Phase 1 Design Paper

2011 Skandic Tundra LT Electric Vehicle (EV) Conversion

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ABSTRACT

This design paper highlights methods and engineering calculations for three major design modifications for a pure electric vehicle conversion on a 2011 Skandic Tundra LT. The first section of this report displays calculations on how to estimate the power requirement for the snowmobile. These power requirement estimates become the basis for the three major design modifications to the snowmobile.

The first major design modification to the 2011 Skandic Tundra LT is the replacement of the gasoline engine with a 35 hp AC electric motor. A comparison between AC and DC motors are highlighted and reasons for running an HPEVS AC 35 motor is provided.

The second major design modification is the replacement of the gasoline tank with a 92.5 V/75 Ah battery pack. A comparison between the four common battery chemistries found in vehicular applications is provided along with reasons for running lithium ion battery technologies. Battery voltage and battery capacity design calculations are shown and explained.

The third major design modification is the replacement of the stock Continuously Variable Transmission (CVT) with a fixed gear ratio of 1.4 using a belt drive. The design equation along with reasons for running a fixed gear ratio belt drive is explained.

INTRODUCTION

Design Motivation

With increasing global warming concerns due to growing CO_2/greenhouse gas emission levels, the automotive industry has been turning to alternative, low/zero emission, technologies to power today's modern vehicles. Many car companies have recently released low emission, hybrid, or electric powertrains in their vehicles. For example, Toyota's Prius line of hybrid vehicles, Ford's Eco-boost line of vehicles, and Chevrolet's electric vehicle (EV) the Volt.

However, the automotive industry isn't the only one that needs to provide these alternative technologies. The recreational vehicle industry accounts for it's fair share of emissions. If the recreational vehicle industry is to develop and incorporate these powertrain's into its own products, the unique technical challenges that present themselves in those vehicles must be overcome.

The Society of Automotive Engineers (SAE) Clean Snowmobile Challenge has also identified another reason for zero emission recreational vehicles. Global Climate research testing locations such as Summit Station in Greenland for the National Science Foundation (NSF) require special modes of transportation to and from their research sites. Due to the delicate nature of the studied constituents at the Greenland Ice Cap, emissions resulting from the burning of fossil fuels on site can hopelessly skew the research results.

The Queen's Fuel Cell Team

The Queen's Fuel Cell Team (QFCT) is an engineering design team based out of Queen's University in Kingston, Ontario, Canada. Originally formed in 2005, the team has always been dedicated to developing commercial applications for fuel cells. The team is largely motivated by the world's growing greenhouse gas emissions and is set on reducing the world's emissions by integrating fuel cell technologies into major emission sources.

Since conception, the QFCT has been involved with fuel cell powertrain development for use in a range of different vehicular applications. The QFCT's first fuel cell powered vehicle was completed in 2007 using a Club Car DS golf cart and Alkaline Fuel Cell (AFC) technology. This success of the golf cart conversion project laid the groundwork for this design paper and entrance into the SAE Clean Snowmobile Challenge.

DESIGN REVIEW

Primary Goals & Objectives

The Queen's Fuel Cell Team's overarching goal is to convert the original 2011 Skandic Tundra Snowmobile into a safe and reliable zero-emission electric snowmobile. The snowmobile will subsequently be converted into one of the world's first fuel cell hybrid snowmobiles.

Figure 1. Original, un-modified, 2011 Skandic Tundra Snowmobile by Bombardier Recreational Products (BRP).

Since the SAE Clean Snowmobile Challenge has never had to consider allowing a fuel cell powered snowmobile compete in the yearly competition; the QFCT hopes to have the first phase of the snowmobile project pass inspection and compete in the 2014 events.

The QFCT's Fuel Cell Hybrid Snowmobile Project has been broken down into two major design phases. Phase 1 consists of the initial conversion of the Internal Combustion Engine (ICE) powertrain to an electric powertrain. Phase 2 being the addition of the range extending fuel cell hybrid module. The QFCT's primary goal is to pass electrical safety inspection and meet the minimum performance target found in Table 1.

