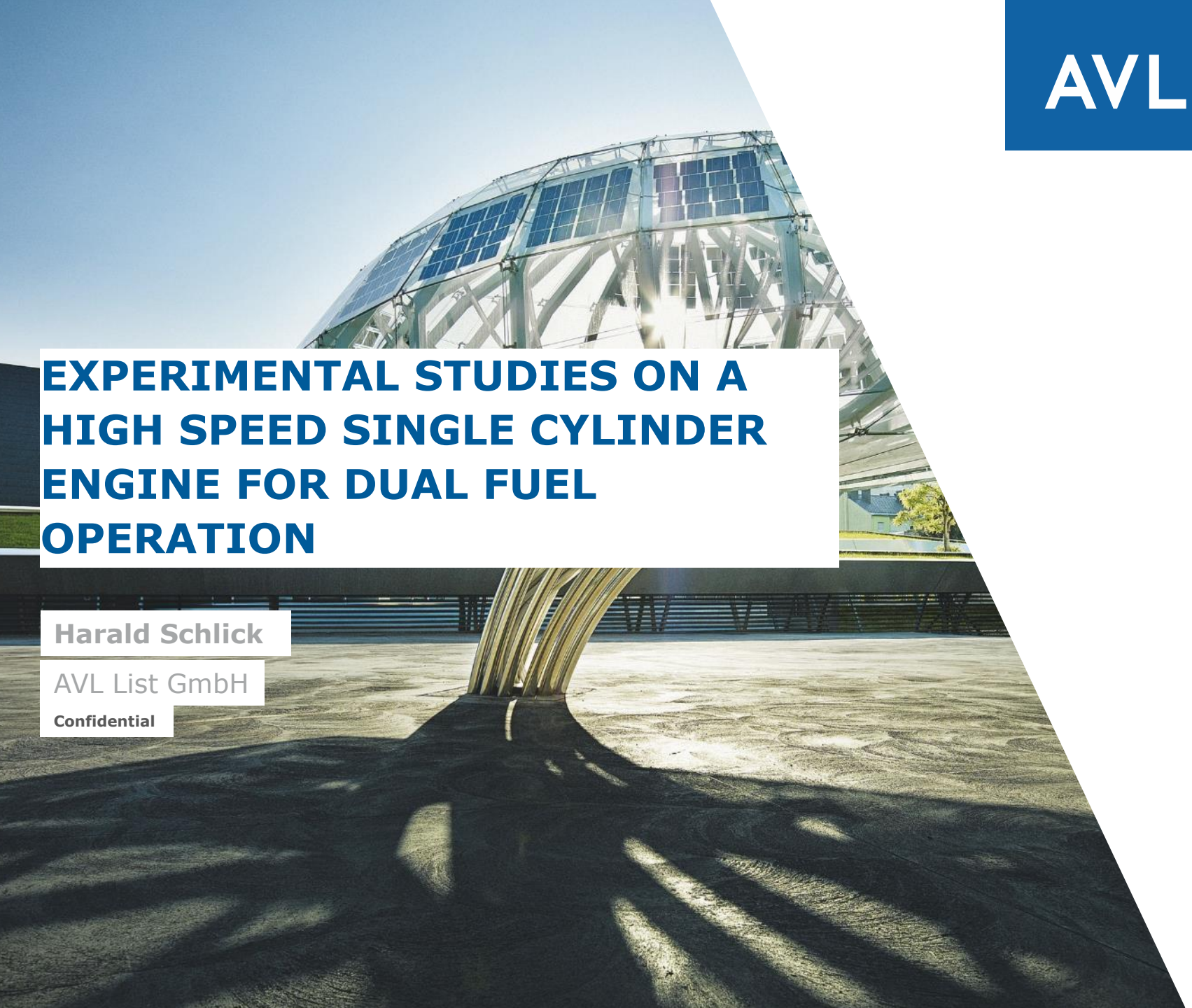

EXPERIMENTAL STUDIES ON A HIGH SPEED SINGLE CYLINDER ENGINE FOR DUAL FUEL OPERATION

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1. Introduction
   - AVL High Speed Single Cylinder Engine
2. Definition of development targets
3. Engine results in Dual Fuel mode
   - Auxiliary mode
   - Knocking behavior
4. Injector requirements
5. Impact of combustion concept to emissions and exhaust gas aftertreatment
6. Summary

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INTRODUCTION

- **Dual Fuel engine technology is already existing for high speed engines**
  - "Dual or Bi Fuel, Dynamic gas blending" engines supplied by OEM's as integrated solutions
  - Retrofit | Aftermarket kits for adaption of diesel engines in field
  - Substitution rates up to 70% are advertised
  - Full load capability in pure Diesel mode is kept
- **Drivers for Dual Fuel technology**
  - Inconsistent gas infrastructure requires diesel mode back up or at least a limp home functionality
  - Expected potential of annual cost savings
- **Dual Fuel engine technology is a "bridge technology"**
  - Engine performance compromised over an optimized state of the art diesel engine with reduced compression ratio and deteriorated over an optimized gas engine
- **Major issues**
  - High methane / total hydrocarbon and carbon monoxide emissions
  - Limitation of achievable substitution rates (real duty cycles)
  - Special injector requirements like as cooling situation and full load capability for Diesel mode
  - Design of engine control system (high dynamic operation; switching strategies between diesel and gas; knock and misfire detection)

INTRODUCTION

- **Investigated engine operating strategies**
  - Diesel mode with and without EGR and reduced compression ratio
  - Substitution of Diesel fuel by Gas at reduced compression ratio
    - Variable Substitution rate with EGR 0-95%
    - Optimized Substitution rate > 95%
      - Lean burn combustion without EGR λ ~1.7
      - Lean burn combustion without EGR λ ~1.4
      - Stoichiometric operation with EGR λ =1.0
- **Gas qualities**
  - Range of methane number: 65 to 94 (Propane mixing)

