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Detailed 0-D/1-D Thermodynamic Model of Target Engine with 2-stage Boosting System Including its Basic Control:

Two-stage Turbocharged Large-Bore Gas SI ICE – Operation under Different NOx Level Conditions

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WP06: R&D for High Efficiency Turbocharging

Coordinator of the WP

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Participants of the WP

PBS Turbo – Ing. Jiří Klíma; Brno University of Technology – doc. Ing. Pavel Novotný, Ph.D.

Main Goal of the WP

The main focus is put on optimization of high pressure turbocharger for specific needs of two stage boost group under both steady operation and transient one. Optimized bearing system with high mechanical efficiency and lower lubricant volume flow rates. Detailed thermodynamic simulations will be performed to maximize engine performance while considering complex control of both engine and two stage turbocharger systems.

Partial Goals for the Current Period

Detailed thermodynamic model of the target engine with 2-stage boost system including its control.

Software for lubricating system design.

Initial design of 2-stage boost system (turbochargers).

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1-WP02-001 (O) | Detailed 0-D/1-D thermodynamic model of target engine with 2-stage boosting system including its basic control. | • R-SW

Complex engine thermodynamic model (based on 0-D/1-D) of target engine (approx.. 1,8MW of effective power) including detailed 1-D model of 2-stage boost system from PBST. The model will feature all necessary controllers to enable complex optimization under both steady state and transient conditions – both engine setting and turbocharger parameters will be optimized to achieve the best possible performance. | 10. 12. 2020 | | CTU FME 0,95 | PBST 0,05 |

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OUTLINE:

- Introduction
- Mathematical Models
- Computed Cases
- Results
- Conclusions

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Introduction:

- Large-bore SI gas engine – high efficiency ('diesel-like') and low pollutants (NOx) => (very) lean mixture concept.
- The concept requires high amount of fresh air => 2-stage turbocharging.
- Future emissions limits: low NOx values while increasing BMEP (possibly over 30 bar).
- Possible use of different fuels (hydrogen, biogas, low energy content gases).
- Complex engine control even at constant engine speed (boost pressure control, mixture composition control, NOx level).

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Introduction – Goals:

- To study the influence of different engine operating conditions while considering future requirements in terms of pollutants (NOx level) and engine load (BMEP level) for the case of large-bore highly turbocharged gas SI ICE.

- Additional Goals:
  - To find limits of 2-stage boost group application.
  - To evaluate both maximum achievable BMEP and minimum BSFC.

- The results were achieved by means of detailed thermodynamic simulation (0-D/1-D model).

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Mathematical Model:

- It is based on 0-D/1-D approach – GT-Power was applied.
- Model of large-bore 2-stage turbocharged SI gas engine was created – the model is based on limited data from engine manufacturer and extensive data of similar engine (different manufacturer).
- Unknown model parameters were estimated by the authors (using experience from similar projects).
- Standard turbomachinery maps provided by PBS Turbo representing the whole family (including changes of efficiency curve shape for high swallowing capacity).
- Sub-models with high predictive ability were applied.
- NOx prediction – calibrated multi-zone model based on Zeldovich mechanism (carried over from different model of a similar engine).
- Simple combustion model, no knocking considered – both assumptions are based on experience and some literature sources of pre-chamber large bore gas SI ICEs.

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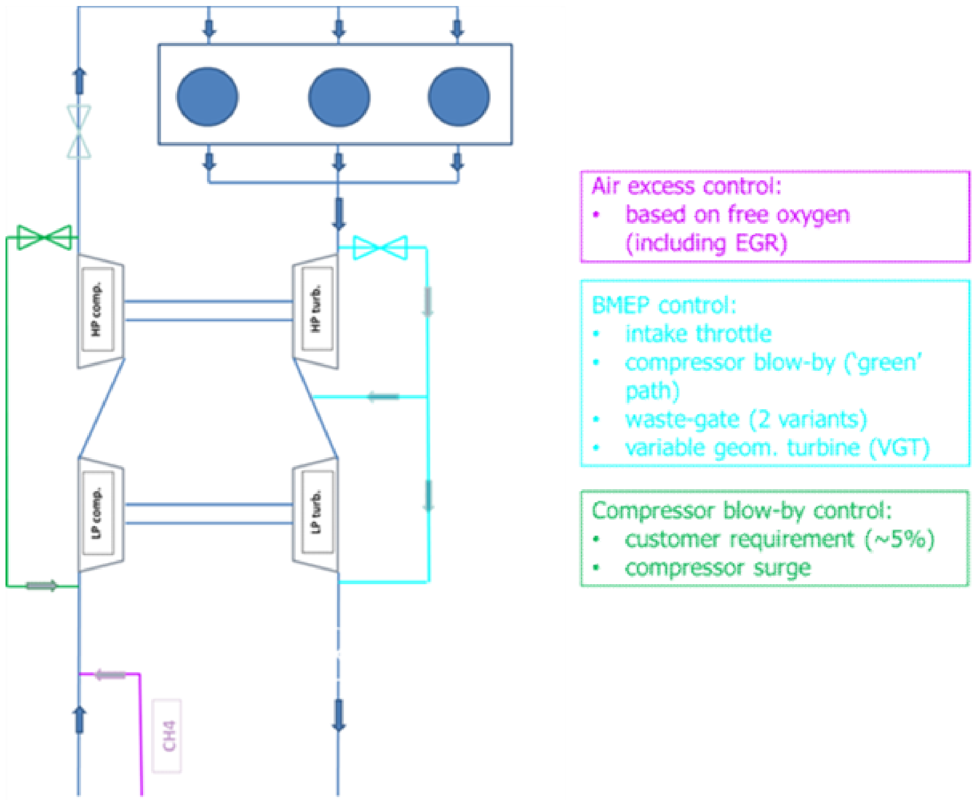
Main ICE Parameters & Engine Layout Scheme

