EV1 RETROSPECTIVE AND THE ELECTRIC VEHICLE REVOLUTION

Bio

• 32 years working for GM (including 5 for Hughes Aircraft Company)
• 27 years developing Power Electronics, Electric Motors, and complete Electric Traction Systems
• Gen I EV1 Power Electronics Mechanical Engineering Manager
• Gen II EV1 Power Electronics Program Manager
• Sr. Engineering Group Manager, Global Electric Motor Development
• VP Engineering – Flex Power Controls Inc.
• EV1 Overview
• EV Landscape over the past 20 years
• EV Trends and industry direction
• OEM plans for EVs (The EV Explosion)
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EV1 Facts

• The IMPACT concept car was first exhibited at the LA Auto Show in 1990
• GM/Hughes Aircraft create small Power Electronics group in Southern California in 1990
• GM instituted a PrEView fleet of 50 IMPACT vehicles to be driven by the public in 1994
• GM made the decision to launch a production EV in response to the CARB ZEV mandate
• EV1 was introduced in December 1996 (Gen I)
• GM marketed and leased the GM EV1 through its Saturn dealership network
• Cars were only available for lease in warm weather climates (CA, AZ, and limited availability in GA)
• Total sales of the vehicle were 1117: Gen I – 660, Gen II – 457
• The EV1 program was discontinued in 2002
• All EV1s were eventually repossessed and the vehicles were destroyed by GM
• An award winning documentary was made entitled “Who Killed the Electric Car” in 2006
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GEN I EV1 (1996-1997) - Traction System and Charging

- Power Electronics Bay (Power Inverter, Accessory Power Module, Power Steering Inverter)
  - Power Inverter
    - 110 kW IGBT based inverter (water cooled) including vehicle controller
  - Accessory Power Module (conduction cooled to inverter)
    - 12V DC-DC Converter for Accessory loads (1.2 kW)
    - 48V DC-DC Converter heated windshield or 48V PTC cabin heater (2 kW)
    - Compressor Motor controller (high voltage 5 kW inverter for HVAC)
  - High voltage 5 kW electric power steering inverter (conduction cooled to inverter)
- 102 kW/149 Nm 3 phase copper AC Induction motor (back iron cooled)
- Single speed reduction offset gearbox (oil lubricated)
- 16.5-18.7 kWh lead acid battery pack (air cooled) – later GEN I models received larger battery
- 6.6 kW Inductively Coupled Charger (Magne Charge)
- DC Charge Port (including electronics)
- Total range: 70 to 100 miles (estimated)
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GEN II EV1 (1999) – Traction System and Charging

- Power Electronics Bay Integrated into a single enclosure (48% volume reduction/40% cost reduction)
  - 110 kW IGBT based inverter (water cooled) including vehicle controller
  - 12V DC-DC Converter for Accessory loads (1.2 kW)
  - 48V DC-DC Converter heated windshield or 48V PTC cabin heater (2 kW)
  - Compressor Motor controller (high voltage 5 kW inverter for HVAC)
  - High voltage 5 kW electric power steering inverter (conduction cooled to inverter)
  - Charging components (rectifiers, 4th element film capacitor)
- 102 kW/149 Nm 3 phase aluminum AC Induction motor (back iron cooled)
- Single speed reduction offset gearbox (oil lubricated)
- 26.4 kWh NiMH battery pack
- Gen II 6.6 kW Inductively Coupled Charger (Magne Charge) – Lower Cost
- AC Charge Port (no power electronics)
- Total Range: 100 to 140 miles (estimated)
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EV1’s Significant Innovations and Lasting Legacy

