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Quiet
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SAE Snowmobile Team

University of Wisconsin Madison

Electric Snowmobile

Presented by:

Ethan Brodsky

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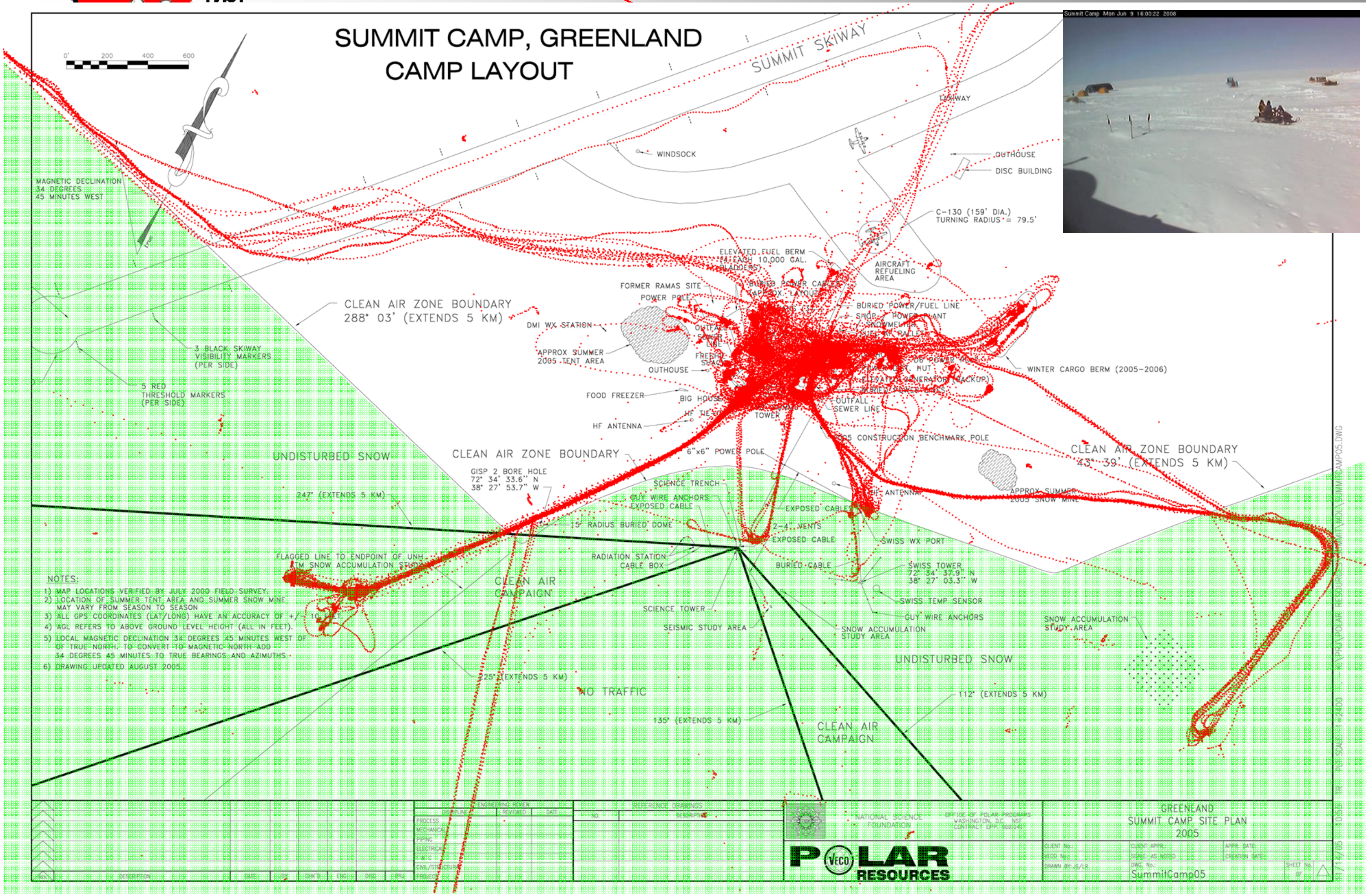
Design Emphasis

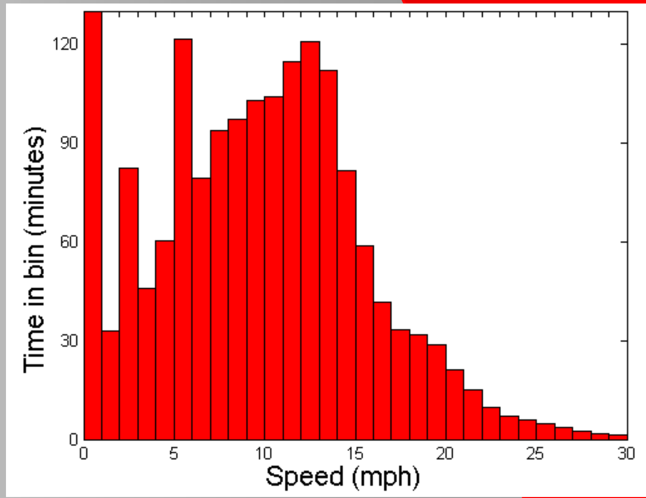
Parameter	NSF Emphasis	CSC Emphasis	UW Emphasis
Range	Primary	Secondary (100 points)	**Primary**
Towing Capacity	Primary	Secondary (100 points)	**Primary**
Weight	Secondary	Secondary (100 points)	Secondary
Handling	Minor (safety only)	Secondary (125 points)	Secondary
Acceleration	None	Minor (50 points)	Secondary
Noise	None	Primary (300 points)	Secondary
Cost	Primary	Minor (50 points)	Secondary
Durability and Maintainability	Primary	Secondary (100 points)	**Primary**

Greenland Summer '08 Trial



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



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Specific Design Goals

Parameter	CSC Goal	UW Goal	UW Achieved
Range	≥ 16 km (10 mi)	≥ 32 km (20 mi)	20 km (12.4 mi)
Top Speed (ZE goal)	≥ 70 km/hr (20 mph)	≥ 140 km/hr (90 mph)	≥ 120 km/hr (76 mph)
Acceleration (150 m)	≤12 s	≤10 s	6.9 s
Emissions	Zero	Zero	Zero
Weight		≤ 340 kg (750 lb)	320 kg (709 lb)
Drawbar Pull		≥ 250 kgf (550 lbf)	250 kgf (550 lbf)
Noise (IC)	≤ 78 dB	≤ 60 dB	55 dB

