Application of Low Pressure Direct Injection and Semi-Direct Injection to a Small Capacity Two-Stroke Engine

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Structure

1. Introduction
2. Combustion system development
3. Engine & vehicle development
4. Benchmark
5. Conclusion
1 Introduction

2 Combustion system development

3 Engine & vehicle development

4 Benchmark

5 Conclusion
Motivation

New European emission legislation EURO III < 50 cm³:

- including cold start emission (weighting factor of 30% (50%))
- catalyst durability (up to 10000km)
Introduction

The Engine

- Basic engine data
  - Capacity: 50 cm³ 2-stroke engine
  - Bore: 40 mm
  - Stroke: 39.2 mm
  - Compression ratio: 11.68
  - Power: 3.7 kW
  - Torque: 5 Nm
  - ...
Introduction

The Engine

- Basic engine data
- Port configuration
  - Loop scavenged
  - 5 transfer ports
  - Reed valve
Introduction

- Direct injection mode
  - Fuel injection during scavenge process
  - Homogenization in the cylinder

Figure 1
Introduction

- **Direct injection mode**
  - Fuel injection during scavenging process
  - Homogenization in the cylinder

- **Stratified mode**
  - Fuel injection through the window of the piston
Introduction

- Direct injection mode
  - Fuel injection during scavenge process
  - Homogenization in the cylinder

- Stratified mode
  - Fuel injection through the window of the piston
  - Stratified scavenging through the boost port
  - Homogenization in the cylinder
Introduction

The strategy

- Direct injection mode
  - low HCs
  - low BSFC
- Stratified mode
  - low BSFC
  - max. Power @ high rpm
  - crankcase cooling
  - stability at idle and part load
  - lower HCs than carburettor

Figure 3
Combustion system development

1. Introduction
2. Combustion system development
3. Engine & vehicle development
4. Benchmark
5. Conclusion
Combustion System Development

Spray Quality and Fuel Pressure

- Two different spray types
  - 400 kPA two holes
  - 700 kPA three holes

Figure 4
Combustion System Development

Spray Quality and Fuel Pressure

Figure 5

- Carburetted
- 700 kPa direct injection
- 400 kPa direct injection

Engine speed [U/min]

HC [ppm]
Combustion System Development

Spray Quality and Fuel Pressure

- 400 kPA injector visualization
- 6000 rpm WOT simulation

Figure 6
Combustion System Development

Spray Quality and Fuel Pressure

- 700 kPA injector visualization
- 6000 rpm WOT simulation

Figure 6
Combustion System Development

Thermodynamic analysis

- losses due to real working gas
- scavange losses
- losses due to heat release rate
- wall heat losses
- charge exchange losses
- indicated efficiency

Figure 7
Combustion System Development

Injection strategies

Figure 8

- Carburetted
- Direct injection
- Stratified
Engine & vehicle development

1. Introduction
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Engine & vehicle development

- Design
  - Cylinder
  - Cylinder head
  - Intake system
  - Exhaust system
  -...

Engine development
Engine & vehicle development

Engine development

- Design
- Prototyping
  - Cylinder
  - Cylinder head
  - Intake system
  - Exhaust system
  - ...

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JSAE 20084759
Engine & vehicle development

Engine development

- Design
- Prototyping
- Engine test bench
  - Performance
  - Emissions
  - Durability
  - ...

[Image of an engine component]
Test bench results – Engine test bench

Torque, Power and BSFC

Figure 9: Torque, Power and BSFC vs. engine speed [U/min].

- Red line: Power
- Blue line: Torque
- Green line: BSFC

Power [kW], torque [Nm], BSFC [g/kWh].
Untreated HC- & CO-Emissions

Test bench results – Engine test bench

Figure 10

Untreated HC- & CO Emissions

![Graph showing emissions](image)

- **Engine speed [rpm]**
- **BSHC [g/kWh]**

- **HC untreated**
- **CO untreated**

Figure 10
Exhaust gas purification

Test bench results – Engine test bench

Equivalence ratio
Equivalence ratio (unburned exhaust gas)
Test bench results – Engine test bench

Conversion ratio of HC and CO
Test bench results – Engine test bench

HC- & CO-Emissions after catalyst

Figure 10

Engine speed [rpm]

BSHC [g/kWh]

HC untreated
HC after catalyst
CO untreated
CO after catalyst

Figure 10
Engine & vehicle development

Vehicle development

- Design
  - Fuel system
  - Oil system
  - Cooling system
  - ...

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Engine & vehicle development

Vehicle development

- Design
- Prototyping
  - 4 prototype vehicles
  - 2 different speed versions
  - 45 km/h ECE R47 (<50 cm³)
  - +60 km/h ECE 40 (<150 cm³)
Vehicle development

- Design
- Prototyping
- Chassis dyno & on road development
  - Performance (CVT setting)
  - Cold start
  - Warm up strategy (emissions)
  - Transient calibration
  - Cold chamber & altitude
  - ...
Test bench results – Chassis test bench

Test cycle ECE R47

- **Warm up phase**
- **Hot phase**

Vehicle speed [km/h]

Time [sec]

0 112 224 336 448 560 672 784 896
Test bench results – Chassis test bench

HC-Emissions

Catalyst light-off for HC < 60sec

Figure 12

Target speed transient emissions accumulated emissions

Warm up phase Hot phase

Vehicle speed [km/h], HC [ppm] x10

accumulated HC [g]

time [sec]
Test bench results – Chassis test bench

CO-Emissions

Catalyst light-off for CO < 30sec

Figure 12
Test bench results – Chassis test bench

Figure 12

NO\textsubscript{x}-Emissions

warm up phase

accumulated NO\textsubscript{x} [g]

