Hyundai Motor Group’s Development of the Fuel Cell Electric Vehicle

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Hyundai / Kia America Technical Center
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1. Hyundai’s ECO friendly strategy
2. FCEV development at Hyundai
3. The Global Approach to FCEVs
4. An OEMs Next steps: Validation and Production
1. Global Issues

- **Paradigm shift in automotive industry is demanded due to global warming & oil depletion**
  - Transportation part captures 21% of total energy consumption, 23% of GHG emission

- **Global Warming**
  - **Carbon Dioxide Increase**
    - CO$_2$ concentration in air
      - 280 ppm (before industrialization) → **379 ppm** (present)
      - Doubled CO$_2$ conc. → Temp. increase 2~4.5°C (3.6~8.1°F)
  - **Climate Change & Natural Disaster**
    - Water shortage, flood & extinction of species

- **Oil Depletion**
  - **Expected Peak Oil**
    - Future limitations on oil discovery and production
  - **Oil consumption increase in BRICS**
    - Oil consumption annual growth rate (‘00~’20)
      - China 4.1%, India 3.8%
    - Dubai oil’s annual price increase rate: 6%
    - Forecast over $200/bbl in 2029
Preserving automobile mobility while creating a harmonious balance with our environment

Hyundai’s Eco-friendly Vehicle Strategy

- Low CO₂ ICE
- Bio Fuel
- Hybrid
- Plug-In
- FCEV, EV

- Continuous improvement of fuel economy
- Responding to regional diversity of fuel usage
- Expanding line-up
- Interim solution
- Ultimate solutions
Hyundai’s Eco-friendly Vehicle Strategy

- Small vehicles for short driving range → EV
- Large vehicles for long driving range → Hydrogen FCEV
2. Fuel Cell Vehicle Development

- SantaFe FCEV (75 kW)
- Sportage (10 kW)

- Sportage FCEV (80 kW)
- Sportage FCEV-II (100 kW)
- FC-BUS II (200 kW)

- Sportage FCEV (80 kW In-house Stack)
- FC-BUS (160 kW In-house Stack)

- Sportage FCEV (80 kW)
- Sportage FCEV-II (100 kW)
- FC-BUS Gen II (200 kW)

- Tucson iX FCEV (100 kW)
- Borrego FCEV (115 kW)
- FC-BUS II (200 kW)

- Sportage FCEV (80 kW In-house Stack)
- FC-BUS (160 kW In-house Stack)

US DOE Fleet Program
(2004.09 ~ 2009.12)

Member of CaFCP
(2000.11 ~ Present)

Validation Program
(2009.12 ~ 2012.05)

Domestic Monitoring Program
(2006.08 ~ 2010.07)

Small Scale Production
(2012 ~)

i-Blue Concept car
• 2006

- Tucson iX FCEV (100 kW)
- Borrego FCEV (115 kW)
- FC-BUS Gen II (200 kW)

• 2004 ~ 2005

- Sportage FCEV (75 kW)
- Sportage (10 kW)

• 2000 ~ 2002

iX FCEV (100 kW)

• 2008 ~ 2011
### Fuel Cell Vehicle Development


<table>
<thead>
<tr>
<th>Feature</th>
<th>80 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell Power</td>
<td>80 kW</td>
</tr>
<tr>
<td>Aux. Power</td>
<td>20kW – LiPB</td>
</tr>
<tr>
<td>Motor System</td>
<td>80 kW</td>
</tr>
<tr>
<td>H₂ Tank</td>
<td>3.7 kg H₂ @ 350 bar</td>
</tr>
<tr>
<td></td>
<td>(8.2 lb @ 5.1 kpsi)</td>
</tr>
<tr>
<td>Fuel Economy</td>
<td>20.7 km/l (48.7 mpg)</td>
</tr>
<tr>
<td>Driving Range</td>
<td>291 km (181 miles)</td>
</tr>
<tr>
<td>Acceleration (0 → 100kph)</td>
<td>16.2 sec</td>
</tr>
<tr>
<td>Max. Speed</td>
<td>141 kph (88 mph)</td>
</tr>
</tbody>
</table>

