# Challenges and opportunities for stage V NRMM

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Aftertreatment System for Diesel Engines

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- Stage V legislation
- Technology road map for Stage V
- Ricardo clean combustion system
- Conclusion

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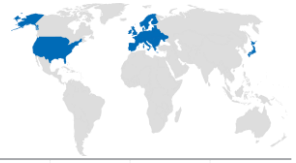
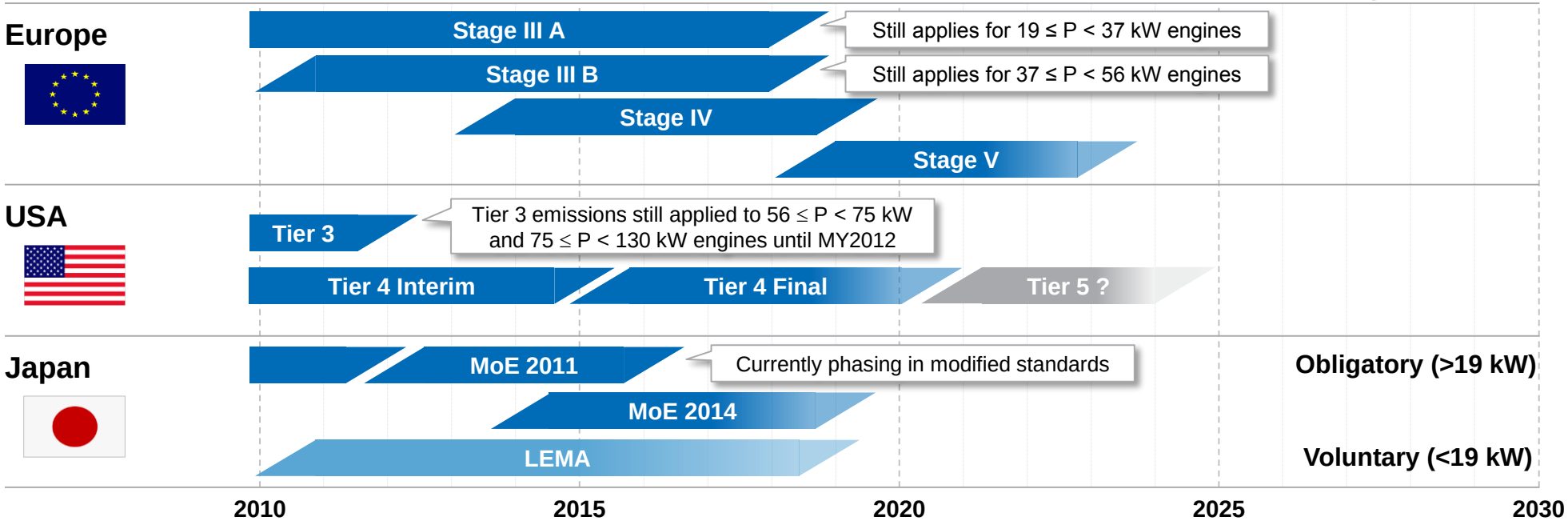
# Off-highway emissions legislation overview



## Emissions Legislation Roadmap




- Stage V regulations announced in Europe from 2018
- No emissions standard beyond Tier 4 Final has been anticipated yet in the US
- Japan has a self-regulating, voluntary emissions legislation <19 kW but an obligatory legislation >19 kW which roughly aligns with the EU and USA current emissions limits

Source: Ricardo EMLEG

# Stage V emission regulation

## Europe – Current and Proposed Future Emission Limits

**19 ≤ P < 560 kW**

| Emission Regulation | Implementation Year | Power Range [kW] | CO [g/kWh] | HC [g/kWh] | NOx [g/kWh] | NOx + HC [g/kWh] | PM [g/kWh] | PN [#/kWh] | Off-cycle / In use compliance |
|---|---|---|---|---|---|---|---|---|---|
| **Stage IV** | >2013 | **130 ≤ P < 560** | 3.5 | 0.19 | 0.4 | - | 0.025 | - | NTE |
| **Stage IV** | >2013 | **56 ≤ P < 130** | 5.0 | 0.19 | 0.4 | - | 0.025 | - | NTE |
| **Stage IIIA/B** | >2012 | **37 ≤ P < 56** | 5.0 | - | - | 4.7 | 0.025 | - | - |
| **Stage V** | >2018 | **130 ≤ P < 560** | 3.5 | 0.19 | 0.4 | - | 0.015 | $1x10^{12}$ | NTE/PEMS |
| **Stage V** | >2019 | **56 ≤ P < 130** | 5.0 | 0.19 | 0.4 | - | 0.015 | $1x10^{12}$ | NTE/PEMS |
| **Stage V** | >2018 | **19 ≤ P < 56** | 5.0 | - | - | 4.7 | 0.015 | $1x10^{12}$ | NTE/PEMS |

- Stage V new emission limits and test requirement:
  - PM limits have been reduced from 0.025 to 0.015 g/kWh in the power range 19 to 560 kW
  - Particle Number limits is introduced to mandate the DPF usage
  - PEMS test is introduced

Source: Ricardo EMLEG

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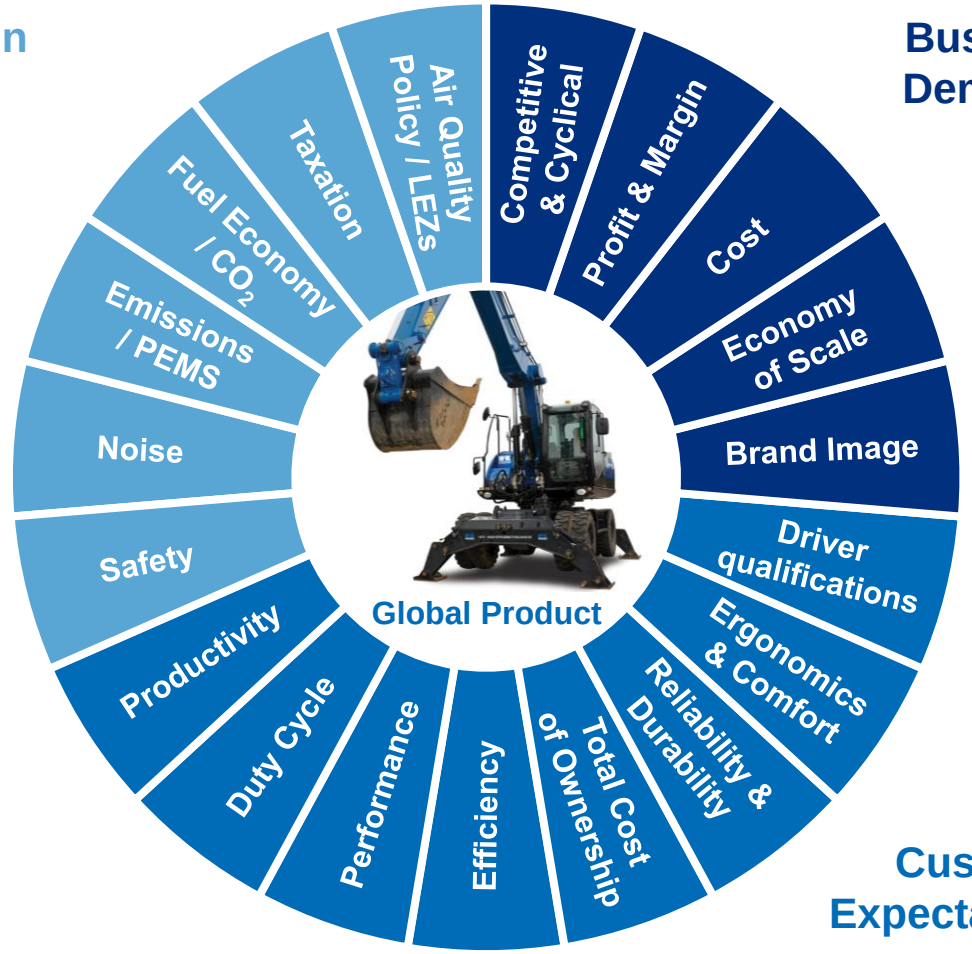
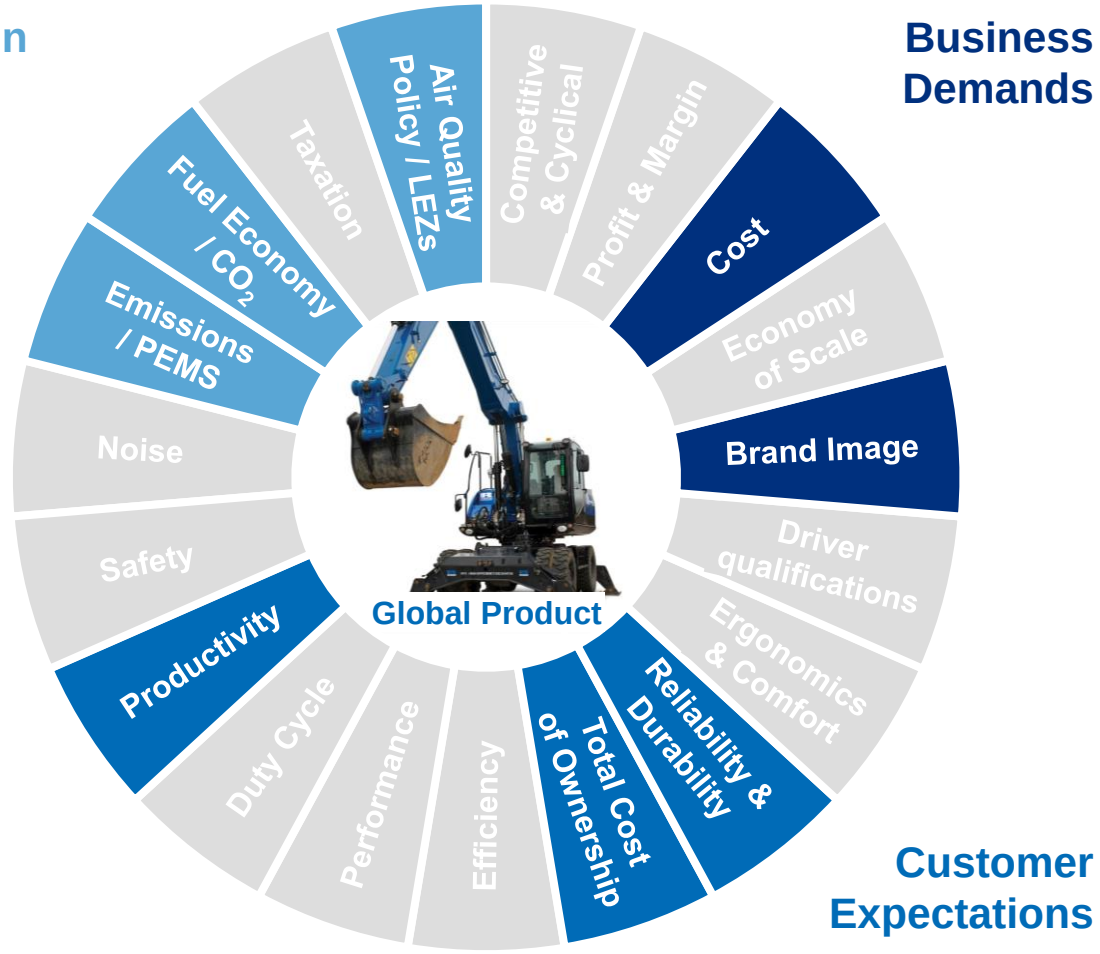
# Legislation is one of the market drivers, those are around legislation and policy, business demands and customer expectations all influence future product solutions

