UCC2 ICE optimization peak thermal efficiency towards 50 %

LONGRUN SCM

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Online

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FEV

The research leading to these results has received funding from the European Union under Grant Agreement no. 874972

Content

- Update roadmap
- Important UC results
- Outlook next 6 months

Update roadmap

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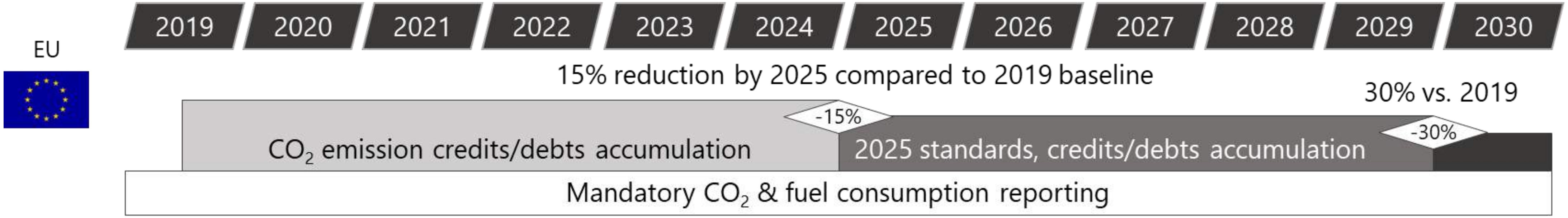
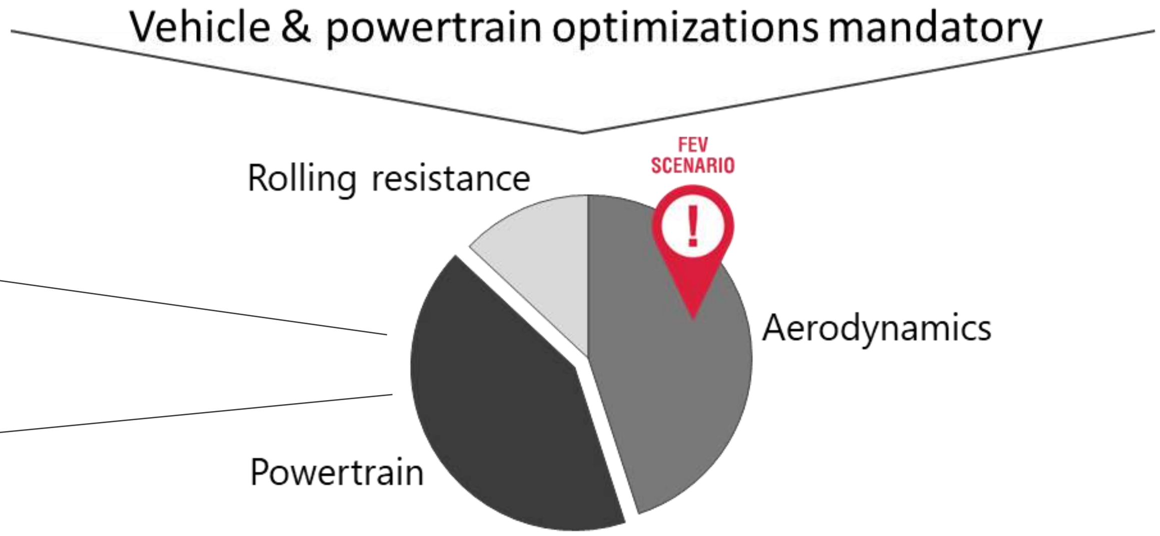
Political impact





- ICE identified as important contributor
  - Implementation of new technologies & further engine optimizations required

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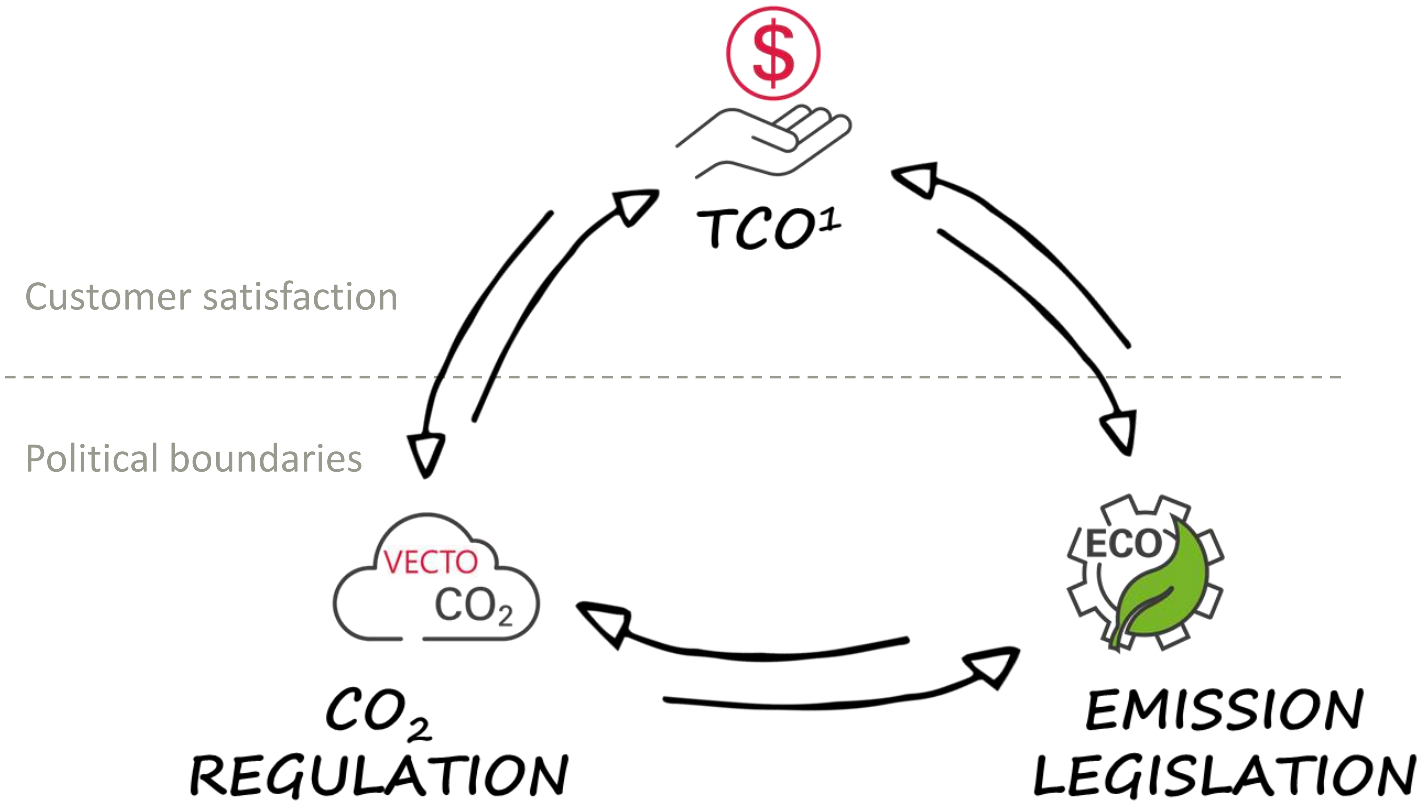
Engine development trade-off