#### 100 kW Fuel Cell Vehicle (2007)

<table>
<thead>
<tr>
<th>Feature</th>
<th>100 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell Power</td>
<td>100 kW</td>
</tr>
<tr>
<td>Aux. Power</td>
<td>Ultra-capacitor (10F)</td>
</tr>
<tr>
<td>Motor System</td>
<td>100 kW</td>
</tr>
<tr>
<td>H₂ Tank</td>
<td>3.7 kg H₂ @ 350 bar</td>
</tr>
<tr>
<td></td>
<td>(8.2 lb @ 5.1 kpsi)</td>
</tr>
<tr>
<td>Fuel Economy</td>
<td>27.2 km/l (64.0 mpg)</td>
</tr>
<tr>
<td>Driving Range</td>
<td>382 km (237 miles)</td>
</tr>
<tr>
<td>Acceleration (0 → 100kph)</td>
<td>12.0 sec</td>
</tr>
<tr>
<td>Max. Speed</td>
<td>155 kph (96 mph)</td>
</tr>
</tbody>
</table>
### Fuel Cell Vehicle Development

#### FC Bus – 1st Generation (2006)

- **Fuel Cell Power**: 160 kW
- **Ultra-capacitor**: Max. 240 kW
- **Motor System**: 240 kW
- **H₂ Tank**: 40kg H₂ @ 350 bar (88 lb @ 5.1 ksi)
- **Acceleration (0 → 50kph)**: 14.2 sec
- **Max. Speed**: 72 kph (45 mph)

#### FC Bus – 2nd Generation (2009)

- **Fuel Cell Power**: 200 kW
- **Ultra-capacitor**: Max. 400 kW
- **Motor System**: 300 kW
- **H₂ Tank**: 30kg H₂ @ 350 bar (66 lb @ 10.2 ksi)
- **Acceleration (0 → 50kph)**: 8.4 sec
- **Max. Speed**: 104 kph (65 mph)
Simpler module design of fuel cell system for volume production

Drastic cost reduction by metallic bipolar plate, AC induction motor, and Li-ion battery

Improved vehicle performance for fleet & general public customers

<table>
<thead>
<tr>
<th>Fuel Cell Power</th>
<th>100 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery</td>
<td>34 kW</td>
</tr>
<tr>
<td>Motor System</td>
<td>AC Induction/100 kW</td>
</tr>
<tr>
<td>H₂ Tank</td>
<td>700 bar</td>
</tr>
<tr>
<td>Fuel Economy</td>
<td>30 km/L (73 mpg_{ge})</td>
</tr>
<tr>
<td>Driving Range</td>
<td>650 km (406 miles)</td>
</tr>
<tr>
<td>Acceleration (0 → 100kph)</td>
<td>12.9 sec</td>
</tr>
<tr>
<td>Max. Speed</td>
<td>160 km/h (100 mph)</td>
</tr>
</tbody>
</table>
Tucson iX Fuel Cell System (2012)

- Size reduction achieved through modularization
- System Power Density: > 640 W/L (DOE Target: 650 W/L)
- Gas/Gas Humidifier
- Cold Start Capability: -25 °C
- System max. Pressure: 1.45 bara
Fuel Cell Vehicle Development

Tucson iX Fuel Cell Stack (2012)

- Max. Power: 100 kW
- Power Density: 1.65 kW/L
- Operating Voltage: 250~450V
- Cold Start Ability: -30 °C
- Max. Air Pressure: 1.35 bara
- Separator: Metal
Fuel Cell Stack Development

- Metal Bipolar Plate
- Injection Molded Gasket
- MEA/GDL Optimization

Operation at Ambient Pressure
Minimum Parasitic Loss
Best Fuel Efficiency in Class
Collision Tests

Front crash test
(Frontal rigid barrier)

Rear crash test
(Rear rigid barrier)

Side impact crash test
(Side deformable barrier)

Rear-offset crash test
(Rear deformable crash barrier)

The hydrogen tank is protected from collisions!

