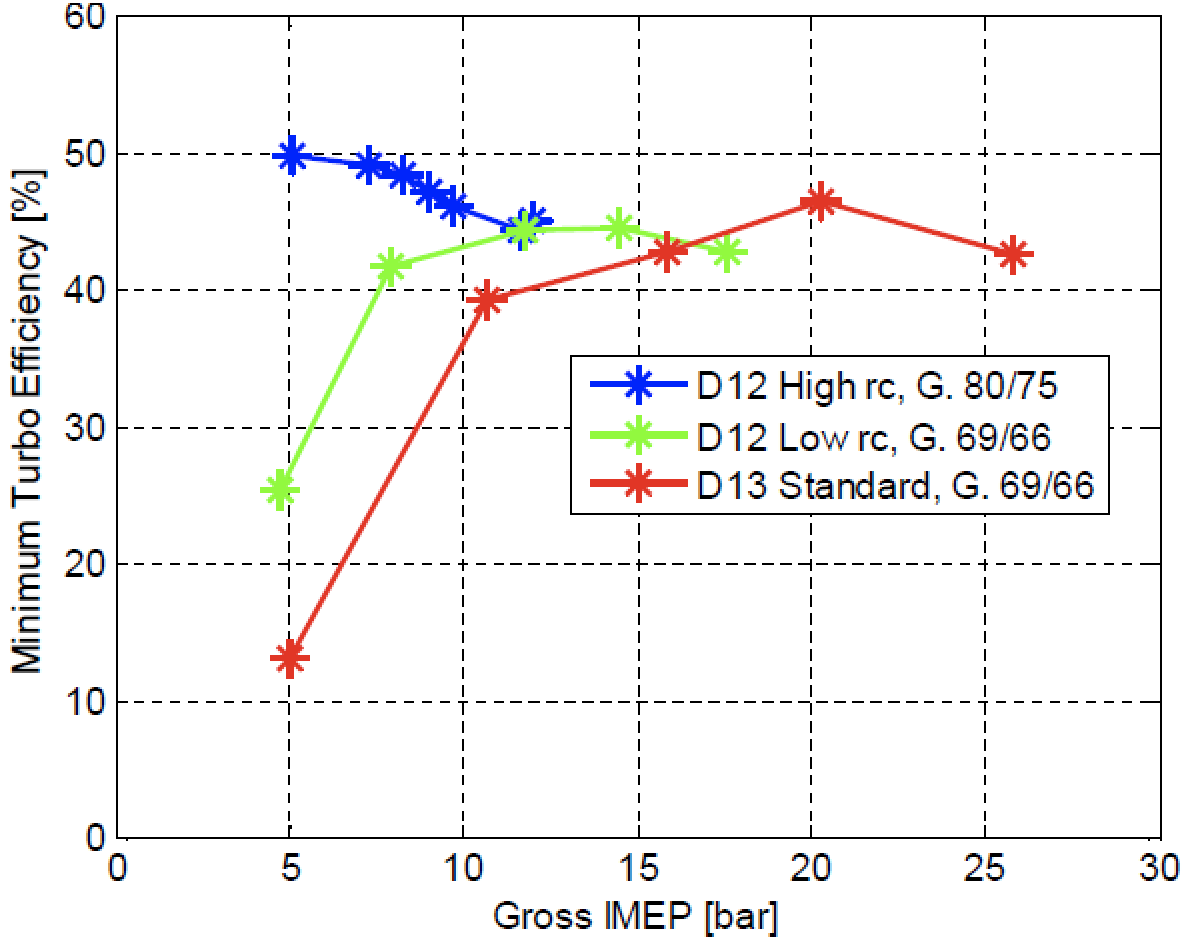
What to do with these fuels?!

Still to be used in SI engines?!

Page 70

Minimum Turbo Efficiency

$$W_{compressor\_ideal} = \eta_{compressor} \cdot \eta_{turbine} \cdot \eta_{mechanical} \cdot W_{turbine\_ideal}$$

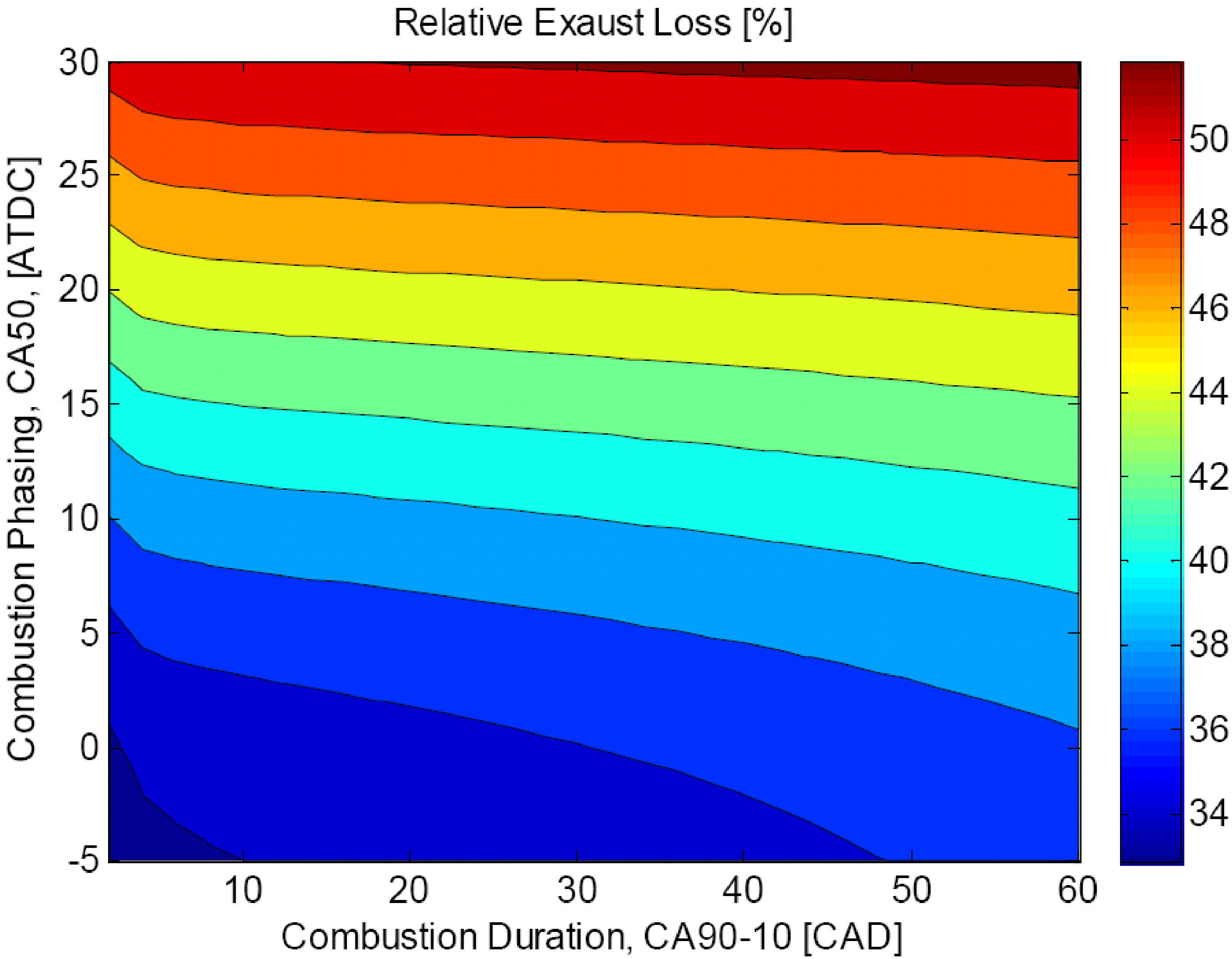


Ideal burn rate?