Parameter	Unit	Value
Bore-to-Stroke Ratio	[-]	0.784
Compression Ratio	[-]	14.0
Engine Speed	[rpm]	1500
Charging		2-stage turbocharged
Fuel		CNG/Hydrogen
Configuration		V20
No. of Intake Valves		2
No. of Exhaust Valves		2
BMEP	[bar]	20-36



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Computed Cases:

- Influence of the following parameters was evaluated:
  - Engine BMEP control (throttle, blow-by, waste-gate)
  - NOx level (TA_Luft), BMEP level
  - Ambient conditions
  - Fuel composition
  - Limit of in-cylinder max. pressure
  - Exhaust back pressure (possible after-treatment device(s))
- Multi-variable multi-constraint single-target optimizations were performed:
  - Targets:
    - min. BSFC at different BMEP levels (20-36 bar)
    - max. BMEP
  - Constraints:
    - Compressor surge
    - Checking: max. turbine inlet temperature, turbo over-speeding
    - Checking: BMEP, blow-by and NOx targets
  - Independent variables:
    - Combustion timing (1 variable)
    - Valve train (4 variables)
    - Turbomachinery (up to 7 variables)

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Computed Cases:

- Multi-variable multi-constraint single-target optimizations (genetic algorithm) were performed:
  - Targets:
    - min. BSFC at different BMEP levels (20-36 bar)
    - max. BMEP
  - Constraints:
    - Compressor surge
    - Checking: max. turbine inlet temperature, turbo over-speeding
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  - Independent variables:
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Results: qqq

Turbine A

inlet_B

animace

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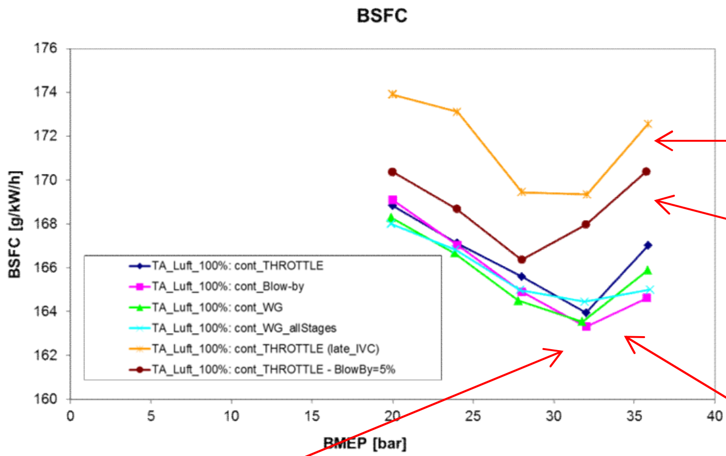
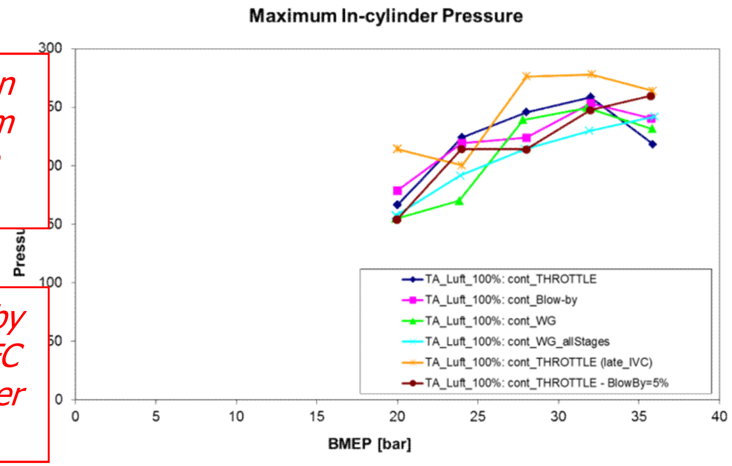
Results: min. BSFC at TA_Luft=100%, diff. control means