AVL HIGH SPEED SINGLE CYLINDER ENGINE

	Unit	Baseline Engine
Cylinder displacement	dm^3	≈5
Operation Mode	-	Diesel / Gas / Dual-Fuel
Rated Speed	rpm	max. 1900
Rated BMEP	bar	max. 30
PFP design limit	bar	< 250
Compression ratio	-	various
Fuel injection system	-	CR System (up to 2500bar)
Gas supply	-	Central Mixing or Port Injection

- „Flexible camshaft“ (cam segments)
- Experimental EGR system
- Special measurement techniques
- Possibility for gas mixing, up to 6 components

DEFINITION OF DEVELOPMENT TARGETS

- **Definition of a V12 Dual Fuel Engine concept**
  - Engine application: Marine propulsion/auxiliary and non road mobile machinery (NRMM)
  - Test cycle: ISO 8178-C1/-E3/-E2/-D2
  - DF Combustion System: Quiescent type – optimized compression ratio – Tier 4 Diesel derivate
  - Turbocharging concept: Single stage turbo charging (SSTC) with Miller intake valve closure
  - After treatment: Depending on engine concept:
    - Methane oxidation catalyst (MOC)
    - Diesel oxidation catalyst (DOC) + SCR

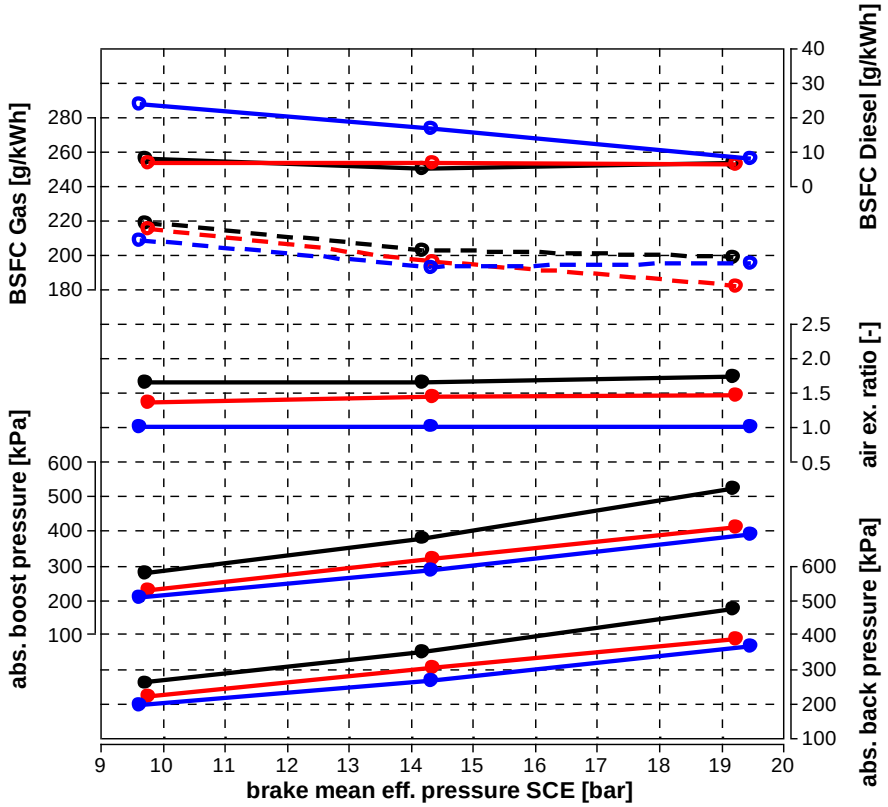
- **Development Methodology**
  - Single cylinder engine tests
  - Supported by thermodynamic simulations
  - Characterization of Methane oxidation catalysts using a mobile catalyst analyzer