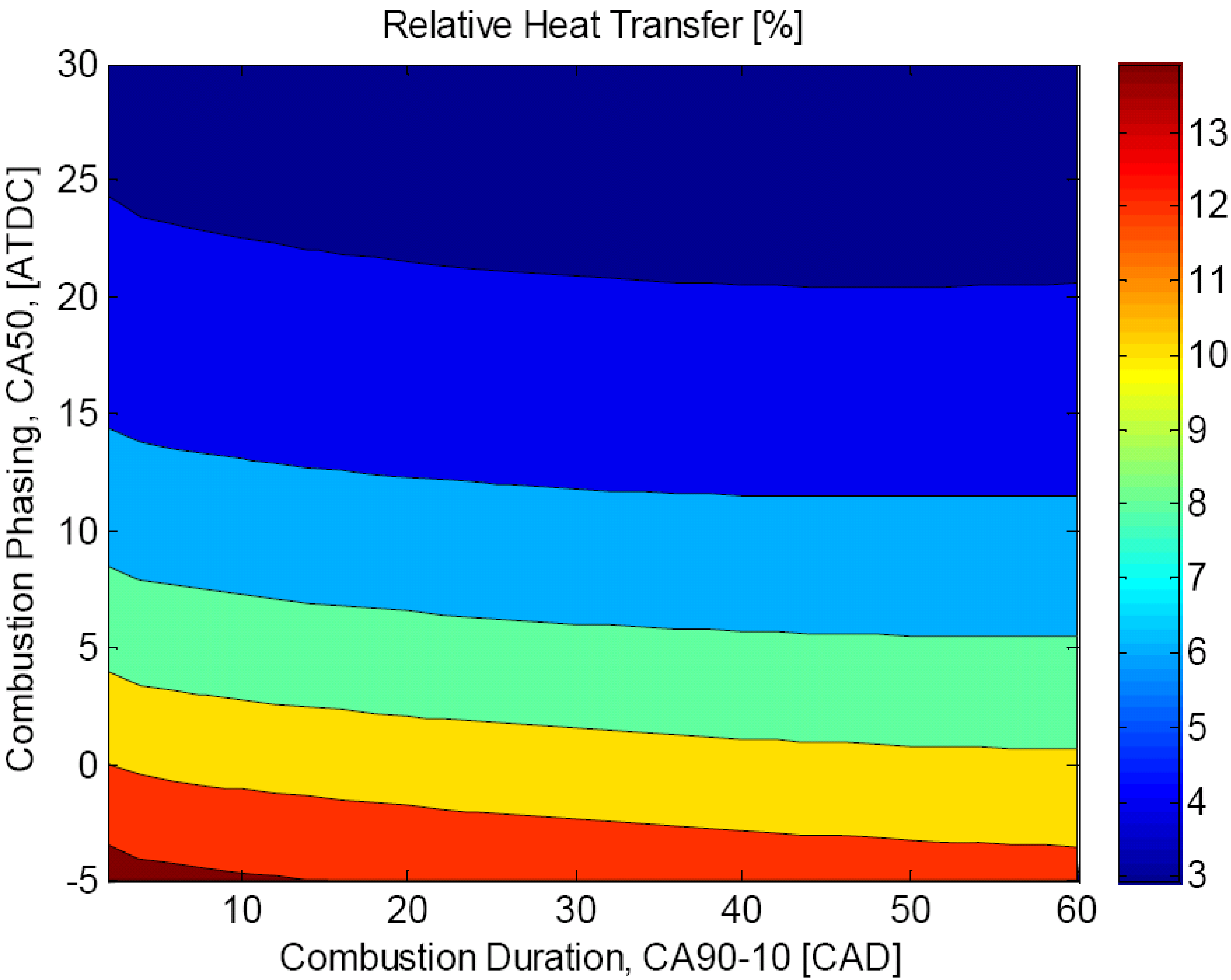
Conditions:

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.

