Investigating the Development of a Zero Emission Electric Utility Snowmobile

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Abstract

This thesis addresses the question: can an electric snowmobile be one of the solutions to help lower snowmobile emissions and energy consumption?

In addressing this question the performance limitations of current electric snowmobile prototypes are investigated and it is shown that, unless a huge leap is seen in current battery technology energy density, electric snowmobiles cannot perform on par with gasoline snowmobile on both range and performance simultaneously.

Despite this, electric snowmobiles do have a certain number of niche applications where they can be useful. This thesis suggests that electric snowmobile powetrain modeling and simulation for these niche applications can potentially help overcome some of the challenges that exist in implanting such a vehicle for regular use. A complete, virtual electric snowmobile model was built and validated using actual electric snowmobile on-snow test data.

Snowmobile emission and energy consumption simulation was performed and demonstrated that Canadian electric snowmobile fuel cycle emissions and energy consumptions were, in general, substantially lower than gasoline snowmobiles. However, this is closely linked with electricity generation techniques and should not be extrapolated to say that this is the case for all potential electric snowmobiles worldwide.

Sommaire

Cette thèse tente d'apporter réponse à la question suivante: est-ce que la motoneige électrique peut faire partie des solutions afin d'aider à diminuer les émissions et la consommation d'énergie des motoneiges?

Afin de répondre à cette question, un questionnement sur les performances des prototypes de motoneiges électriques actuelles est entrepris et il en ressort qu'à moins qu'une énorme percée technologique ne vienne changer la donne, la densité d'énergie des technologies de piles présentement disponibles fait en sorte qu'une motoneige électrique ne peux pas envisager performer de façon similaire à une motoneige conventionnelle à essence sur le plan de l'autonomie et de la performance de façon simultanée.

Ceci étant dit, il existe tout de même des applications de niche pour lesquelles une motoneige électrique est parfaitement apte à accomplir le travail requis. Cette thèse suggère que l'utilisation de la modélisation et de la simulation peut s'avérer un outil précieux afin de surmonter certains obstacles à l'implantation de motoneiges électriques. Un modèle virtuel de motoneige électrique est assemblé et une simulation virtuelle est complétée et ensuite validée en utilisant des données obtenues lors d'essais sur neige avec une vraie motoneige électrique.

Une simulation est faite et permet de démontrer que sur la totalité de son cycle de carburant, une motoneige électrique canadienne émet généralement moins d'émissions et consomme moins d'énergie qu'une motoneige conventionnelle à essence, et ce, de façon substantielle. Cependant, puisque ce résultat est fortement lié aux méthodes de production d'énergie il ne peut pas être élargi afin de s'appliquer à l'ensemble des motoneiges électriques pouvant potentiellement un jour fouler la neige de notre planète.

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1. Introduction

Worldwide, an extensive amount of research and development is being performed with the goal of reducing emissions and energy consumption associated with transportation. One of the areas receiving the most attention is the passenger car sector. This research brought to market the use of electronic fuel injection and catalytic converters. Both technologies have now been widely implemented in passenger cars for many years. This widespread implementation has yielded great improvements in emissions and energy consumption in passenger cars. Lately, the use of battery electric technology has been under strong investigation as a means of further improving passenger car emissions and energy consumption.

Snowmobiles have not received as much research interest as passenger cars. Snowmobile manufacturers have only recently started to implement 4-stroke engine technology and electronic fuel injection on multiple snowmobile models. Furthermore, catalytic converters are still an oddity in the snowmobile world. While lower research interest is likely a key factor in this reality, it most likely isn't the only one. The reality of consumer expectations on the performance of snowmobiles, regardless of how extreme the terrain and conditions are, plays a non-negligible role in this apparent lag in snowmobile technology when compared to passenger cars.

1.1 Snowmobile Description

The definition of a snowmobile is fairly broad. It says that a snowmobile is "a motor vehicle with a revolving tread in the rear and steerable skis in the front, for traveling over snow"[1].

The first attempts at building a vehicle that would move over snow on runners happened over 70 years ago. In 1935, a snowmobile was built with skis in front and a sprocket wheel and track system in back. It carried 12 people. Family doctors, veterinarians, ambulance and taxi drivers were first in line to purchase one[2]. Nowadays, most North Americans, when hearing the word snowmobile, picture a small, open chassis, track propelled and ski steered vehicle, which can be straddled by a driver (and sometimes one or two passengers). Such a vehicle can be seen in Figure 1 below.

Figure 1: Snowmobile with Utility Cargo Box in the Rear

However, it took a while between the introduction of the first “large” snowmobiles in 1935 and the arrival of the first “modern” snowmobiles. “*It was the late 1950s, with the development of smaller gasoline engines, before the one- or two-passenger lightweight chassis snowmobile was marketed”*[3]*. “Ten years later, there were dozens of manufacturers producing snowmobiles”*[4]*.*

Today, the majority of snowmobiles in the world are manufactured by the four members of the International Snowmobile Manufacturer Association (ISMA: Arctic Cat, BRP, Polaris, Yamaha). These vehicles are powered by gasoline internal combustion engines. The engine’s power is usually transferred to the track via a V-belt continuously variable transmission (CVT) and a step-down secondary ratio. The CVT, which also houses a centrifugal clutch, allows the snowmobile to seamlessly go from idling mode to various motoring ratio modes with nothing more than driver pressure on a handle bar mounted “throttle” lever.

Today's snowmobiles are one of the simplest and fastest ways to transport people and cargo on snow covered ground and frozen bodies of water.

The following statistical information regarding the snowmobile industry comes from the ISMA's online snowmobile fact book[5]:

- In 2008 there were 163,753 snowmobiles sold worldwide; 79,552 were sold in the U.S. and 50,556 were sold in Canada. Worldwide sales have generally been declining since 1998 (257,936 units).
- There are approximately 1.62 million registered snowmobiles in the US and 708,490 registered snowmobiles in Canada.
- Approximately 80% of snowmobilers use their snowmobile for trail riding and touring on marked and groomed trails. 20% of snowmobilers use their snowmobile for work, ice fishing or transportation.

The snowmobile industry, like many other transportation industries, has, in recent years, been criticized for some of its perceived negative environmental impacts. Areas of criticism include:

- Noise
- Emissions
- Effects on wildlife
- Energy consumption
- Effects on snow, water and soil
- Effects on plants and crops

While there is a some debate between a number of organisations and individuals on many of these perceived issues, at least one aspect seems to unite snowmobile manufacturers, snowmobilers, politicians, environmentalists and all others taking a stand in these debates: the improvement of snowmobile emissions and efficiency is a positive development and hopefully emissions and energy consumption will continue to improve in the future.

1.2 Electric Vehicles

Electric vehicles, despite all the recent “buzz” on plug-in electric hybrid vehicles, are nothing new. Electric vehicles were already around back in the 19^{th} century. Despite all the technological improvements electric vehicles have seen since their inception, land and sea transportation systems have, for many years, mostly relied on fuel burning engines to transport people and cargo from point A to point B.

Passenger cars, which are to on-road transportation what snowmobiles are to on-snow transportation, have recently seen an increased interest in the potential use of electric drivetrain technology (on its own or paired with other technologies) as a means of lowering their energy consumption and emissions. While it appears unlikely that the use of electric cars will soon surpass the use of internal combustion engine cars, electric drivetrains are rapidly making their way to market as hybrid electric vehicles are finding more and more buyers.

Hybrid electric vehicles try to take the best of electric and internal combustion engine technology and combine them in such a way that, as they work together, each technology can compensate for the other’s weaknesses. Ultimately, if technological advances can allow electric drivetrain technology’s downsides to be overcome, one might see hybrid vehicles with greater and greater “all electric range” make their way to market until, one day, all the distance travelled with a vehicle can be achieved in “all electric mode”. The higher efficiency of electrical drivetrains and the lack of significant emissions during use make an all electric vehicle an interesting vehicle for more than one reason.

As the automotive industry examines electric drivetrains as a promising technology for passenger cars, one can rightfully wonder what this technology could do in other transportation sectors.

1.3 Objectives

Emissions and energy consumption are two areas where snowmobile manufacturers are trying to improve today's vehicles. One legitimate question on this subject is: can an electric snowmobile be one of the solutions to help lower snowmobile emissions and energy consumption?

In order to be a true improvement on some perceived problems, a solution must:

I. Help resolve the problem
II. Be implementable
III. Be viable

A thorough analysis of electric snowmobiles must be conducted before concluding that an electric snowmobile can be a true solution in order to reduce snowmobile emissions and energy use.

This thesis investigates the design and development of electric snowmobiles as utility vehicles in order to see if they can be considered a proper solution for the reduction of snowmobile emissions and energy use.

This investigation looks at three different areas of interest which, when put together, demonstrate the current potential for the reduction of snowmobile emissions and energy use issues via the use of an electric snowmobile. The three areas under investigation are the following:

1. Electric Snowmobile Design
2. Electric Snowmobile Implementation
3. Electric Snowmobile Fuel Cycle Emissions, Energy Use and Resource Use

1.3.1 Electric Snowmobile Design

In this section, the main physical and technological obstacles facing the design of an electric snowmobile are presented in details.

Following this, a brief overview of electric snowmobiles built to date (both at McGill University and from around the world) is given.

Lastly, the section concludes with a discussion on the implication of the main electric snowmobile design obstacles on the possible implementation and viability of electric snowmobiles.

1.3.2 Electric Snowmobile Implementation

The performance limits of electric snowmobiles, given today's technology, make it unfeasible to use them in a wide range of applications. These limitations make them only suitable, performance wise, in specific applications where only limited range is required.

Even in applications where limited range is required, a few obstacles pose a problem to electric snowmobile implementation. At least two of them relate to the cost of the electric snowmobile:

1. How can one ensure that a given electric snowmobile will meet the duty cycle requirements of a given application? Given the cost of an electric snowmobile, without the assurance that an electric snowmobile can fulfill the requirements of the duty cycle of a given application, it is unlikely that an end user will be willing to purchase such a vehicle. Since a number of applications where electric snowmobiles can be implemented are in remote locations, an onsite trial and error methodology is, in many cases, an extremely costly option.
2. Even in cases when it has been determined that an electric snowmobile can fully complete the duty cycle of a specific application, the initial cost of purchasing an electric snowmobile can be prohibitive to its implementation.

In this section, electric snowmobile modeling and simulation is looked at as a potential way of determining if an electric snowmobile design can adequately perform on a given duty cycle. Furthermore, modeling and simulation is used as a tool to custom design electric snowmobiles for specific applications, limiting the costs associated with expensive energy storage and powertrain components.

A detailed look at the modeling and simulation process is taken all the way from simulation platform selection to simulation results validation.

This level of simulation however is limited to performance simulation and does not cover the relative environmental impact of the electric snowmobile in the given application. This aspect is covered in section 3.

1.3.3 Electric Snowmobile Fuel Cycle Emissions, Energy Use and Resource Use

Electric vehicles are often perceived by some as solutions to certain issues solely on the basis of their in-use characteristics. Electric snowmobiles are no different. If one looks only at the in-use emissions and energy consumption, electric snowmobiles meet solution criteria I. (help solve the problem). However, more often than not, to truly improve a situation, one must take a step back and investigate if a potential solution is:

a. simply a “local” improvement which only has beneficial impact in a specific area without regards for potential negative impacts upstream or downstream of the “local” focal point

or

b. a “global” improvement which has an overall beneficial impact throughout the areas of impact of the source of the problem

This last section covers this aspect; it looks at whether electric snowmobiles are only a “local” solution to some perceived gasoline snowmobile issues or if they are indeed a “global” solution. This is achieved by using recognized energy use and emissions production simulation software and creating a standard basis on which to compare an electric snowmobile and a 4-stroke gasoline snowmobile.

2. Electric Snowmobile Design

If electric snowmobiles are going to be one of the potential solutions in order to improve snowmobile emissions and energy consumption, some electric snowmobile will have to be built and put into regular use.

However, none of the four major snowmobile manufacturers produce an electric snowmobile model. As far as press releases indicate, none of them even seem to be thinking about it. Additionally, traditional academic literature on the subject is almost non-existent, and so far, none of the few prototypes built worldwide come close to attaining the range an average gasoline powered snowmobile can obtain on one fuel tank. One may ask: "Is it really that difficult to build an electric snowmobile that can keep up with a conventional gasoline powered snowmobile? ".

This section tries to answer this question.