## Market Drivers



# Solutions for the Stage V emission legislation need to consider the implications on product cost, reliability, total cost of ownership, productivity, brand image to mention few of the more important drivers

## Market Drivers



# Typical Stage IV Solutions for 56-560 kW engines
# SCR is commonly adopted and the state of art engines do not use DPF and DOC

**56-560 kW**

**A**

**Low Soot**
Combustion System
**No EGR**
**No DPF**
**SCR η ≥ 96%**

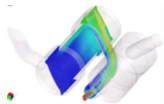
**Low Soot Combustion System**

**Common Rail (<1800 bar)**

**WGT**

**EGR**

**DOC** (optional)



**SCR + ASC (η ≥ 96%)**

**SCR Thermal Management**

**B**

**Low Soot**
Combustion System
**10-20% EGR**
**No DPF**
**SCR η ≥ 94%**

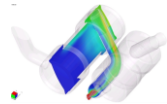
**Low Soot Combustion System**

**Common Rail (1800-2000 bar)**

**WG-VGT**

**Cooled EGR (10-20% EGR rate)**

**DOC** (optional)



**SCR + ASC (η ≥ 94%)**

**C**

**Traditional**
Combustion System
**> 20% EGR**
**DPF**
**SCR η ≥ 92%**

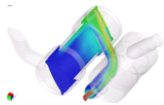
**Traditional Combustion System**

**Common Rail (>2000 bar)**

**VGT**

**Cooled EGR (>20% EGR rate)**

**DOC + active DPF**



**SCR + ASC (η ≥ 92%)**

- The three Technology Options presented above represent the majority of Stage IV 56-560 kW diesel engines available today
- Other variations and combinations of these three options are also available, such as Option A or B without DOC for engines with very good oil control (Engine Out oil derived HC on PM <5mg/kWh)
- Low soot combustion means: 6 to 9 mg/kWh Engine Out soot on cycle

# Potential Stage V Solutions for 56-560 kW engines
## A DPF is included in the technology package to meet the PM and PN limit

**56-560 kW**

**A**

**Low Soot**
Combustion System
**No EGR**
**DPF**
**SCR η ≥ 96%**

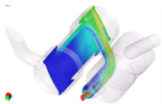
**Low Soot Combustion System**

**Common Rail (<1800 bar)**

**WGT**

**EGR**

**DOC + passive DPF**



**SCR + ASC (η ≥ 96%)**

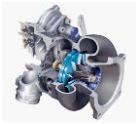
**Thermal Management**

**B**

**Low Soot**
Combustion System
**10-20% EGR**
**DPF**
**SCR η ≥ 94%**

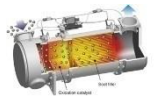
**Low Soot Combustion System**

**Common Rail (1800-2000 bar)**

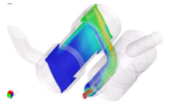


**WG-VGT**

**Cooled EGR (10-20% EGR rate)**



**DOC + passive DPF**



**SCR + ASC (η ≥ 94%)**

**Thermal Management**

**C**

**Traditional**
Combustion System
**> 20% EGR**
**DPF**
**SCR η ≥ 92%**

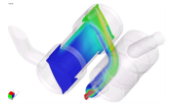
**Traditional Combustion System**

**Common Rail (>2000 bar)**

**VGT**

**Cooled EGR (>20% EGR rate)**

**DOC + active DPF**

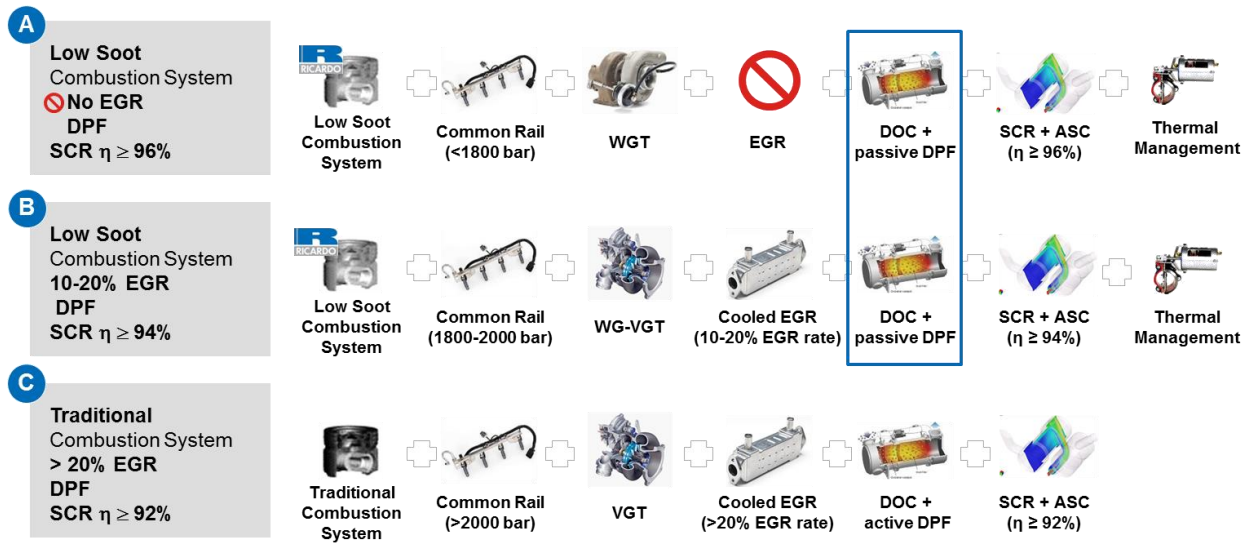


**SCR + ASC (η ≥ 92%)**

- Both Option A and Option B require the addition of a **passive DPF**
- SCR and DPF **thermal management** is required on option A and B
- A common variation for Option A and B will be to replace the DPF + SCR with **SCRF**
- **Low soot combustion** means: 6 to 9 mg/kWh soot on cycle

