University of Wisconsin Madison

Electric Snowmobile

Presented by:

Ethan Brodsky
<table>
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<tr>
<th>Parameter</th>
<th>NSF Emphasis</th>
<th>CSC Emphasis</th>
<th>UW Emphasis</th>
</tr>
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<tbody>
<tr>
<td>Range</td>
<td>Primary</td>
<td>Secondary (100 points)</td>
<td>Primary</td>
</tr>
<tr>
<td>Towing Capacity</td>
<td>Primary</td>
<td>Secondary (100 points)</td>
<td>Primary</td>
</tr>
<tr>
<td>Weight</td>
<td>Secondary</td>
<td>Secondary (100 points)</td>
<td>Secondary</td>
</tr>
<tr>
<td>Handling</td>
<td>Minor (safety only)</td>
<td>Secondary (125 points)</td>
<td>Secondary</td>
</tr>
<tr>
<td>Acceleration</td>
<td>None</td>
<td>Minor (50 points)</td>
<td>Secondary</td>
</tr>
<tr>
<td>Noise</td>
<td>None</td>
<td>Primary (300 points)</td>
<td>Secondary</td>
</tr>
<tr>
<td>Cost</td>
<td>Primary</td>
<td>Minor (50 points)</td>
<td>Secondary</td>
</tr>
<tr>
<td>Durability and Maintainability</td>
<td>Primary</td>
<td>Secondary (100 points)</td>
<td>Primary</td>
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Greenland 2008 Summary

- Most trips are short
  - Typical trip: Big House or Balloon Barn to Sat Camp
    - 2.2 km (1.4 mi) round-trip
  - Trip length: (of 72 trips >0.1 mi in a ten day period)
    - 47 ≥0.5 mi, 14 ≥1.0 mi, 6 ≥2 mi, 3 ≥3 mi.
  - Longest trips – 6 mi round-trip
- Total usage
  - 341 km (212 mi) in 57 days (4 mi daily average)
  - 26 hr of operation (non-zero speed)
  - Typical speeds: 5-15 mph
- Practical range
  - 5-10 mi with a 1500 lb towed payload
  - 2x-3x reduction from maximum unloaded range
- Required range?
  - Vehicle capabilities affects trip choices
## Specific Design Goals

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<th>UW Goal</th>
<th>UW Achieved</th>
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<td>≤10 s</td>
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<td>Emissions</td>
<td>Zero</td>
<td>Zero</td>
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<td>Weight</td>
<td>≤ 340 kg (750 lb)</td>
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<td>≤ 78 dB</td>
<td>≤ 60 dB</td>
<td>55 dB</td>
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Design Overview

- **Delphi/GM EV1 AC Induction Motor**
- **Azure Dynamics DMOC445LC Variable Speed Drive Inverter**
- **Milwaukee Tool V28 Lithium Ion Batteries (8 strings x 91 cells)**
- **Woodward/Mototron PCM555 Embedded Controller**
- **Solectria 400V → 12V DC/DC Converter**
- **Brusa NLG503 3 kW 120/240 VAC On-Board Charger**
- **Polaris Industries IQ Fusion Chassis**
- **Delphi/GM EV1 AC Induction Motor**

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**University of Wisconsin Clean Quiet FAST SAE Snowmobile Team**
Battery Chemistry Comparison

<table>
<thead>
<tr>
<th></th>
<th>Pb-Acid</th>
<th>NiMH</th>
<th>Li-ion</th>
<th>Petrol</th>
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<tbody>
<tr>
<td>Energy Density (Gravimetric)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Wh/kg)</td>
<td>30-40</td>
<td>40-120</td>
<td>100-180</td>
<td>12000</td>
</tr>
<tr>
<td>Energy Density (Volumetric)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Wh/L)</td>
<td>60-75</td>
<td>140-400</td>
<td>200-300</td>
<td>9000</td>
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<tr>
<td>Power Density (W/kg)</td>
<td>180</td>
<td>300-1000</td>
<td>1000-5000</td>
<td></td>
</tr>
<tr>
<td>Cycle efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(% charge/discharge)</td>
<td>70-92%</td>
<td>65-80%</td>
<td>95-99%</td>
<td></td>
</tr>
<tr>
<td>Cycle life (total cycles)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>500-800</td>
<td>500-1000</td>
<td>500-15000</td>
<td>1</td>
</tr>
<tr>
<td>Self-discharge (%/month)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3-20%</td>
<td>~30%</td>
<td>5-10%</td>
<td></td>
</tr>
<tr>
<td>Current cost ($/Wh)</td>
<td>0.15-0.30</td>
<td>0.30-0.60</td>
<td>0.50-2.50</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
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## Battery Chemistry Comparison

