The *Bloodhound* Supersonic Car: Innovation at 1,000 mph

01/11/14
Introducing the Presenters

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Setting a Land Speed Record

- Certified by Fédération Internationale de l'Automobile (FiA)

- Multiple LSR Categories
  - i.e. Wheel Driven, Electric, Motorcycle

- Outright World Land Speed Record
  - No engine or drivetrain restrictions
  - Driver must be in full control
  - Must have 4 wheels
  - Speed over 1 mile with flying start
  - Average of 2 attempts within 1 hour

- Current Record:
  - Thrust SSC – 1997 – 763.035 mph

Thrust SSC lays shock waves across the Black Rock Desert, Oct 15th 1997
Key Milestones in History of LSR

- 1898 – Jeantaud Duc – 57.7 mph
  - Earliest recorded land speed attempt
  - Electric coach piloted by Gaston de Chasseloup-Laubat

- 1906 – Stanley Rocket – 127.7 mph
  - First record over 200 km/h
  - Steam powered car piloted by Fred Marriott

- 1927 – Sunbeam 1000 hp – 203.8 mph
  - First record over 200 mph
  - Internal combustion car piloted by Henry Segrave

- 1935 – Blue Bird – 301.1 mph
  - First record over 300 mph
  - Internal combustion car piloted by Malcolm Campbell

- 1947 – Railton Mobil Special – 394.19 mph
  - Last record without jet/rocket propulsion
  - Internal combustion car piloted by John Cobb
Key Milestones in History of LSR

- **1963 – Spirit of America – 407.4 mph**
  - Marks shift to jet powered propulsion
  - Turbojet powered car piloted by Craig Breedlove

- **1965 – Spirit of America Sonic 1 – 600.6 mph**
  - First record above 600 mph
  - Turbojet powered car piloted by Craig Breedlove

- **1970 – Blue Flame – 630.5 mph**
  - First record above 1000 km/h
  - Rocket powered car piloted by Gary Gabelich

- **1997 – Thrust SSC – 763.5 mph**
  - Standing record to this day
  - First supersonic car
  - Turbofan powered car piloted by Andy Green

- **2015 – Bloodhound SSC – 1050 mph target**
  - Spiritual successor to Thrust SSC
  - If successful, first record above 1000 mph
## Bloodhound mission

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Weight (kg)</th>
<th>Max Power (hp)</th>
<th>Average Fuel Consumption (mpg)</th>
<th>Turning Circle (ft)</th>
<th>Max Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyota Camry</td>
<td>1470</td>
<td>178</td>
<td>35.0</td>
<td>37</td>
<td>131</td>
</tr>
<tr>
<td>Ferrari 458</td>
<td>1400</td>
<td>605</td>
<td>20.0</td>
<td>40</td>
<td>205</td>
</tr>
<tr>
<td>Bloodhound</td>
<td>~7800</td>
<td>135,000</td>
<td>0.04</td>
<td>788</td>
<td>1050</td>
</tr>
</tbody>
</table>
Bloodhound mission

- To extend the world land speed record set by Thrust SSC in 1997 (763.035 mph)
- Raise the record to 1000mph.
Bloodhound mission

- Attempt at Hakskeen Pan, Northern Cape, South Africa

13.0 miles
**Bloodhound mission profile**

- Cover measured mile at 1000mph
- Constrained by 12 mile course length
- Complete reciprocal run within one hour.
Engines – jet

1x Eurojet, EJ200

\[ T_{\text{dry}} = 60\text{kN} \ (13,500\text{lb}) \]
\[ T_{\text{reheat}} = 90\text{kN} \ (20,000\text{lb}) \]

Type: 2 power Eurofighter
Fuel: 1040lb (900lb useable)
Engines – jet

Recently installed on the chassis at the workshop in Avonmouth, England.
Engines – rocket

Mounted below the EJ200 engine

\[ T_{\text{max}} = 122\text{kN} \ (27,500\text{lb}) \]
\[ T_{\text{av}} = 111\text{kN} \ (25,000\text{lb}) \]

Type – Hybrid
Oxidiser - H\textsubscript{2}O\textsubscript{2} HTP
Solid fuel - Hydroxyl Terminated Polybutadiene (HTPB (C\textsubscript{4}H\textsubscript{6})\textsubscript{c}OH)

Target specific impulse – 200 lb.s/lb
Engines – auxiliary power unit

APU supplies power to accessory drive gearbox to:
• Start the EJ200 engine;
• Power electrical equipment;
• Power hydraulic wheel brakes;
• Pump HTP fuel to the rocket.