- First automotive high voltage IGBT based inverter (110 kW)
- First high voltage “Power Electronics Bay” for integrated PE, Cooling, and HV Safety
- Rapid Active discharge and HV disconnect safety circuitry
- Electric power steering (high voltage)
- Inductive charging (6.6 kW to 50 kW)
- Regenerative braking and brake blending
- Extensive light-weighting
  - Cast aluminum shock towers
  - Magnesium seat frames
  - Squeeze cast aluminum wheels
  - Cast aluminum cradle
  - Aluminum space frame
- Low rolling resistance tires
- Sealant tires with pressure check system
- Dual air bags
- Ultra low drag coefficient: $C_d = 0.19$
<table>
<thead>
<tr>
<th>Car Type</th>
<th>1996 EV1</th>
<th>2017 Chevy Bolt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>169.7</td>
<td>164</td>
</tr>
<tr>
<td>Width</td>
<td>69.5</td>
<td>69.5</td>
</tr>
<tr>
<td>Height</td>
<td>50.5</td>
<td>62.8</td>
</tr>
<tr>
<td>Mass (lbs)</td>
<td>3086 (Lead Acid)/2908 NiMH</td>
<td>3563</td>
</tr>
<tr>
<td>Battery Capacity</td>
<td>16.6-18.7 kWh (Lead Acid)/26.4 kWh (NiMH)</td>
<td>60 kWh (Li-ion)</td>
</tr>
<tr>
<td>Power</td>
<td>102 kW/137 bhp</td>
<td>150 kW/200 bhp</td>
</tr>
<tr>
<td>Torque</td>
<td>149 Nm/110 lb-ft</td>
<td>360 Nm/266 lb-ft</td>
</tr>
<tr>
<td>Range (Miles)</td>
<td>70-100 (Lead Acid)/100-140 (NiMH)</td>
<td>238 (EPA)</td>
</tr>
</tbody>
</table>
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Major OEM BEV Introductions since the EV1


**Toyota:** RAV4 Gen 1 (1997), Gen II (2012)

**Nissan:** Leaf Gen 1 (2011), Gen II (2017)

**VW:** eGolf (2015)

**Honda:** Fit EV (2012), Clarity (2018)

**Tesla:** Roadster (2008), Model S (2012), Model X (2015), Model 3 (2017)

**Ford:** Focus EV (2012)

**Chrysler:** Fiat 500e (2013)

**Hyundai/Kia:** IoniQ (2016) and Soul (2015)

**BMW:** i3 (2014)

**Mercedes:** B Class Electric Drive (2015)
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### All-electric car EPA rated range per full charge

2016/2017 MY models priced under US$50,000 in the U.S. market (miles)

<table>
<thead>
<tr>
<th>Model</th>
<th>Range (miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tesla Model 3 long range</td>
<td>238</td>
</tr>
<tr>
<td>Chevrolet Bolt EV</td>
<td>220</td>
</tr>
<tr>
<td>Tesla Model 3 standard</td>
<td>187</td>
</tr>
<tr>
<td>BYD e6</td>
<td>115</td>
</tr>
<tr>
<td>2017 Volkswagen e-Golf</td>
<td>125</td>
</tr>
<tr>
<td>Hyundai Ioniq Electric</td>
<td>124</td>
</tr>
<tr>
<td>2017 Ford Focus Electric</td>
<td>114</td>
</tr>
<tr>
<td>BMW i3 94 A-h</td>
<td>107</td>
</tr>
<tr>
<td>Nissan Leaf 30 kW-h</td>
<td>93</td>
</tr>
<tr>
<td>Kia Soul EV</td>
<td>87</td>
</tr>
<tr>
<td>Mercedes-Benz B250e</td>
<td>68</td>
</tr>
<tr>
<td>Nissan Leaf 24 kW-h</td>
<td>84</td>
</tr>
<tr>
<td>Fiat 500e</td>
<td>84</td>
</tr>
<tr>
<td>2016 Volkswagen e-Golf</td>
<td>83</td>
</tr>
<tr>
<td>Chevrolet Spark EV</td>
<td>82</td>
</tr>
<tr>
<td>BMW i3 60 A-h</td>
<td>81</td>
</tr>
<tr>
<td>2016 Ford Focus Electric</td>
<td>76</td>
</tr>
<tr>
<td>Smart electric drive</td>
<td>68</td>
</tr>
<tr>
<td>2016 Mitsubishi i-MiEV</td>
<td>62</td>
</tr>
<tr>
<td>2017 Mitsubishi i-MiEV</td>
<td>59</td>
</tr>
</tbody>
</table>
Vehicle Sales Worldwide and US