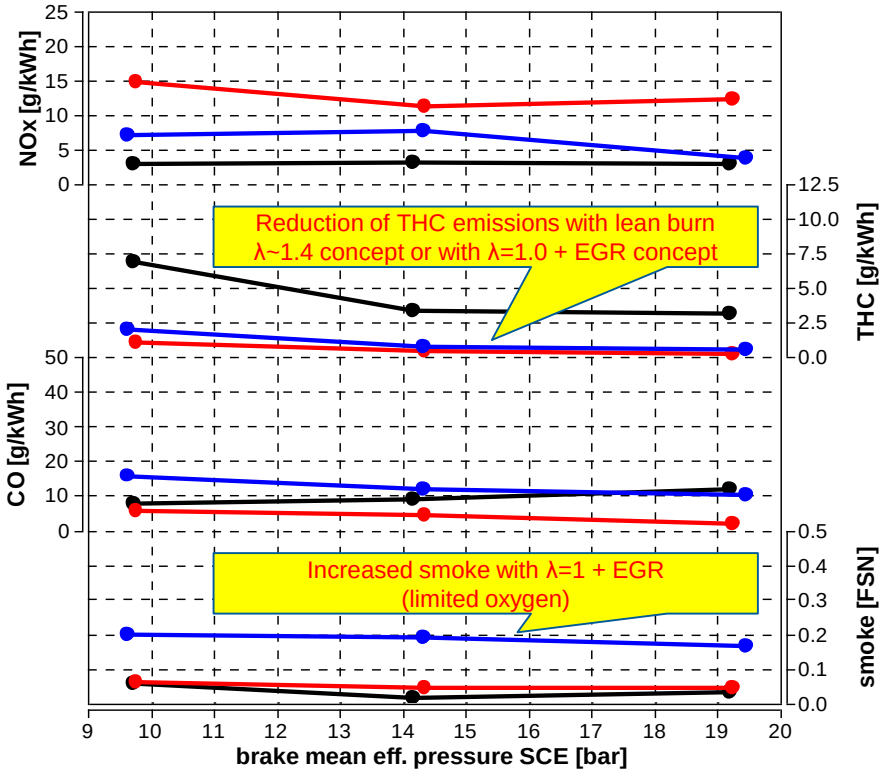
CONTENT

ENGINE RESULTS - AUXILIARY MODE

Substitution > 95%

Mode 1/2/3 of ISO 8178 – E2/D2-cycle | CR=13.5:1 | M520 | pRail 1000bar

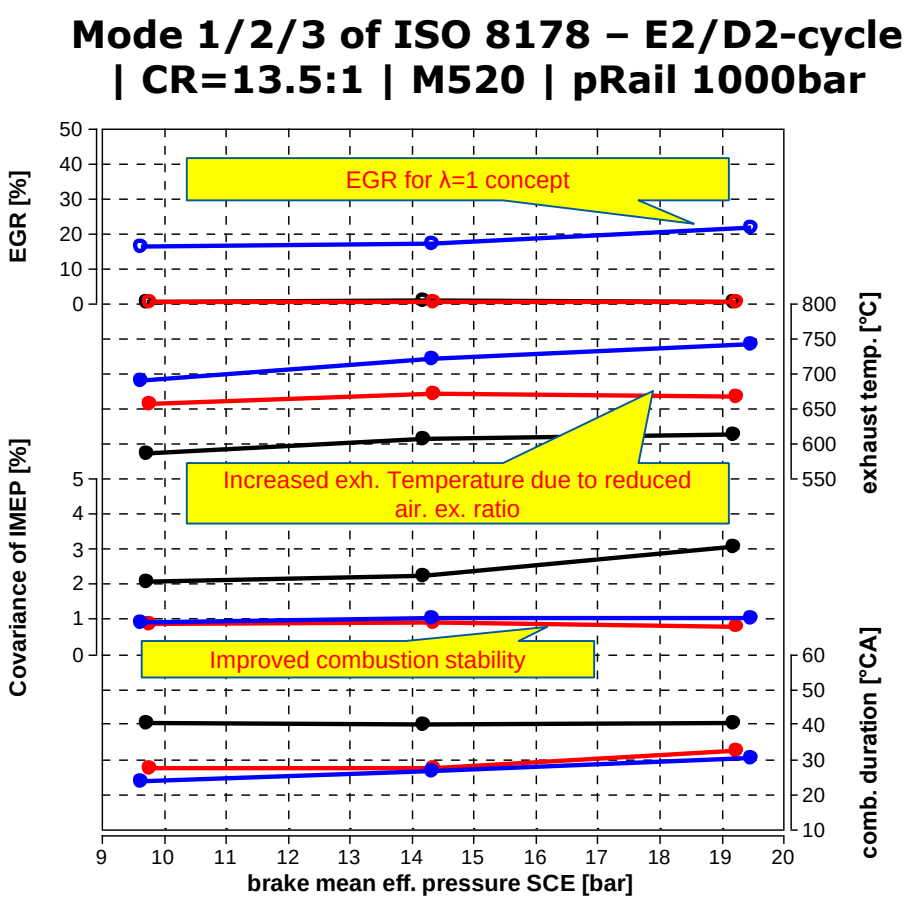


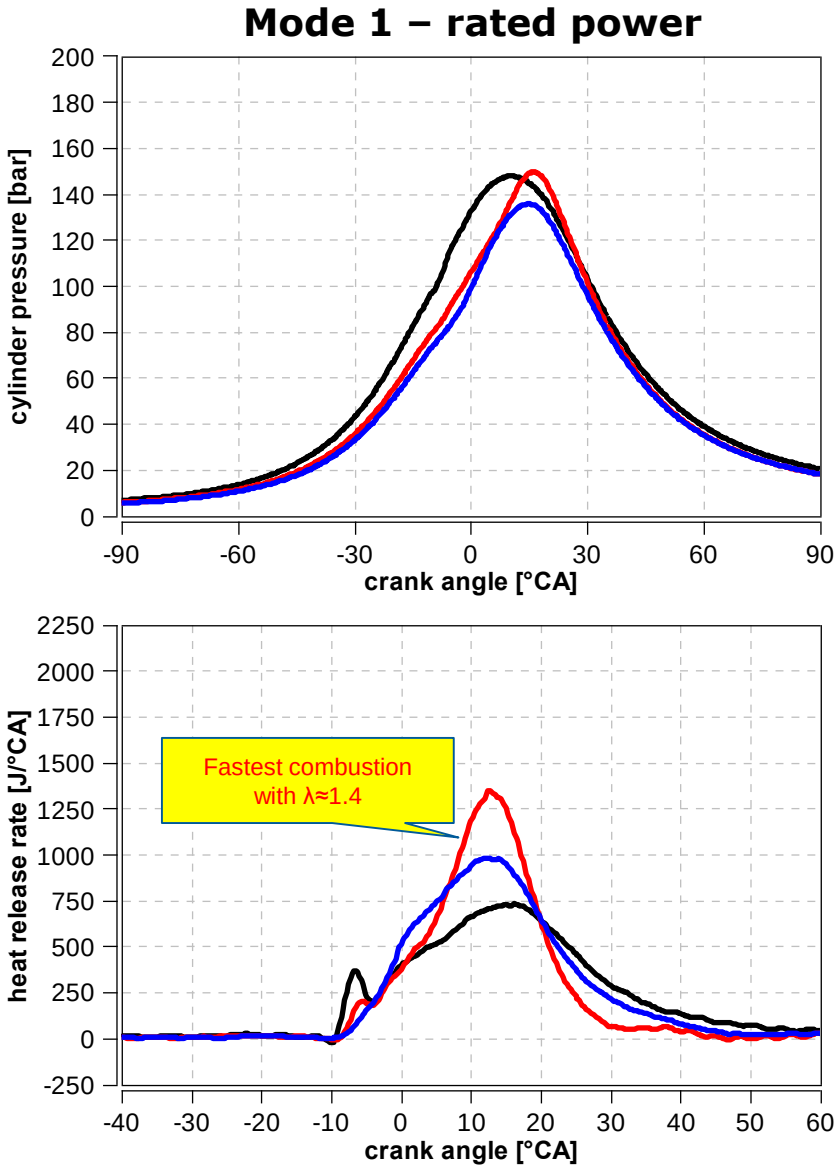


Dual Fuel w/o EGR λ≈1.7
Dual Fuel w/o EGR λ≈1.4
Dual Fuel w EGR λ=1.0

ENGINE RESULTS - AUXILIARY MODE

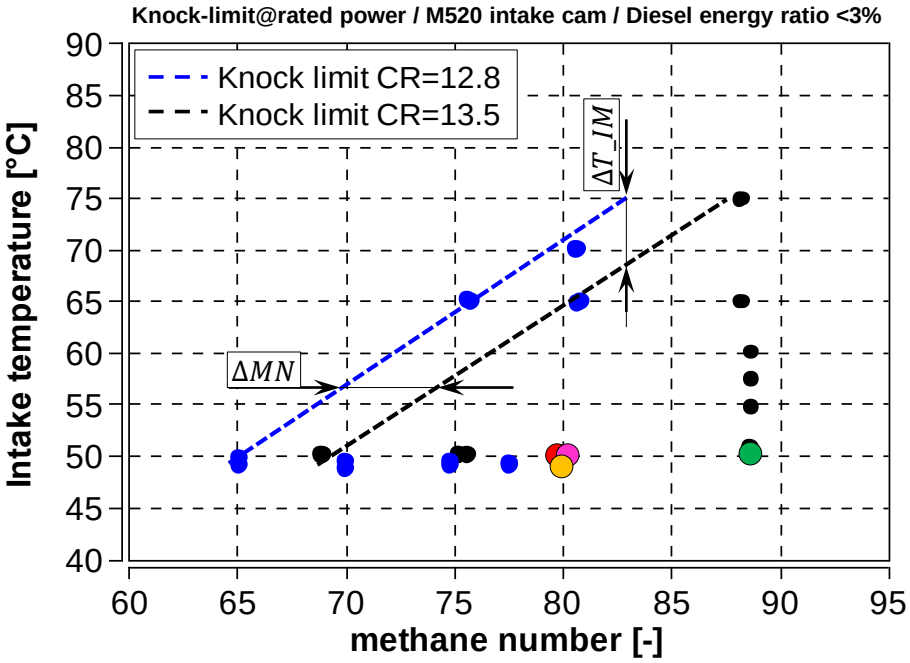
Substitution > 95%





KNOCKING BEHAVIOR IN DUAL FUEL MODE

Impact of compression ratio and intake valve closing to measured knock limit



- With compression ratio 13.5 the margins to knock limit are reduced
  - ΔMN ~5
  - ΔT_IM ~6°C

- Further investigations were carried out with different compression ratios and Miller timings – intake valve closings:
  - …CR=15.5 / M520: ~15% EGR is required for engine operation without knocking in rated power
  - …CR=14.0 / M520: Light knocking detected at 50°C intake temperature and methane number 80
  - …CR=14.0 / M500: Stronger Miller timing results in knock free engine operation
  - …CR=14.8 / M500: No knocking; additional margin to lower methane number and/or increased intake temperatures

CONTENT

INJECTOR REQUIREMENTS

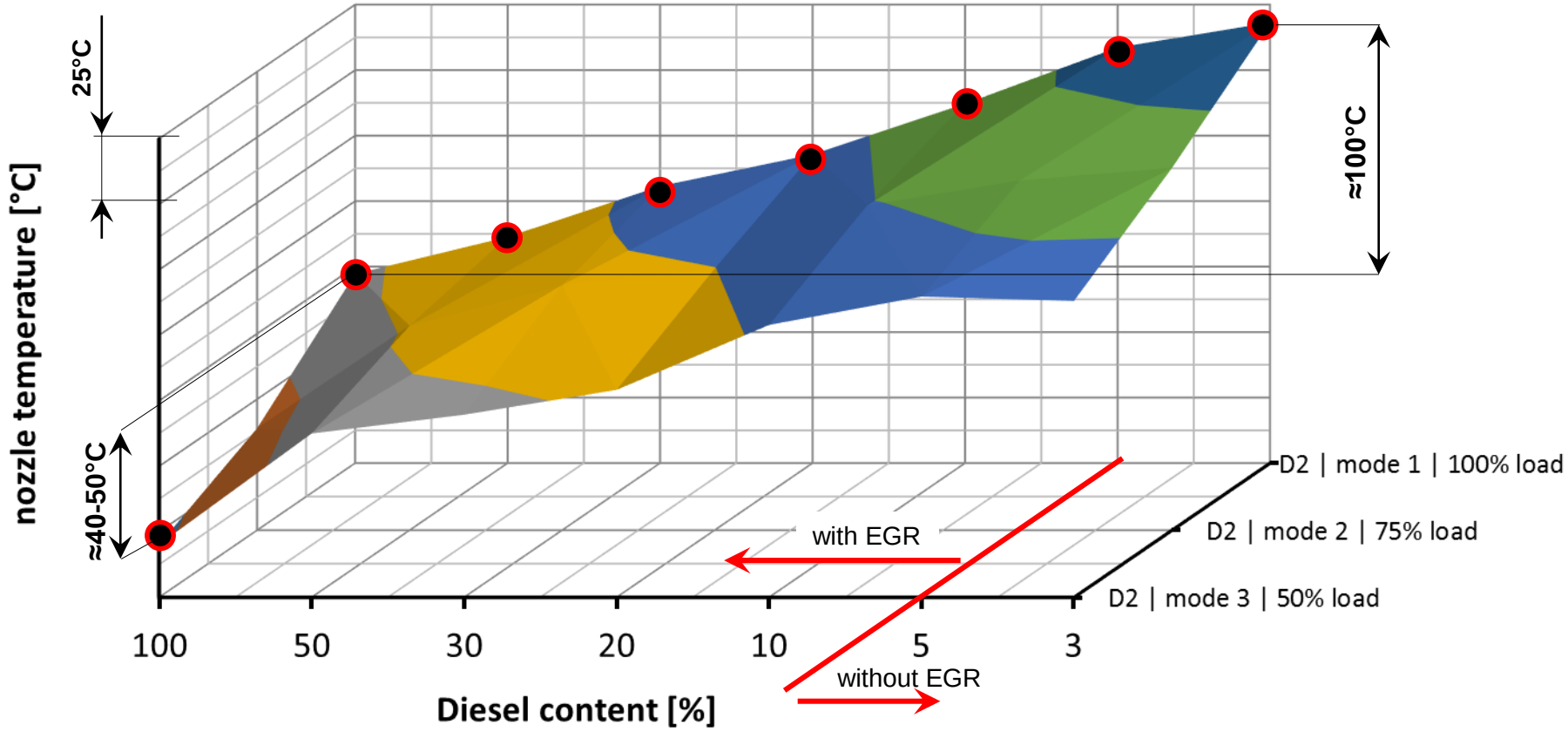
- Wide range of injection quantities must be covered
- Pure Diesel to Dual Fuel mode with <3% Diesel quantity in mixture
  - DF operation at Full and high loads: < 18mg/stroke
  - DF operation at Part load: < 28mg/stroke
  - Operation with 100% Diesel at Rated Power: ~ 540mg/stroke