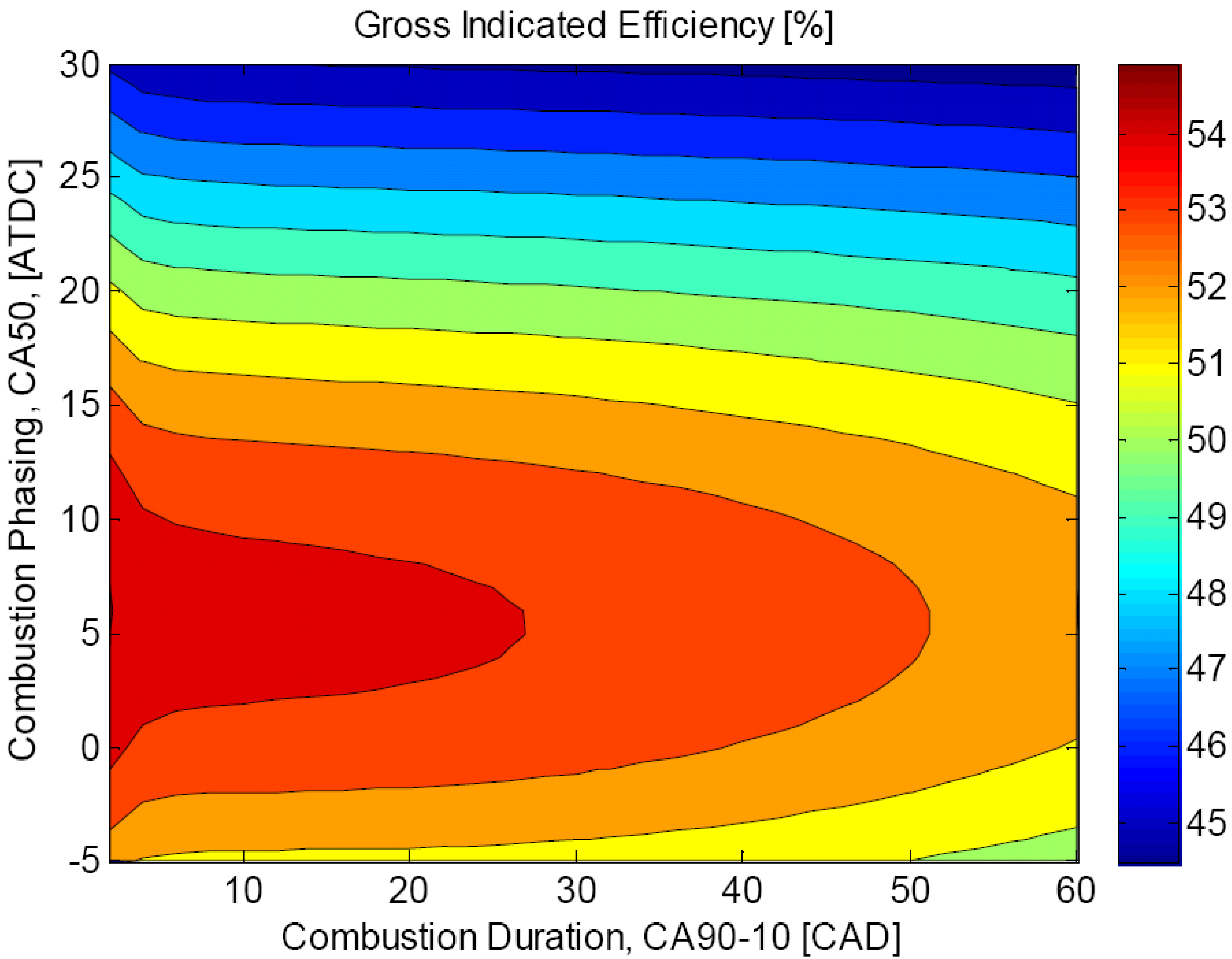
Exhaust Loss



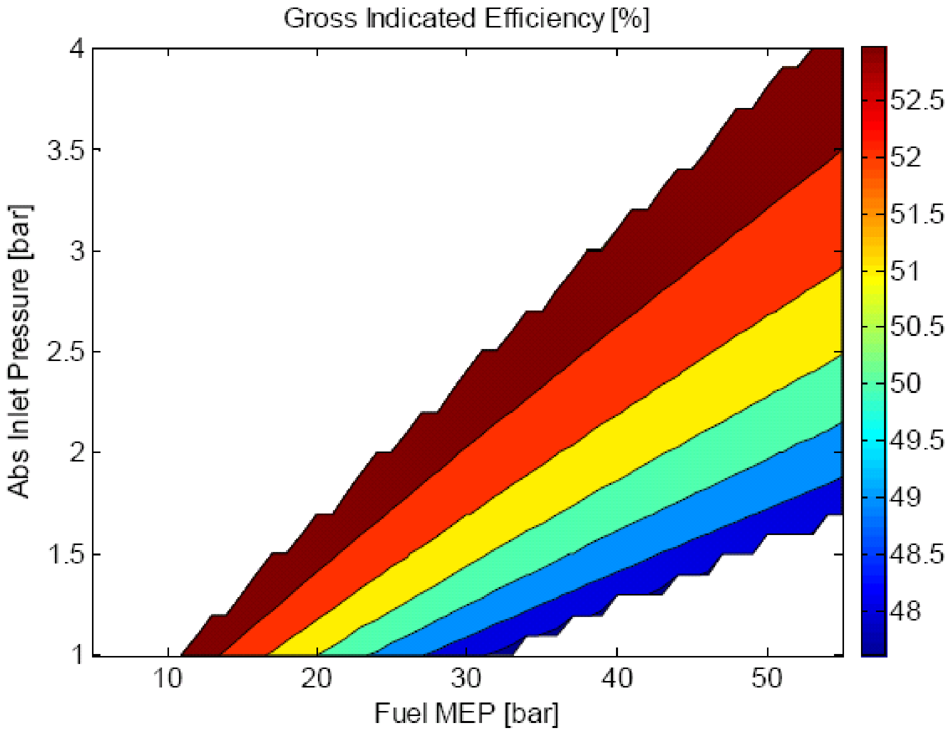
Heat transfer loss

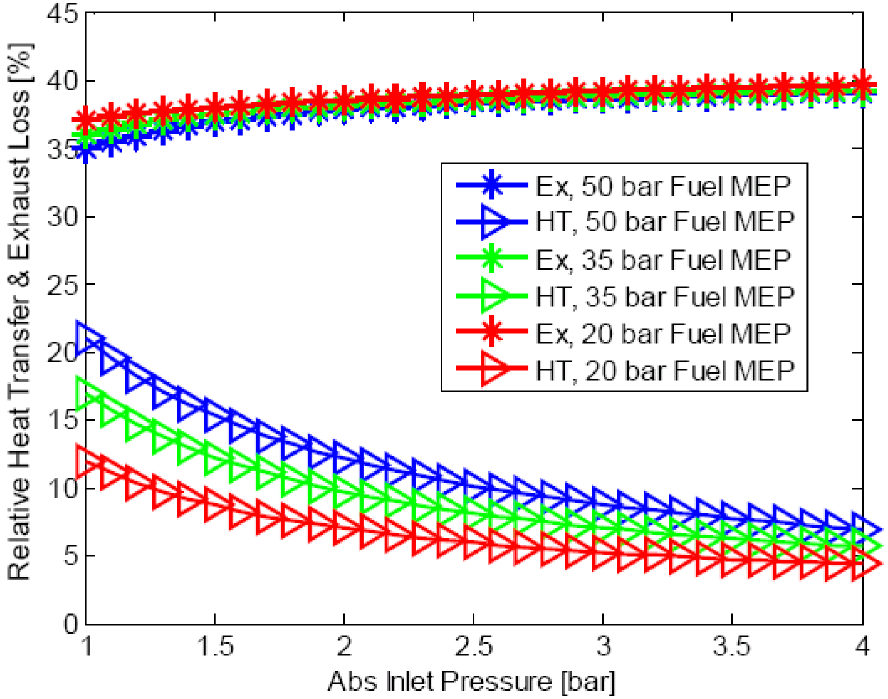


The rest (useful work)



Boosting reduce heat losses





A-B-C of Fuel Consumption

A. Car size
B. Engine size
C. Engine efficiency in right operating conditions

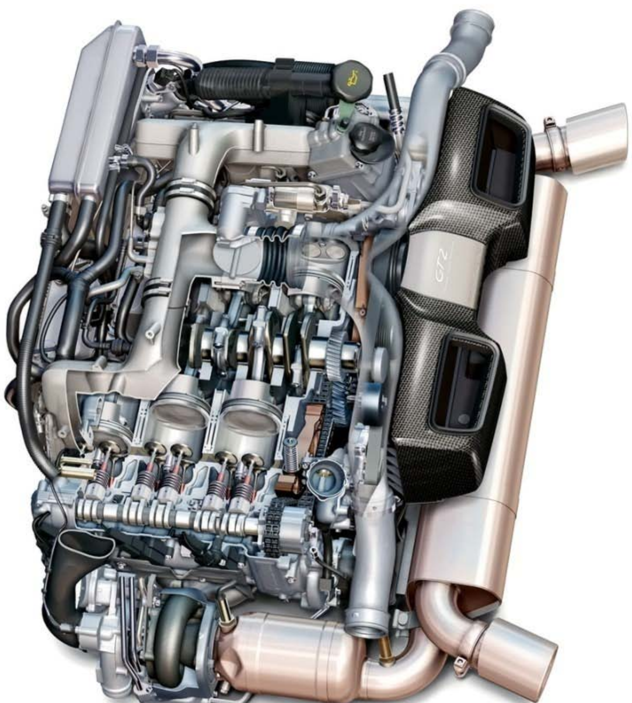
Porsche 911 performance with 100+ mpg?