# Potential Stage V Solutions for 56-560 kW engines
## Systems comparison

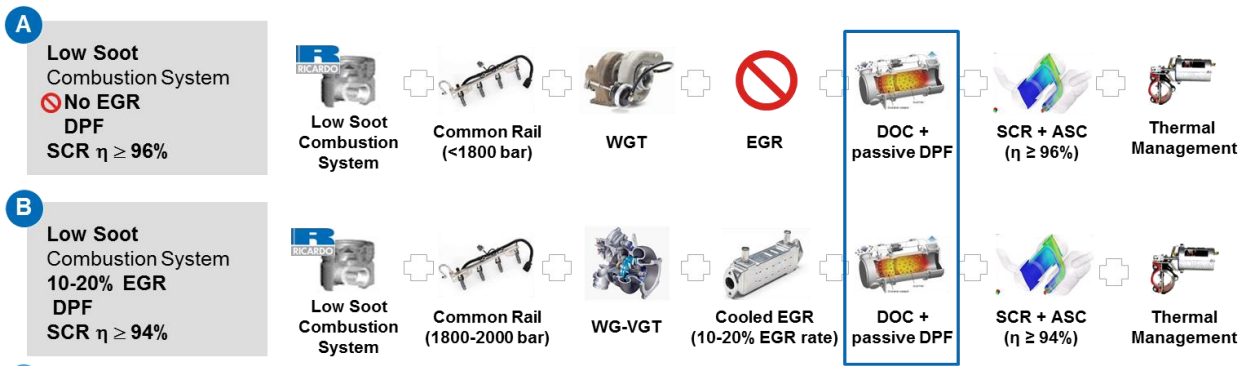
| *technology* | Low soot combustion, No EGR, High Eff SCR | Low soot combustion, low EGR, High Eff SCR | Conventional combustion, high EGR, High Eff SCR |
|---|---|---|---|
| EGR | | | |
| SCR or SCRF | | | |
| DPF regeneration type | | | |
| BSFC | | | |
| AdBlue consumption | | | |
| Total cost of fluid | | | |
| Development effort | | | |
| First cost | | | |
| Total cost ownership | | | |
| Turbo tech. demand | | | |
| Vehicle cooling | | | |
| Thermal mgnt effort | | | |
| Reliability | | | |
| Packaging | | | |



# Potential Stage V Solutions for 56-560 kW engines
## Systems comparison

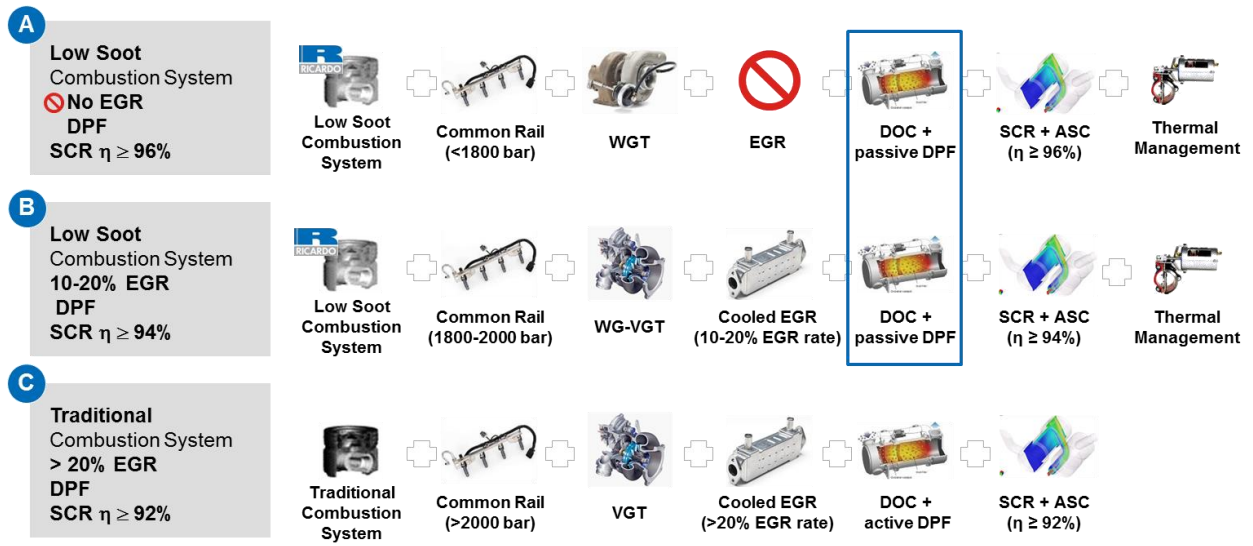
| *technology* | Low soot combustion, No EGR, High Eff SCR | Low soot combustion, low EGR, High Eff SCR | Conventional combustion, high EGR, High Eff SCR |
|---|---|---|---|
| EGR | no | ≤ 20% | |
| SCR or SCRF | eff ≥ 96% | eff ≥ 94% | |
| DPF regeneration type | passive | passive | |
| BSFC | | | |
| AdBlue consumption | | | |
| Total cost of fluid | | | |
| Development effort | | | |
| First cost | | | |
| Total cost ownership | | | |
| Turbo tech. demand | | | |
| Vehicle cooling | | | |
| Thermal mgnt effort | | | |
| Reliability | | | |
| Packaging | | | |




- Clan low soot combustion systems - Option A and B - use a smaller and **passive DPF** with better total cost of fluid and lower product cost
  - **SCRF** can be used thanks to the high NOx/Soot ratio and the mainly passive regeneration with reduced risk of thermal deactivation
- SCR (and DPF) **thermal management** using intake or exhaust flap is required on option A and B with some fuel consumption penalty
- No EGR solution allow the lower **base engine cost**

# Potential Stage V Solutions for 56-560 kW engines
## Systems comparison

| *technology* | Low soot combustion, No EGR, High Eff SCR | Low soot combustion, low EGR, High Eff SCR | Conventional combustion, high EGR, High Eff SCR |
|---|---|---|---|
| EGR | no | ≤ 20% | > 20% |
| SCR or SCRF | eff ≥ 96% | eff ≥ 94% | eff ≥ 92% |
| DPF regeneration type | passive | passive | active |
| BSFC | | | |
| AdBlue consumption | | | |
| Total cost of fluid | | | |
| Development effort | | | |
| First cost | | | |
| Total cost ownership | | | |
| Turbo tech. demand | | | |
| Vehicle cooling | | | |
| Thermal mgnt effort | | | |
| Reliability | | | |
| Packaging | | | |

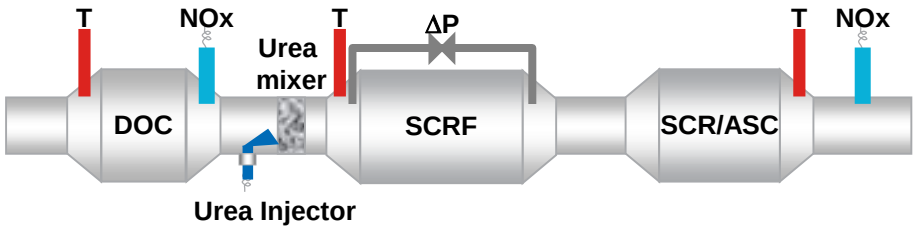



- Clan low soot combustion systems - Option A and B - use a smaller and **passive DPF** with better total cost of fluid and lower product cost
  - **SCRF** can be used thanks to the high NOx/Soot ratio and the mainly passive regeneration with reduced risk of thermal deactivation
- SCR (and DPF) **thermal management** using intake or exhaust flap is required on option A and B with some fuel consumption penalty
- No EGR solution allow the lower **base engine cost**
- Conventional combustion system is not recommended: high engine out soot require active DPF with impact on fuel consumption, reliability, higher turbocharger cost, vehicle cooling

# SCRF aftertreatment is an option for high NOx and low soot engine out engines

## Comparison of aftertreatment options for Stage V 56-560 kW engines

### DOC + SCRF



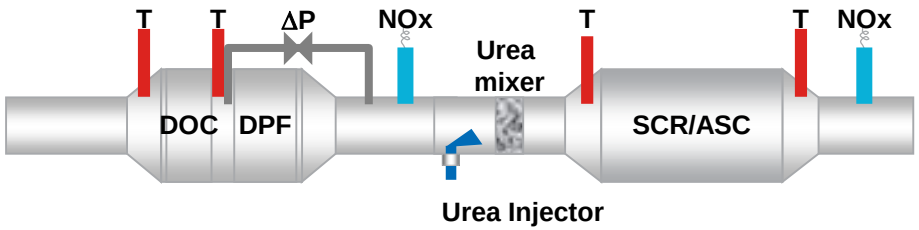

**Pros**

- Fast light off for SCR
- Low and mid temperature NOx control
- Packaging
- Cost

**Cons**

- $NO_2$ competing reactions with $NH_3$ and carbon
- Control challenge for multiple SCR bricks
- Dedicated ASC brick if second SCR not required
- Ash impact/service interval
- Not suitable for high soot emitting engines