- Generally, the design space is only for one injector available
- "Idle Quantities" determine stability of DF operation at full load
- Closed loop quantity control is preferable (shot-to-shot variation,…)
- Improved cooling in Dual Fuel mode is required due to low Diesel flow rate through injector

INJECTOR REQUIREMENTS

Nozzle tip temperature = f(BMEP, Diesel Energy ratio) at 1800rpm

Hardware: CR=13.5 | M520
Rail pressure: Diesel 2200bar | Substitution/DF 1000bar
Methane number 93 (Russian NG)
NOx~3g/kWh (US EPA T4f NRMM)



Nozzle tip temperature at full load in DF > +100°C over Diesel operation

INJECTOR REQUIREMENTS

Open questions:

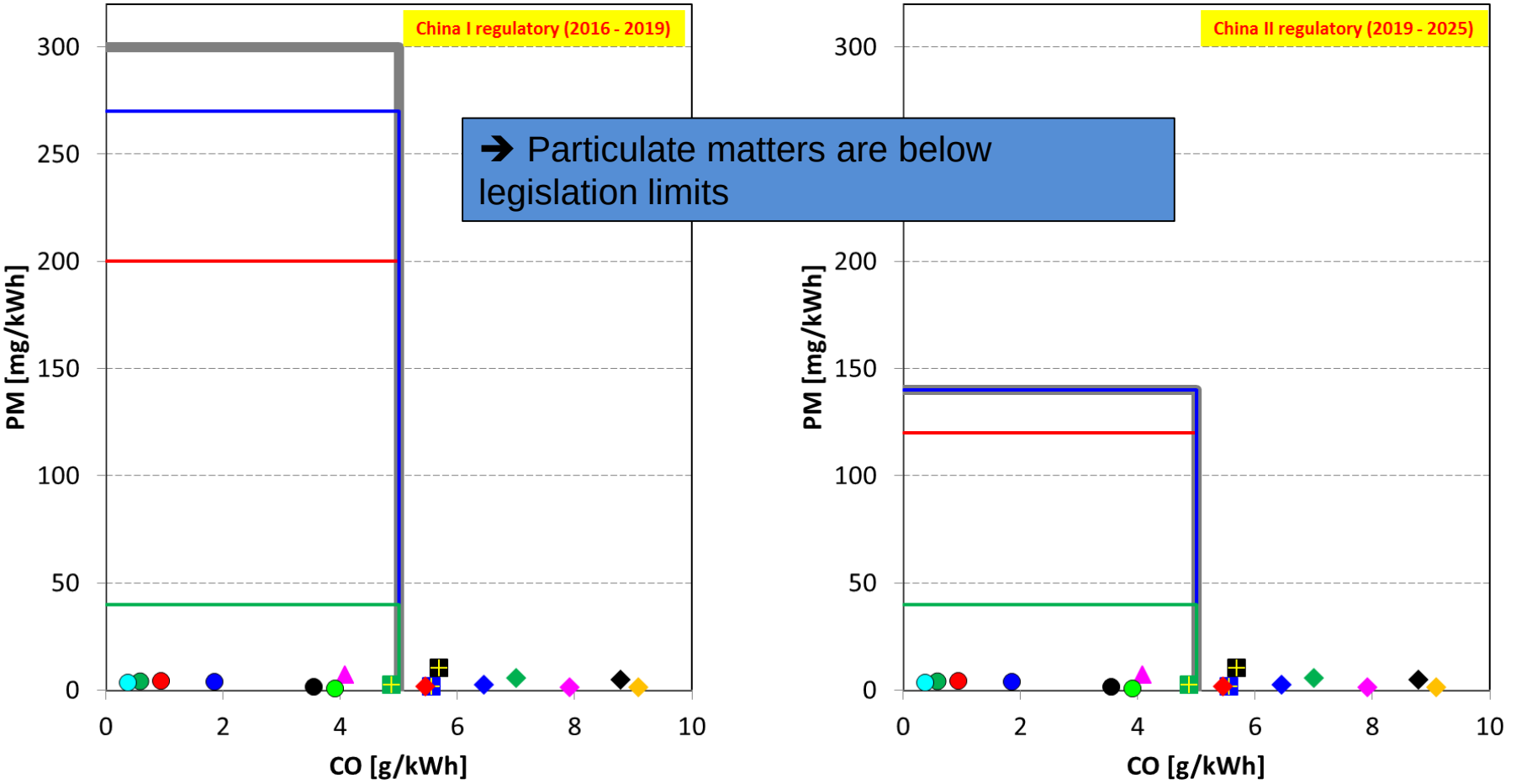
- Injector cylinder to cylinder deviation in Dual Fuel mode (smallest quantities)?
- Injector degradation over lifetime?
- Degradation of engine calibration over lifetime?
- Injector classification / coding standards not sufficient