Annexe A and Annexe B contain further information on the electric snowmobiles built to date.

2.1 The Challenges of Making an Electric Snowmobile

Why is the design of a practical electric snowmobile such a challenge?

The short, two word, answer is: **energy density**.

The long answer is:

It is a challenge because of the relative energy density of batteries when compared to currently permissible alternatives in the regions where they are in use. (i.e. gasoline snowmobiles in North America).

Let us look at electric and gasoline snowmobiles in more detail to see why energy density is a tremendous obstacle to overcome for electric snowmobiles.

2.1.1 Energy Density

Using a value of 8760 Wh/l[6] as the energy available in gasoline and looking at the size of the fuel tanks offered by the four main snowmobile manufacturers on one of their small utility snowmobile models, Table 1 shows that, on average, their utility snowmobiles carry 355,875 Wh of energy on-board.

Table 1: On-Board Energy of 2008 Model Year Gasoline Powered Utility Snowmobiles

Vehicle	Fuel Volume (l)	Energy On Board (Wh)
Arctic Cat Bear Cat 570[7]	49.2	430,992
Polaris 340 LX[8]	44.6	390,696
Ski-Doo Skandic Tundra[9]	34	297,840
Yamaha Venture Multi-Purpose[10]	36	315,360
Average	***40.95***	***358,722***

Using a mass of 0.73 kg/l[11] as the specific mass of gasoline, the weight of the average 355,875 Wh of energy carried on-board those snowmobiles is 29.66kg.

In order to compare battery energy density with gasoline, Table 2 looks at the energy density of four of the main battery technologies mature enough for use in electric snowmobiles: lead acid (PbA), Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH), Lithium-Ion (Li-ion).

Table 2: Energy Density of Common Battery Technologies

Battery Technology	Gravimetric Energy Density (Wh/kg)	Volumetric Energy Density (Wh/l)
PbA [12]	33.5	76.2
NiCd [13]	54	95
NiMH[14]	60	155
Li-ion[15]	105	284

It is clear from Table 2 that none of the common battery technologies have energy densities approaching the 12,000Wh/kg and 8760Wh/l of gasoline. Nevertheless, in Table 3, all four battery technologies and gasoline are compared head-to-head on weight and volume basis in the case where they would be installed in a common utility snowmobile.

Table 3 answers the following three questions:

If one was to use a Ski-Doo Skandic Tundra snowmobile with 297,840Wh of energy on board (as seen in Table 1), for different energy carriers, what would be

- the energy carrier (EC) volume ?
- the energy carrier (EC) weight ?
- the ratio of energy carrier (EC) weight to vehicle dry weight?

Table 3: Head-to-Head Comparison of Raw Energy Density of Common Battery Technologies and Gasoline in a Snowmobile

Energy Carrier (EC)	Gasoline	Li-ion Batteries	NiMH Batteries	NiCd Batteries	PbA Batteries
Vehicle	Ski-Doo Tundra				
Dry Weight	172 kg				
Energy On-Board	297,840 Wh				
EC Volume	34 (l)	1049 (l)	1292 (l)	3136 (l)	3910 (l)
EC Weight	24.8 (kg)	2837 (kg)	4965 (kg)	5516 (kg)	8892 (kg)
Ratio: EC Weight / Vehicle Dry Weight	0.144	16.5	28.9	32	51.7

As Table 2 has shown, the “raw” energy density of battery technologies is nowhere near the “raw” energy density of gasoline. Consequently, as shown in Table 3, unrealistically large amounts of batteries would have to be used to equate the on-board energy of a standard gasoline snowmobile.

Why is the term “raw” energy density being used?

The term “raw” energy density is used since the values in Table 2 only consider the energy density of the batteries themselves. For a more accurate comparison between the energy density of batteries and gasoline, one should also account for the weight and volume of the containment chamber or other means of holding the gasoline and batteries on board. To this, one must add the difference in weight and volume, of energy transfer systems (i.e. fuel pump and tube vs. battery management system and wires). Lastly, the reduction in battery energy density related to cold temperature and high discharge rates should be taken into account for a true comparison between battery technology and gasoline.

Taking all these factors into account can be termed the “net” energy density comparison. In general, the “net” energy density comparison will make the difference between the energy density of gasoline and battery technologies even greater than the “raw” energy density comparison.

In a best case scenario, (see Table 3), in order to have as much energy on-board an electric snowmobile as on a gasoline powered snowmobile, one would have to carry over 2800kg (6173lbs) of batteries. In a utility snowmobile such as Ski-Doo's Skandic Tundra weighting 172kg (379lbs) (dry weight)[16], this represents a “fuel” weight 16.5 times larger than the weight of the vehicle itself! Furthermore, unlike liquid fuels, the mass of the batteries will not diminish as energy is consumed. It is clear that such a vehicle to fuel weight ratio is not suitable for a snowmobile.

It is established that a large energy density difference between gasoline and battery technology exists and that, given this large difference, with current technology, it is impractical for one to have as much energy as a standard gasoline snowmobile on-board an electric snowmobile. Next, we investigate if this energy density difference can be compensated by the energy efficiency difference between gasoline powered technology and electrically powered technology.

2.1.2 Energy Efficiency

To see if energy efficiency can offset the energy density difference between gasoline and batteries, we investigate a theoretical best case scenario for the battery technology. For this best case scenario the following steps and assumptions are used:

1. Two identical snowmobiles with the same weight distribution and drive characteristics are used
2. One is given 24.8 kg of gasoline, the other 24.8 kg of the best battery technology as listed in Table 2 (Li-ion)
3. The amount of available energy on-board is calculated using "raw" energy density (Table 2)
4. The electric snowmobile is assumed to have maximal theoretical efficiency. All the energy in the battery is transferred to the ground without any losses)
5. Based on all of the above, the efficiency value of the gasoline snowmobile powertrain required for the gasoline snowmobile to have exactly the same performance as the electric snowmobile is calculated.

Table 4 below summarizes this procedure and its result.

Table 4: Comparison of Required Theoretical Efficiencies for Equivalent Vehicle Performance

Energy Carrier (EC)	Gasoline	Batteries (Li-ion)
Vehicle	Ski-Doo Tundra	
Dry Weight	172 kg	
Energy Carrier Weight	24.8 kg	
Energy On-Board	297,840 Wh	2,604 Wh
Theoretical Efficiency for Equivalent Performances	0.87%	100%
Energy Used to Propel the Snowmobile	2,604 Wh	

Table 4 shows that even using “raw” energy density values and assuming a theoretical electric snowmobile drive system efficiency of 100%, the gasoline powered snowmobile’s drive system would have to be less than 1% efficient for the two vehicles to be equal in terms of range and performance with the same mass of energy carrier (EC) on-board.

Calculations based on results from the SAE Clean Snowmobile Challenge results[17] indicate that snowmobile engine efficiencies generally tend to range in between 17 and 24 % (depending on operating point) with some specific operating points on some specific engines sometimes achieving up to 28% efficiency.

It is clear from this exercise that electric snowmobiles cannot compete with gasoline snowmobiles on both range and performance simultaneously. The gap in energy density between battery technology and gasoline is so large that, even when using an ideal theoretical scenario when factoring in energy efficiency, one cannot fully compensate for this fundamental difference.

However, not all applications require all the maximum range and performance modern gasoline utility snowmobiles offer. Some applications require only a limited range. Potentially, electric snowmobiles could be used in such applications. Also, some applications exclude the use of current gasoline snowmobiles since they cannot be used due to their exhaust emissions. In such cases, an electric snowmobile can be a very interesting solution.

Given this, it comes as no surprise that at least a handful of electric snowmobiles have been built in the past decade.

2.2 Overview of Electric Snowmobile Designs

To date, there is no evidence of electric snowmobiles being mass produced. The challenge of finding sufficient applications with similar requirements which can be satisfied with a single electric snowmobile design in order to make mass production viable is probably the biggest obstacle to mass production of electric snowmobiles.

Despite the lack of a mass produced electric snowmobile offered by the four major snowmobile manufacturers members of the International Snowmobile Manufacturer Association (ISMA), a handful of applications have seen their needs for an electric snowmobile fulfilled. All of these applications have seen their requirements satisfied by electric snowmobiles produced as either prototypes or ultra low volume units. Many of these units have been designed and built by students for the purpose of the Society of Automotive Engineer's Clean snowmobile Challenge (SAE CSC). There is one thing all these units have in common: they were all built as conversions based on a gasoline snowmobile mass produced chassis.

Annex A contains a list of some of these electric snowmobiles built in the last decade along with links to more information about them.

Separately, Annex B contains a list, along with images, of all electric and hybrid-electric snowmobile prototypes designed and built by McGill University students from 2002 to 2008.

McGill University's early snowmobile prototypes were purely a learning experience for students since no one involved in these vehicles had any experience with snowmobile or electric vehicles. Approximations and trial and error methodologies were the main design strategies. Designs were based on manufacturer specification information of selected components. As students gained experience, it was quickly realized that some of the manufacturer specifications were often inadequate for the level of precision needed for design decisions. Thus, testing equipment and data acquisition equipment were acquired. The use of this equipment took the guess work out of the design process. Testing (and data acquisition) results were integrated into the design process of new vehicles. While all this data acquisition and interpretation were initially perceived as tedious it was actually found to accelerate and reduce the overall cost of the design process. In most cases it eliminated the time consuming iterative process of a full scale trial and error design cycle.

2.3 Conclusion

It was previously defined that in order to be a true improvement for some problems, a solution must:

I. Help resolve the problem
II. Be implementable
III. Be viable

From the analysis done in this section, electric snowmobiles, due to the energy density of current battery technology, cannot perform on par with gasoline snowmobiles on both performance and range simultaneously. Based on criteria II (be implementable), one can conclude that electric snowmobiles, given the current state of technology, cannot be a large scale solution to some of today's gasoline snowmobile issues.

Nevertheless, there are some specific applications where an electric snowmobile can be considered “implementable”. These applications are ones where either very limited range is required or only moderate range and power are required. In both these types of applications, an electric snowmobile can be an implementable solution. Current electric snowmobile prototypes are tangible examples of this (See Annex A and B).

However, the fact that an electric snowmobile can perform adequately for the needs of some applications should not be seen as a statement that electric snowmobiles should (or will) be used in these applications. Given an application where an electric snowmobile can be used, the next question is: is it viable for all involved to have an electric snowmobile perform the duties of this application?

The following section, using advanced powertrain modelling and simulation software, defines a methodology that can be used to answer the question of viability for any given application.

3. Electric Snowmobile Implementation

To use an electric snowmobile in a given application, one requires more than just the knowledge that a given application requires limited range and power; one needs to know if using an electric snowmobile is a viable option. In other words, one looks at all the pros and cons of an electric snowmobile and the possible alternatives, and decides if an electric snowmobile is appropriate for the application.

The three options below can provide snowbound transportation. In many cases they are evaluated in parallel for applications that only require limited range and power:

1. use an electric snowmobile
2. use a gasoline snowmobile (or a similar gasoline powered vehicle which can perform adequately on snow)
3. do not use a motorized vehicle

In some applications, all three options are a possibility; in other applications, it is possible that only options 1 and 3 are available due to strict local emissions regulation. It is also possible to have only 1 and 2 as available options in cases where motorized transport is a must.

In applicable cases, the availability of electricity, the duty cycle limitations due to recharge time and the initial cost of an electric snowmobile can be obstacles to the viability of an electric snowmobile option.

From end user feedback, in applications where electric snowmobiles could potentially be implemented, the perceived cost/benefit ratio of implementing an electric snowmobile is the biggest obstacle to the implementation of these vehicles. Two factors, previously introduced in section 1.3.2, seem to greatly contribute to this problem:

1. How can one ensure that a given electric snowmobile will meet the duty cycle requirements in a given application? Given the cost of an electric snowmobile,

without the assurance that an electric snowmobile can fulfill the requirements of the duty cycle, it is unlikely that an end user will be willing to purchase such a vehicle. Since a number of applications where electric snowmobiles can be implemented are in remote locations, an onsite trial and error methodology is in many cases an extremely costly option.

2. Even in cases when it has been determined that an electric snowmobile can fully complete the duty cycle of a specific application, the initial cost of purchasing an electric snowmobile can be prohibitive.

