Highly Boosted & Efficient Ethanol Engine Concepts

José Guilherme Coelho Baêta, DSC
Co-founder & R&D Technical Director

Training, consultancy, engineering development & electronic diagnostic tools for the automotive sector

Location and Contact:

The Company's headquarters is located in the Technological Park of São José dos Campos.

Bloco CECOMPI

Presidente Dutra Road, Km138 – Eugênio de Melo. Post Code: 12247-004

Contact Numbers:

Phone: (+55)(12) 3876-7719; Mobile: (+55)(31) 8642-3698

Highly Boosted & Efficient Ethanol Engine Concepts

Summary:

1. **What is going on around the globe concerning Ethanol?**
2. **Why Ethanol?**
3. **Brazilian R&D Ethanol Projects for Light & Heavy Duty since 2007**
4. ***Ethanol & CNG DI Combustion Development for Heavy Duty***
   a) **R&D Methodology implementation**
   b) **Main Issues & Technical Results**
   c) **Conclusions & Lessons Learned**
5. ***Ethanol PFI & DI Combustion Development for Light Duty***
   a) **R&D Methodology & Workhorse Modifications**
   b) **Technical Results**
   c) **Conclusions & Lessons Learned**

What is going on around the globe concerning Ethanol?

USA

MEDIUM DUTY

In This Issue

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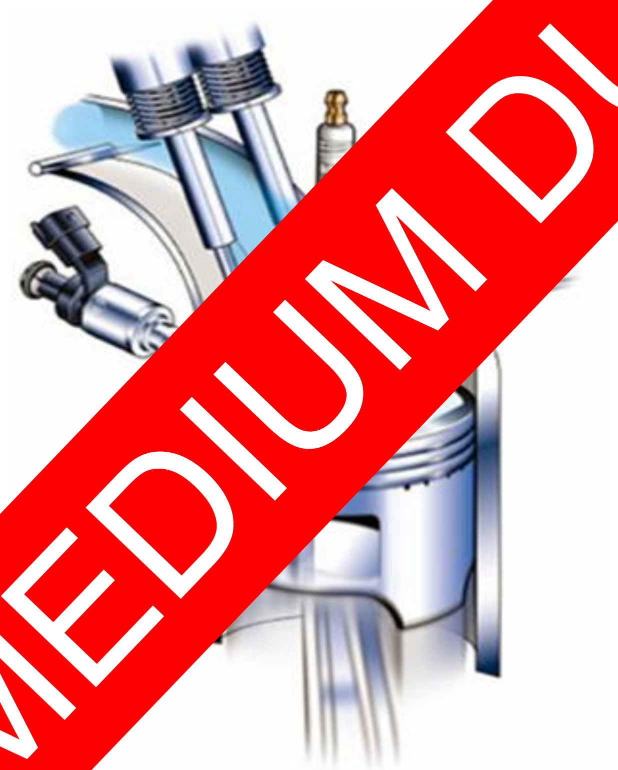
Ethanol Direct Injection Te... gy Could Rival Diesel at Less Co...

by Bill Siuru
05/13/2010



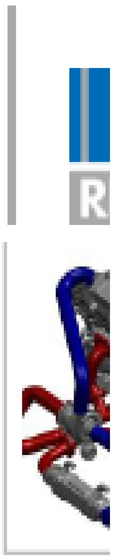
...vehicles operating ... of gasoline and ...educe the use of fossil ... However, this comes with a ...economy penalty of about 30 ...ercent because of ethanol's lower energy content. This could be overcome by directly injecting ethanol and gasoline separately into the combustion chamber to optimize the use of both fuels.

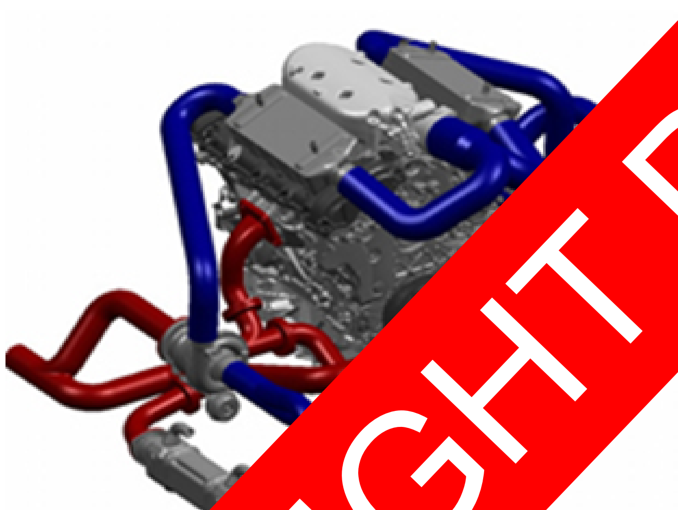
Ford is developing an E85 direct injection boosting system that's combined with gasoline port fuel injection (PFI). This brings higher fuel economy because the gasoline, with its greater heating value, is primarily used during most driving modes. Directly injecting ethanol into the cylinder suppresses knock because of the evaporative cooling effect on the air-fuel mixture. Suppressing knock allows increasing compression ratio to gain additional power, plus higher boost pressures can also be used in turbocharged or supercharged engines. These advantages allow smaller engines to provide performance equivalent to larger engines running without the technology.

What is going on around the globe concerning Ethanol?

LIGHT DUTY

Ricardo in Detroit is developing a similar technology it calls Ethan… Boosted Direct Injection (EBDI) to take full advantage of ethanol's best pr… s – higher octane and higher heat vaporization. The EBDI project is a co… between Ricardo, Behr, Bosch, Delphi, Federal Mogul, GW… Honeywell. A prototype 3.2-liter V-6 EBDI engine can ope… or up to 100 percent ethanol. By adding other advance… ect injection, variable valve timing, optimized ignition, an… as recirculation, it's possible to produce more power t… e.





…rdo say their …w gasoline …ver performance, …d durability levels …e with diesel engines, …lower price. According to …do, the company is able to …uce engine displacement by …5 to 50 percent while not only delivering torque that is competitive with direct-injection diesels, but fuel economy as well.

…el

Ford's E85 DI + gasoline PFI, like modern diesel engines, features turbocharging, direct injectio… nstruction to handle the higher pressures, and comp… , there are several important differences that make DI + PFI a … proach, including the fact that the DI + PFI engine requires a … expensive conventional three-way catalyst. The E85 DI + gasoline PF… e also uses a renewable fuel in a leveraged manner to significantly red… e petroleum consumption and total net CO^2 emissions. Likewise, Ricardo's EBDI technology relies on affordable and well-established three-way catalyst after-treatment technology to meet EPA emissions regulations.

What is going on around the globe concerning Ethanol?

BREAKING NEWS Think recalls City over gearshift linkage issue

Challenge Bibendum: Audi's E100-capable A5 can get to 25 mpg and 146 mph

by **Sebastian Blanco** (**RSS feed**) on Jun 25th 2010 at 6:05PM

E100-capable Audi A5 prototype – Click above for high-res image gallery

- Engine 2.0 TFSI 132 kW (180 PS), 320 Newton-meters of torque
- Manual 6-gear quattro transmission
- 0-100 kilometers per hour in 6.9 seconds
- Top speed: 236 km/h (146 miles per hour)
- Weight: 1,310 kilograms

The car officially consume 9.9 liters per 100 km (24 mile per gallon U.S.) when running on ethanol, but drivers managed 9.5 l/100 km (25 mpg) on ethanol during the Michelin Chalenge Bibendum Rallye.

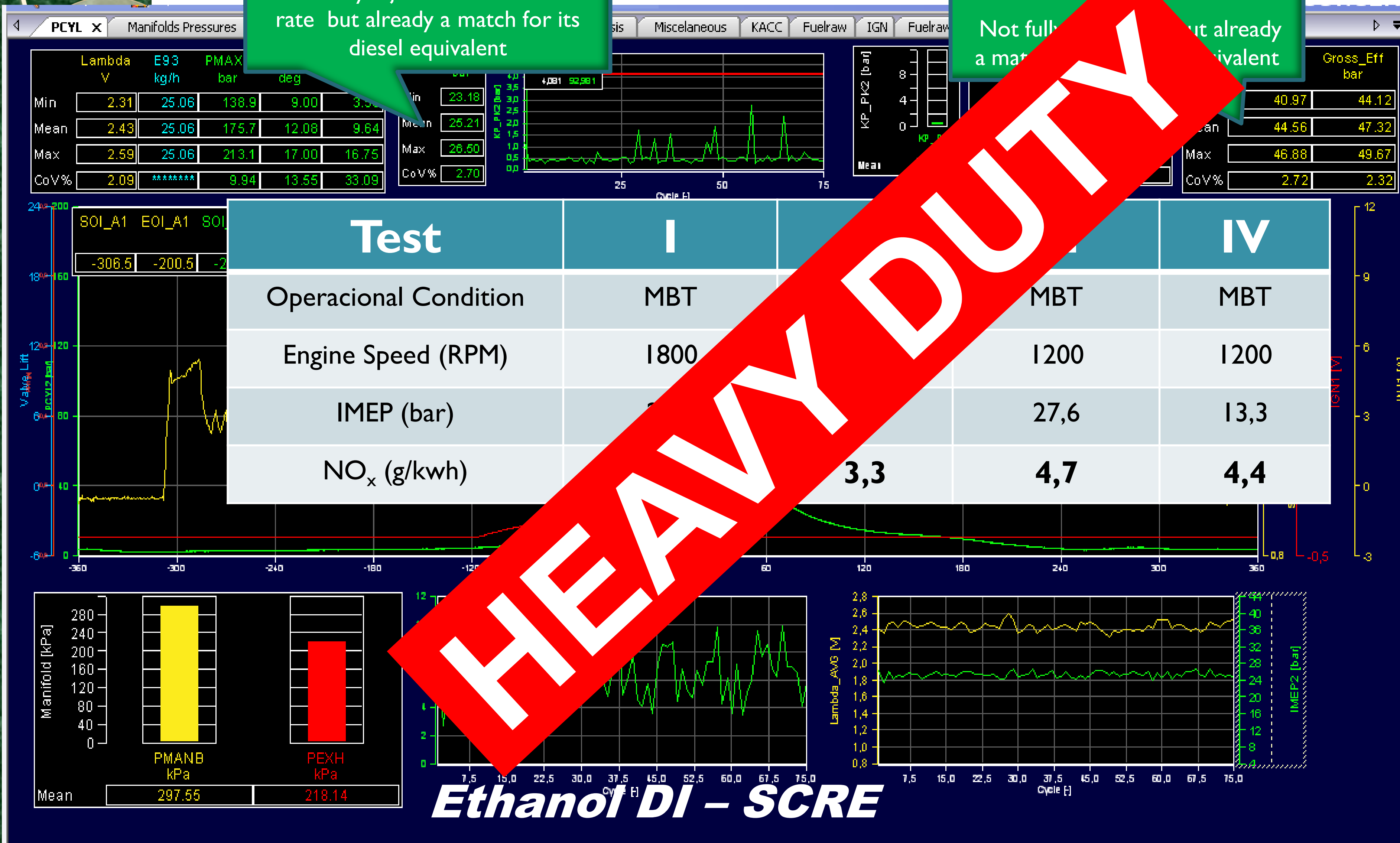
What is going on around the globe concerning Eth[illegible]

IMEP > 25 BAR

Limited by injector maximum fuel rate but already a match for its diesel equivalent

GROSS EFFICIENCY > [illegible]7%

Not fully [illegible] ut already a mat[illegible] ivalent

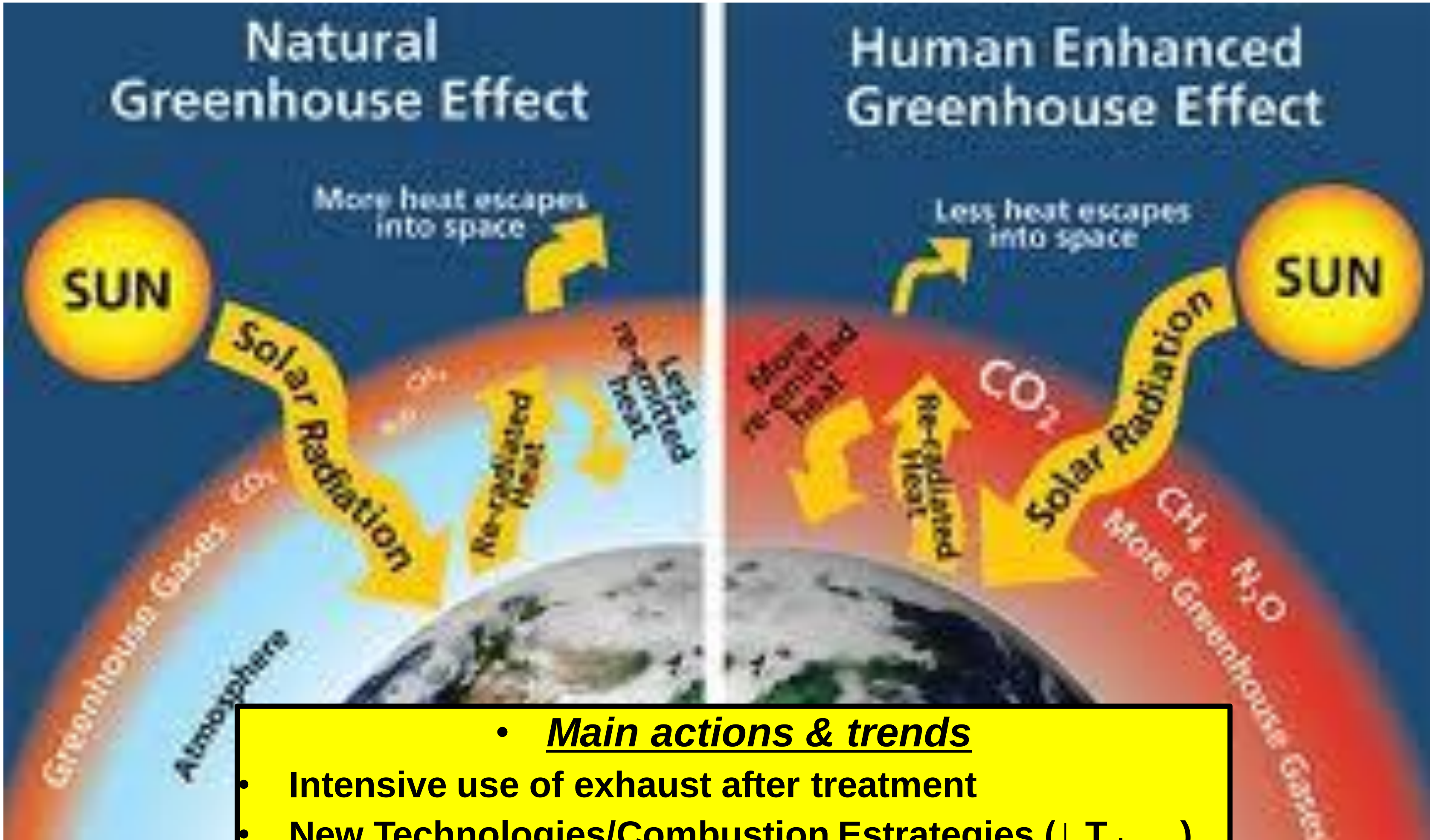


Test	I			IV
Operacional Condition	MBT		MBT	MBT
Engine Speed (RPM)	1800		1200	1200
IMEP (bar)	[illegible]		27,6	13,3
NO_x (g/kwh)		**3,3**	**4,7**	**4,4**

HEAVY DUTY

Ethanol DI – SCRE

Why Ethanol?



- ***Main actions & trends***
- **Intensive use of exhaust after treatment**
- **New Technologies/Combustion Estrategies (↓ T_{chama})**
- **Renewable Fuels – Ethanol / Biodiesel**
- **Renewable sources – Solar / Eolic**
- **Electrification/Hibridization**

Greenhouse … bustion.

Particulate M

CO: Extreme

NOx: Acid rain (mainly Diesel)

Why Ethanol?

The major oil companies

60% of the world oil is concentrated in 11 countries.

Why Ethanol?

World Scenario - Fuel Consumption

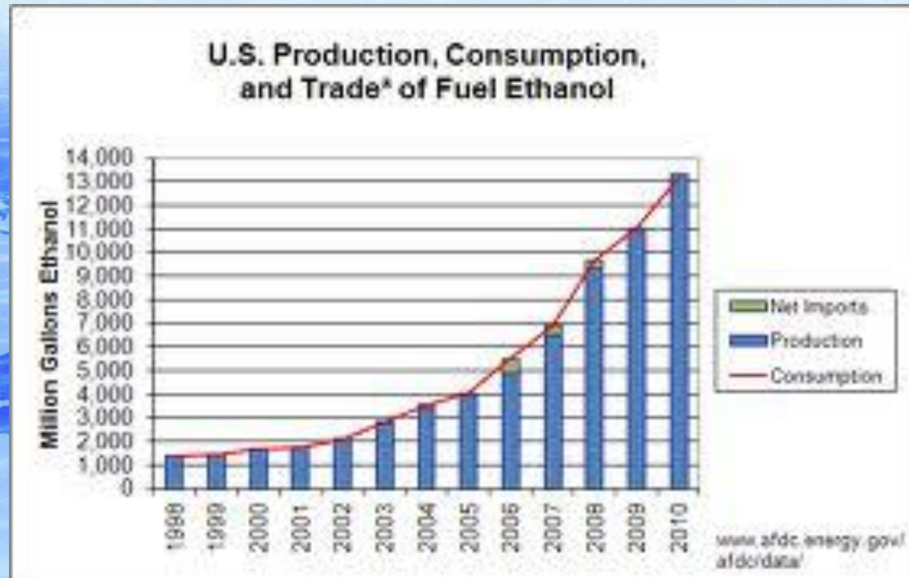
Domain of fossil fuels for transportation

Why Ethanol?

World Scenario - Fuel Consumption

Why Ethanol?

World Scenario - Fuel Consumption

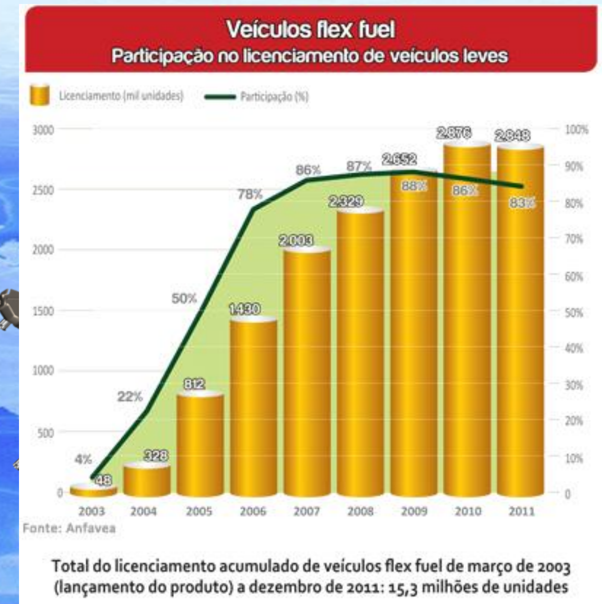


Ethanol
Gasoline
Diesel

Ethanol from corn - E85
RFS2 – Minimum
1 MJ → 1,7 MJ

Why Ethanol?

World Scenario - Fuel Consumption

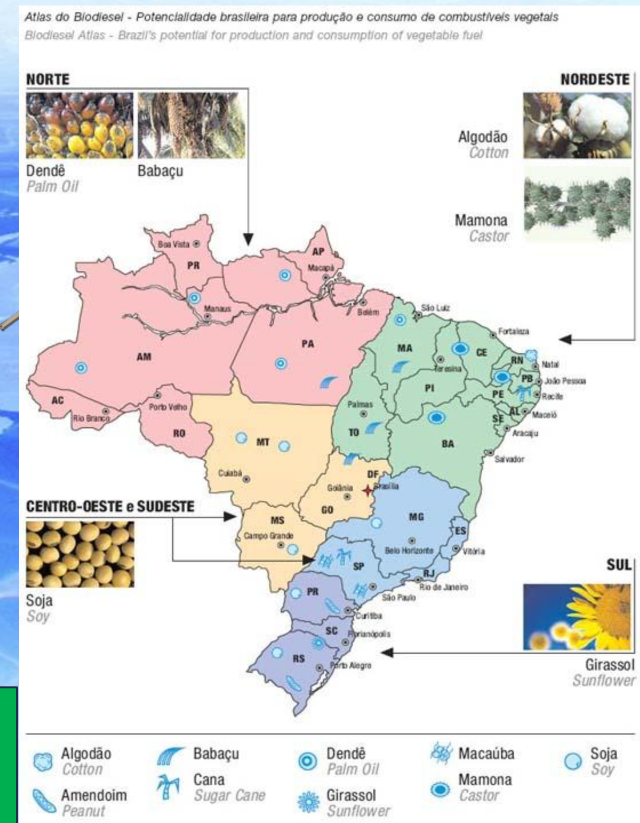


Ethanol from sugar cane E94 e E22 1 MJ → 8 MJ
Compared to Ethanol from Corn 1 MJ → 1,7 MJ
Use of bagasse use to produce

https://www.youtube.com/watch?feature=player_embedded&v=t6KhU0tWMy4

Why Ethanol?

World Scenario - Fuel Consumption



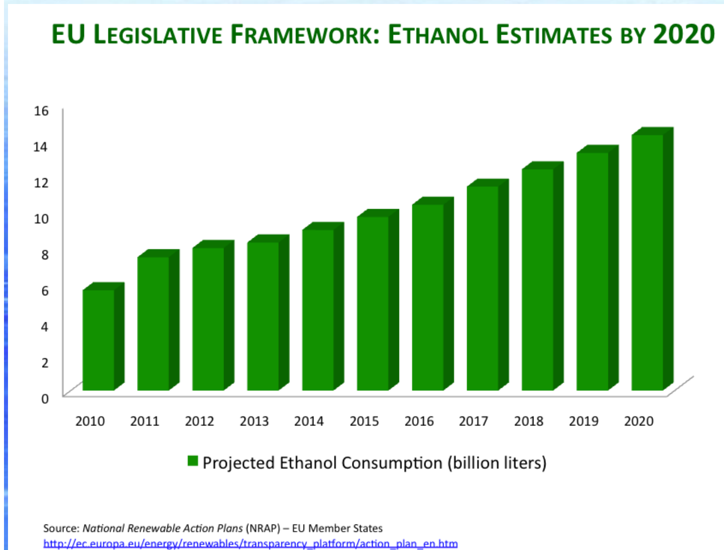
Biodiesel

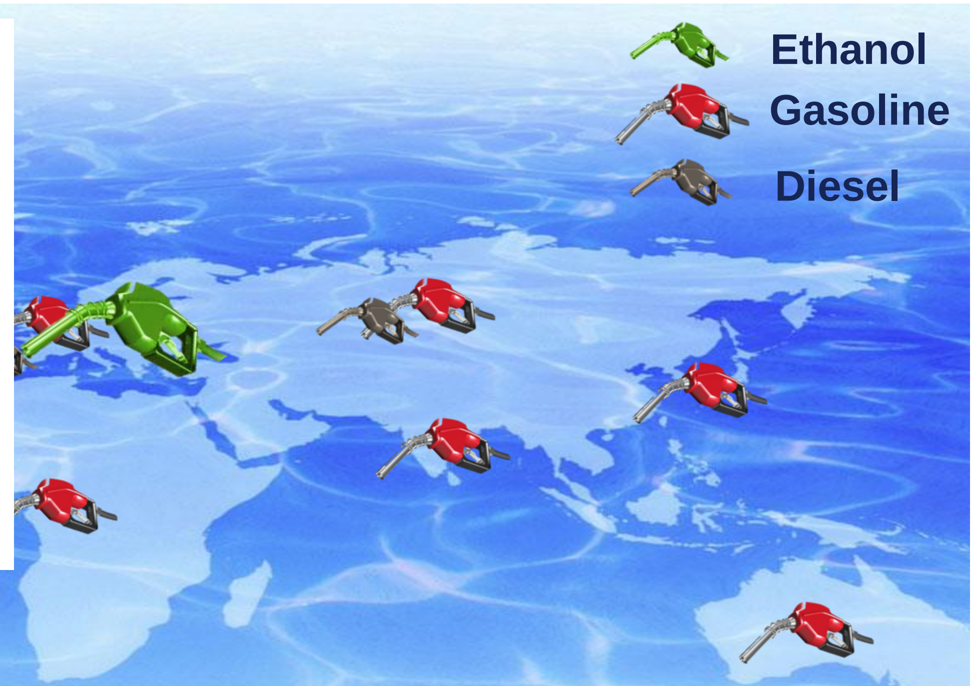
B2 - Beginning in 2006 / Mandatory in 2008

B5 - Until 2013, several oilseeds

Why Ethanol?

World Scenario - Fuel Consumption





2nd market for Brazilian Ethanol - E85 and E10

Sweden, Germany - Government incentives & distribution infrastructure installed. France, Spain and others

Why Ethanol?

World Scenario - Fuel Consumption

Ethanol
Gasoline

Biodiesel

Major consumption of biodiesel is in the U.S.. mainly used in public transportation.

Why Ethanol?