TCO[1]: Total cost of ownership
RFNBO[2]: Renewable fuels of non-biological origins

Fact is

- CO_2 regulation foresees financial penalties in case of non-compliance
  - 2025: 4,250 € per gCO_2/tkm
  - 2030: 6,800 € per gCO_2/tkm

FEV analysis

- Engine-related efficiency improvements
  - Optimal “€ / % CO_2 reduction” trade-off
  - Other technologies like powertrain hybridization and waste heat recovery on other € / % CO_2 level
- TCO will remain key element
- Base engine measures can be utilized with all RFNBO[2] fuels

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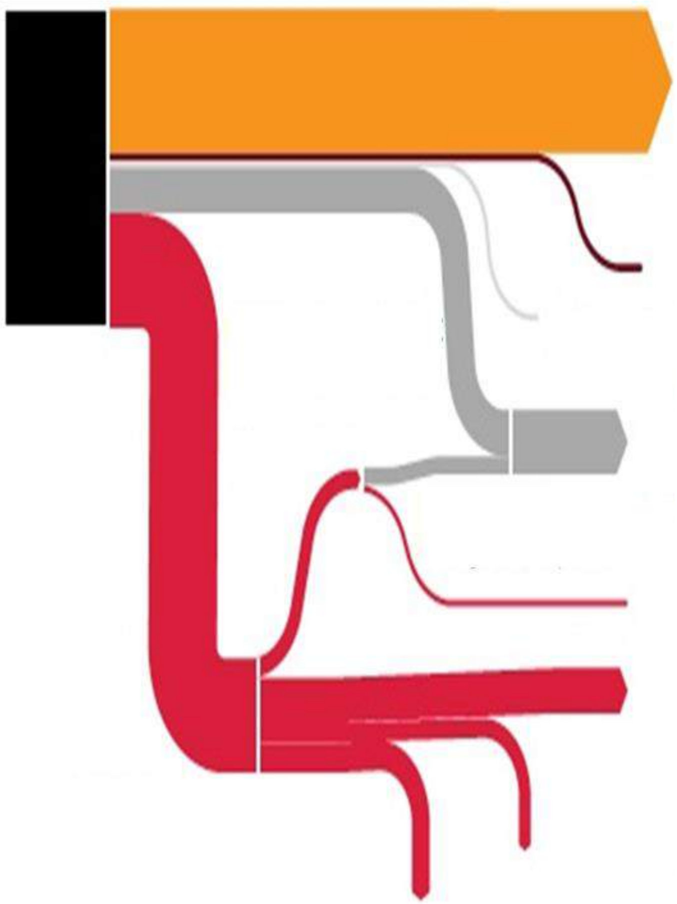
Energy flux and dissipation evaluation

» CASE EXAMPLE



Path	Fuel Energy Conversion / %
Brake Power	**46.0**
Friction Loss	2.5
Pumping Loss	0.8
Coolant	19.7
• Block	14.1
• EGR cooler	5.6
Exhaust Gas	36.6
• EGR piping	0.7
• Tailpipe	14.4
• EATS	6.3
• Turbocharger	9.6

FEV analysis

- State-of-the-art MY2018 HD engine
- Energy flux analysis of an averaged state-of-the-art heavy-duty EU VI-C with a BTE of 46.0 %
- In total, more than 50 % of fuel energy unused or wasted
    - High share through engine coolant & exhaust gas
    - Lower share for friction or gas exchange
- High energy dissipation of coolant (engine block & EGR) into environment via coolant heat exchanger