To overcome these obstacles, an electric snowmobile powertrain model was developed and a simulation was performed for a hypothetical application duty cycle. The reasoning behind this is:

- Since applications where electric snowmobiles can perform the required duties adequately are limited, it is unlikely that mass production can be used to bring down the cost of a complete electric snowmobile.
- All electric snowmobiles previously reviewed were built on mass produced snowmobile chassis, but the electric drivetrains were not mass produced drivetrains. The bulk of the cost of these electric snowmobile prototypes (and thus the cost difference with gasoline powered snowmobiles) comes from their electric drivetrain.
- Electric drivetrain cost is closely linked to an electric snowmobile's performance. Thus, in minimizing an electric snowmobile's cost, one must be extremely careful and make sure that cost reduction measures do not affect the snowmobile's performance to the point where it doesn't meet the baseline performance criteria for a given application.
- Given all three points above, electric snowmobile powertrain modeling and application duty cycle simulation were thought of as a means to try and minimize

drivetrain cost while simultaneously ensuring that the resultant design can fully satisfy the needs of the application's duty cycle. This methodology allows the virtual design of a snowmobile drivetrain tailor-made for any given application without the high cost of full scale trial and error electric snowmobile prototyping and testing.

- By having the possibility of rapidly and efficiently determining an optimal electric powertrain design for a given application, the cost of an electric snowmobile can be brought down to its lowest possible point for this application while ensuring the end users that the electric snowmobile will meet their needs (i.e., ensure maximum benefit to the end user for the lowest possible cost) .

3.1 Electric Snowmobile Powertrain Modelling, Simulation & Validation

After some research on the subject, no standardized electric snowmobile powertrain modelling and simulation platform was found. The closest thing to such a platform that could be found was the work of Philip S. Auth from Idaho University[18]. In this work the "backward facing" modeling environment ADVISOR was used to investigate the feasibility of hybrid electric snowmobile design. For this, Auth used a gasoline powered snowmobile as a baseline to determine the snowmobile's power requirement in a given set of snow conditions at different vehicle speeds. The "backward facing" modeling environment ADVISOR was used to get a performance estimate for hybrid electric snowmobiles for various speeds. The results obtained by Auth give a general idea of what one might expect if one were to design a generic hybrid electric snowmobile. It seems however that the final results were not tested against a real-life hybrid electric snowmobile.

For this thesis, the electric snowmobile powertrain modelling and simulation goal is more specific than in Auth's work. The goal here is to create a method by which one can take an existing snowmobile application (terrain and expected speed trace) and run a virtual snowmobile on this terrain and at the corresponding driver input in such a way that the simulation can be used as an exact virtual model of the application with transient modeling capability. Then, for validation, this methodology is to be tested against the performances of a real-life electric snowmobile. Once validated this platform should enable the user to eliminate any need for on-location testing prior to implementing an electric snowmobile in a given application.

The only previous work in snowmobile advanced powertrain simuation used a backward facing modeling environment. While “backward facing” models are generally simpler and faster to compute, the fact that they are static models limits some of the possibilities these types of models offer. For modeling activities where more detailed modeling than what “backward facing” models can offer is expected, “forward facing” models can be used.

How do they work?

- The backward facing model takes as an input the vehicle’s speed vs. time trace and simply “back-calculates” the drivetrain operating parameters based on the vehicle’s speed at every time step.
- The forward facing model is more complex but more realistic. It takes in a driver speed demand and calculates/predicts the vehicle speed and its drivetrain operating parameters.

It was found that standard “forward facing” advanced powertrain simulation software platforms are currently widely used in the automotive world. Given this, a methodology was implemented in order to use the automotive world’s existing simulation capabilities and apply them to electric snowmobiles.

3.1.1 Methodology

The following methodology was followed in order to obtain an electric snowmobile model:

1. Simulation Platform selection:

   The first step in creating an electric snowmobile model was to select a proper simulation platform since inherent platform constraints can influence the way one needs to construct its model. The selected platform was Argonne National Laboratory's Powertrain System Analysis Toolkit (PSAT) software

2. Drive cycle definition:

   Usually, a drive cycle is a speed trace defined over time, which a given vehicle must follow. There are currently no public standard snowmobile drive cycles in widespread use. Thus, in order to perform a simulation, a drive cycle, specific to a moderately powered utility snowmobile application, was defined. Given the difficulty for a driver to replicate a speed trace cycle on a snowmobile in a real life environment, the drive cycle was defined as a modal cycle where each mode is defined by an accelerator lever position maintained by the driver for a given distance. In this case, the drive cycle is more of a "drive methodology" where driver behaviour is fixed.

3. On-snow data acquisition:

   Three types of on-snow tests were used.

   i. The modal "drive methodology" from point 2 was performed and data logged. The results from this test were kept for use in the validation stage of the simulation.
   ii. Acceleration tests were performed. For these tests, the snowmobile was accelerated from stop to whatever speed it would attain with the accelerator lever in a fixed, predetermined position. This was done for different accelerator lever positions, back and forth, repeatedly, on the same straight line course. Since the "drive methodology" test (i) is modal and thus has little

acceleration time, these acceleration specific tests allow one to better see the model's behaviour under rapid changes in vehicle speed.

iii. A coast down test was used in order to gather the data required to model the snowmobile chassis power dissipation. For this test the snowmobile was accelerated to a given speed and then it was turned off and left to coast down to a stop.

4. Application duty cycle modelling:

   To have a complete application duty cycle model on which to simulate the electric snowmobile model, speed and grade at each time step of the test are needed. Thus, a terrain model for the slope encountered by the snowmobile at any given point in time during on-snow data acquisition was constructed; it was then superimposed on the snowmobile's required speed trace to create an application duty cycle model.

5. Bench test data acquisition:

   Electric snowmobile sub-systems and components were removed from the chassis and bench tested. This ensured good sub-system and component data independent from the on-snow data acquisition tests.

6. Electric Snowmobile modelling:

   Using the gathered data, snowmobile component models were built and then assembled into a complete electric snowmobile model.

7. Simulation

   Simulation parameters were selected in PSAT and the electric snowmobile model was run through the previously defined application duty cycle model.

8. Validation

   Results from the on-snow data acquisition (step 3) were retrieved and compared to the simulation results.

3.1.2 Simulation Platform Selection

3.1.2.1 Introduction to Simulation Software Platform

Given the type of modeling and simulation work to be done, Argonne National Laboratory's Powertrain System Analysis Toolkit (PSAT) software was chosen as the main simulation software to perform the electric snowmobile simulations.

PSAT is a forward facing simulation tool. Based on models of its individual components, a complete vehicle model is assembled within PSAT. Once this complete vehicle model is assembled, one can virtually drive the vehicle (vehicle model) through a given drive cycle on a given terrain grade. After such a simulation has been completed, PSAT provides the user with extensive feedback on the behaviour of the vehicle, its subsystems and each of its components during the tested drive cycle.

A key feature of PSAT is that once a vehicle model has been created in PSAT, it can simulate many different cycles to see how a given vehicle configuration behaves under different drive cycle scenarios. Also, in order to compare the effect of different vehicle settings, it can be made to drive the same cycle over and over with different vehicle configurations. In a way, PSAT is to powertrain component selection what computer assisted drawing (CAD) is to technical drawing: a tool that greatly accelerates the creation of optimized designs.

PSAT is a Matlab®/Simulink®/Stateflow® based toolkit. Thus, in order to use PSAT's capabilities, the models must be built using Matlab®/Simulink®/Stateflow® and be in accordance with PSAT's standard structure and nomenclature. The quality of the data used to build the each individual component model impacts the final vehicle model's fidelity. Thus, in order to build high quality models for PSAT to perform a high fidelity simulation, extensive work must go into data gathering and data analysis.

The data used for this snowmobile model comes both from on-snow testing of McGill's latest electric snowmobile prototype and from bench testing of some of the electric snowmobile drivetrain's main components and sub-systems.

Example:

PSAT has been designed to suit the needs of the automotive industry. For an overview of PSAT, let us examine a quick example of how PSAT works using a hybrid car such as the Toyota Prius.

Figure 2 shows all the components which PSAT requires to build a complete split-hybrid car model.

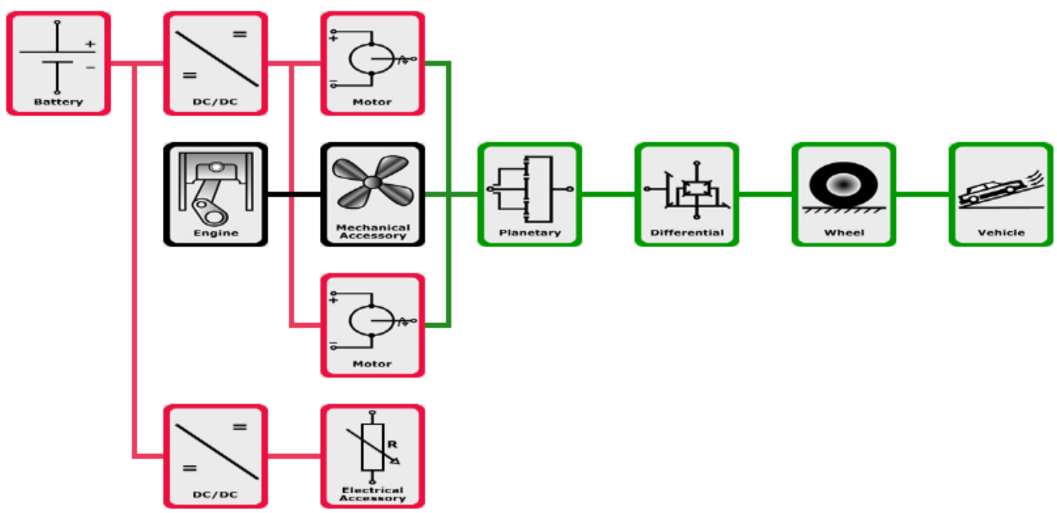

Figure 2: Split-Hybrid Car Component Model Tree (PSAT)

Parameters for each component/sub-system in the model tree must be gathered and combined into one single model in PSAT. Once each individual model has been completed, PSAT links them up into a complete vehicle model.

In order to use this vehicle model in PSAT, a drive cycle on which to run the model must be selected/defined. In the case of a passenger car, such a drive cycle could potentially be the United States Environmental Protection Agency (US EPA) Federal Test Procedure

(FTP), the drive cycle used for standard passenger vehicle fuel mileage estimates in the United States. The FTP drive cycle speed trace can be seen in Figure 3 below

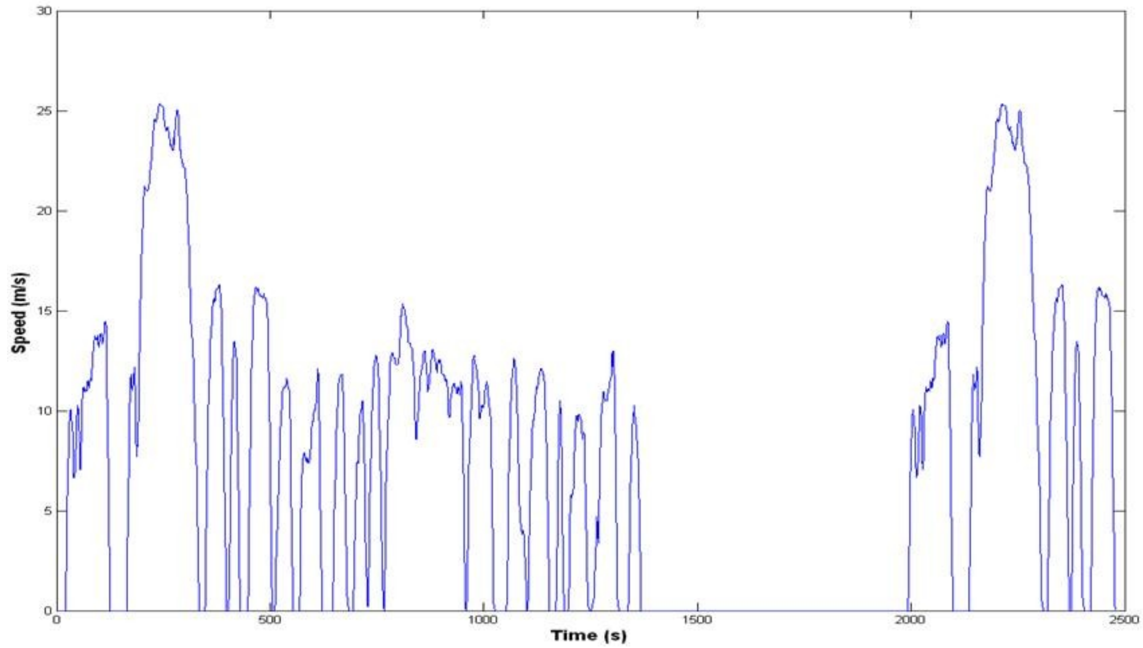

Figure 3: US EPA FTP Drive Cycle Speed (m/s) vs Time (s)

Lastly, the terrain on which this hybrid passenger car needs to perform this drive cycle needs to be defined. In the case of an FTP cycle, the standard would be to have the test performed on flat ground. The terrain model would thus be defined as a 0 degree slope at every time step.