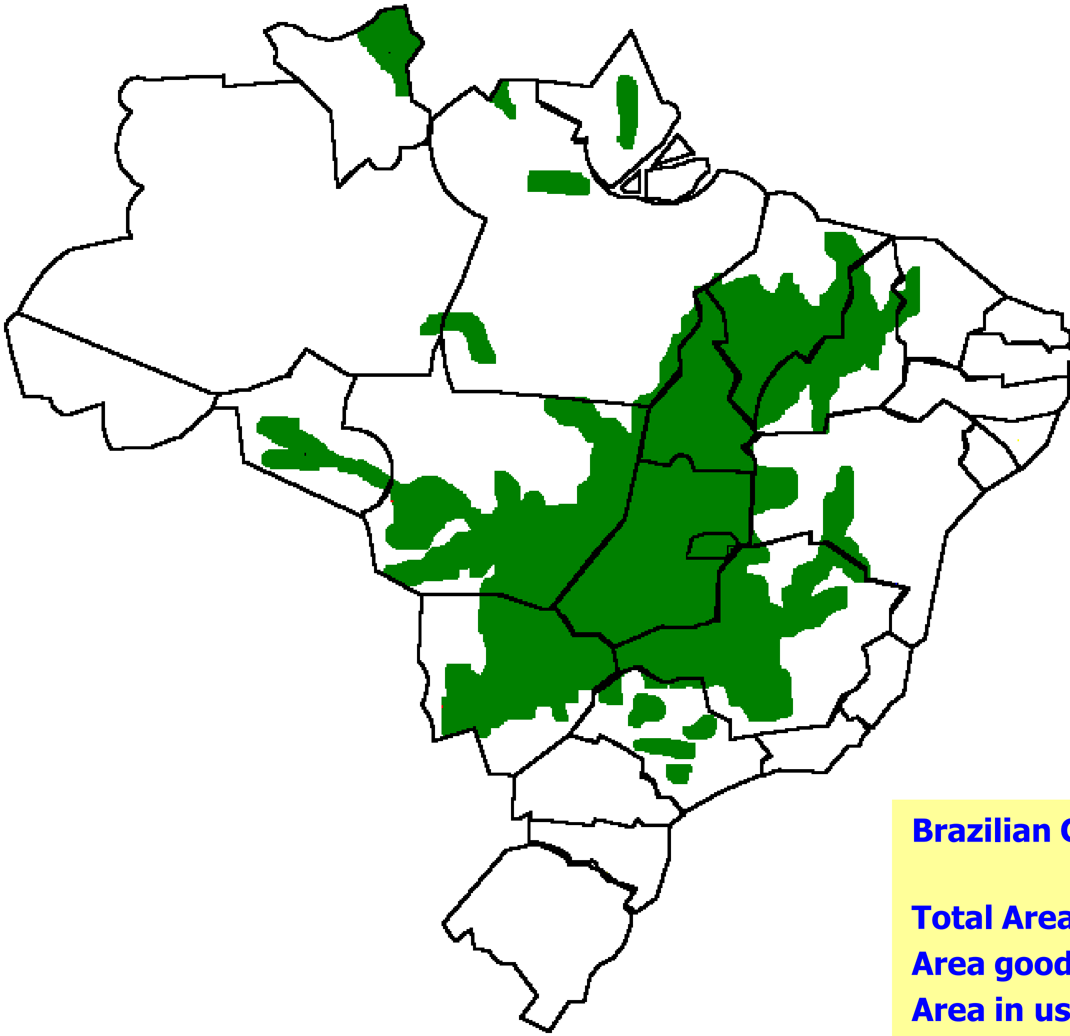
Used land in Brazil

	million of hectares
Brazil´s Territory	~850.00
Total Arable Land	320.00
Cultivated - all crops	60.40
- with Sugar Cane	5.34
- for ethanol	2.66
Area needed to supply Japan with	
E3	0.27
E10	0.90

Source: Ministry of Agriculture, Livestock and Food Supplies

Why Ethanol?

Available land in Brazil

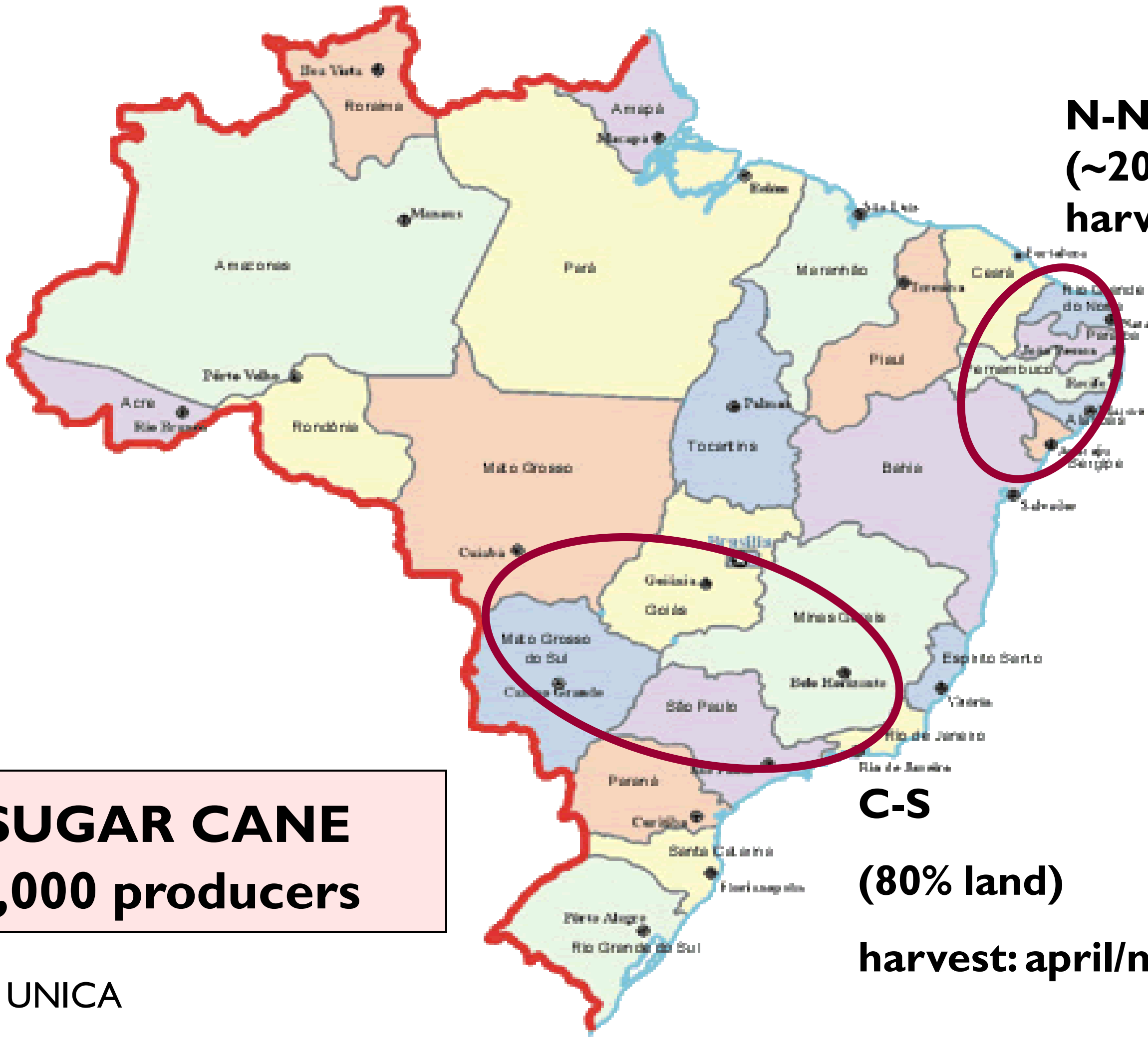


Brazilian Cerrado (million hectares)

Total Area	204
Area good for agriculture......	137
Area in use for cattle raising...	(35)
Occupied area (forests & plantations)	(12)
Available Area for expansion.....	90

Why Ethanol?

Main Sugar Cane Areas in Brazil



N-NE
(~20% land)
harvest: sept/march

C-S

(80% land)

harvest: april/november

SUGAR CANE
~ 60,000 producers

Source: UNICA

Why Ethanol?

Exportation (Fossil-Fuels x Bio-Fuels)

- Oil price tends to increase in the international market;
- Oil sales abroad is not subject to government control because of concerns about inflation;
- Due to its lower energy content, the farther you need to transport ethanol (abroad) the greater the drawback of ethanol in economic terms;
- Part of the revenue from oil exports or derivatives may subsidize ethanol consumption in the country;
- Partial substitution of ethanol for gasoline and diesel will easily meet country emission targets for CO_2 reduction in years to come.
- In the coming years will increase the availability of ethanol (not instantly)

Why Ethanol?

Etanol vs Biodiesel - Otto or Diesel cycle?

1- The process for Biodiesel production is more expensive than the Diesel and much more expensive than ethanol;

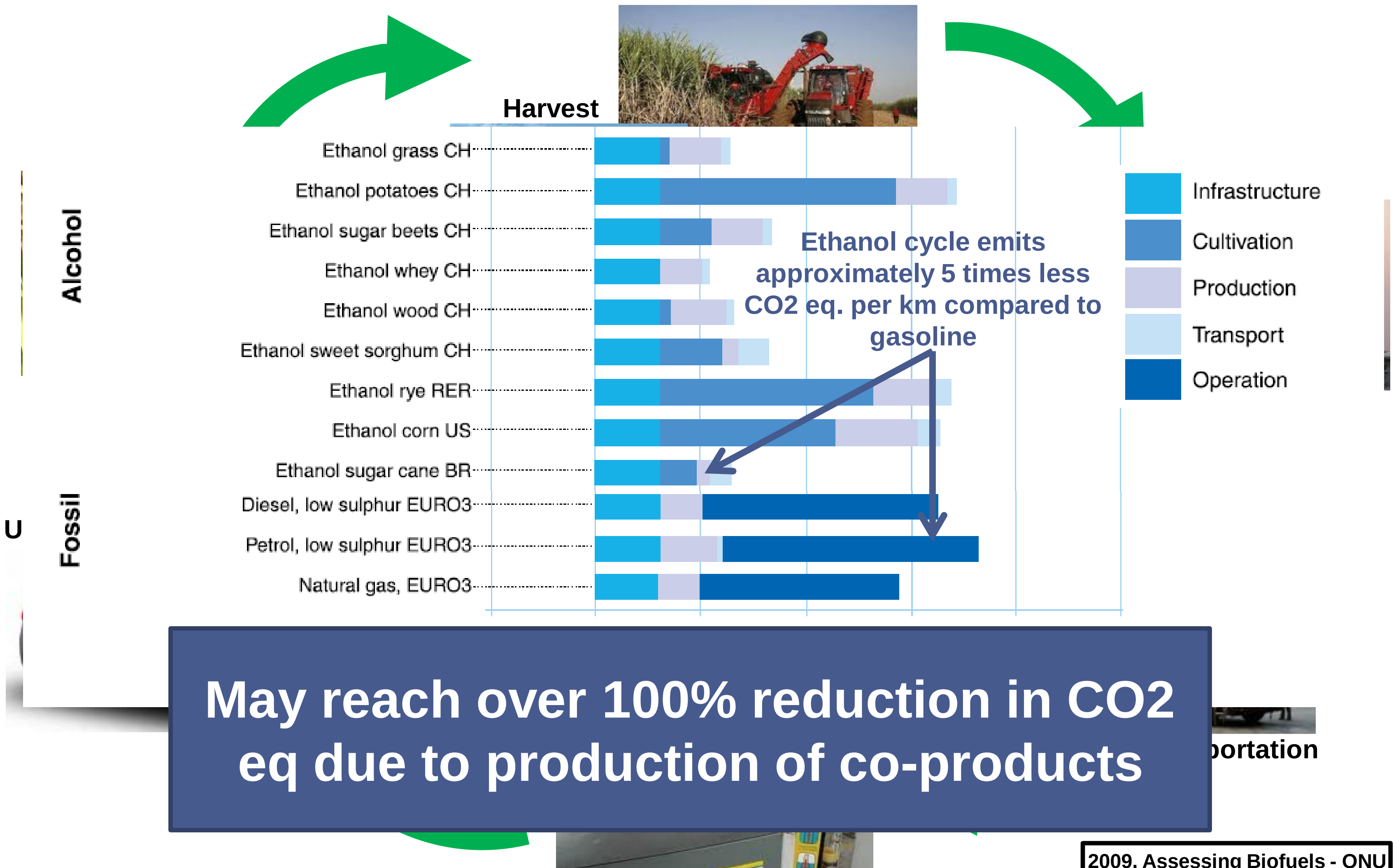
2- The properties of ethanol make it ideal for application of downsizing techniques;

3- Otto engines are much cheaper than diesel unit and can produce much higher power for engines of the same displacement;

4- Ethanol engines operating on diesel cycle require specific additive to change its fuel properties generating a logistic problem and additional cost, besides the limitation of power due to the extremely high compression ratios;

5- Engines operating on diesel cycle generate a higher manufacturing cost due to the need of a complex exhaust after treatment, while Otto engines powered with direct injection Ethanol meet emissions requirements with oxidation catalyst;

Why Ethanol?



May reach over 100% reduction in CO_2 eq due to production of co-products

2009, Assessing Biofuels - ONU

Why Ethanol?

1. **Renewable Fuel (GHG Reduction)**
2. **Su**
3. **An**
4. **Ava**

Low CO_2 emissions due to CO_2 absorption during crop growth and reduced fossil fuel consumption for production

Opportunity to redesign the current engines optmizing them for etha

PROPERTIES

Knoc ugh its high cha cooling gh octane number

Tor		
Tot		
Fib		
Ethanol (l/ha)		k – 3.6k
Plantation		
Cycle		
Plantation cost/ha (R$)		

Design and calibration biased to much higher load operation (Downsizing & Downspeeding)

Why Ethanol?

Ethanol – saccharine sorghum

Saccharine Sorghum

Complementary alternative to sugar cane for ethanol production;

Fast cycle → 4 months to competitive cost due to sharing investments;

May decrease variation in the price of ethanol between harvests.

Why Ethanol?

Current government vision - renewable sources

Dilma defende etanol e migração para fontes renováveis

14 de junho de 2012 • 14h46

No momento em que o Brasil sedia a Conferência das Nações Unidas sobre Desenvolvimento Sustentável (Rio+20), a presidente Dilma Rousseff defendeu o uso mais intenso de fontes de energia renováveis. Ao participar da solenidade de entrega de um selo de qualidade às empresas do setor sucroalcooleiro que respeitam os direitos dos trabalhadores, no Palácio do Planalto, Dilma citou que 45% da matriz energética do Brasil vêm de fontes renováveis, enquanto a média internacional é 11%. E defendeu o etanol brasileiro.

Confira a programação com os principais eventos
Veja onde está ocorrendo a Rio+20

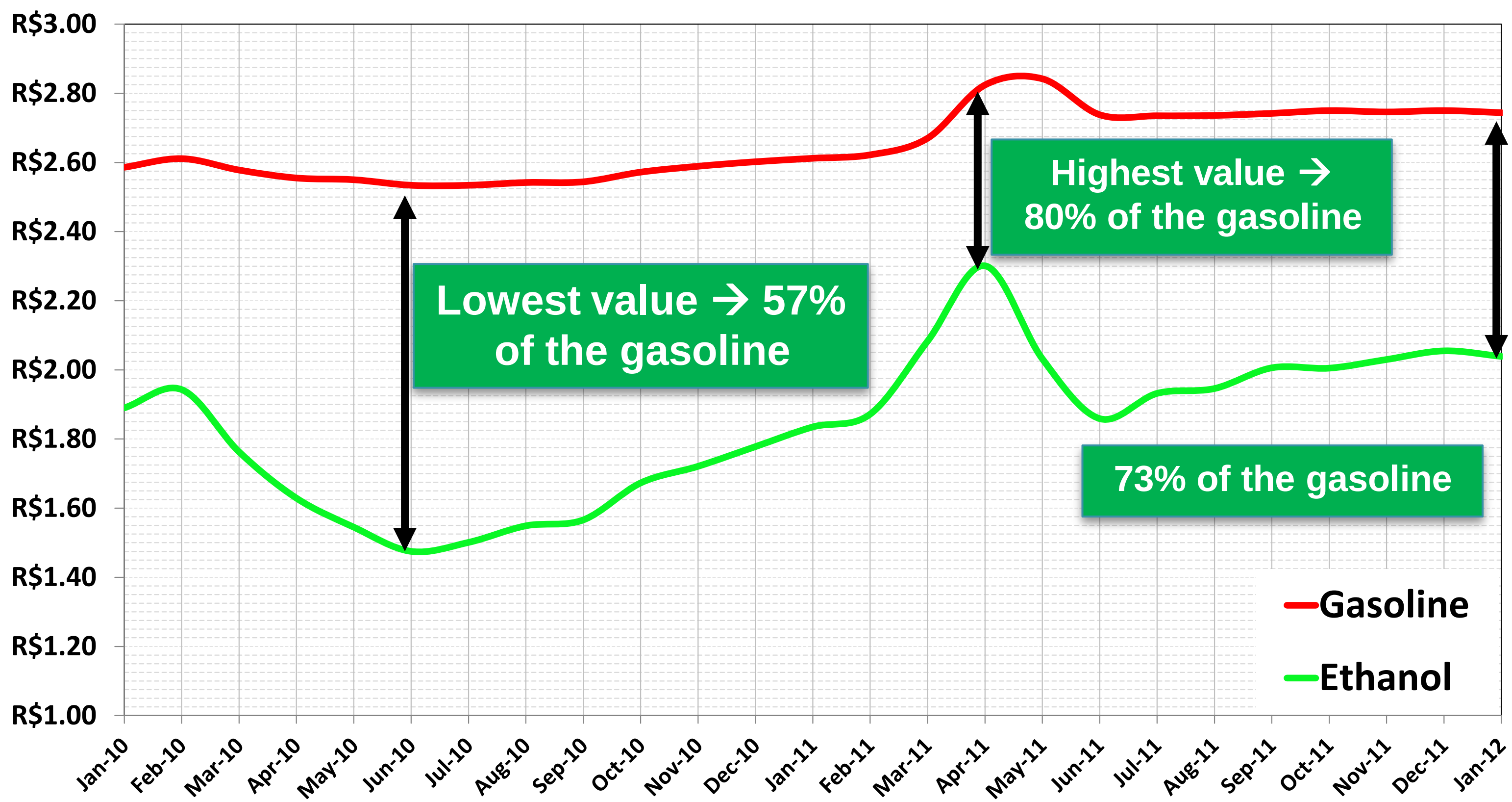
"O Brasil hoje tem uma matriz energética das mais renováveis do mundo porque tem na sua composição, principalmente na matriz de combustível, o etanol. É bom que a gente sempre lembre que o mais difícil, no que se refere à energia renovável, é a substituição, complementação ou criação de novas tecnologias na matriz de combustível. É ela que explica por que maior parte do mundo tem uma matriz tão concentrada em fontes fósseis", disse.

E complementou: "muitos de nós não sabem que o uso do etanol é a diferença entre nós e os demais países no que se refere a uma matriz renovável". A Rio+20 começou ontem. Sob coordenação das Nações Unidas, serão promovidas discussões sobre preservação ambiental, desenvolvimento sustentável e economia verde na busca de estabelecer um novo padrão internacional para o ambiente.

Why Ethanol?

Ethanol vs Gasoline

Prices comparision in the last 2 years



Source: ANP

Why Ethanol ?

λ=1 Ethanol/Gasoline Engines: A Low-Cost Solution to Efficiency and Emissions Challenges?

λ=1 operation with three-way catalyst

- Low Cost
- Proven ultra-low emissions potential

SI Ethanol/Gasoline technology

- Lower cost compared to DI diesel
- Robust operation
- Boosted operation yields reasonable power density
- Reduced packaging constraints

Efficiency – SOLUTION REQUIRED

- Traditional Ethanol/Gasoline engine
- Knock limited performance
- Overfuelling at high loads & high sp
- Pumping losses at partial loads
- Very high thermal loads on turbocha

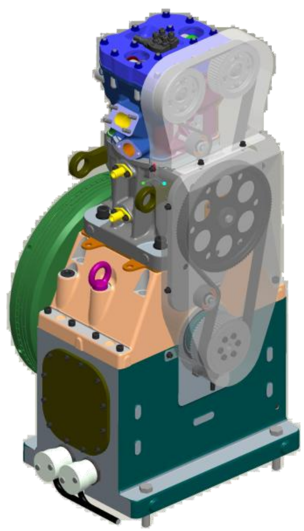
DOWNSIZED & DOWNSPEEDED ETHANOL ENGINE TECHNOLOGY

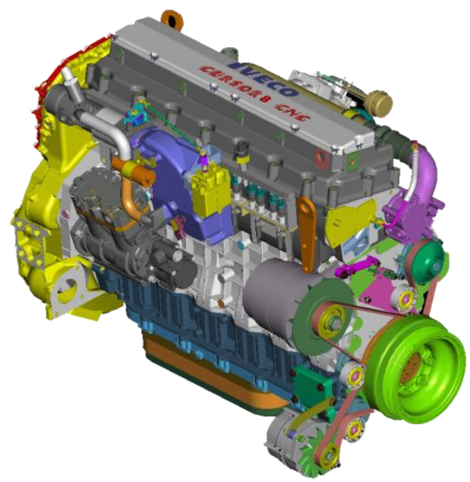
- High knock suppression capability
- Full calibration at Stoichiometric operation
- De-throttling application by WG control
- Lower thermal loads on TC by means of downspeeding & fuel properties

Brazilian R&D Ethanol Projects for Light & Heavy Duty since 2007

Highly Boosted & Efficient Ethanol Engine Concepts

Heavy Duty

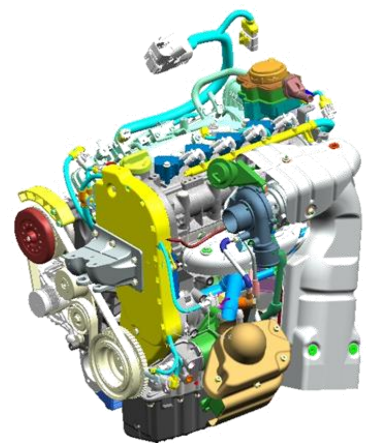




[Project Challenge 2007 – 2010]()

The main goal was to define an new combustion chamber design that fully exploit Ethanol & CNG DI Potential in order to match Diesel Brake Efficiency & Performance index

Light Duty



[Project Challenge 2011 – 2012]()

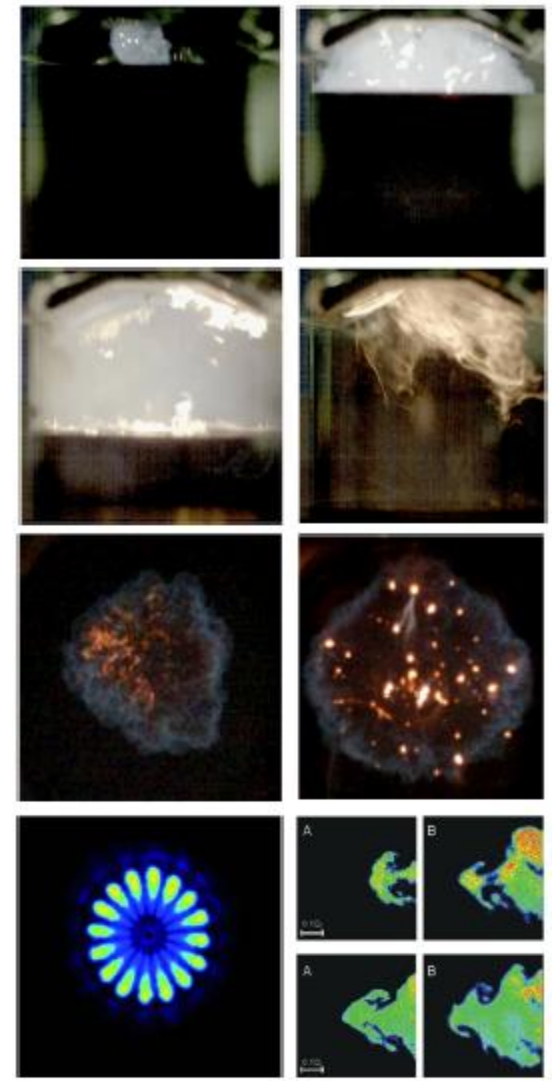
The main goal was to define an engine architecture that fully exploit Ethanol Potential in order to match E22 fuel mileage with the same performance index

Ethanol & CNG DI Combustion Development for Heavy Duty Engines

This R&D program aimed at investigating two different approach:

i. The first one is the Liquid Ethanol DI focused on spray guided mode since the main goal is to maximize brake efficiency exploiting diluted mixture to evaluate the technology boundaries;

ii. The second one covers the implementation of air-assisted injection system redesigned to operate with air or CNG & Ethanol at the same injector for a flex-fuel operation (gaseous & liquid fuels).