➢ **Development and support from injector supplier is required**

CONTENT

IMPACT OF COMBUSTION CONCEPT TO EMISSIONS AND EXHAUST GAS AFTERTREATMENT

CO versus PM – engine out emissions:



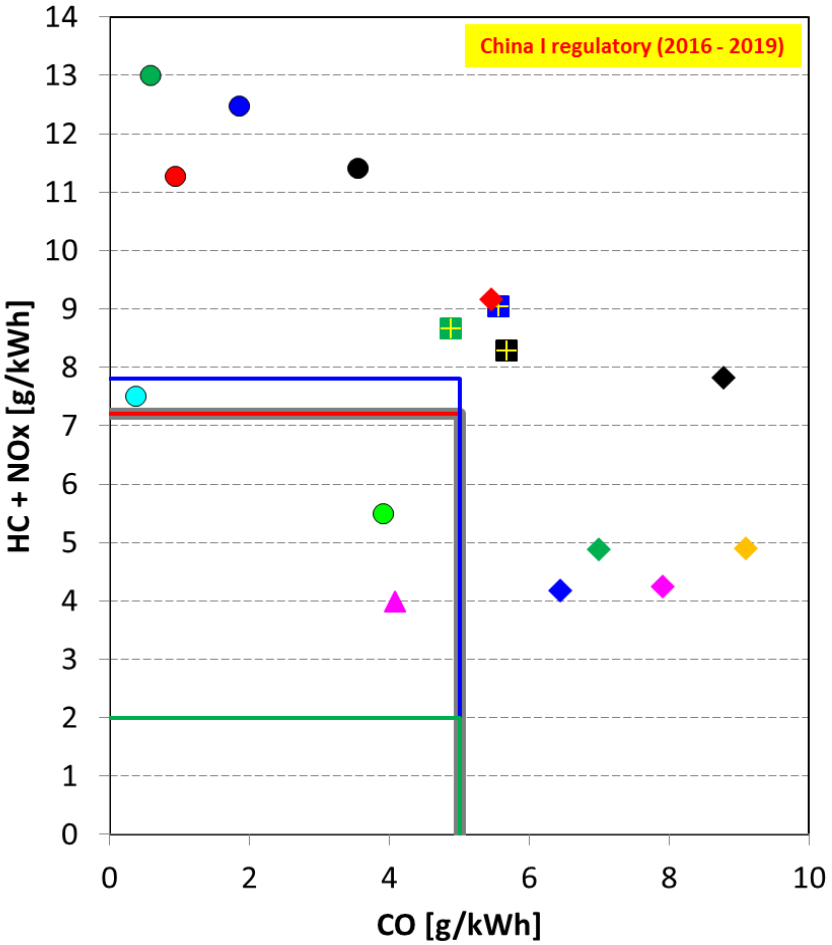
➔ Particulate matters are below legislation limits

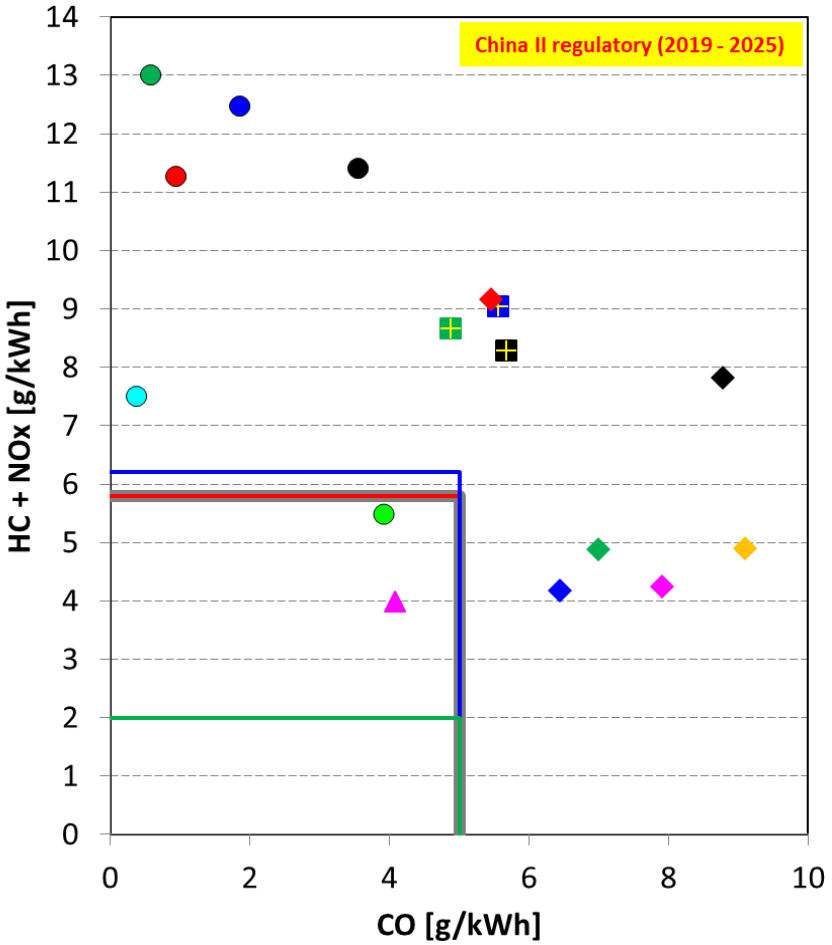
China I/II: 0.9dm³ < SV < 1.2dm³
China I/II: 1.2dm³ < SV < 5.0dm³
China I/II: 5.0dm³ < SV < 15.0dm³
US EPA T4 final: 600kW < P < 3700kW