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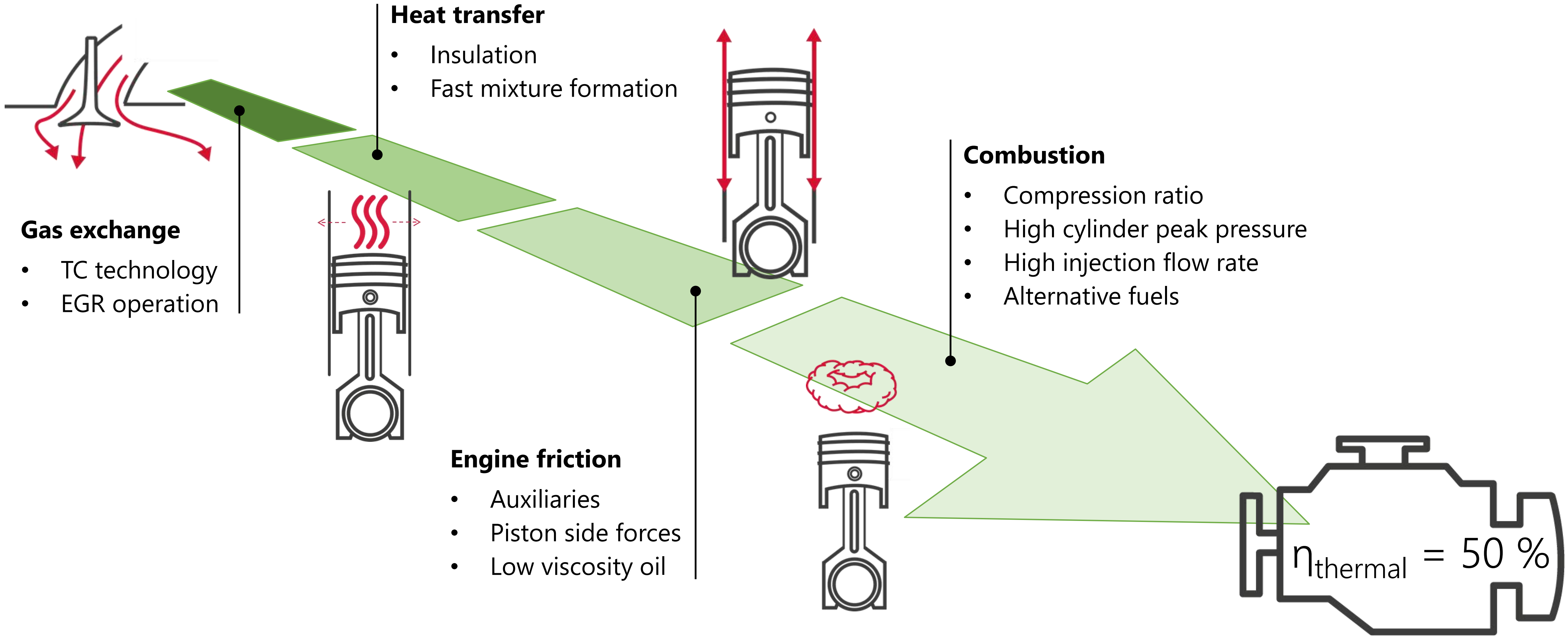
Identified pathways



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Objectives

	Engine upgrade	Combustion improvement, incl. heat transfer reduction	Mechanical improvement	Air handling	BTE Target
DAF development	1.0 %	1.3 %	0.7 %	1.0 %	50.0 %
VOLVO development		2.0 %	1.0 %	2.0 %	50.0 %
FPTi development		3.0 %	1.0 %	3.0 %	46.0 %
Coatings		0.5 %			0.5 %

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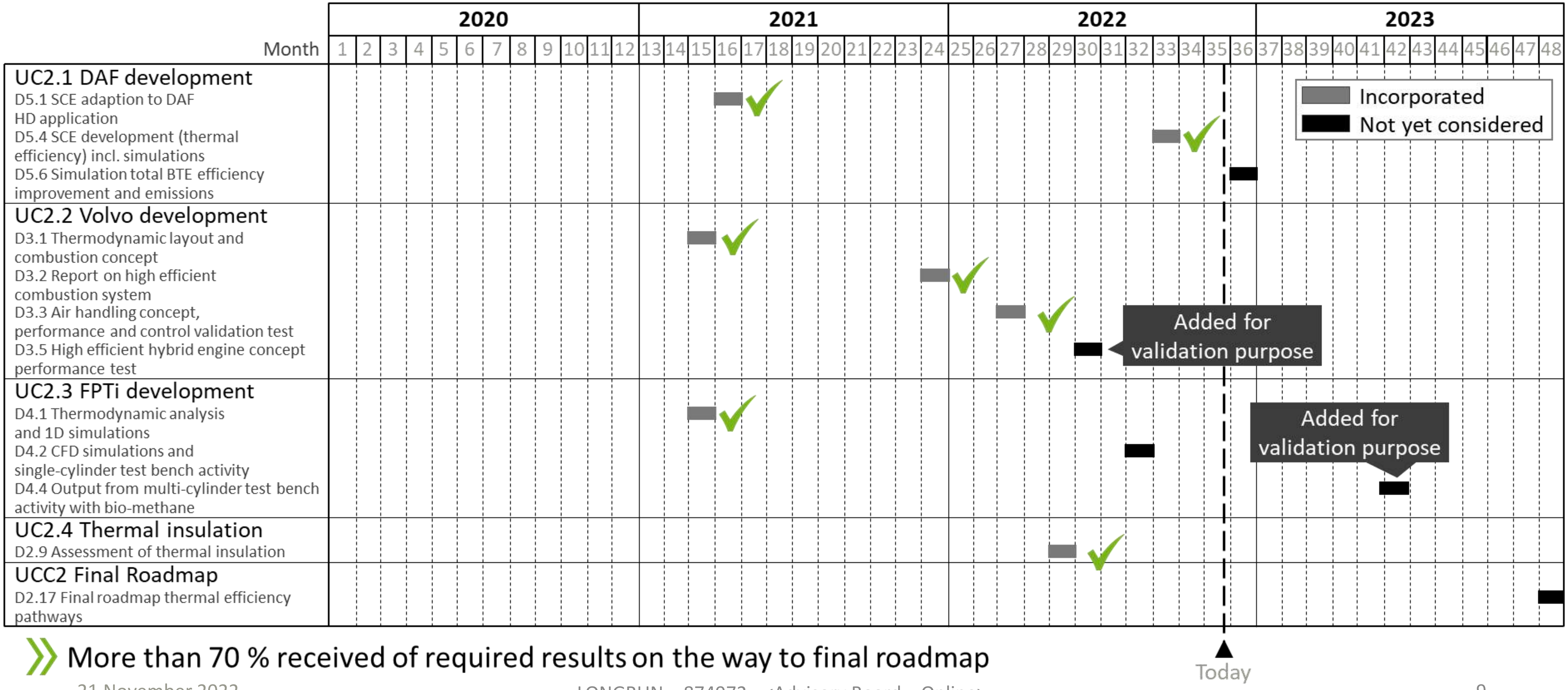
Status of deliverables input

