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 ultimately using 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 many different alternative, low/zero emission, technologies to power today's modern vehicles. Many car companies have recently released low emission, hybrid or electric powertrain's 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 its 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 low/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. Being originally formed in 2005, the team has always been dedicated to developing commercial applications for fuel cells. The team is largely motivated by the worlds growing greenhouse gas emissions and is set on reducing the world's emissions through fuel cell technologies.

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 successful golf cart conversion project laid the groundwork for this design paper and entrance into the SAE Clean Snowmobile Challenge. The golf cart has since been retrofitted with a new Polymer Electrolyte Membrane (PEM) fuel cell and new components and is running again. This project has given the team great experience with hybrid design and will aid in the future conversion of the snowmobile to fun on a fuel cell of similar chemistry.

DESIGN REVIEW

Primary Goals & Objectives

The Queen’s Fuel Cell Team’s overarching goal is to convert the original 2011 Skandic Tundra Snowmobile to a safe and reliable zero-emission electric snowmobile that will be easily integrated 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 pure EV version of the snowmobile project pass inspection and compete in the 2015 events.

The QFCT’s Fuel Cell Hybrid Snowmobile Project has been broken down into two major design phases. Phase 1 being 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 and/or surpass minimum performance targets set by the competition rules. Table 1 lists the main design goals for Phase 1 of the design.

Table 1: The Queen's Fuel Cell Team's Phase 1 design goals for the 2015 SAE Clean Snowmobile Challenge

Design Elements	**Target**
Electrical Safety Inspection	Pass SAE CSC Inspection
Pure Electric Cruising Range[1]	10+ mi / 25 km
Energy Conversion Efficiency	
Dry Sled Weight	< 350 kg
Cold Start to 100 ft	< 40 sec.
Draw Bar Pull Weight	100+ lbs. / 45.4+ 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 certain 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 air’s 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.

$$F_{rr} = \mu_{roll} m g \tag{3}$$

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.

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

Equation 4 represents the force of gravity working against the snowmobile in the case that it is climbing a hill. Trigonometry tells us that for a slope with a slope of α (in degree's),

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

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

$$Power = F_{total} * v \tag{5}$$

An estimate of how much power would be required to accelerate our vehicle up to our 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.

$$E_{accel} = \frac{1}{2} m v^2 \tag{6}$$

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

$$P_{accel} = \frac{E_{accel}}{t} \tag{7}$$

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. Note that cruising speed of 20 mph and an acceleration time is 5 seconds was evaluated for both the pure electric snowmobile and the future fuel cell hybrid module to be added.

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	18.91 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

When considering the assumptions made in the calculations and the overall design of the snowmobile, there are many challenges to meeting the requirements. First of all, the weight of the snowmobile is only an estimate and the battery case now in use along with all auxiliary components will affect the performance of the vehicle. The friction is also an estimate and the actual performance will depend on particular conditions. Another challenge was managing to mount the motor in such a way that it would be able to provide the power needed to the track while still being secure and safe. This was done with extensive CAD modelling and testing and now it integrates a stand along with transmission cover and securing bracket in order to keep the motor secure. The final step in assessing the performance will be to actually program the motor controller. This will require some experimentation with the system in place and will have a large impact on the performance.

Motor Selection Process

Once the power requirements were estimated using the force analysis methods described in the previous section. The selection of the motor was accomplished.

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 doesn't 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 speeds [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:

- 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. This is because a lighter motor would result in a lower required power, and higher efficiencies would allow for high power utilization from the batteries/fuel cell. Final considerations were given to the AC motors' torque versus RPM performance curves.

Upon evaluation of 18 potential AC motors, High Performance Electric Vehicles' (HPEV) AC 35 motor was selected. Furthermore, a noticeable advantage of the HPEV AC motors was its highly compatible, fully programmable, high efficiency DC/AC motor controller. Figure 2 displays the HPEV AC 35 motor with its Curtis 1238 AC Motor Controller.

Figure 2: HPEV 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 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. 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

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 than NiCad and Lead Acid	• High 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 containers	• More expensive than Ni-Cd • Very high self-discharge	• Most expensive • Potential safety problem • Require control of charge/discharge limits • Degrade at high temp.