Fuel Cell Vehicle Tests
Fuel Cell Vehicle Tests

Freeze Capability Tests

@ -20°C (-4°F)
in Environmental Chamber

Outside Temp: -19 °C (-2.2°F)
on Taebak Mountains
(Jan., 2011)
## Hydrogen Safety Tests

### Fire Tests

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Gasoline Vehicle</th>
<th>FCEV with Type 3 Tanks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire initiated from the ashtray</td>
<td>Fire tank exploded after 40 minutes.</td>
<td>PRD activated after 22 minutes.</td>
</tr>
</tbody>
</table>

### CNG Tank (150 bar/2.2 kpsi) vs. Hydrogen Tank (350 bar/5.1 kpsi)

<table>
<thead>
<tr>
<th>Test Condition</th>
<th>Result</th>
</tr>
</thead>
</table>
| Fire Source: LPG gas | PRD activated: CNG vent  
Max. flame height: 11 m (36 ft)  
PRD activated: H₂ vent  
Max. flame height: 8 m (26 ft) |

**Note:** PRD stands for Pressure Relief Device.
Facilities for Fuel Cell System Development

FC System Test Bench (Bread Board)

FC Stack Test Station (100 kW Class)
Facilities for Fuel Cell System Development

Motor Test Equipment (100 kW Class)

Motor Test Equipment (250 kW Class)
### Fuel Cell Stack Development

**Durability**

*Durability = func. (Operation parameters, driving mode, environmental effects)*

- Verification of degradation mechanism
  - (Start-up / Shut-down / Cold start Up / High temperature operation)
- Development of new material (Catalyst / Membrane)

**Graph: Bench Test: Vehicle Test Mode**

- Test Results
- Target

**Year**

- 2006
- 2007
- 2008
- 2009
- 2010
- 2011
- 2012

**Fuel Cell System Durability (hrs)**

- 0
- 1,000
- 2,000
- 3,000
- 4,000
- 5,000
- 6,000
- 7,000
- 8,000
- 9,000

**Real Road Target**

**Bench Test: Vehicle Test Mode**
Cost Estimation

- Achieved: 1/3 of '08 Cost
  - Design & Production Technology Improvement
  - Low Cost Bipolar Plate & Gasket Material
- Target: Promising 1/6 of '08 Cost
- Target: 1/20 of '08 Cost
- Target: 1/40 of '08 Cost

Cost

Annual Production

- Mass Production Effect
- MEA/GDL Cost Reduction

- MEA
- GDL
- Bipolar Plate
- Gasket
- Balance of Stack
3. Hyundai’s Global Approach

- Hyundai has a global approach to FCEV development: Working in Asia, Europe & North America.
- Each region is being evaluated for viability of the technology and infrastructure.
1. **Period:** 2006. 8 ~ 2010. 12 (4 years)

2. **Vehicles:** 30 SUVs, 4 Buses

<table>
<thead>
<tr>
<th>Year</th>
<th>SUV</th>
<th>Bus</th>
<th>Station</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>4</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2nd</td>
<td>8</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3rd</td>
<td>18</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

3. **Budget:** $ 46.6 million (Government 50%)

4. **Hydrogen Stations:** 11 in operation as of Feb. ’11
   - Had 4 stations in ’07 (SK, GS-Caltex, KOGAS, HMC Mabuk)
   - Planned 5 more stations by ’10 (Seoul, HMC Namyang, Jeju Island, Ulsan, Yeosu)

4. **Results**
   - Total: 1,297,799km (806,587 miles)
   - Avg. fuel economy: 19.2km/l (45.2 mpg)
Domestic Fleet Program (2nd Stage)

- Launched in Dec. 2010 as Phase 2
  - 100 vehicles to general customers in capital area and Ulsan (center of auto & oil industry)
  - 13 stations are ready by 2011
  - Total mileage: 1,137,789 km (706,989 miles)
H₂ Stations in Korea