Table 1. The Queen's Fuel Cell Team's Phase 1 design goals for the 2014 SAE Clean Snowmobile Challenge

Design Elements	**Target**
Electrical Safety Inspection	Pass SAE CSC Inspection
Pure Electric Cruising Range[1]	10 mi / 25 km
Dry Sled Weight	< 350 kg
Cold Start to 100 ft	< 40 sec.
Draw Bar Pull Weight	330 + lbs. / 150 + kg

Power Requirement Calculations

In order to select and source all the components for the snowmobile, a force analysis was required for a few different scenarios. The forces considered in the force analysis are listed below.

- Force exerted by powertrain (F_{total})
- Drag force from air (F_{air})
- Rolling resistance (F_{rr})
- Gravitation forces from incline ($F_{incline}$)

The force exerted by the powertrain must be greater than or equal to the last three forces considered above. The snowmobile will maintain a constant speed if F_{total} is equal to these resistive forces. The vehicle will accelerate if F_{total} is greater than the resistive forces.

$$F_{total} = F_{air} + F_{rr} + F_{incline} \tag{1}$$

The drag force on the snowmobile is represented by the drag equation (Equation 2). This should hold true for most vehicular cases where turbulent airflow occurs due to bulk air movement.

$$F_{air} = \frac{1}{2} C_d A \rho v^2 \tag{2}$$

Where C_d is the drag coefficient for the snowmobile, A is the reference area of the snowmobile, p is the density of air, and v is the velocity of the snowmobile.

Equation 3 represents the rolling resistance for the snowmobile. The force required to overcome the rolling resistance is proportional to the coefficient of friction between the skies/track and the ground.

$$F_{rr} = \mu_{roll} mg \tag{3}$$

Where μ_{roll} is the coefficient of friction between the skies/track and ground, m is the mass of the snowmobile, and g is the gravitational constant.

Equation 4 represents the gravitational force working against the snowmobile in the case that it is climbing a hill. Trigonometry tells us that for a slope with angle α (in degrees),

$$F_{incline} = \sin(\alpha)\, mg \tag{4}$$

For a rigid body, the required tractive power to maintain a speed of v is calculated using Equation 5,

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[1] Cruising range is defined as the range of the snowmobile at competition set cruising speed (20 mph/32.2 kmh)

$$Power = F_{total} * v \qquad (5)$$

An estimate of how much power would be required to accelerate the vehicle up to cruising speed was also required. We assumed that a kinetic energy calculation would be sufficient to estimate the additional power required to accelerate the snowmobile. Equation 6 is the kinetic energy calculation used to determine the amount of additional energy required to accelerate the snowmobile.

$$E_{accel} = \frac{1}{2} m v^2 \qquad (6)$$

The result from Equation 6 was used in Equation 7 to determine the additional power to accelerate the vehicle.

$$P_{accel} = \frac{E_{accel}}{t} \qquad (7)$$

Where t is the time required to accelerate up to the required speed.

The results of the above force analysis on the snowmobile are found in Table 2. The major assumptions made are found in Appendix A along with the details of the calculations and sample calculations for each scenario evaluated. A cruising speed of 20 mph and an acceleration time of 5 seconds was used to calculate both the pure electric snowmobile and the future fuel cell hybrid power requirements.

Table 2. Summary of results from force analysis for a no incline, 10-degree incline, pure EV, and hybrid vehicle scenario.

Results (No Incline – Pure EV)	
Raw Cruising Power Requirements	8.5 hp
Additional Accelerative Power	3.6 hp
Total Accelerative Power	12.1 hp
Results (10-Degree Incline – Pure EV)	
Raw Cruising Power Requirements	15.3 hp
Additional Accelerative Power	3.6 hp
Total Accelerative Power	18.9 hp
Results (10-Degree Incline – Hybrid Vehicle)	
Raw Cruising Power Requirements	22.3 hp
Additional Accelerative Power	5.3 hp
Total Accelerative Power	27.6 hp

Motor Selection Process

Once the power requirements were estimated using the force analysis methods described in the previous section. An electric motor had to be sized to replace the stock ICE in the snowmobile.

DC versus AC Motors

The first step to selecting an electric motor was to evaluate the differences between DC and AC motor systems in an electric snowmobile.

DC motors often require more maintenance and have a shorter lifetime when compared to AC motors [1][2][3][4]. DC motors also cannot run as high in rpm due to the brushes [2]. However, brushless DC motors exist but result in higher costs and complicated control methods [1][2][3][4]. DC motors have an added level of control in varying its output torque and speed when compared to AC motors [1].