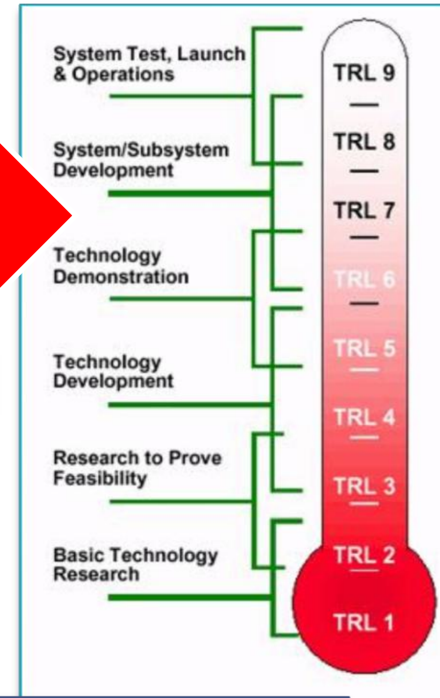


Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Potential Investigations for Highly efficient ICE - Technologies Approach

Technology Strategy

Mature Technologies → Advanced Technologies → Breakthrough



40% | **Lower efficiencies** | 42 – 43 % | 45 - 47% | **Higher efficiencies**

Lower risks ↔ **Higher risks**

- **Liquid Direct Injection**
- **Air-assisted Direct Injection**
- **Massive cooled EGR**
- **High Energy Ignition**

- **Advanced Combustion Chamber**
- **Dedicated to DI ethanol application**
- **Fuel Stratification**
- **Advanced Miller Cycle**
- **Flex DI combustion chamber**

- **Extended Stratification**
- **CNG-assisted Ethanol DI**
- **Ethanol 2 stroke CAI**
- **New supercharging methods**

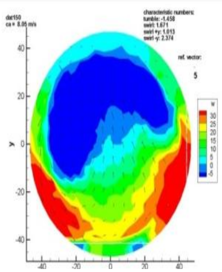
Ethanol & CNG DI Combustion Development for Heavy Duty Engines

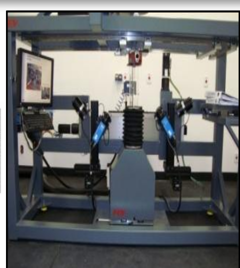
R&D Methodology implementation

This approach permits a fully optmized DI combustion chamber development process aiming at *"state of the art" or "breakthrough' technologies development through a complete and integrated R&D engineering team.* By means of a *scientific research methodology it is possible to acquire a step by step knowledge making possible to achieve rupture innovation.*

Laboratorial research chain sequence integrated with computational tools and design engineering

Cylinder head flow characterization





3D PIV FLOW BENCH

Spray characterization

SPRAY BENCH

Mixture / combustion development & emissions

SCRE

Structural head test

Valvetrain bench

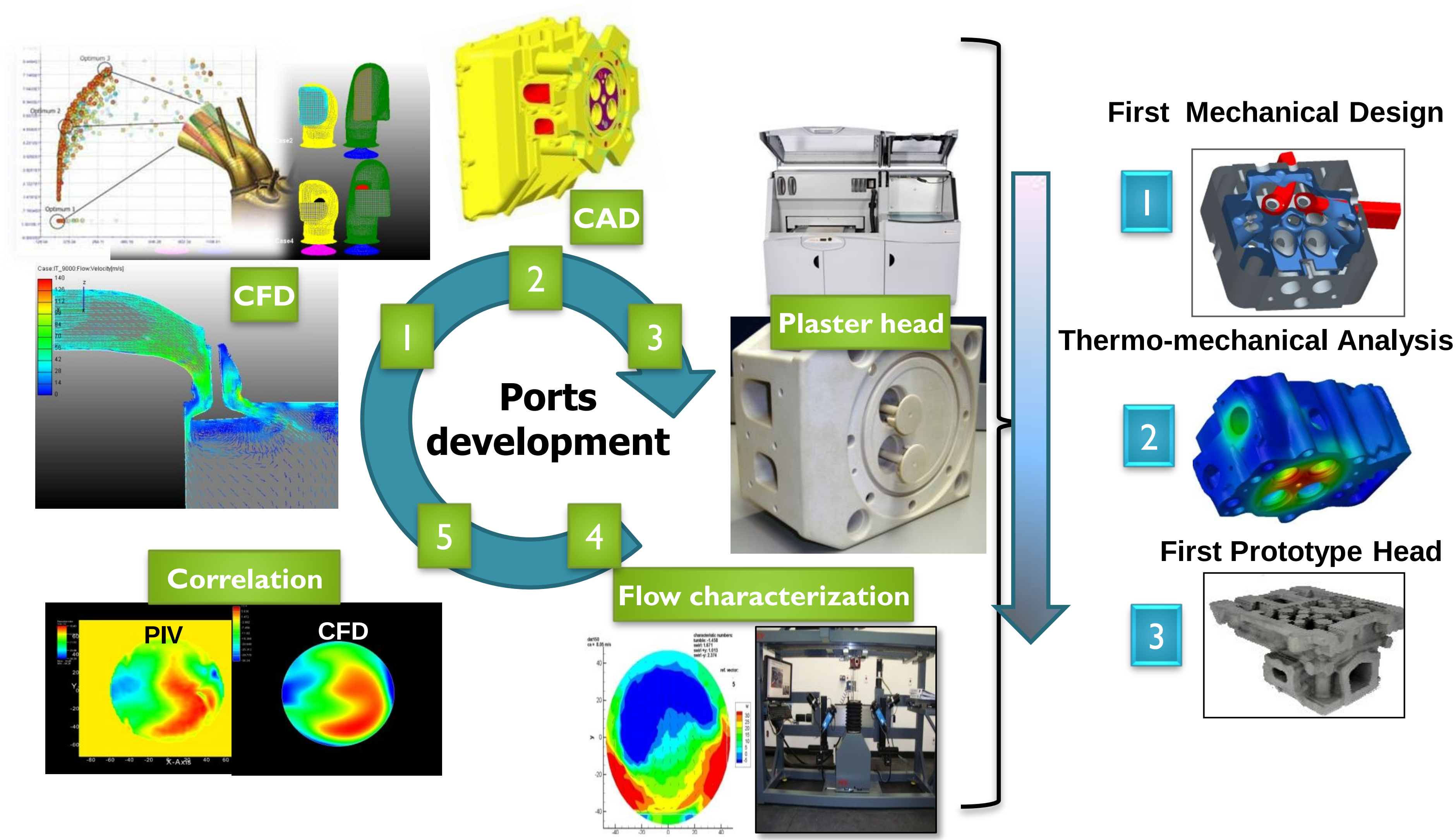
Electronic Control

CFD

Mechanical Design

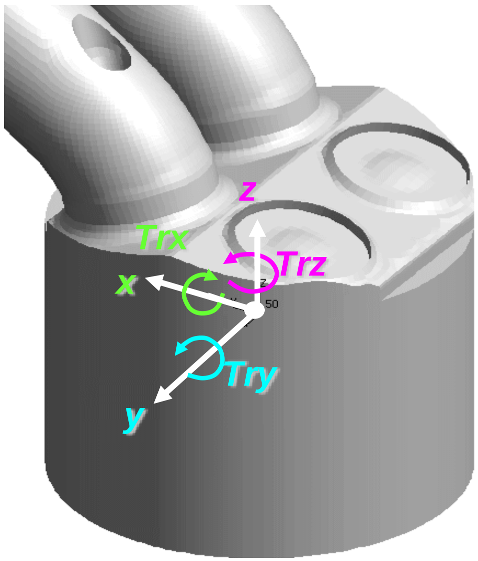
Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Intake ports flow Pre-design

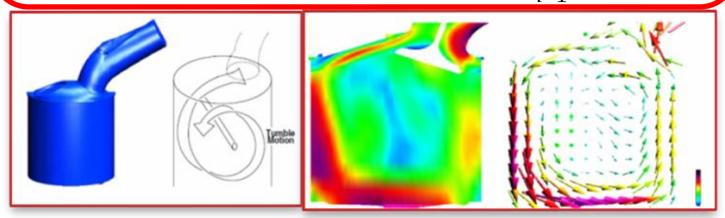


Ethanol & CNG DI Combustion Development for Heavy Duty Engines

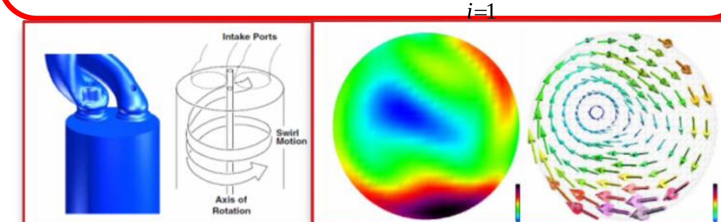
In-cylinder flow coeficients



$$Tumble = Tr_y = \frac{\pi}{4} \cdot \frac{D_{cilindro}}{c_a} \cdot \frac{\sum_{i=1}^{n} (-w_i \, x_i)}{\sum_{i=1}^{n} x_i^2}$$

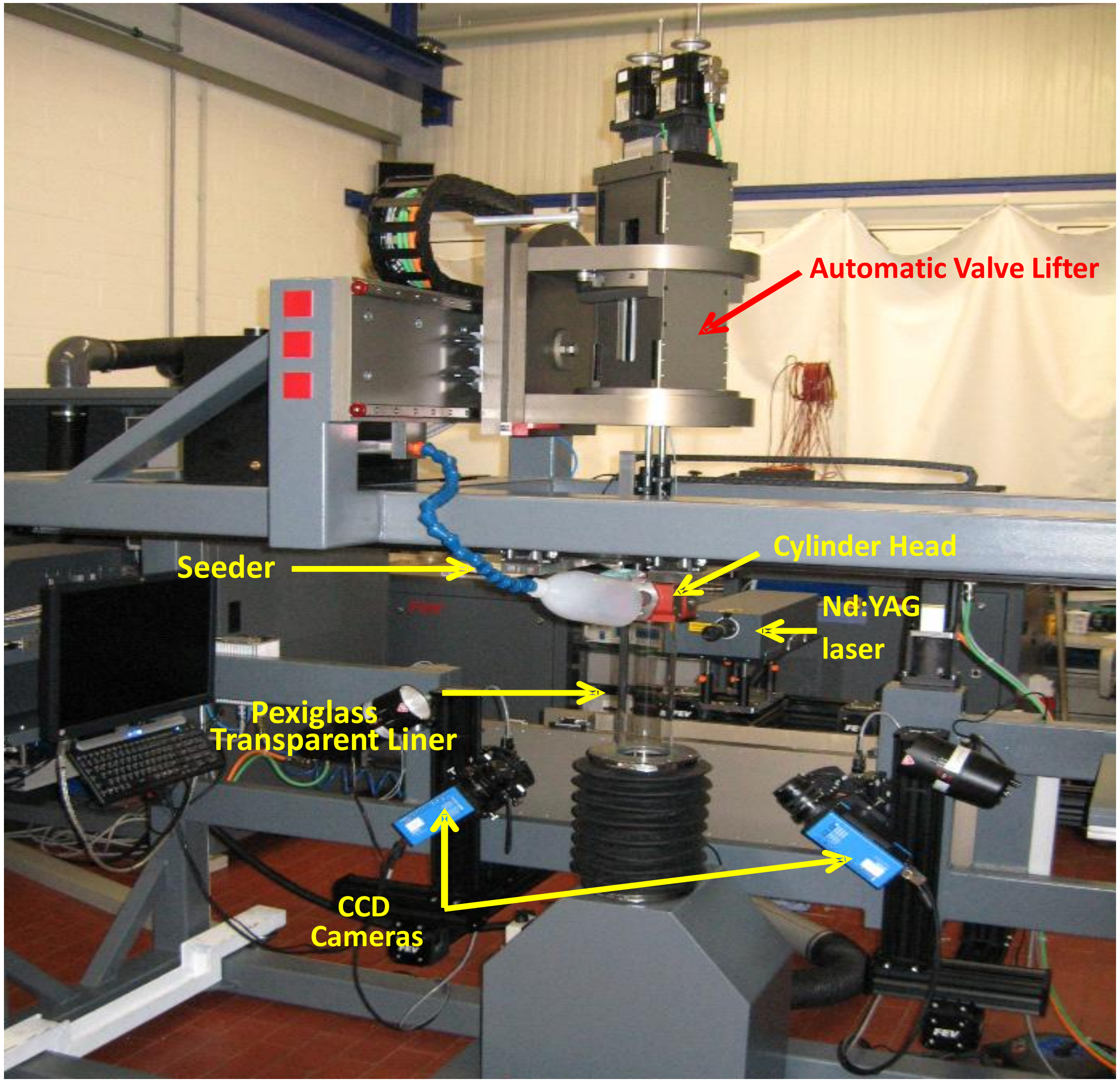


$$Swirl = Tr_z = \frac{\pi}{4} \cdot \frac{D_{cilindro}}{c_a} \cdot \frac{\sum_{i=1}^{n} (v_i \, x_i - u_i \, y_i)}{\sum_{i=1}^{n} (x_i^2 + y_i^2)}$$



Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Cylinder head flow test rig

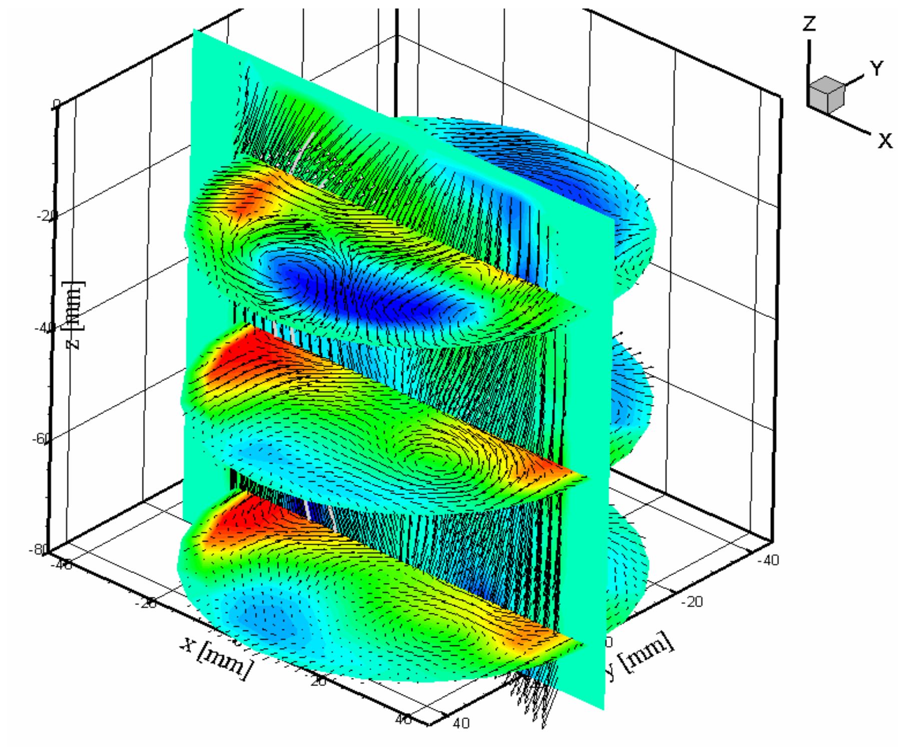


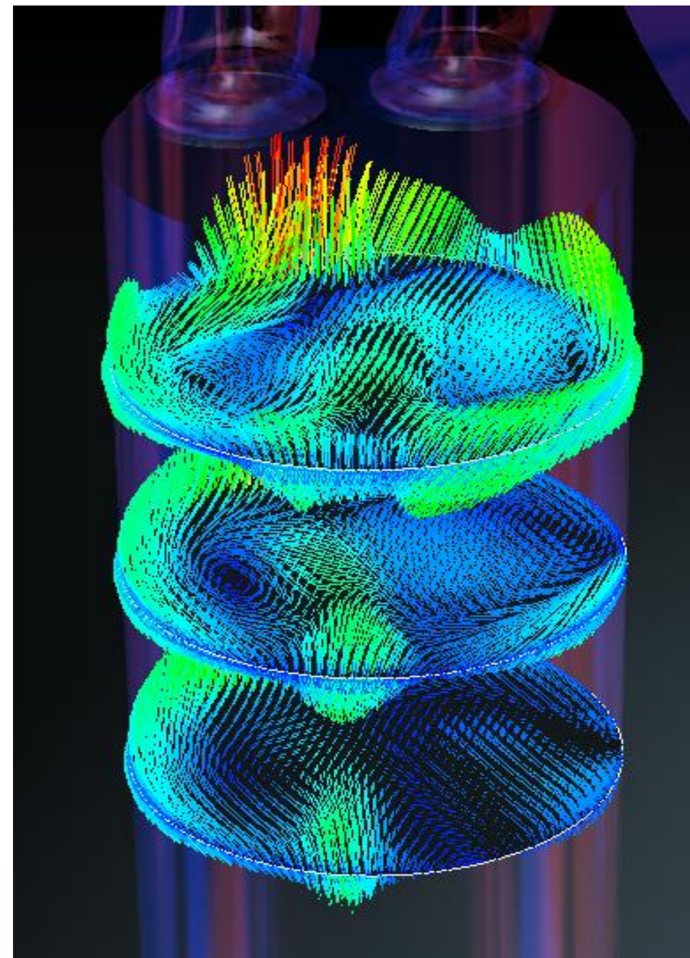
Ethanol & CNG DI Combustion Development for Heavy Duty Engines

In-cylinder flow characterization

Velocity fields are required to completely recover all terms in Navier-Stokes equation:

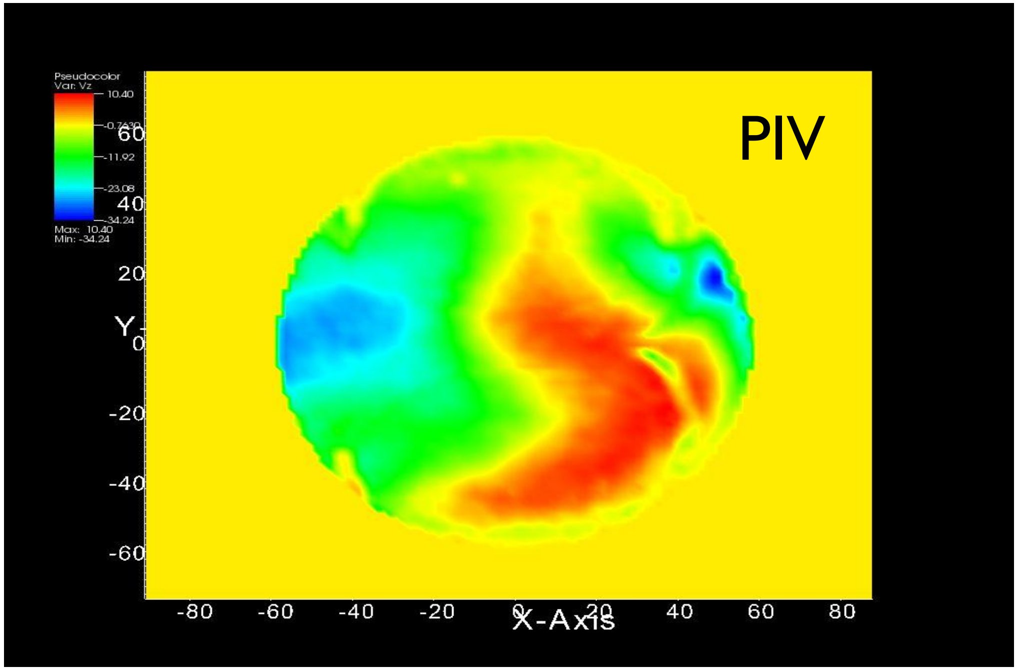
$$\rho\frac{D\mathbf{U}}{Dt}=-\nabla p+\mu\nabla^{2}\mathbf{U}+\mathbf{F}$$

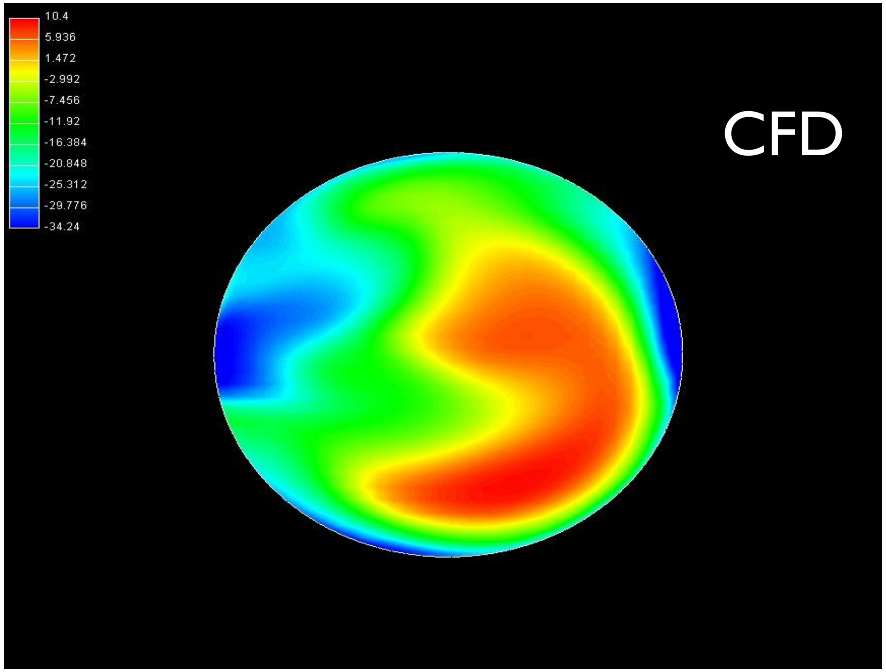




Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Measurements X Simulation





$$Swirl = Tr_z = \frac{\pi}{4} \cdot \frac{D_{cilindro}}{c_a} \cdot \frac{\sum_{i=1}^{n} (v_i\, x_i - u_i\, y_i)}{\sum_{i=1}^{n} (x_i^2 + y_i^2)}$$

PIV	CFD	Variance
0,55	0,57	3,5 %

Ethanol & CNG DI Combustion Development for Heavy Duty Engines

DI characterization & pre-design

INJECTOR DESIGN
- Nozzle geometry
- Opening time
- Closing time
- Pintle bonuce
- Driver capacitive delay

INJECTION CONDITIONS
- Fuel rail pressure
- Injection duration
- Injection rate
- Single vs. Split injection

FUEL TYPE
- Viscosity
- Specific gravity
- Surface tension
- Fuel volatility

AMBIENT CONDITIONS
- Ambient pressure
- Ambient temperature
- Ambient density
- Air flow field

Spray Characteristics

SPRAY STRUCTURE
- Fuel mass distribuition
- Spray asymmetry
- Offset from injector axis
- Collapse vs. Non collapse

SPRAY CONFIGURATION
- Cone angle
- Penetration
- Spray diameter
- Wetted footprint

Droplet characteristics
- Size
- Velocity
- Momentum
- Weber number
- Time history
- Spatial distribuition

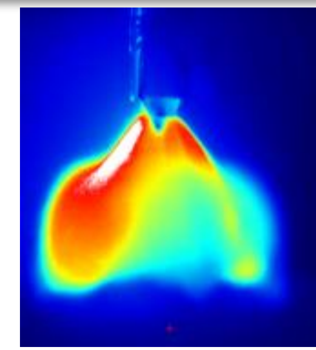
OTHERS
- Sac spray
- Spray finger
- After-injection spray
- Spray-to-spray variation
- Injector-to-injector spray Variation
- Spray torque for swirl injector

Ethanol & CNG DI Combustion Development for Heavy Duty Engines

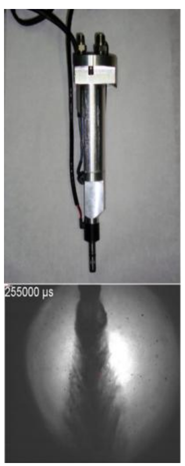
DI characterization & pre-design

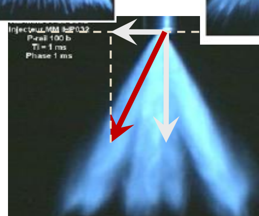
SPRAY CHARACTERIZATION

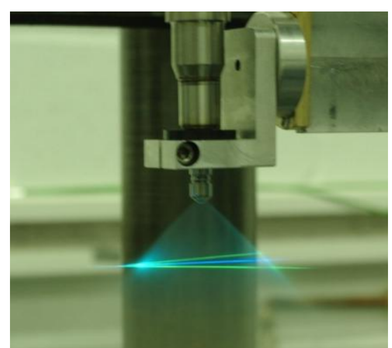
CFD CALIBRATION MODEL



air-assisted **Bosch HDEV4** **Continental** **Magneti Marelli**





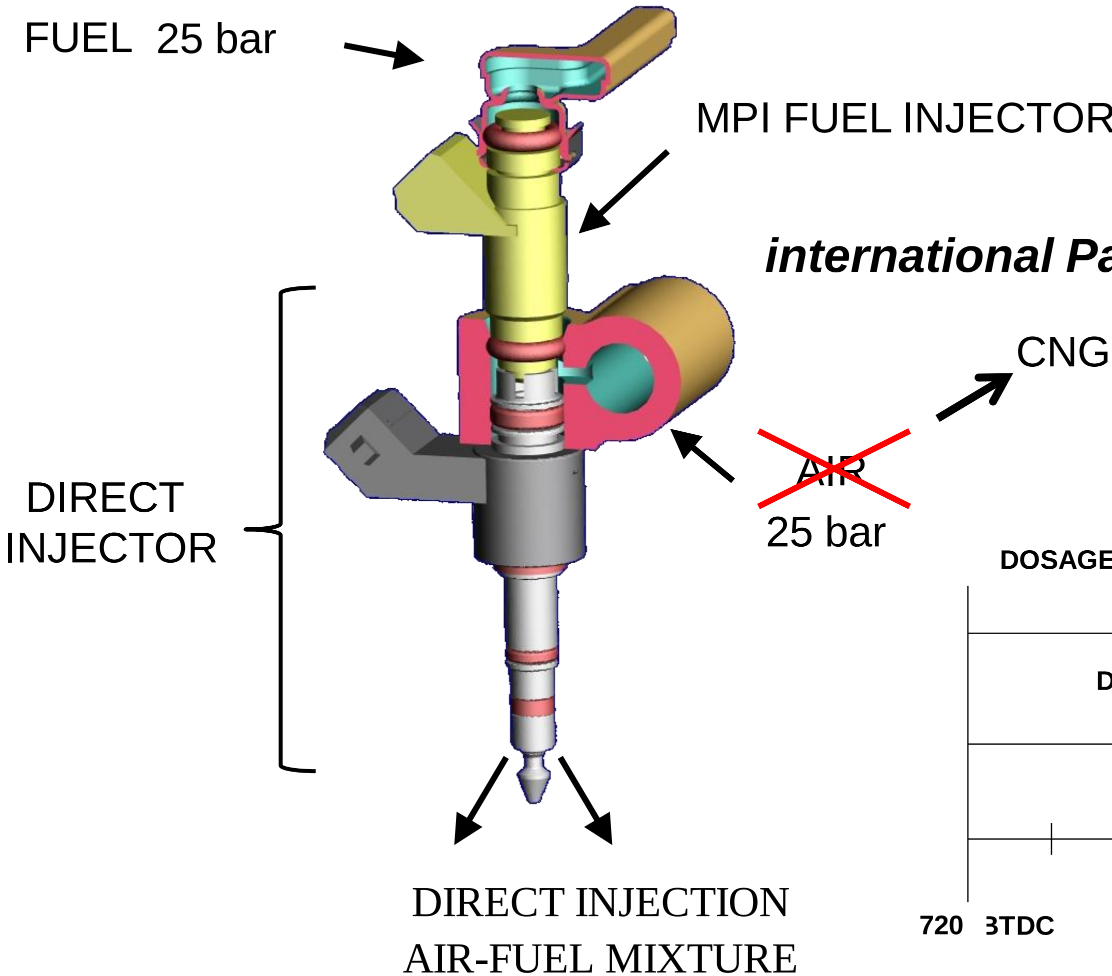


MAIN FEATURES

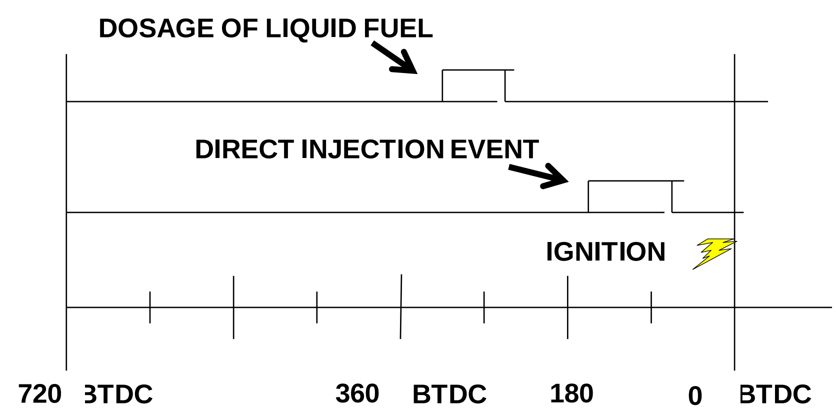
- Cone angle
- Droplet distribuition
- Droplet sizes
- Spray velocity
- Wetted foot print
- Spray asymmetry
- Spray penetration
- Spray diameter

Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Air-assisted Injector system



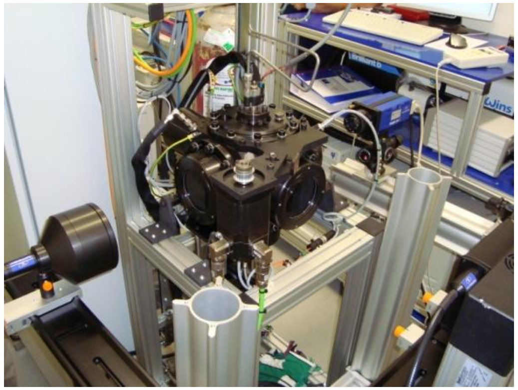
international Patent application PI 1002727-0