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.

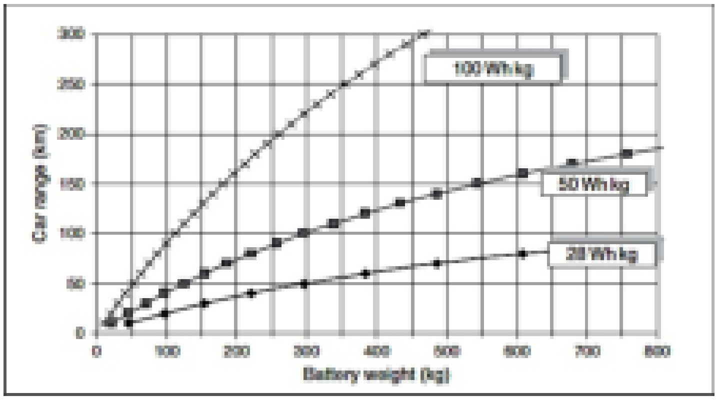

Figure 3: Electric vehicle range versus battery weight with varying cell energy densities [5].

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

<u>Lithium Ion Battery Pack Design Specifications</u>

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 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.

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

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 included

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 its cycle life, pulse discharge capabilities, and energy density. The selected battery cell is a Dow Kokam XALT^{TM} 75 Ah High Power lithium ion polymer pouch cell. Figure 4 is a picture of the Dow Kokam XALT^{TM} 75 Ah pouch cell used in the snowmobile.

Figure 4: Dow Kokam's XALT^{TM} 75 Ah High Power lithiom ion polymer pouch cell.

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

Cycle life @ 1C & 80% SOC	5000
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

The challenges associated with this choice were incorporating the single pouches into a full battery pack. This required a great deal of work and has resulted in a large battery pack that is heavy and takes up a large amount of space. The capacity of the batteries though does add to the overall range and for phase 2 of the project, some of the batteries will be removed and that will reduce the weight of the vehicle and increase the space for other systems needed for the fuel cell.

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.

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

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 calculated from the track to the AC motor. Since the AC motor's torque versus speed profile was known from the motor supplier's 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. This direct drive system allows for few losses and a very easy installation. There are no extra parts needed for the belt drive other than the sprockets and a belt, which reduces weight and the number of parts that could fail. It is also easy to enclose and maintenance is simple and quick.

The only downsides to this system as opposed to the original CVT are that the gear ratio is fixed during operation. The parameters of the motor can be changed intermittently through the motor controller, but during use the gear ratio is fixed which could reduce motor efficiency and possibly hinder performance. Overall, the simplicity and efficiency of the direct belt drive design was the reason that it was chosen.

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.