With these 3 items (vehicle model, drive cycle speed trace and terrain model), PSAT can perform a vehicle simulation and then output results on an array of parameters concerning energy consumption and power use both at the vehicle level as well as at the component and sub-system level.

After having performed the previously defined baseline test, one could save the results and then, in order to compare both designs, run the same drive cycle on the same terrain, except this time do it without using a DC/DC converter between the battery and the motor in the vehicle design (Figure 4).

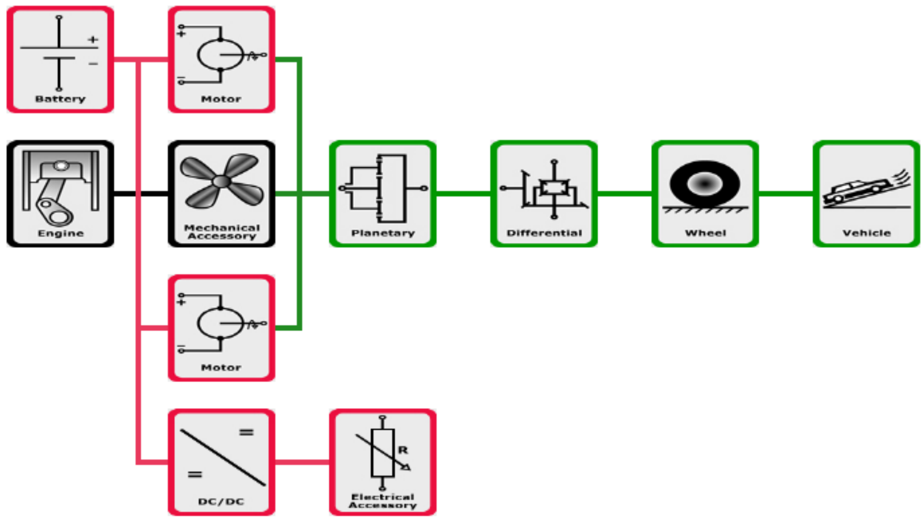

Figure 4: Split-Hybrid Car Component Model Tree (same as baseline configuration but without a DC/DC converter between the battery and the motor) (PSAT)

Results from these two tests could then be compared and used to find an optimal design for use during FTP drive cycle on flat ground.

Another possibility could be to use the same baseline split-hybrid vehicle on flat ground except perform a test using a different drive cycle such as the US EPA US06 drive cycle (Figure 5) and examine how this change in drive cycle affects some specific components and the vehicle's total energy consumption and power usage.

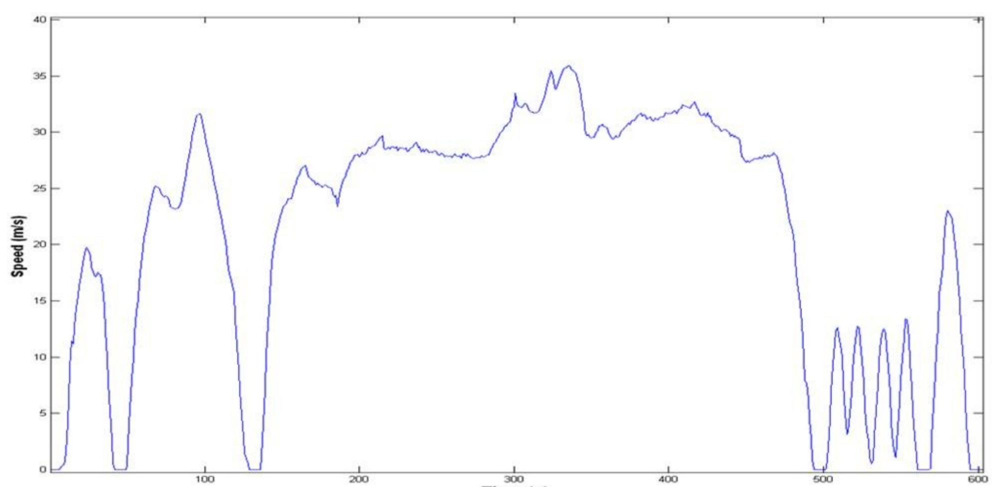

Figure 5: US EPA US06 Drive Cycle Speed (m/s) vs Time (s)

One could also keep the same vehicle and drive cycle and investigate the effect of mountainous terrain on the vehicle by inputting a non-zero slope at some time steps during the drive cycle.

While PSAT was not originally designed with electric snowmobile simulation in mind, its broad range of parameter inputs makes it possible for one to use it for such a task. Once an electric snowmobile model has been completed, it is then possible to virtually operate it on any terrain, year-round, and also make changes to the electric snowmobile's powertrain and test the difference these changes can make without the cost and time investment required to do so on a full scale prototype.

3.1.3 Drive Cycle Definition

To run a simulation, PSAT needs to know at what speed the vehicle is required to move at each time step (i.e., PSAT needs a drive cycle input).

Passenger cars have a large number of standard drive cycles commonly use by industry and governmental organisations; however, this is not the case in the snowmobile world. Without a list of standard snowmobile drive cycles to pick from, the only choice left was to create one.

The way drive cycles are defined and used in the passenger car world is the following:

- Each drive cycle is defined as a speed trace over time.
- A professional driver must then match this speed trace (within a certain error margin) with the car mounted on a dynamometer.
- If during testing the driver did not fully match the speed trace within the error margin, the test must be rejected and a new test performed.

When this drive cycle testing methodology was investigated for use with the electric snowmobile, a problem immediately came up.

Without easy access to a snowmobile chassis dynamometer which can adequately replicate real world driving loads, the snowmobile was going to have to be driven “for real” on a snow course in order to acquire the proper data to validate the model. Unfortunately, following a speed trace within a narrow margin on a snow course is an extremely difficult task. In all likelihood, the only way to achieve it would be to greatly increase the allowable error margin. Unfortunately, doing so also greatly diminishes the test’s precision.

Since this test could not be performed the same way the automotive industry performs it, different ways of applying this test had to be determined. In the end, the following testing methodology was chosen to try and get a sample representative of what a utility snowmobile could possibly see as a low speed people and equipment mover at the base of a ski resort:

- Six different accelerator lever positions were used.
- Each position was maintained for the same amount of distance to be travelled.
- To accurately keep the same accelerator position for any subsequent runs, a set of stoppers of appropriate lengths were manufactured.
- For the test to be valid, the driver must maintain correct throttle position throughout the prescribed distance and not use the brake.

Since this is not a drive cycle with a fixed speed at each time step, but rather a “drive methodology” the driver must follow, it has certain limitations as to what it can be used for. However, in the case of this electric snowmobile testing, extracting the resultant speed trace for the on-snow test “drive methodology” and using it as a drive cycle input into PSAT is sufficient to accomplish the task at hand.

Furthermore, knowing the accelerator position (fixed at all times) and the exact brake input (zero at all times) is an advantage. By using this information, after performing a simulation, one can verify that PSAT has performed the simulation exactly the way the vehicle was driven by making sure that the brake is never applied during the simulation (reflecting the actual drive test).

With a known simulation platform and a defined drive cycle methodology in hand, drive testing can now begin.

3.1.4 Testing and Modeling

For PSAT to provide good results, proper testing and modeling must be done on:

- The snowmobile and all its components
- The application in which it will perform

Once data has been acquired on the elements composing the snowmobile, as well as on the terrain and speed of the selected application duty cycle, virtual models of these are assembled and put together, giving:

- A virtual electric snowmobile
- A virtual application duty cycle model

Only once both a virtual snowmobile and a virtual application duty cycle model have been assembled can the actual simulation start.

To have a virtual electric snowmobile in PSAT, one needs to define a powertrain configuration and create a virtual model for each of the elements of the powertrain. The selected electric snowmobile powertrain configuration in PSAT can be seen in Figure 6.

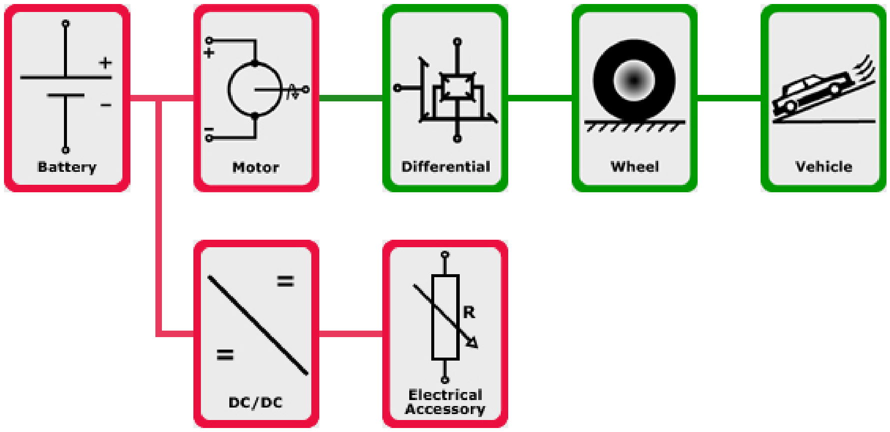

Figure 6: Electric Snowmobile Component Model Tree Used in PSAT (PSAT)

Thus, to complete a virtual electric snowmobile model, 7 individual elements need to be modeled individually and then assembled in PSAT.

1. The battery
2. The motor (actually includes three items: the motor itself as well as the controller and the CVT)
3. The differential (The snowmobile does not have a differential, but this PSAT block is used to model the snowmobile's fixed secondary ratio.)
4. The wheels (The snowmobile does not have wheels the same way a car does; however, its track and drive sprocket assembly can be modeled within this PSAT block.)
5. The vehicle chassis drag and other losses
6. The DC-DC converter losses
7. The accessory load

As previously mentioned, a virtual electric snowmobile model is only half of what is required to run a PSAT simulation. The other half is an application duty cycle model. For this exercise, the application duty cycle model is composed of two things:

1. Speed at every time step
2. Grade at every time step

The electric snowmobile model was assembled using a combination of on-snow data and bench test data, while the application duty cycle model was assembled using only on-snow data.

The following sub-sections show how the on-snow data was acquired and how it was used to assemble an application duty cycle model. First, the application duty cycle model assembly is presented, followed by the bench testing data acquisition. Finally, a description of how it was combined with some of the on-snow data to create the electric snowmobile's virtual model is given.

3.1.4.1 On-Snow Data Acquisition

On-snow testing was performed, under special authorization from the McGill Farm Manager, on open field at McGill's MacDonald Campus research farm complex. In the summer, the fenced out field is relatively flat with a slight incline going downwards from the southwest corner to the northeast corner. It was initially assumed that using this field would make it possible to assume that the terrain for the application was flat. Unfortunately, record breaking snowfall and high winds during the test season made it such that, assuming the vehicle was being operated on flat terrain would add a non-negligible systematic error to the results.

Three different tests were performed during on-snow testing:

1. A "drive methodology" test
2. An acceleration test
3. A coast down test

For each test, the data acquisition was performed using an Isaac Instruments V7 Professional Black Box data recorder.

Some of the most important recorded parameters were:

- CVT Driven Frequency (RPM) (sampling rate of 0.2 second)

- Battery Voltage (V) (sampling rate of 0.2 second)
- Battery Current (A) (sampling rate of 0.2 second)
- GPS Speed (km/h) (sampling rate of 1 second)
- GPS Direction (degrees) (sampling rate of 1 second)

In order to try and minimize the effect of changing snow conditions on the vehicle's behaviour, the track and the slides were lubricated using Hipertech SSL Track Lubricant.

3.1.4.1.1 "Drive Methodology" Test

The "drive methodology" test was performed following the methodology outlined in section 3.1.3. The distance travelled in each mode was 390m on a pre-tracked loop shaped almost like a track and field competition track (see figure 7) .