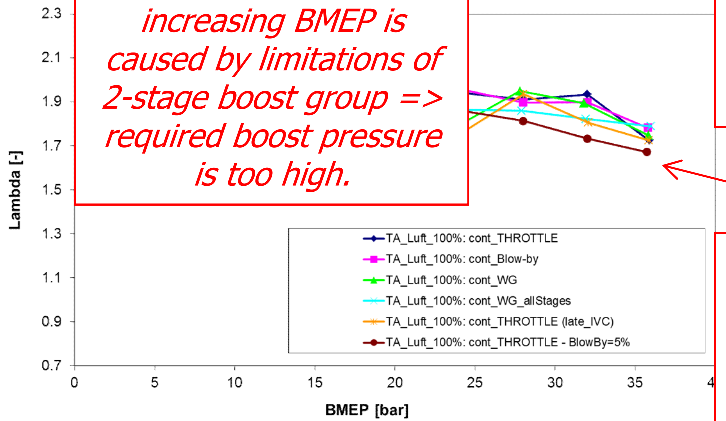


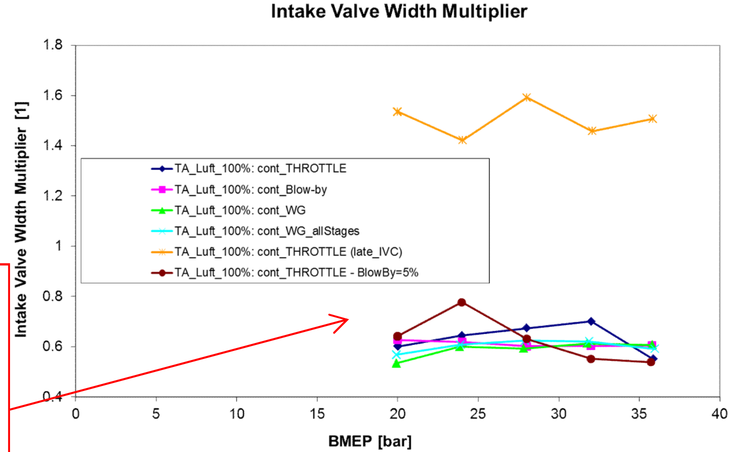
Application of Atkinson cycle (wide intake cam profile) leads to high BSFC penalty.

When requiring blow-by of 5%, significant BSFC penalty is applied under high engine load.

Increase of BSFC when increasing BMEP is caused by limitations of 2-stage boost group => required boost pressure is too high.

Little difference while considering different means of BMEP control.





When increasing BMEP, required air excess drops (slightly) while level of Millerization is increased and combustion is positioned more into expansion stroke.

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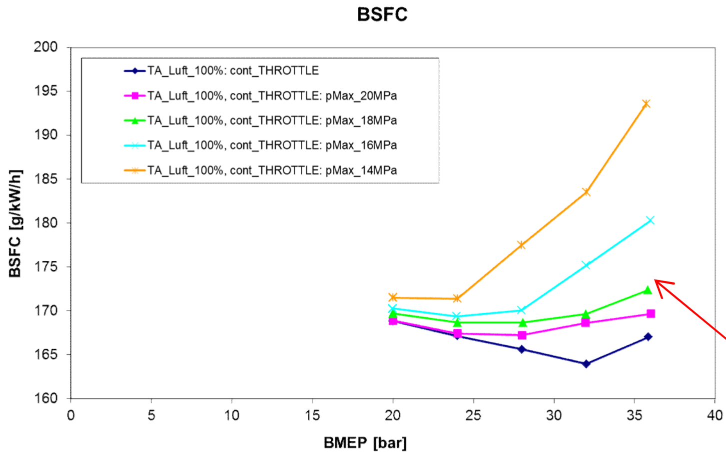
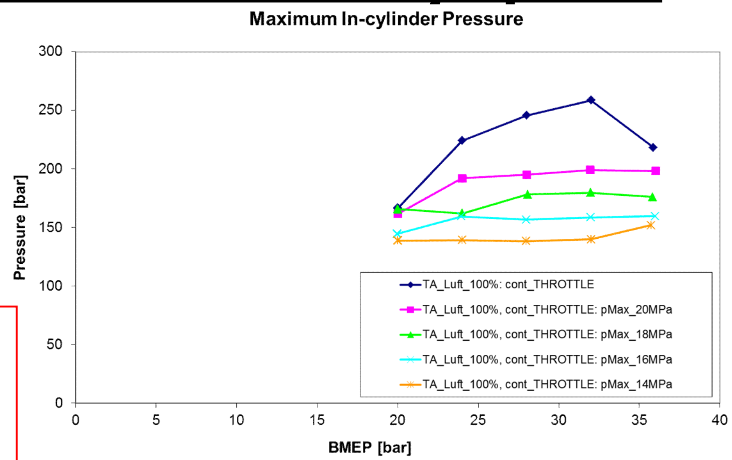
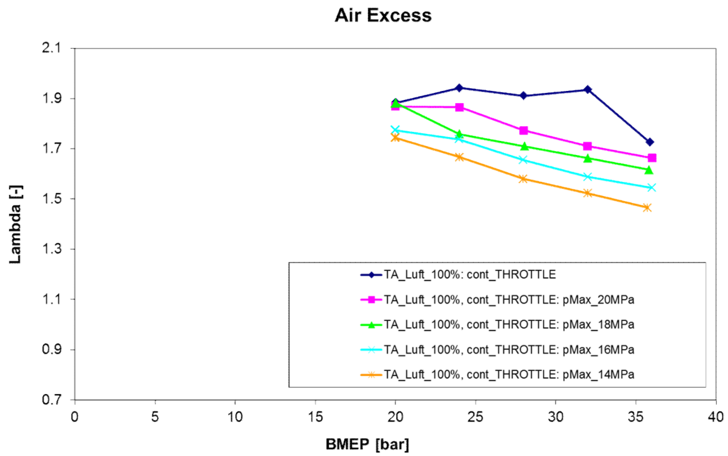
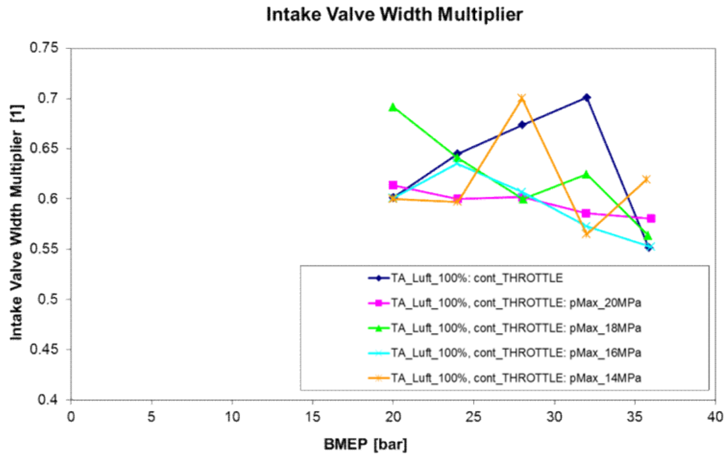
Results: min. BSFC at TA_Luft=100%, infl. of max. in-cyl. press.