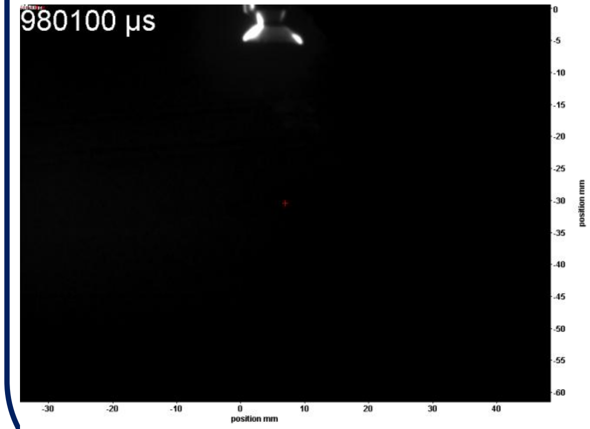


Ethanol & CNG DI Combustion Development for Heavy Duty Engines

DI characterization & pre-design

CFD

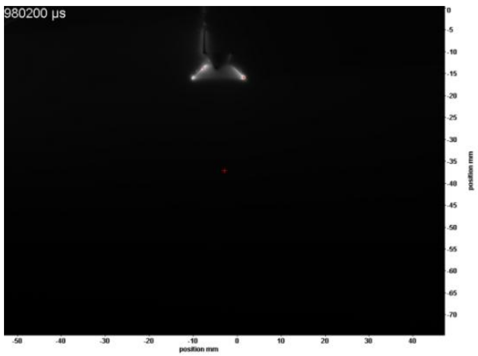




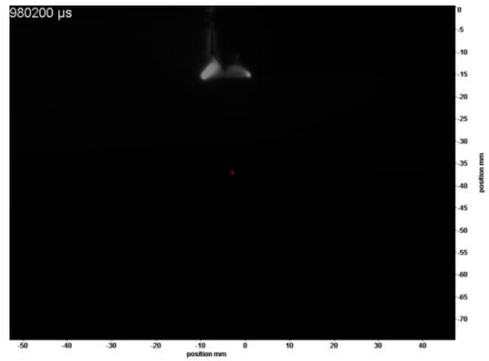
SCRE

Ethanol & CNG DI Combustion Development for Heavy Duty Engines

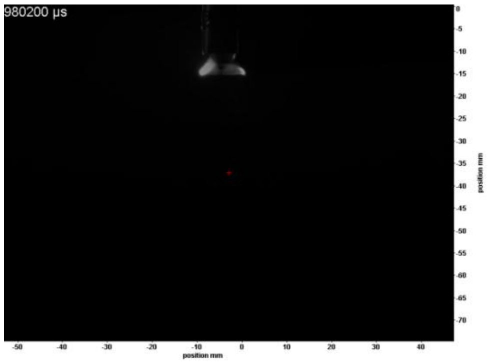
DI characterization & pre-design (counter pressure)



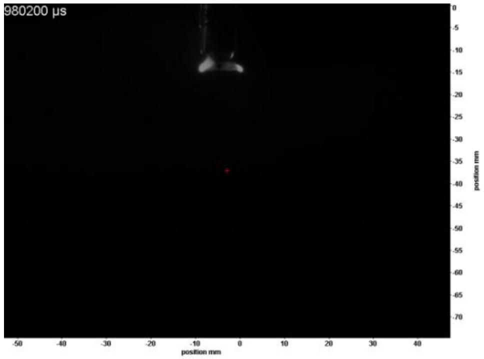
0 bar



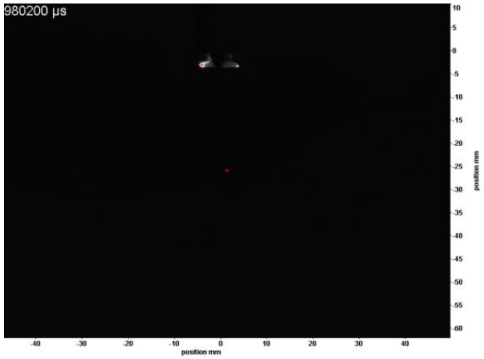
10 bar



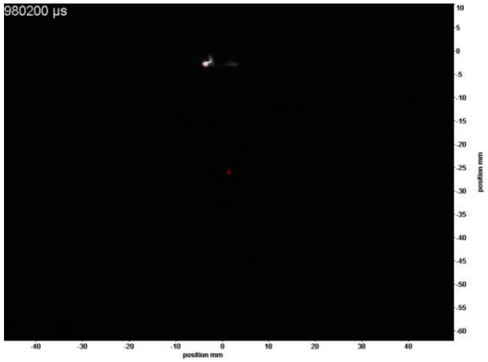
20 bar



30 bar



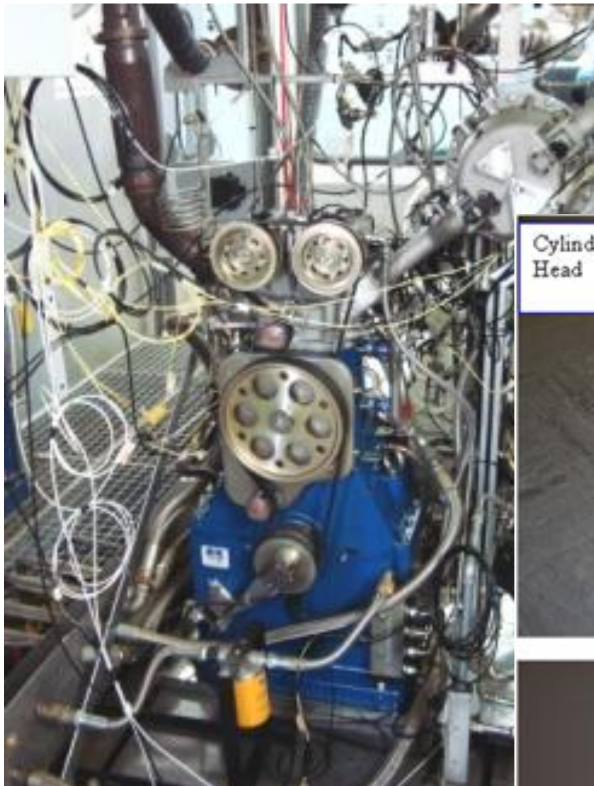
40 bar



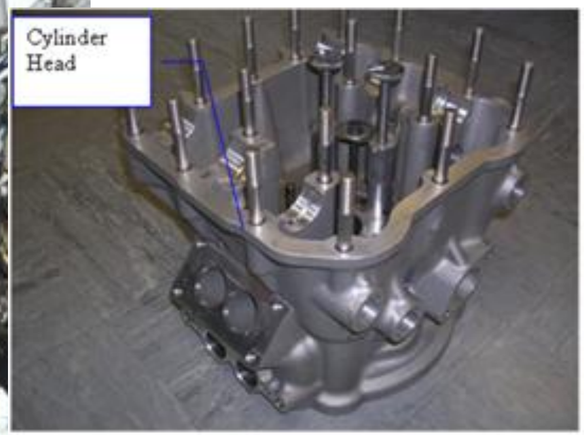
50 bar

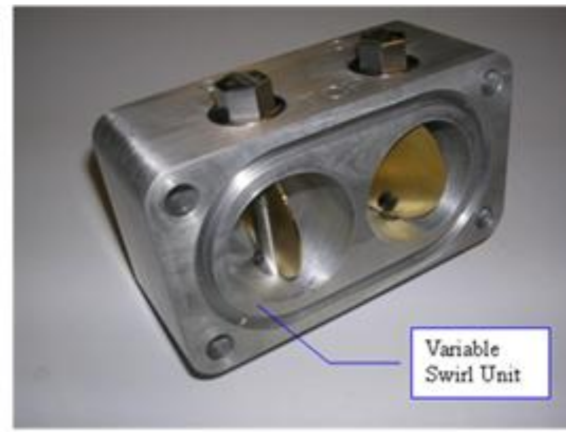
Ethanol & CNG DI Combustion Development for Heavy Duty Engines

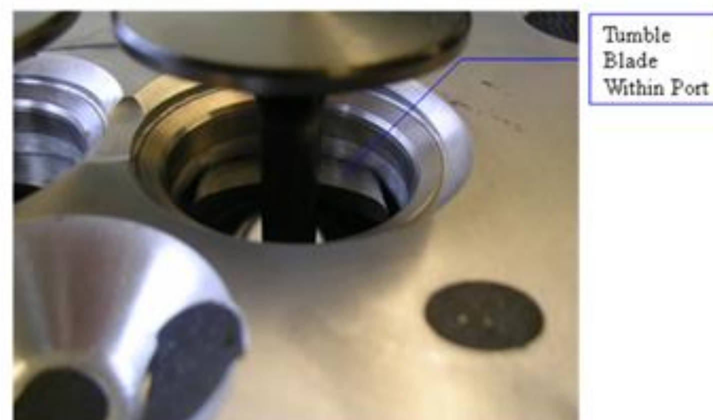
Flow, Mixture Formation, Combustion & Emission Integration



Single Cylinder Research Engine





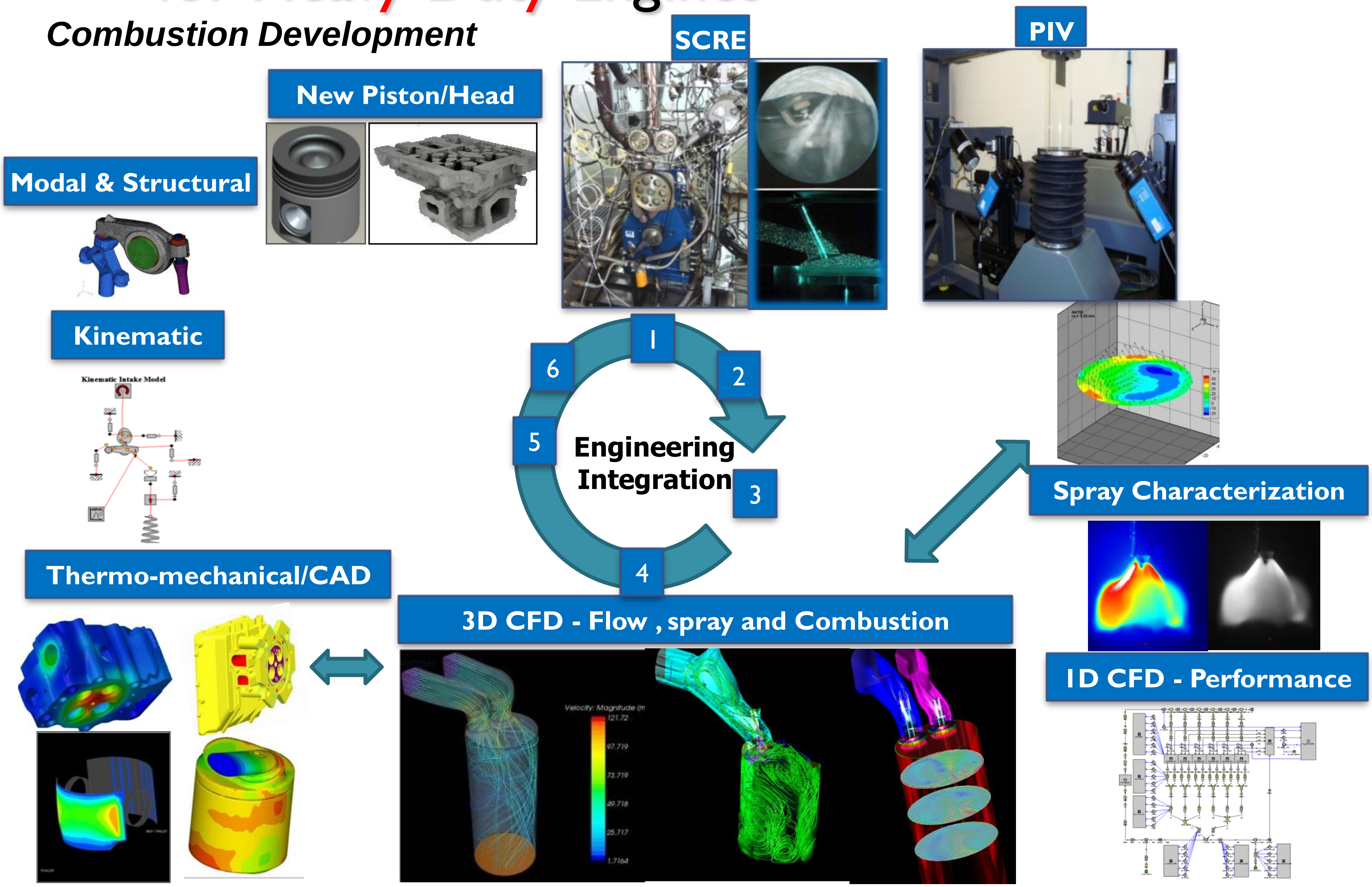


Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Flow, Mixture Formation, Combustion & Emission Integration

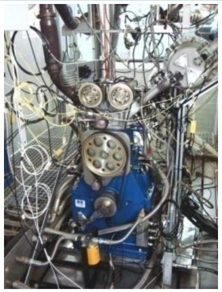
Single Cylinder Research Engine

Ethanol & CNG DI Combustion Development for Heavy Duty Engines



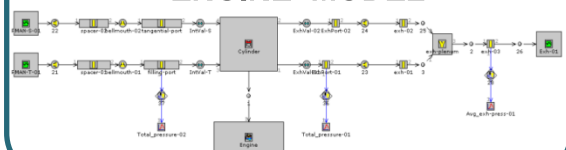
Ethanol & CNG DI Combustion Development for Heavy Duty Engines

R&D Methodology implementation



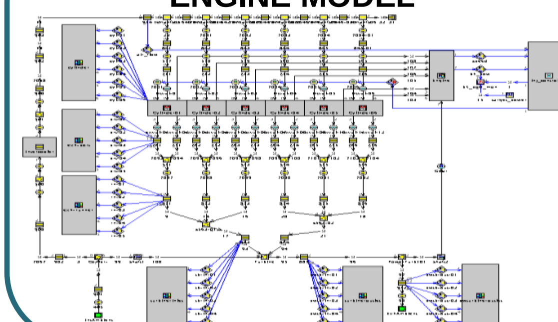
DI SINGLE CYLINDER RESEARCH ENGINE

DI SINGLE CYLINDER RESEARCH ENGINE MODEL

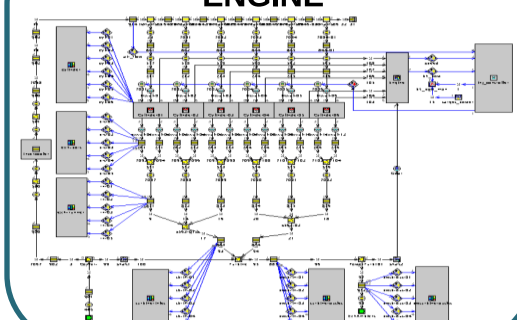


PFI MULTI-CYLINDER ENGINE

PFI MULTI-CYLINDER ENGINE MODEL



DI MULTI-CYLINDER ENGINE



Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Main Issues & Technical Results

- Direct Injection
- Cooled EGR
- Miller Cycle
- High Energy Ignition System

Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Main Issues & Technical Results

Advantages of Direct Injection

✓ Charge cooling (mixture fuel / air / burnt gases)

✓ Fuel estratification

✓ More accurate fuel metering

✓ Elimination of fuel overlap

✓ Much better cold start & warm-up

Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Main Issues & Technical Results

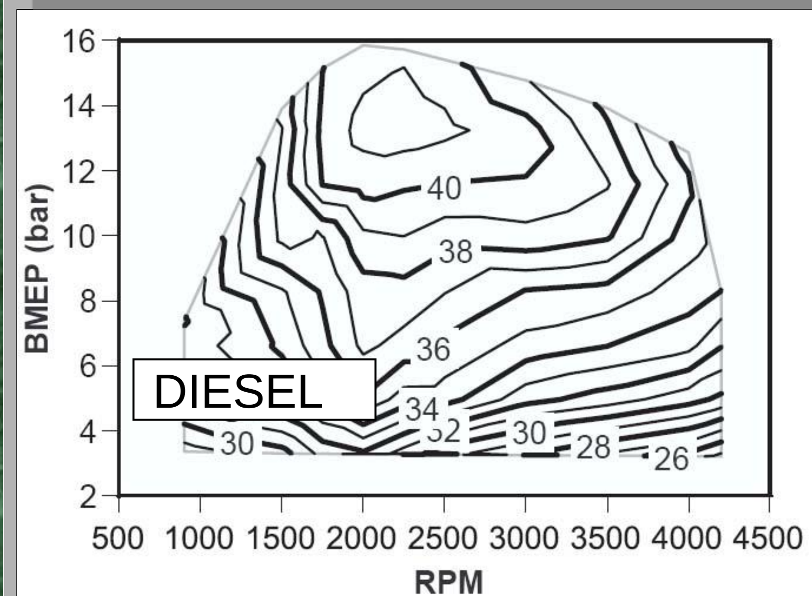
Advantages of Cooled EGR

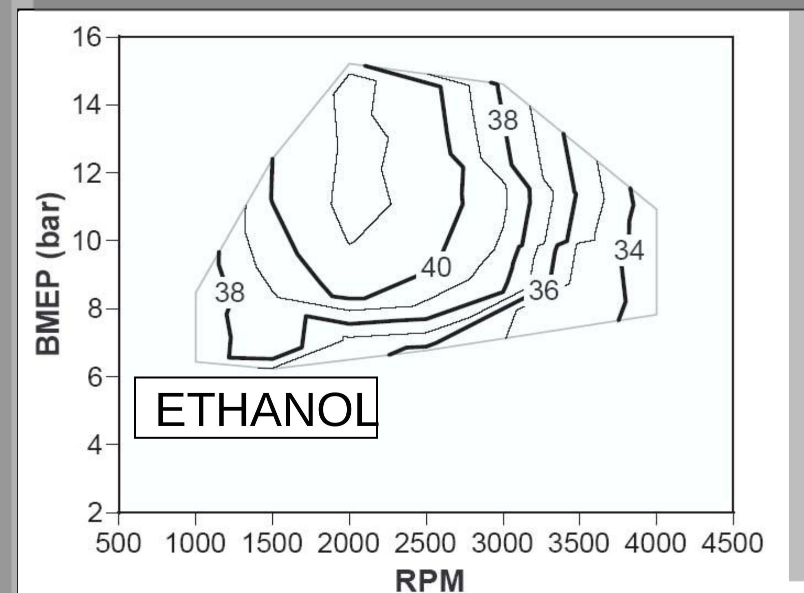
- ✓ Mitigation of Knock occurrence
- ✓ Mitigation of Pre & Post-ignition
- ✓ *Mega-knock suppression*
- ✓ Reduction of Pmax
- ✓ Exhaust Higher enthalpy at high loads operation
- ✓ Reduction of gross NO_x emission
- ✓ Feasible efficient operation of 3 way catalist

Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Main Issues & Technical Results

Advantages of Cooled EGR





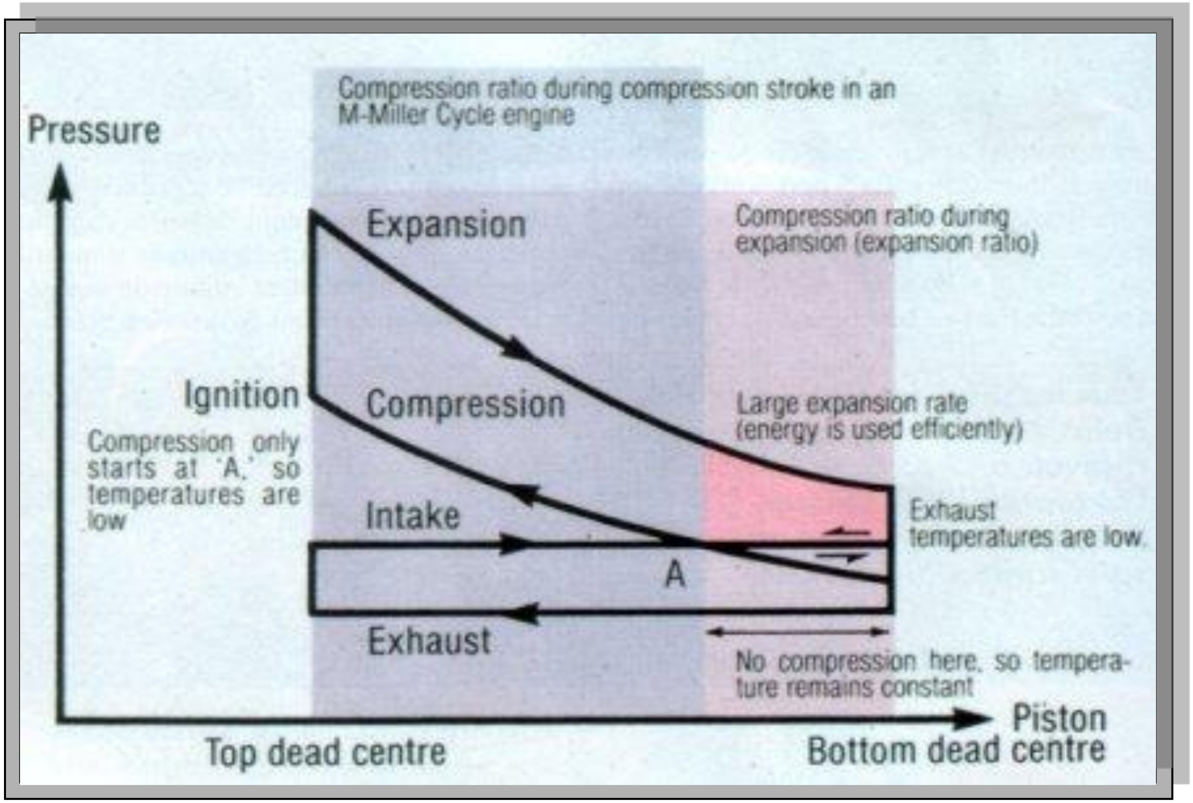
1.9 l, 4 CYLINDERS, 19.5:1 COMPRESSION RATIO, HIGH-SWIRL

SAE 2002-01-2743

Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Main Issues & Technical Results

Advantages of Miller Cycle



- ✓ Lower Cycle Pressures
- ✓ Higher Knock Resistence
- ✓ Lower NO_X Emissions
- ✓ Higher Energy Recovery

Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Conclusions & Lessons Learned

Deficiencies Found

- Less than optimum flame propagation:
  - ✓ off-center burned zone;
  - ✓ too early turbulence decay;
  - ✓ slow end-gas combustion.
- Substantial differences in combustion from cycle-to-cycle:
  - ✓ peak cycle pressures;
  - ✓ combustion efficiency;
  - ✓ knock likelihood;
  - ✓ emissions.

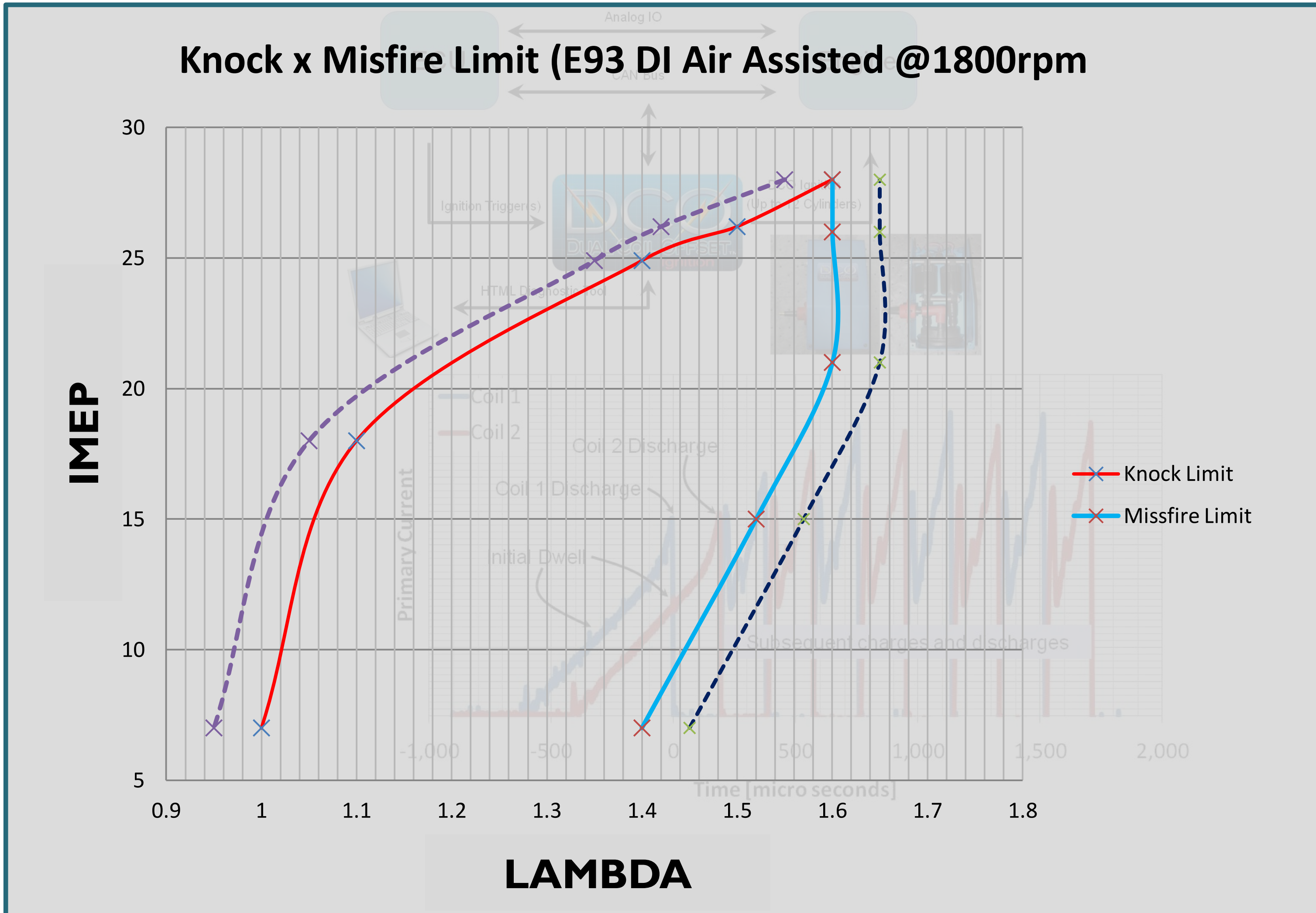
Solutions

- Development targets:
  - ✓ more effective intake-induced coherent flow dissipation around TC;
  - ✓ moderate flow velocity in the vicinity of spark plug at spark timing;
  - ✓ combustion CG displaced towards combustion end;
  - ✓ decoupling between earlier-to-be-burned and end-gas mixture properties;
  - ✓ more intense better-distributed turbulence past TC.

Patent Filed

Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Main Issues & Technical Results **- Advantages of High Energy Ignition System**



Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Conclusions & Lessons Learned

- Feasible operation above 25 bar BMEP.
- Competitive efficiencies at high load operation.
- Feasible compliance with emission regulations using simple exhaust aftertreatment system.
- A lot of room for improvement of:
  - ✓ combustion system;
  - ✓ engine operation & configuration.