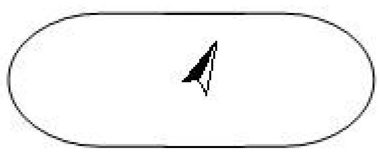

Figure 7: Approximate Shape of "Drive Methodology" Test Track

This “drive methodology” test yielded 6 speed “plateaus” (+ or – approximately 3m/s maximum per plateau) as can be seen in figure 8 below.

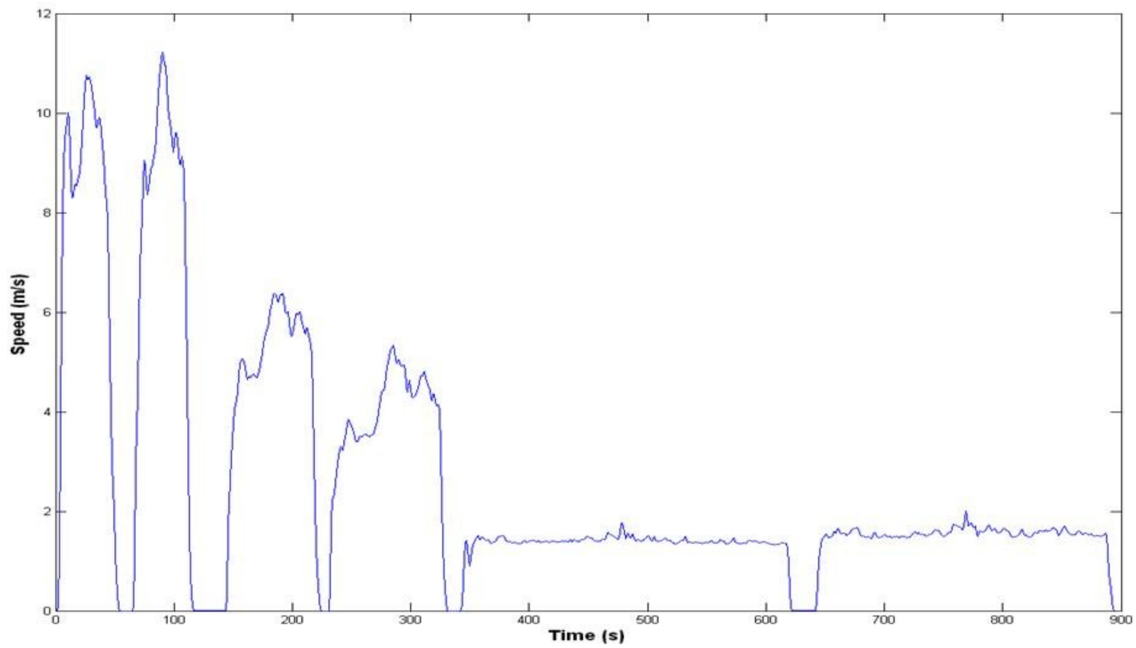

Figure 8: Speed vs. Time Resultant Drive Cycle Trace Obtained from the "Drive Methodology"

3.1.4.1.2 Acceleration Test

The acceleration test consisted of 8 acceleration runs. Two acceleration runs were done for each of the four fastest throttle positions used during the drive cycle test. The runs were done always on the same track with each run of a pair of runs using the same throttle position done in opposite directions. The selected area for the runs was the longest available straight line which was as flat as possible in the field. The approximated position of the run is depicted as a dashed line in Figure 9.

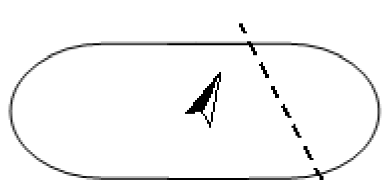

Figure 9: Approximate Position of Acceleration Test Track

The result of this test (Figure 10) is a speed trace with 8 “high” peaks, each one representing an acceleration run, with some low speed traveling (“low” peaks) between them as a result of the snowmobile doing a hard turn to get into position for the next run.

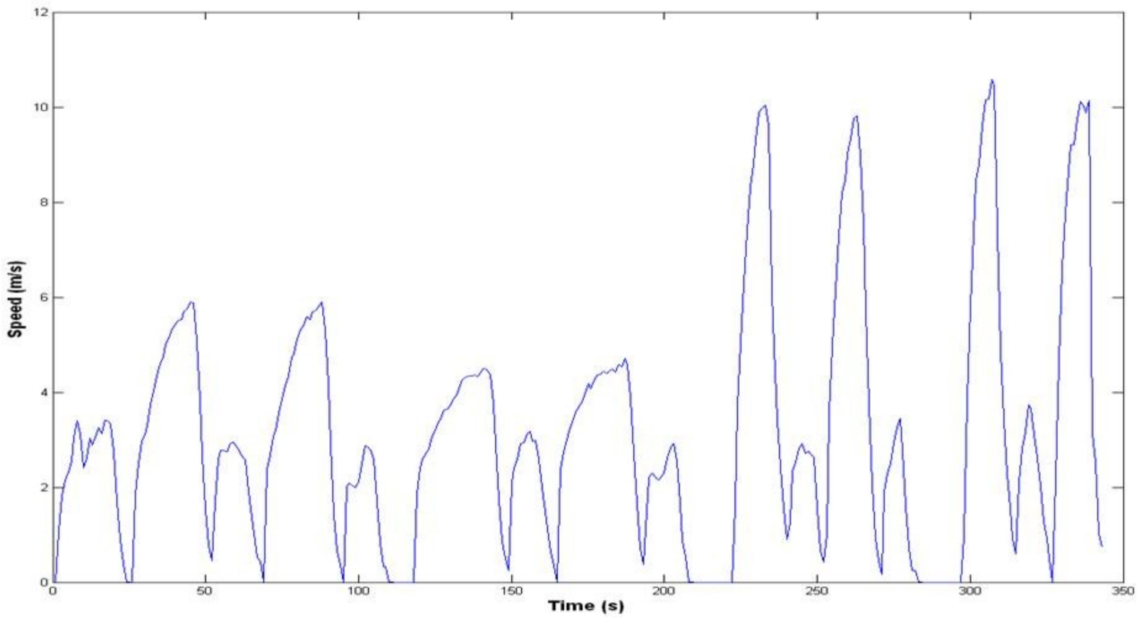

Figure 10: Acceleration Test Speed Trace

3.1.4.1.3 Coast Down Test

For this test, the snowmobile was brought up to speed, using the fastest accelerator lever position from the drive cycle test, and once cruising speed was reached then the accelerator lever was rapidly released and the snowmobile was left to coast down to a halt. This test took place in the northern straight line of the drive cycle loop, shown in bold in Figure 11 below.

Figure 11: Approximate Location of Coast Down Test

The resultant speed trace from the coast down test can be seen in Figure 12 below.

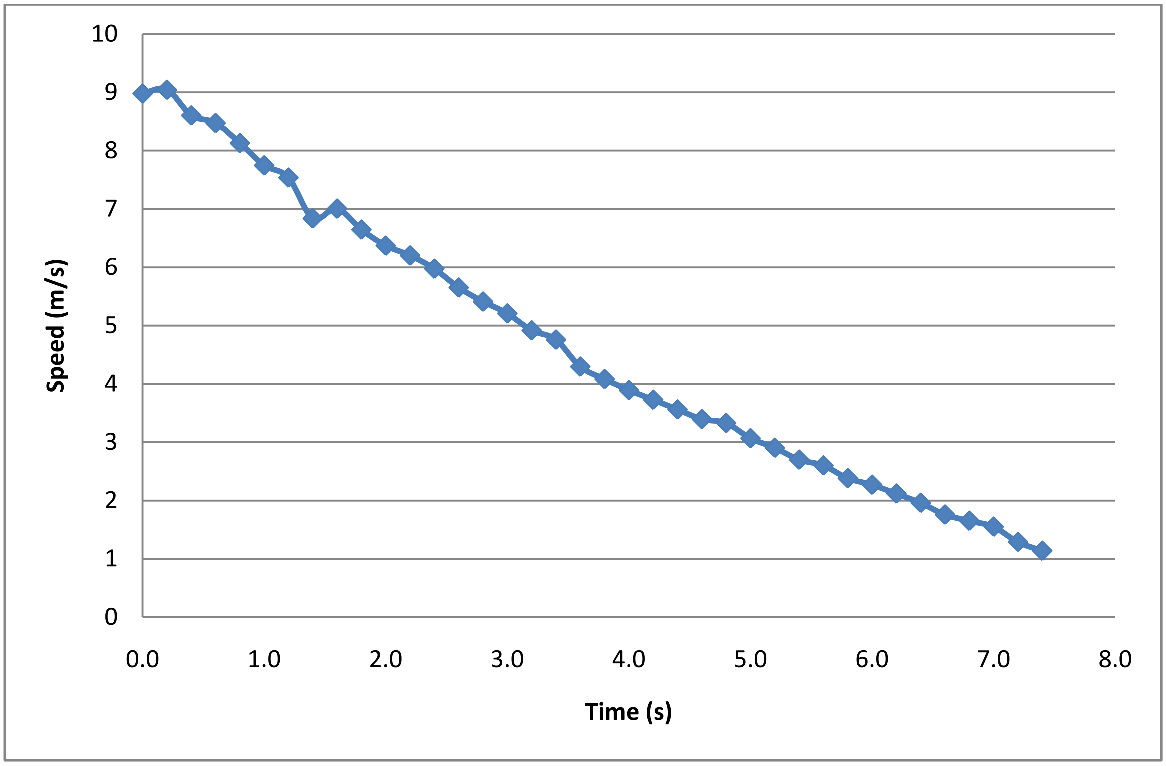

Figure 12: Coast Down Speed Trace

3.1.4.2 Application Duty Cycle Modelling

As previously defined in section 3.1.1, two things are needed in order to create an application duty cycle model:

1. Speed (at every time step)
2. Grade (at every time step)

3.1.4.2.1 Speed

The drive cycle speed trace obtained from the “drive methodology”, previously seen in Figure 8, was used as the application duty cycle model’s speed input.

3.1.4.2.2 Grade

Ideally, testing would have been performed on perfectly flat snow surface and grade would have been zero at all time steps, which would have made the application duty cycle model simple to assemble. Initially it was thought that the chosen test field would be close enough to flat that assuming a zero grade at every time step would be a valid assumption with negligible consequences. Unfortunately a perfectly flat snow field was not a possibility for this test. Thus, grade at every time step had to be accounted for.

The following methodology was used to determine grade at every time step.

1. Twenty runs were completed on the drive cycle test track at the slowest accelerator position setting used in the previously defined “drive methodology”. This yielded near constant speed runs with small fluctuations in power.
2. For each of these runs the average power consumed was calculated from the time the snowmobile reached its cruising speed to the point just before the driver let go of the accelerator.
3. It was assumed that, at any given time step, the deviation from this average power came from a change in the potential energy of the snowmobile during this time step. Thus for a given time step the deviation of power input from the

average value of power input was multiplied by duration of the time step. This result gave the amount of energy used to increase potential energy of the vehicle during a given time step. While doing this, small differences in speed were compensated for by calculating the energy required to accelerate the vehicle using the following formula

$$\text{Energy} = \frac{1}{2} m v^2$$

where m is the mass of the snowmobile with driver and v is the difference in speed between 2 adjacent data points.

4. The remaining amount of energy was used to calculate the height gained by the snowmobile during each time step. This was done by using the following formula:

$$\text{Height} = E/(mg)$$

where E is the energy calculated as a result of step 3, m is the mass of the vehicle with the driver and g is gravitational acceleration.

5. The relative height vs. position curves for each of the 20 runs were then all superimposed on the same graph. All these curves were then manually given a position offset (if required) in order to properly align their peaks. This ensured they would all be on the same position coordinate system. In other words, since each run did not start *exactly* from the same position in the field, a position offset was incorporated to each run, when needed, to ensure that each test would be measured on the same absolute position coordinate system, and not a coordinate system relative to its own starting position.
6. Using the average relative height and the distance travelled between each adjacent data point, the slope experienced by the vehicle at each point on the track was calculated using the following formula:

$$\text{Slope} = \text{Arctan}\,(h/s)$$

where h is the height difference between 2 adjacent data points and s is the distance travelled between these same adjacent data points.

7. Once this was performed, a 21 point moving average of the points defining the slope vs position curve for all 20 runs combined was taken. The resultant average slope vs. position can be seen in Figure 13 below along with the standard deviation and the error on the moving average (standard deviation divided by square root of 21).