Design Overview

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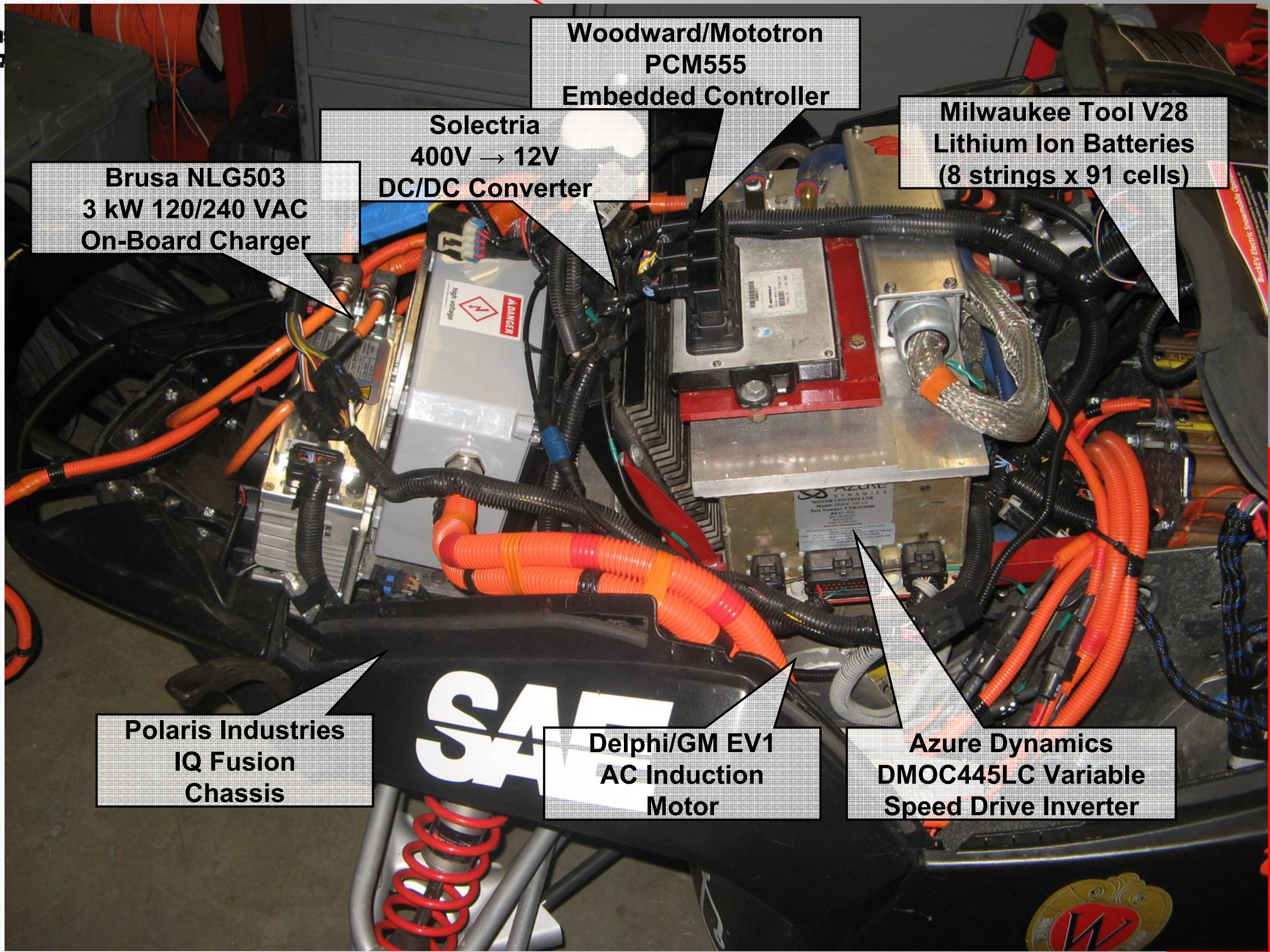

Battery Chemistry Comparison

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

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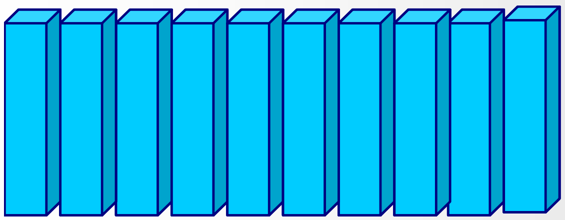
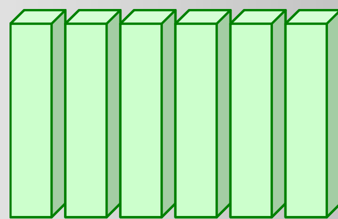
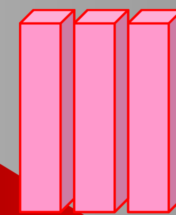
Battery Chemistry Comparison







Nickel Metal Hydride	Lead Acid	Lithium-Ion
1.25 Volts/Cell	2.12 Volts/Cell	4.00 Volts/Cell
364 V → 291 Cells	364 V → 172 Cells	364 V → 91 Cells