### DOC + DPF + SCR

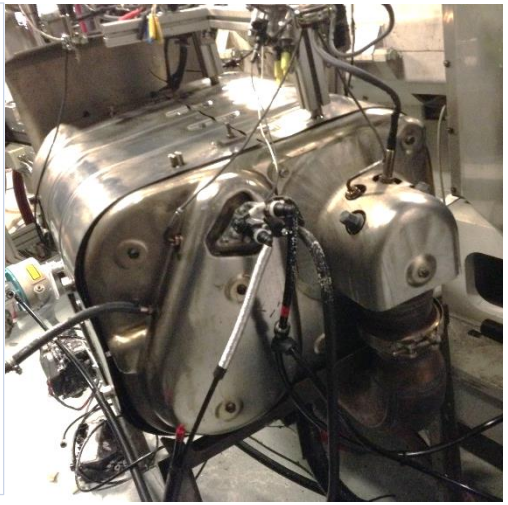



**Pros**

- Enhanced passive soot oxidation
- ASC coated on back of SCR brick

**Cons**

- Low temperature / real world NOx control challenge
- Packaging



# Typical Stage III B Solutions for 37-56 kW engines
# SCR is not required and the state of art engines do not use a DPF


**a**

**Low Soot**
Combustion System
**<15% EGR**
**No DPF**


**b**

**Traditional**
Combustion System
**15-20% EGR**
**DPF**


**c**

**Traditional**
Combustion System
**No EGR**
**DPF**


- The three Technology Options presented above represent the majority of Stage III B 37-56 kW diesel engines available today
- Other variations and combinations of these three options are also available.
- A few basic engines in this power category still have mechanical FIE with alone DPF systems

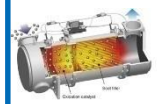
# Potential Stage V Solutions for 37-56 kW engines
# All Stage V solutions are expected to have a DPF


**a**

**Low Soot**
Combustion System
**<15% EGR**
**DPF**







**b**

**Traditional**
Combustion System
**15-20% EGR**
**DPF**





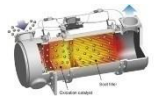


**c**

**Traditional**
Combustion System
**No EGR**
**DPF**






- For Stage V Option (a) will require the addition of a passive DPF
- Options (b) and (c) are likely to remain unchanged, unless the DPF needs to be upgraded to achieve the PN limits or to improve fuel consumption and machine reliability

# Potential Stage V Solutions for 37-56 kW engines
## Systems comparison

| *technology* | Low soot combustion, low EGR | Conventional combustion, high EGR | No EGR |
|---|---|---|---|
| EGR | | | |
| SCR or SCRF | | | |
| DPF regeneration type | | | |
| BSFC | | | |
| Development effort | | | |
| first cost | | | |
| Total cost ownership | | | |
| Turbo tech. demand | | | |
| Vehicle cooling | | | |
| Thermal mgnt effort | | | |
| Reliability | | | |
| Packaging | | | |

**a** **Low Soot** Combustion System **<15% EGR** **DPF**


**b** **Traditional** Combustion System **15-20% EGR** **DPF**


**c** **Traditional** Combustion System **No EGR** **DPF**

# Potential Stage V Solutions for 37-56 kW engines
## Systems comparison

| *technology* | Low soot combustion, low EGR | Conventional combustion, high EGR | No EGR |
|---|---|---|---|
| EGR | up to 20% | > 20% | |
| SCR or SCRF | no | no | |
| DPF regeneration type | passive | active | |
| BSFC | | | |
| Development effort | | | |
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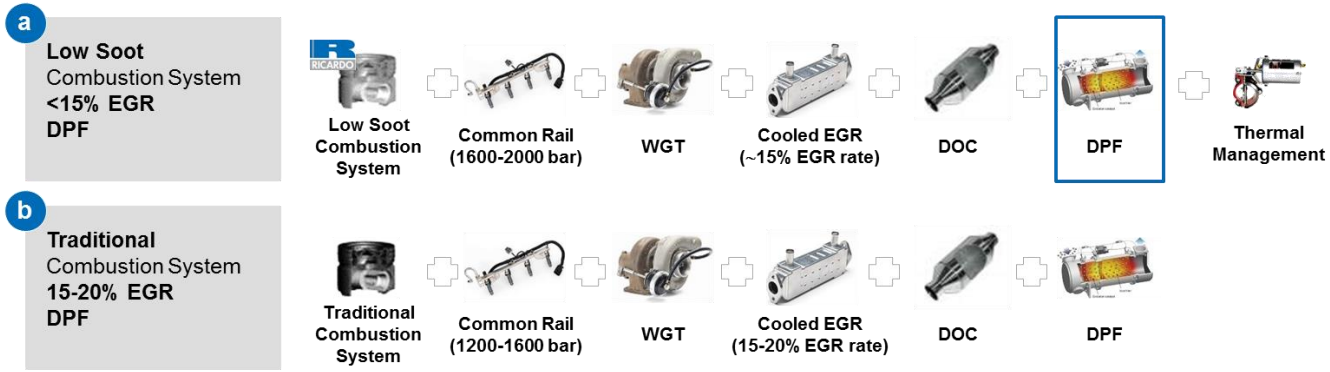


- Low soot combustion system allow a smaller **passive DPF** with benefit on
  - Fuel consumption
  - Machine reliability
  - Development cost

# Potential Stage V Solutions for 37-56 kW engines
## Systems comparison

| *technology* | Low soot combustion, low EGR | Conventional combustion, high EGR | No EGR |
|---|---|---|---|
| EGR | up to 20% | > 20% | no |
| SCR or SCRF | no | no | no |
| DPF regeneration type | passive | active | active |
| BSFC | | | |
| Development effort | | | |
| first cost | | | |
| Total cost ownership | | | |
| Turbo tech. demand | | | |
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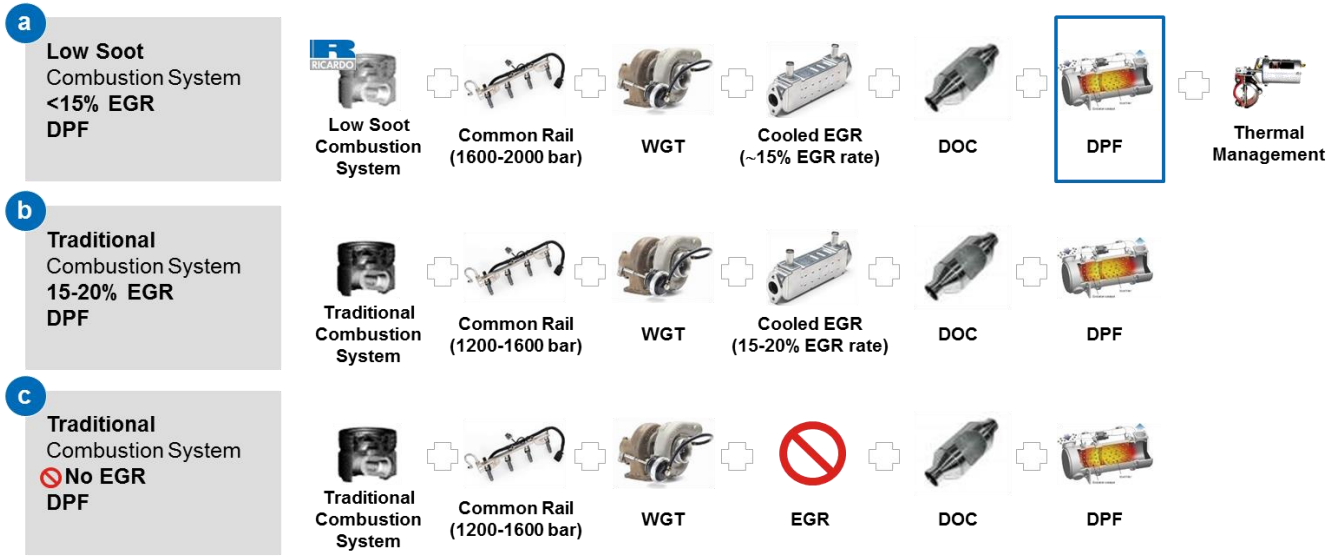
| Thermal mgnt effort | | | |
| Reliability | | | |
| Packaging | | | |




- Low soot combustion system allow a smaller **passive DPF** with benefit on
  - Fuel consumption
  - Machine reliability
  - Development cost
- A no EGR solution is possible with highly retarded timing and impact on fuel consumption and possible machine reliability