» STATUS M34



» More than 70 % received of required results on the way to final roadmap

Important UC results

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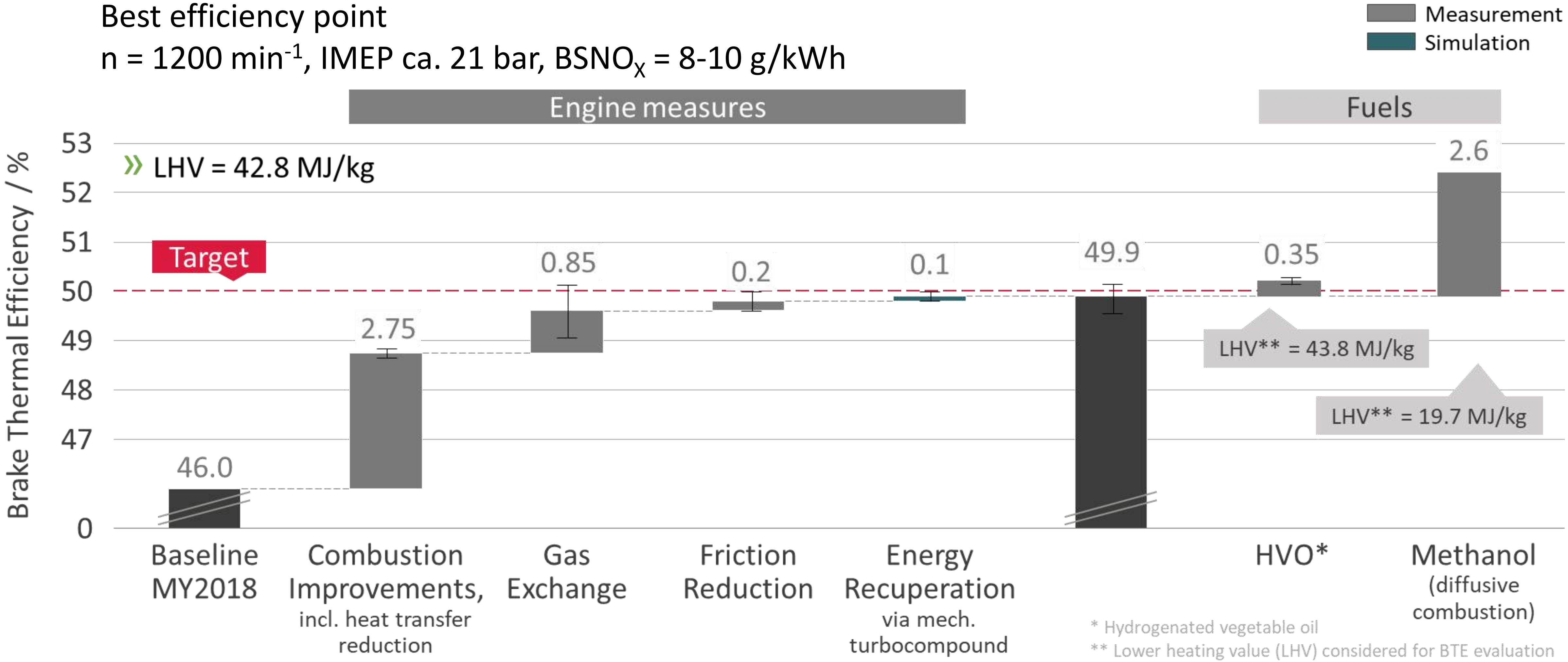
CI diesel ICE improvements Summary

» STATUS M34

Best efficiency point

n = 1200 min^{-1}, IMEP ca. 21 bar, $BSNO_X$ = 8-10 g/kWh



* Hydrogenated vegetable oil

** Lower heating value (LHV) considered for BTE evaluation

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CI – Combustion improvements Compression ration & peak cyl. pressure

» STATUS M34

DESCRIPTION

- Increased compression ratio (CR) enhances efficiency of thermodynamic combustion process as long as peak cylinder pressure (PCP) is not limited
- By limited PCP capability the higher peak cylinder pressure must be compensated by retarded beginning of injection
- Increased peak firing pressure helps to avoid fuel consumption penalties

ASSESSMENT

BTE impact	Around 1.8 %-point BTE improvements
Invest	Moderate invest expected
Maturity 2025-2030	Medium/high maturity level

Impact: low medium high

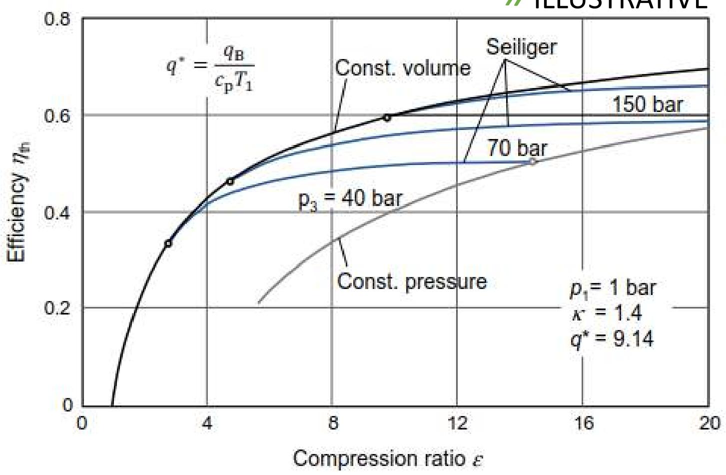
ADVANTAGES

- Increased compression ratio to increase efficiency

RISKS / CHALLENGES

- Higher thermal and mech. stress require more durable engine components
- Smaller piston bowl volume require adaption of injector tech. to keep good mixture formation
- Increased NO_X emissions have to be compensated with improved EATS

» ILLUSTRATIVE



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CI – Combustion improvements Fuel injection system