- 13 stations in operation (Jan., 2012)

<table>
<thead>
<tr>
<th>#</th>
<th>City</th>
<th>Installer</th>
<th>Year</th>
<th>Type</th>
<th>Pressure</th>
<th>Project</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yongin</td>
<td>HMC</td>
<td>2005</td>
<td>Truck-in</td>
<td>350/700bar</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Seoul</td>
<td>GS-Caltex</td>
<td>2006</td>
<td>Naphtha reforming</td>
<td>350 bar</td>
<td>H₂ station development</td>
</tr>
<tr>
<td>3</td>
<td>Incheon</td>
<td>KOGAS</td>
<td>2007</td>
<td>NG reforming</td>
<td>350 bar</td>
<td>↑</td>
</tr>
<tr>
<td>4</td>
<td>Daejeon</td>
<td>SK Energy</td>
<td>2007</td>
<td>LPG reforming</td>
<td>350 bar</td>
<td>H₂ station development</td>
</tr>
<tr>
<td>5</td>
<td>Seoul</td>
<td>KIST</td>
<td>2008</td>
<td>Mobile</td>
<td>350 bar</td>
<td>FCEV Fleet</td>
</tr>
<tr>
<td>6</td>
<td>Hwaseong</td>
<td>HMC</td>
<td>2008</td>
<td>Truck-in</td>
<td>350/700bar</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>Ulsan</td>
<td>Dongdeok Gas</td>
<td>2009</td>
<td>↑</td>
<td>350 bar</td>
<td>FCEV Fleet</td>
</tr>
<tr>
<td>8</td>
<td>Yeosu</td>
<td>SPG Chemical</td>
<td>2009</td>
<td>↑</td>
<td>350 bar</td>
<td>FCEV Fleet</td>
</tr>
<tr>
<td>9</td>
<td>Seoul</td>
<td>HMC</td>
<td>2009</td>
<td>Mobile</td>
<td>350 bar</td>
<td>2nd FCEV Fleet</td>
</tr>
<tr>
<td>10</td>
<td>Seoul</td>
<td>City of Seoul</td>
<td>2010</td>
<td>Truck-in</td>
<td>350 bar</td>
<td>FCEV Fleet</td>
</tr>
<tr>
<td>11</td>
<td>Seoul</td>
<td>City of Seoul</td>
<td>2011</td>
<td>Landfill gas reforming</td>
<td>350 bar</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>Jeju</td>
<td>HMC</td>
<td>2011</td>
<td>Electrolysis</td>
<td>350 bar</td>
<td>FCEV Fleet</td>
</tr>
<tr>
<td>13</td>
<td>Ulsan</td>
<td>Dongdeok Gas</td>
<td>2011</td>
<td>Truck-in</td>
<td>700 bar</td>
<td>2nd FCEV Fleet</td>
</tr>
</tbody>
</table>
Hyundai’s Hydrogen Station

1. Yongin
   - Capacity: 26 vehicles/day
   - Refueling pressure: 350/700 bar

2. Hwaseong
   - Capacity: 43 vehicles/day
   - Refueling pressure: 350/700 bar

3. Seoul
   - Capacity: 13 vehicles/day
   - Refueling pressure: 350 bar
<table>
<thead>
<tr>
<th>Period</th>
<th>Vehicle type</th>
<th># of fueling (Vehicle/month)</th>
<th>Avg. pressure (bar)</th>
<th>H₂ (H₂ kg/Vehicle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Sep</td>
<td>16</td>
<td>96</td>
<td>3.21</td>
</tr>
<tr>
<td></td>
<td>Oct</td>
<td>21</td>
<td>117</td>
<td>2.92</td>
</tr>
<tr>
<td></td>
<td>Nov</td>
<td>25</td>
<td>134</td>
<td>2.52</td>
</tr>
<tr>
<td></td>
<td>Dec</td>
<td>15</td>
<td>97</td>
<td>3.53</td>
</tr>
<tr>
<td>2011</td>
<td>Jan</td>
<td>SUV 34</td>
<td>127</td>
<td>2.92</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bus 4</td>
<td>97</td>
<td>15.5</td>
</tr>
<tr>
<td></td>
<td>Feb</td>
<td>SUV 59</td>
<td>136</td>
<td>2.77</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bus 3</td>
<td>96</td>
<td>12.4</td>
</tr>
</tbody>
</table>