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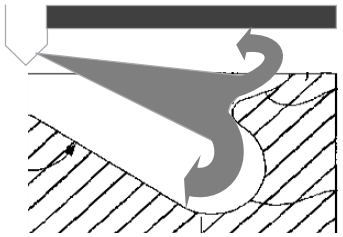
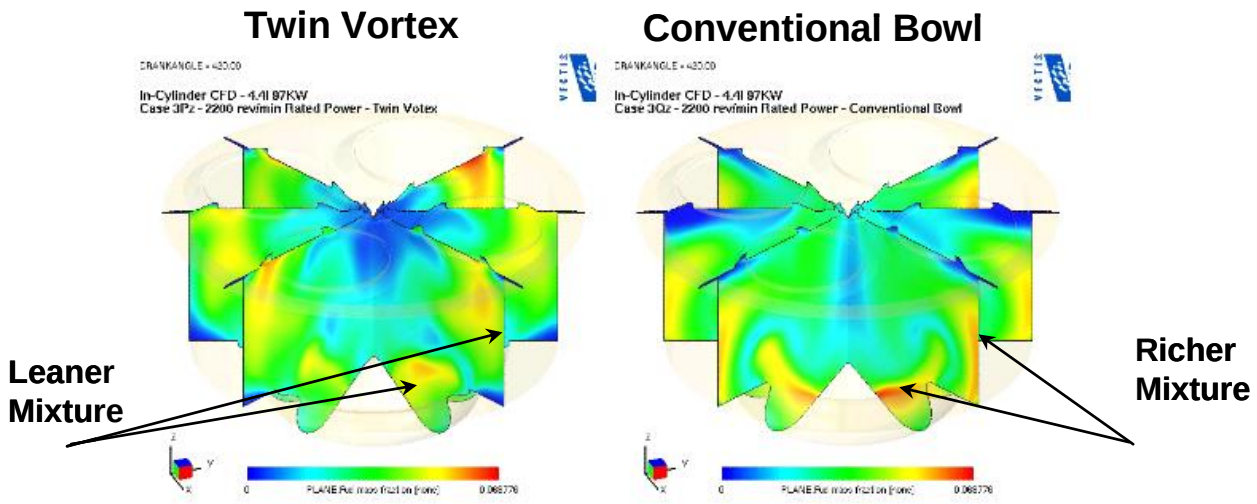
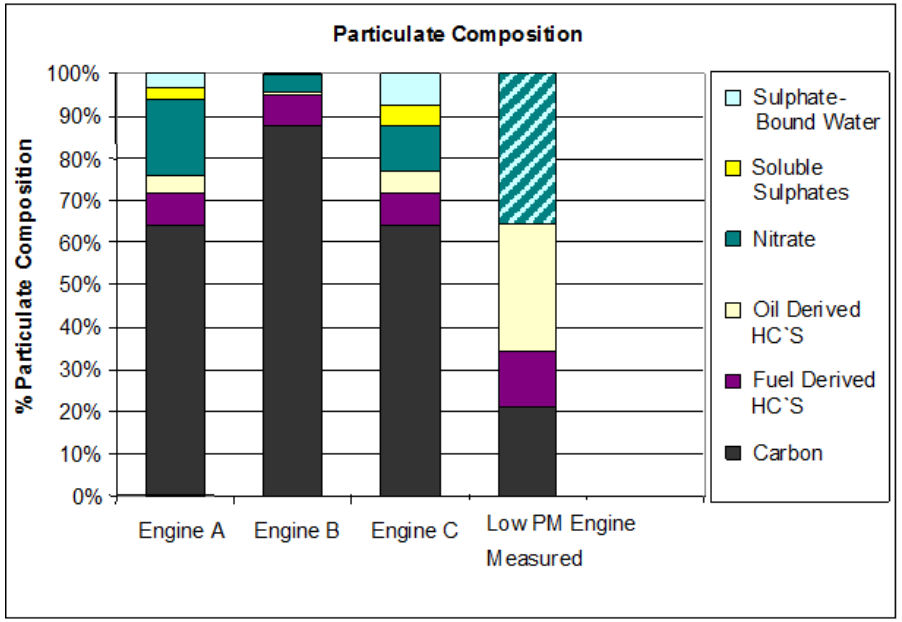
# Clean and Efficient Combustion
# Ricardo Twin Vortex Combustion System (TVCS)

TVCS is a low soot combustion system patented by Ricardo
It is a special combination of combustion bowl, air and fuel motion to manage the air/fuel mixture into a more homogeneous distribution with lower soot:



- Split of the fuel spray with generation of two vortices
  - → Better mixing vs. conventional bowl
  - → No risk of overspray
- Faster decay of rich mixture & quicker soot oxidation process.



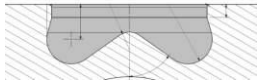



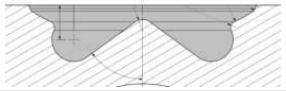
# Clean and Efficient Combustion
# PM and BSFC trends

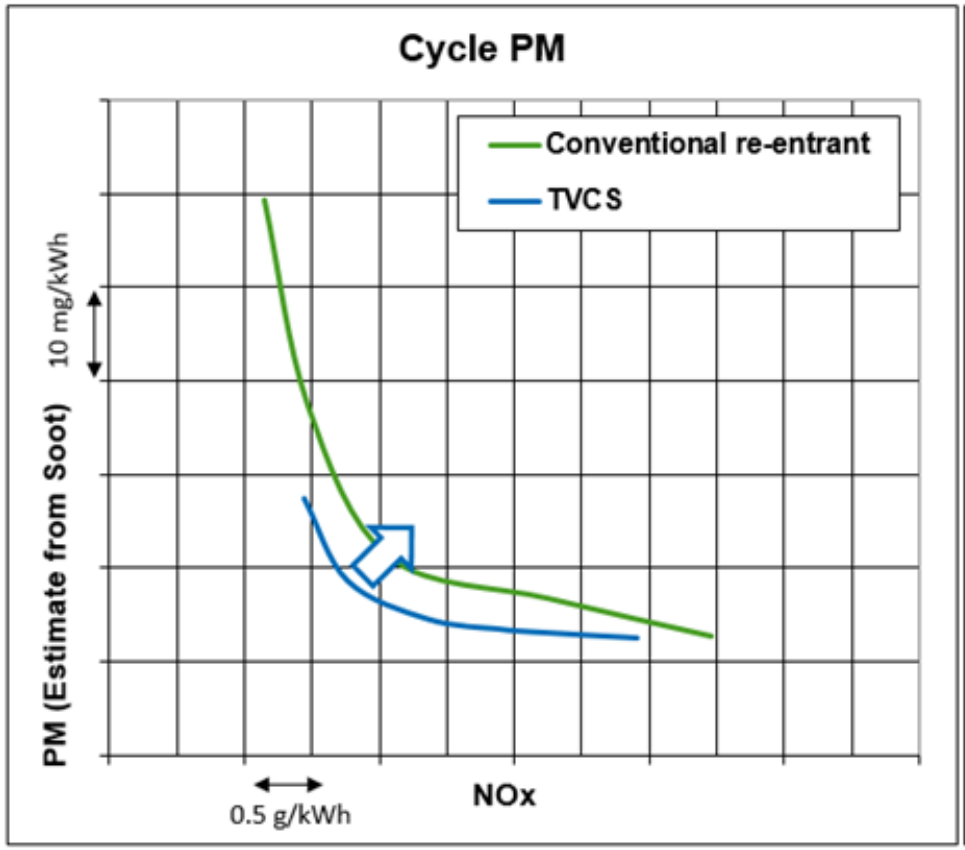
- Stage IV:  TVCS simultaneously achieved lower PM and BSFC than conventional systems
- Stage V:  DPF is mandatory. The engine out soot can afford marginal increase, to gain even better BSFC