REFERENCES

1. SAE uses the Chicago Manual of Style in formatting references. In the text of the paper the citations are numerically identified using square brackets [1]. Up to four authors should be listed; more than four, et al. should be used after the fourth author is listed. Refer to the SAE Technical Paper Style Guide for formatting of different types of references. Below are some examples.
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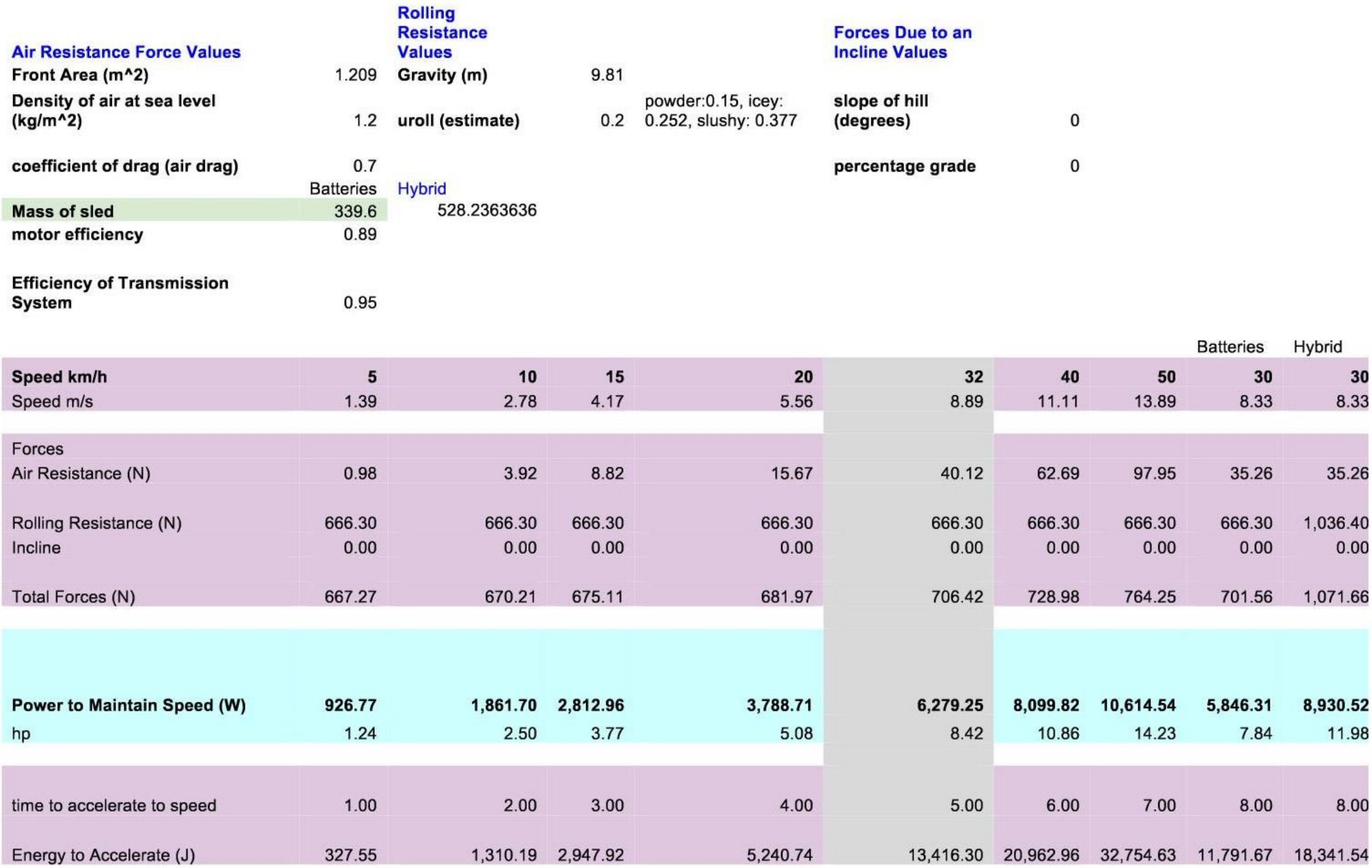
DEFINITIONS/ABBREVIATIONS

