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Dual-fuel Technology

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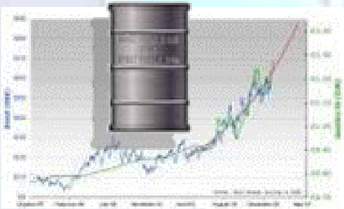
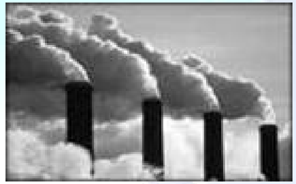
1. Motivation & Market Trends

World under Fuel Alternative Pressure!



Unstable Oil Price



Pollution

Natural Resources Renewable Fuels

Global Warming

1. Motivation & Market Trends

Market	Drivers Enablers	Alternatives
Developed Countries (USA, EU, Japan)	CO_2 reduction Emissions	→ Hybrid → Electric → Hydrogen → Natural Gas
Emerging markets	Costs (operational costs reduction and low taxation)	→ Bio-diesel → Ethanol → Natural Gas

→ Biofuels and Natural Gas are economically feasible and available solutions for several markets.

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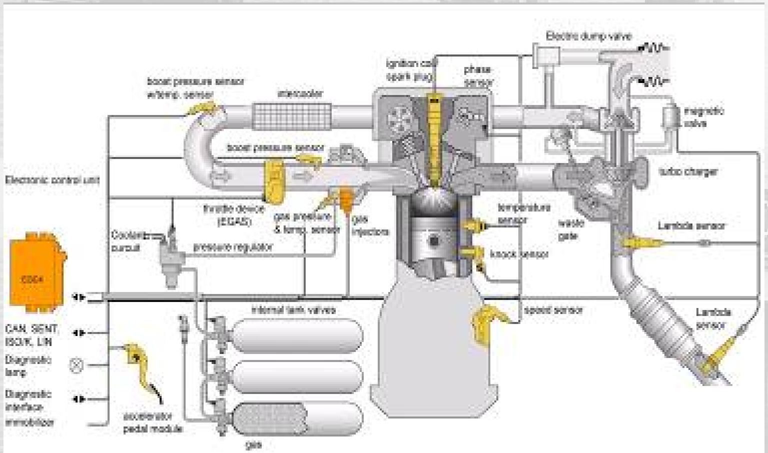
2. Bosch CNG Experience

CNG Otto System



1998 — **1st Spark ignited CNG engine with Bosch system launched in the EU market**

2010 — **4 new applications to be launched in the EU, India and China markets**

2011 — **4 new applications to be launched in the Indian and Japanese markets**

➔ The development of the CNG spark ignited engine injection & ignition systems allowed Bosch to improve its product portfolio providing reliable components with state of the art technology to the market

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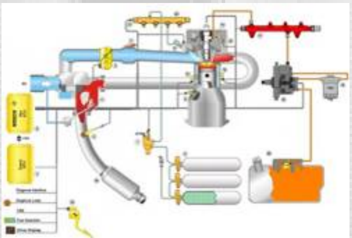
2. Bosch CNG Experience

Dual-Fuel System



2006	**Start researching the Dual-Fuel technology with mechanical Diesel injection systems using CNG**
2008	**First emissions homologation in Brazil of a Dual-Fuel Diesel / CNG powered engine**
2008	**Start of research with electronically controlled Diesel injection systems**
2009	**Dual-Fuel system development for applications with Natural Gas, Biomethane and Ethanol for original vehicles**

→ Robert Bosch, worldwide leader in development and application of the Diesel technology, is dedicating its knowledge and experience to the development of a Dual-Fuel system, using the state of the art technology in components and software.

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3. Diesel-Gas System Concept

Dual-Fuel	**Existent Diesel engines**, adapted with a **second injection system** to manage the NG fuel injection and the air control. The basic configuration of the original Diesel engine remains unchanged. **Ignition by Diesel injection.**
Operational Modes	Possible to operate either in original Diesel Mode or in Diesel-NG Mode, with significant substitution of Diesel by the Natural Gas.
Alternative fuels	System components and software compatible with: Natural Gas (**CNG** & **LNG**) and **Biomethane**.
Other features	Knock control strategy, diagnosis and monitoring function in Diesel-NG mode, closed loop strategy.

➔ Diesel-Gas integrates the high performance of diesel engines with the fuel flexibility.