The APU delivers 800hp - 200hp more than that Ferrari!
Engines – mission sequence

EJ200 Reheat

EJ200 engine opened up to 100% dry thrust

15 s  100 mph      +0.5'g' to +0.7'g'

35 s  350 mph      +1.5'g' to +2.0'g'

Rocket engine engaged

36 s  3600 mph  +0.5'g' to 0.0'g'
Systems - fuel

The jet fuel (Jet A1) system has a capacity of:

- Main tank, 730lb
Systems - fuel

...and further capacity of

- Auxiliary tanks, 170lb and 140lb
Systems - fuel

The rocket fuel tank has a capacity of 2900lb HTP

Pumped by APU at 110lb/s for 20s burn.

Construction – stainless steel
Having reached 1050mph, the car has 660MJ of energy, to be dissipated in 60s: an average of 15,000 bhp.

The braking system comprises three components:

• Airbrakes
• Parachutes (if needed)
• Wheel brakes

In addition, the drag of the car is effective in decelerating from the highest speeds – 15 tons at M=1.4 (96,000 bhp).
Systems - airbrakes

Airbrakes applied at 800mph, but designed for 1000mph:

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Speed (mph)</th>
<th>Brake Angle (°)</th>
<th>Brake Force (lbf)</th>
</tr>
</thead>
<tbody>
<tr>
<td>57</td>
<td>1050</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>59</td>
<td>1000</td>
<td>15</td>
<td>6560</td>
</tr>
<tr>
<td>60</td>
<td>940</td>
<td>30</td>
<td>13050</td>
</tr>
<tr>
<td>62</td>
<td>873</td>
<td>45</td>
<td>21100</td>
</tr>
<tr>
<td>63.5</td>
<td>777</td>
<td>60</td>
<td>23600</td>
</tr>
</tbody>
</table>
Systems – braking safety

Braking options:

- Airbrakes, one parachute and wheel brakes stop car in <4.5 miles;
- Second parachute available if necessary;
- If the airbrakes fail, both parachutes and wheel brakes can stop the car in 4.5 miles;
- If both parachutes fail, airbrakes and wheel brakes will stop the car, but using the overrun distance.
Braking – mission sequence

- 57 s  1050 mph  -3.0'g'
- Engines cut; car drag (15t) decelerates the car
- 62 s  800 mph  -2.5'g'
- Air brakes start to deploy at an increasing angle
- 96 s   200 mph             -0.5'g'
- Wheel brakes applied
- 68 s   600 mph           -1.3'g'
- Parachute deployed
Systems – cockpit

- Fuel quantity & battery voltage indicators
- Pressure & temperature gauges
- Parachute (3) and airbrake (4)
- Trigger fires rocket
- Brake Pedal
- Jet Pedal
Aerodynamics – car evolution

Configuration 0, August 2007

- Twin intakes, large delta fin, rocket above jet, no rear wheel fairings
- Curved intake, swept horizontal surfaces, contoured aft body


Configuration 1, Spring 2008

Configuration 2, August 2008

Configuration 9, Sept 2009

Configuration 12, Aug 2010

On-going refinement of body contours.
Aerodynamics – intake compression

Shock wave angles at M=1.4 (1050mph).

Much CFD on intake design to avoid surge issues (surge margin of EJ200 eroded for increased performance).
Aerodynamics – whole body

Making the car lift-neutral over the speed range has been a primary goal.

Shock waves at M=1.3 from the nose, cockpit surround and wheel fairings.
Aerodynamics – aft body

Reducing the lift of the aft body at $M > 1.0$ has been a major challenge – achieved using ventral aerofoils.