Battery Selection

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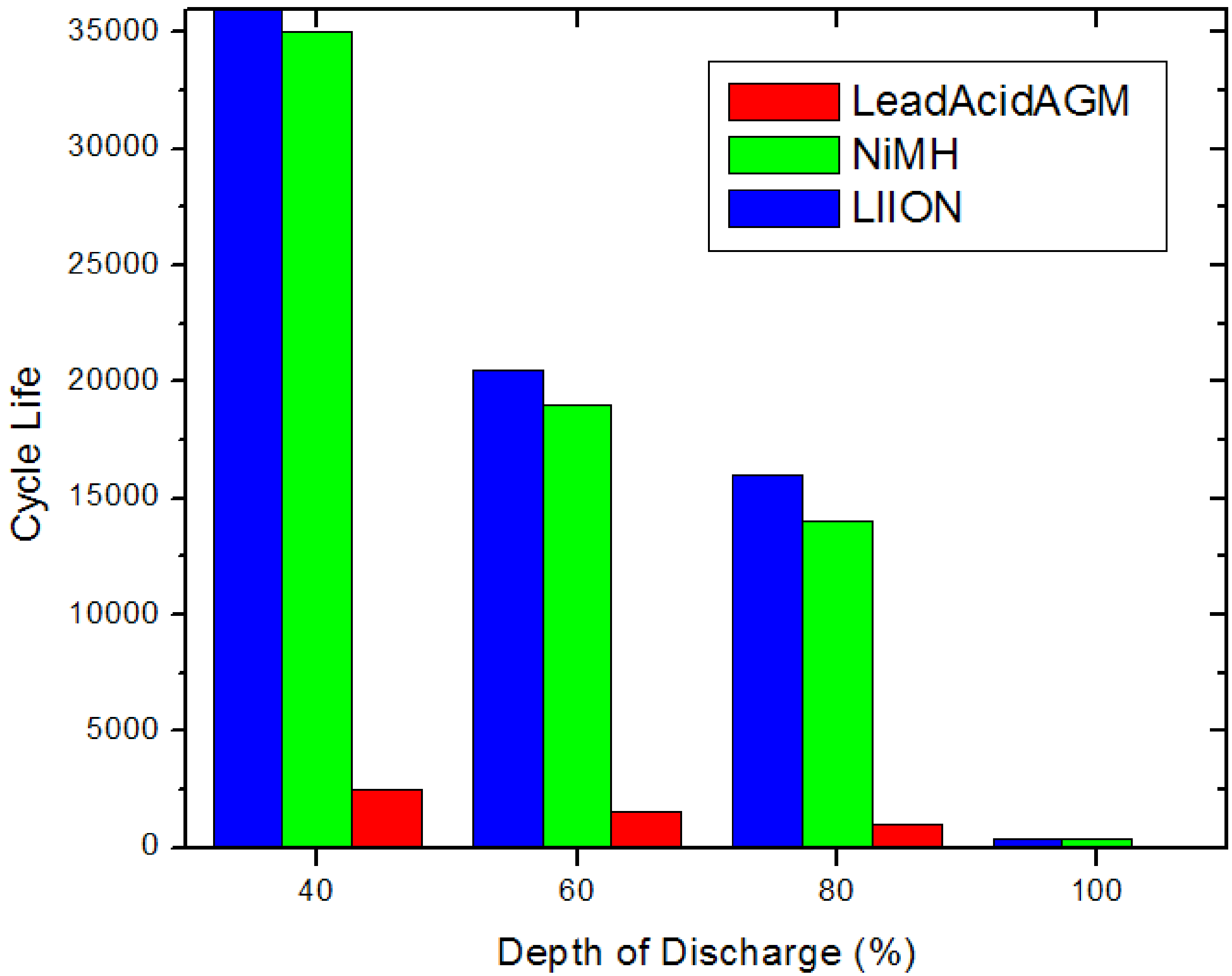

Battery Packaging

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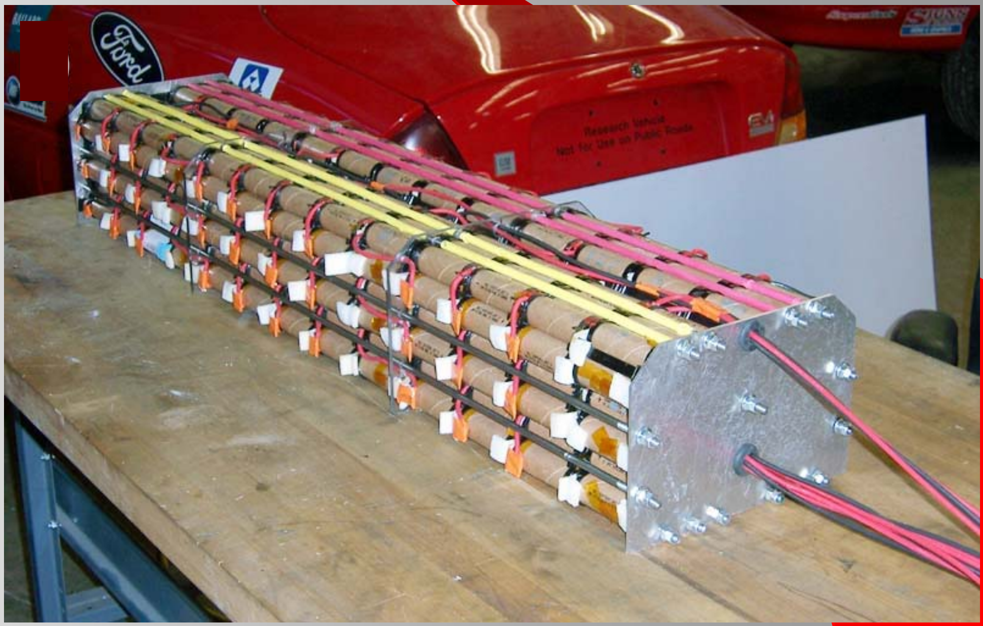
Milwaukee Tool V28 Li-Ion Battery Modules

2008 Design

7 strings x 12 Modules
6.5 kW-hr @ 336 $V_{nominal}$
90 kg (198 lb)

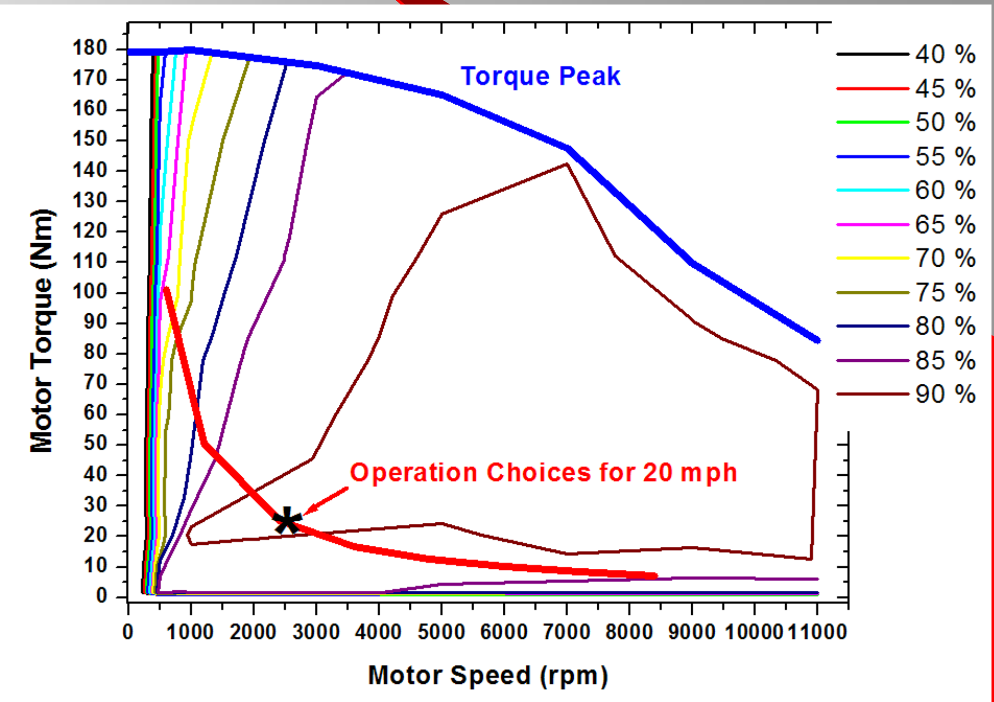


2009 Design

8 strings x 13 Modules
8.2 kW-hr @ 364 $V_{nominal}$
84 kg (185 lb)