» STATUS M34

DESCRIPTION

- Modern HD diesel engines use common rail systems, systems with up to 2,700 bar pressure are state-of-the-art, whereas 3,000 bar is under development
- “Leakage free” injectors increase injection pressure with affecting fuel consumption positive
- Higher pressure breaks the trade-off between good air utilization at low engine speeds and high engine output power
- Strong benefits by high pressure only in combination with EGR

ADVANTAGES

- Reduced PM emission
- Enables further optimization of PM/NO_X trade off (only with applied EGR concept)
- Enables good mixture formation for high CR concepts

RISKS / CHALLENGES

- Lower reliability due to the increased stress caused by high pressure
- Increase of frictional losses
- Higher costs (improved injectors / components required)

ASSESSMENT

BTE impact	Around 0.5 %-point BTE improvements by better air utilization
Invest	Moderate invest expected
Maturity 2025-2030	Medium/high maturity level, ready for series production

Impact: low medium high

Source: Denso

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CI – Combustion improvements Alternative fuels – HVO

» STATUS M34

DESCRIPTION

- Hydrotreated Vegetable Oil (HVO) is a transparent paraffinic and a most-promising alternative to diesel fuel
- Feedstock and industrial processes availability
- Increased low heating value and more reactive ignitability enables > 2 % fuel economy benefit compared to diesel
- HVO is a drop-in capable fuel
  - Fulfills EN 15940 regulation and calibration changes not required

ADVANTAGES

- Drop-in capability
- Significant lower PM emission due to absent of aromatics
- Excellent ignitability also at cold start due to high Cetane number
- > 90 % WtW CO_2 reduction

RISKS / CHALLENGES

- Phase out of HVO made from high indirect land use change from 2022 due to EU RED II

ASSESSMENT

BTE impact	Max. 0.4 %-point BTE improvements by better combustion behavior
Invest	Low invest
Maturity 2025-2030	Already released for series application

Impact: low – medium – high

Source: Neste

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CI – Gas exchange Intake Miller

» STATUS M34

DESCRIPTION

- Miller cycle increases ratio between expansion and compression
- An increased geometric CR is compensated by reducing the effective CR at high load through early/late intake valve closing; a valve train with variable intake valve timing is required
- Potential power losses in part load can be balanced with increased boosting pressures

ADVANTAGES

- Potential to increase the compression ratio without increasing the peak firing pressure

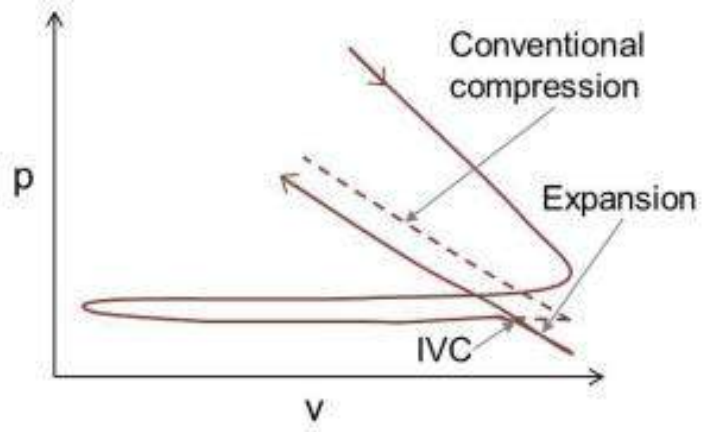
RISKS / CHALLENGES

- High degree of boosting required to compensate for less cylinder filling
- Lower NO_x reduction efficiency compared to EGR

ASSESSMENT

BTE impact	Around 0.3 %-point
Invest	Moderate invest expected
Maturity 2025-2030	High maturity level, series production

Impact: low … medium … high



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CI – Gas exchange Turbocharger efficiency

» STATUS M34

DESCRIPTION

- More efficient turbocharger enables lower engine back pressure and reduces work of gas exchange
- Reduced temperature downstream compressor for a given boost pressure level
- Less delta pressure over EGR route needs to be considered and requires recalibration

ASSESSMENT

BTE impact	Around 1.0 %-point BTE Improvement by reduction gas exchange and increased cylinder filling
Invest	Moderate to medium invest expected
Maturity 2025-2030	High maturity level

Impact: low medium high

ADVANTAGES

- Lower gas exchange losses increase engine efficiency and with better fuel economy
- Enables reduced PM tendency
- Potential to increase altitude margin

RISKS / CHALLENGES

- Reduced engine back pressure limits EGR availability
- If required, new manufacturing methods have to be established

Source: Daimler

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CI – Energy recuperation Turbocompound

» STATUS M34

DESCRIPTION

- Additional turbine downstream of the turbocharger
- The recovered waste heat energy gets reintroduced into the system via mechanical connection of turbine to the crankshaft
- Turbocompound can support downspeeding and/or downsizing by supplying additional mechanical power to the crankshaft
- In order to leverage full turbocompound potential an (more expensive) axial flow turbine is required

ADVANTAGES

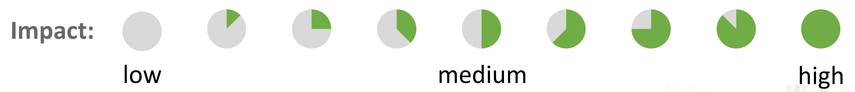
- Lower fuel consumption and therefore less CO_2 emissions
- Proven technology for CO_2 reduction (commercial vehicle applications)
- Increased back pressure can be used for higher EGR rates

RISKS / CHALLENGES

- Complex gear drive to adjust turbine to engine speed
- Potential fuel saving towards higher loads & higher back pressure
- Usage of waste-heat from EGR not possible