- Two persons
- 100 liter of storage capacity

Porsche 911 data

M=1550 kg
Cr=0.012
Av=1.96 m2
Cd=0.33

Vd=3.8 liter
P=355 PS (hp)
T=400 Nm



Performance
0-60: 4.6 s
V,max=300 km/h (186.5 mph)
Fuel consump.= 12.0 l/100 km (19.6 mpg)

Power needed @300 km/h (186.5 mph)

$$P = \left(C_R mg + 0.5\rho_a C_D A_v v^2\right)v =$$

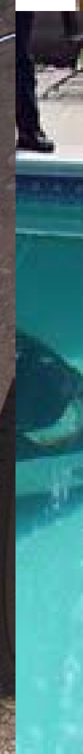
$$\left(0.012x1550x9.81 + 0.5x1.2x0.33x1.96x\left(\frac{300}{3.6}\right)^2\right)x\left(\frac{300}{3.6}\right)$$

$$= \; 239.8kW = 326.1hp$$

The ”Cigar”

Two person capacity is often enough

UK National Office of Statistics:
“The average car occupancy is 1.6 people per car and for commuting it's 1.2 “



A carpool in California is a car with ONE person if the car is fuel efficient…

The "Cigar"

Existing large model use large BMW 1200 cc MC engine. With turbo a top speed of 315 km/h and fuel consumption of 3.5 l/100 km (67 mpg)

http://www.peraves.ch/

Power needed @300 km/h (186.5 mph)

<u>Cigar design specifications</u>
Cd=0.1
Av=0.5-1 m^2
m= 250 kg
Cr=0.012 (two wheels)

$$P = \left(C_R mg + 0.5\rho_a C_D A_v v^2\right)v =$$

$$\left(0.012x250x9.81 + 0.5x1.2x0.10x1.0x\left(\frac{300}{3.6}\right)^2\right)x\left(\frac{300}{3.6}\right)$$

$$= \ 37.2kW = 49.7hp$$

Power needed at 50 and 100 km/h (31- 62 mph)

Porsche 911 vs. cigar

Speed (km/h)	911	Cigar	Unit	Ratio
50	3.57	0.57	kW	6.28
100	13.4	2.1	kW	6.36
300	239.8	37.2	kW	6.45
50	4.86	0.77	hp	6.28
100	18.2	2.9	hp	6.36
300	326.1	49.7	hp	6.45

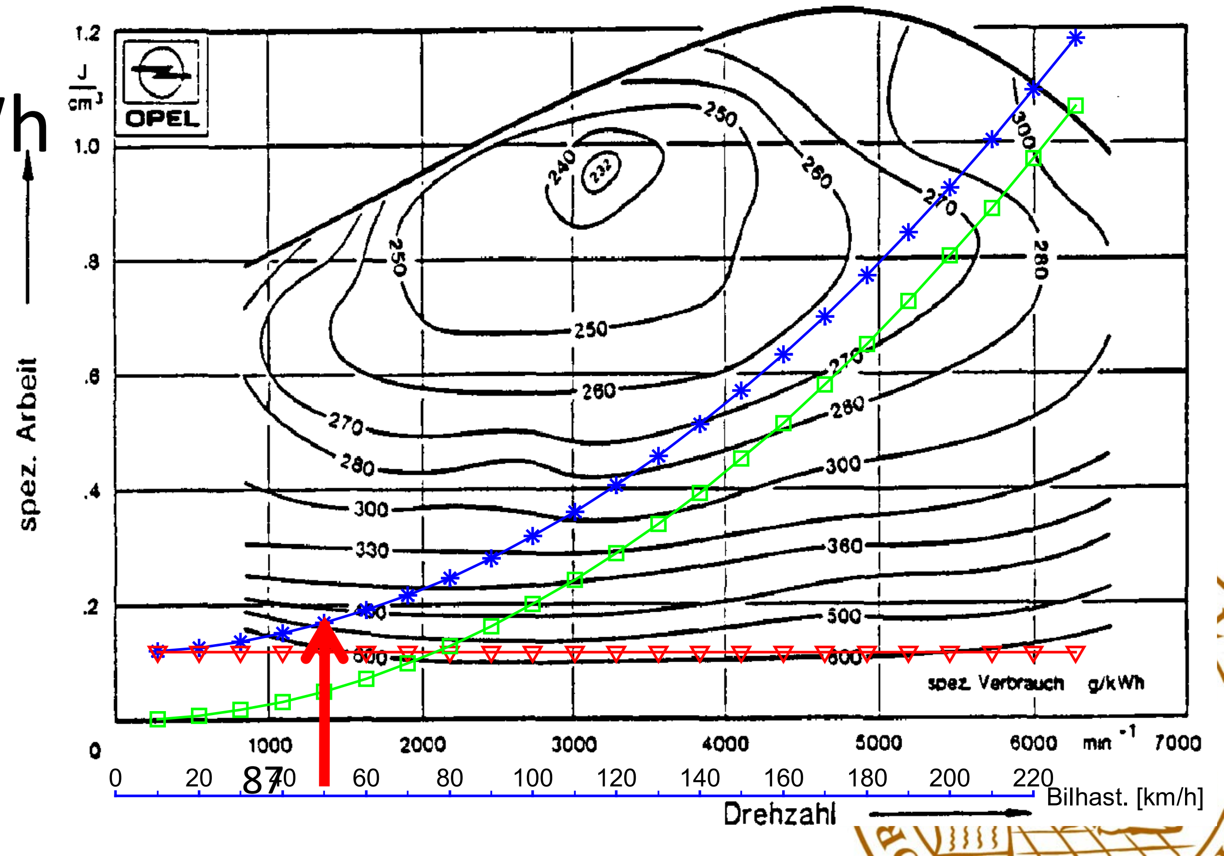
Acceleration proportional to power/mass ratio:
Cigar: 250/49.7=5.03 kg/hp
911: 1550/355=4.37 kg/hp

A. Car size

- With more correct car size the engine size can be reduced a factor of 6 i.e. single cylinder version of 911 engine with 633 cc displacement is enough
- Porsche 911 has a fuel consumption of 12 l/100 km (19.6 mpg)
- Cigar would have 12/6=2 l/100 km (117.6 mpg) without any need of new engine technology. (Scaling both engine and car size)

B. Engine size

- A Porsche 911 does not operate at optimum load points in normal driving.
- At 50 km/h the estimated load is only 2 bar BMEP or less
- Bsfc=400 g/kWh (η_b=21 %)

