Experience of the fuel cell bus operation: Technical findings

Results from Deliverable 2, by WP4, WP5 and WP6

Presented by Maria Saxe & Jonas Strömberg
Deliverable 2

**Infrastructure**

- WP1: Electrolysis based H2 Production
- WP2: Fossil fuel based H2 Production
- WP3: Filling station & garage

**Bus operation**

- WP4: Climate conditions
- WP5: Topographic conditions
- WP6: Traffic conditions

**Accompanying activities**

- WP7: Quality & Safety
- WP8: Education
- WP9: Environmental, technical and economic surveys
- WP10: Exploitation & cont. dissemination
- WP 11: Project management
General results

- The total amount of kilometres driven and hours operated has continuously increased during the project.
- The number of kilometres driven and hours operated per month have increased during the project.
General results

• The number of road calls and incidents per 1000 km have decreased.
Kilometres operated

- Average: 94,000 km

Hours operated

- Average 7,000 h
## Conditions and Routes in the 9 CUTE cities

<table>
<thead>
<tr>
<th>Site</th>
<th>Boundary conditions</th>
<th>Operation on number of routes</th>
<th>Main route/Test route</th>
<th>Length of route</th>
<th>Number of stops</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amsterdam</td>
<td>Easy traffic</td>
<td>2</td>
<td>35</td>
<td>10,3</td>
<td>23</td>
</tr>
<tr>
<td>Barcelona</td>
<td>Hot</td>
<td>3</td>
<td>64</td>
<td>10</td>
<td>34</td>
</tr>
<tr>
<td>Hamburg</td>
<td>Flat</td>
<td>All routes</td>
<td>–</td>
<td>8</td>
<td>21</td>
</tr>
<tr>
<td>London</td>
<td>Heavy traffic &amp; Humid</td>
<td>2</td>
<td>RV1</td>
<td>6,5</td>
<td>18</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>Easy traffic</td>
<td>All routes</td>
<td>9</td>
<td>22,2</td>
<td>48</td>
</tr>
<tr>
<td>Madrid</td>
<td>Heavy traffic</td>
<td>3</td>
<td>52</td>
<td>7</td>
<td>25</td>
</tr>
<tr>
<td>Porto</td>
<td>Hot &amp; Hilly</td>
<td>1</td>
<td>20</td>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>Stockholm</td>
<td>Cold</td>
<td>2</td>
<td>66</td>
<td>7,5</td>
<td>27</td>
</tr>
<tr>
<td>Stuttgart</td>
<td>Hilly</td>
<td>1(2)</td>
<td>44</td>
<td>9,8</td>
<td>25</td>
</tr>
<tr>
<td><strong>CUTE average:</strong></td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>9,9</td>
<td>27,3</td>
</tr>
</tbody>
</table>
## Results in the 9 CUTE cities

<table>
<thead>
<tr>
<th>Site</th>
<th>Average speed [km/h]</th>
<th>Average fuel consumption [kg/100km]</th>
<th>Diesel equivalents [l/100km]</th>
<th>Availability [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amsterdam</td>
<td>18,1</td>
<td>21,6</td>
<td>71,8</td>
<td>86,3</td>
</tr>
<tr>
<td>Barcelona</td>
<td>12,9</td>
<td>27,4</td>
<td>91,0</td>
<td>60,1</td>
</tr>
<tr>
<td>Hamburg</td>
<td>16,2</td>
<td>20,4</td>
<td>67,8</td>
<td>78,7</td>
</tr>
<tr>
<td>London</td>
<td>13,9</td>
<td>24,0</td>
<td>79,7</td>
<td>88,2</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>17,9</td>
<td>20,9</td>
<td>69,4</td>
<td>79,7</td>
</tr>
<tr>
<td>Madrid</td>
<td>13,8</td>
<td>28,8</td>
<td>95,7</td>
<td>79,4</td>
</tr>
<tr>
<td>Porto</td>
<td>8,9</td>
<td>30,0</td>
<td>99,7</td>
<td>80,3</td>
</tr>
<tr>
<td>Stockholm</td>
<td>9,7</td>
<td>26,6</td>
<td>88,4</td>
<td>89,9</td>
</tr>
<tr>
<td>Stuttgart</td>
<td>11,4</td>
<td>22,1</td>
<td>73,4</td>
<td>99,6</td>
</tr>
<tr>
<td><strong>CUTE average:</strong></td>
<td><strong>13,6</strong></td>
<td><strong>24,6</strong></td>
<td><strong>81,9</strong></td>
<td><strong>82,5</strong></td>
</tr>
</tbody>
</table>
An example - The waterline in Stockholm