Delphi EV1 Motor

AC Induction



≥ 90% efficient

100 kW continuous

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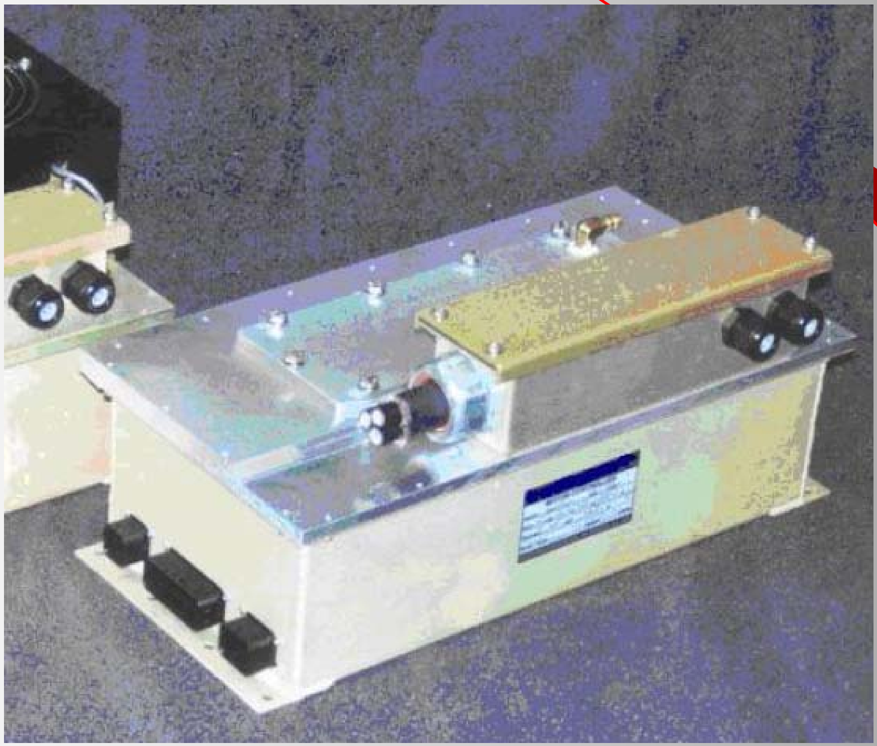
Motor Controller



Azure DMOC445LC Motor Controller

Current Drivetrain (2008 Design)

Silent Chain in Oil Bath with Sealed Case

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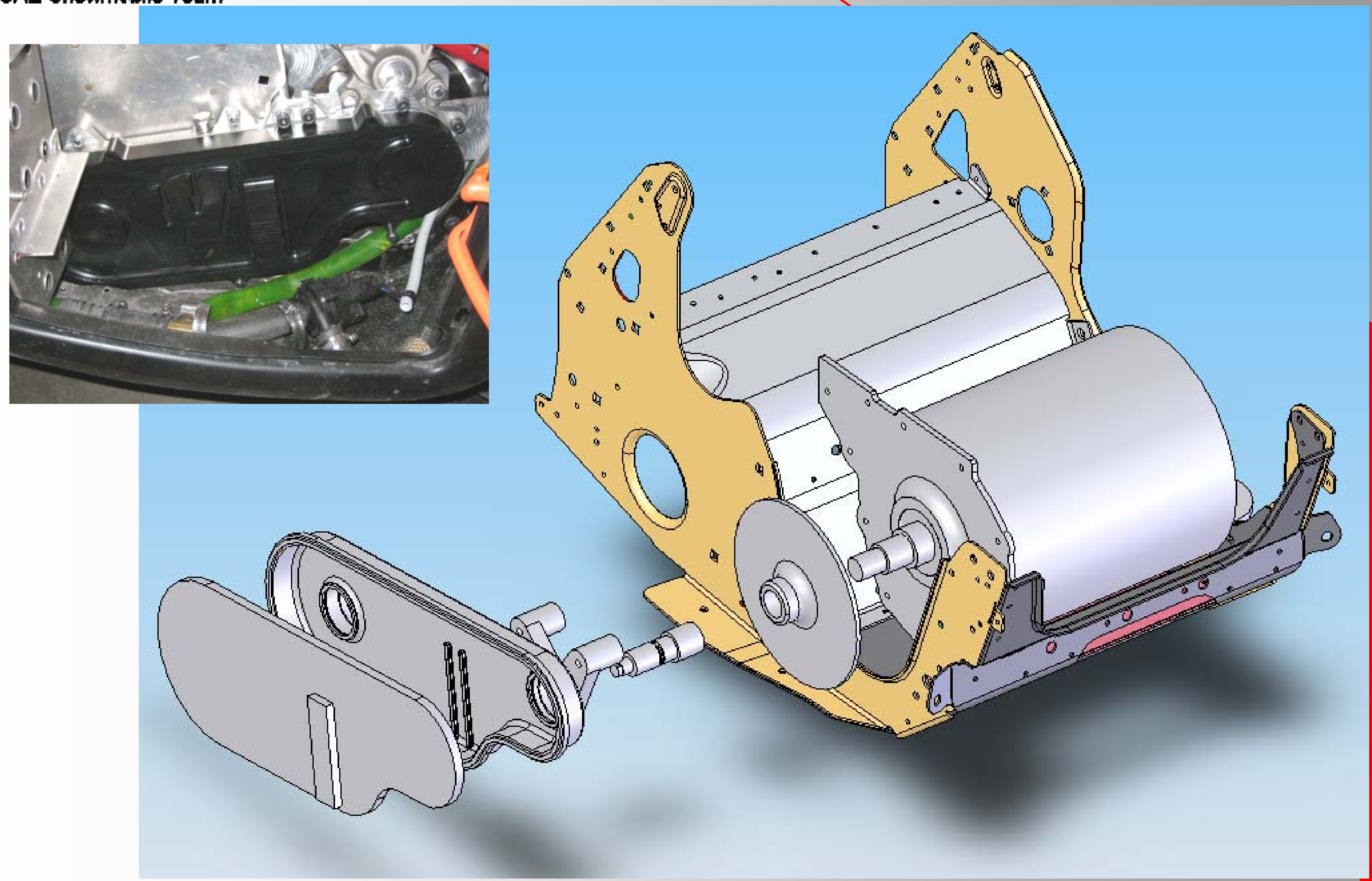