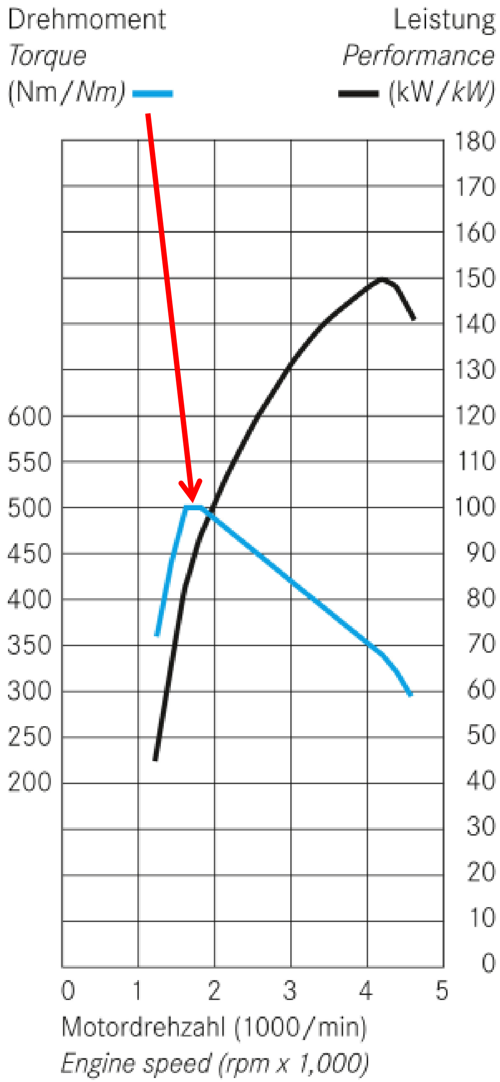


Engine downsizing

Three options

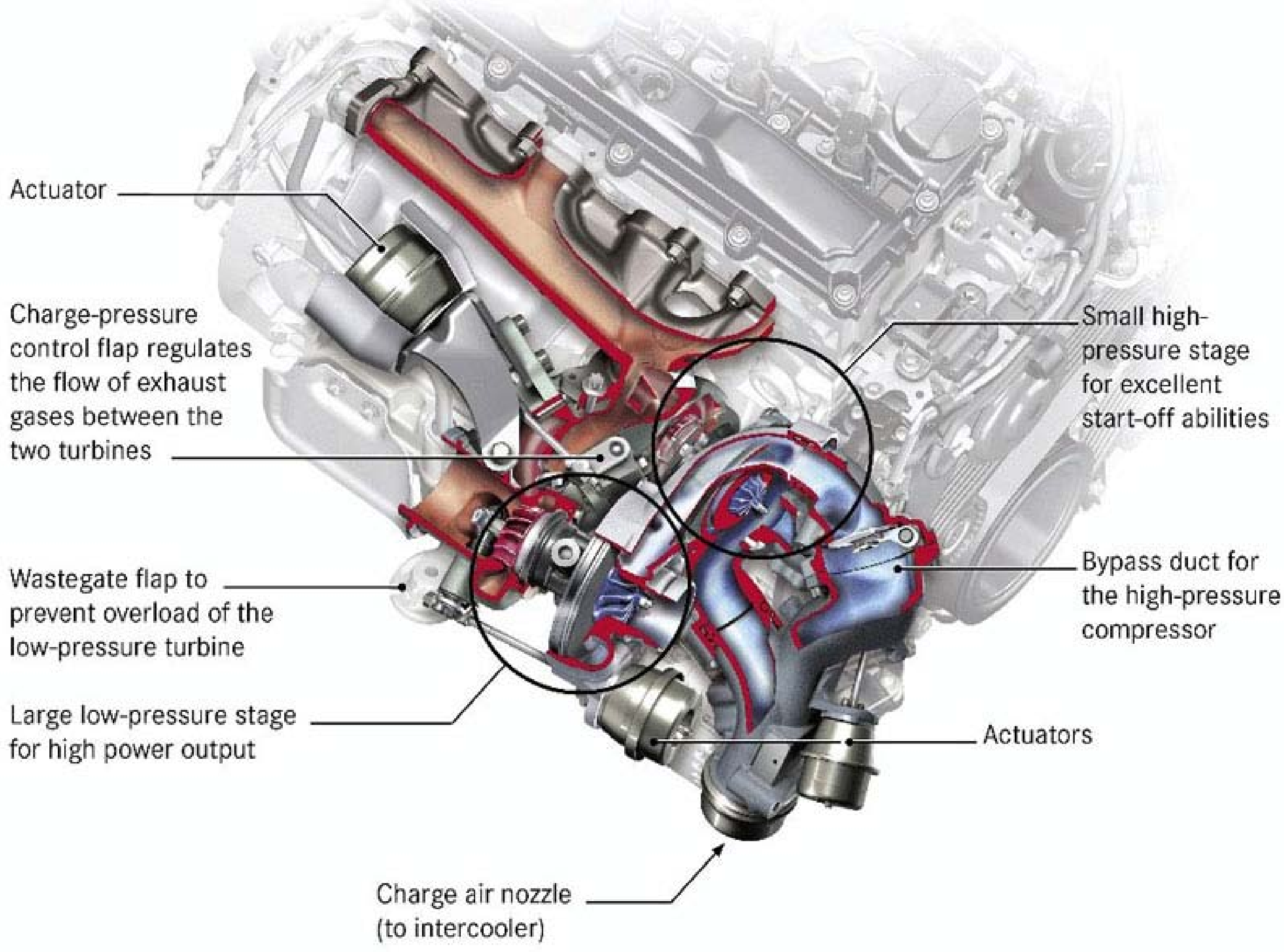
1. Turbo or supercharge a small engine
2. Cylinder deactivation of large engine
3. Variable displacement i.e. variable engine size

B.1. Mercedes CDI 250, 2.1 liter



Vd=2143 cc
Torque= 500 Nm (369 lb-ft)

Two stage turbo



Engine downsizing- MB 250 CDI

Displacement of 2.1 liter giving 224 hp and 500 Nm of torque :
30 bar BMEP is now full load **NOT** 10 or 20 bar