Route conditions:
- Flat
- Downtown traffic
- Low average speed 10 km/h
- Many stops and generous timetable
Histogram of drive modes
- Average from tests on the waterline, July 2004
An average power consumption of 73.5 kW corresponds to 73 l/100 km in diesel equivalents.

The average power dump on the route is 11% of the total average fuel consumption, corresponding to 8 l/100 km in diesel equivalents.
Climate conditions in the 9 CUTE cities

- Warmest month average
- Coldest month average
- Driest month average
Climate effects on operation

- **Cold start**
  Yes! Preheating of the cooling system.

- **Driving characteristics**
  A 2.5 ton heavier bus

- **Fuel cell efficiency**
  No, no shown effect

- **Availability**
  No, no climate related problems

- **Fuel consumption**
  Yes, an increase at temperatures below 0°C and above 18°C
Climate effects on fuel consumption
- trends over the project period

- Fuel consumption MIPP
- Average fuel consumption Watter route
- Temperature
- Average fuel consumption Route 66
- Humidity

- Fuel consumption [kg/100km]
- and
- Temperature [°C]

- Humidity [%]
Climate effects on fuel consumption - difference between cold and warm periods?

<table>
<thead>
<tr>
<th></th>
<th>Porto</th>
<th>Madrid</th>
<th>London</th>
<th>Stockholm</th>
</tr>
</thead>
<tbody>
<tr>
<td>fuel consumption [kg/100km] cold</td>
<td>30</td>
<td>29</td>
<td>26</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>warm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>34</td>
<td>32</td>
<td>33</td>
</tr>
</tbody>
</table>

Legend:
- cold (nov, dec 2004 & jan, feb 2005)
- warm (jun, jul, aug, sept 2005)
Tests on route 66 in Stockholm

September 2004

17.1 °C
60.6%

Fuel cell Stack

Power Dump 14% 11.5 kW

100% Fuel = 81 kW

DC/AC Engine

Losses in DC/AC inverter and in electric motor 5.5% 4.5 kW

Auxiliary systems 14.5% 12 kW

Traction 27% 21.5 kW

March 2005

-4.7 °C
83.0%

Fuel cell Stack

Power Dump 5.5% 6 kW

100% Fuel = 109 kW

HVAC resistor – Cabin Heat 16% 17 kW

DC/AC Engine

Losses in DC/AC inverter and in electric motor 4.5% 5 kW

Auxiliary systems 13% 14 kW

Traction 22% 24 kW
Topography

- Gradient
- Height difference
- Number of climbs
Topography in the CUTE cities

- Stuttgart, Luxembourg and Barcelona have the largest difference in altitude; 120-150 m.
- Madrid and Porto have a difference in altitude of 70-90 m.
- Amsterdam, London and Hamburg are flat!
- Stockholm has a difference in altitude of 30 m, that is climbed twice on a route.
Topography effects on fuel consumption

![Bar chart showing average fuel consumption and demand ranking for various cities.](image-url)
Traffic – What is traffic?

- Traffic situation
- Number of stops (bus stops and red light)
- Bus lanes
- Drive mode pattern (not only traffic also driver behaviour)
- Passengers

London & Luxembourg
Traffic affect on fuel consumption
- Average speed an indication of traffic?