2009 Gen2 Drivetrain Concept

Gates PolyChain GT Carbon Belt

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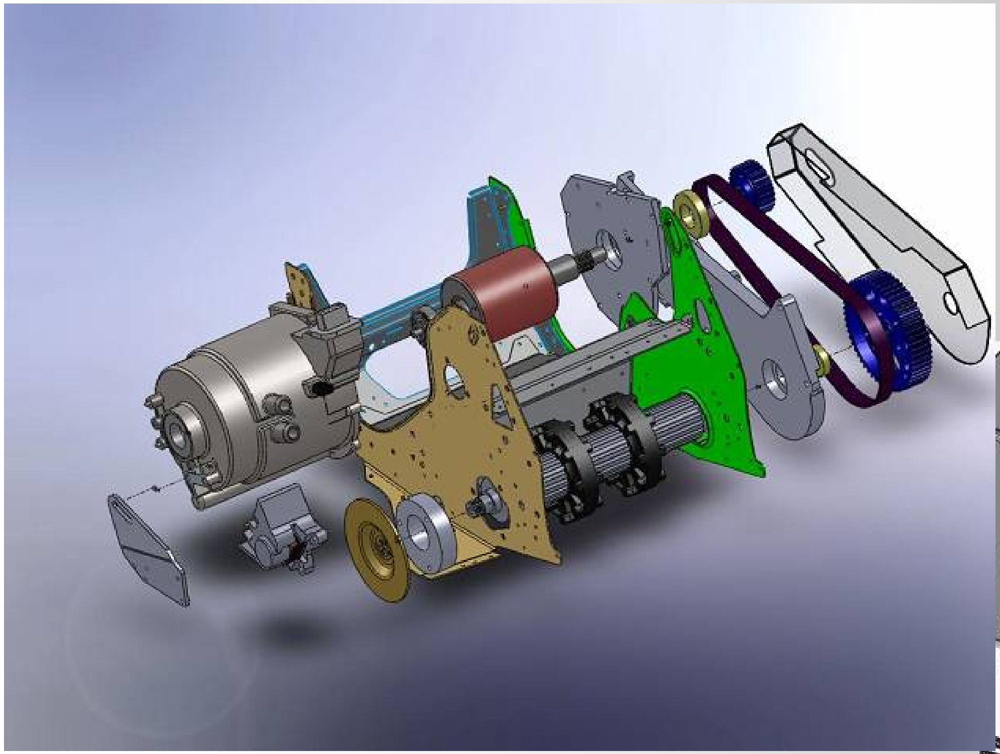