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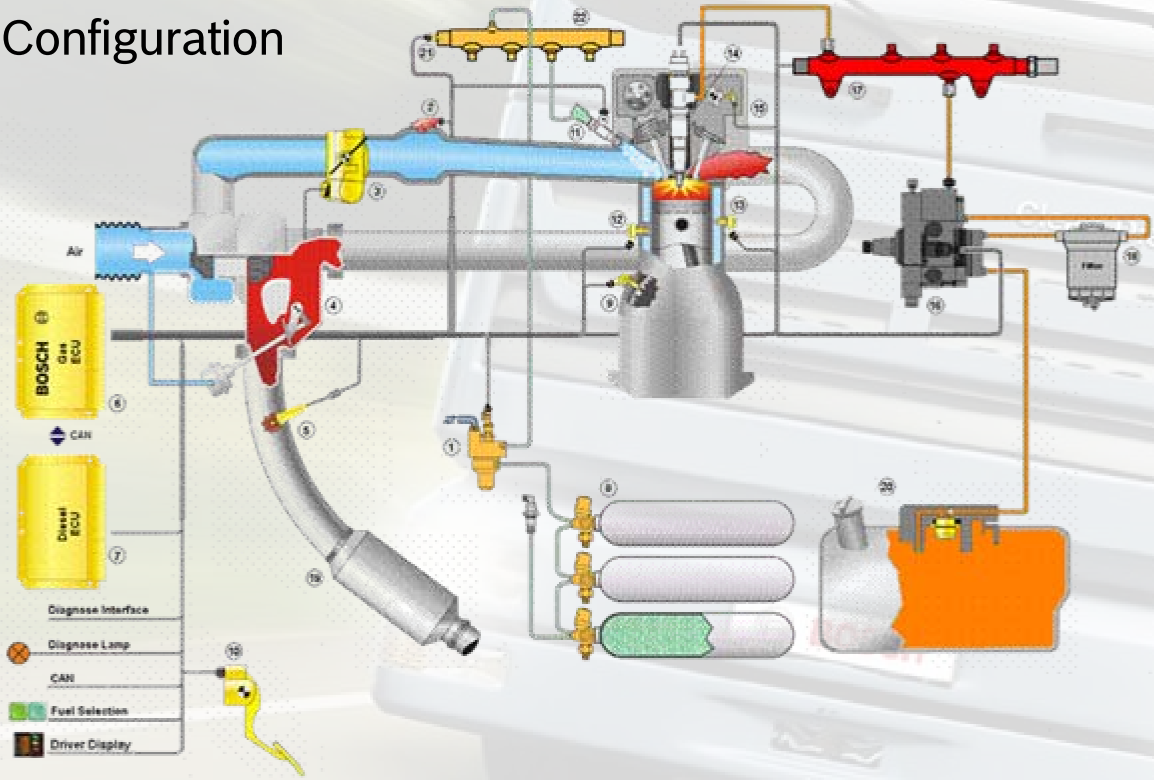
3. Diesel-Gas System Concept

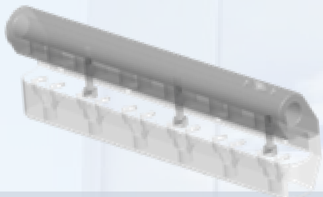
Configuration



01 – CNG pressure regulator
02 – Boost pressure & temperature sensor
03 – Throttle valve
04 – Boost actuator
05 – Lambda sensor
06 – CNG ECU
07 – Diesel ECU
08 – CNG storage tank
09 – Engine speed sensor
10 – Accelerator pedal
11 – CNG injector
12 – Knock sensor
13 – Coolant temperature sensor
14 – Diesel injector
15 – Phase sensor
16 – High pressure pump
17 – Diesel common rail
18 – Fuel filter
19 – Oxidation catalyst
20 – Diesel tank
21 – CNG pressure & temperature sensor
22 – CNG rail

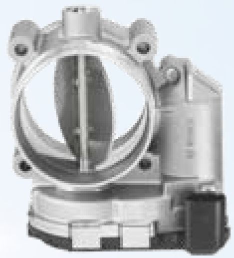
3. Diesel-Gas System Concept

Components



CNG Rail
FCA with DS-M1-TF

Dual-Fuel ECU
EGC10



Throttle Valve
RKL-E1

0_2 Sensor
LSU4.9

Knock Sensor
KS-4-S

CNG Injector
NGI2-CP

3. Diesel-Gas System Concept

Benefits to the customers

Fuel cost reduction	Maximize substitution rate of diesel by Natural Gas or Biomethane
Emissions compliance	Keeps same emissions level of engine on Diesel-only mode with enhanced particulate material, NOx and CO_2 emissions
Fuel flexibility	Allows driver to switch between Diesel-NG and Diesel-only modes with the same performance
Maintenance and lifetime	Reliability and tradition of Diesel engines
Affordable cost	Estimated ~10% of increase in the vehicle acquisition costs

→ Diesel-Gas keeps original integrity of the Diesel engines providing the same performance and fuel consumption efficiency still benefiting of high scale production

