COMBINING MILLER CYCLE AND VTG
A PROMISING CONCEPT FOR FUTURE GASOLINE ENGINES?

Shanghai, 30.11.2016
R. Aymanns, F. Xia, B. Franzke, D. Lückmann, T. Uhlmann, B. Höpke, R. Tharmakulasingam, Y. Yao
FEV view – “Best CO2/costs ratio with friction optimization, Miller cycle and 2-step VCR”

ASSESSMENT - COSTS VS EFFICIENCY (EXAMPLE CURRENT FEV DEVELOPMENT)

FEV view – “Best CO2/costs ratio with friction optimization, Miller cycle and 2-step VCR”

ASSESSMENT - COSTS VS EFFICIENCY (EXAMPLE CURRENT FEV DEVELOPMENT)

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FEV view – “Best CO2/costs ratio with friction optimization, Miller cycle and 2-step VCR”

ASSESSMENT - COSTS VS EFFICIENCY (EXAMPLE CURRENT FEV DEVELOPMENT)

FEV view – “Best CO2/costs ratio with friction optimization, Miller cycle and 2-step VCR”

ASSESSMENT - COSTS VS EFFICIENCY (EXAMPLE CURRENT FEV DEVELOPMENT)

### Base Powertrain

<table>
<thead>
<tr>
<th>Base Technology</th>
<th>Technology Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC-GDI 1.0l 3 Cyl.</td>
<td>max. torque 200 Nm, specific power 95 kW/l</td>
</tr>
<tr>
<td>C-segment vehicle with 6 gear MT</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>#</th>
<th>Base Technology</th>
<th>Technology Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base friction</td>
<td>Optimized friction (base engine measures)</td>
</tr>
<tr>
<td>2</td>
<td>D-VVT</td>
<td>2-step VVL</td>
</tr>
<tr>
<td>3</td>
<td>Conventional cycle</td>
<td>Miller w. 2-Stage TC</td>
</tr>
<tr>
<td>4</td>
<td>Conventional cycle</td>
<td>Miller w. 1-Stage TC</td>
</tr>
<tr>
<td>5</td>
<td>Internal EGR only</td>
<td>cEGR w. 2-Stage TC</td>
</tr>
<tr>
<td>6</td>
<td>Internal EGR only</td>
<td>cEGR w. 1-Stage TC</td>
</tr>
<tr>
<td>7</td>
<td>No VCR</td>
<td>2-step VCR</td>
</tr>
</tbody>
</table>

Combining Miller Cycle and VTG / Aymanns / 16.09.2016
Engine targets and design parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>l</td>
<td>1.5</td>
</tr>
<tr>
<td>Cylinder number</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>-</td>
<td>11.4</td>
</tr>
<tr>
<td>Bore/stroke</td>
<td>-</td>
<td>82 / 94.6</td>
</tr>
<tr>
<td>Max. torque</td>
<td>Nm</td>
<td>239 @ 1250 1/min</td>
</tr>
<tr>
<td>Max. power</td>
<td>kW</td>
<td>110 @ 5500 1/min</td>
</tr>
<tr>
<td>Max. Miller ratio</td>
<td>with earliest IVO = 20 °CA bTDC (ref. 1 mm lift)</td>
<td>1.23 / 1.05</td>
</tr>
</tbody>
</table>

Miller ratio = $\frac{V_{H, \text{ expansion}}}{V_{H, \text{ compression, effective}}}$

Combining Miller Cycle and VTG / Aymanns / 16.09.2016
Turbocharger matching process with “FEV TC Tools” for optimized layout

**FEV Engine Database**
- Pressure losses
- Friction losses
- Combustion profile
- GT-Power models

**FEV TC Toolkit**
- Efficiency correction
  - heat transfer
  - friction
- Scaling
  - global scaling
  - housing variation
- Map extrapolation
  - incl. VGT