Considering DC motor applications in electric vehicles, they are often the option of choice since batteries output DC power. Using a DC motor also allows for increased system efficiencies since the DC power source does not have to be converted to AC before being sent to the motor. A DC to AC conversion can result in losses on the order of 20%.

AC motors are naturally more compact, rugged, and have increased lifetimes when compared to DC motors [1][2][3][4]. AC motors have recently become just as good at varying output torque and speed when compared to their DC counterparts [1]. An AC motor's primary advantage when applied to electric vehicles comes down to its ability to provide a high torque output over a much larger range of rpms [3]. This consequently leads to an easier and lighter transmission conversion since a fixed gear ratio can be used without sacrificing performance [4]. Furthermore, when comparing an AC motor to an equivalent DC motor in power output at a specified rpm, the AC motor will be more efficient in converting the electrical power to mechanical power.

In conclusion, an AC motor type was chosen as the best option for the electric snowmobile for the following reasons in order of importance:

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[1] Bloom, M.,"AC vs. DC Gear Motors: What's the Difference, and Which Offers More Gear Motor Advantages?" *Sinotech*, 2013. Available: http://www.sinotech.com/blog/ac-vs-dc-gear-motors-gear-motor-advantages/

[2] Ohio Electric Motors, "What is the difference between AC and DC motors," *Ohio Electric Motors*, 2011. Available: http://www.ohioelectricmotors.com/what-is-the-difference-between-an-ac-motor-and-a-dc-motor-673

[3] Gallant Motor, "AC motor vs DC motor," *GallantMotor.com*, 2007. Available: http://www.gallantmotor.com/acvsdc

[4] Rye, C., "Electric Car Motors: AC vs. DC," *Electric Vehicle Authority,* 2008. Available: http://evauthority.com/dc-vs-ac-electric-car-motors/

- Less intensive transmission conversion
- Higher energy conversion efficiency
- More compact
- Longer lifetime and higher reliability

AC Motor Selection

In order to select the optimal AC motor for use in the electric snowmobile, all AC motors that fit the calculated power requirements were compared by the following specifications:

- Efficiency
- Weight
- Cost
- Operating Voltage
- Operating Current
- Peak RPM
- Continuous RPM
- Peak HP
- Continuous HP
- Peak Torque
- Continuous Torque

The AC motors where then evaluated against how closely they matched the continuous and peak HP requirements. The AC motors were then ranked based on weight and efficiency. A lighter motor would result in lower power requirements, and higher efficiencies. This leads to higher power utilization from the batteries/fuel cell. Final considerations were given to the AC motors' torque versus RPM performance curves.

Upon evaluation of a dozen different AC motors, High Performance Electric Vehicle Systems (HPEVS) AC 35 motor was selected. The AC35's power characteristics matched the calculated power requirements the best. Furthermore, it had the highest efficiency and longest constant torque region of all considered motors. Another noticeable advantage was its highly compatible, fully programmable, high efficiency DC/AC motor controller. Figure 2 shows a HPEVS AC 35 motor with its Curtis 1238 AC Motor Controller.

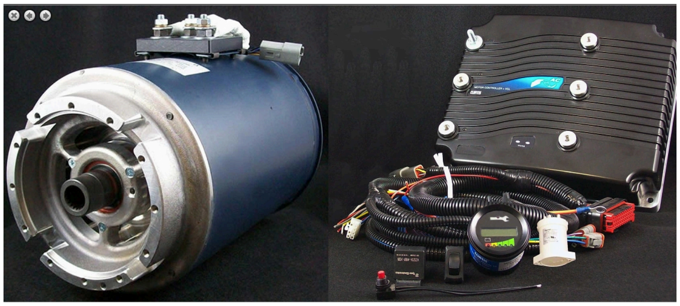

Figure 2. HPEVS AC 35 motor with accompanying Curtis 1238 AC motor controller and EV circuit components.