ASSESSMENT

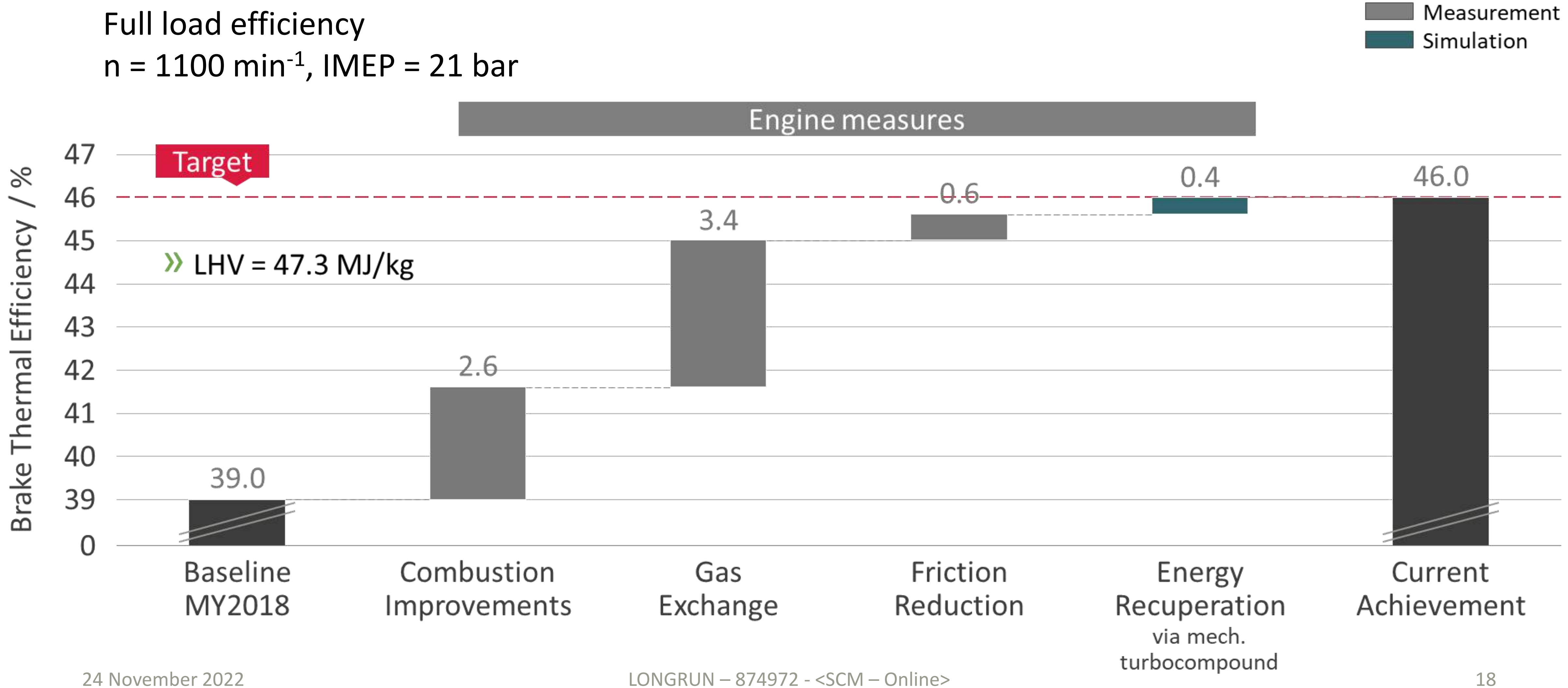
BTE impact	Around 0.1 %-point BTE improvement by waste energy utilization
Invest	Medium invest expected
Maturity 2025-2030	High maturity level, series production



Source: Volvo

SI natural gas ICE improvements Summary

» STATUS M34



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SI – Combustion improvements Application of high CR & EGR

» STATUS M34

DESCRIPTION

- Increased compression ratio enhances efficiency of thermodynamic combustion process as long as knock tendency is not present
- Application of EGR suppresses knock tendency without retarding spark timing at high engine loads
- In part load operation, EGR allows to de-throttle the engine operation

ADVANTAGES

- Increased compression ratio to increase efficiency
- Fuel consumption benefits due to de-throttling of the engine

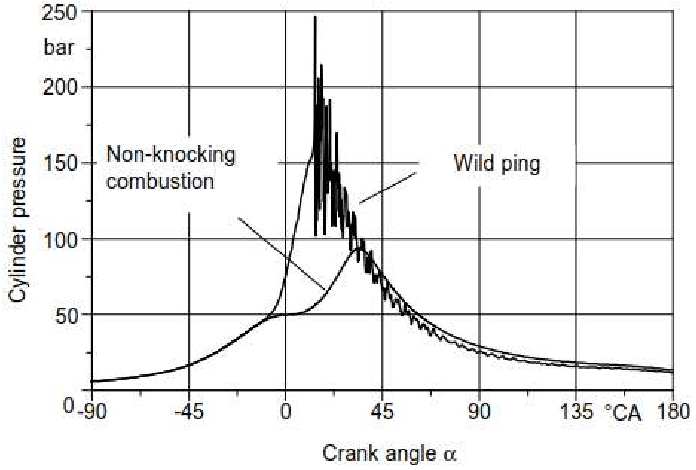
RISKS / CHALLENGES

- Increased combustion temperatures enhance knock tendency
- Components of EGR path have to be durable for high exhaust temperatures at full load
- Implementation of swirl charge motion

ASSESSMENT

BTE impact	Around 3.4 %-point BTE improvements
Invest	Moderate invest expected
Maturity 2025-2030	Medium/high maturity level

Impact: low medium high



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SI – Combustion improvements Charge motion: Swumble™

» STATUS M34

DESCRIPTION

- Increased compression ratio enhances efficiency of thermodynamic combustion process as long as knock tendency is not present
- Application of EGR suppresses knock tendency without retarding spark timing at high engine loads
- In part load operation, EGR allows to de-throttle the engine operation

ADVANTAGES

- Increased compression ratio to increase efficiency
- Fuel consumption benefits due to de-throttling of the engine