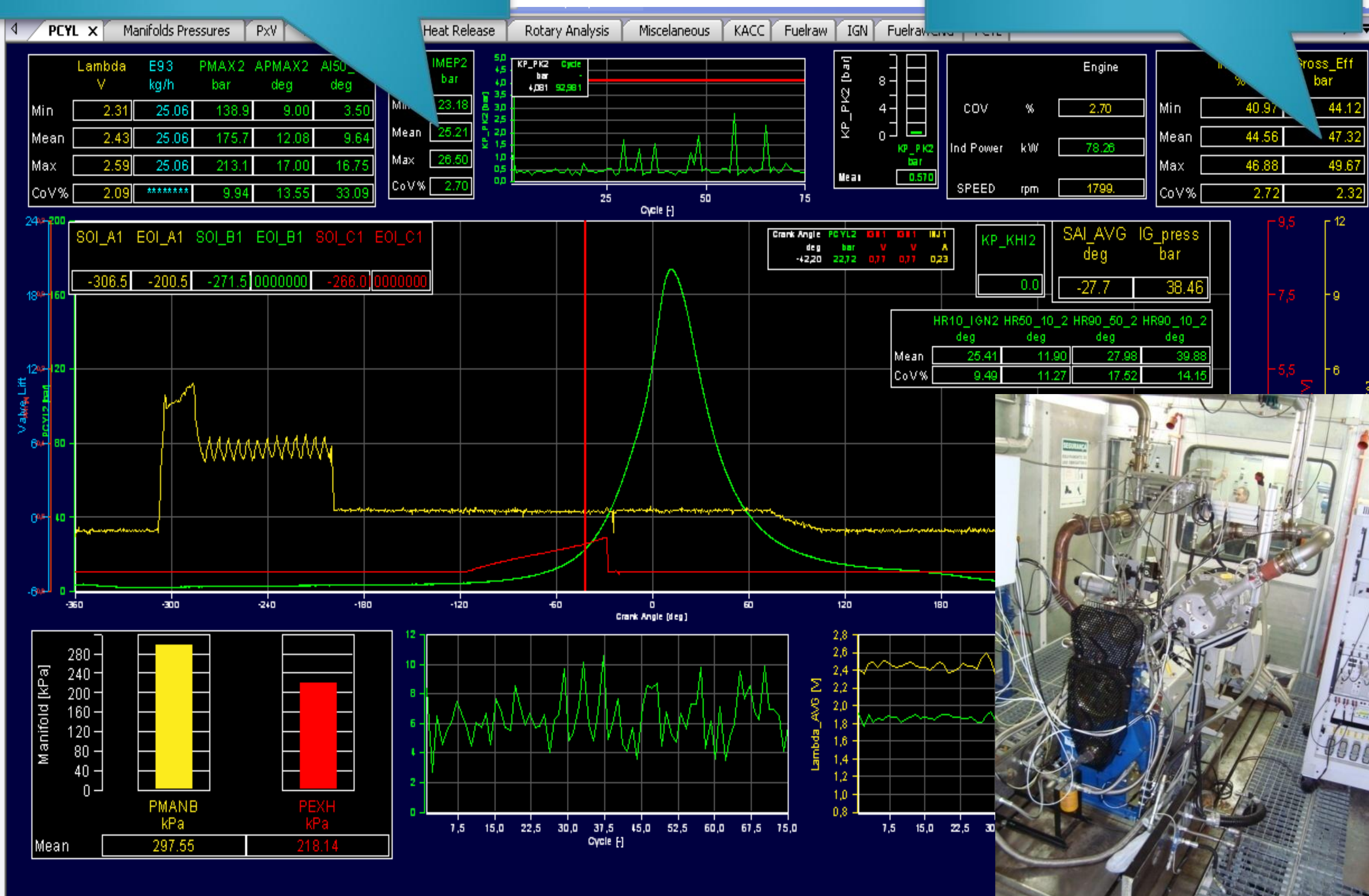
Ethanol & CNG DI Combustion Development for Heavy Duty Engines

IMEP > 25 BAR

IMEP limited by maximum injector fuel flow.

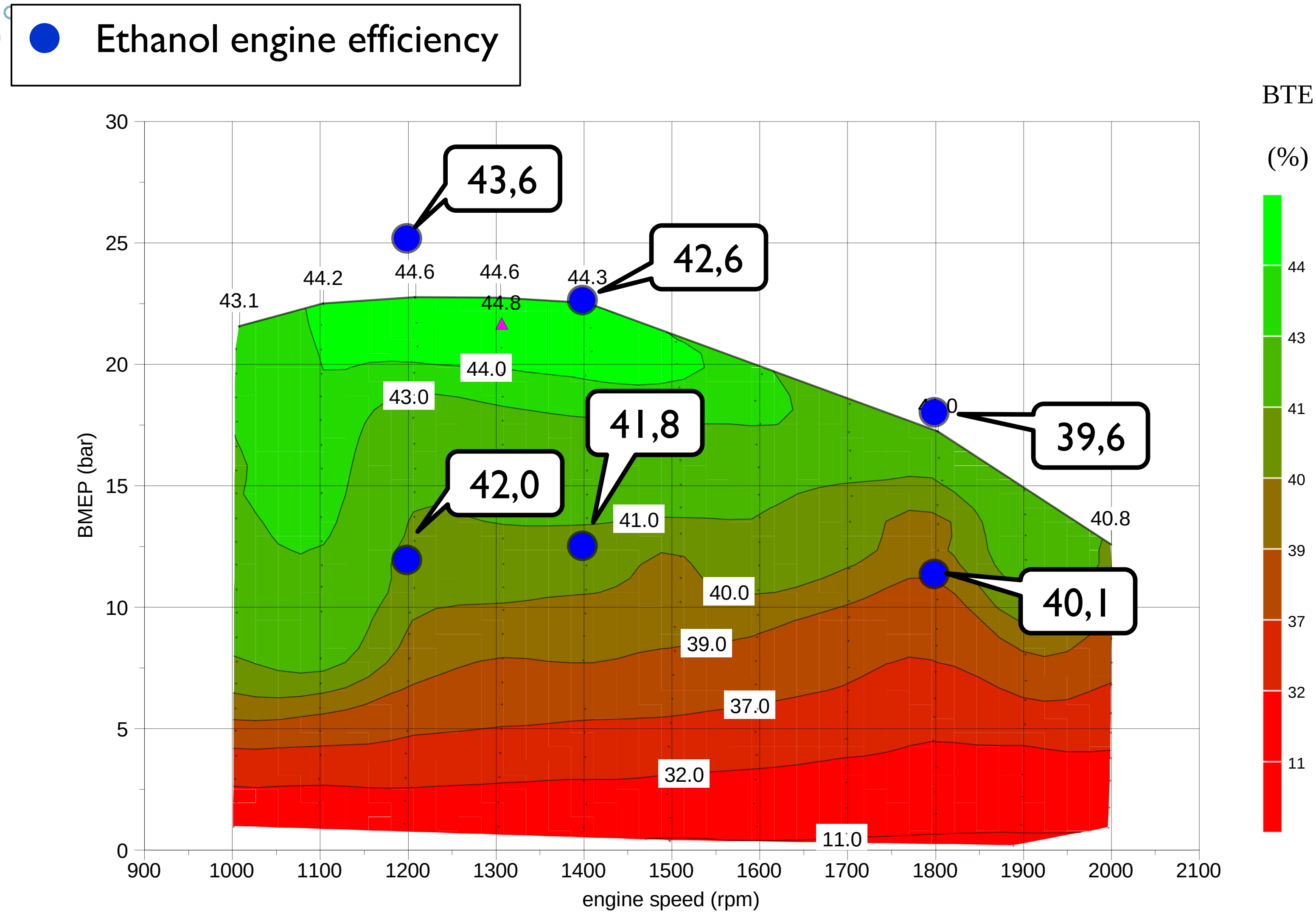
Gross efficiency > 47%

Matching diesel units.



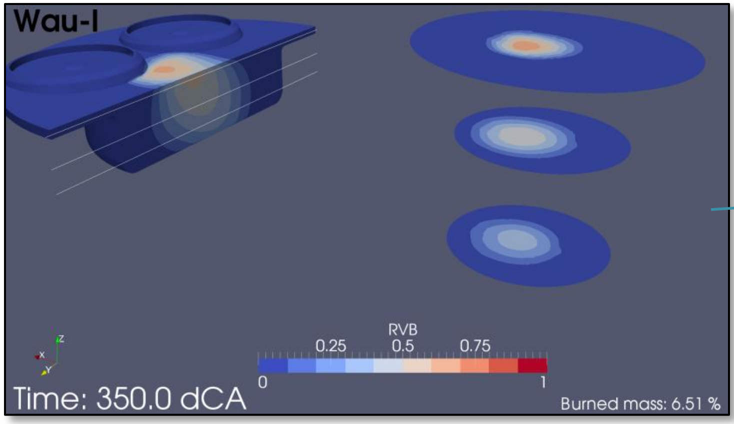
Ethanol & CNG DI Combustion Development for Heavy Duty Engines

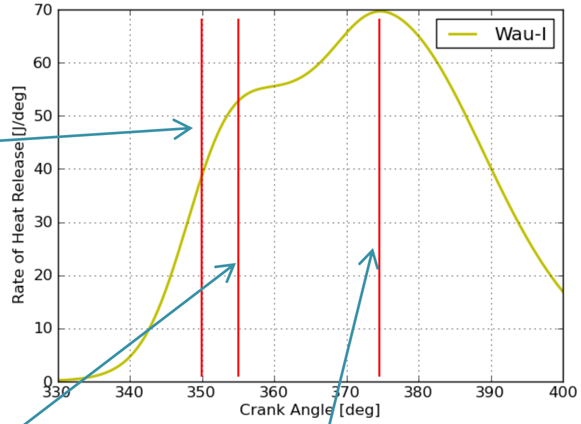
Conclusions & Lessons Learned

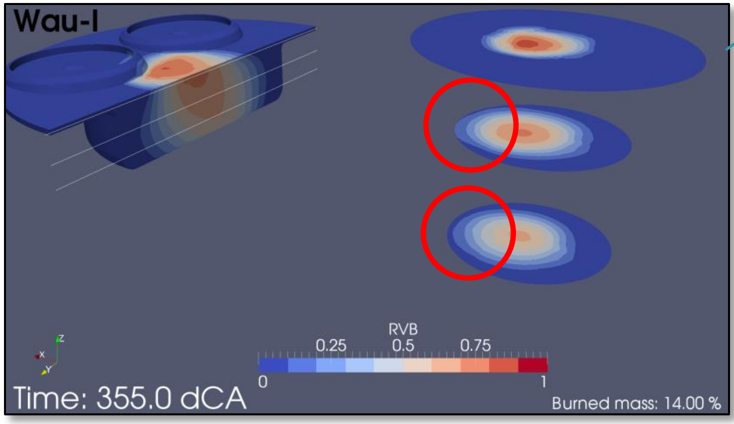


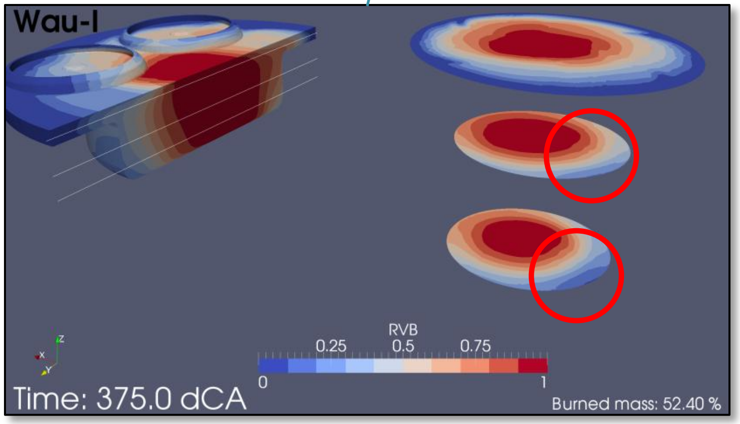
Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Off-center burned zone



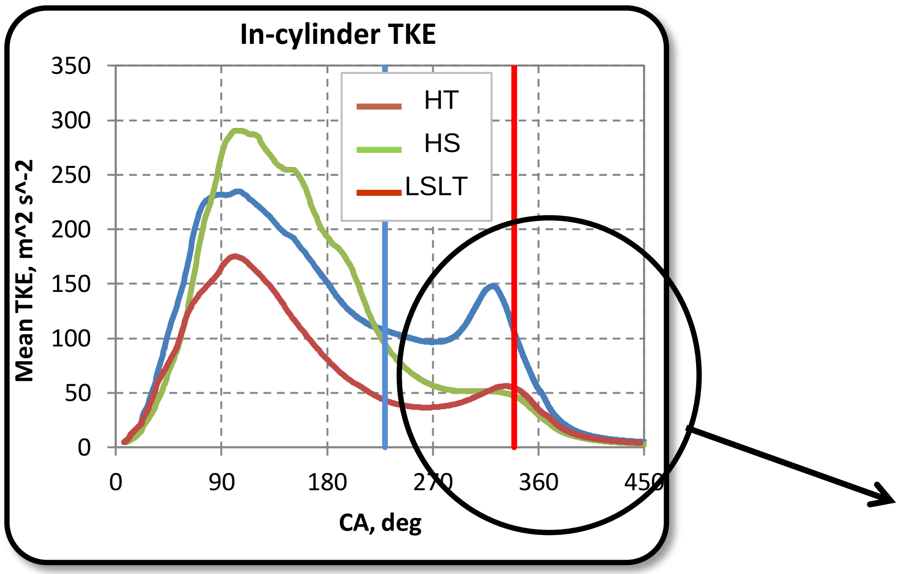


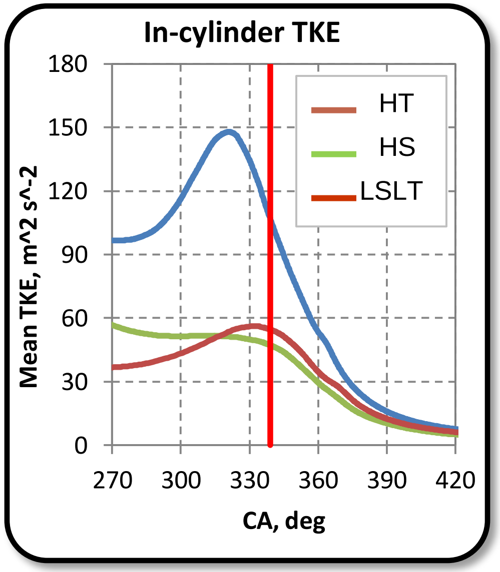




Ethanol & CNG DI Combustion Development for Heavy Duty Engines

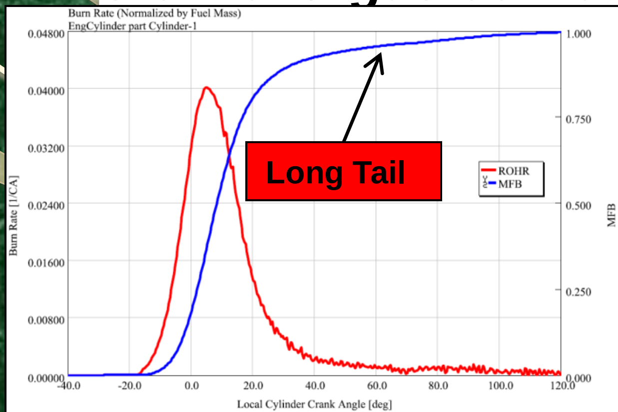
Early turbulence decay

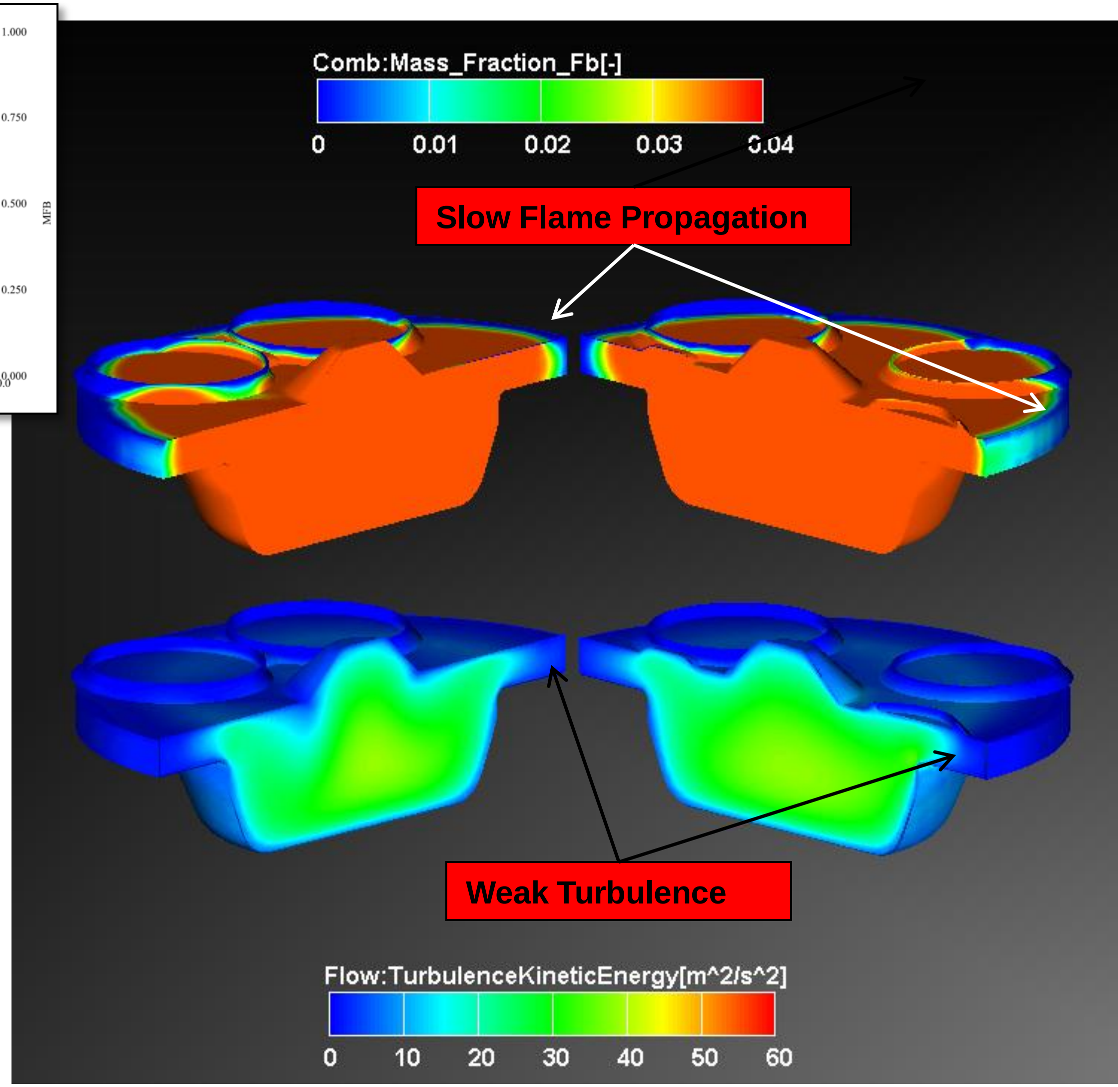




Ethanol & CNG DI Combustion Development for Heavy Duty Engines

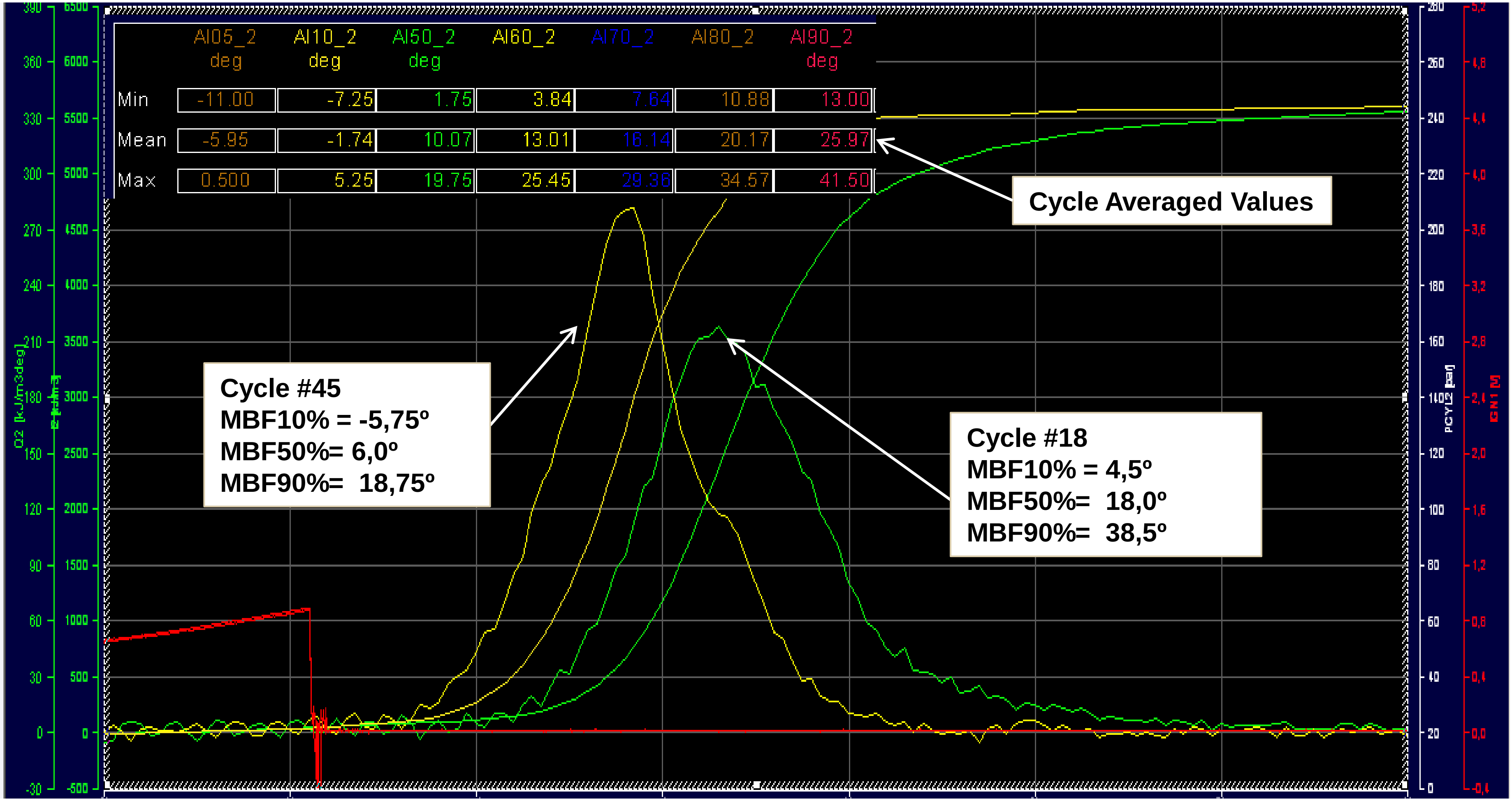
Slow end-gas combustion





Ethanol & CNG DI Combustion Development for Heavy Duty Engines

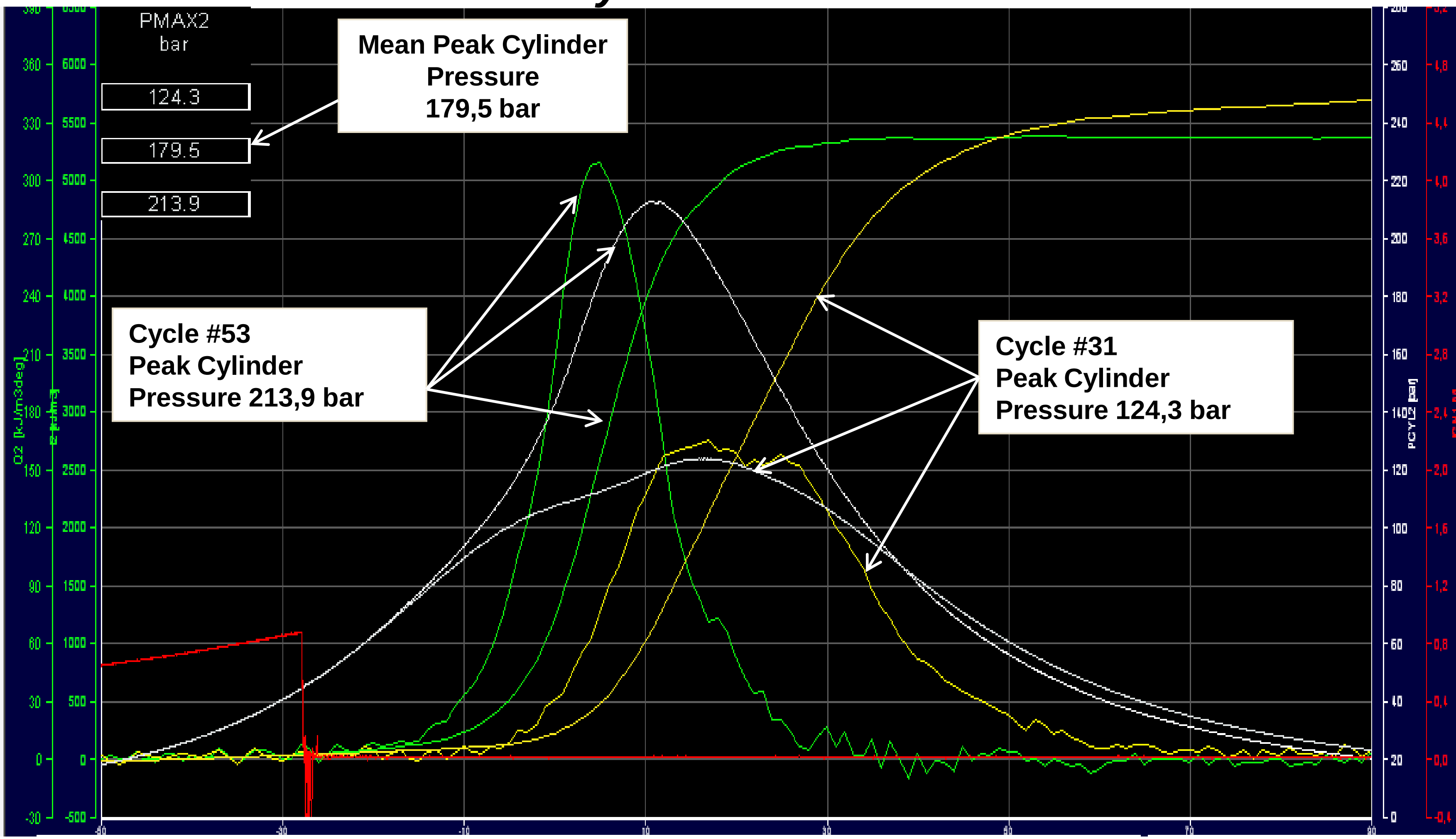
Combustion Variability



	AI05_2 deg	AI10_2 deg	AI50_2 deg	AI60_2	AI70_2	AI80_2	AI90_2 deg
Min	-11.00	-7.25	1.75	3.84	7.64	10.88	13.00
Mean	-5.95	-1.74	10.07	13.01	16.14	20.17	25.97
Max	0.500	5.25	19.75	25.45	29.36	34.57	41.50