Battery Selection Process

Once the motor was selected, the power source for the electric motor had to be sized and sourced. A set of performance requirements for the battery pack was assembled. The battery pack must be able to meet the following pure electric performance capabilities:

- Deep discharge cycle capabilities
- Continuous and pulse discharge current capabilities
- High reliability
- Good cold weather performance

However, the snowmobile will become a hybrid in Phase 2 of the project. Therefore, the battery pack must also have the following performance capabilities:

- High pulse discharge currents
- Be able to handle repetitive shallow discharge cycles
- Be able to interface well with an energy management system

Battery Chemistry Selection

In order to determine the best battery chemistry for the application, a decision had to be made between a primary (non-rechargeable) cell and secondary (rechargeable) cell. Evidently, since both electric and hybrid vehicles must be able to replicate vehicle drive cycles, a secondary cell was the clear choice.

Next, the best secondary cell chemistry for the snowmobile's performance targets had to be selected. The four main battery chemistries often considered for vehicular applications are lead-acid, nickel cadmium (NiCad), nickel metal-hydride (NiMH), and lithium ion (Li-ion)[5]. Table 3 displays a pros and cons table for the four main battery chemistries.

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[5] Pistoia, G., "Battery Operated Devices and Systems - From Portable Electronics to Industrial Products," *Elsevier*, 2009.

Table 3. Pros and cons evaluation between the four main secondary cell chemistries for vehicular applications[5][6][7][8].

Battery Type	**Lead Acid**	**Ni Cad**	**Ni MH**	**Li-Ion**
Battery Voltage	2.1 V	1.25 V	1.2 V	3.7 V
Pros	• Superior long-term reliability • Most Economical	• High mechanical strength • High efficiency charge • Charge cycle: 500 times • Good cold weather discharge abilities	• No heavy metals • Relatively high capacity • Charge cycle: 500 times • Better energy density then NiCad and Lead Acid	• High 3.7V voltage • No memory effect • Low self-discharge • Very high energy density • Superior cycling abilities
Cons	• Relatively low cycle life • Low energy • High self-discharge in flooded batteries • Heavy • Poor low temperature discharge abilities	• Low energy • Memory effect • Toxicity • High self-discharge especially in sealed cells	• More expensive than Ni–Cd • Very high self-discharge (more than NiCad)	• The most expensive • Potential safety problems • Requires control of charge/disch. limits • Degrades at high temperature

An important consideration for the battery chemistry is the energy density of the cells. In electric and hybrid vehicle applications, the energy density of the cell has a large effect on the range of the vehicle. Figure 3 displays the range of an electric vehicle versus the weight of the battery pack for 3 different energy densities. One can clearly identify that higher energy densities result in significant increases in electric vehicle ranges.

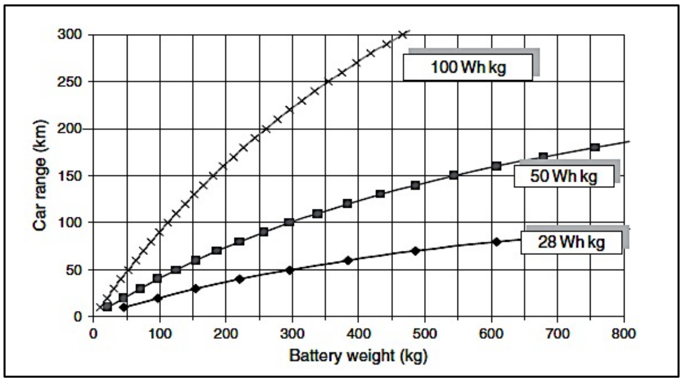

Figure 3. Electric vehicle range versus battery weight with varying cell energy densities [5].

The above evaluation of the different battery chemistries yielded a clear choice. Lithium ion battery technologies were to be considered further. The following reasons were deemed the most important:

- Highest energy density
- No memory effects
- Low self-discharge
- Superior cycling abilities

Lithium Ion Battery Pack Design Specifications

Battery Voltage

The voltage of the battery pack was chosen as 92.5 V due to two constraints.

- The HPEVS AC 35 motor controller can only handle voltages between 72-96 V
- Lithium ion battery cells have a nominal voltage of 3.7 V
  - Therefore, the battery pack voltage must have a nominal voltage that is a multiple of 3.7

In order to minimize the current draw from the batteries (in other words minimize battery capacity), the highest possible voltage that was under 96 V and a multiple of 3.7 was 92.5 V.