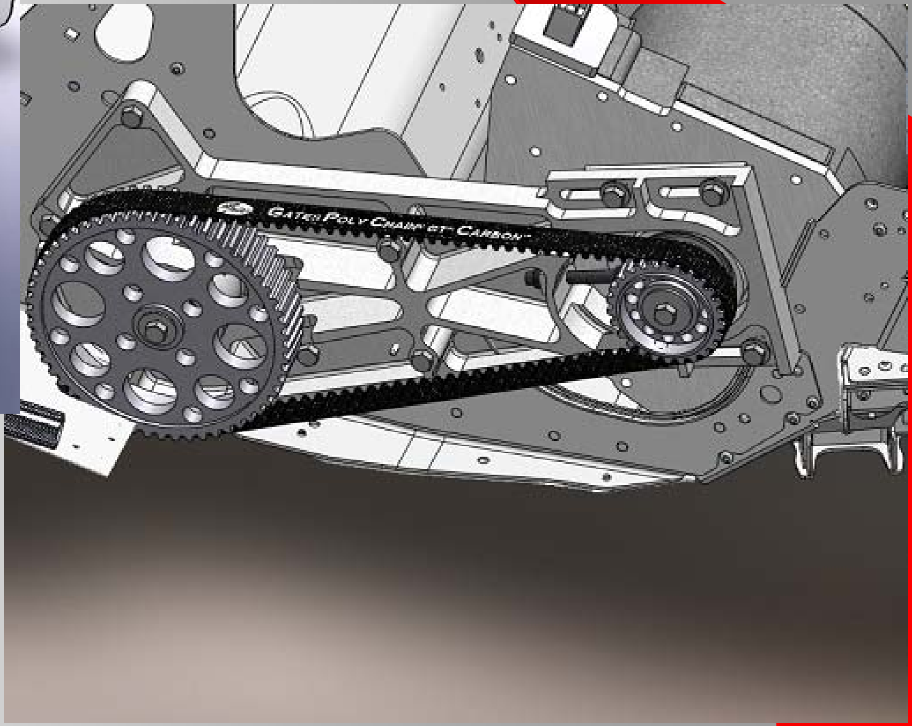

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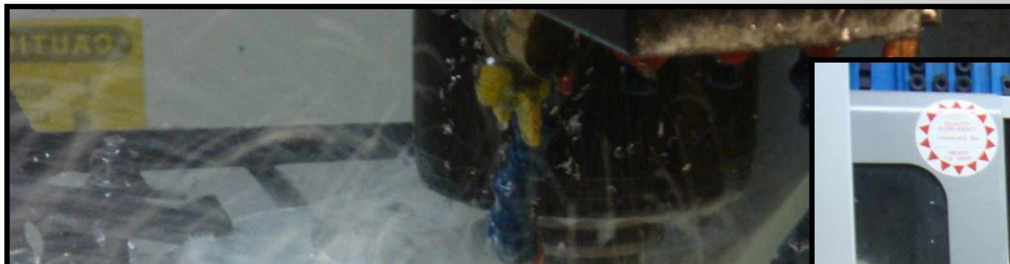
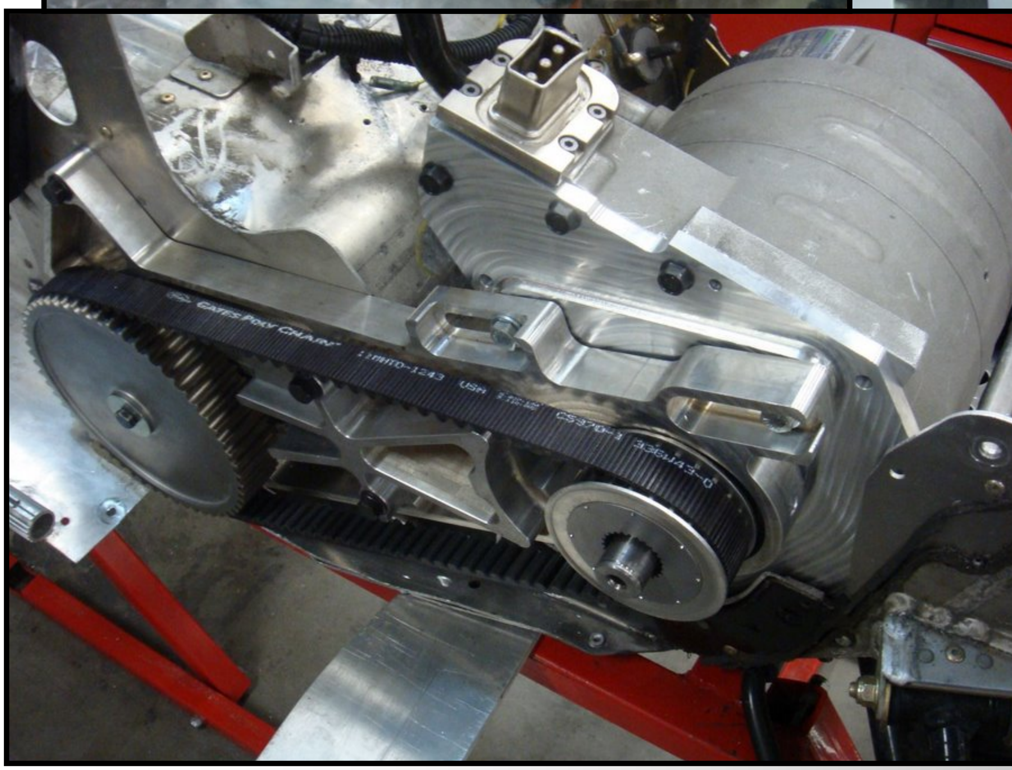
2009 Gen2 Drivetrain Concept

Gates PolyChain GT Carbon Belt





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Vehicle Management

- Monitors:
  - Battery: V, I_{string}, T_{string}, HV isolation
  - Motor/Inverter: τ_{actual}, $T_{mot/inv}$, 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

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CAN
Hub

INPUTS

Key Switch

Accelerator Position

Brake Switch

Reverse/Cruise Button

Kill Switch

OUTPUTS

Coolant Pump

Speedometer

Torque Gauge

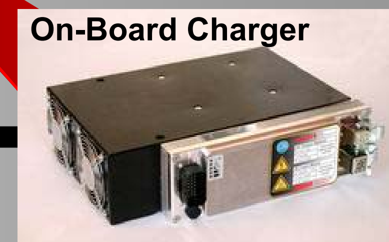
Malfunction Indicator Light

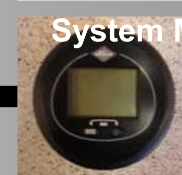
Reverse Indicator Light

Low Battery Indicator Light

Brake Lights

Accessory Power Driver





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/Faultse
  - 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

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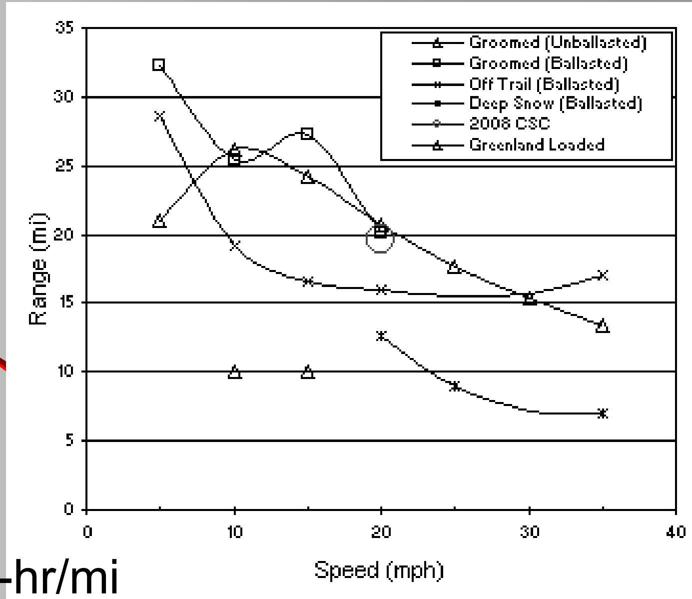
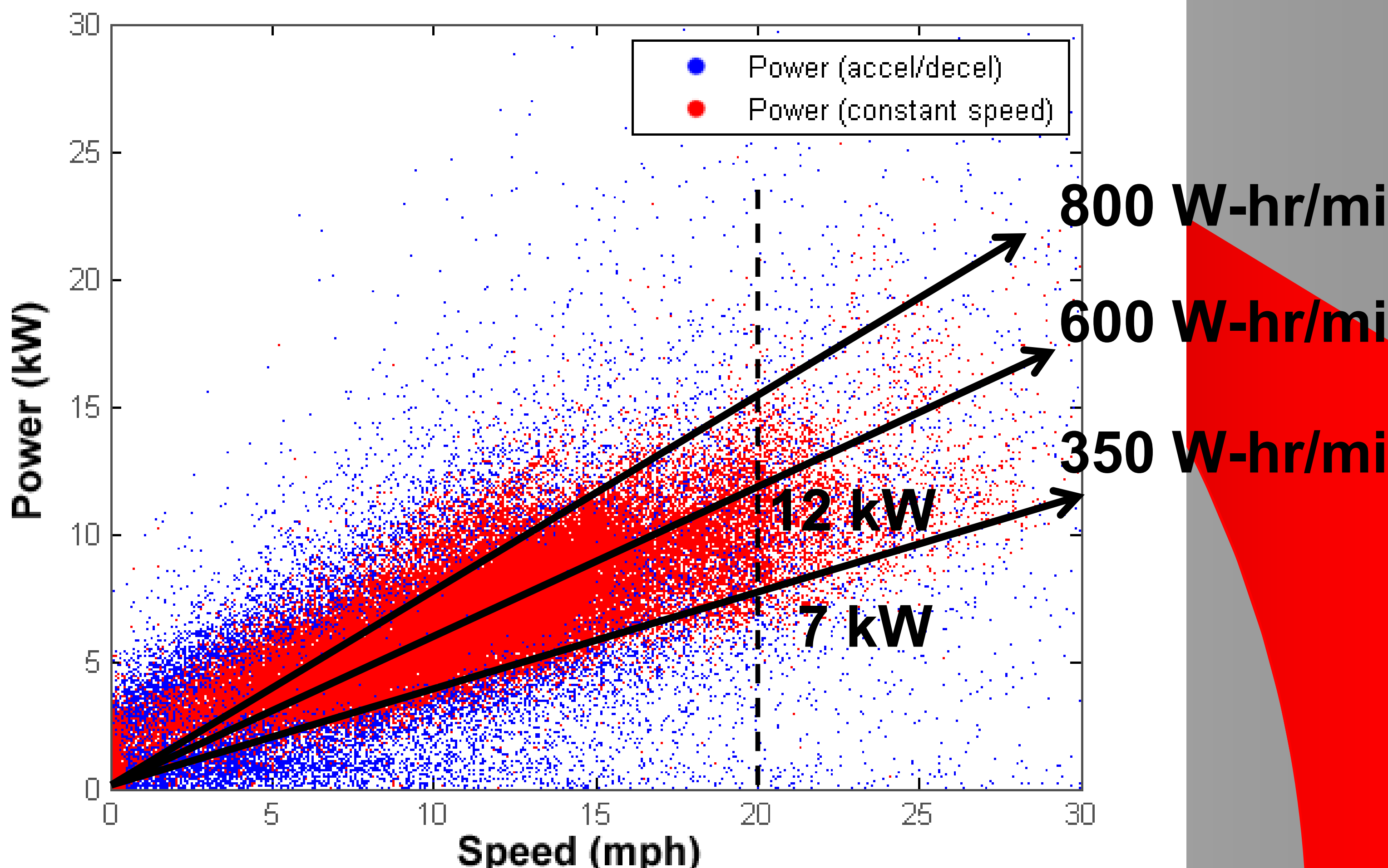
2008 Range