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<thead>
<tr>
<th></th>
<th>Nickel Metal Hydride</th>
<th>Lead Acid</th>
<th>Lithium-Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage/Cell</td>
<td>1.25 Volts/Cell</td>
<td>2.12 Volts/Cell</td>
<td>4.00 Volts/Cell</td>
</tr>
<tr>
<td>Voltage Total</td>
<td>364 V → 291 Cells</td>
<td>364 V → 172 Cells</td>
<td>364 V → 91 Cells</td>
</tr>
</tbody>
</table>
Battery Selection

![Battery Selection](image)

- **Lead Acid AGM**
- **NiMH**
- **LiION**

Cycle Life vs Depth of Discharge (%)
Battery Packaging

Milwaukee Tool V28 Li-Ion Battery Modules

2008 Design
7 strings x 12 Modules
6.5 kW-hr @ 336 V<sub>nominal</sub>
90 kg (198 lb)

2009 Design
8 strings x 13 Modules
8.2 kW-hr @ 364 V<sub>nominal</sub>
84 kg (185 lb)
Delphi EV1 Motor

AC Induction

100 kW continuous

≥ 90% efficient
Motor Controller

Azure DMOC445LC Motor Controller
Current Drivetrain (2008 Design)
Silent Chain in Oil Bath with Sealed Case
2009 Gen2 Drivetrain Concept
Gates PolyChain GT Carbon Belt
2009 Gen2 Drivetrain Concept
Gates PolyChain GT Carbon Belt
Vehicle Management

- Monitors:
  - Battery: \( V, I_{\text{string}}, T_{\text{string}}, \text{HV isolation} \)
  - Motor/Inverter: \( T_{\text{actual}}, T_{\text{mot/inv}}, \text{faults} \)
  - Vehicle Speed
  - Rider torque and brake cmd

- Controls
  - Motor torque (CAN)
  - On-board charger (CAN)
  - Coolant circulation pump
  - Cruise control
  - Main battery contactors
  - Indicators/gauges

MotoTron PCM555
Powertrain Control Module
Ratings
Automotive/Marine
-40° to 130 ° C
18 g Shock Load
Immersion to 3 m underwater
MATLAB Simulink Control Models
MotoHawk Automatic Code Gen
CAN Communication
Vehicle Control Layout

**Inputs**
- Key Switch
- Accelerator Position
- Brake Switch
- Reverse/Cruise Button
- Kill Switch

**Outputs**
- Coolant Pump
- Speedometer
- Torque Gauge
- Malfunction Indicator Light
- Reverse Indicator Light
- Low Battery Indicator Light
- Brake Lights
- Accessory Power Driver

**Components**
- Motor Controller
- On-Board Charger
- Data-logger
- GPS
- System Monitor Gauge
- Diagnostic Port
Datalogging System

- **Hardware**
  - Woodward/Mototron ARDAQ embedded controller
  - 12V Bus Powered, Battery Backup for RTC
  - Dual CAN + analog/digital inputs
  - 512 MB on-board flash
  - USB port

- **Software**
  - Developed by Argonne National Laboratory
  - MATLAB/Simulink Block Diagrams
  - Realtime Workshop (RTW) Code Generation

- **Functionality**
  - Automatically records specified CAN fields
  - Can record several months of operation in on-board flash
  - Downloads to USB flash disk
    - Data file emailed back to Madison every 2 weeks
Datalogging System

- Values recorded during operation (1 s sampling period)
  - Time
  - GPS Lat/Lon/Speed
  - Power Up Count/Time
  - Track Speed
  - Battery Voltage, estimated SoC
  - Commanded/Actual Torque
  - Accel/Brake Commands
  - Reverse Mode
  - Kill Switch Position
  - Battery current (per-string)
  - Motor Controller Status/Faults
  - Inverter and Motor Temperature
  - Cruise Control Active/Target Speed
  - Battery temperatures
  - Aux (12V) battery voltage
  - Active fault codes