SUV avg. 28 118 2.89
Bus avg. 4 97 14.2

Built in Sep., 2010

Fueled hydrogen

Amount of H₂/kg

Most H₂ from chemical process
Annual capacity: 1.171 million ton
By-product H₂: 100k ton
20% of By-product H₂ → 100k FCEV/year
No additional investment for H₂ production for early market introduction

Projected Scenario

Phase 1 (~’14)
- 20 stations
- Focusing on densely-populated area + H₂ production sites

Phase 2 (~’20)
- 100 stations
- Spreading out to large cities

Phase 3 (~’30)
- 500 stations
- Networking the large cities
European Fuel Cell development
Distribution of FCEV in Europe

- FCV test & deployment project with Scandinavian countries (Jan., 31, 2011)
  - Norway, Sweden, Denmark and Iceland
  - FCVs developed by Hyundai’s proprietary technology will be supplied

- Partnership with CEP (Clean Energy Partnership) (Feb., 25, ’11)

Construction of refueling stations
(Scandinavian Hydrogen Highway Partnership)
Activities with EU Government

**EU Government Supported Projects**

1. **H2MOVES**
   - Budget: Total 2.43M € (0.97M € by EU).
   - Period: ’09. 11~ ’12. 12 (3 years)
   - Participated in the events (Germany (HME), UK (Ecovelocity), Italy (EcoDolomites) and Denmark (COTY Jury events, Copenhagen))

2. **H2CONNECT**
   - Budget: Total 9.77M € (3.39M € by EU).
   - Period: ’12. 9~ ’15. 8 (3 years)
   - 25 Vehicles will be deployed in Germany (10 vehicles), Italy (10 vehicles) and Sweden (5 vehicles)

3. **EU Parliament Officials Test Driving**
   - Available to test-drive by members of European Parliament, Commissioners, EU officials and other policy makers
   - Period: ’11. 10 ~ ’12. 03 (6 months)
Field Test In Denmark May, 2011

Karub ➔ Ringkobing ➔ Herning ➔ Holstebro ➔ Copenhagen: 341 km for 3.7 hr
Michelin Challenge Bibendum (May 2011, Berlin)
## ZERO Rally in Oslo, Norway (June, 2011)

<table>
<thead>
<tr>
<th>Date</th>
<th>Zero Rally in Oslo</th>
</tr>
</thead>
</table>
| June 7, 2011 | √ Driving Mileage: 144 km (89 miles)  
              | √ Test Driving for Vehicle Performance Evaluation  
              | 1) Slalom Tests – Twice  
              | 2) Racing Test – Once  
              | √ We successfully completed the whole rally with a Tucson iX vehicle. |
| June 8, 2011 | √ Driving Mileage: 180 km (112 miles)  
              | √ Uphill Climbing (Grading) Test – Once (Gradability = 10 ~ 15%) |
Other Activities in Europe (Sep.-Oct., 2011)

- 1st Eco-Velocity 2011 in London, UK (Sep., 2011)

- Klima Mobility 2011 in Italy (Sep., 2011)

- EcoDolomites 2011 in Italy (Sep., 2011)

- France FCEV Show in France (Oct., 2011)
U.S. Fuel Cell development
US (DOE) Fleet Program History


2. Budget: $105 million (Consortium, Government 50%)

3. Partners: Chevron Texaco (Hydrogen Filling Station)
   UTCFC (Fuel Cell Stack)
   AC Transit, SCE, US Army, CARB (Fleet Operators)