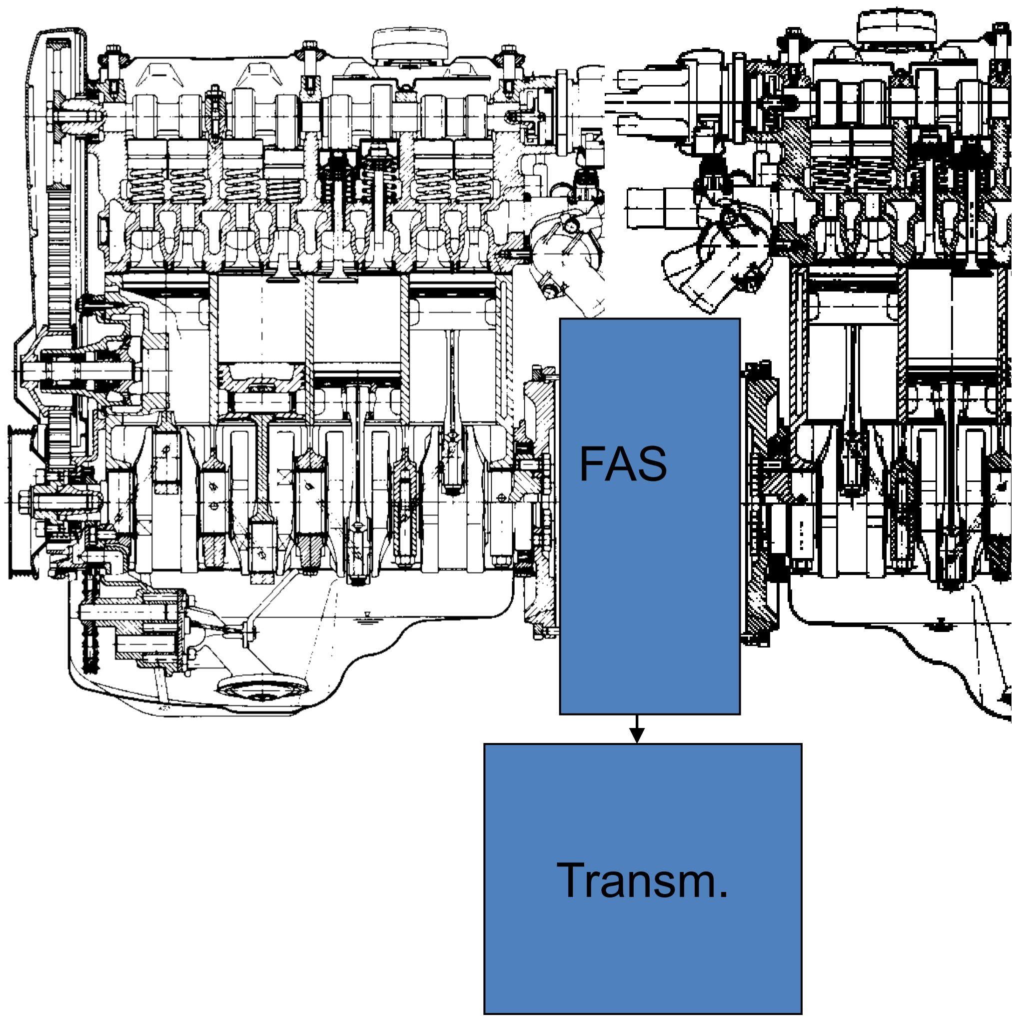
Fuel consumption;
C-class 5.1 l/100 km (46.1 mpg),
E-class 5.3 l/100 km (44.4 mpg),
S-class 5.9 l/100 km (39.9 mpg)

CO_2:
C-class 139 g/km
E-class 143 g/km
S-class 155 g/km

B2: Dual engine concept

- Use one small and one large engine
- As an example:
  - One 2 cylinder 1 liter engine
  - One 4 cylinder 2 liter engine
- This gives us 1, 2 or 3 liter to choose from

Layout 4 +2 cyl



Fiat 2-cylinder production engine

Operation

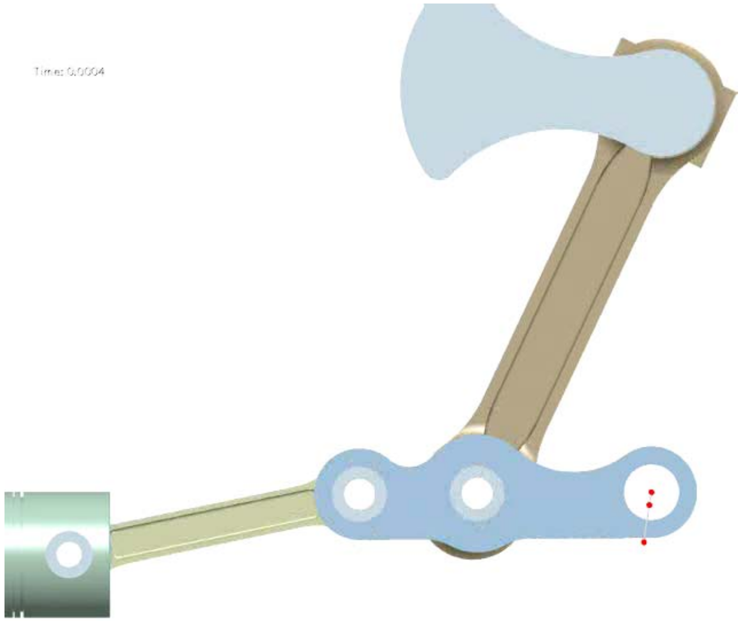
- 2-cyl at low loads
- 4-cyl operation at higher load operation (Autobahn)
- 6-cyl operation at highest loads
- 6-cyl + FAS at transients
  (with FAS start of 4-cyl)
- FAS for regenerative braking
- FAS for lowest speed operation (< 5 km/h)
- Manual selection should be possible

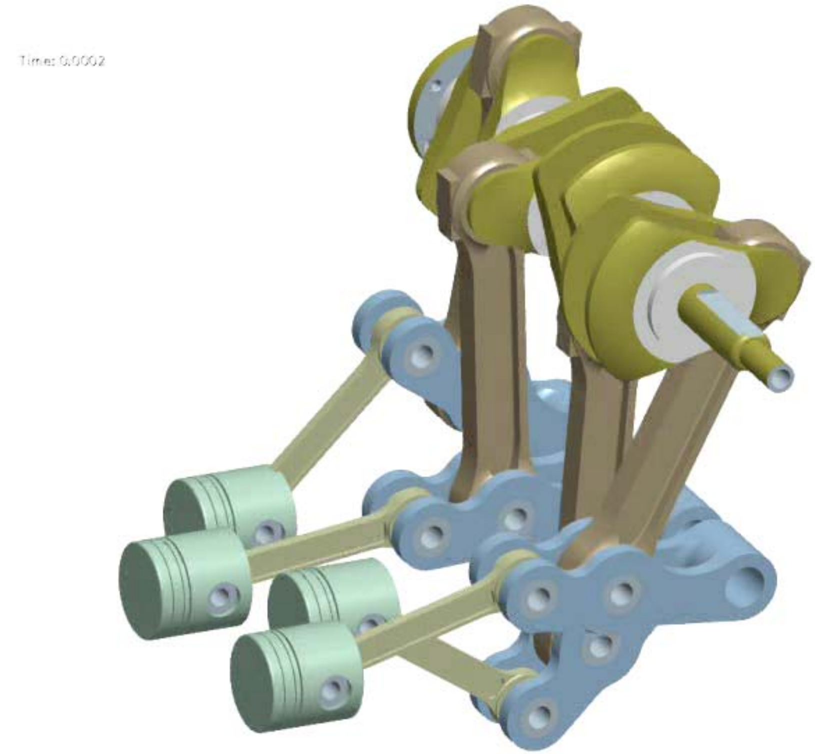
B3: Variable displacement engine

- If we can change displacement, V_d, engine load, P, can be controlled without reducing BMEP!