Battery Capacity

The challenge with sizing an appropriate battery pack comes down to battery capacity ratings. Battery capacities are rated in units of Amp-hours (Ah) and the capacities of a battery cell range with the rate of discharge and the temperature at which

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[5] Ibid.

[6] Crompton, T.R., "Battery Reference Book," Elsevier *Newnes*, 2000, ISBN: 978-0-7506-4625-3.

[7] The European Association for Advance Rechargeable Batteries, "Lithium ion cell (Li-ion/Li-polymer)," Re-charge, 2013.

[8] Dhameja, S., "Electric Vehicle Battery Systems," *Elsevier*, 2002, ISBN: 978-0-7506-9916-7.

the cell is being discharged [8][9]. The higher the current draw is from the batteries, the lower the capacity of the battery. Peukert's law has commonly explained this rate of discharge effect on capacity [9][10]. Peukert's equation is displayed in Equation 8 [9][10].

$$t = H\left(\frac{C}{IH}\right)^{n} \tag{8}$$

Where H is the rated discharge time, C is the rated discharge capacity, I is the actual discharge current, n is the Peukert's constant for the specific battery chemistry, and t is the actual time of discharge.

It is noted that Peukert's law is only accurate on batteries under constant discharge currents and temperature [9]. Furthermore, if a battery is discharged under transient currents and temperature, one can expect an underestimation from Peukert's law[9]. For this design, Peukert's law was assumed to be a reasonable approximation and a safety factor of 1.2 accounted for any underestimations from Peukert's law.

The required battery capacity was calculated using the electric vehicles power requirements on a 10-degree incline found in Table 2. The power requirements where then coupled with the range performance target found in Table 1. The powertrain efficiency had to also be factored into the lithium ion battery pack's energy capacity calculation. Therefore, the required capacity from the batteries was estimated from Equation 9.

$$C_{required} = \frac{\left(\dfrac{P * \dfrac{v}{Range}}{\eta_{mech}\eta_{elec}}\right)}{V_{pack}} \tag{9}$$

Where $C_{required}$ is the required battery pack capacity in amp-hours, P is the calculated power requirement in watts, v is the cruising velocity of the snowmobile, $Range$ is the performance target for the range of the snowmobile, η_{mech} is the efficiency of the snowmobile's mechanical powertrain (i.e. motor, gears, track), η_{elec} is the efficiency of the electrical tractive system (i.e. motor controller, batteries, resistive losses, auxiliary loads), and V_{pack} is the battery pack voltage.

The required capacity was then used in Peukert's equation (Equation 8) in order to account for the rate of discharge effect. Lastly, lithium ion cells shouldn't be discharged completely in order to increase the lifetime of the cells [5][6][8]. Only about 80% of the cell's total capacity should be used, therefore, the required capacity was additionally increased by 20%. Table 4 summarizes the results of the analysis along with the primary assumptions made in the calculations.

Table 4. Summary of results from battery capacity calculations on pure EV on 10-degree incline. Main assumptions are also indicated.

Assumptions	
η_{mech}	85 %
η_{elec}	80%
Lithium Ion Peukert's Constant	1.05
Cruising Speed	20 mph
Peukert's Law Safety Factor	1.2
80% SOC Operating Range Factor	1.2
Results	
Required Capacity of Lithium Ion Cells	75 Ah

Battery Cell Selection

With the major battery specifications determined, a battery cell was selected based on it's cycle life, pulse discharge capabilities, and energy density. The selected battery cell is a Dow Kokam XALT™ 75 Ah High Power lithium ion polymer pouch cell. Figure 4 is a picture of the Dow Kokam XALT™ 75 Ah pouch cell used in the snowmobile.

Figure 4. Dow Kokam's XALT™75 Ah High Power lithium ion polymer pouch cell.

Key attributes of the selected Dow Kokam cell are found in Table 5.

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[8] Ibid

[9] Doerffel, D., and Sharkh, S. A., "A Critical Review of using the Peukert Equation for Determining the Remaining Capacity of Lead-Acid and Lithium-Ion Batteries." *Journal of Power Sources, 2006,* 155 (2): 395-400. http://resolver.scholarsportal.info/resolve/03787753/v155i0002/395_acroutcolalb.