●…Dual Fuel lean burn concept SCR
◆…Dual Fuel lean burn wo EGR
▲…Stoichiometric concept w EGR
■…Substitution concept w EGR

IMPACT OF COMBUSTION CONCEPT TO EMISSIONS AND EXHAUST GAS AFTERTREATMENT

CO versus HC+NOx – engine out emissions:





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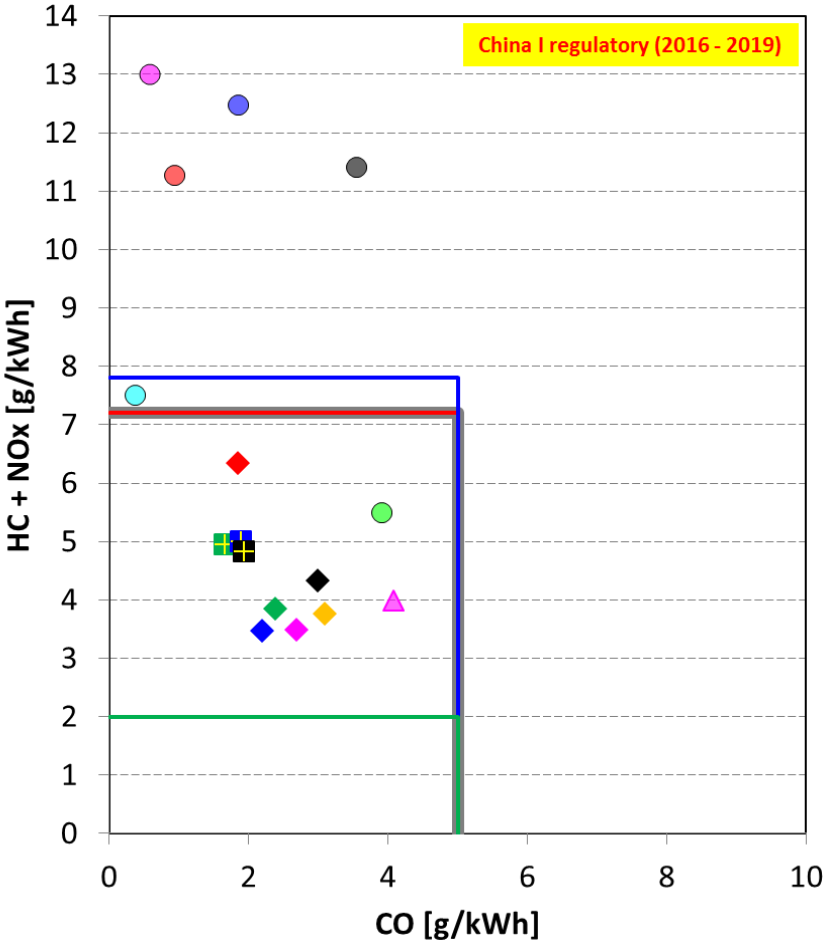
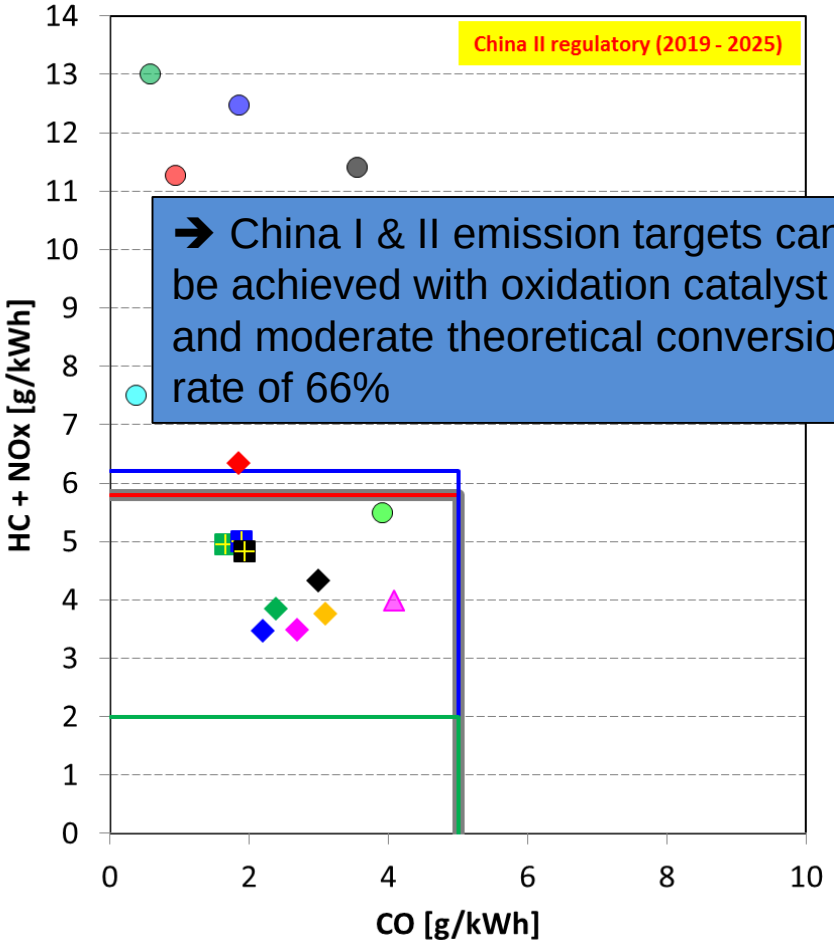
IMPACT OF COMBUSTION CONCEPT TO EMISSIONS AND EXHAUST GAS AFTERTREATMENT

CO versus HC+NOx – tail pipe emissions with oxidation catalyst (theoretical conversion rate 66%):