0 0,5 1 1,5 2 2,5

vehicle speed [km/h], NO\textsubscript{x} [ppm]

0 10 20 30 40 50

time [sec]

0 112 224 336 448 560 672 784 896
### ECE R 47 emission results

**Procedure**
- ECE R47 after 1000 km

**Results**

<table>
<thead>
<tr>
<th>Emissions warm up</th>
<th>weighting factor</th>
<th>Emissions [g/km]</th>
<th>% of limit</th>
<th>weighting factor</th>
<th>Emissions [g/km]</th>
<th>% of limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO [g/km]</td>
<td>0.90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC + NOx [g/km]</td>
<td>1.14</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emissions hot</th>
<th>weighting factor</th>
<th>Emissions [g/km]</th>
<th>% of limit</th>
<th>weighting factor</th>
<th>Emissions [g/km]</th>
<th>% of limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO [g/km]</td>
<td>0.24</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC + Nox [g/km]</td>
<td>0.22</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emissions warm up</th>
<th>weighting factor</th>
<th>Emissions [g/km]</th>
<th>% of limit</th>
<th>weighting factor</th>
<th>Emissions [g/km]</th>
<th>% of limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO [g/km]</td>
<td>0.44</td>
<td>43.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC + NOx [g/km]</td>
<td>0.50</td>
<td>41.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emissions hot</th>
<th>weighting factor</th>
<th>Emissions [g/km]</th>
<th>% of limit</th>
<th>weighting factor</th>
<th>Emissions [g/km]</th>
<th>% of limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO [g/km]</td>
<td>0.57</td>
<td>57.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HC + NOx [g/km]</td>
<td>0.68</td>
<td>56.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 13

< 50 %  
< 60 %
Test bench results – Chassis test bench

Test cycle ECE 40 <150 cm³

- EURO II warm up phase (2003)
- EURO II measurement phase
- EURO III measurement phase

Vehicle speed [km/h]

Time [sec]

0 195 390 585 780 975 1170

0 10 20 30 40 50 60
Test bench results – Chassis test bench

HC-Emissions

Figure 15
Test bench results – Chassis test bench

CO-Emissions

Figure 15

Vehicle speed [km/h], CO [ppm x 10]

Time [sec]
Test bench results – Chassis test bench

**Figure 15**

- **NO$_x$-Emissions**
  - Vehicle speed [km/h], NO$_x$ [ppm x 10]
  - Time [sec]
  - Acc. NO$_x$-Emissions

- **Graph Details**
  - Red line: NO$_x$-Emissions
  - Orange line: Acc. NO$_x$-Emissions
## Test bench results – Chassis test bench

### ECE 40 emission results

**Procedure**
- ECE 40 after 1000 km

**Results**

<table>
<thead>
<tr>
<th>Emission results ECE 40 urban cycle (mileage ~ 1000 km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions warm up + hot phase</td>
</tr>
<tr>
<td>CO [g/km]: 2</td>
</tr>
<tr>
<td>HC [g/km]: 0.8</td>
</tr>
<tr>
<td>NOx [g/km]: 0.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emissions [g/km]</th>
<th>% of the Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO 0.31</td>
<td>15.46</td>
</tr>
<tr>
<td>HC 0.62</td>
<td>77.06</td>
</tr>
<tr>
<td>NOx 0.10</td>
<td>69.55</td>
</tr>
</tbody>
</table>

Figure 14
Benchmark

1. Introduction
2. Combustion system development
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Benchmark

- **Procedure**
  - Comparison of 3 different low emission concepts
  - ECE R47

- **Technologies**
  - 50 cm³ four-stroke, efi, 3-way-catalyst
  - 50 cm³ two-stroke, air-assisted direct injection, oxidation catalyst
  - 50 cm³ two-stroke, low-pressure direct injection, oxidation catalyst

Figure 28
Benchmark

Euro II - EURO III

○ Euro II (since 2003) without coldstart
□ Euro III (from 20XX) including coldstart

Euro IV ?

HC+ NOx [g/km]

CO [g/km]

Euro II - EURO III

ASDI
LPDI
4T
=1

ASDI
LPDI
4T
=1

0,0
0,2
0,4
0,6
0,8
1,0

0,0 0,2 0,4 0,6 0,8 1,0 1,2

HC+ NOx [g/km]

Euro II - EURO III

ASDI
LPDI
4T
=1

ASDI
LPDI
4T
=1

0,0
0,2
0,4
0,6
0,8
1,0

0,0 0,2 0,4 0,6 0,8 1,0 1,2

HC+ NOx [g/km]
Conclusion

1. Introduction

2. Assessment of mixture preparation systems

3. Analysis of the 2-stroke scavenging process

4. CFD-Simulation of spray and mixture preparation

5. Conclusion
Conclusion

- It was demonstrated that with the introduced injection strategy the reduction of untreated HC emissions is ~ 40%.
- The reduction of scavenge losses lead to a ~ 25% lower fuel consumption.
- Very lean exhaust gas due to the stratification of the scavenge process increase the conversion ratio of HC and CO.
- The increased exhaust gas temperature shortens the cat light-off time leading to reduced cold start emissions.
- There is no need for specific technology development (standard two-stroke engine with standard injection components) therefore the development risk is comparatively low.
- Focusing costs and market acceptance, this strategy is a valuable alternative to existing DI-systems.
Thank you for your attention