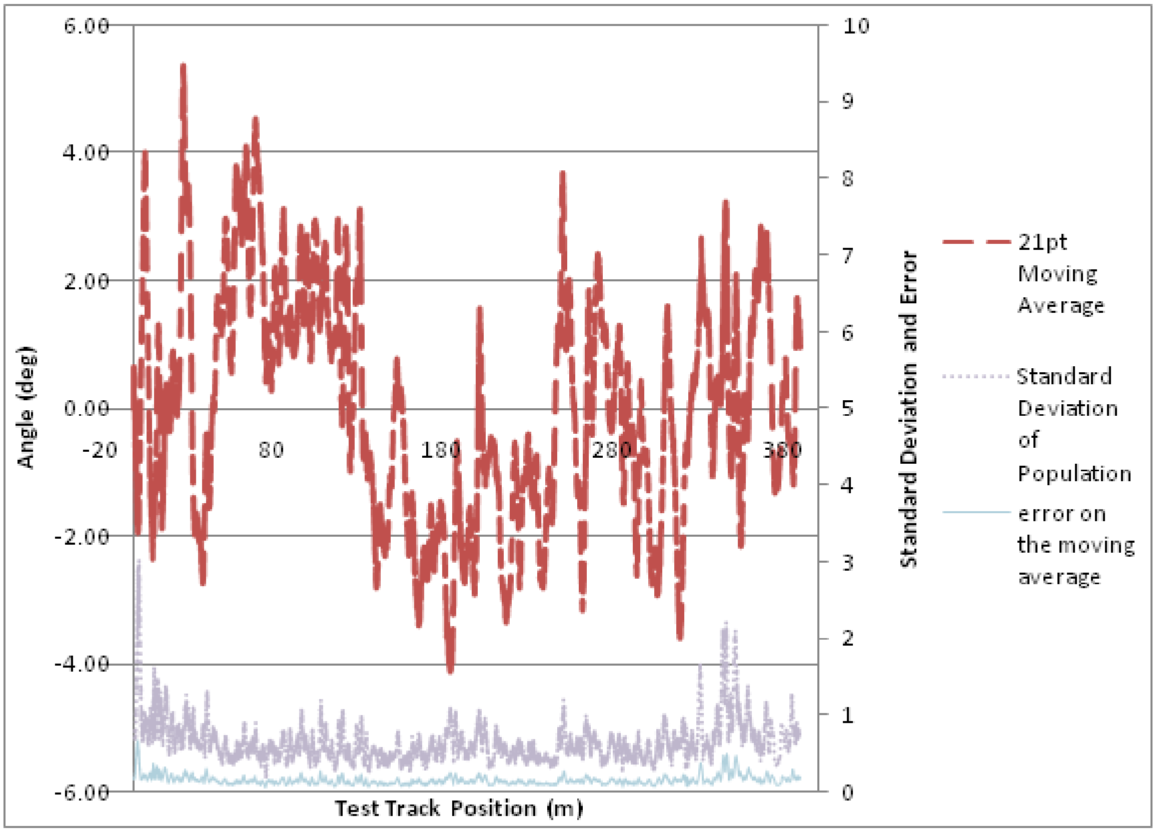

Figure 13: Average Slope vs. Position on the Test Track

8. Lastly, using speed data calculated from CVT driven frequency, and GPS direction data, each point on the drive cycle speed trace (Figure 8) was matched to the terrain grade slope based on the slope vs. position trace obtained in step 7. This produced a speed trace with corresponding slope for each time step, namely, an application duty cycle model.

With both the speed and grade at every time step tabulated, the application duty cycle model is complete and thus efforts must now go into completing the electric snowmobile model. The first step in completing the snowmobile model is to acquire all the relevant data.

3.1.4.3 Bench Test Data Acquisition

Bench testing was used to obtain data for the following items in the electric snowmobile model tree (Figure 6):

- The motor
- The DC-DC converter losses
- The accessory load

3.1.4.3.1 Motor

In order to obtain the motor efficiency map, the McGill VERT project's, AC motor, in-line, shaft-to-shaft test dynamometer was used (Figure 14).

Figure 14: McGill VERT Project Dynamometer Test Bench

It was equipped with a custom made CVT adapter as shown in Figure 15.

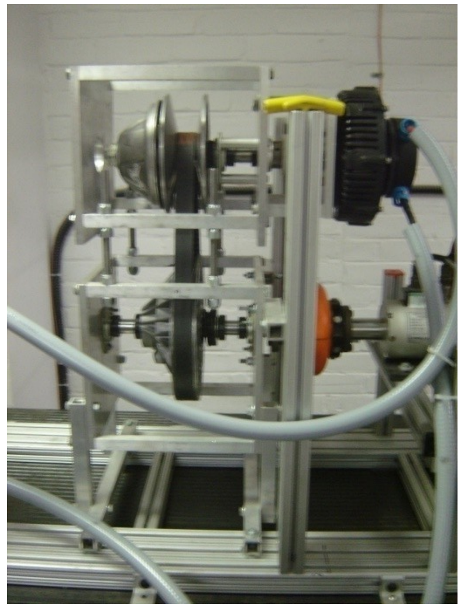

Figure 15: McGill VERT Project Dynamometer CVT Adapter

The snowmobile motor was mounted to the CVT adapter. Its terminals were connected to the actual electric snowmobile used for on-snow testing which was placed right next to the dynamometer. Power going to the motor was regulated by using the electric snowmobile's thumb actuated acceleration lever.

Voltage input and current input were recorded manually at given torque and frequency points.

Frequency and torque output were measured using a S. Himmelstein and company MCRT 9-02T non-contact torquemeter with values displayed on a S. Himmelstein and company Model 721 mechanical power instrument.

Voltage input was measured and displayed using a Fluke 189 true RMS multimeter.

Current input was measured using a Fluke i410 AC/DC current clamp and displayed using an Equus #4302 multimeter.

3.1.4.3.2 DC-DC converter losses

The DC-DC converter losses were approximated by manually recording the difference between the DC-DC converter's input and output power while the electric snowmobile was at rest.

Voltage input and output were measured and displayed using a Fluke 189 true RMS multimeter.

Current input and output were measured using a Fluke i410 AC/DC current clamp and displayed using an Equus #4302 multimeter.

3.1.4.3.3 Accessory Load

The accessory load was approximated by manually recording the DC-DC converter's output power while the electric snowmobile was at rest.

Voltage was measured and displayed using a Fluke 189 true RMS multimeter.

Current was measured using a Fluke i410 AC/DC current clamp and displayed using an Equus #4302 multimeter.

3.1.4.4 Electric Snowmobile Modelling

To create the electric snowmobile model in PSAT, a model of each of the 7 components in the selected model tree (Figure 6) must be completed. These 7 components to be modeled are:

1. The battery
2. The motor (actually includes three items: the motor itself as well as the controller and the CVT)
3. The differential (The snowmobile does not have a differential, but this PSAT block is used to model the snowmobile's fixed secondary ratio)

4. The wheels (The snowmobile does not have wheels the same way a car does, however, its track and drive sprocket assembly can be modeled within this PSAT block.)
5. The vehicle chassis drag and other losses
6. The DC-DC converter losses
7. The accessory load

3.1.4.4.1 Battery

The PSAT Lead Acid Battery Generic Map model was used as the electric snowmobile battery model.

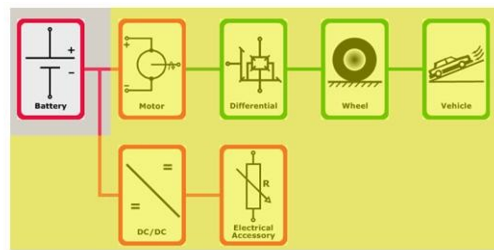

Figure 16: Position of Battery Model in the Electric Snowmobile Model Tree (PSAT)

It was then modified in order to make the chosen model behave like the electric snowmobile's lithium batteries.

Based on an array of lithium cell data gathered through various projects within the McGill VERT Project lab as well as data from the McGill Electric Snowmobile Team and the McGill Hybrid Racing team, the following parameters were changed in the initialization file:

- The initial state of charge of the battery pack was set to 86.6 % to reflect the initial state of charge at the beginning of the on-snow testing.
- The number of cells per module was set to 1 since each of the lithium modules used in the snowmobile contained one cell
- The total number of module was set to 20 in accordance with the number of modules in the electric snowmobile used for on-snow testing.
- The nominal voltage for each module was set to 3.6V based on manufacturer data.

- The minimum voltage for each module was set to 3V based on manufacturer data.
- The maximum voltage for each module was set to 4.2V based on manufacturer data.
- The mass for each module was set to 1.5 kg based on manufacturer data.
- The cells were given a minimum state of charge of 0 (i.e. they were allowed to fully discharged if required).
- The cells were given a maximum state of charge of 1 (i.e. they were allowed to be fully charged if required).
- The cells were given a coulombic efficiency of 95% .
- The internal resistance map was changed to the values seen in Table 5 below:

Table 5: Module internal Resistance Map

State of Charge(%)	0	10	20	30	40	50	60	70	80	90	100
Resistance in milliohms	4.07	3.70	3.38	2.69	1.93	1.51	1.31	1.23	1.17	1.18	1.22

- The module open circuit voltage map was changed to the values seen in Table 6 below:

Table 6: Module Open Circuit Voltage Map

State of Charge(%)	0	10	20	30	40	50	60	70	80	90	100
Voltage (V)	3.0	3.25	3.4	3.5125	3.6	3.6875	3.775	3.85	3.925	4.0	4.2

3.1.4.4.2 Motor

A PSAT built-in Permanent Magnet motor model was used as the electric snowmobile motor model.

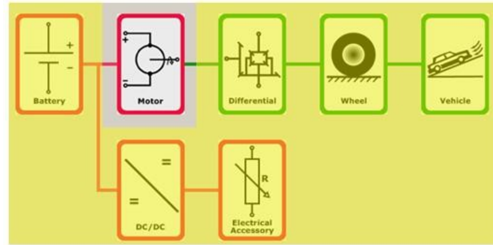

Figure 17: Position of the Motor Model in the Electric Snowmobile Model Tree (PSAT)

It was then modified in order to make the chosen model behave like the electric snowmobile motor.

In it the following parameters were changed:

- The motor inertia was set to 0.0297kg.m^2 based on manufacturer specifications and an approximation of the inertia of some drive components based on their approximate mass and shape.
- The motor mass was set to 15.14 kg based on measured mass of motor, CVT and coupling components.
- The controller mass was set to 2.27 kg based on the measured mass of the controller.
- The maximum allowable current was set to 130A based on the percentage of maximum current set in the controller during on-snow testing.
- Motor manufacturer data was used to set the maximum continuous speed and torque index. The manufacturer data used can be seen in table 7 below[19].

Table 7: Maximum Continuous Speed and Torque Index

Torque (Nm)	0	5	10	15	20	25	30	35	38
Speed (1/min)	3532	3495	3458	3420	3383	3346	3308	3271	3249

- The values in Table 8 below were used as the speed index of the motor power and efficiency maps.

Table 8: Speed Index for Motor Power and Efficiency Maps

Speed (1/min)	0	500	1000	1500	2000	2500	3000	3500

- The values in Table 9 were used as the torque index of the motor power and efficiency map

Table 9: Torque Index for Motor Power and Efficiency Maps

Torque(Nm)	0	5	10	15	20	25	30	35	40

Figure 18 below shows the four quadrant motor mechanical power map.