$$P = bmep\, V_d \, \frac{N}{n_t}$$

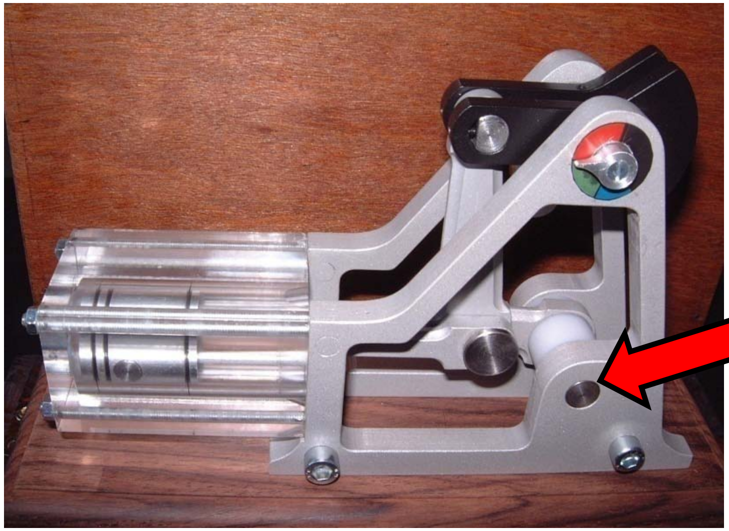
Atkinson Cycle

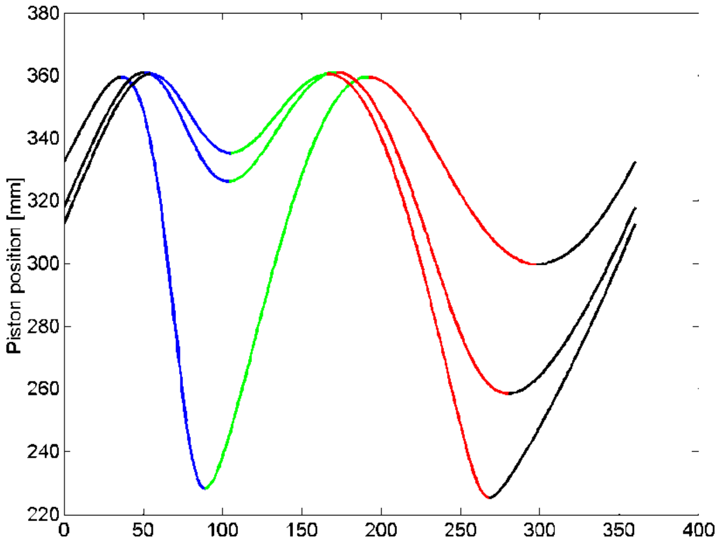


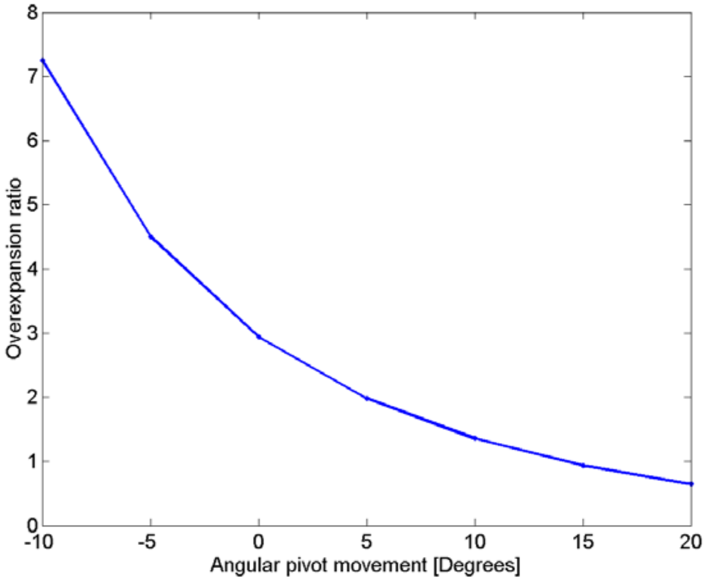


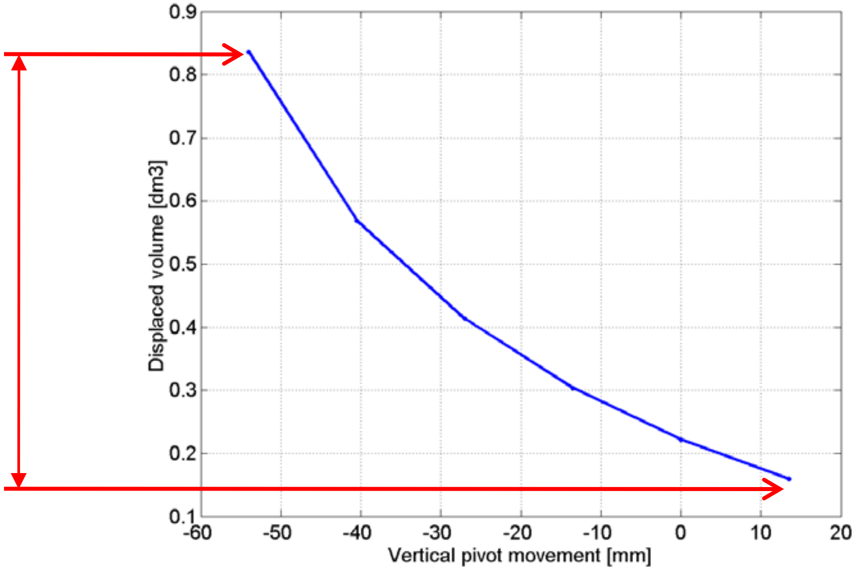
Displacement from 0.15 to 0.85 l per cylinder gives 0.6 to 3.4 l four cylinder engine at full load (@max BMEP)