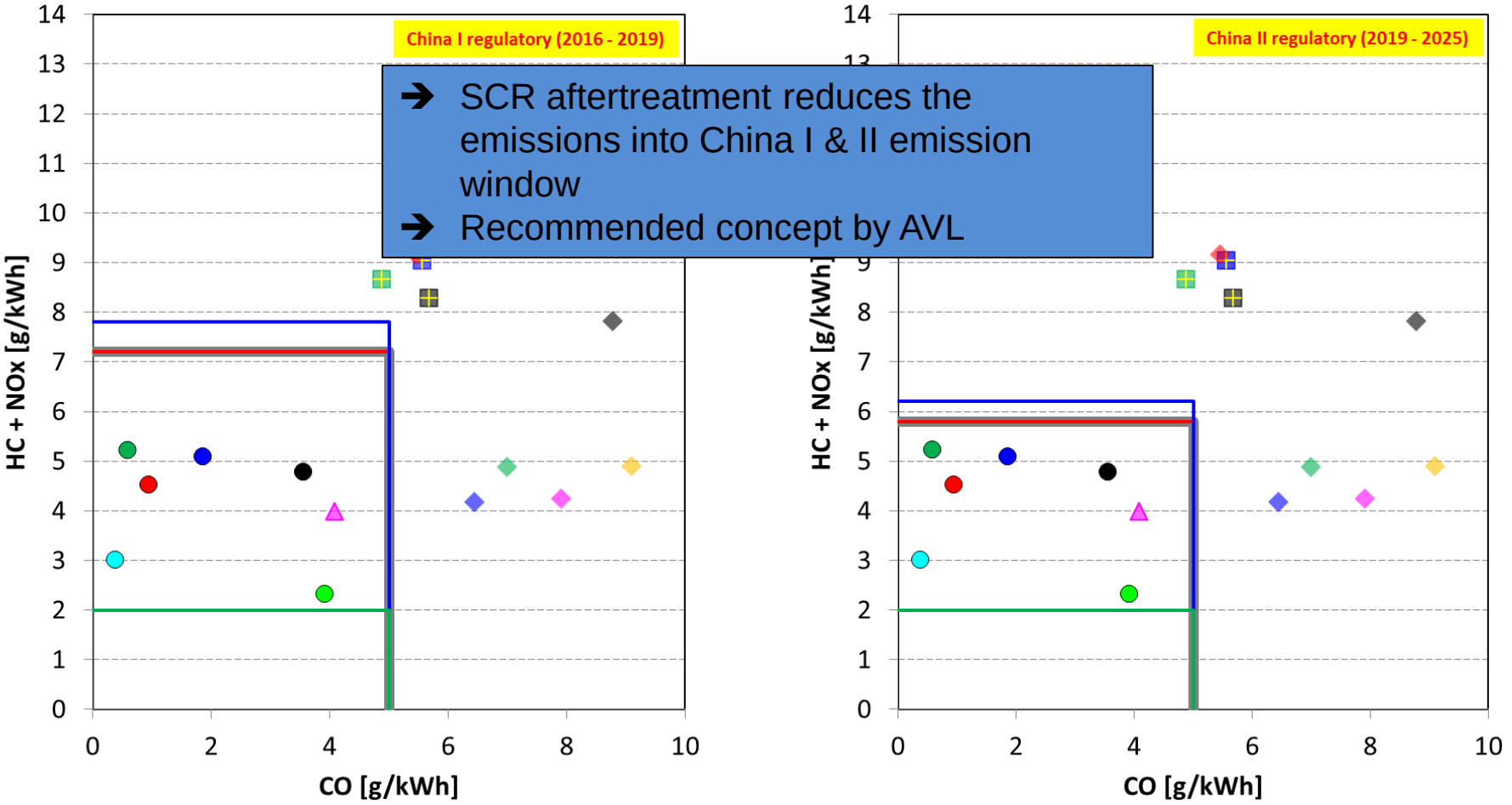
➔ China I & II emission targets can be achieved with oxidation catalyst and moderate theoretical conversion rate of 66%

- China I/II: 0.9dm³ < SV < 1.2dm³
- China I/II: 1.2dm³ < SV < 5.0dm³
- China I/II: 5.0dm³ < SV < 15.0dm³
- US EPA T4 final: 600kW < P < 3700kW

- ● …Dual Fuel lean burn concept SCR
- ◆ …Dual Fuel lean burn wo EGR
- ▲ …Stoichiometric concept w EGR
- ■ …Substitution concept w EGR

IMPACT OF COMBUSTION CONCEPT TO EMISSIONS AND EXHAUST GAS AFTERTREATMENT

CO versus HC+NOx – tail pipe emissions with SCR aftertreatment (theoretical conversion rate 60%):



➔ SCR aftertreatment reduces the emissions into China I & II emission window

➔ Recommended concept by AVL

China I/II: 0.9dm³ < SV < 1.2dm³
China I/II: 1.2dm³ < SV < 5.0dm³
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●…Dual Fuel lean burn concept SCR
◆…Dual Fuel lean burn wo EGR
▲…Stoichiometric concept w EGR
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CONTENT

SUMMARY

- For the Chinese Marine inland waterway legislation, the emission limits can be achieved with optimized Dual fuel lean burn combustion
- AVL's recommendation for stricter emission limits in Dual Fuel Marine business (IMO, EPA, EU or China) is a lean burn concept with SCR exhaust gas aftertreatment system
- The advantages of the lean burn DF concept (EAR ~1.4) with SCR are:
  - Better efficiency
  - Better combustion stability; reduced covariance in IMEP
  - Significantly reduced THC and CH4 emissions
  - Significantly reduced CO emissions
  - Less requirements for the turbocharger compressor design:
    - Lower compressor pressure ratio (CPR) is required
    - Waste gate only is sufficient
    - Engine bypass is not needed (as for lean burn DF with EAR 1.7)
    - Design as single stage turbo charger

Thank you for your attention

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