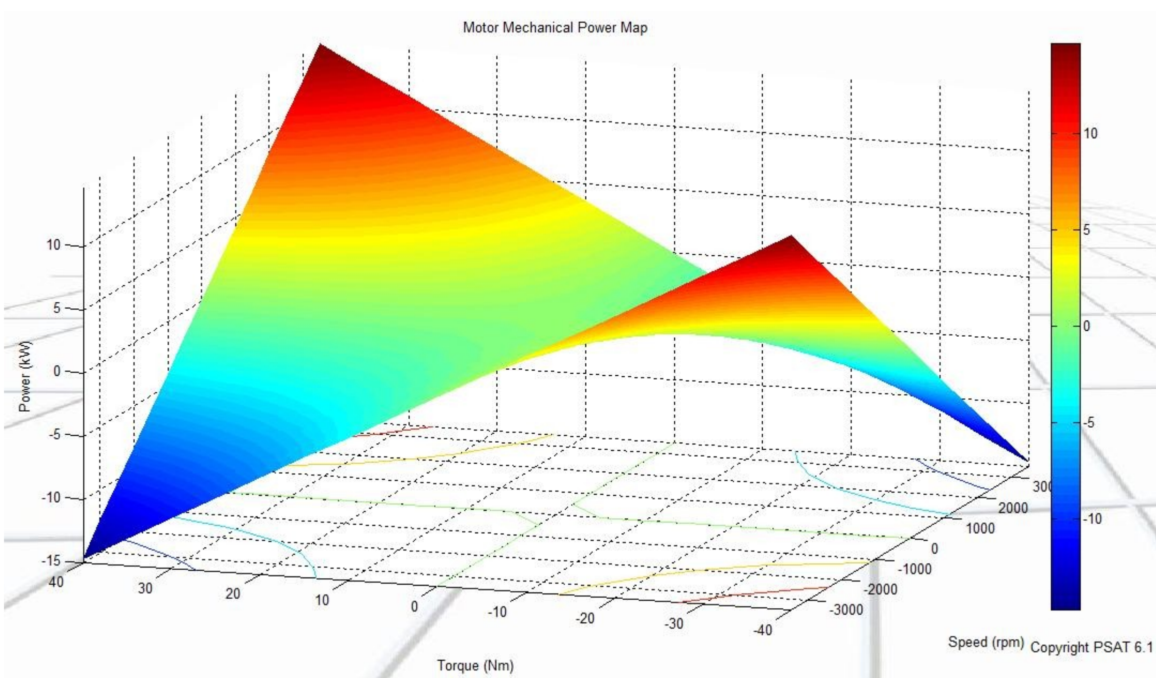

Figure 18: Motor Output Power Map (PSAT)

- The motor efficiency map was changed to reflect the results obtained during bench testing. Furthermore, points at 0 speed and points at 0 torque were given a value of 0.01. Points outside the speed range attainable for a given torque when bench testing the motor were given the value of the point at the highest speed tested for that torque.

Figure 19 below shows the four quadrants normalized motor power loss map.

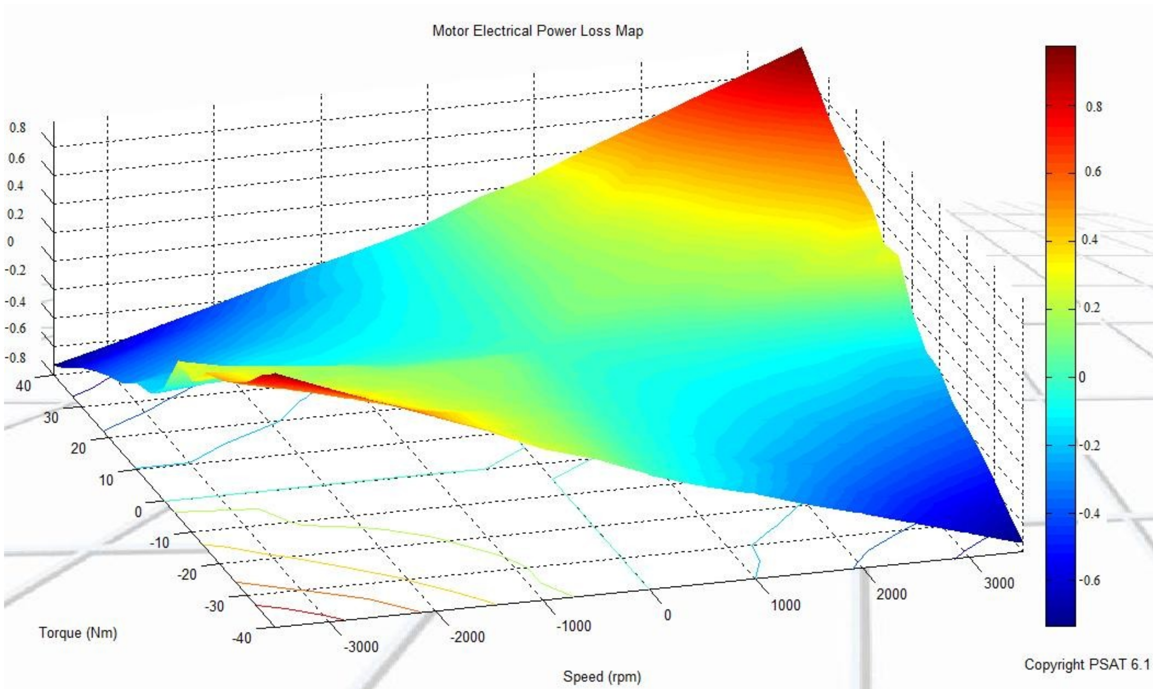

Figure 19: Normalized Motor Power Losses as a Function of Speed and Torque (PSAT)

3.1.4.4.3 Differential

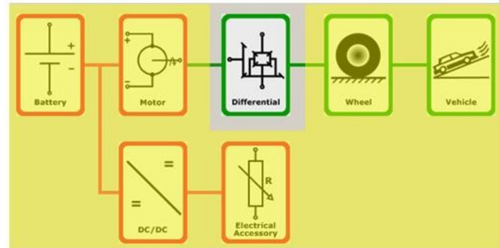

Figure 20: Position of the Differential Model in the Electric Snowmobile Model Tree (PSAT)

A PSAT built in differential model was used as the electric snowmobile differential model. This model was actually used to represent the silent chain secondary ratio between the CVT driven shaft and the track drive sprockets shaft in the snowmobile.

This differential model was then modified in order for it to represent the snowmobile's secondary ratio. In it the following parameters were modified:

- The gearing ratio was set to 2.647 in accordance with the test snowmobile's secondary ratio.
- The inertia was changed to 0.0238kg.m^2. This was based on the calculated inertia of the secondary ratio's drive components based on their approximate mass and shape.
- The mass was set to 7.05kg based on measured data of the electric snowmobile's secondary ratio.
- The efficiency of the secondary ratio was set to 99%; this was based on information for maximum efficiency of a silent chain obtained from Ramsey Products[20], a silent chain manufacturer.

The resulting efficiency map for the secondary ratio is a flat surface as can be seen in Figure 21 below.

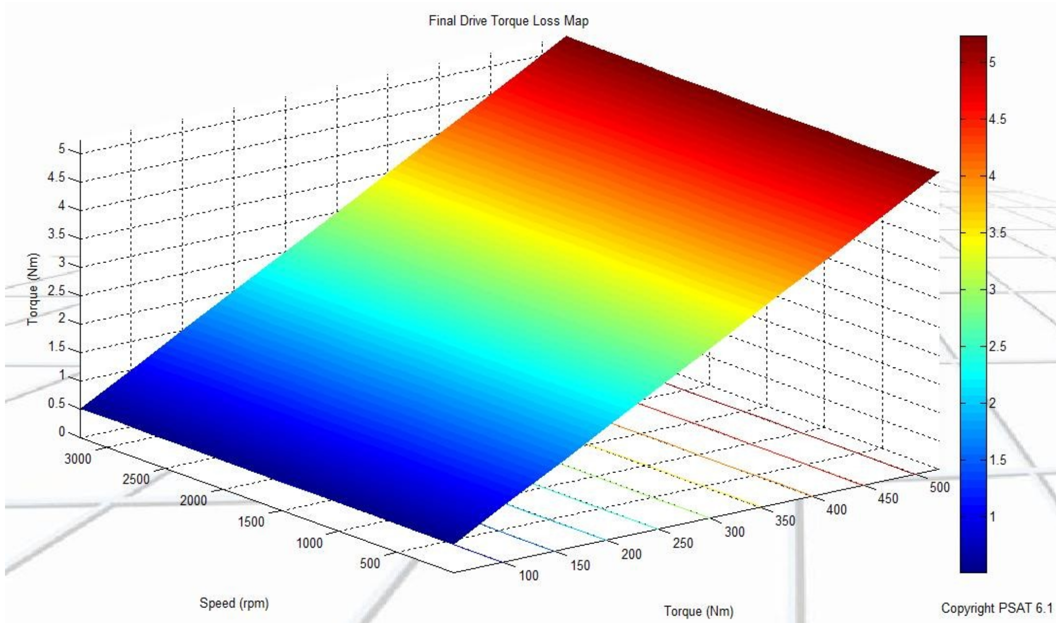

Figure 21: Map of Torque Loss Associated with the Secondary Ratio as a Function of Torque and Speed (PSAT)

3.1.4.4.4 Wheel

The PSAT two wheel drive generic model for curve fit losses was used as the electric snowmobile wheel model. This model is actually used to represent the snowmobile's drive sprockets, drive shaft and track assembly.

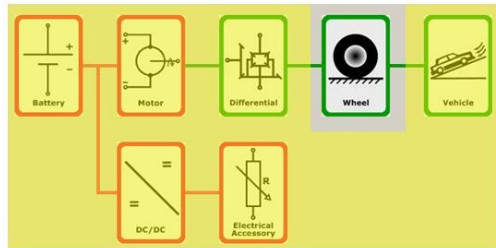

Figure 22: Position of the Wheel Model in the Electric Snowmobile Model Tree (PSAT)

This wheel model was modified in order for the model to represent the snowmobile's drive sprockets, drive shaft and track assembly. In it the following parameters were modified:

- The number of wheels was set to 1.
- The inertia for the wheel was set to 0.1472 kg.m^2 based on the sum of the individual inertia of the drive sprockets, drive shaft and track assembly calculated based on their approximate mass and shape.
- The wheel radius was set to 0.09168m based on measured values from the electric snowmobile.
- The wheel mass was set to 18.364kg based on the sum of the measured mass of the individual components.

3.1.4.4.5 Vehicle

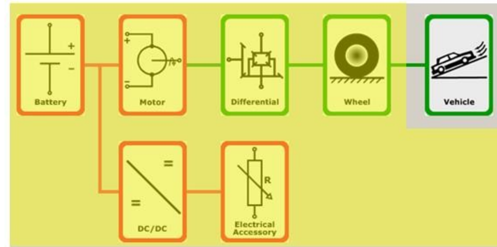

Figure 23: Position of the Vehicle Model in the Electric Snowmobile Model Tree (PSAT)

A generic PSAT vehicle model specific to curve fit losses was used as the electric snowmobile vehicle model. Normally, in the automotive world, the empirical vehicle model is a second degree polynomial that has the following form:

$$\text{Force} = Cv^2+Bv+A$$

where v = vehicle speed and A, B and C are empirical constants.

The empirical model defines a vehicle's chassis losses as a lumped parameter system which is an alternative to individually finding losses due to, aerodynamic drag, rolling resistance and any other chassis losses. For this equation, in PSAT, the aerodynamic drag losses are assumed to be represented by the quadratic term. The velocity term is associated with losses from higher order coefficients of the PSAT rolling resistance equation and some bearing losses in axles. The A term is assumed to be caused entirely by rolling resistance losses[21]. Thus, in general, for cars, the squared term tends to be almost negligible at low speed when air resistance is low and as speed increases it becomes more and more significant to the point where in some cases it dominates the other two terms.

However, when examining the force required to drive the snowmobile on and through snow as a function of speed (see Figure 24 below), no such increase is observed at the higher speeds.