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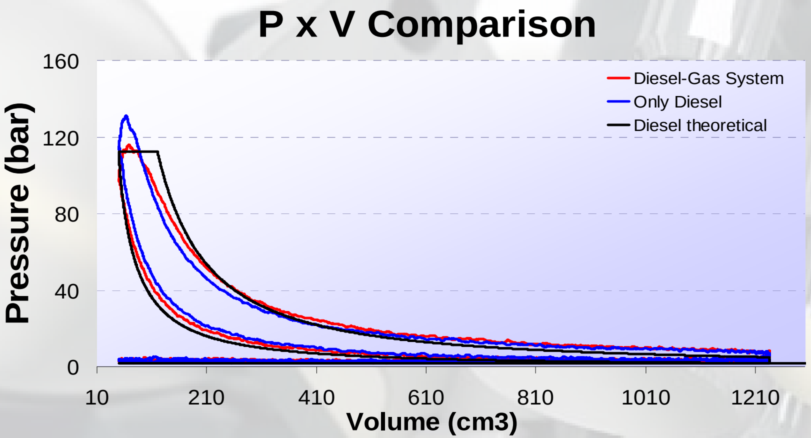
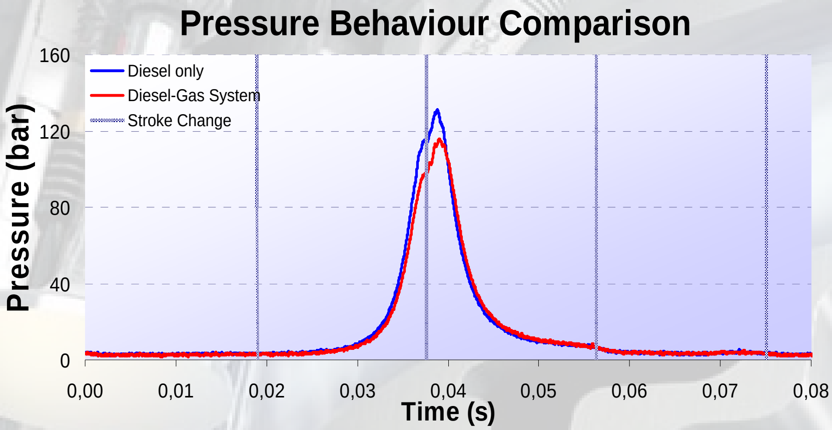
4. Combustion Phenomena





Engine test condition: 1600rpm, 100% load, 90% substitution rate

- Diesel-gas P X V curve is closer to the Diesel theoretical curve compared to diesel only
- P X V diagram shows equivalent area in the diesel-gas combustion process compared to diesel only, but with lower upper limit pressure and wider shape due to lower pressure decreasing rate
- Diesel-gas combustion behavior remains close to the adiabatic cycle due to CH_4 low flame speed and retarded diesel injection timing
- Cycles' losses are very similar not being possible to notice differences
- Combustion peak pressure in diesel-gas mode lower than in diesel only mode

→ Upper limit pressures in diesel-gas mode trends to generate less mechanical stress in the engine parts

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1. Motivation
2. Bosch CNG Experience
3. Diesel-Gas System Concept
4. Combustion Phenomena
5. **Engine Results in Test Bench**
6. Emissions Approach & Strategy
7. ECU HW and SW Configuration
8. Compatibility with other Diesel FIEs
9. Project Main Targets
10. Economical Feasibility Study
11. Conclusions

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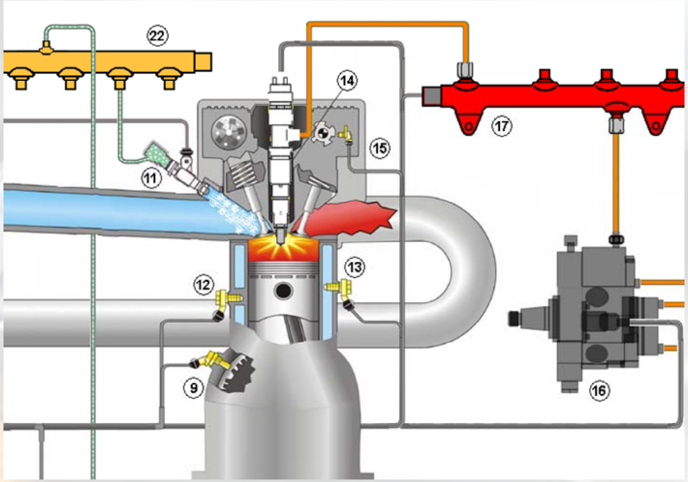
5. Engine Results in Test Bench

Research with a Diesel prototype EUIV engine with EGR

Calibration parameters:

- Natural gas feed pressure ~ 9bar
- Multipoint injection (2 injectors / cylinder)
- Steady-state calibration on test cell
- Brazilian field Diesel



Engine data:

- Diesel engine with CRSN
- Power: 160 kW @ 2200 rpm
- 6 cylinder, 7.2 L
- EGR and electronic turbo control

5. Engine Results in Test Bench

Research with a Diesel prototype EUIV engine with EGR

- **Calibration targets:** maximize the substitution ratio and substitution efficiency of dual-fuel Diesel-Gas combustion compared to original Diesel
- **Success factors:** stable combustion; same engine performance; >85% average diesel substitution rate in steady-state condition; no undesirable side-effects
- **Controlled parameters:**
  - Diesel injection timing
  - Diesel injection quantity and pressure
  - Natural gas injection timing
  - Natural gas injection quantity
  - Air flow
- **Restrictions:**
  - Knock occurrence – measurement through combustion pressure behavior and knock sensor signal
- **Out of scope:** dynamic calibration