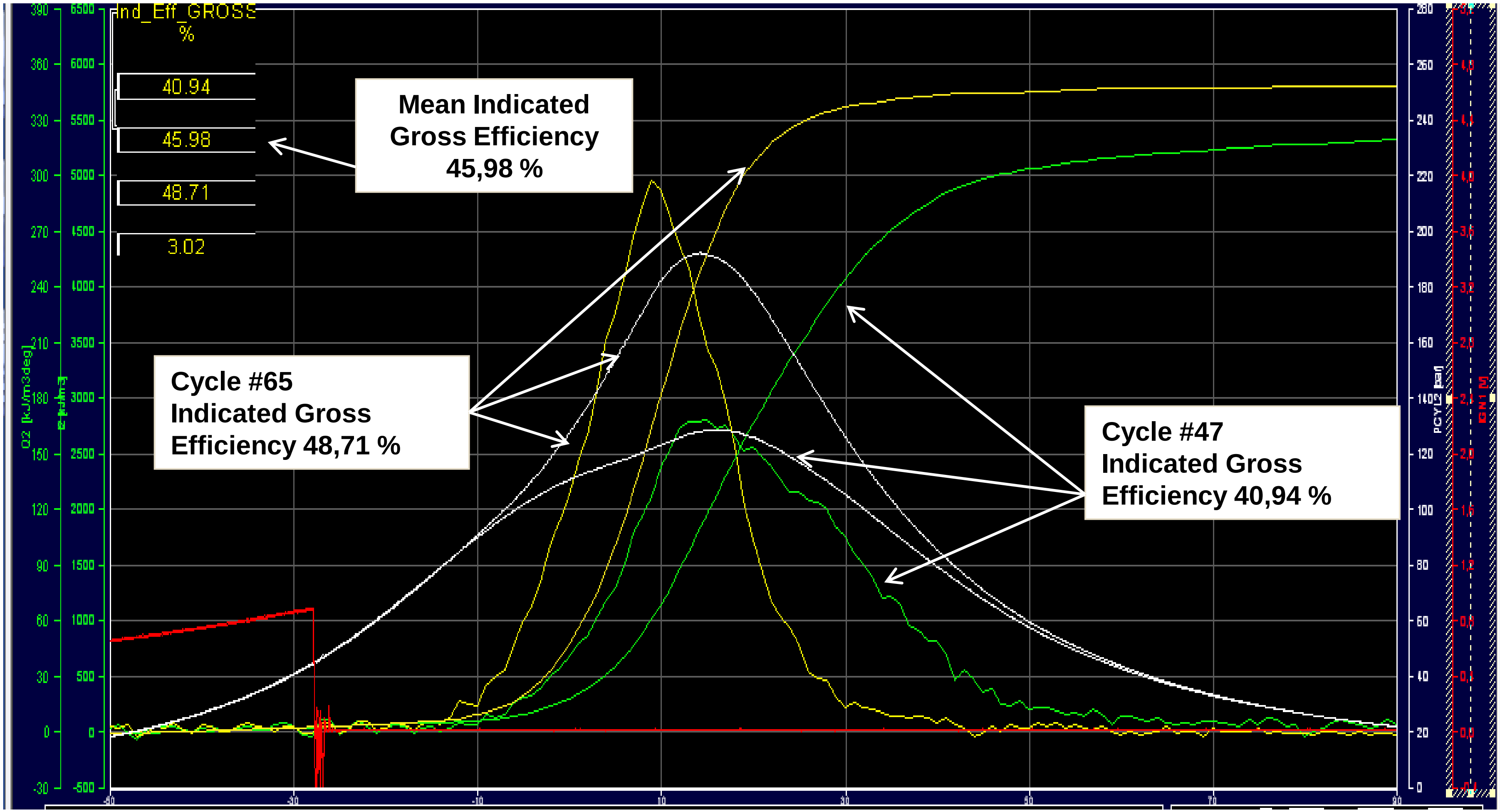
Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Peak Pressure Variability



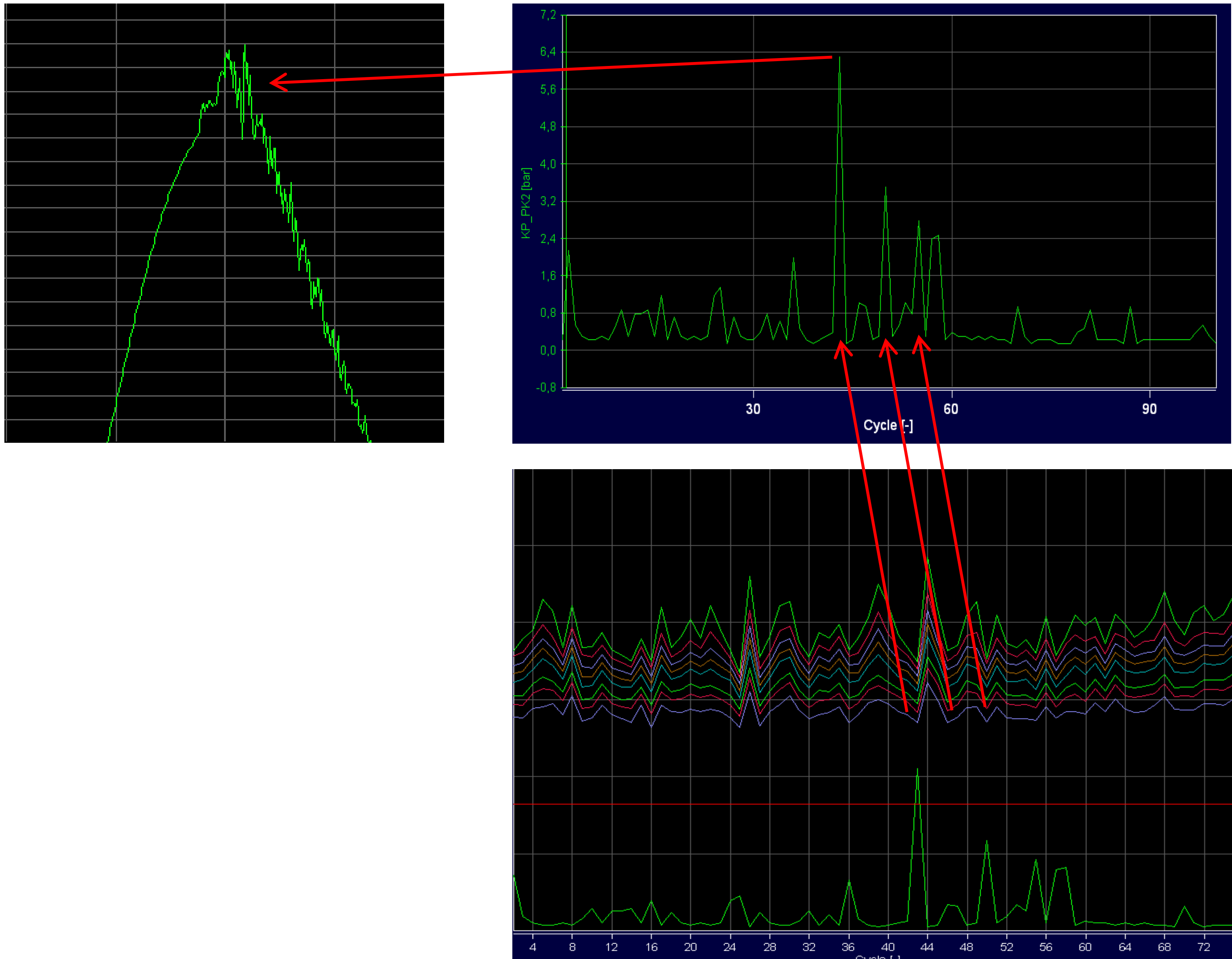
Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Efficiency Variability



Ethanol & CNG DI Combustion Development for Heavy Duty Engines

Knock Variability

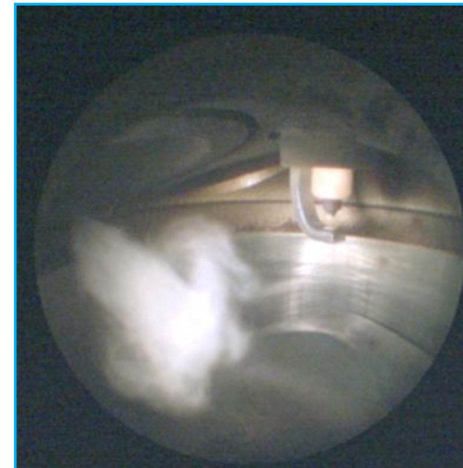


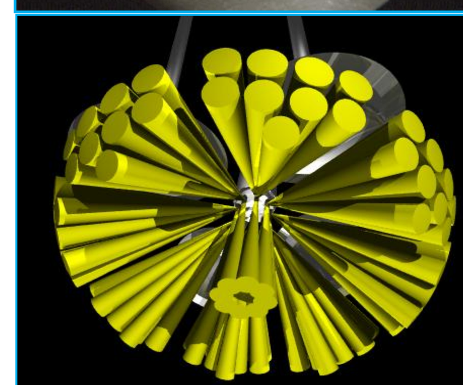
Ethanol PFI & DI Combustion Development for Light Duty Engines

- The main goal is to define an engine architecture that fully exploit *Ethanol Potential* in order to match E22 fuel mileage with the same performance index.

   i. The first phase comprises the development of a PFI engine concept that will be coupled to a prototype car to evaluate the technology boundaries;

   ii. The second phase covers the implementation of Ethanol DI concept in order to extend and evaluate further efficiency gains & its cost-effectiveness.



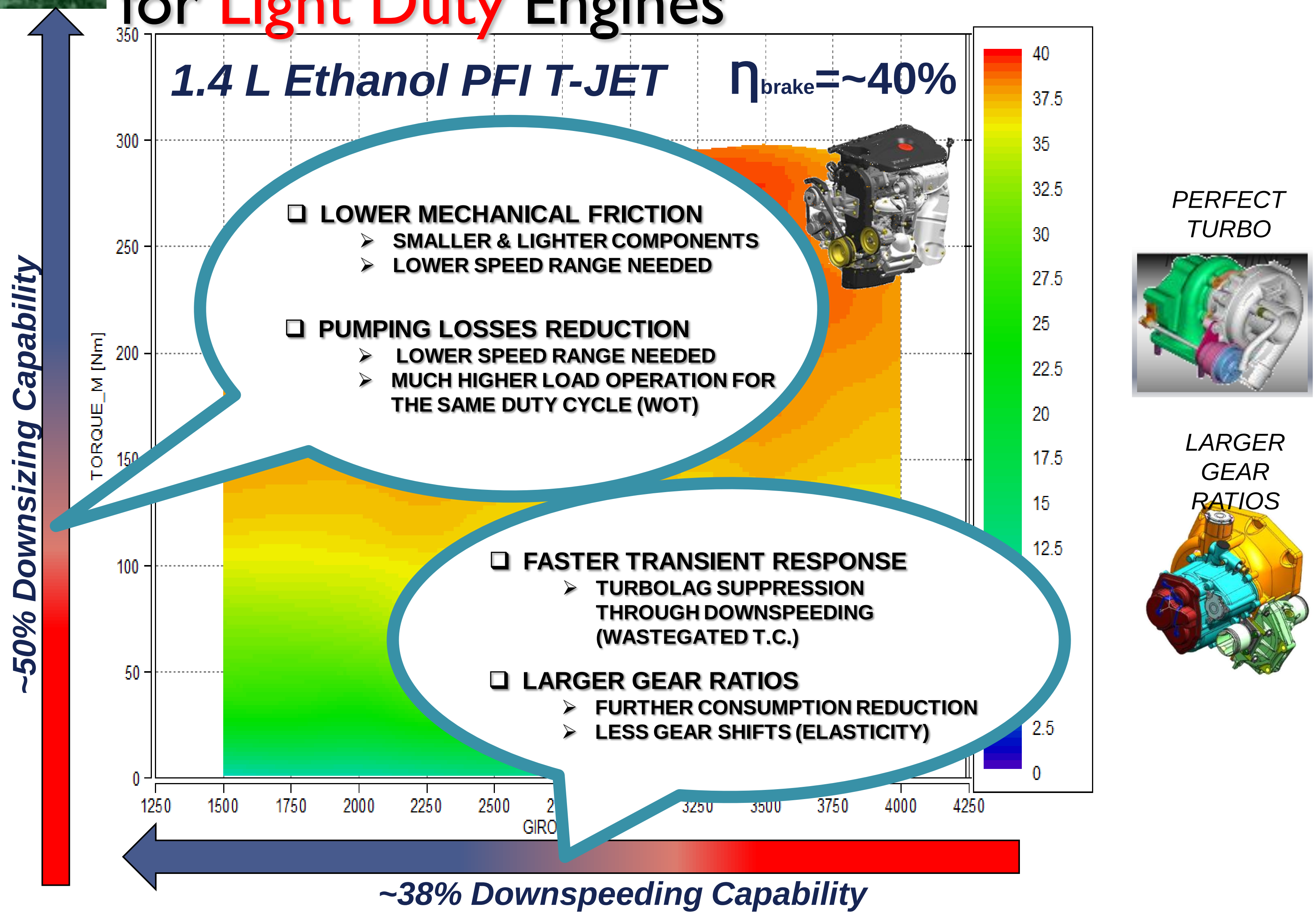


Ethanol PFI & DI Combustion Development for Light Duty Engines

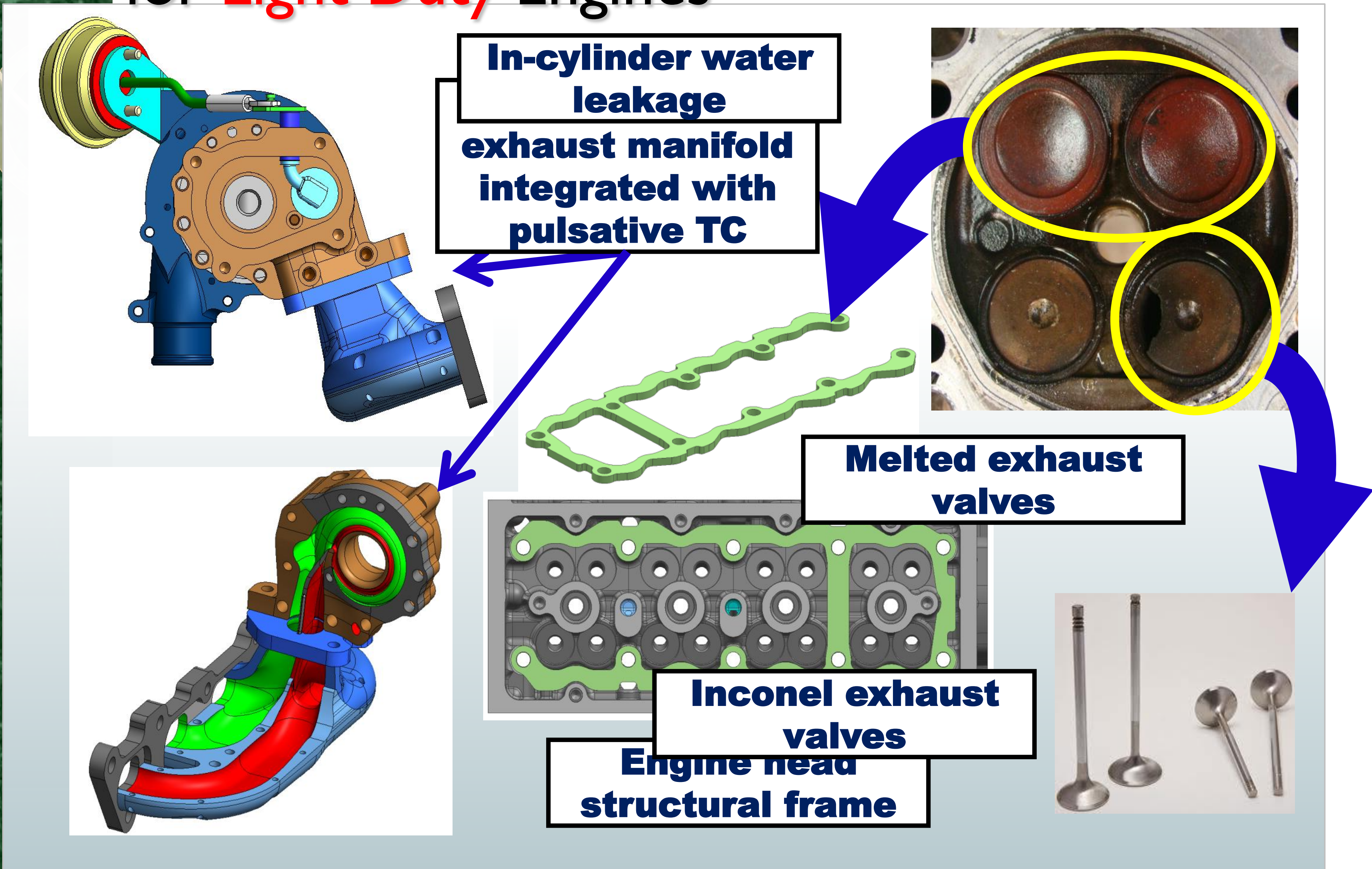
Challenge

Is it possible to conceive an Ethanol Engine with the same Volumetric Consumption and same torque curve as a Gasoline Counterpart ?

Ethanol PFI & DI Combustion Development for Light Duty Engines



Ethanol PFI & DI Combustion Development for Light Duty Engines - Workhorse Modifications



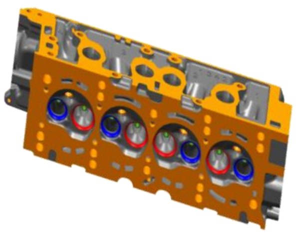
Ethanol PFI & DI Combustion Development for Light Duty Engines - Workhorse Modifications

Intake valve opening by high intake boost pressure

Intake valve spring load increased

Ethanol PFI & DI Combustion Development for Light Duty Engines - R&D Methodology

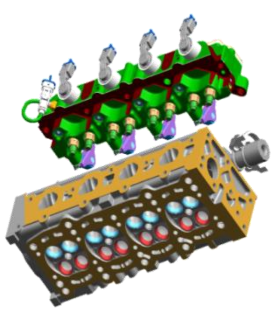
Modified 8V N.A. FIRE EVO Cylinder Head



8V High Swirl

- ✓ **Swirl coef. from *1.6*, Redesigned ~ *3.0***

Modified 16V T.C. Tjet FIRE Cylinder Head



16V High Tumble

- ✓ **Tumble coef. from 1.2, Redesigned ~ 2.5**

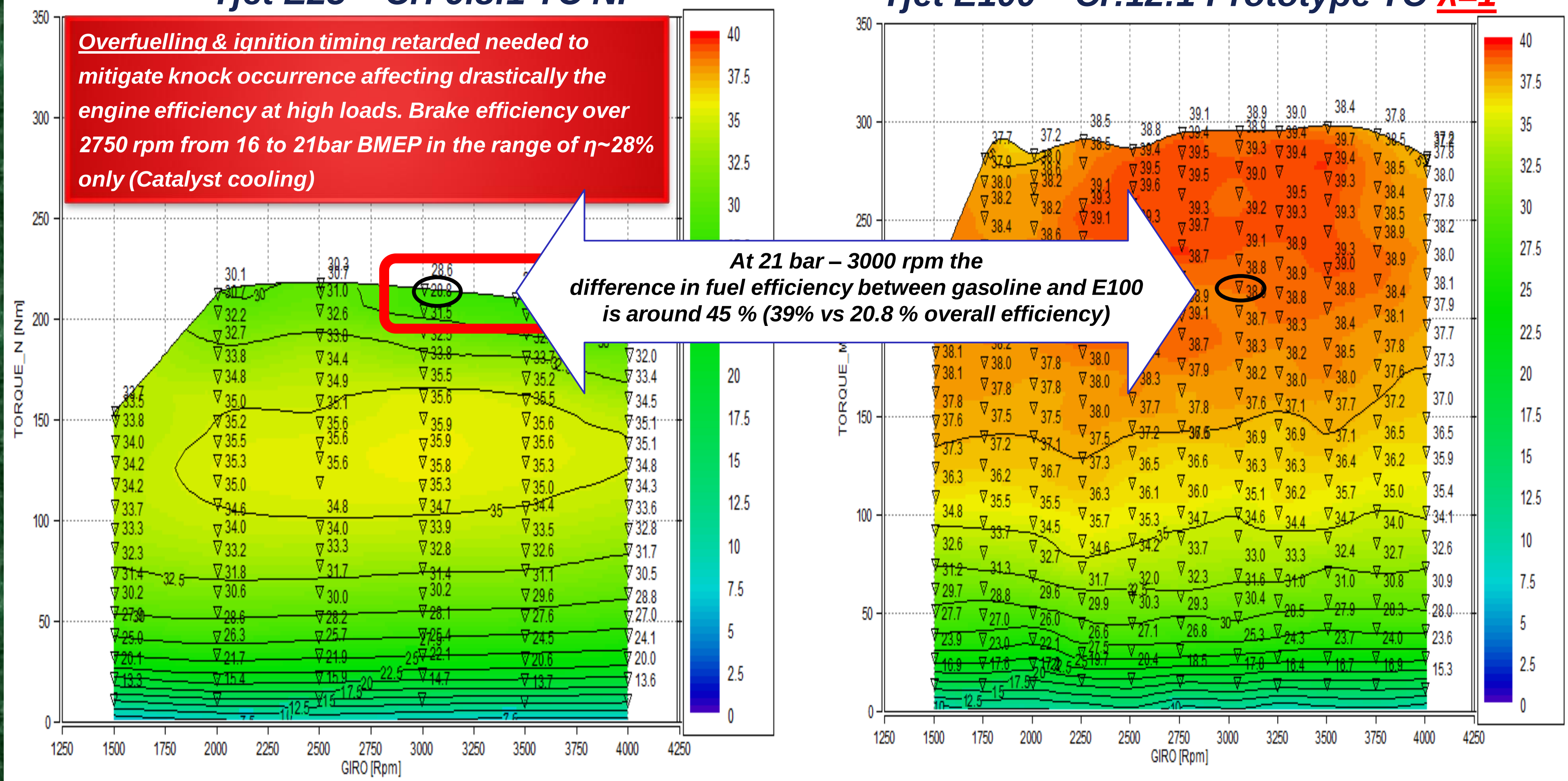
Research to Optimize a High-Boosted Ethanol PFI Engine through Combustion Control by relative AFR, Cr & In-Cylinder Flow Structure parameters.

For the Downspeeding approach an 8V solution seems the most cost-effective.

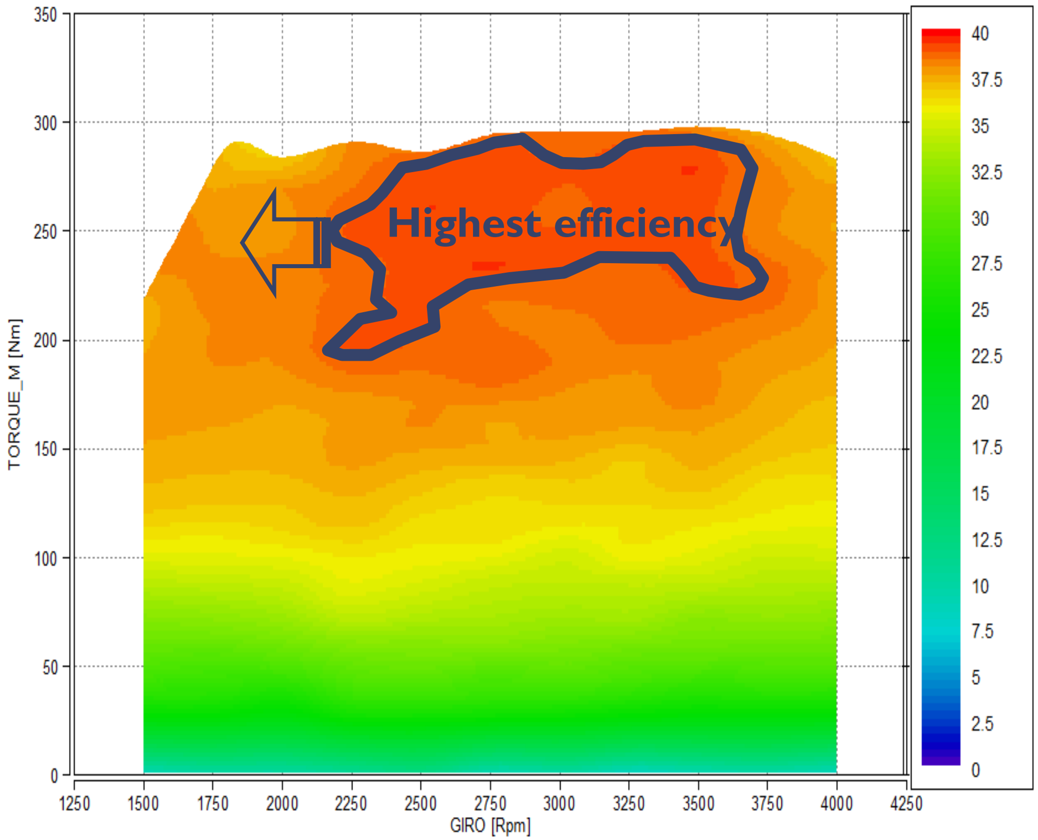
Ethanol PFI & DI Combustion Development for Light Duty Engines - Technical Results