When max. in-cylinder pressure limit is set too low, there is very high BSGC penalty.





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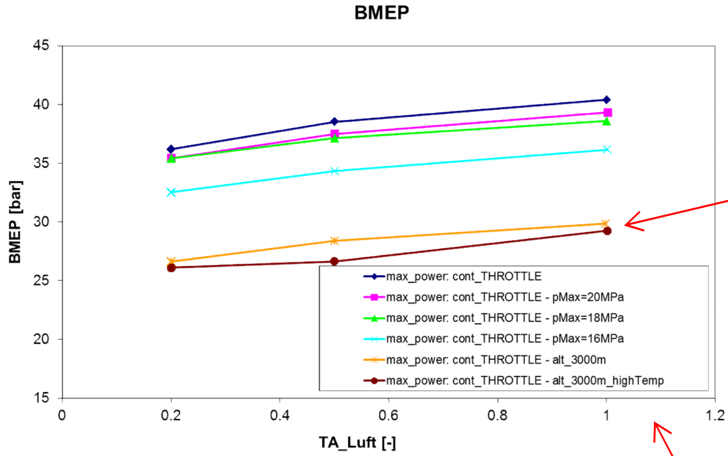
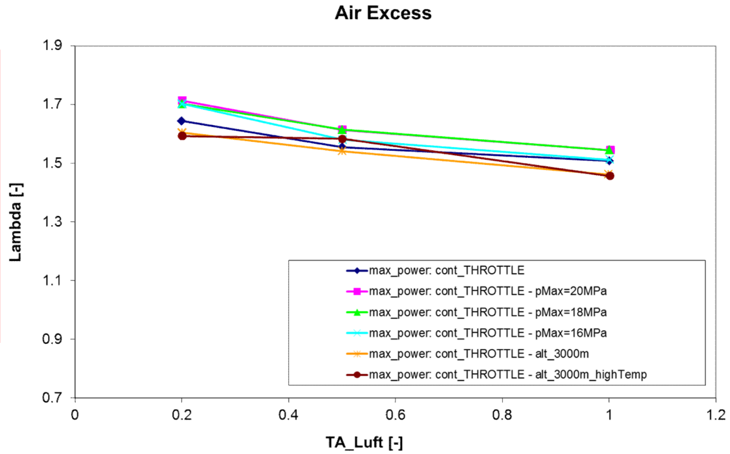
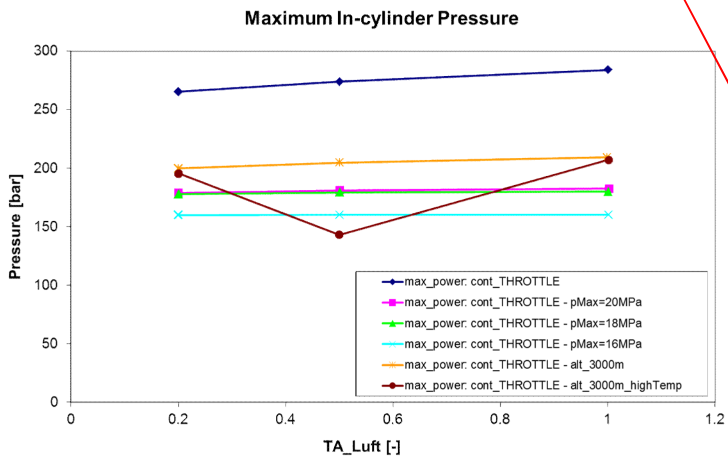
Results: max. BMEP, infl. of max. in-cyl. press. + ambient cond.

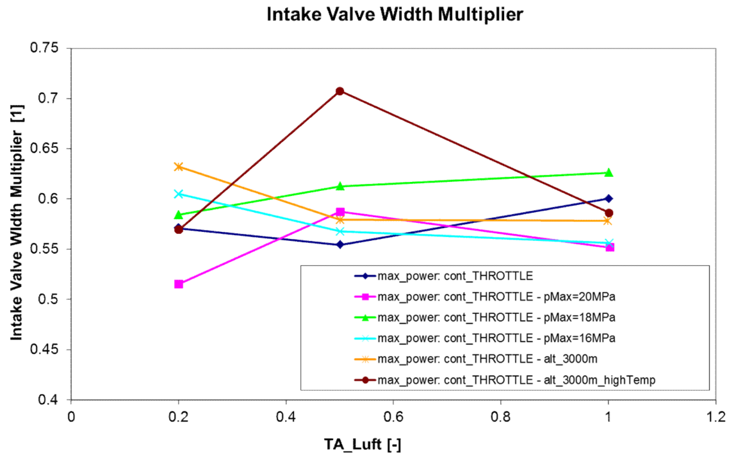


When ICE is operated at high altitude, its performance significantly drops due to limitations of 2-stage boost group (too high boost pressure is required).