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

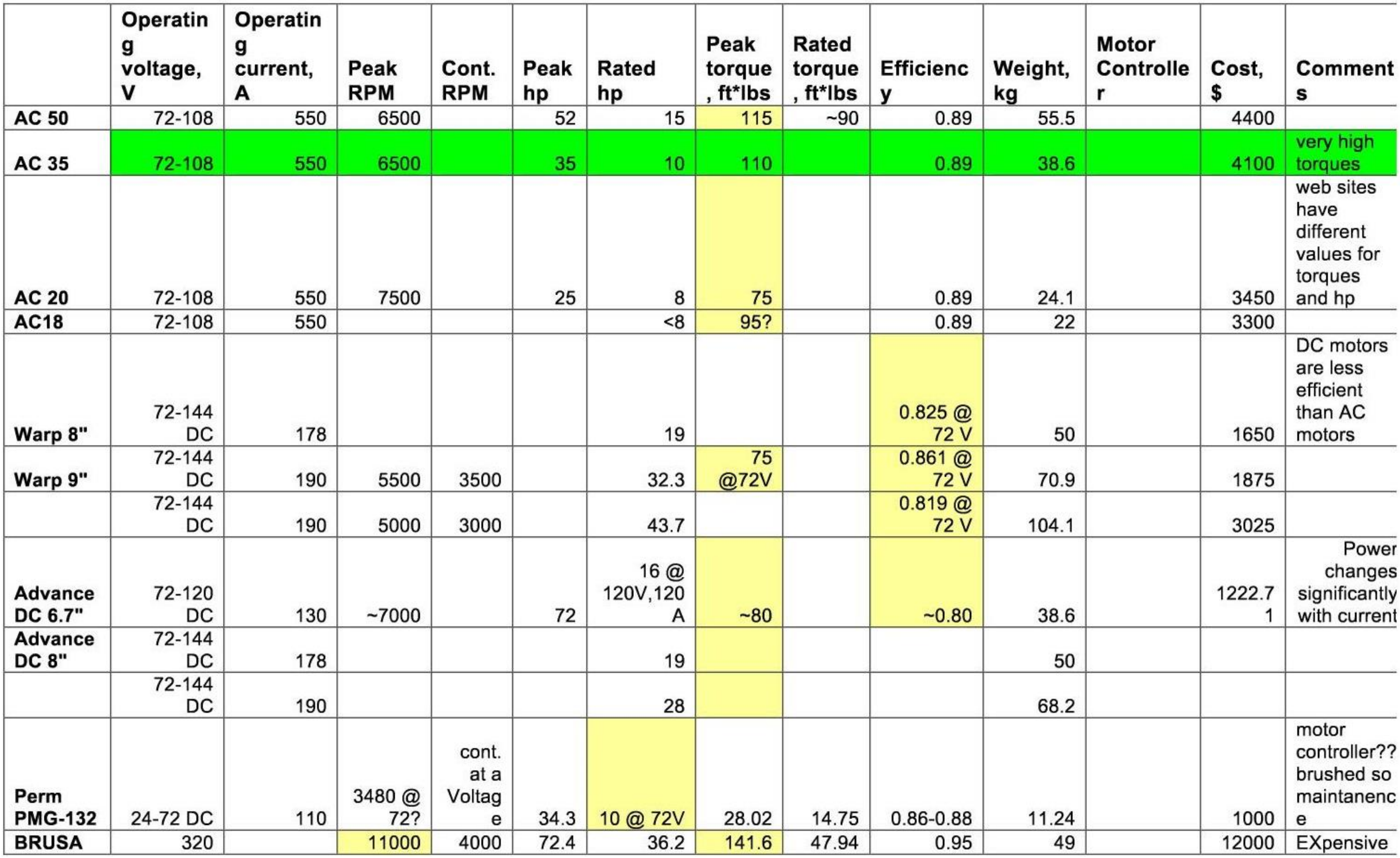


Air Resistance Force Values		**Rolling Resistance Values**			**Forces Due to an Incline Values**	
Front Area (m^2)	1.209	**Gravity (m)**	9.81			
Density of air at sea level (kg/m^2)	1.2	**uroll (estimate)**	0.2	powder:0.15, icey: 0.252, slushy: 0.377	**slope of hill (degrees)**	0
coefficient of drag (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