[10] Fruchter, L., Gilles, C., and Alain Le Mehaute., "Batteries, Identified Fractal Objects." *Journal of Power Sources,* 1986, 18 (1): 51-62. doi:10.1016/0378-7753(86)80101-X.

[9] Ibid.

[5] Ibid.

[6] Ibid.

Table 5. Key attributes of Dow Kokam's XALT^{TM}75 Ah High Power pouch cell.

Cycle Life @ 1C & 80% SOC	5,000
Pulse Discharge Current	750 A
Operational Discharge Temperature Range	(-30 – 60) °C
Maximum Charge Current	225 A
Maximum Discharge Current	450 A
Energy Density	≈150 mAh/g

Transmission Modifications for Draw Bar Pull & Cruising Speed Performance Targets

Production snowmobiles use an adjustable gear ratio controlled by a continuously variable transmission (CVT). The continuously variable transmission allows for the optimization of the torque and speeds at the track for the engine's various operating points. However, a fixed ratio may be used since the tractive performance of an electric motor is better representative of what is actually required at the track. Furthermore, the levels of torque that electric motors produce can lead to durability issues on CVT's. For these reasons, it became clear that a fixed ratio transmission system would be ideal.

The selected fixed gear ratio must hold a balance between the two performance targets. The draw bar pull requires high torque at low speed. The cruising speed performance target requires minimal torque at high speeds. This contradiction is a major challenge when deciding which fixed gear ratio should be used.

Equation 10 was used to theoretically calculate the mechanical advantages between a two-gear system.

$$Ratio = \frac{\omega_1}{\omega_2} = \frac{R_2}{R_1} = \frac{N_2}{N_1} = \frac{T_2}{T_1} \qquad (10)$$

Where R_1 is the radius of the input gear, ω_1 is the angular velocity of the input gear, N_1 is the number of teeth on the input gear, and T_1 is the input torque on the input gear; R_2 is the radius of the output gear, and ω_2 is the angular velocity of the output gear.

Since the power from the motor is transferred through a series of gears before being exerted by the track, Equation 10 had to be used on the series of gears between the motor and the track. The calculated power requirements had to be available at the snowmobiles track; therefore, a gear ratio was back calculated from the track to the AC motor. Since the AC motor's torque versus speed profile was known from the motor suppliers dynamometer data, it was possible to determine the required gear ratio.

Theoretical calculations using Equation 10, and the performance targets in Table 1 in Microsoft Excel yielded an optimal gear ratio of 1.4 (Appendix D). The snowmobile should maintain a speed of 20 mph with this gear ratio while maintaining enough torque to accelerate the completed fuel cell hybrid vehicle.

The 1.4 gear ratio was calculated with the full weight of the fuel cell hybrid snowmobile, therefore, the pure electric sled should approximately drawbar pull the difference in weight between the fuel cell hybrid version and the pure electric version. This weight difference was approximated at 150 kg.

Belt Drive Selection

The CVT was replaced with a Gates Polychain GT Carbon belt and sprockets. A synchronous belt was chosen for the system because of its high efficiency of 98%, ease of use, and lack of noise. The gear ratio of the belt drive is 0.6.

SUMMARY/CONCLUSIONS

The performance targets, design calculations, and engineering analysis of the various technologies yielded the need for a 35 hp peak, 10 hp continuous, AC motor from HPEVS to replace the original ICE. A 92.5 V lithium ion battery pack made of up Dow Kokam XALT^{TM} 75 Ah High Power pouch cells to meet the 10 mile range requirements. A fixed gear ratio of 1.4 for the AC 35 motor will ensure a good balance between torque and speed at the track along with ensuring a 150 kg draw bar pull.