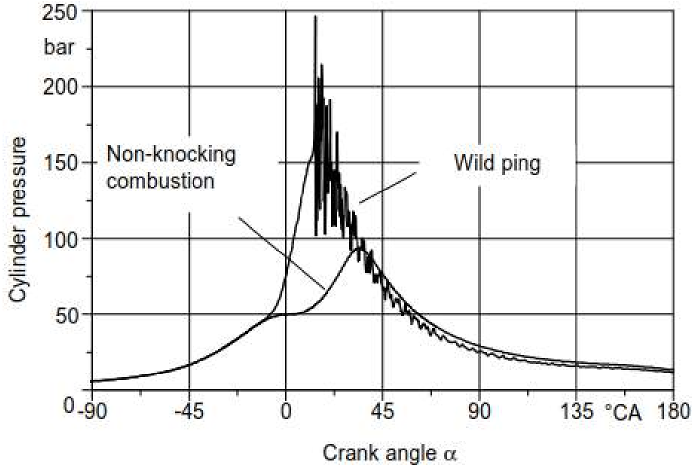
RISKS / CHALLENGES

- Increased combustion temperatures enhance knock tendency
- Components of EGR path have to be durable for high exhaust temperatures at full load
- Implementation of swirl charge motion

ASSESSMENT

BTE impact	Around 2.6 %-point BTE improvements
Invest	Moderate invest expected
Maturity 2025-2030	Medium/high maturity level

Impact: low … medium … high



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SI – Gas exchange Intake Miller

» STATUS M34

DESCRIPTION

- Miller cycle increases ratio between expansion and compression
- Miller reduced combustion knock tendency due to reduced temperature at the end of compression and of combustion process
- Late IVC supports swirl formation for EGR compatibility
- Potential cylinder filling losses in part load can be balanced with increased boosting pressures

ADVANTAGES

- Potential to increase the compression ratio without increasing combustion process temperature that lowers knock tendencies
- Increased EGR compatibility

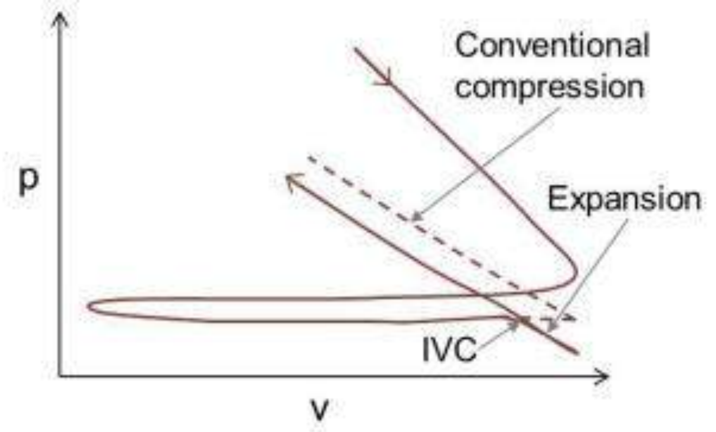
RISKS / CHALLENGES

- High degree of boosting required to compensate for less cylinder filling
- Lower NO_x reduction efficiency compared to EGR

ASSESSMENT

BTE impact	Around 0.8 %-point
Invest	Moderate invest expected
Maturity 2025-2030	High maturity level, series production

Impact: low medium high



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ADVANTAGES

- Lower gas exchange losses increase engine efficiency and with better fuel economy
- Potential to increase altitude margin

RISKS / CHALLENGES

- Reduced engine back pressure limits EGR availability
- If required, new manufacturing methods have to be established

ASSESSMENT

BTE impact		Around 0.3 %-point BTE Improvement by reduction gas exchange
Invest		Moderate to medium invest expected
Maturity 2025-2030		High maturity level,

Impact: low medium high

Source: Daimler

SI – Energy recuperation Turbocompound

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DESCRIPTION

- Additional turbine downstream of the turbocharger
- The recovered waste heat energy gets reintroduced into the system via mechanical connection of turbine to the crankshaft
- Turbocompound can support downspeeding and/or downsizing by supplying additional mechanical power to the crankshaft
- In order to leverage full turbocompound potential an (more expensive) axial flow turbine is required

ASSESSMENT

BTE impact	Around 0.4 %-point BTE improvement by waste energy utilization
Invest	Medium invest expected
Maturity 2025-2030	High maturity level, series production

Impact: low medium high

ADVANTAGES

- Lower fuel consumption and therefore less CO_2 emissions
- Proven technology for CO_2 reduction (commercial vehicle applications)
- Increased back pressure can be used for higher EGR rates

RISKS / CHALLENGES

- Complex gear drive to adjust turbine to engine speed
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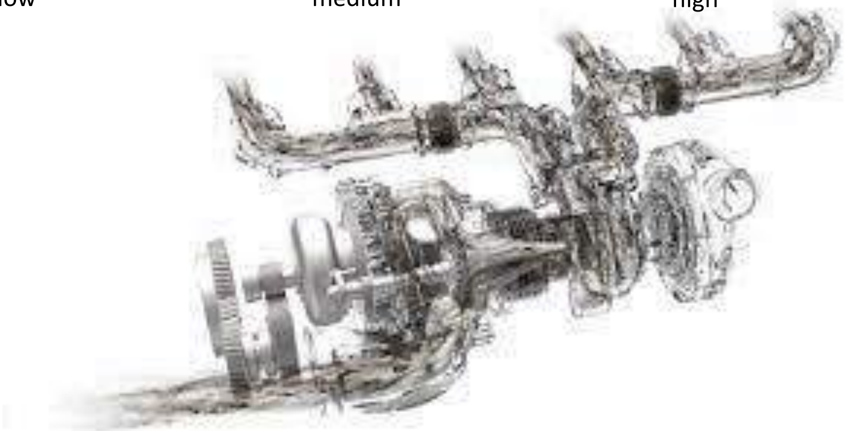
- Usage of waste-heat from EGR not possible