**DOE Optimization**

**Optimized Matching**
- TC layout
- Valve layout
- Valve timing

Combining Miller Cycle and VTG / Aymanns / 16.09.2016
“FEV TC Tools” – Full extrapolation of turbine maps (incl. VTG)
Turbocharger matching results for three turbine configurations

BMEP

- BMEP at LET / bar
- VTG Position / -
- Normalized turbine size / -

BSFC

- BSFC at LET / g/kWh
- VTG Position / -
- Normalized turbine size / -

Legend

- WG TC

LET = low end torque
RP = rated power
Turbocharger matching results for three turbine configurations

<table>
<thead>
<tr>
<th>BMEP</th>
<th>BSFC</th>
</tr>
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<tbody>
<tr>
<td>BMEP at LET / bar</td>
<td>BSFC at LET / g/kWh</td>
</tr>
<tr>
<td>BMEP at RP / bar</td>
<td>BSFC at RP / g/kWh</td>
</tr>
</tbody>
</table>

Normalized turbine size / -

Legend

- 🌟 WG TC
- ✡ VTG
- Variability of VTG position

LET = low end torque
RP = rated power
Turbocharger matching results for three turbine configurations

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<th>BMEP</th>
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<tr>
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</tr>
<tr>
<td>BMEP at RP / bar</td>
<td>BSFC at RP / g/kWh</td>
</tr>
</tbody>
</table>

Normalized turbine size / -

Legend

- **WG TC**
- **VTG**
- **VTG+WG**
- Variability of VTG position

LET = low end torque
RP = rated power

Combining Miller Cycle and VTG / Aymanns / 16.09.2016
Turbocharger matching results for three turbine configurations

**Legend**

- **WG TC**
- **VTG**
- **VTG+WG**
- Variability of VTG position
- Line of constant flow capacity

**Let** = low end torque
**RP** = rated power

Combining Miller Cycle and VTG / Aymanns / 16.09.2016
Engine performance results at full load operation

Miller ratio 1.05

![Graph showing engine performance results at full load operation with Miller ratio 1.05. The graph compares BMEP (Barometric Mean Effective Pressure) with engine speed, highlighting the performance of different configurations: WG TC, VTG, and VTG+WG.](image-url)
Engine performance results at full load operation

Miller ratio 1.05

<table>
<thead>
<tr>
<th>Engine speed / 1/min</th>
<th>WG TC</th>
<th>VTG</th>
<th>VTG+WG</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>6000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7000</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

BSFC / g/kWh

Engine speed / 1/min

0 1000 2000 3000 4000 5000 6000 7000
Engine performance results at full load operation

Miller ratio 1.05

- BMEP / bar
- BSFC / g/kWh
- Total exhaust TC efficiency

- WG TC
- VTG
- VTG+WG

Waste gate opens at 20 g/kWh

Engine speed / 1/min
Engine performance results at full load operation

<table>
<thead>
<tr>
<th>Miller ratio 1.05</th>
<th>Miller ratio 1.23</th>
</tr>
</thead>
</table>

- **Engine speed / 1/min**
  - **BMEP / bar**
    - **WG TC**
    - **VTG**
    - **VTG+WG**
  - **BSFC / g/kWh**
    - 20 g/kWh
  - **Total exhaust TC efficiency**
    - waste gate opens

LET not achieved with WG TC and VTG

Combining Miller Cycle and VTG / Aymanns / 16.09.2016
Engine performance results at full load operation

Miller ratio 1.05

Miller ratio 1.23

\( \text{LET not achieved with WG TC and VTG} \)

\( \text{RP not achieved with WG due to TC speed limit} \)

\( \text{Full load target not achieved} \)
Engine fuel consumption in part load operation

Miller ratio 1.05

1250 l/min (LET)

BSFC / g/kWh

5 g/kWh

WG TC
VTG
VTG + WG

3000 l/min

BSFC / g/kWh

VTG fully opened

5 g/kWh

5500 l/min (RP)