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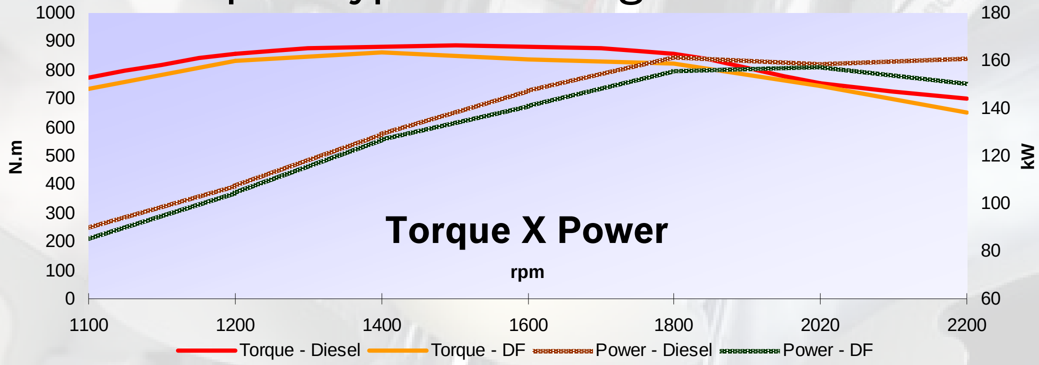
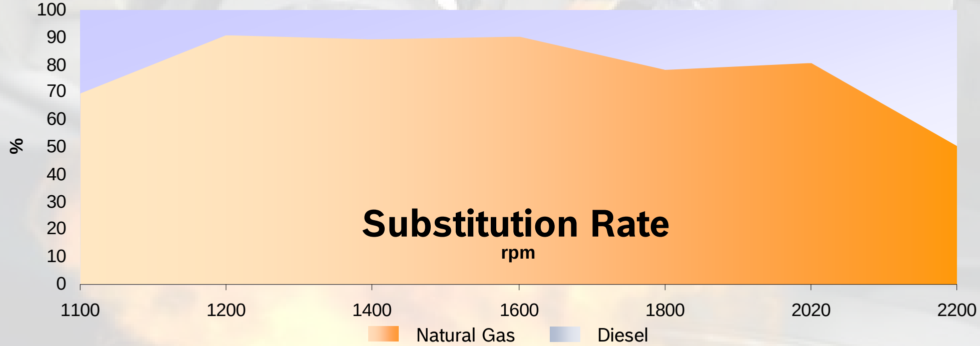
5. Engine Results in Test Bench