Source: Volvo

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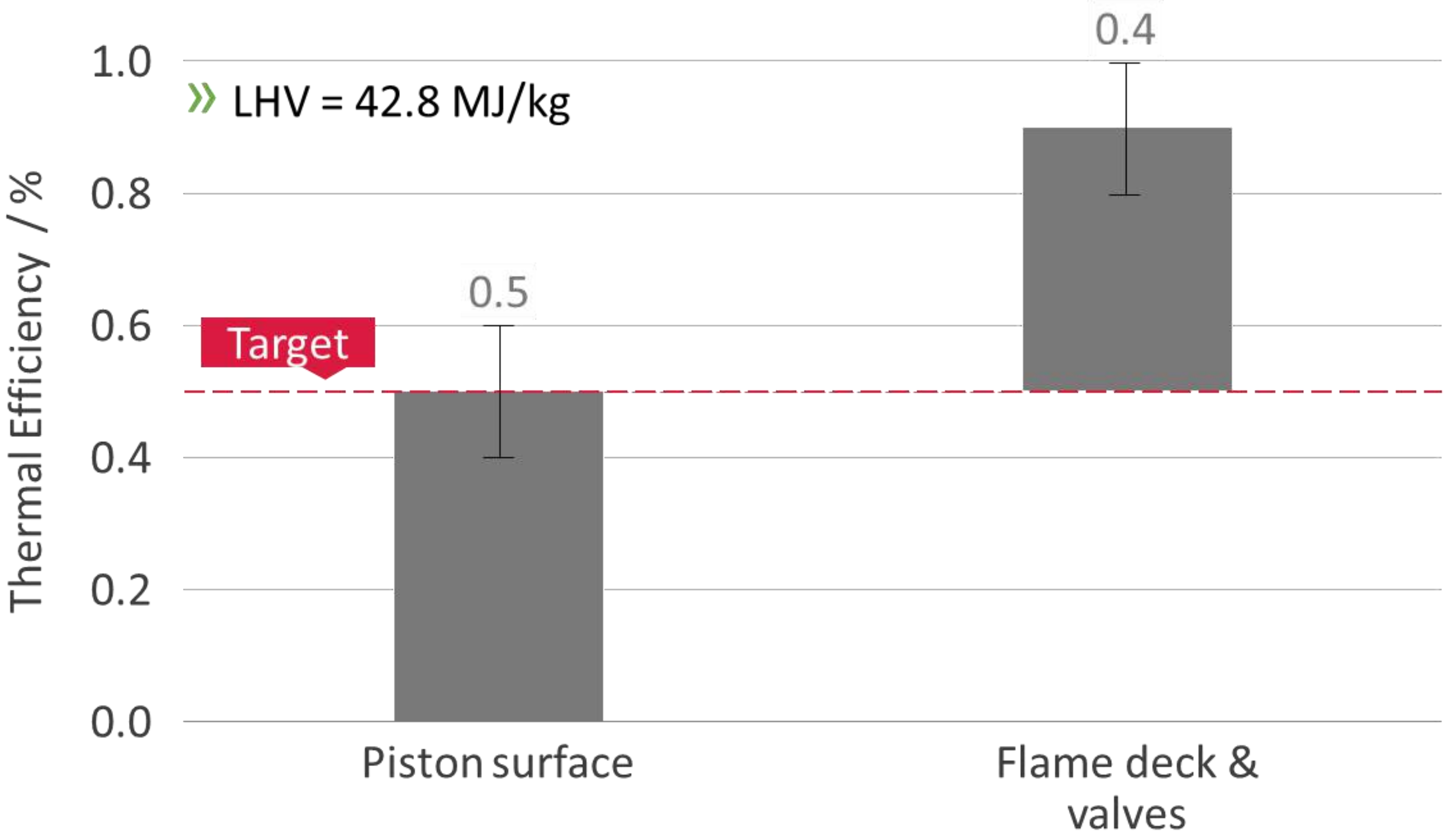
ICE improvements by coatings Summary

» STATUS M34

Best efficiency point

n = 1200 min^{-1}, IMEP ca. 21 bar, $BSNO_X$ = 8-10 g/kWh



UCC 2 | Surface coatings

» STATUS M34

DESCRIPTION

- Coating of advanced materials on metallic surfaces to insulate components from large and prolonged heat loads
  - Highly dynamic gas temperature behavior
    Utilization of thin coatings enabling thermal swing effect, e.g. combustion chamber
  - Inert gas temperature behavior
    Utilization of thicker coatings enabling thermal barrier, e.g. turbocharger, exhaust system
- A typical material used in automotive applications are plasma-applied ceramic coatings

ADVANTAGES

- Reduced thermal strain on components
- Higher thermal efficiencies due to reduced heat loss
- Less add-on parts due to reduced heat shielding need

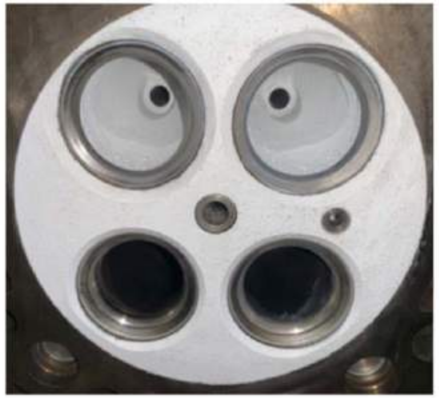
RISKS / CHALLENGES

- Increased costs
- Preparation of internal surfaces prior to coating
- Durability of coatings
- Higher temperatures in turbocharger cooling requirements for e.g. TC shaft bearings

ASSESSMENT

BTE impact	Around 0.9 %-point Improved thermal efficiency by reduction of wall heat transfer
Invest	Medium invest expected
Maturity 2025-2030	Medium maturity level expected

Impact: low — medium — high



Outlook

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Outlook – Next 6 months

Use case	Action
1 DAF development	• Multi cylinder engine • High efficiency eTurbo
2 Volvo development	• Initial multi cylinder engine investigations
3 FPTi development	• Initial analysis of SI pre-chamber technology on thermal efficiency • Initial analysis of energy recovery system e.g. eTurbo
4 Coatings	• Completed
5 Final roadmap	• Preparation of initial working document

Thank you

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