The diagrams show dependency of max. achievable BMEP on NOX level (based on TALuft norm => the lower the value, the lower NOx in exhaust gases).



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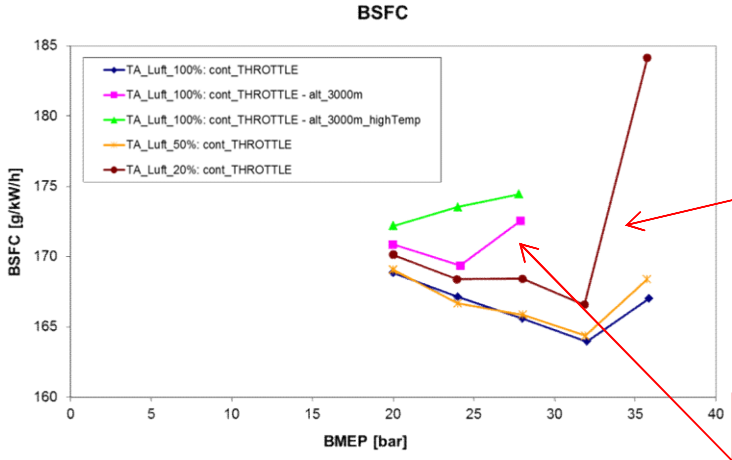
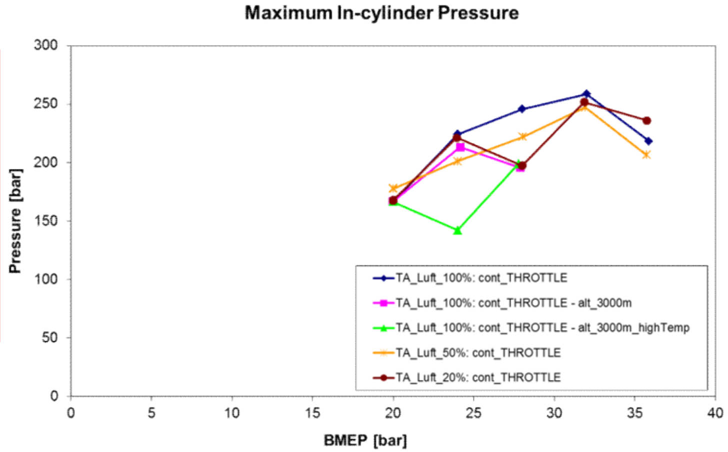
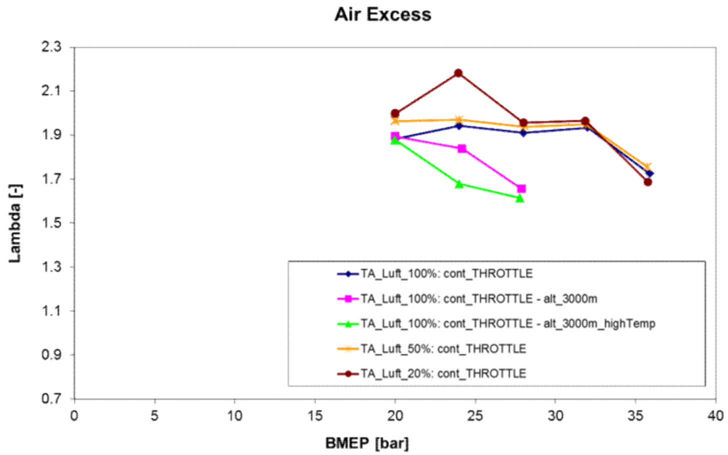
Results: min. BSFC, influence of NOx level + ambient cond.

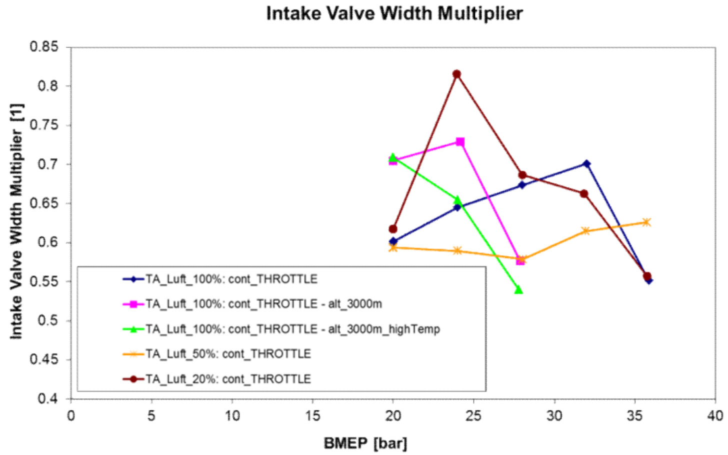


More strict requirement of NOx level leads to higher BSFC. Again, BSFC is limited by 2-stage boost group performance under high BMEP.