- 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

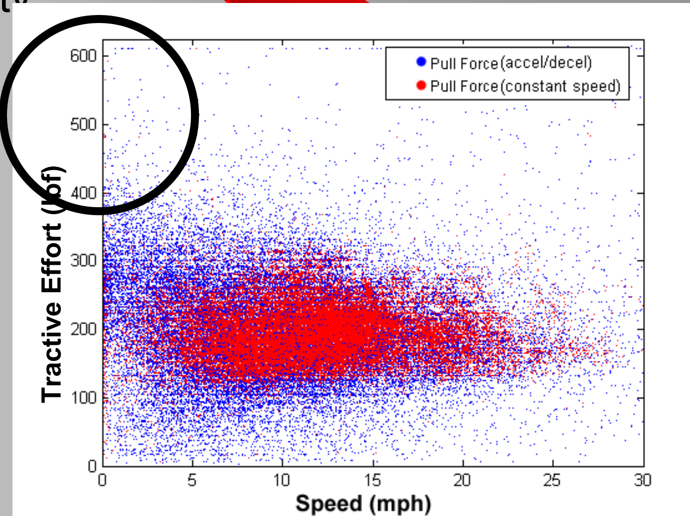


2009 Range

- 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

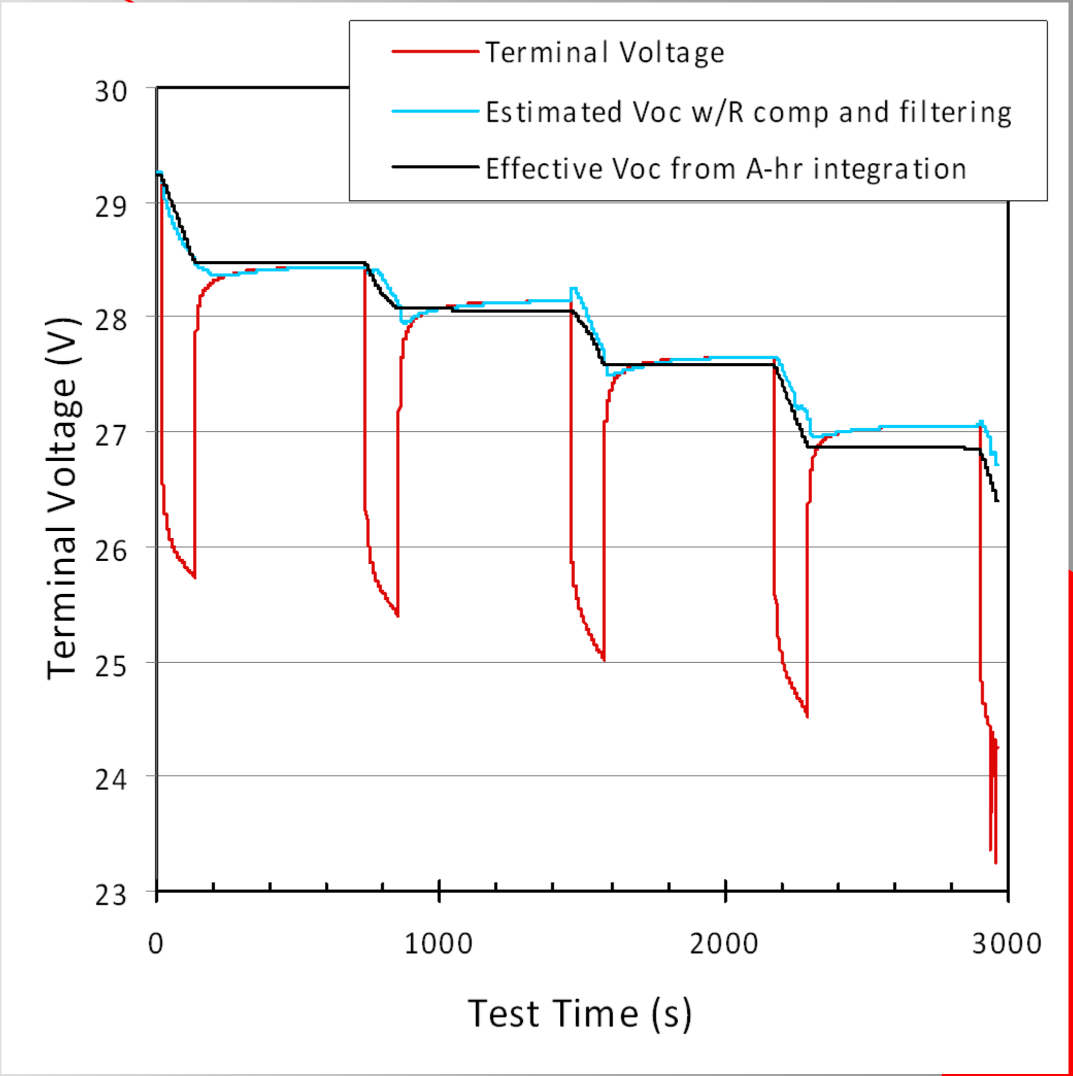
- Traction dominated
  - 2008 scores ordered by weight
  - Weight hurts every other aspect
    - ↓ range, ↓ acceleration, ↓ handling, ↓ load capacity
- Solutions
  - Adjust weight balance aft
    - Moved more batteries under seat
  - Improve coefficient of traction
    - Studded track
- Results
  - Torque 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 * μ_s = ??? lbf