Research with a Diesel prototype EUIV engine with EGR



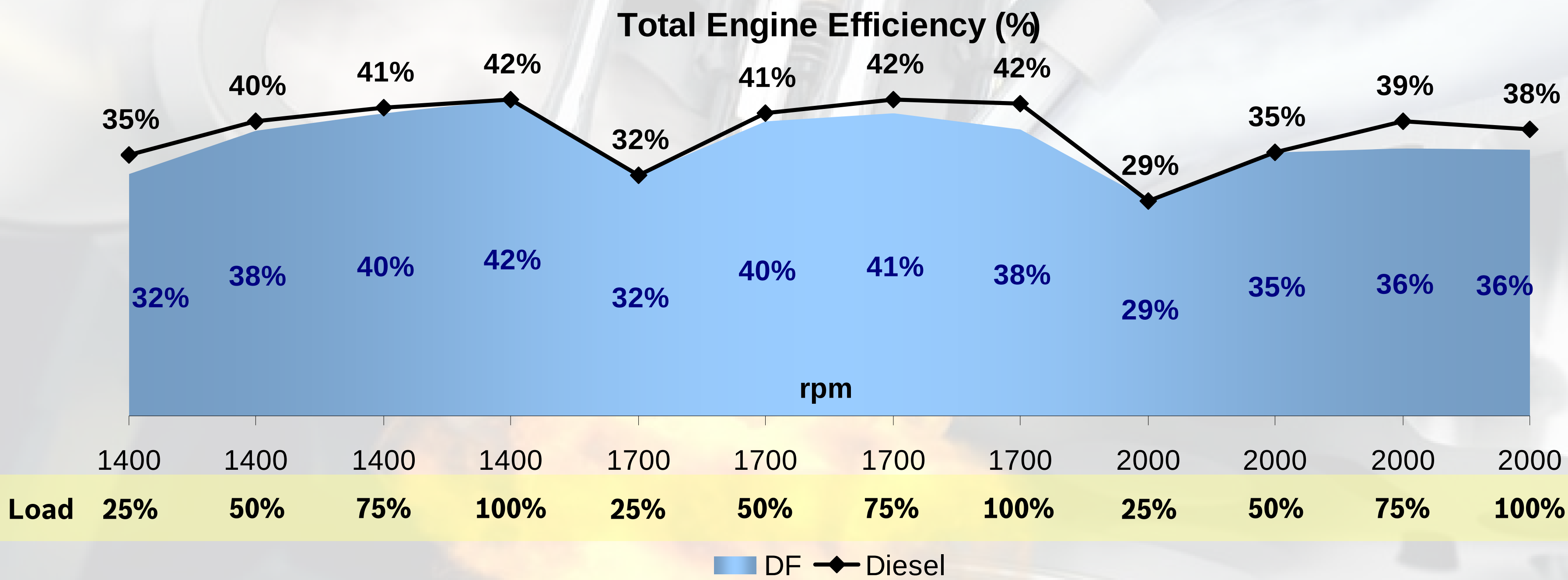


➔ Same original Diesel engine performance achieved on dual-fuel mode

5. Engine Results in Test Bench

Efficiency =
Engine power / Fuel heat content

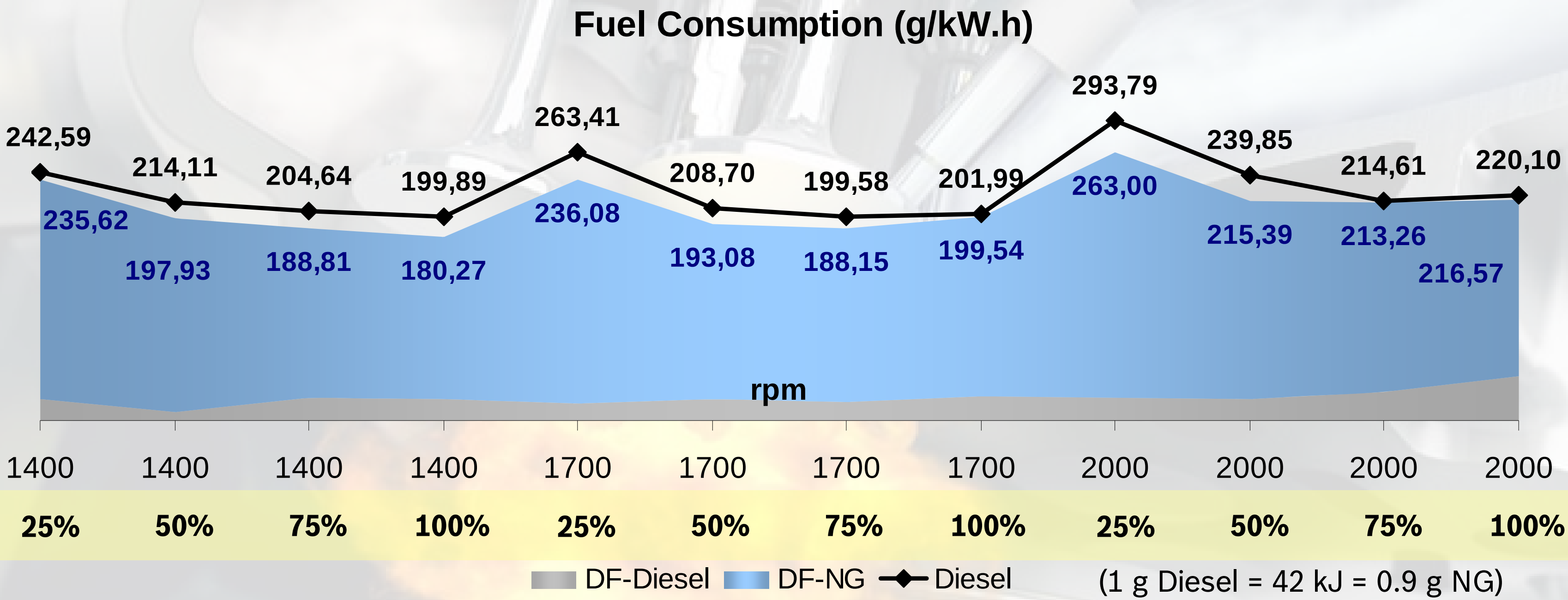
Research with a Diesel prototype EUIV engine with EGR



→ Engine thermal efficiency → similar to original Diesel mode

5. Engine Results in Test Bench

Research with a Diesel prototype EUIV engine with EGR



➔ Engine specific consumption ➔ slightly lower in dual-fuel mode

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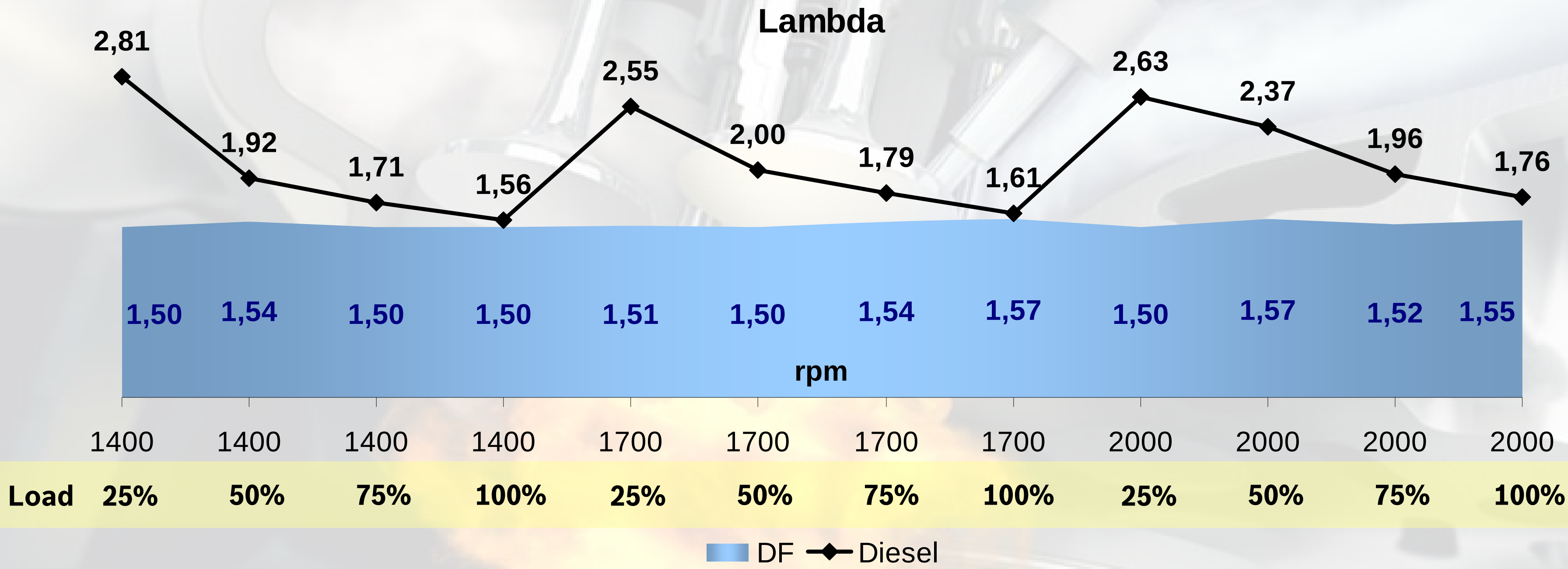
5. Engine Results in Test Bench