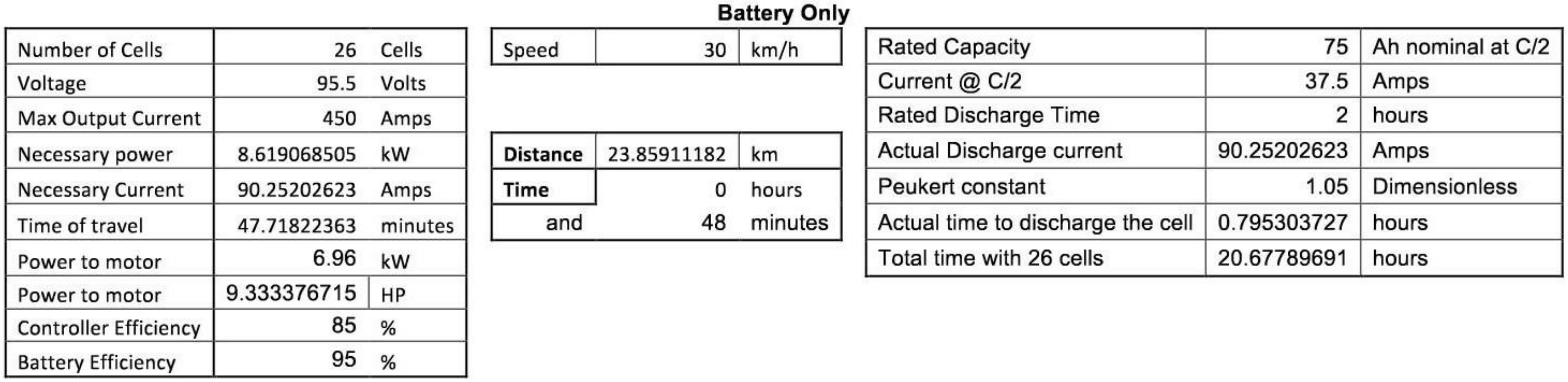
APPENDIX B – MOTOR EVALUATION SHEET



	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



Battery Only

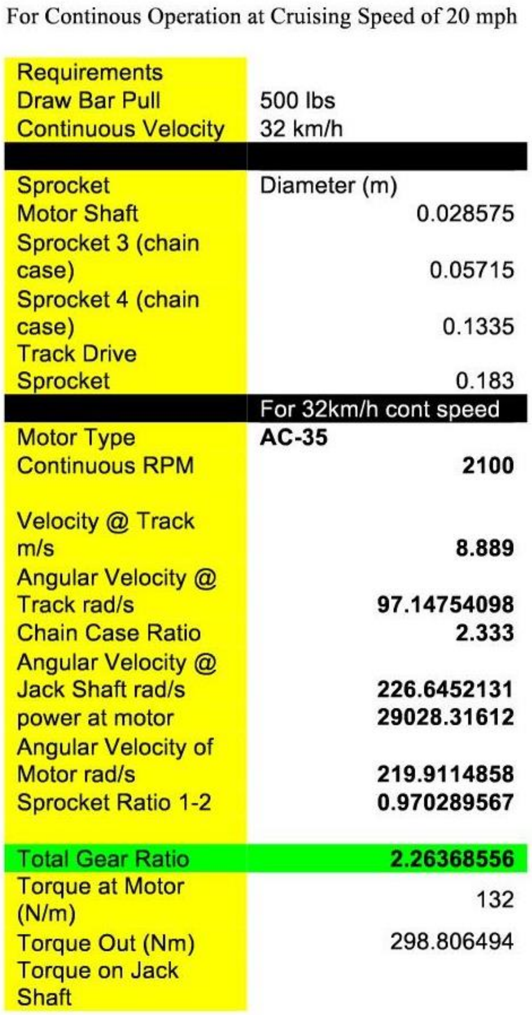
Number of Cells	26	Cells
Voltage	95.5	Volts
Max Output Current	450	Amps
Necessary power	8.619068505	kW
Necessary Current	90.25202623	Amps
Time of travel	47.71822363	minutes
Power to motor	6.96	kW
Power to motor	9.333376715	HP
Controller Efficiency	85	%
Battery Efficiency	95	%

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	

For draw-bar pull scenario

Requirements				
Draw Bar Pull	800 lbs			
Continuous Velocity	32 km/h	9.7m/s		
Sprocket	Diameter (m)	Radius (m)		
Motor Shaft	0.0285	0.01425		
Sprocket 3 (chain case)	0.05715	0.028575		
Sprocket 4 (chain case)	0.1335	0.06675		
Track Drive Sprocket	0.183	0.0915		
Motor Type	AC-35			
Rolling Resistance Calculated from Power Calculations (MECH A1)	Fair+Froll			
Powder	529.54	N		
Ice	862.35	N		
Slush	1270.12	N		
DBP of Sled				
Torque Nm	132			
Speed (rpm)	2100			
Gear Reduction	2.2			
DBP Force powder (N)	2,644.23	594.45	lbf	
DBP Force ice	2,311.42	519.63	lbf	
DBP Force Slush	1,903.65	427.96	lbf	
Force of Load			Mass of Load	750 kg
Rolling powder	1,103.63		coeff of friction	0.15
Rolling ice	1,854.09			0.252
Rolling Slush	2,773.78			0.377
Force Drag (Air)	15.75		Coeff of Drag	1.05
Total Force Powder	1,119.38			
Total Force ice	1,869.84			
Total Force Slush	2,789.53			

Speed Out (m/s)	32.93