BSFC / g/kWh

VTG fully opened

5 g/kWh
Engine fuel consumption in part load operation

Miller ratio 1.05

- WG TC
- VTG
- VTG+WG

<table>
<thead>
<tr>
<th>RPM</th>
<th>BSFC / g/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1250 l/min (LET)</td>
<td>5 g/kWh</td>
</tr>
<tr>
<td>3000 l/min</td>
<td>5 g/kWh</td>
</tr>
<tr>
<td>5500 l/min (RP)</td>
<td>5 g/kWh</td>
</tr>
</tbody>
</table>

Load control by:
- ---- throttling
- --- valve timing (earlier IVC)

VTG fully opened
Engine fuel consumption in part load operation

Miller ratio 1.05

Miller ratio 1.23

BSFC / g/kWh

VTG fully opened

load control by
--- throttling
- - valve timing (earlier IVC)

5 g/kWh
Engine fuel consumption in part load operation

**Miller ratio 1.05**

- **WG TC**
- **VTG**
- **VTG+WG**

**Miller ratio 1.23**

- **Intake event retarded**
- **TDC**

**Combining Miller Cycle and VTG / Aymanns / 16.09.2016**
Load control strategy for a VTG turbine with additional WG

<table>
<thead>
<tr>
<th>WG diameter / mm</th>
<th>VTG position / mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>4</td>
<td>0.2</td>
</tr>
<tr>
<td>6</td>
<td>0.3</td>
</tr>
<tr>
<td>8</td>
<td>0.4</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>12</td>
<td>0.6</td>
</tr>
<tr>
<td>14</td>
<td>0.7</td>
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<tr>
<td>16</td>
<td>0.8</td>
</tr>
<tr>
<td>18</td>
<td>0.9</td>
</tr>
<tr>
<td>20</td>
<td>1.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BMEP / bar</th>
<th>1250 1/min (LET)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
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<tr>
<td>6</td>
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<td>18</td>
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<tr>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BMEP / bar</th>
<th>5500 1/min (RP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
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<tr>
<td>6</td>
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<td>14</td>
<td>14</td>
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<tr>
<td>16</td>
<td>16</td>
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<tr>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>20</td>
<td>20</td>
</tr>
</tbody>
</table>

BSFC / g/kWh

Combining Miller Cycle and VTG / Aymanns / 16.09.2016
Load control strategy for a VTG turbine with additional WG

1250 1/min (LET) 5500 1/min (RP)

BMEP / bar

WG diameter / mm

BMEP / bar

WG diameter / mm

Path of optimum BSFC

BSFC / g/kWh

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Engine transient response behavior at engine speed 1500 1/min

Miller ratio 1.05

Miller ratio 1.23

BMEP / bar

Time / s

1500 1/min

Full load target

WG TC
VTG
VTG+WG

Combining Miller Cycle and VTG / Aymanns / 16.09.2016
Engine transient response behavior at engine speed 1500 1/min

Miller ratio 1.05

- Full load target
- WG TC
- VTG
- VTG+WG
- VTG matched for transient response

Miller ratio 1.23

- Full load target
- WG TC
- VTG
- VTG+WG
- VTG matched for transient response
Combining Miller cycle and VTG –
A promising concept for future gasoline engines?

SUMMARY AND CONCLUSION

- **Combination of Miller cycle and VTG**
  - significant improvement of the fuel consumption throughout the whole boosted operation range (up to 15 g/kWh)
  - Improved full load performance for the Miller cycle engine
  - Improved transient response behavior

- **Upgrading the VTG with an additional waste gate**
  - allows for a wider flow control range
  - Improves fuel consumption at higher engine speed and load

- **Yes, the combination of VTG and Miller cycle is a promising concept that achieves**
  - very good fuel consumption with at the same time
  - good full load performance and
  - good engine responsiveness
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