Research with a Diesel prototype EUIV engine with EGR



➔ Lambda ➔ experiments show lambda close of 1,55 for best combustion efficiency

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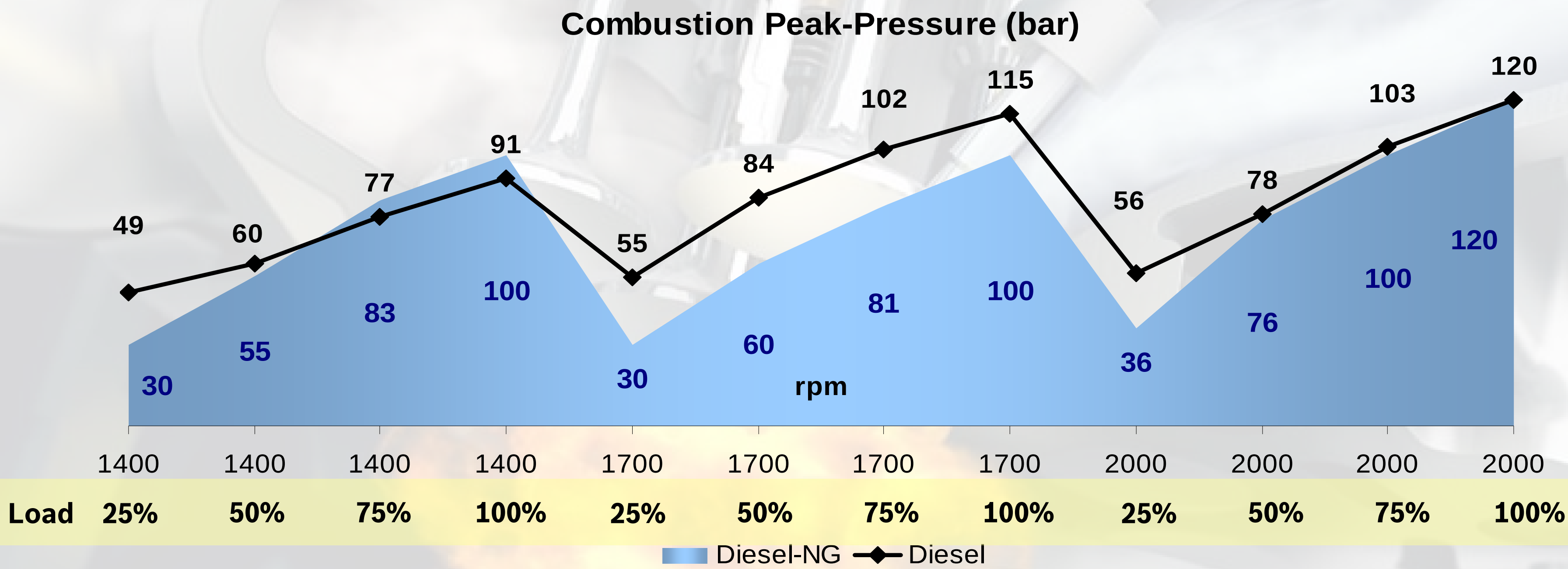
5. Engine Results in Test Bench

Research with a Diesel prototype EUIV engine with EGR



➔ Combustion Pressure ➔ in average is lower than original Diesel mode

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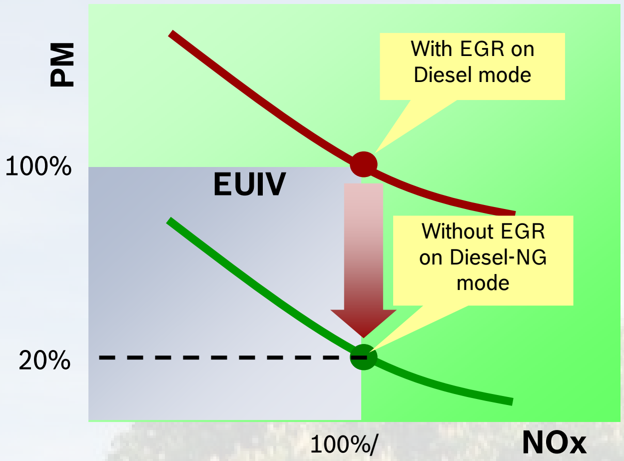
6. Emissions Approach and Strategy