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DEFINITIONS/ABBREVIATIONS

EV	Electric Vehicle
HPEVS	High Performance Electric Vehicle Systems (Supplier)
QFCT	Queen's Fuel Cell Team
SAE	Society of Automotive Engineers
rpm	Rotations per minute
mph	Miles per hour
NSF	National Science Foundation
AFC	Alkaline Fuel Cell
AC	Alternating Current
DC	Direct Current
ICE	Internal Combustion Engine
NiCad	Nickel Cadmium
NiMH	Nickel Metal Hydride
Li-ion	Lithium Ion
Ah	Amp-hour
CVT	Continuously Variable Transmission

APPENDIX A – POWER REQUIREMENT CALCULATIONS

Air Resistance Force Values		**Rolling Resistance Values**			**Forces Due to an Incline Values**	
Front Area (m^2)	1.209	**Gravity (m)**	9.81			
Density of air at sea level (kg/m^2)	1.2	**uroll (estimate)**	0.2	powder:0.15, icey: 0.252, slushy: 0.377	**slope of hill (degrees)**	0
coefficient of drag (air drag)	0.7				**percentage grade**	0
	Batteries	Hybrid				
Mass of sled	339.6	528.2363636				
motor efficiency	0.89					
Efficiency of Transmission System	0.95					

								Batteries	Hybrid
Speed km/h	**5**	**10**	**15**	**20**	**32**	**40**	**50**	**30**	**30**
Speed m/s	1.39	2.78	4.17	5.56	8.89	11.11	13.89	8.33	8.33
Forces									
Air Resistance (N)	0.98	3.92	8.82	15.67	40.12	62.69	97.95	35.26	35.26
Rolling Resistance (N)	666.30	666.30	666.30	666.30	666.30	666.30	666.30	666.30	1,036.40
Incline	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total Forces (N)	667.27	670.21	675.11	681.97	706.42	728.98	764.25	701.56	1,071.66
Power to Maintain Speed (W)	**926.77**	**1,861.70**	**2,812.96**	**3,788.71**	**6,279.25**	**8,099.82**	**10,614.54**	**5,846.31**	**8,930.52**
hp	1.24	2.50	3.77	5.08	8.42	10.86	14.23	7.84	11.98
time to accelerate to speed	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	8.00
Energy to Accelerate (J)	327.55	1,310.19	2,947.92	5,240.74	13,416.30	20,962.96	32,754.63	11,791.67	18,341.54

Power to accelerate to speed (W)	**327.55**	**655.09**	**982.64**	**1,310.19**	**2,683.26**	**3,493.83**	**4,679.23**	**1,473.96**	**2,292.69**
hp	0.44	0.88	1.32	1.76	3.60	4.69	6.27	1.98	3.07
Total Power Requirement at Track Sprocket (W)	**1,254.32**	**2,516.80**	**3,795.60**	**5,098.89**	**8,962.51**	**11,593.65**	**15,293.77**	**7,320.27**	**11,223.21**
hp	1.68	3.38	5.09	6.84	12.02	15.55	20.51	9.82	15.05
Power Into Motor with 85% efficiency in Drive train and motor efficiency	**1,493.23**	**2,996.19**	**4,518.57**	**6,070.11**	**10,669.66**	**13,801.96**	**18,206.87**	**8,714.61**	**13,360.97**
hp	2.00	4.02	6.06	8.14	14.31	18.51	24.42	11.69	17.92
With Safety Factor of 1.1	2.20	4.42	6.67	8.95	15.74	20.36	26.86	12.86	19.71
Power out of Motor with 85% Efficiency in Drive Train Constant Speed	975.55	1,959.69	2,961.01	3,988.11	6,609.74	8,526.13	11,173.20	6,154.01	9,400.55
hp	1.31	2.63	3.97	5.35	8.86	11.43	14.98	8.25	12.61
With Safety Factor of 1.1	1.44	2.89	4.37	5.88	9.75	12.58	16.48	9.08	13.87
Power into motor to maintain constant speed	1,103.30	2,216.31	3,348.76	4,510.37	7,475.30	9,642.65	12,636.35	6,959.90	10,631.57
hp	1.48	2.97	4.49	6.05	10.02	12.93	16.95	9.33	14.26
with safety factor of 1.1	1.63	3.27	4.94	6.65	11.03	14.22	18.64	10.27	15.68