Tjet E25 – Cr: 9.8:1 TC NP

Tjet E100 – Cr:12:1 Prototype TC λ=1



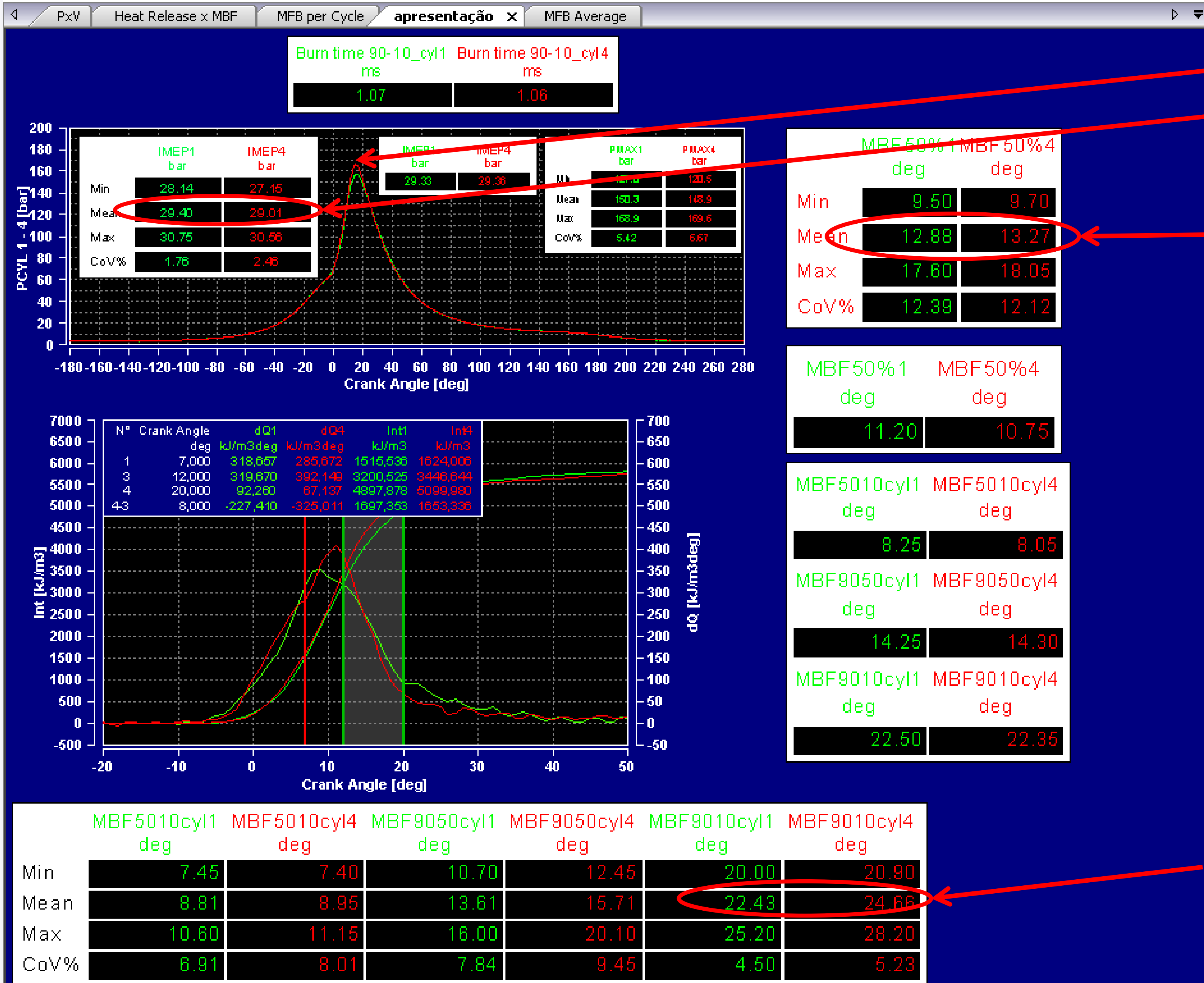
Ethanol PFI & DI Combustion Development for Light Duty Engines - Technical Results



DoE Between downsizing & downspeeding aiming at optimizing W2W FC

- **HEAT LOSSES REDUCTION AT LOW SPEEDS THRU FASTER COMBUSTION PROPAGATION**
  - MAXIMUM TUMBLE BIASED TO LOWER ENGINE SPEEDS
  - TO OPTMIZE THE TURBOCHARGER MAPS FOR DOWNSPEEDING (ENTROPY REDUCTION)
- **MIXTURE FORMATION OPTIMIZATION**
  - INJECTOR POSITIONING, SPRAY PATTERN & INJECTION TIMING AIMING AT SUPRESSING LIQUID FILM FOR A HOMOGENEOUS COMBUSTION
- **2 VALVES CYLINDER HEAD EVALUATION**
  - HIGH SWIRL FOR STABLE COMBUSTION AT LOW SPEEDS
  - REDUCTION OF CYCLICAL VARIABILITY FOR HIGHER EFFICIENCY
- **FURTHER REDUCTION OF CAMSHAFT MECHANICAL FRICTION AT LOW SPEEDS**
  - OIL PUMP REDESIGN ANALYSIS
  - CAMSHAFT BEARINGS STUDY

Technical Results



Burn time 90-10_cyl1 ms	Burn time 90-10_cyl4 ms
1.07	1.06

	IMEP1 bar	IMEP4 bar
Min	28.14	27.15
Mean	29.40	29.01
Max	30.75	30.56
CoV%	1.76	2.46

IMEP1 bar	IMEP4 bar
29.33	29.36

	PMAX1 bar	PMAX4 bar
Min	[illegible]	120.5
Mean	150.3	148.9
Max	168.9	169.6
CoV%	5.42	6.67

N°	Crank Angle deg	dQ1 kJ/m3deg	dQ4 kJ/m3deg	Int1 kJ/m3	Int4 kJ/m3
1	7,000	318,657	285,672	1515,536	1624,006
3	12,000	319,670	392,149	3200,525	3446,644
4	20,000	92,260	67,137	4897,878	5099,980
43	8,000	-227,410	-325,011	1697,353	1653,336

	MBF50%1 deg	MBF50%4 deg
Min	9.50	9.70
Mean	12.88	13.27
Max	17.60	18.05
CoV%	12.39	12.12

MBF50%1 deg	MBF50%4 deg
11.20	10.75

MBF5010cyl1 deg	MBF5010cyl4 deg
8.25	8.05

MBF9050cyl1 deg	MBF9050cyl4 deg
14.25	14.30

MBF9010cyl1 deg	MBF9010cyl4 deg
22.50	22.35

	MBF5010cyl1 deg	MBF5010cyl4 deg	MBF9050cyl1 deg	MBF9050cyl4 deg	MBF9010cyl1 deg	MBF9010cyl4 deg
Min	7.45	7.40	10.70	12.45	20.00	20.90
Mean	8.81	8.95	13.61	15.71	22.43	24.66
Max	10.60	11.15	16.00	20.10	25.20	28.20
CoV%	6.91	8.01	7.84	9.45	4.50	5.23

3500rpm

Pmax – 160bar

IMEP=29 bar

ITorque=32 kgf.m

MBF50%

Fast Combustion
24 CAD MFB 10-90%

For lean burn operation the 30 degrees of combustion burn duration (CAD) is the best burn duration for maximizing the break efficiency (gamma effect). On the other hand, for a constant stoichiometric AFR the best burn duration will be carefully investigated and if it is the same, the burn rate could be speeded down around 8 degrees by means of cooled EGR aiming at maximizing the brake efficiency achieving the optimum flame speed propagation. Furthermore, the cooled EGR will make possible to get further benefits as more spark authority allowing higher Cr & Nox reduction level. (adiabatic flame temperature reduction)

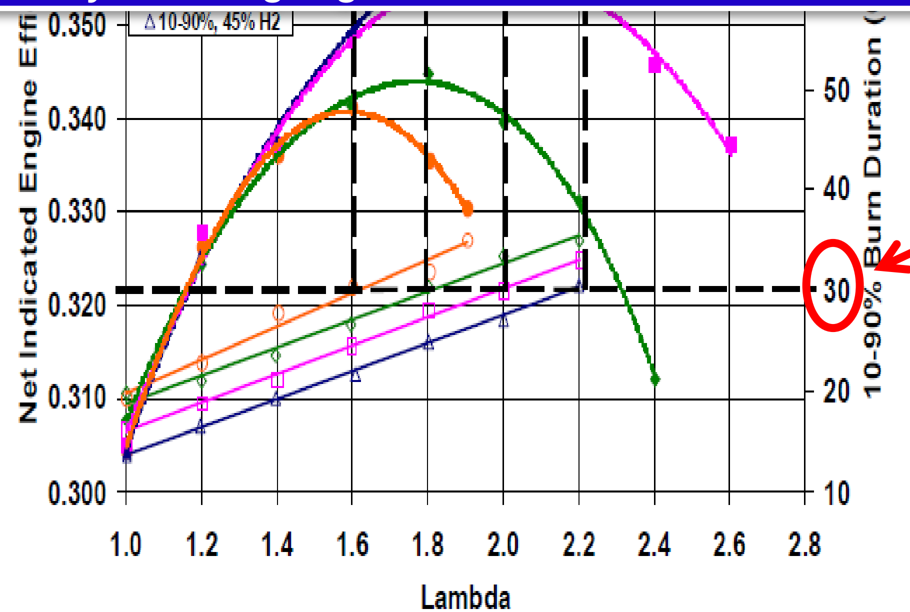


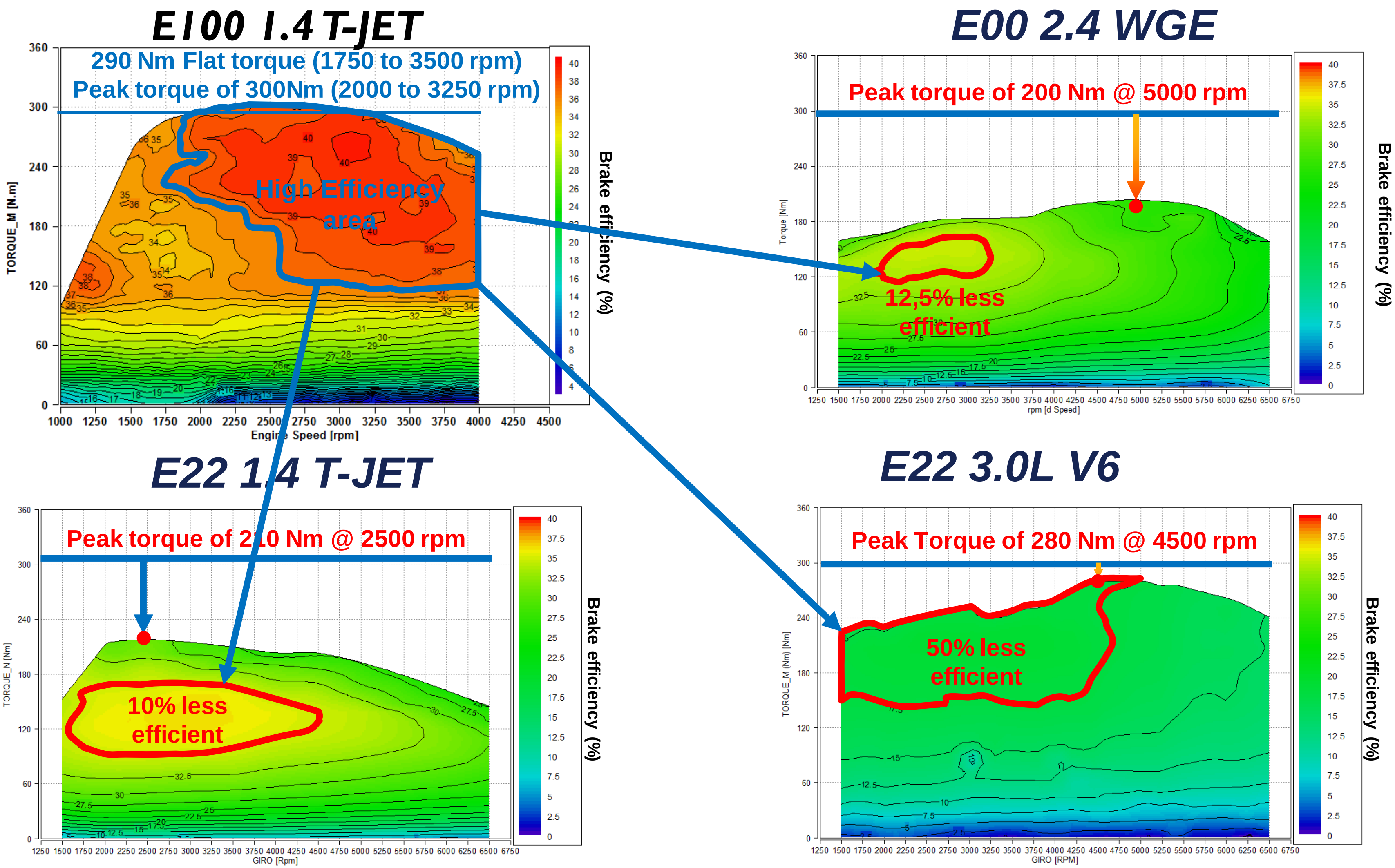
Fig. 7 – Air-fuel ratio effect on efficiency and burn duration for different levels of hydrogen enhancement; MBT timing, 1500 RPM, r_c=13.4:1, NIMEP = 3.5 bar, Indolene

Combustion duration from 10% to 90% MBF ~ 22 ca

10% to 50% MBF ~ 8.7 ca; 50% to 90% MBF ~ 13 ca _Partial analysis_

The increase in burn rate as described on the work conducted by Prof. Heywood SAE 2006-01-0229, becomes truly relevant for the engine efficiency only if the combustion becomes very slow (more than 30 ca), which could be the result from a very large dilution level and might not be necessary for stoichiometric ethanol use. This way the effect of high tumble to speed up the combustion flame propagation might not be directly translated into efficiency gains and could generate a loss of efficiency depending on the increase of the convective coefficient. ***The High Swirl for 2V approach will be carefully investigated.***

Ethanol PFI & DI Combustion Development for Light Duty Engines - Technical Results



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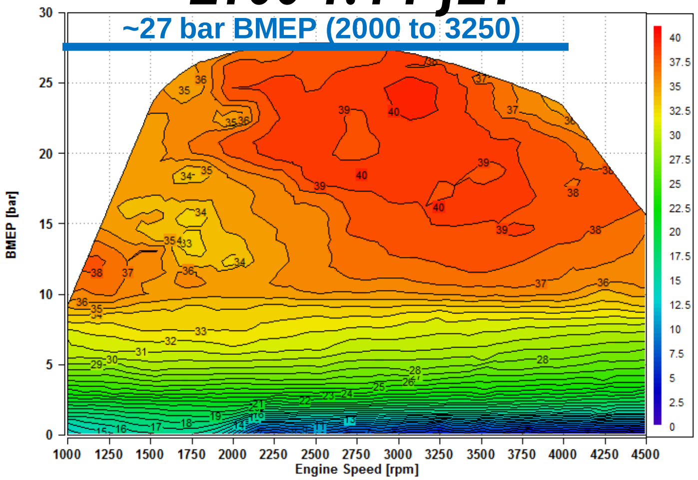
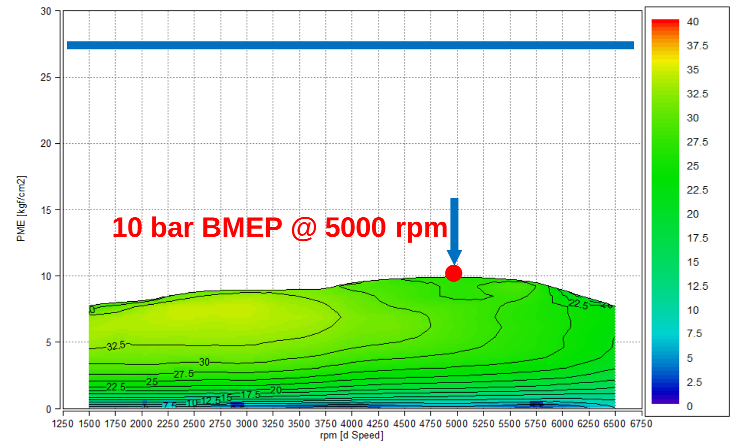
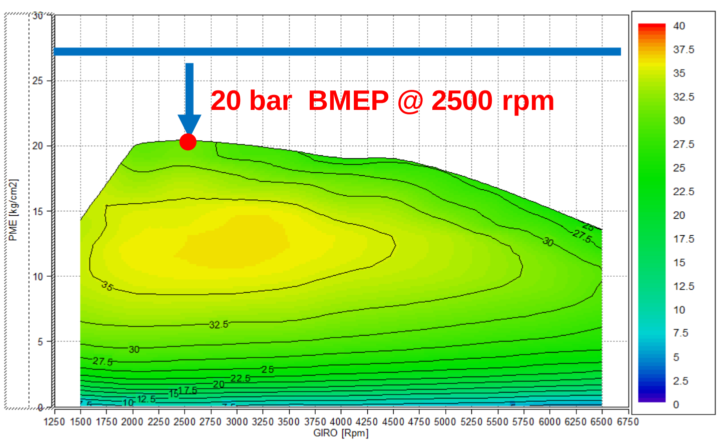
E100 1.4 T-JET



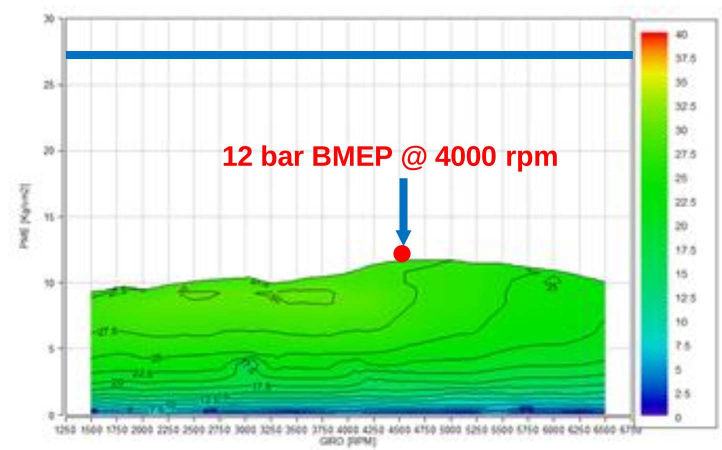
E22 2.4 WGE



E22 1.4 T-JET



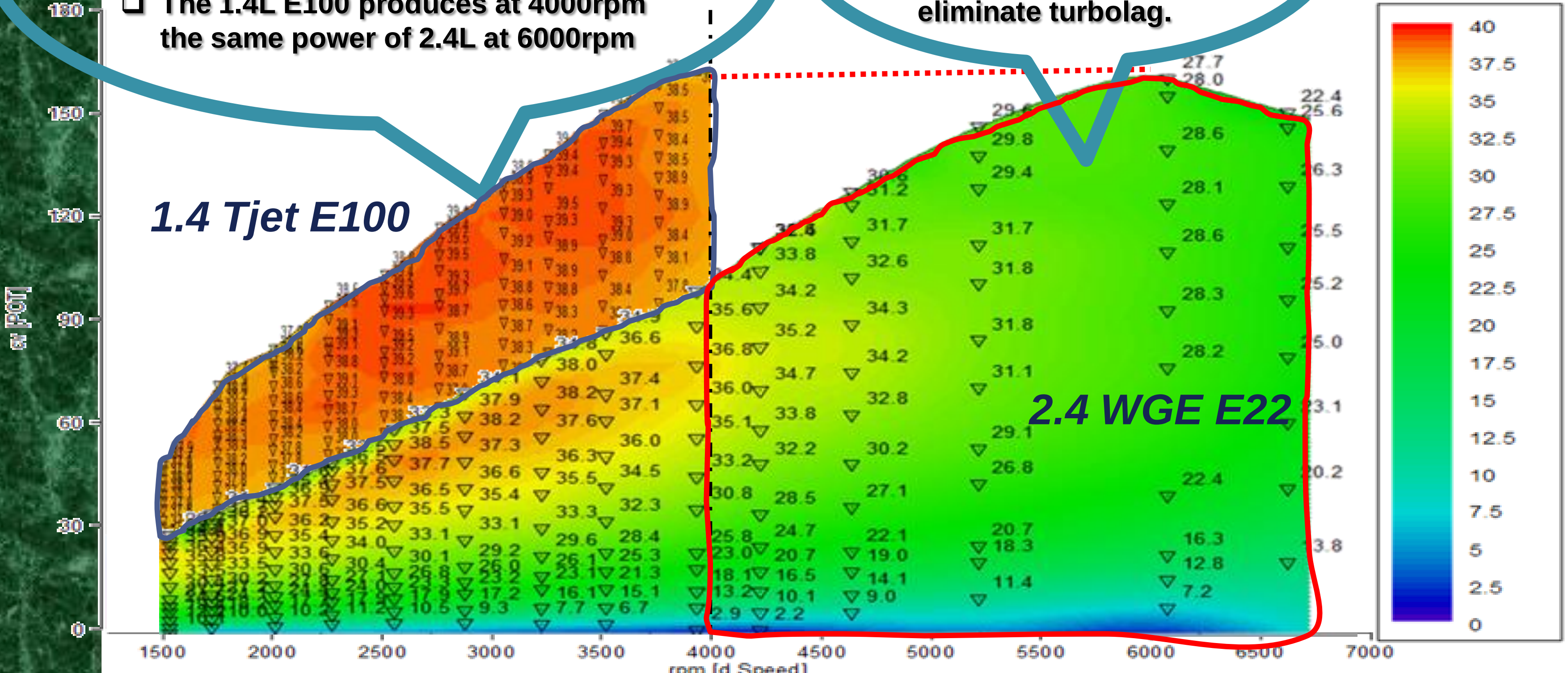
E00 3.0L V6



Ethanol PFI & DI Combustion Development for Light Duty Engines - Technical Results

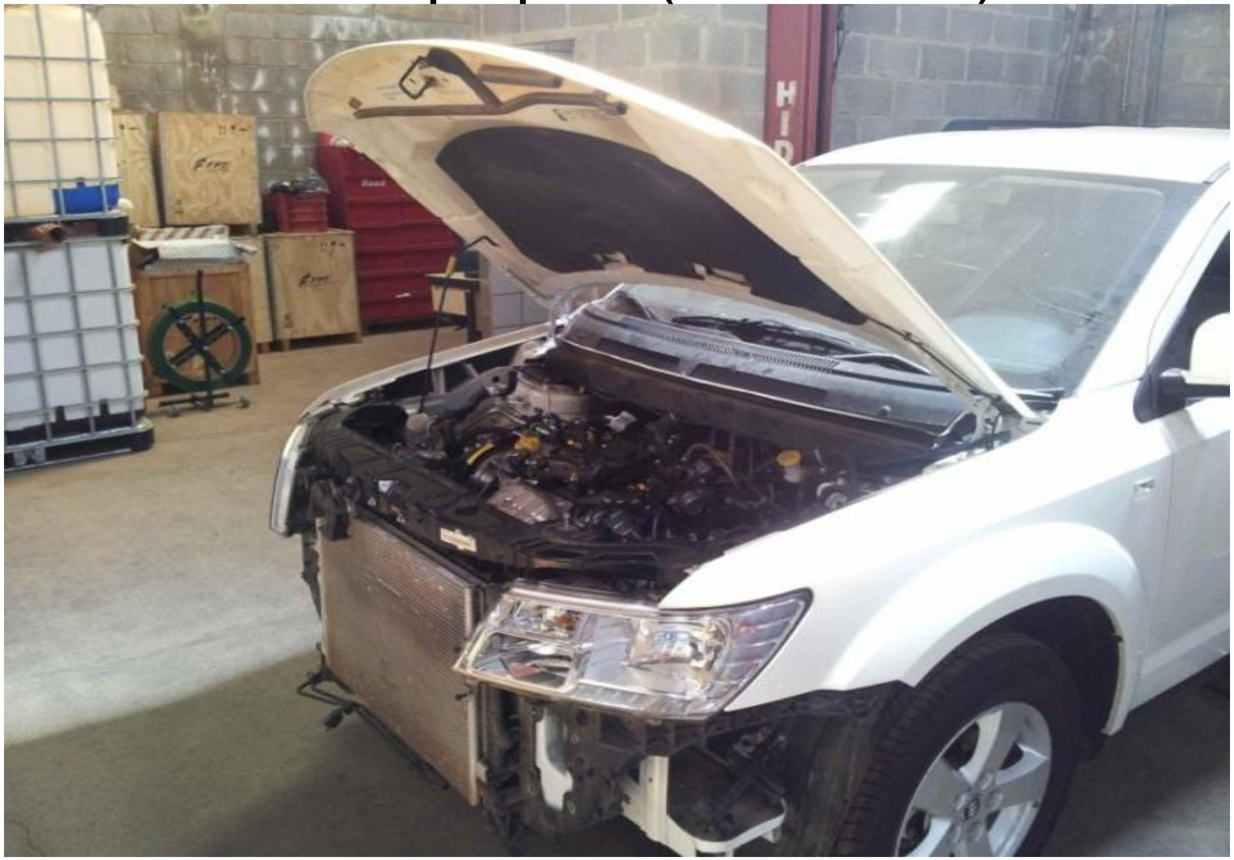
- Much Higher Brake Efficiency
- Plenty room for Gear Ratios Enlargement
- Much Higher torque Availability
- The 1.4L E100 produces at 4000rpm the same power of 2.4L at 6000rpm

- Engine speed over 4000rpm is avoided in order to reduce Friction, pumping losses & to eliminate turbolag.



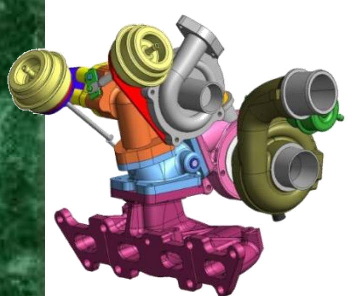
Ethanol PFI & DI Combustion Development for Light Duty Engines - Technical Results

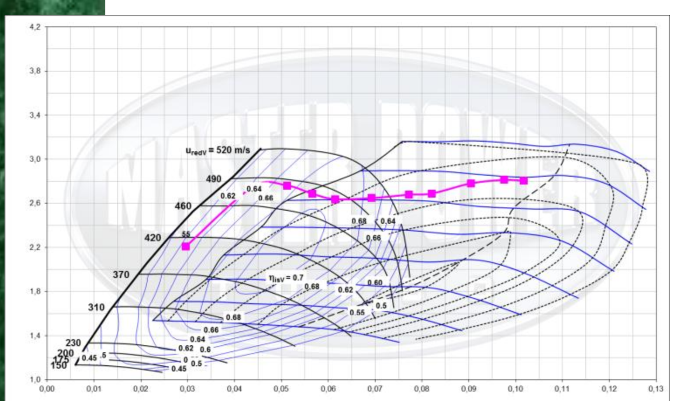
- Vehicle is currently finalizing on-road calibration phase for demonstration purpose (15-06-2012).