Previous design – $C_p > 0$ over much of underside.

Current design – $C_p = 0$ over much of underside.
Structures - materials

- **Air Brakes**: Carbon Composite Face Sheets, Aluminum Core
- **Forward Bodyshell and nose fairing**: Carbon Composite
- **Aft Upper Bodyshell**: Ti Skins and Longerons and Al Frames
- **Aft Lower Bodyshell**: Steel Skins and Al Frames
- **Mid-length Joint**: Forged 7037 Aluminum Wheels
- **HTP Tank**: Stainless Steel
- **Carbon Composite Jet Fuel Tank**: containing Flexible Bladder
Structures - manufacture

Follows experience in aerospace and motorsport:
• Hand lay-up – labour intensive, but it’s a one-off
• Autoclave cure – expensive plant, but not dedicated to *Bloodhound* manufacture.

Completion of the cockpit/intake monocoque at URT Group.
Structures - manufacture

Lower chassis in steel sheet with aluminum frames:
• Rivets provide sufficient strength
• Redux bonding adds stiffness.

The complete lower chassis following riveting and bonding.
Structures - manufacture

Upper chassis in titanium sheet with aluminum frames and titanium stringers:

- Frames support the EJ200 engine
- Aft, heavy frames support fin.

Aluminum frames for the upper chassis, Feb 2014.
Structures - analysis

- Static analysis - ultimate factor of 2.4 for composites
- Fatigue – not considered: short vehicle life; part replacement as required
- Damage tolerance - not considered:
  - Large ultimate factor on plain strength
  - Low number of cycles, limiting damage growth
  - Inspection after test runs, giving opportunity for repair/replace.
- Natural frequencies – minimum frequency requirements to avoid flutter issues.

Load distribution from finite element analysis (FEA, Nastran).
Airbrake analysis examines static and dynamic response:

- Static calculation of:
  - Hinge and actuator bolted attachment forces
  - Face sheet running loads/stresses
  - Core transverse shear force.

- Dynamic assessment of natural frequency (>45Hz of fin).

Dimensions in mm:

- 50 max
- 36
- 7
- 7

50 max
The car *must* have four wheels.
The wheels:
• are 36” diameter
• rotate at 9800rpm at 1050mph
• experience 50000’g’ at the rim
…hence are of solid Aluminum alloy.

Equivalent hoop stress 86ksi (600MPa).

Spin test at Rolls-Royce, Derby, Aug 26th 2014
Bloodhound in education

Key feature of the Bloodhound program:

• The education program, supplying ideas and resources across a range of school curricula

• Visiting STEM ambassadors explain the technology in schools

• Careers advice

• and...

website provides a wealth of resources for the teacher (and the engineer!)

http://www.bloodhoundssc.com/
## Competition for the Record

<table>
<thead>
<tr>
<th></th>
<th>Bloodhound SSC</th>
<th>North American Eagle</th>
<th>Aussie Invader 5R</th>
<th>Jetblack</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Origin</strong></td>
<td>UK</td>
<td>North America</td>
<td>Australia</td>
<td>New Zealand</td>
</tr>
<tr>
<td><strong>Engine</strong></td>
<td>Turbofan, Hybrid Rocket</td>
<td>Turbojet, Afterburner</td>
<td>Bi-propellant Liquid Rocket</td>
<td>Turbojet, Hybrid Rocket</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>135,000 HP</td>
<td>52,000 HP</td>
<td>200,000 HP</td>
<td>81,000 HP</td>
</tr>
<tr>
<td><strong>Length</strong></td>
<td>44 ft</td>
<td>56 ft</td>
<td>52 ft</td>
<td>43 ft</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>14,000 lb</td>
<td>13,000 lb</td>
<td>14,000 lb</td>
<td>16,000 lb</td>
</tr>
<tr>
<td><strong>Speed</strong></td>
<td>1000+ mph</td>
<td>800+ mph</td>
<td>1000+ mph</td>
<td>1000+ mph</td>
</tr>
</tbody>
</table>
Bloodhound SSC’s attempt