- Values recorded during charging (10 s sampling period)
  - All above
  - Mains voltage and current
  - Charge algorithm state (CC, CV, finished)
  - Charger temperature
  - Charger faults
Pack Capacity
- 19.6 A-hr → 6.5 kW-hr

Road load
- Initial model [Auth] – 4.6 kW at 20 mph – 230 W-hr/mi
- Testing (reduced pack and ballast)
  - Extremely variable based on snow conditions (and speed)
  - 6 kW at 20 mph (packed trail) – 300 W-hr/mi
  - 7 kW at 20 mph (another packed trail) – 350 W-hr/mi
  - 8 kW at 20 mph (deep snow) – 400 W-hr/mi
  - 10 kW at 20 mph (6-8” soft packed snow) – 500 W-hr/mi

Predicted range
- 20 mi absolute maximum (optimal conditions, full discharge)
- 15 mi practical range (typical conditions, limited discharge)

Achieved range
- 18.4 mi (20 mph on hard-packed trail)
- 360 W-hr/mi
Greenland Road Load Measurement

- 7 kW
- 12 kW
- 600 W-hr/mi
- 350 W-hr/mi
- 800 W-hr/mi

Power (accel/decel)
Power (constant speed)

Speed (mph)

Power (kW)

800 W-hr/mi
600 W-hr/mi
350 W-hr/mi
12 kW
7 kW
2009 Range

- **Pack Capacity**
  - 24% increase in energy (6.5 → 8.1 kW-hr)

- **Road load**
  - Sled unchanged from ’08
  - Snow conditions much poorer than ‘08
    - Soft wet snow leads to 2x-3x road load
      - (comparable to pulling trailer)

- **Predicted range**
  - Optimal conditions: 40 km (24 mi)
  - Expected competition conditions: 26 km (16 mi)

- **Achieved range**
  - 12.4 mi
    - Extremely poor course conditions (8” standing water) – 550 W-hr/mi
    - Batteries did not yield expected capacity (18.7 instead of 22.4 A-hr)
      - Reduction in rated capacity from manufacturer
Towing Capacity

- **Traction dominated**
  - 2008 scores ordered by weight
  - Weight hurts every other aspect
    - ↓ range, ↓ acceleration, ↓ handling, ↓ load capacity

- **Solutions**
  - Adjust weight balance aft
    - Moved more batteries under seat
  - Improve coefficient of traction
    - Studded track

- **Results**
  - Torque limits of electric drive
    - 275 kgf (650 lbf) max tractive effort
    - Maintained up to 35 mph (unlike DC motor solutions)
  - 261 kgf (575 lbf) officially achieved
  - How necessary are pull forces >>300?
    - 2000 lbf weight * $\mu_s = ???$ lbf
Battery Management

Estimate state-of-charge (SOC)

• Battery terminal voltage model
  • Voltage source
  • Series resistance
    • $R$ based on temperature
  • Series RC element
    • $\tau, R$ based on temperature
• Estimate SOC based on
  • $V_{\text{terminal}}$
  • $I_{\text{instantaneous}}, I_{\text{LPF}}$
  • Battery temperature
• Outputs
  • SOC, DTE indications
  • Warn rider at 10%
  • Terminate operation at 3%
• Working with industry partners to obtain automotive/turn-key system for 2010
Cold Performance

90% power available within 105 s

Nearly full capacity available

Rated by manufacturer at -10°C
Acceleration

Beats competition IC minimum of 12 s to 500 ft
8.34 s to 500 ft
2nd place overall
Best non-studded (IC or ZE)
Handling

2008 results
Within 0.09 s of best “Objective Handling” time (overall)
Won “Subjective Handling” (overall)
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2008 Greenland Summer Season
Fuel Savings Analysis

- Gasoline-Powered Snow Machine
  - Estimated 10 mpg
  - 0.1 gallon/mile

- Electric Snow Machine
  - 350-500 W-hr/mi
  - Diesel generator efficiency
    - 15 kW-hr/gallon
    - 0.02-0.05 gallon/mile

- Savings over 200 mi
  - 10-20 gallons
  - @ 6 lbs/gallon → weight of sled in ~5-10 years

- Other benefits
  - Diesel genset also provides building heat, snow melting
  - Reduced emissions → Enhanced research platform
    - Stationary source instead of mobile source pollution
    - Improved after-treatment possible on genset

- Alaska
Questions?