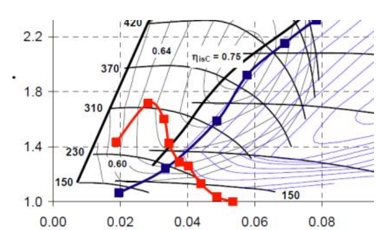


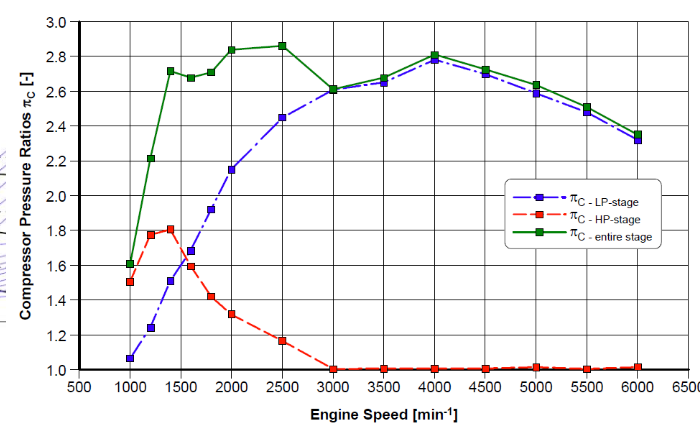
Ethanol PFI & DI Combustion Development for Light Duty Engines

- Downsizing boundaries:
  - Twin Stage Turbo set in order to double engine power output range to evaluate downsizing capability

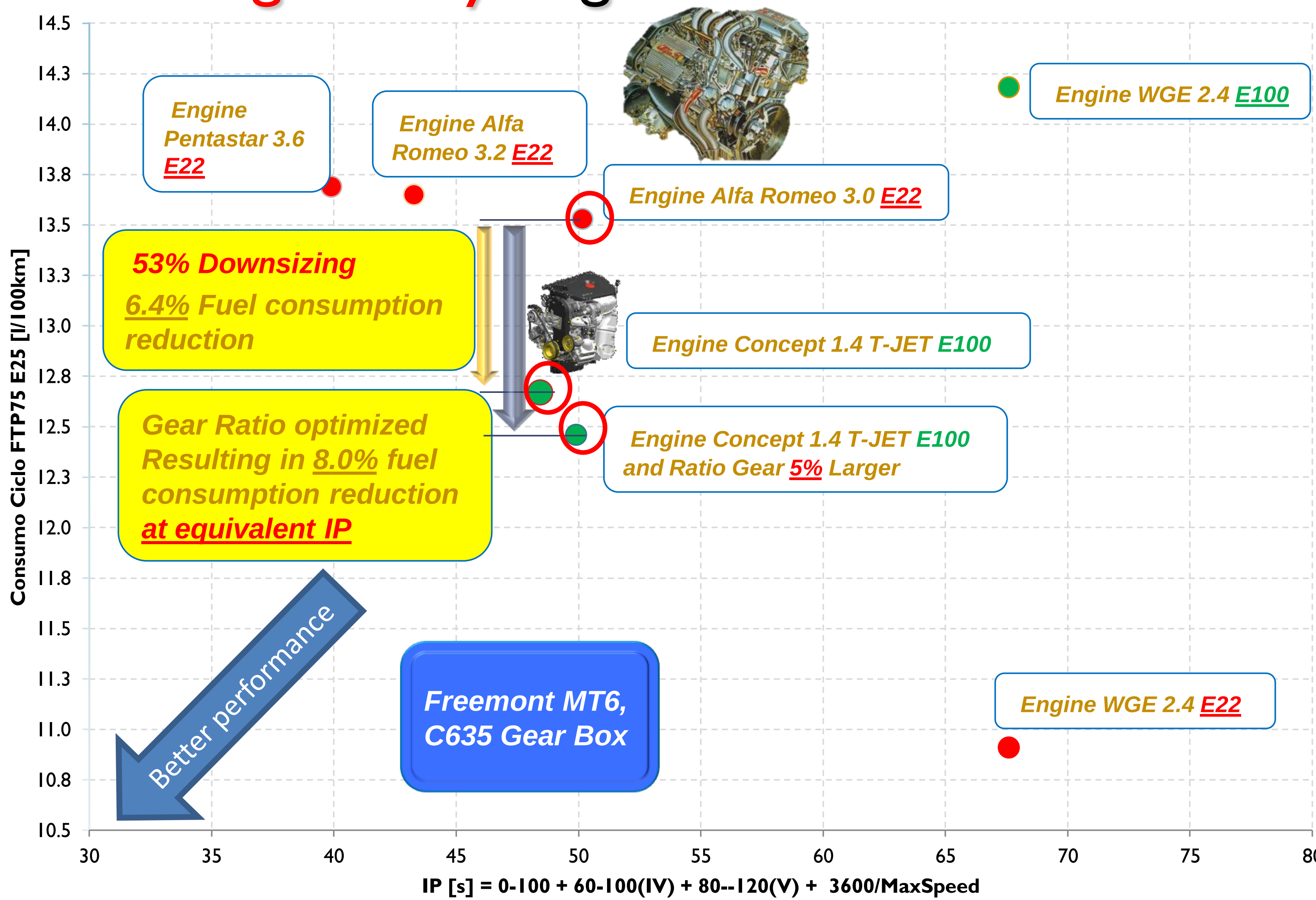




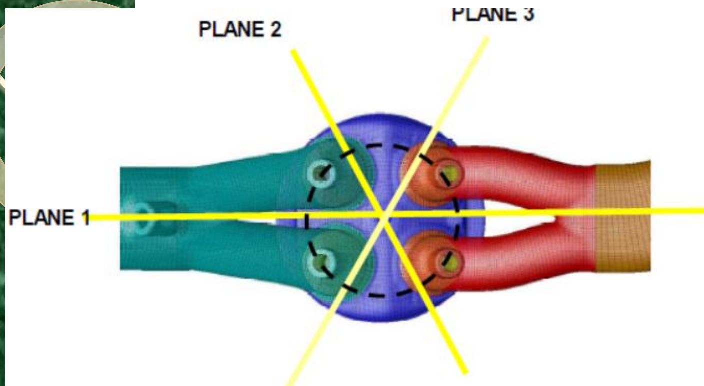




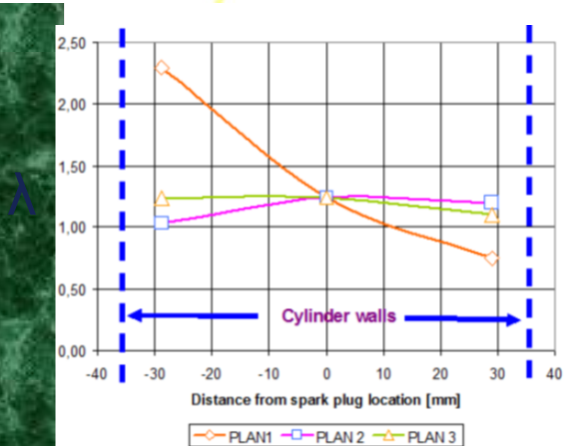
Ethanol PFI & DI Combustion Development for Light Duty Engines - Technical Results

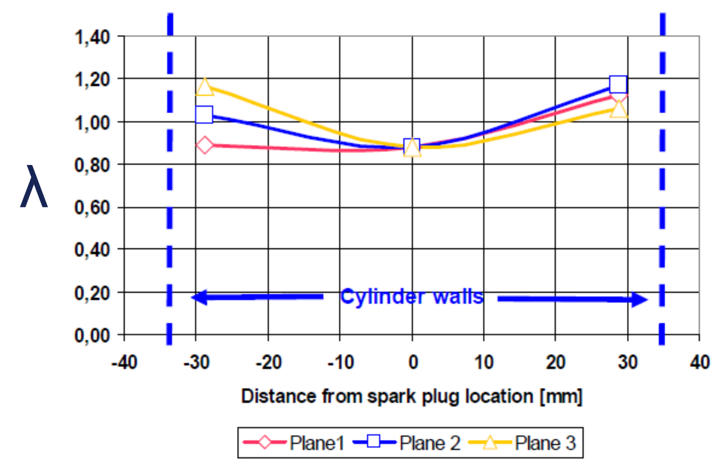


Ethanol PFI & DI Combustion Development for Light Duty Engines - Technical Results



$$\lambda\, Distribution = 1 - \frac{\lambda \max - \lambda min}{\lambda max}$$

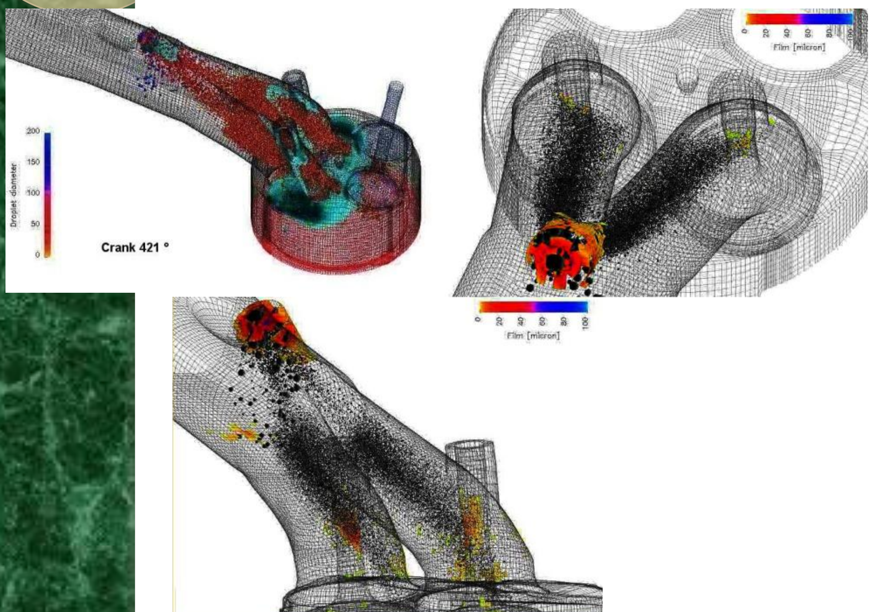




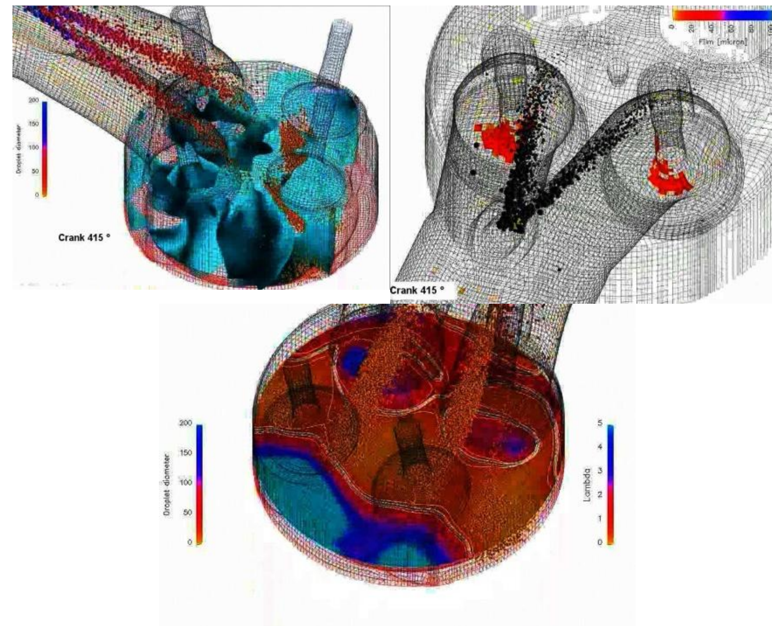
In-cylinder Mixture Homogeneity Factor	
On-going PFI Injector (BOSCH)	0.33
Optimized Injector (Marelli)	0.76

Ethanol PFI & DI Combustion Development for Light Duty Engines - Technical Results

BOSCH INJECTOR



MARELLI INJECTOR - OPTIMIZED



In-cylinder Mixture Homogeneity Factor	
On-going PFI Injector (BOSCH)	0.33
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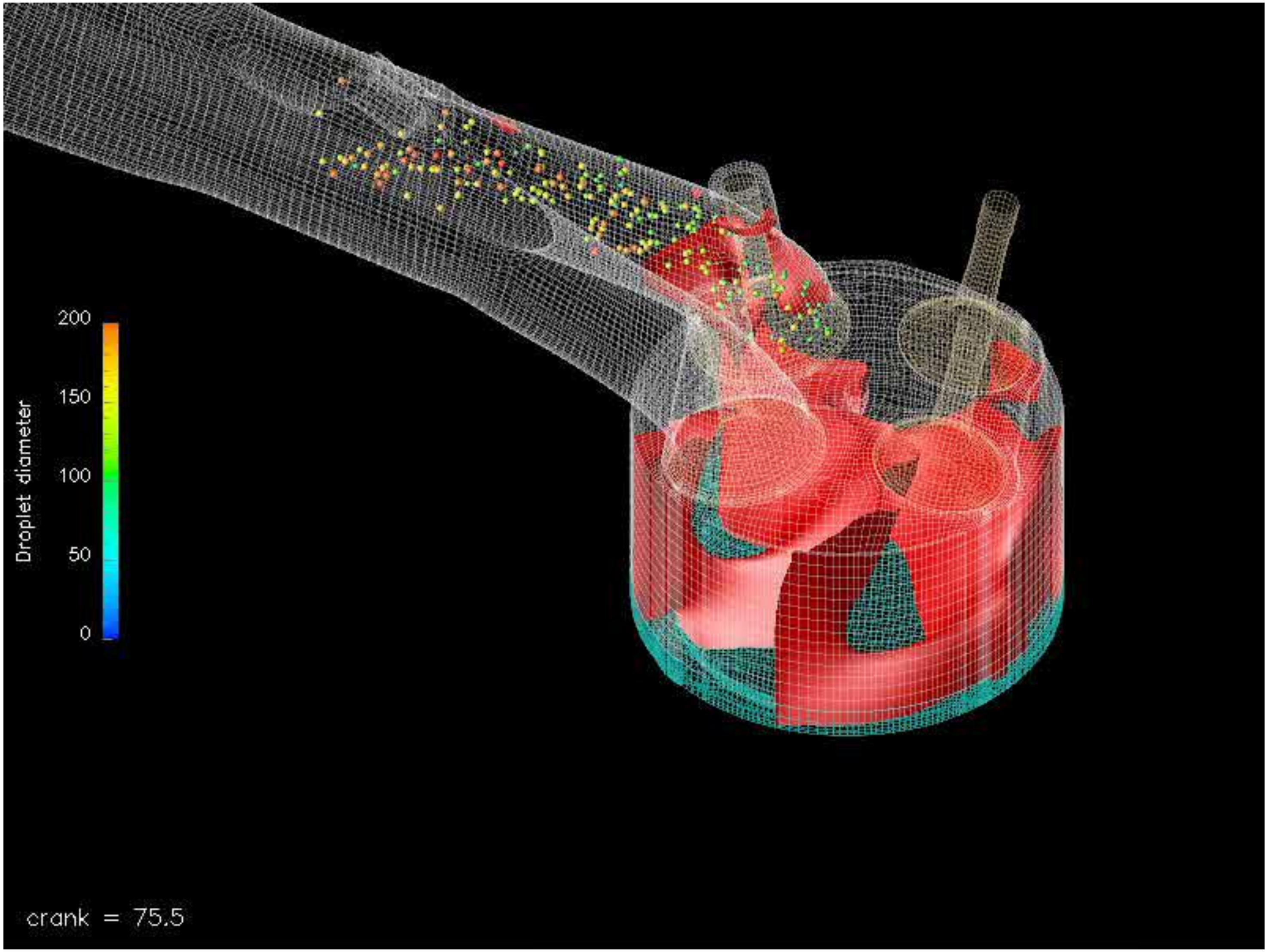
Ethanol PFI & DI Combustion Development for Light Duty Engines - Technical Results

Dropplet Diameter



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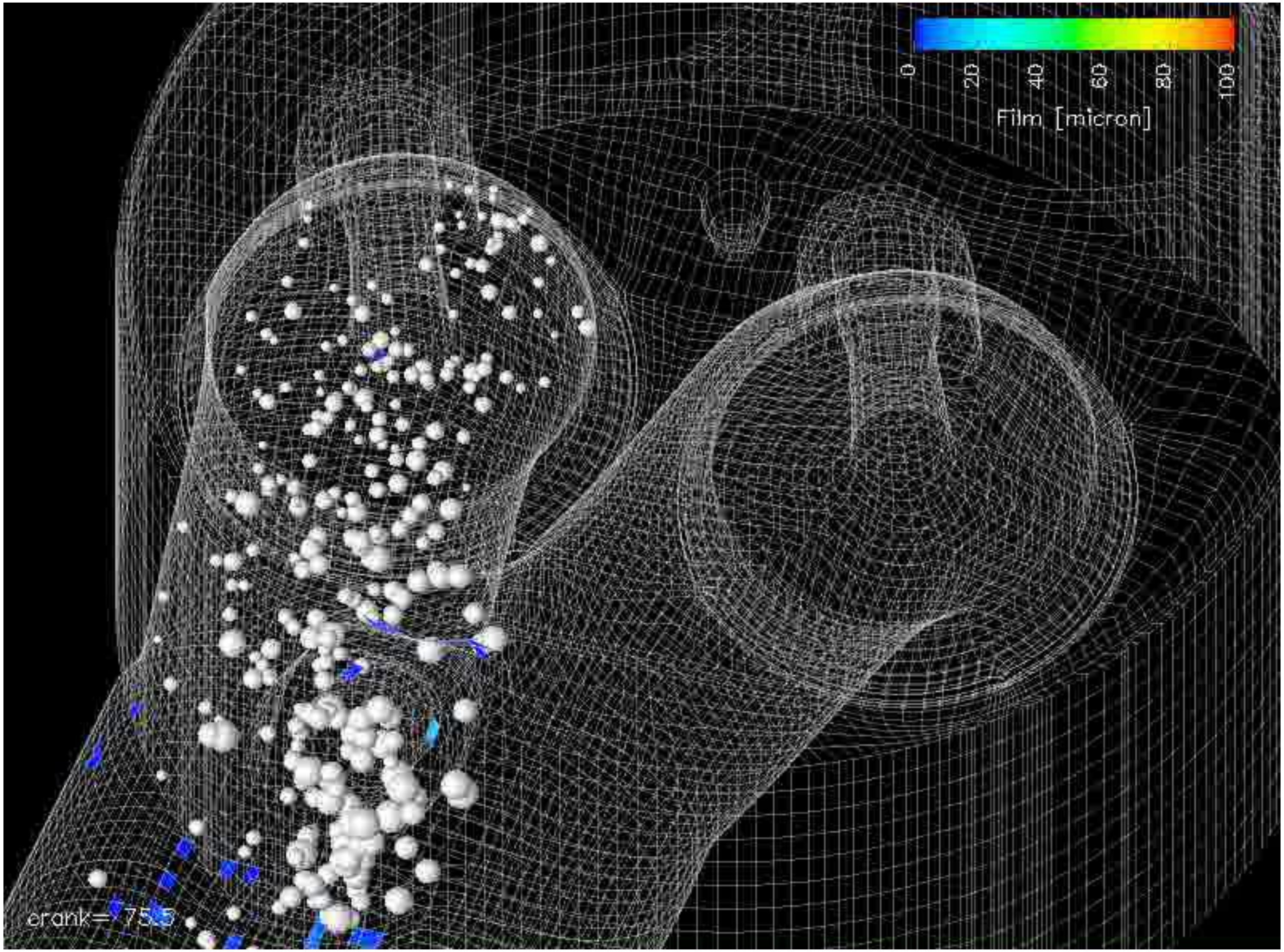
Wall Film



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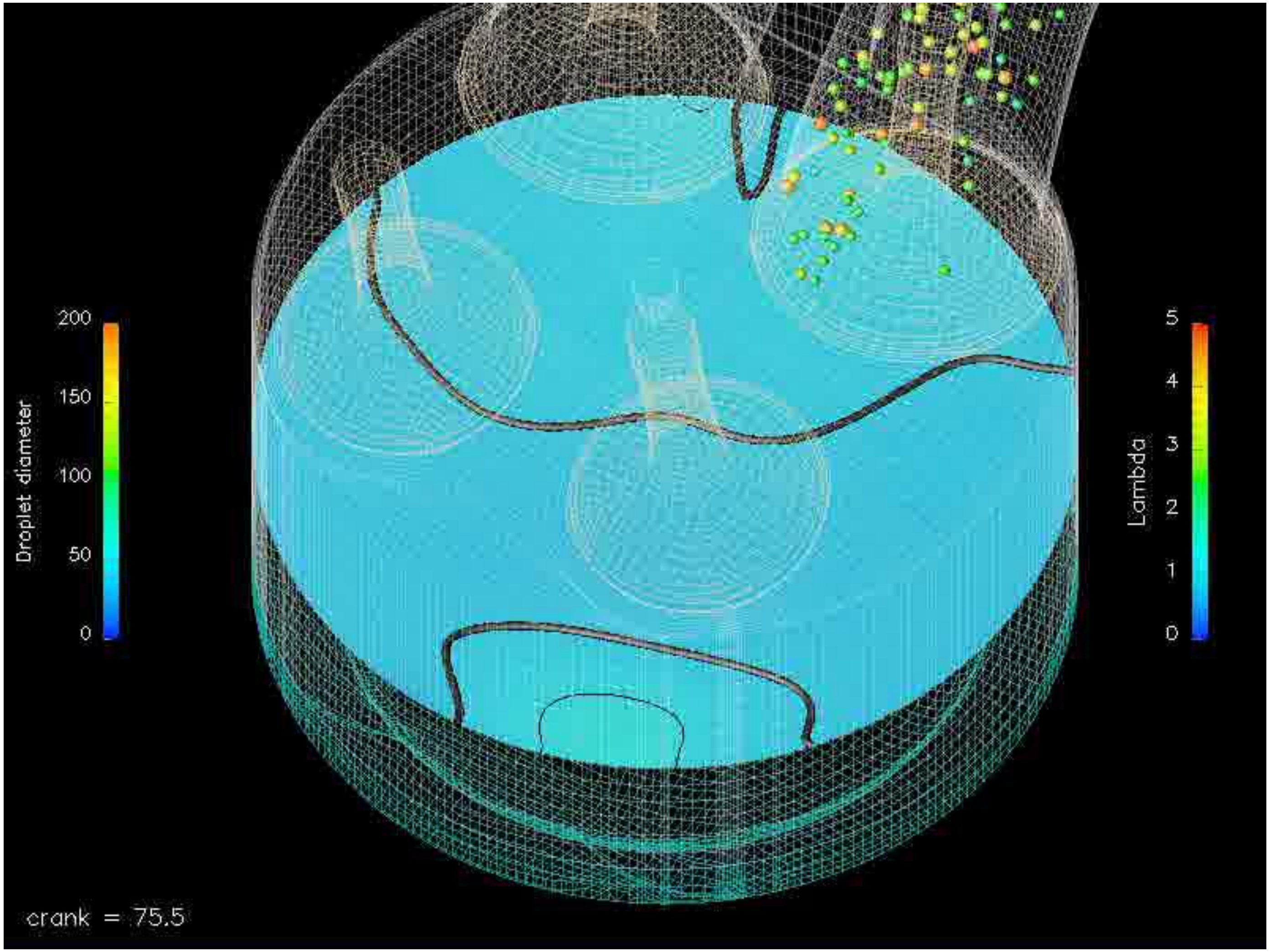
Lambda Swirl (horizontal Plan)



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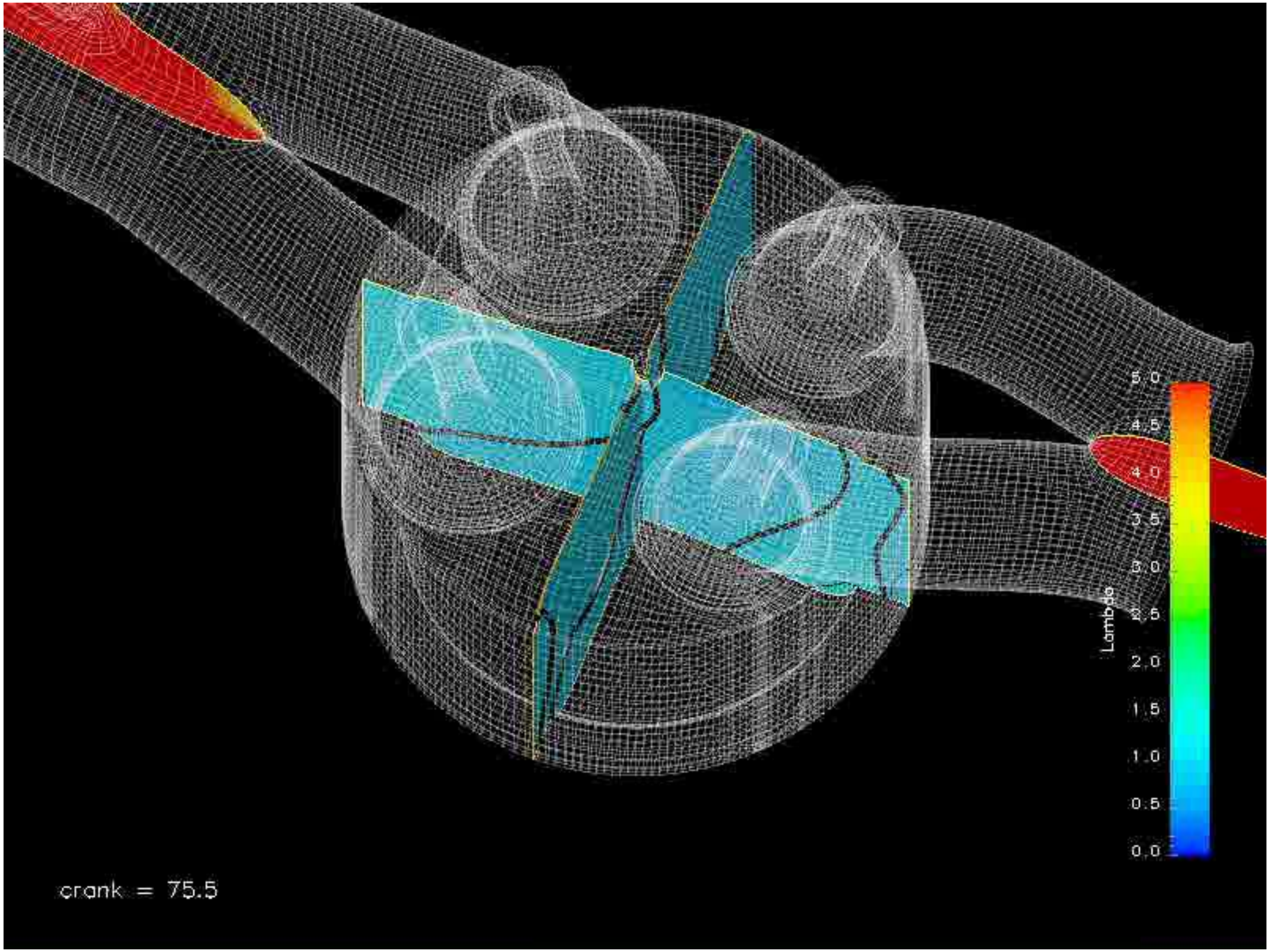
Lambda 2 (vertical) tumble Plans



Conclusions & Lessons Learned

1. ***There is an ample room to optimize the use of brazilian fuel energy matrix by means of the development of new "national" engine technologies ;***
2. ***Ethanol fuel properties make possible to match diesel efficiency in an Otto highly Boosted Engine by means of downsizing & downspeeding techniques implementation ;***
3. ***Test results demonstrate feasibility of this engine technology concept. A more robust workhorse engine is needed to fully exploit the boundaries of the ethanol properties. The diesel engine hardware would be a promissing choice.***
4. ***Highly Boosted Downsized Ethanol Engines can match E22 fuel mileage;***
5. ***The DI implementation could lead to an extra fuel consumption reduction increasing the downsizing capability. In other words, the downsizing needed of 50% for a PFI could be in the range of 42% if the E100 DI is implemented. (Additional benifit to justify DI implementation - The E22 cold start system can be suppressed!)***

Conclusions & Lessons Learned

6. ***Cooled EGR implementation makes possible E22 implementation mitigating its performance losses for a flex fuel investigation.***

7. ***Literature and previous investigation show that swirl flow structure seems to be promising for efficiency optimization & further cost reduction (2 valves/cylinder) & it is recommended to be carefully investigated. (Synchronized dissipation is still an issue)***

Contacts

The Hybrid E-controls website is still under construction and it will be operational by the end of 2012

Phone: (+55)(12) 3876-7719;

Mobiles:

José Guilherme C. Baêta (+55)(31) 8642-3698
Celso de Souza Corsino (+55)(12) 8816-1838

Email: jgcbaeta@hybridecontrols.com.br
celso@hybridecontrols.com.br