High altitude operation leads to high BSFC and limited achievable BMEP.







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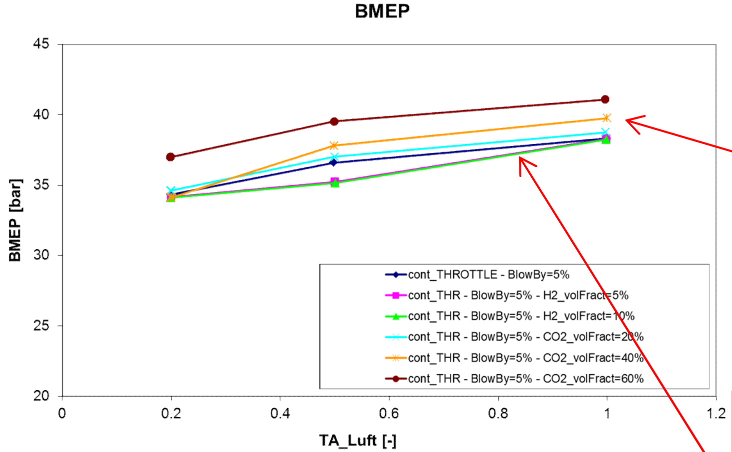
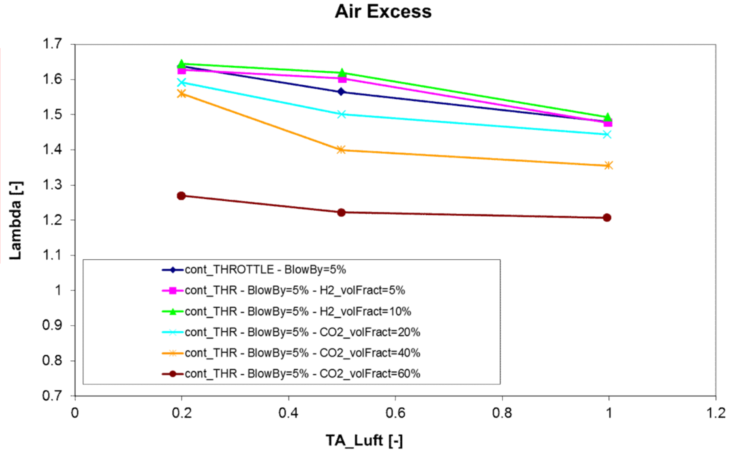
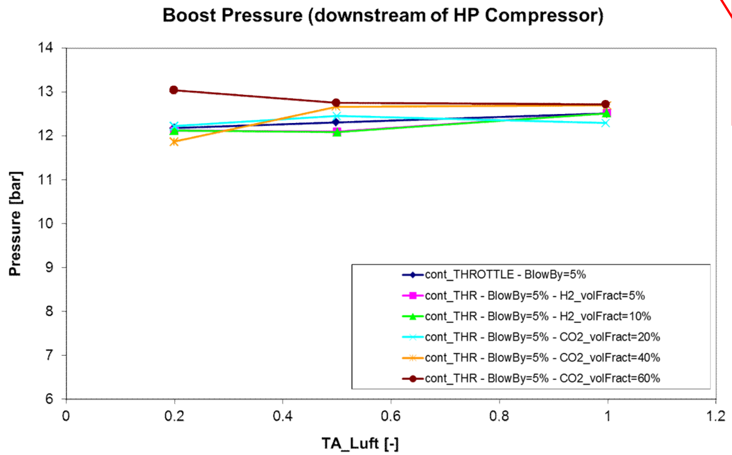
Results: max. BMEP, diff. fuel composition

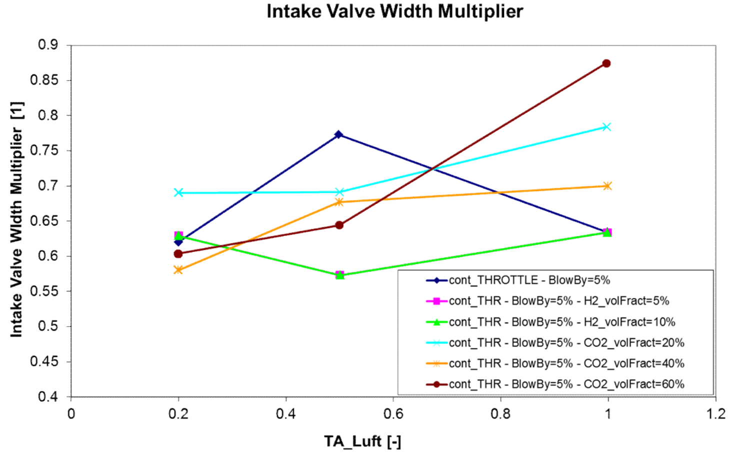


High content of CO_2 in the gaseous fuel enables to increase achievable BMEP due to its high thermal capacity of CO_2.





Due to very low density of hydrogen (H_2), its volumetric content has almost no effect on ICE performance.