NOx & PM



- Current measurements show EGT may not be necessary for some EUIV engines on dual-fuel mode
- PC and LD EUIV applications may not need DPF on dual-fuel mode
- Little modifications necessary to convert EUIV engine in EUV. Improved EGT systems
- Potential to achieve EUV without EGT on dual-fuel mode depending on calibration strategy and engine HW

- Dual-Fuel EUV worst case -> less complex EGT to keep emissions on Dual-Fuel mode
  - SCR -> less urea injection
  - EGR -> less recirculation rate (may require turbocharger matching in addition)
- EUVI engines -> potential to achieve emissions using SCR and disabling EGR on Dual-Fuel mode

➔ DPF not necessary
➔ SCR/EGR less complex

6. Emissions Approach and Strategy

HC & CO

- CH_4 and CO expected to increase above emissions limits
- Oxidation catalyst will be necessary
- High precious metal (Platinum) charge necessary to convert CH_4. Other precious metals charge may be not necessary (i.e. expensive 3-way catalyst not applicable)
- CH_4 conversion to start at 300ºC -> significant conversion at 400ºC
- Close coupled high temperature positioning of the oxidation catalyst necessary
- Conversion efficiency expected to reach 95%
- Oxidation catalyst will reach the light-off temperature earlier in dual-fuel systems due to the prior conversion of the NMHC
- HC oxidation helps reducing PM due to association between sulfates and HC

→ Oxidation catalyst necessary for EUIII up to EUVI applications
→ Platinum higher charge and optimum catalyst positioning to convert CH4

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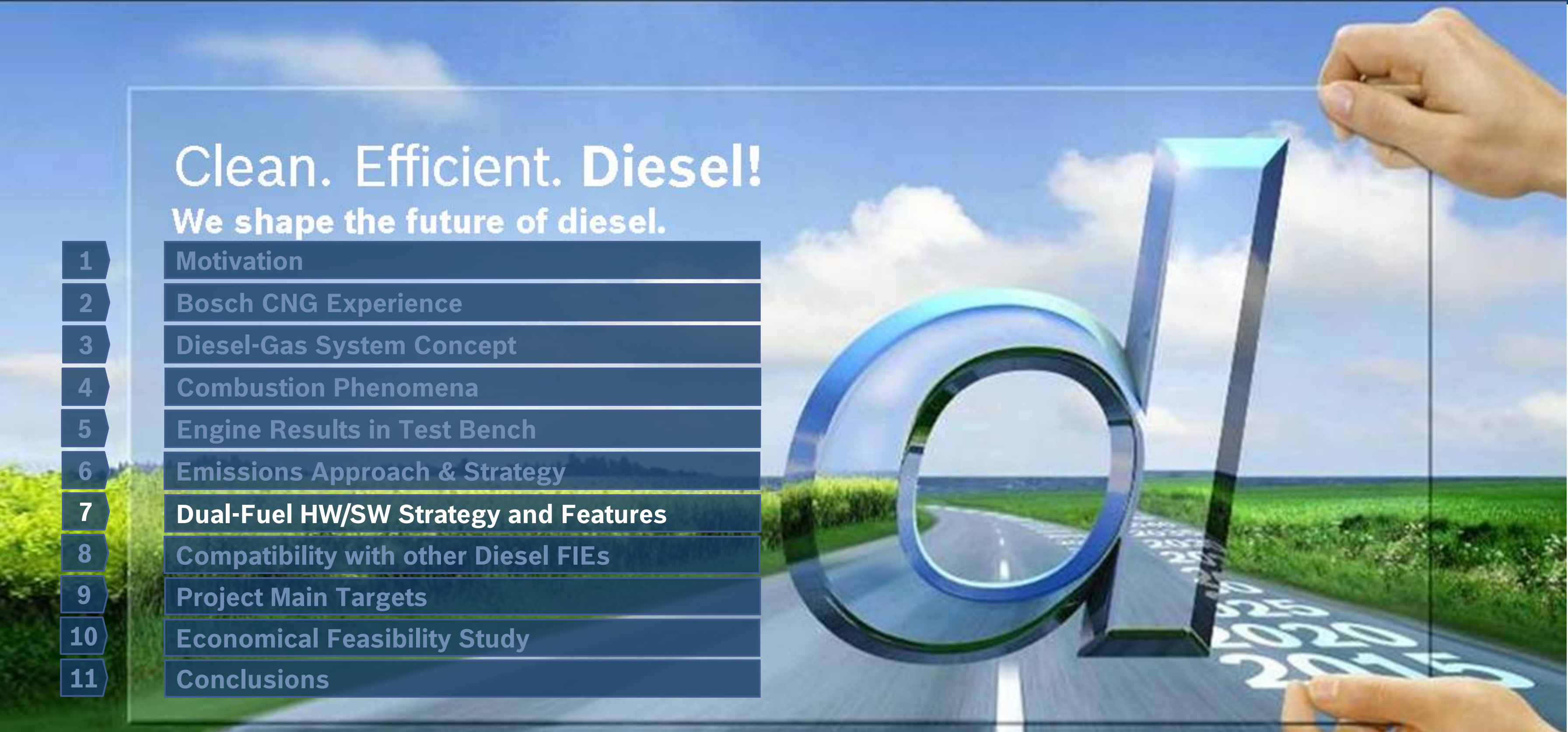