4. Vehicles: 32 Tucson/Sportage FCEVs

5. Accomplishments
   - Total: 835,212 km (522,000 miles)
   - Cold weather drivability proved for 3 years in Michigan

1st Vehicle for Demo Fleet Program (2005. 12.16)
US Hydrogen Station Completion (2005. 2.18)
### Fuel Cell Vehicle Development

**Borrego FCEV: San Francisco → LA Driving Test (396 miles, 2008)**

![Departure Point](image1.png)

![Traveling Route](image2.png)

![Arrival Point](image3.png)

<table>
<thead>
<tr>
<th>Item</th>
<th>Contents</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual Mileage</td>
<td>634 km</td>
<td>396 miles</td>
</tr>
<tr>
<td>H₂ Consumed</td>
<td>6.65 kg (84%)</td>
<td>• Actual H₂ Fueling Quantity: 7.76 kg (98%)</td>
</tr>
<tr>
<td>Total Capacity of H₂ Tank</td>
<td>7.92 kg (100%)</td>
<td>• Based on Avg. Fuel Economy (@ 100% H₂ Consumption)</td>
</tr>
<tr>
<td>H₂ Remained</td>
<td>1.27 kg (16%)</td>
<td></td>
</tr>
<tr>
<td>Avg. Fuel Economy</td>
<td>25.7 km/L (60.7 mpgge)</td>
<td></td>
</tr>
<tr>
<td>Additional Available Distance</td>
<td>121 km (75 miles)</td>
<td></td>
</tr>
<tr>
<td>Driving Range</td>
<td>758 km (471 miles)</td>
<td></td>
</tr>
</tbody>
</table>
FCEV team will drive from San Francisco to New York between September 1st – 28th

In addition to raising awareness for childhood cancer, the tour will demonstrate Hyundai’s commitment to creating a cleaner future through environmental leadership.

The tour gives Hyundai the opportunity to highlight a potential future technology and the resulting environmental advantages.
1. **DOE Opportunity:** 2012. ~ 2017 (5 years)

2. **Hyundai Motor Group**
   - Hyundai internal Designed fuel Stack Systems
   - Tucson Vehicle Architecture

3. **Vehicles:** 10 FCEV SUVs (Tucson) in 2 phases
   - Phase 1: 7 vehicles
   - Phase 2: 5 vehicles (2 carry over from Phase 1)

4. **Plan**
   - Operated in L.A. California Area
   - Hyundai; Ca FCP, SCAQMD driving applications
4. Roadmap of FCEV Commercialization

**Step 1**
- Core Technology Development
- Outsourced Stack - 1st FCV
- Several FCEVs/year

**Step 2**
- System Technology Development & Fleet Operation
- Stack Bipolar Plate - Graphite
- Tens of FCEVs/year

**Step 3**
- Semi-Automatic Production
- Stack Bipolar Plate - Metal
- Hundreds of FCEVs/year

**Step 4**
- Pre-commercial Production (Pilot-scale)
- 1,000 FCEVs/year

**Step 5**
- Commercial Production - Initial Market
- Full Automation
- 10,000 FCEVs/year

**1st Gen. (’00~’04)**

**2nd Gen. (’05~’08)**

**3rd Gen. (’09~’11)**

**4th Gen. (’12~’14)**

**5th Gen. (’15~)**
FCEV Commercialization in the U.S.

Pre Commercial and Commercial US Implementation

- Fuel Cell Vehicles (Hyundai / OEMs)
  - Infrastructure deployment studies (Market identification)
  - Continued System validation In North America (Environmental conditions)
  - Customer acceptance (Validation of Production intent designs)
  - Validation of Production Intent Components and Suppliers (Pre-commercial Volumes)

- Infrastructure
  - Training and preparation of dealer supply network for FCEVs
  - Refueling Infrastructure: Currently the single biggest inhibitor for FCEV deployment

- Next Steps (Recommended)
  - Increased emphasis from Government entities to support Infrastructure (Tax Incentives, Mandates, Legislation)
  - Industry support for infrastructure, collaboration with CaFCP and other similar organizations in the US.
Thank you!