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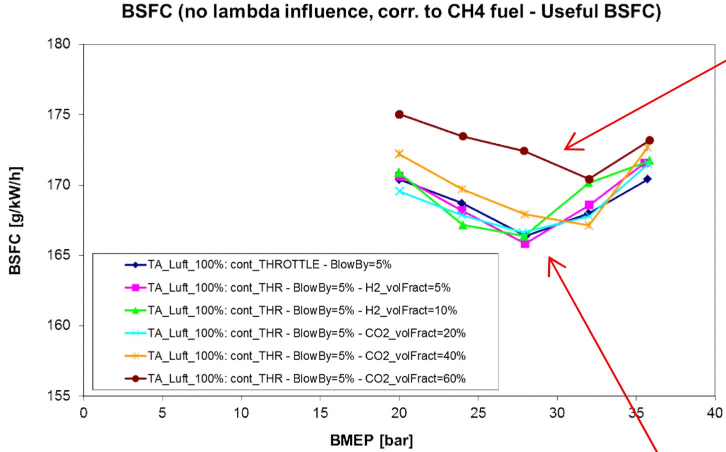
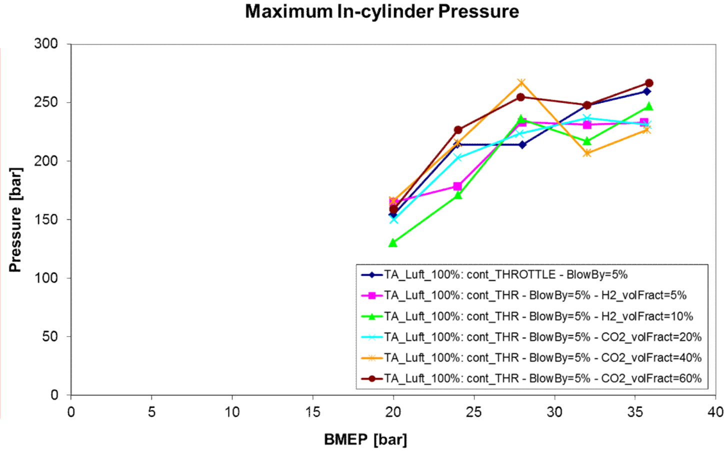
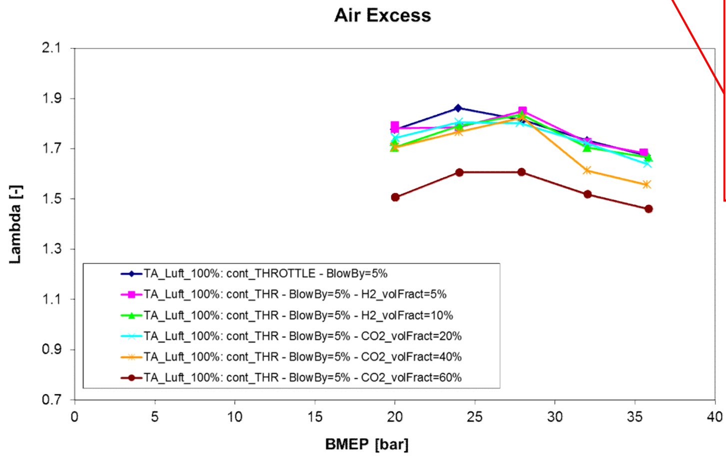
Results: min. BSFC at TA_Luft=100%, diff. fuel composition



High content of CO2 in the gaseous fuel leads to higher BSFC due to high thermal capacity of CO2 (negative effect when transforming chemical energy to internal one during combustion phase).





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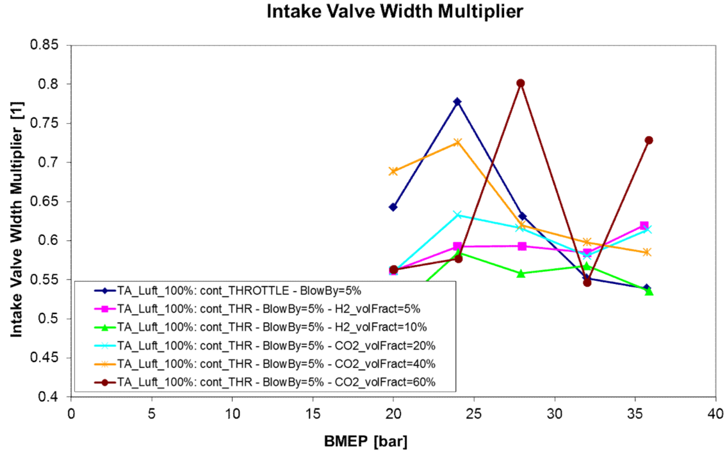