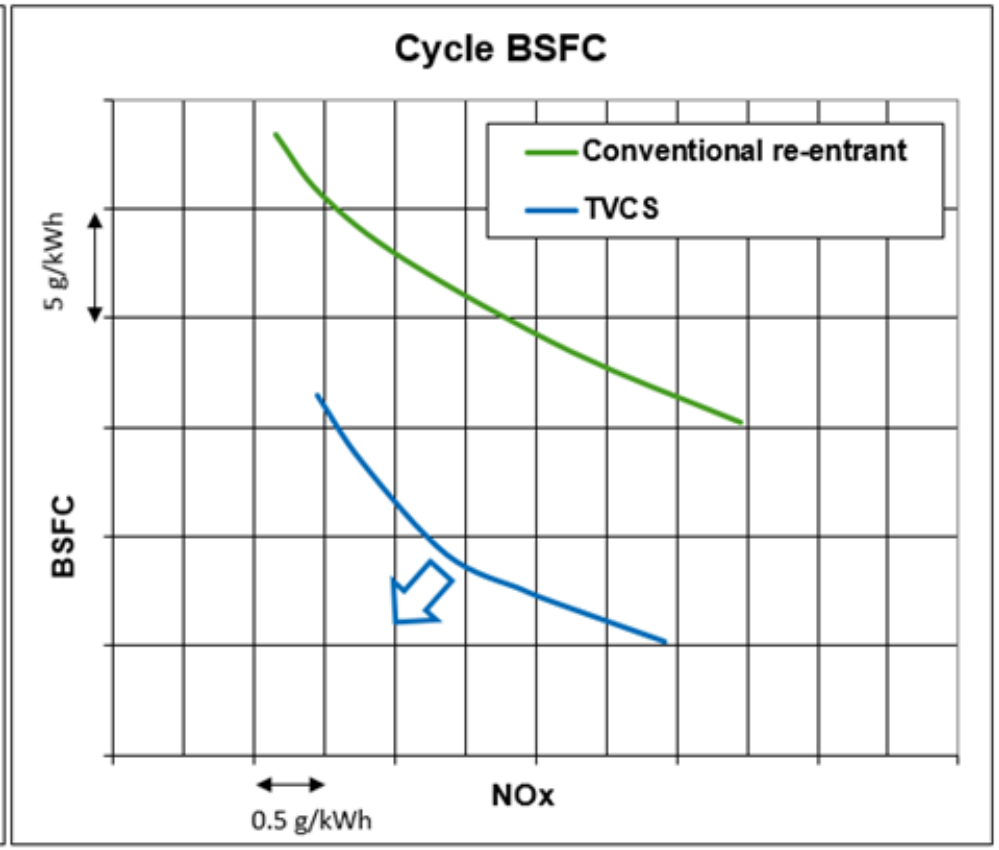
**Conventional re-entrant bowl**



**TVCS bowl**

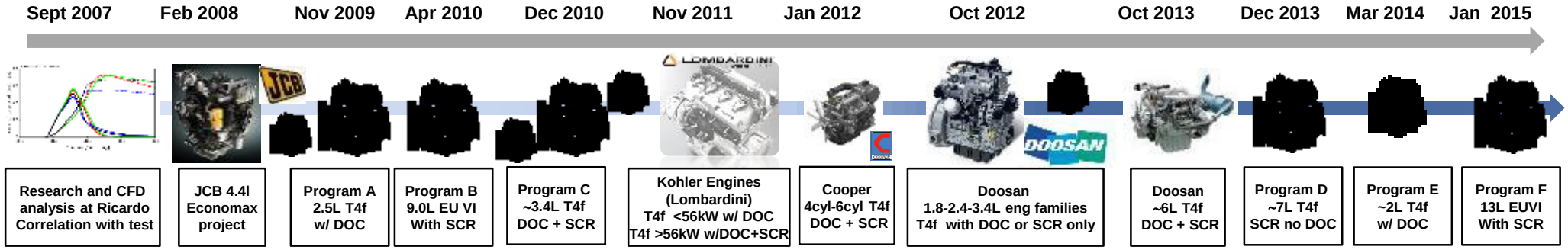


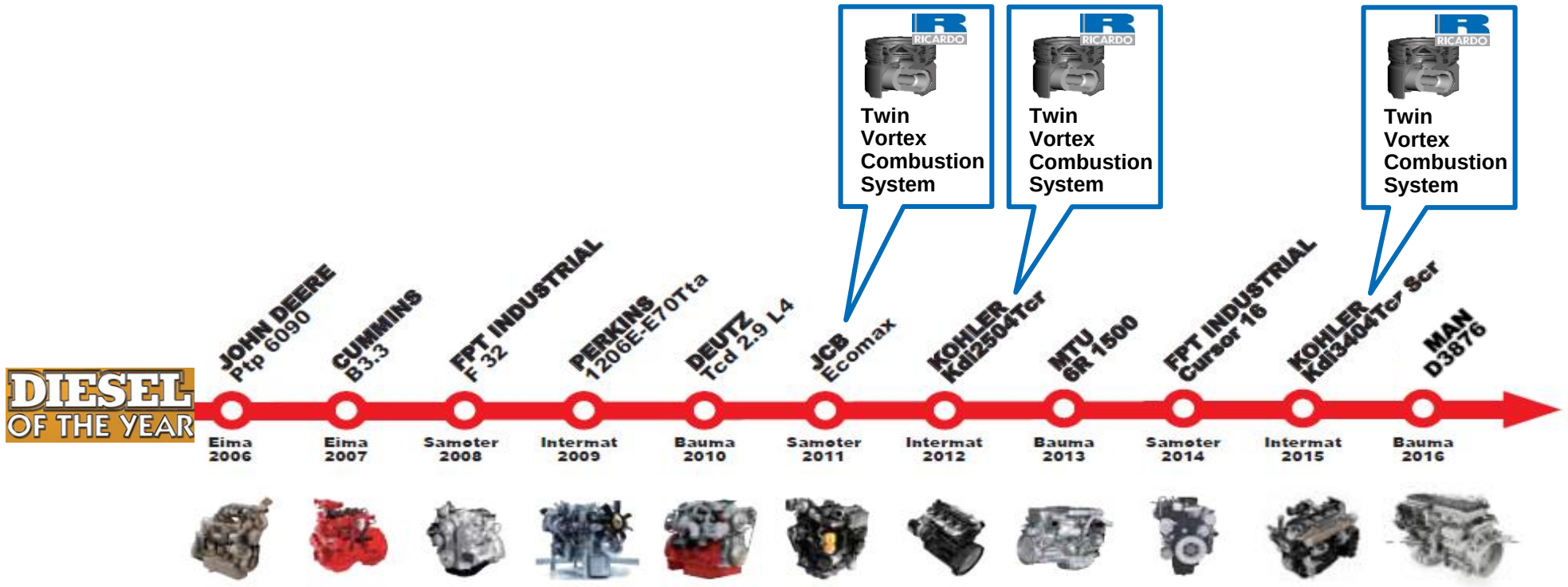


# Ricardo TVCS is applied on the 2011, 2012, 2015 engines of the year….what next ?



# Ricardo is developing the next generation of TVCS
# Full Load Analysis, Compression Ratio sweep 16 to 23:1 on a 13L HDD

- Sweeps of compression ratio have been run maintaining constant max cylinder pressure (Pmax) by adjusting injection timing

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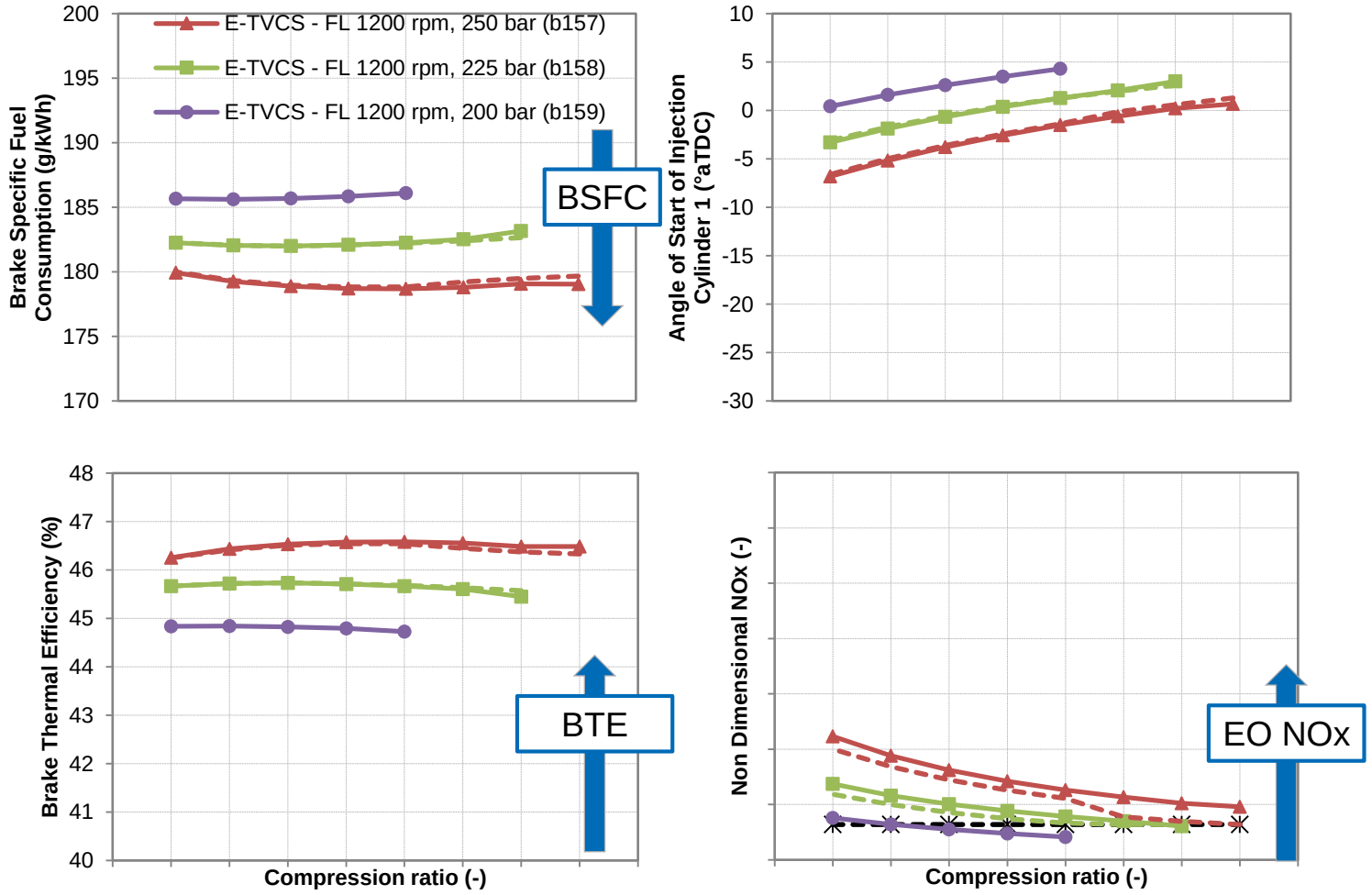
Pmax