- Estimated Sales of 90 Million Vehicles worldwide in 2017
  - Record sales volume
  - Total Electric Vehicle (PEV) Sales – approx. 1 million
    - Roughly 1% total vehicle sales

- Estimated Sales of 17 Million Vehicles in the US in 2017
  - Down for the first time since 2009
  - Total Electric Vehicle Sales 199.8K
    - Up 25% over
    - Subsidies and tax breaks nearing the end

- Estimated Sales of 29 Million Vehicles (estimated) in China
  - Total Electric Vehicle Sales 500K in 2016
  - Estimated to drop in 2017 due to reduction in subsidies
Why is the EV Revolution Happening Now?

- China
- China
- China
- China
- “Dieselgate”
- Tesla
  - Major Luxury OEMs are tired of losing sales to Tesla
  - Model 3
- General Motors
  - **Bolt was a game changer** (238 miles range)
Trends Looking Forward

- Move towards pure Electric and away from Hybrid (HEV)
  - 200 plus mile range (except city cars)
  - $\geq 60$ kWh energy storage
  - Mass of vehicles $> 3,500$ lbs.
    - Larger vehicles (increased utility)
    - Vehicle structures mass being reduced, but greater energy storage being required
  - Efficient Fundamentals
  - Propulsion power $\geq 150$ kW
    - Meet reasonable acceleration
    - Must be “fun to drive”
- Packaging
  - “Skateboard” chassis allows for production reuse and multiple vehicle types
  - Integration into flat package
Faraday Future VPA

- All electric
- Front and Rear electric motors
- Battery flat pack
- One platform that scales
  - Passenger and SUV
- Expandable platform
  - Increase energy storage for larger vehicles
  - Increase voltage (possibly max of 650 to 700V)
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Trends Looking Forward

• Transformation of Transportation “Mobility as a Service”
  • Autonomous EVs
  • 15 year/300K miles
• Charging
  • Extreme Fast Charging
  • Wireless dynamic charging
  • Autonomous charge (wireless with auto docking)
• Secondary impacts
  • Electric Grid infrastructure improvements
Enablers for Future EVs

- WBG Devices (SiC and GaN)
  - Higher Switching Frequencies
  - Lower power dissipation
  - Higher operating voltages
  - Higher power density
- Higher voltage battery packs
  - Lower motor phase currents
  - Lower charging currents for DC Fast Charge
- Lower battery costs with increased scale, improved chemistry, manufacturing capability, and new suppliers
Announced Plans – “The EV Explosion”

**GM:** 3 new models in 18 months, 20 new models by 2023

**Toyota:** 10 new models by early 2020s

**Nissan/Renault/Mitsubishi:** 12 new models by 2022

**VW Group:** 300 models will have electric variant by 2030 ($84B investment in Electric Vehicles)

**Honda:** 2 new EVs in 2018, 2/3 of all vehicles will be “electrified” by 2030

**Tesla:** New Roadster, Semi-Truck

**Ford:** Electric SUV in 2019, 15 new models for China by 2025

**FCA:** 2 electric Maseratis by 2020

**Hyundai/Kia:** 14 new EV models by 2025

**BMW:** 12 EVs by 2025

**Mercedes:** Electric versions of every vehicle by 2022 (EQ brand)
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What Has to Happen to Insure Mass Market Adoption

• Legislation (already occurring in China and Europe)
  • China is driving the EV market and vehicle development
• Tax Credits continue in the short term (U.S.)
• Higher Gas Prices in the U.S. (We love our SUVs and Full Size Trucks)
• Significant Infrastructure Changes to the Electric Grid
• Real Commitment from the Automotive OEMs
  • Competitive vehicles with adequate range and utility
  • Competitively priced options vs. conventional powertrains
  • Styling and performance equivalent to IC engine variants
• EV components continue to come down the cost curve (PE, Batteries, Motors)
• New Urban Mobility models emerge in large cities
  • Allows for higher sales of EVs
  • Car sharing services utilizing EVs (Lyft, Uber, Maven, Zip Car)
  • Autonomous EVs (allows for lower operating costs)