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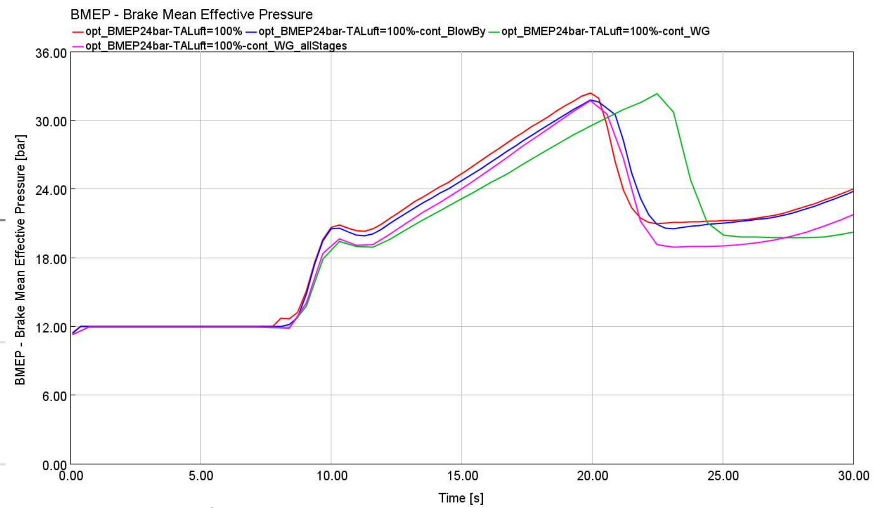
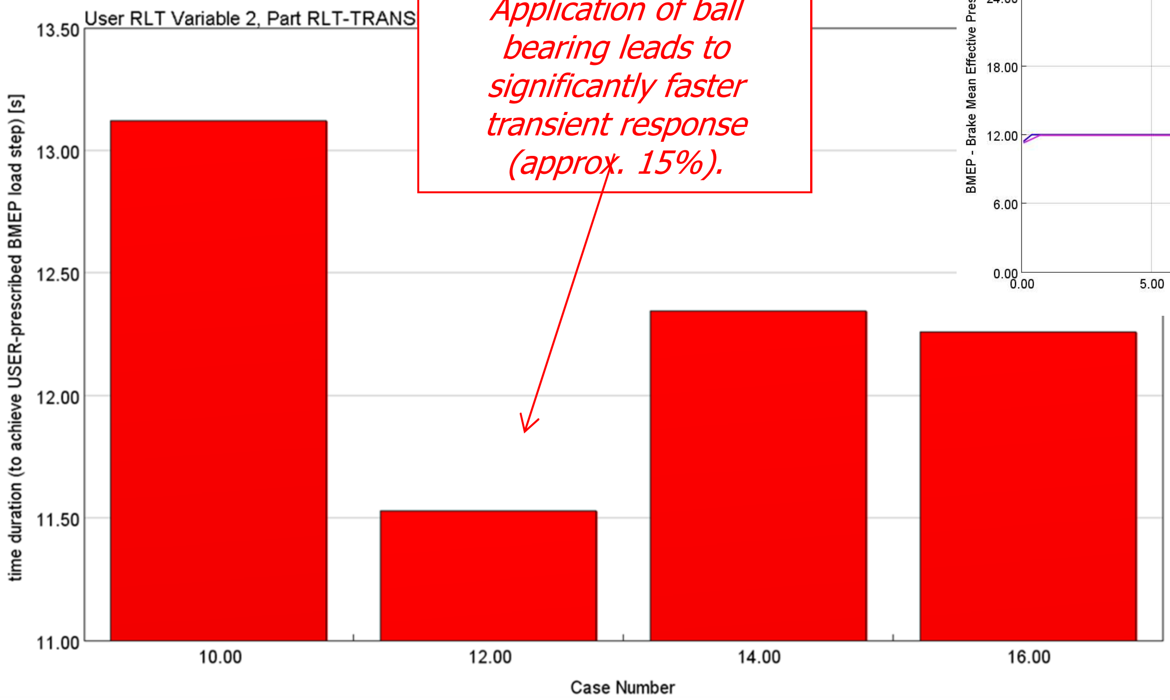
Results: transient response



Application of ball bearing leads to significantly faster transient response (approx. 15%).



The diagrams show transient response from 12bar of BMEP up to 32bar.

Sliding bearing: HP + LP	Ball bearing: HP + LP	Sliding bearing: HP Ball bearing: LP	Ball bearing: HP Sliding bearing: LP

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Conclusions:

- Future operating conditions of 2-stage turbocharged large-bore gas SI ICE were studied while using 0-D/1-D simulation model – different NOx levels, BMEP levels and fuel compositions were considered.
- As required boost pressure is usually very high, the influence of applied boost control is very small (in terms of BSFC).
- Increasing servicing intervals (i.e., requiring compressor blow-by level at 5%) introduces BSFC penalty of 2-5 g/kW/h.
- Millerezation level is relatively high, Atkinson cycle leads to high BSFC penalty.
- If maximum in-cylinder pressure is forced, it could lead to significant BSFC penalty at high BMEP or low NOx level.
- Engine performance drops significantly at high altitude levels. This gets even worse when high ambient temperature is considered. High BMEP or low NOx could not be achieved.

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Conclusions:

- When dealing with non-standard fuels (containing also H2 and/or CO2), it can significantly worsen engine efficiency (high CO2 content). As H2 density is very low, its influence is almost negligible within considered range.
- 2-stage boost group operates on its limit (very high boost pressure levels are needed) and usually causes increase of BSFC for high BMEP levels.
- Very low NOx level is achieved by means of strong Miller cycle, retarded combustion and relatively 'standard' air excess (below 2.0). The data suggest that no SCR (or any other after-treatment device) is needed.
- As BMEP is increased, stronger Miller and more retarded combustion timing is applied while air excess drops slightly (possible influence of 2-stage boost group operating on its limit).

- Only steady state operation was considered. Strong Miller cycle leads to very poor transient performance => intake VVT system (or switching intake cam profile) would be needed?

Current contribution of Contents of Work Package WP 06 R&D for High Efficiency Turbocharging

Thank you for you attention

This research has been realized using the support of Technological Agency, Czech Republic, programme National Competence Centres, project # TN01000026 Josef Bozek National Center of Competence for Surface Vehicles.

All the help has been gratefully appreciated.