- Increasing Pmax increases brake thermal efficiency, but also NOx



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# Full Load Analysis 1200rpm, Compression Ratio sweep 16 to 23:1 on a 13L HDD

- Sweeps of compression ratio have been run maintaining constant max cylinder pressure (Pmax) by adjusting injection timing

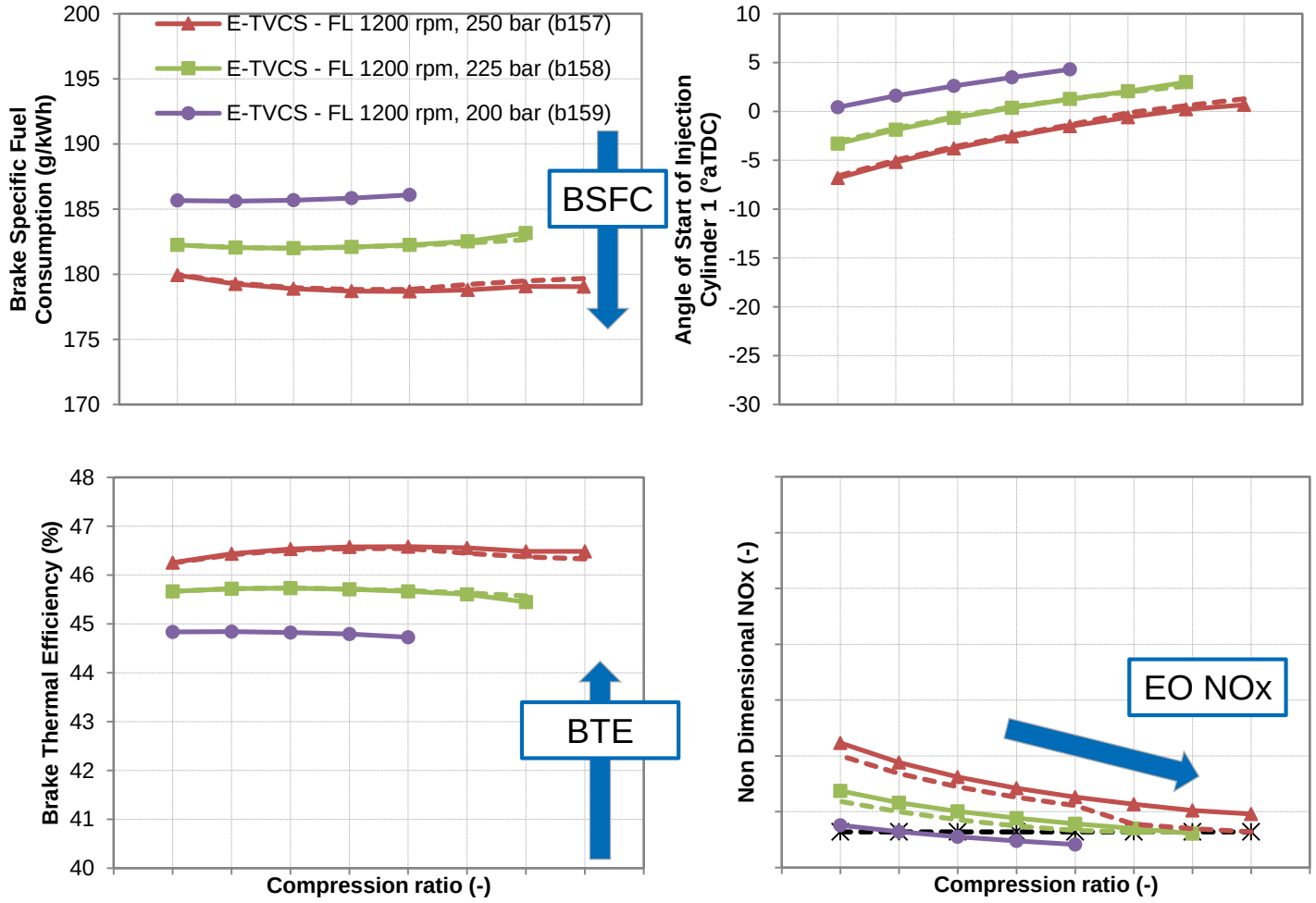
Pmax

- Increasing Pmax increases brake thermal efficiency, but also NOx

CR

- Increasing CR at the same time maintains higher efficiency but gives lower NOx

- NOx can be fully compensated by increasing EGR whilst still giving high efficiency (dotted red line)



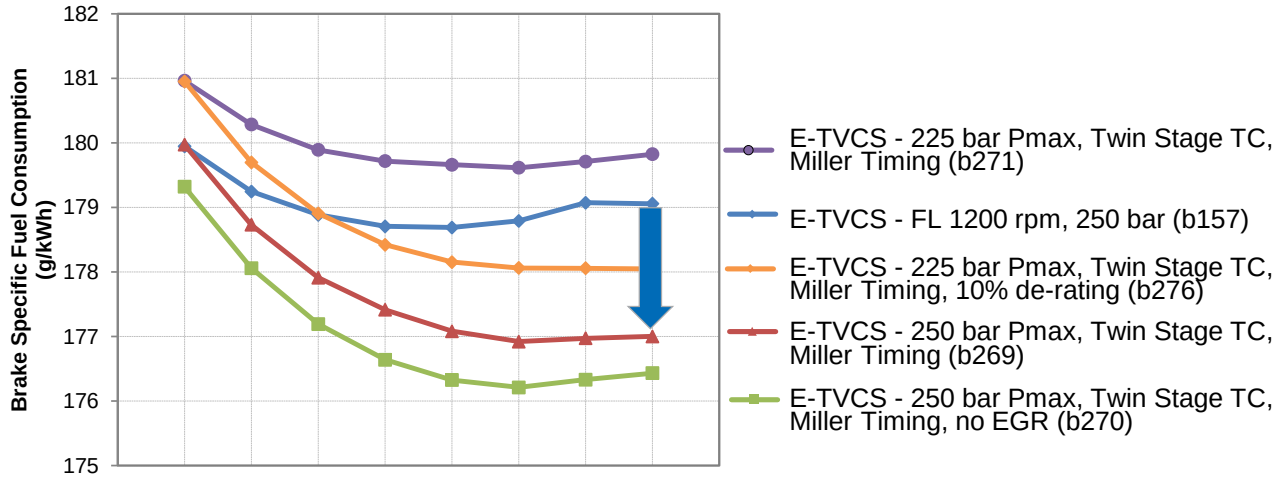
# Miller valve timing (early intake valve closing) and 2 Stage Turbocharging allow further fuel consumption benefit

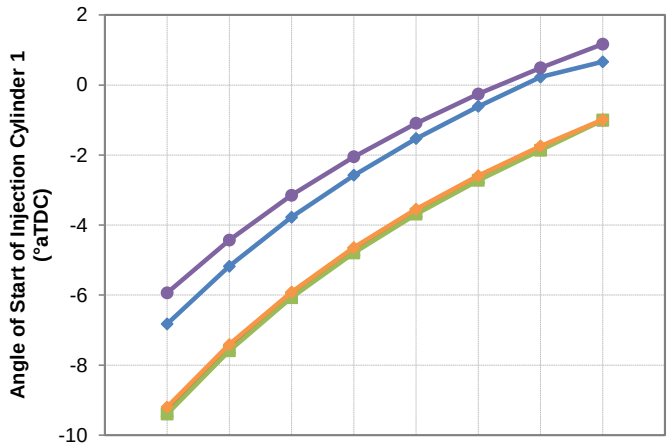
- Results for 2 stage turbocharging models with Miller valve timing have been compared to the single stage VGT, 250 bar Pmax engine model