Battery Management

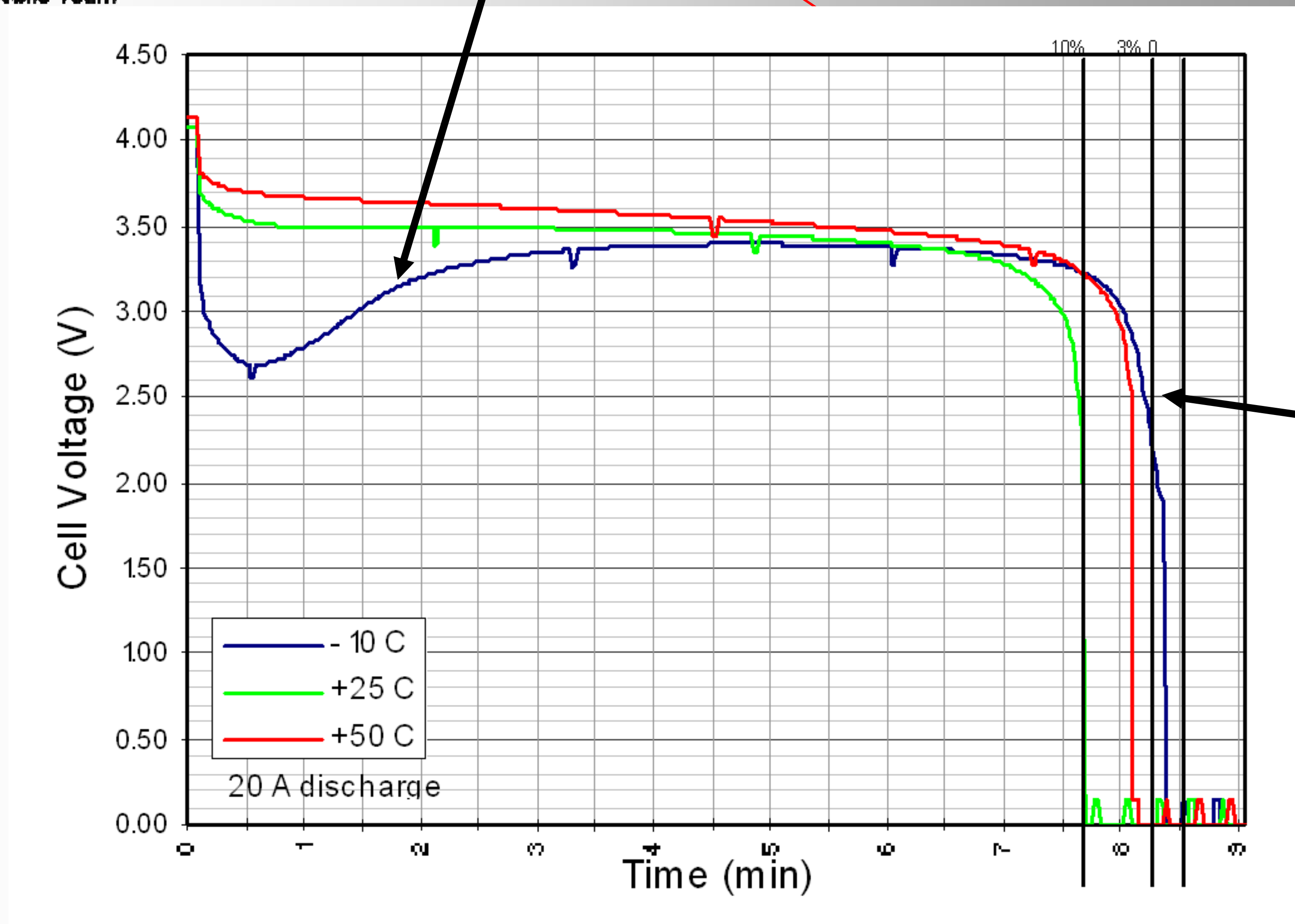
Estimate state-of-charge (SOC)

- Battery terminal voltage model
  - Voltage source
  - Series resistance
    - R based on temperature
  - Series RC element
    - τ,R based on temperature
- Estimate SOC based on
  - $V_{terminal}$
  - $I_{instantaneous}$, I_{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

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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)

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Handling

2008 results

- Within 0.09 s of best “Objective Handling” time (overall)
- Won “Subjective Handling” (overall)

Goal Recap

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Parameter	Competition Goal	UW Goal	UW Achieved
Range	≥ 16 km (10 mi)	≥ 32 km (20 mi)	20 km (12.4 mi)
Top Speed (IC goal)	≥ 70 km/hr (45 mph)	≥ 140 km/hr (90 mph)	≥ 122 km/hr (76 mph)
Acceleration (150 m)	≤12 s	≤10 s	6.9 s
Emissions	Zero	Zero	Zero
Weight		≤ 340 kg (750 lb)	320 kg (709 lb)
Drawbar Pull		≥ 250 kgf (550 lbf)	207 kgf (455 lbf)
Noise (IC)	≤ 78 dB	≤ 60 dB	56 dB

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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

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Questions?