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7. Dual-Fuel HW/SW Strategy and Features

ECU software and hardware features

Feature	Benefit
Main sensors are common for both ECU´s	Economical
Software compatible to EOBD	Standardised Software for all markets
Gas leak detection function	Meets high safety standards
Automatic selection of fuel mode	Benefit of best of both the fuels
Limp home in 100% Diesel mode	Advantage of not loosing efficiency
CNG quality adaptation by SW function	Optimum operation everywhere

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8. Compatibility with non CRS Diesel FIEs

In-line mechanical Pumps

In-line Pump Conventional Injection System

Possible to use current ECU - EGC 10 with some modification in Software and Hardware

Required adaptations for A and P Pump:

- Electronic control of the injection quantity governing (i.e. by using a electronic rack stop switch – LDA controlled by ECU)
- Additional sensors and actuators
- Further development of EGC10, if it is used also for controlling A and P pump

Risks and challenges :

- Limitation of Gas substitution ratio
- High Knocking because of limitation of injection timing control
- Poor driveability during mode switch over and transient conditions
- Economic viability because of low substitution ratio

➔ Probability of the need of the after-treatment is very high for Euro IV and onwards

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8. Compatibility with non CRS Diesel FIEs

VE mechanical Pumps

VE Pump Conventional Injection System

Possible to use current ECU - EGC 10 with some modification in Software and Hardware

Required adaptations for VE Pump :
- Electronic control of the injection quantity governing
- Additional sensors and actuators
- Further development of EGC10, if it is used also for controlling VE pump

Risks and challenges :
- Limitation of Gas substitution ratio
- High Knocking because of limitation of injection timing control
- Poor driveability during mode switch over and transient conditions
- Economic viability to be evaluated

➔ Probability of the need of the after-treatment is very high for Euro IV and onwards

8. Compatibility with non CRS Diesel FIEs

UIS

Unit Injector Injection System

Possible to use current ECU - EGC 10 with some modification in Software and Hardware

Required adaptations:
- Modification of current software of the UI control unit, or
- Further development of EGC10 to control UI system
- Additional sensors and actuators

To be evaluated:
- Gas substitution ratio
- Efficiency, Driveability and performance
- Economic viability to be evaluated

→ Need of the after-treatment for Euro IV and onwards to be studied

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8. Compatibility with non CRS Diesel FIEs

UPS

Unit Pump Injection System

Possible to use current ECU - EGC 10 with some modification in Software and Hardware

Required adaptations :
- Modification of current software of the UP control unit, or
- Further development of EGC10 to control UP system also
- Additional sensors and actuators

To be evaluated:
- Gas substitution ratio
- Efficiency, Driveability and performance
- Economic viability to be evaluated

→ Need of the after-treatment for Euro IV and onwards to be studied

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9. Diesel-Gas Project Main Targets

Average substitution rate

- Environmental conditions
- Gas quality
- Vehicle configuration
- Duty-cycle

Target 85%

Performance & drivability

Diesel original performance

Emissions enhancement

- Performance requirement
- Environmental conditions
- Aftertreatment configuration

NOx	PM	HC	CO	CO_2
↓	↓ -80%	-	-	↓ -20%

- NOx reduction depends on Diesel EGT strategy

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10. Economical Feasibility Study

Brazilian Case: Urban Buses

Substitution rate	75%
Diesel/NG price relationship	55% (Diesel at 1,72BRL*)
Vehicle acquisition cost	10% add-on to original Diesel vehicle
Vehicle maintenance costs	~original Diesel vehicle
Specific consumption	Worst case = original Diesel vehicle
Mileage/day	~350km/day
Vehicle resale	~70% depreciation during 7 years

* Reference to ANP fuel prices dated from Aug. 27th, 2010 - http://www.anp.gov.br/preco/prc/Resumo_Semanal_Index.asp

- ➔ Dual-Fuel Diesel-Gas allows transp. companies to end up a period of 7 years with very positive cash-flow considering possibility to resell the vehicle
- ➔ ROI expected to not exceed 1,5 years
- ➔ Dual-fuel Diesel-Gas fits market economic requirements

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11. Conclusions

- Alternative fuels for Diesel engines are demanded in several markets due to political, economical and environmental aspects.
- In most markets transportation companies need confidence to acquire alternative fuels powered vehicles where:
  - Flexibility is important
  - Shall keep original Diesel engine operation characteristics unchanged
  - Shall have feasible vehicles acquisition and operational costs
  - Vehicle resale market is mandatory for companies operational cash-flow
- Alternative fuels may represent the most prominent emissions reduction factor worldwide.
- Significant CO_2 reduction is also mandatory worldwide.
- If flexibility is **not necessary** (Diesel mode only for "limp-home" function) less complex after-treatment systems would be possible due to engine emissions trade-off curves improvement by substituting Diesel per alternative fuels (i.e. DPF not necessary and SCR or EGR calibration to reduce lower level of NOx than the Diesel original engines).

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Thank you!

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