Atkinson engine with variable displacement

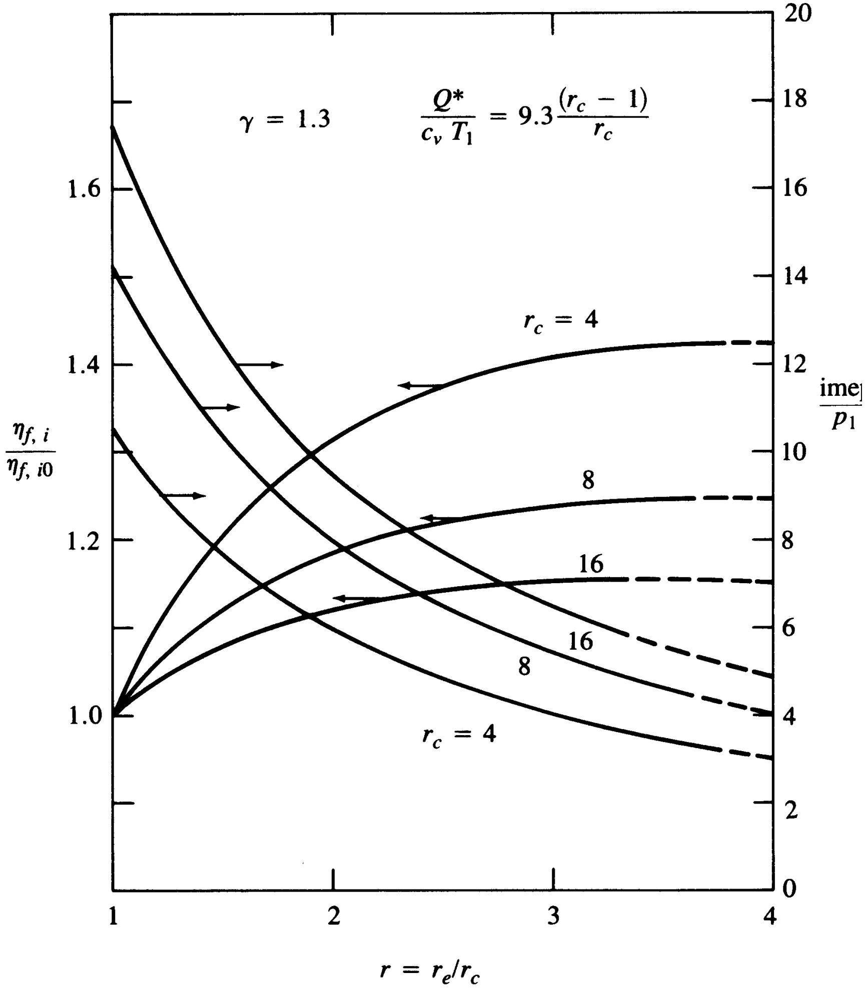


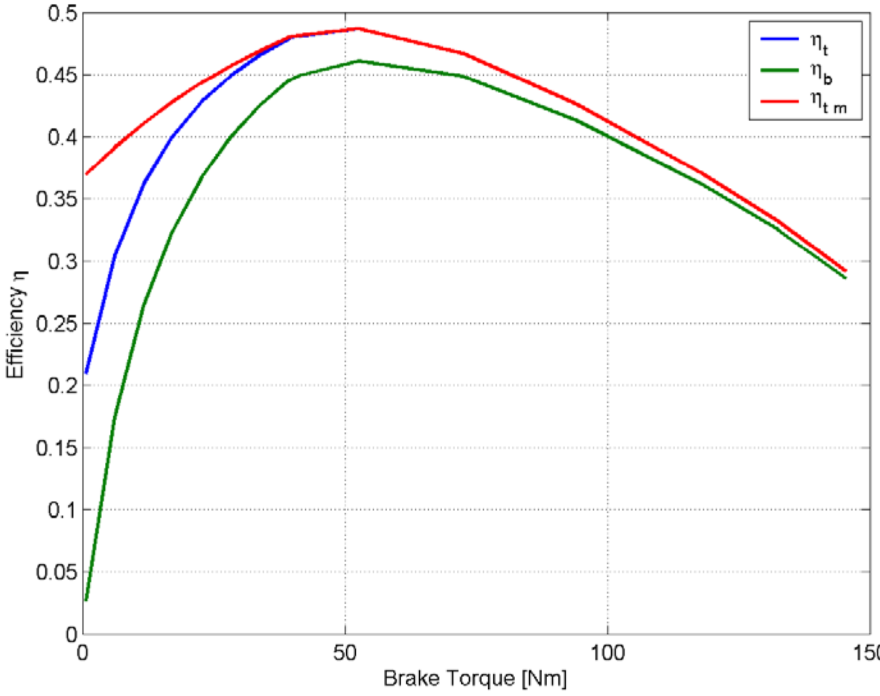




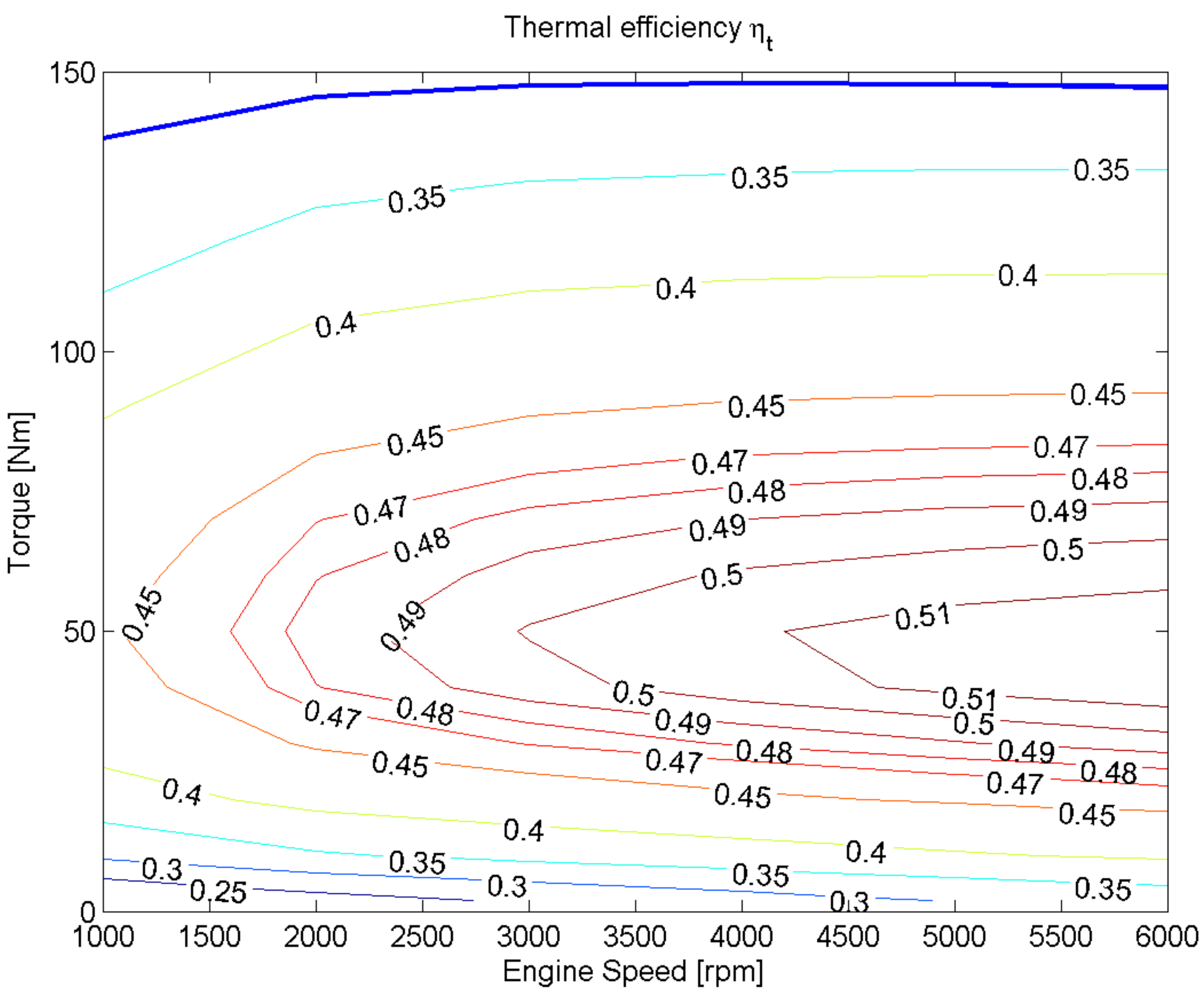


Atkinson engine efficiency





Atkinson engine thermal efficiency



A-B-C of Fuel Consumption

A. Car size
B. Engine size
C. Engine efficiency in right operating conditions (Maximum engine efficiency)

Summary /ABC of fuel consumption

A. Correct car size gives factor of 6 in fuel consumption
B. Correct load point gives factor 2 in fuel consumption (21%-42% or 400-200 g/kWh)
C. Partially Premixed Combustion have the potential to extend brake efficiency to 50% with US10/Euro emissions. With further optimization 55% could be reached
D. With waste heat recovery 60% should be possible giving a factor of 3 from today.

A total reduction potential of factor 18!

Cars and traffic situation