<table>
<thead>
<tr>
<th>City</th>
<th>Stops per kilometer</th>
<th>Average speed</th>
<th>Average Fuel consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amsterdam</td>
<td>2.2</td>
<td>18.1</td>
<td>3.6</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>2.2</td>
<td>17.9</td>
<td>2.6</td>
</tr>
<tr>
<td>Hamburg</td>
<td>2.6</td>
<td>20.4</td>
<td>13.9</td>
</tr>
<tr>
<td>London</td>
<td>2.8</td>
<td>24</td>
<td>13.8</td>
</tr>
<tr>
<td>Madrid</td>
<td>3.6</td>
<td>28.6</td>
<td>12.9</td>
</tr>
<tr>
<td>Barcelona</td>
<td>3.4</td>
<td>27.4</td>
<td>11.4</td>
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<td>22.1</td>
<td>9.7</td>
</tr>
<tr>
<td>Stockholm</td>
<td>3.6</td>
<td>26.6</td>
<td>8.9</td>
</tr>
<tr>
<td>Porto</td>
<td>3.1</td>
<td>30</td>
<td>8.9</td>
</tr>
</tbody>
</table>
Test runs in 4 cities

<table>
<thead>
<tr>
<th>City</th>
<th>Speed [km/h]</th>
<th>Fuel consumption [kg/100km]</th>
<th>Length of route [km]</th>
<th>Number of bus stops [#]</th>
<th>Number of bus stops per kilometre [#/#/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amsterdam</td>
<td>21.6</td>
<td>21.9</td>
<td>10.3</td>
<td>22</td>
<td>2.1</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>19.8</td>
<td>20.2</td>
<td>22.2</td>
<td>48</td>
<td>2.2</td>
</tr>
<tr>
<td>London</td>
<td>10.8</td>
<td>24.6</td>
<td>6.5</td>
<td>18</td>
<td>2.8</td>
</tr>
<tr>
<td>Stockholm</td>
<td>10.9</td>
<td>23.8</td>
<td>7.5</td>
<td>27</td>
<td>3.6</td>
</tr>
</tbody>
</table>

High average speed = low fuel consumption
Low average speed = high fuel consumption
Drive mode in the 4 cities

- Low average speed cities
- High average speed cities

Bar chart showing the percentage of time spent in different drive modes in Amsterdam, Luxembourg, London, and Stockholm.
Indications
- influence on fuel consumption by traffic

The collected data indicates:

- **Heavy urban** traffic, defined as low average speeds, **below 14 km/h**, and **more than 3 bus stops per kilometre** demands
  
  27-30 kg/100km (90-100 l/100 km diesel equivalents)

- **Easy Urban** traffic with average speeds **higher than 16 km/h** and **less than 3 bus stops per kilometre** demands
  
  20-22 kg/100 km (66-73 l/100km diesel equivalents)

Note: Traffic is both traffic situation and passenger load/flow. Passenger load is a key factor that has to be further investigated!
Conclusions of the operation

- The buses have been assessed reliable under European, climate, topography and traffic conditions.
- The minimum current limitation - power dump - is part of the answer to why the fuel cell buses are less fuel efficient than conventional buses.
- The average fuel consumption figures from the project showed clear correlations with climate and traffic but not with topography.
  - An influence on fuel consumption due to climate was found when the temperature was below 0 °C or above 18 °C. This was primarily due to the need to heat or cool the cabin.
  - A challenging topography causes an increase in fuel consumption, this is however not a key factor for fuel consumption in the CUTE cities.
  - Average speed seems to be a key factor for fuel consumption. However, the weight of the buses (including the passengers) is also an important factor that needs further investigation.
Optimisation potentials

Fuel consumption related:
- Removing the power dump alone could save up to 15% fuel.
- Hybridisation with regenerative breaking would save approximately another 20%.
- Auxiliary systems: AC, generators, door openers, etc. should be adapted to an electric power source – some percents could be saved.
- Gearbox removal – some percents could be saved
- Cabin heating system should be optimized for using the heat from the fuel cell, this could save up to 17 % of fuel consumption in cold days.

Note! These are not additive but:

In total electrification and hybridization would save 20-40 %!
Optimisation potentials

Other:

• Noise
• Design potential – electric driveline enables free placing of components.
• Cold starts without preheating.
• Insulation on tubing (corrected during project).
Thank you!

Fuel cell bus club meeting in Stockholm, September 20-21, 2005