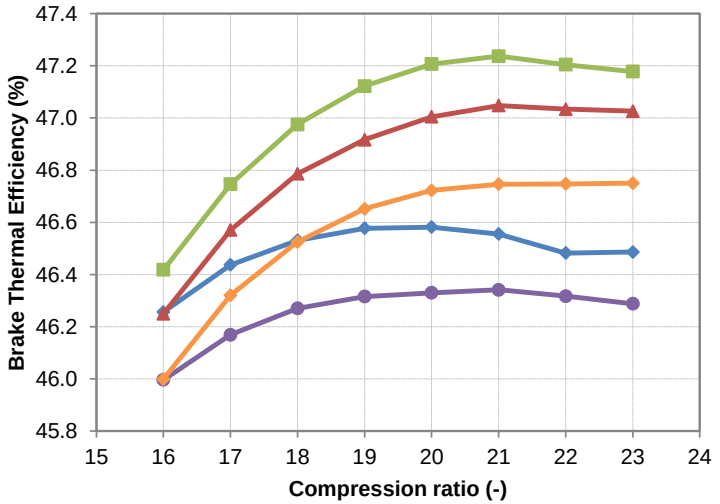
# Miller valve timing (early intake valve closing) and 2 Stage Turbocharging allow further fuel consumption benefit

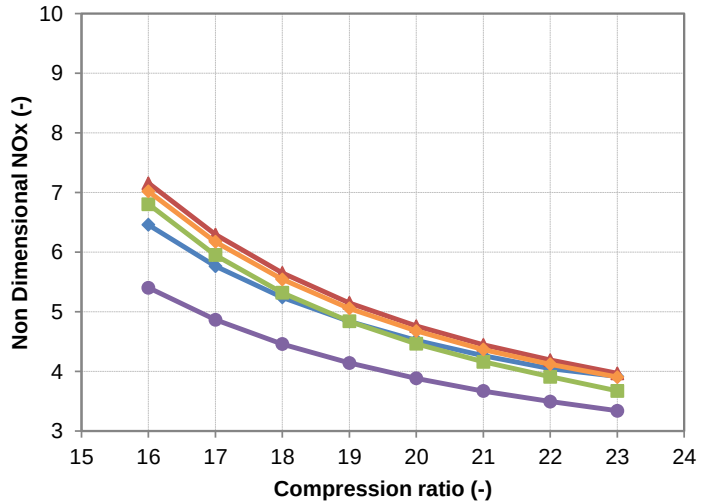
- Results for 2 stage turbocharging models with Miller valve timing have been compared to the single stage VGT, 250 bar Pmax engine model

- For the 250 bar engine variant, switching to twin-stage and alternative valve timing gives BSFC benefits at all CRs, reaching a minimum of 176.9 g/kWh (b269)



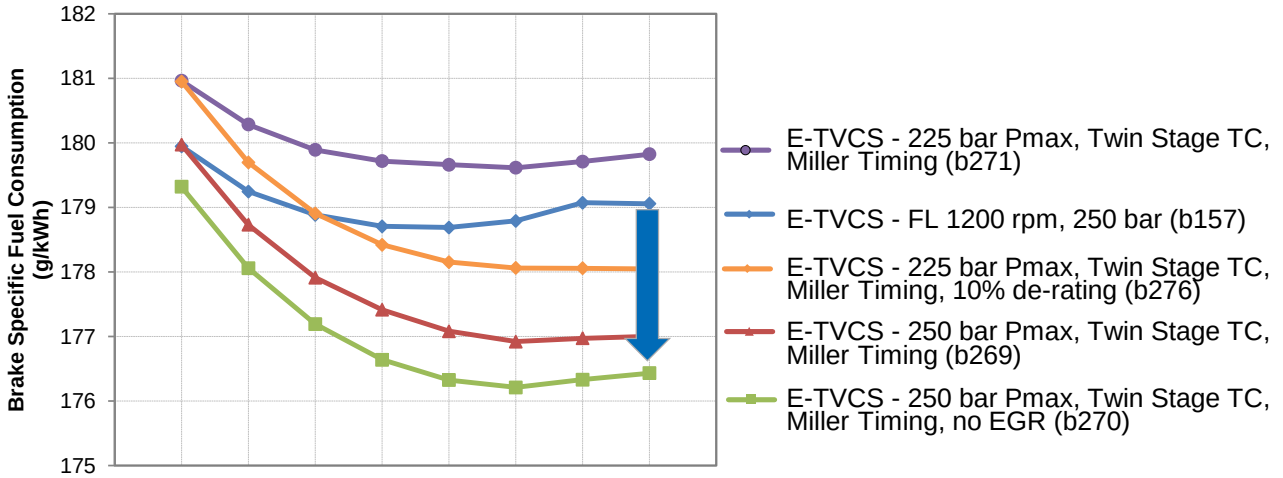



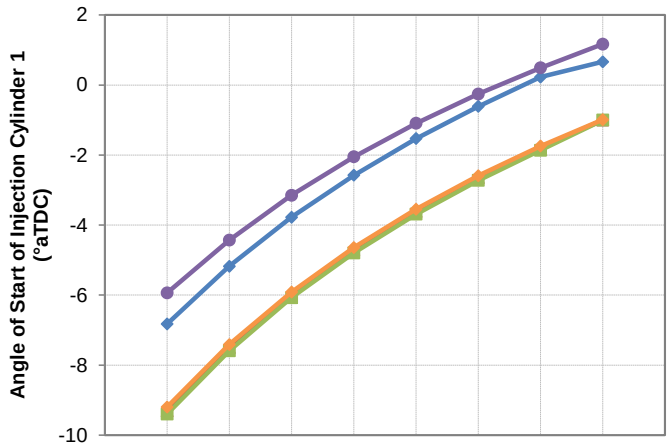



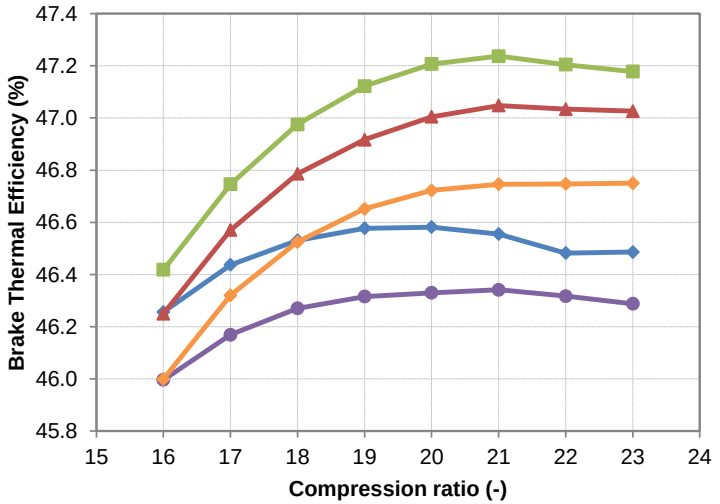
# Miller valve timing (early intake valve closing) and 2 Stage Turbocharging allow further fuel consumption benefit

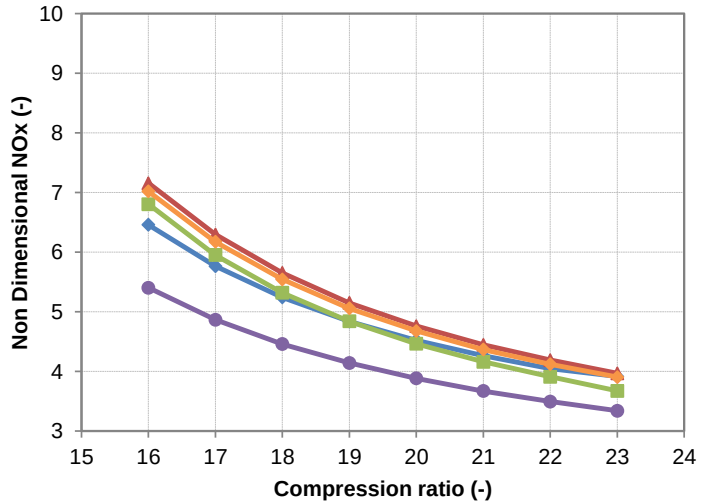
- Results for 2 stage turbocharging models with Miller valve timing have been compared to the single stage VGT, 250 bar Pmax engine model

- For the 250 bar engine variant, switching to twin-stage and alternative valve timing gives BSFC benefits at all CRs, reaching a minimum of 176.9 g/kWh (b269)
- Further BSFC reduction (176.2 g/kWh – 0.4%) can be achieved by running no EGR (b270)



# Contents

- Stage V legislation
- Technology road map for Stage V
- Ricardo clean combustion system
- **Conclusion**

# Conclusion

- Stage V regulation nearly finalized with focus on PM, PN and in use emission compliance
- Several technology options available to meet Stage V: with or without EGR, active or passive DPF, DPF plus SCR or SCRF:
  - A clean combustion system is key to achieve passive DPF/SCRF regeneration with benefit on product cost (small DPF, no active regen devices), machine reliability and productivity
- Further engine efficiency improvement is under development at Ricardo, including increased Pmax and Compression ratio and with advance turbocharging and valve timing



# THANK YOU!