APPENDIX B – MOTOR EVALUATION SHEET

	Operating voltage, V	Operating current, A	Peak RPM	Cont. RPM	Peak hp	Rated hp	Peak torque, ft*lbs	Rated torque, ft*lbs	Efficiency	Weight, kg	Motor Controller	Cost, $	Comments
AC 50	72-108	550	6500		52	15	115	~90	0.89	55.5		4400	
AC 35	72-108	550	6500		35	10	110		0.89	38.6		4100	very high torques
AC 20	72-108	550	7500		25	8	75		0.89	24.1		3450	web sites have different values for torques and hp
AC18	72-108	550				<8	95?		0.89	22		3300	
Warp 8"	72-144 DC	178				19			0.825 @ 72 V	50		1650	DC motors are less efficient than AC motors
Warp 9"	72-144 DC	190	5500	3500		32.3	75 @72V		0.861 @ 72 V	70.9		1875	
	72-144 DC	190	5000	3000		43.7			0.819 @ 72 V	104.1		3025	
Advance DC 6.7"	72-120 DC	130	~7000		72	16 @ 120V,120 A	~80		~0.80	38.6		1222.71	Power changes significantly with current
Advance DC 8"	72-144 DC	178				19				50			
	72-144 DC	190				28				68.2			
Perm PMG-132	24-72 DC	110	3480 @ 72?	cont. at a Voltage	34.3	10 @ 72V	28.02	14.75	0.86-0.88	11.24		1000	motor controller?? brushed so maintanence
BRUSA	320		11000	4000	72.4	36.2	141.6	47.94	0.95	49		12000	EXpensive

ASM 6.17.12													
MES 200-75 and 200 - 150	185 V rated		9000	2850		12 - 24 (motor for every 3 kW (~4 hp))	63	22.127 - 44.254	~85	34 - 45			Water cooled! high rpms
MES 200-175 and 200 - 250	185 V rated		9000	2850		28 - 40 (motor for every 3 kW (~4 hp))		51.63 - 73.76		49 - 61			Water cooled!
MES 200-330	185 V rated		9000	2850	n/a	53.64	221.27	95.88		80		6425	Too powerful for our purposes
EMC-RT200	12 - 72 DC	200 cont	5000 rpm @ 72v unloaded		30.84 - 1 minute	15.42	80 stall torque	18		18		1500	
Gen4 Brushless PMAC	0-96 DC - controller	180 cont	5000	3000	40	16	69 stall	24	~0.83	16			fan cooled
Azure dynamics AC24	100 - 400		12000	4600	63	20	68	31	<87	40 (+15, for controllers and gear box that we probably dont need)			air cooled
ROTAX 550F I.C.E.			**6800**		**56**	**15**	**50**						

APPENDIX C – BATTERY CAPACITY SPREADSHEET

Number of Cells	26	Cells
Voltage	95.5	Volts
Max Output Current	450	Amps
Necessary power	8.619068505	kW
Necessary Current	90.25202623	Amps
Time of travel	47.71822363	minutes
Power to motor	6.96	kW
Power to motor	9.333376715	HP
Controller Efficiency	85	%
Battery Efficiency	95	%

Battery Only

Speed	30	km/h

Distance	23.85911182	km
Time	0	hours
and	48	minutes

Rated Capacity	75	Ah nominal at C/2
Current @ C/2	37.5	Amps
Rated Discharge Time	2	hours
Actual Discharge current	90.25202623	Amps
Peukert constant	1.05	Dimensionless
Actual time to discharge the cell	0.795303727	hours
Total time with 26 cells	20.67789691	hours

APPENDIX D – GEAR RATIO CALCULATION SPREADSHEET

For Continous Operation at Cruising Speed of 20 mph

Requirements	
Draw Bar Pull	500 lbs
Continuous Velocity	32 km/h
Sprocket	Diameter (m)
Motor Shaft	0.028575
Sprocket 3 (chain case)	0.05715
Sprocket 4 (chain case)	0.1335
Track Drive Sprocket	0.183
	For 32km/h cont speed
Motor Type	**AC-35**
Continuous RPM	**2100**
Velocity @ Track m/s	**8.889**
Angular Velocity @ Track rad/s	**97.14754098**
Chain Case Ratio	**2.333**
Angular Velocity @ Jack Shaft rad/s	**226.6452131**
power at motor	**29028.31612**
Angular Velocity of Motor rad/s	**219.9114858**
Sprocket Ratio 1-2	**0.970289567**
Total Gear Ratio	**2.26368556**
Torque at Motor (N/m)	132
Torque Out (Nm)	298.806494
Torque on Jack Shaft	