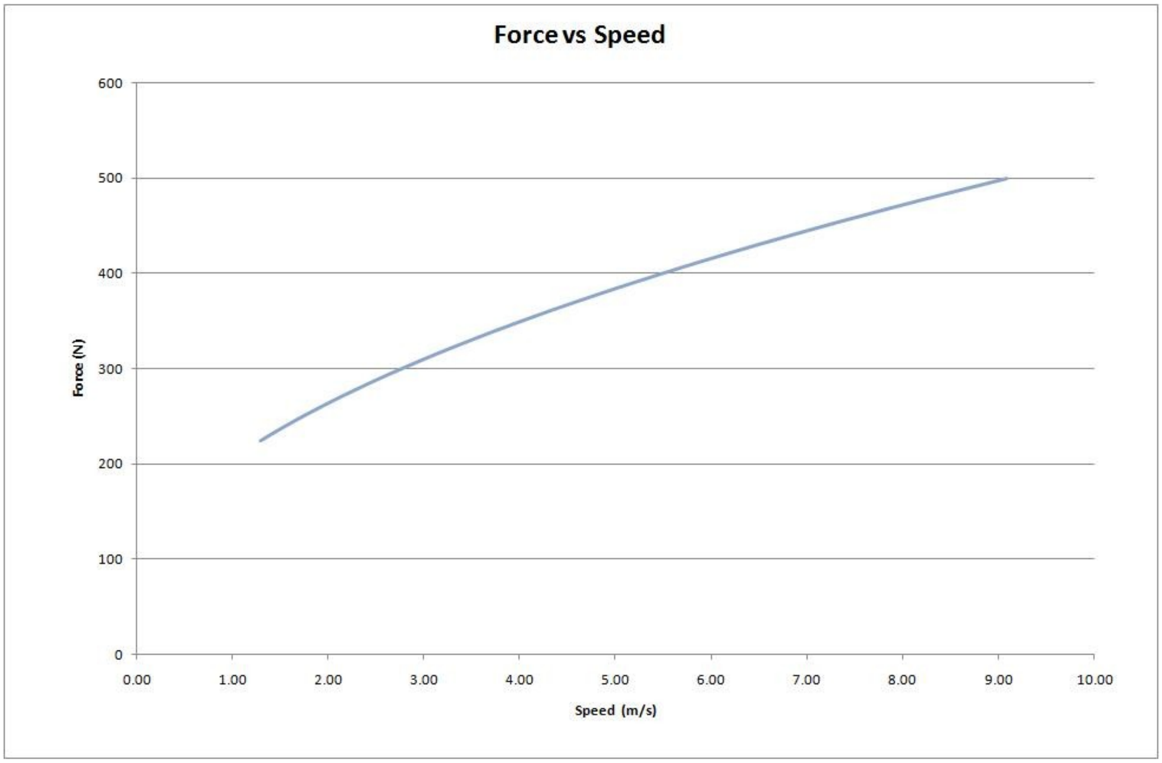

Figure 24: Electric Snowmobile Force Required at the Track for a Given Vehicle Speed

This is likely due to the fact that the speeds at which the snowmobile was tested were below 40 km/h (11.11m/s), typical of a utility snowmobile application. Thus, for this model, it will be assumed that a first-order polynomial can be used to obtain a vehicle model force vs speed equation of the form shown below:

$$\text{Force} = Bv+A$$

where B and A are empirical constants and v is the snowmobile velocity.

After a curve fitting exercise that included a correction of elevation differences in the coast down test track, the resulting empirical model can be compared with the measured data previously shown in Figure 12. Other than the vehicle chassis losses coefficients (B and A), the following values were inputted into the existing generic model:

- The body mass was set to 152kg based on vehicle total mass minus all the mass included in the other models.
- The vehicle wheel base was set to 0.5m based on the approximate distance between the snowmobile's track and the skis.
- The amount of cargo mass was set to 0kg.

Figure 25 below, shows the resultant model coast down data versus the actual coast down data. It can be seen, that absolute error throughout the coast down test is never greater than 2.5km/h (0.7m/s) and that the highest error points all happen at very low speed (lower than walking speed). Based on this result, it is believed that the decision to use a first-order polynomial to approximate the electric snowmobile's force vs. speed trace for speeds below 40km/h (11.11m/s) is valid for the purpose of this model.

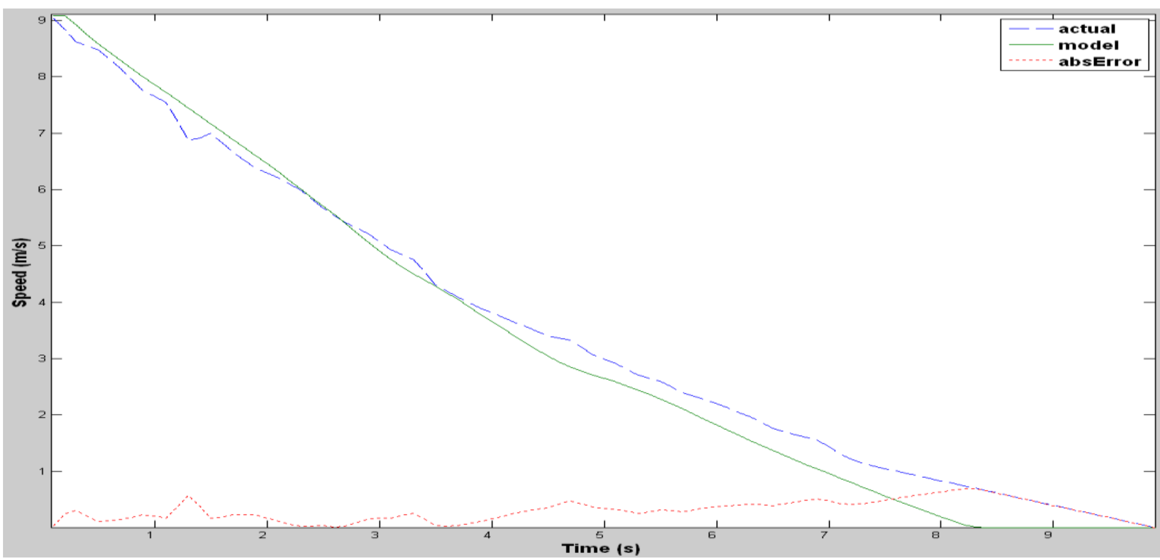

Figure 25: Simulated Coast Down vs. Actual Coast Down

3.1.4.4.6 DC-DC Converter

A PSAT generic constant efficiency DC-DC converter model was used as the electric snowmobile DC-DC converter model and modified to reflect the data gathered during bench testing

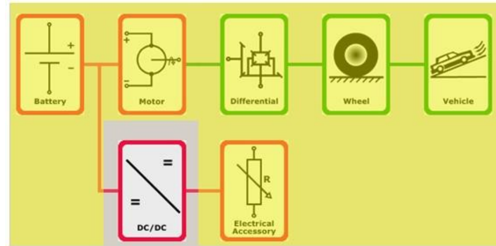

Figure 26: Position of the DC-DC Converter Model in the Electric Snowmobile Model Tree

3.1.4.4.7 Electrical Accessory

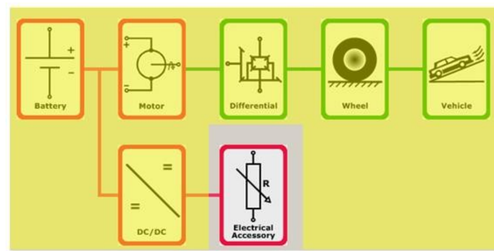

Figure 27: Position of the Electrical Accessory Model in the Electric Snowmobile Model Tree

Since the headlights were always turned off during on-snow testing and the only electrical accessory power draw came from relays, contactors and the data acquisition system, it was assumed that the load from the electrical accessories could be modeled as being constant. Thus, a PSAT generic constant electric power loss model was used as the electric snowmobile electrical accessory model. It was modified to closely reflect the data gathered during bench testing. The mass of the electrical accessories was given a value of 0kg (these items are being accounted for in the vehicle model mass).

3.1.5 Simulation

With a model in hand for each component in the electric snowmobile's PSAT model tree and a complete application duty cycle model with speed and grade, simulation of the electric snowmobile in this application can now be pursued.

In order to perform a simulation in PSAT a driver model as well as a propelling and braking strategy must be specified.

3.1.5.1 Driver Model

The driver model has two functions.

1. The first one is simple: the PSAT driver model adds the driver's weight to the vehicle weight.
2. The second one is a little less trivial: the PSAT driver model is what enables the virtual electric snowmobile model to follow the specified speed trace from the application duty cycle model. In a way, it is this driver model that "operates" the virtual electric snowmobile's brake and acceleration lever. It does this by continuously comparing the model's speed with the application duty cycle's speed trace and it uses a "Proportional-Integral" (PI) controller to try and rectify any difference by regulating the vehicle's torque demand.

The driver model used for this simulation is the PSAT generic model for vehicles which are modeled using curve fit loss coefficients. The driver mass was set to 68 kg.

A PI controller is used in order to match the input speed trace. If the PI controller is not properly tuned, the virtual electric snowmobile can overshoot or undershoot the desired speed especially during drive cycles with hard accelerations and decelerations. Having a vehicle that properly follows the speed trace using a well calibrated driver is a must for the validity of all other results from the test. The proportional gain (kp) was set to 200 and the integral gain (ki) was set to 5.

3.1.5.2 Propelling Strategy

Propelling strategies in PSAT are often used in order to tell the driver when to shift gears. In this case, the driver does not have to shift gears as the vehicle is equipped with a CVT and the CVT's shifting characteristics have already been incorporated to the motor model. Thus a generic PSAT propelling strategy for a powertrain without transmission was used.

3.1.5.3 Braking Strategy

Since this is an electric vehicle, PSAT automatically gives it the possibility of having regenerative braking. Since the electric snowmobile does not have regenerative braking, some parameters must be changed in the PSAT braking strategy for electric vehicles in order to make sure that the model does not have regenerative braking available. To do this, the percentage of total braking power available for regenerative braking has been reduced to 0%.

3.1.6 Results and Validation

In this section, the performance of the electric snowmobile model will be evaluated on 3 points:

1. Ability to follow the speed trace
2. Instantaneous power use
3. Overall energy use

Points 1 and 2 will be evaluated using both:

- the application duty cycle previously defined

and

- the acceleration test with the assumption that is was performed on a flat surface

Point 3, given the very short duration of the acceleration test, will only be tested using the application duty cycle.

3.1.6.1 Ability to Follow the Speed Trace

In both cases the model accurately followed the speed trace.

For the application duty cycle, the electric snowmobile model was never off the target speed trace by more than 3.2km/h (0.89m/s).

The plot below (Figure 28) shows how well the target speed and the simulated model speed overlap.

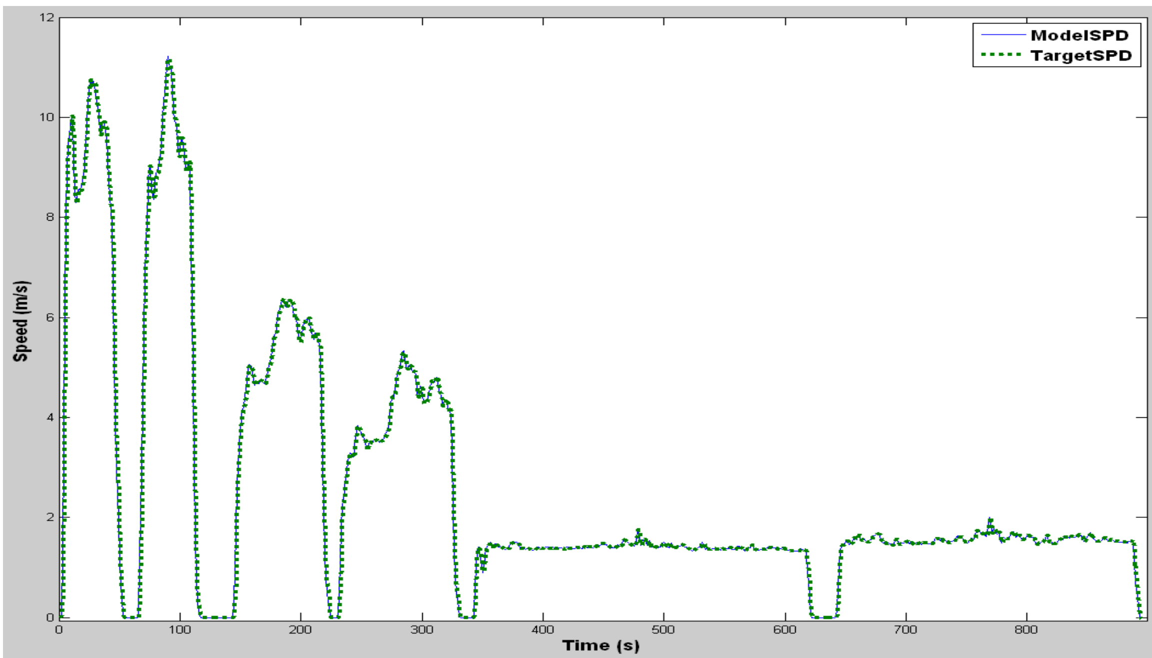

Figure 28: Target Speed Trace Overlapping Electric Snowmobile Model Speed Trace on Application Duty Cycle

For the acceleration test, the electric snowmobiles model was off the target speed trace by more than 3.2km/h (0.89m/s) for only 2.1 seconds over the total duration of the test.

The plot below (Figure 29) shows that, once again in this case, the target speed and the simulated model speed overlap nicely throughout the simulation.

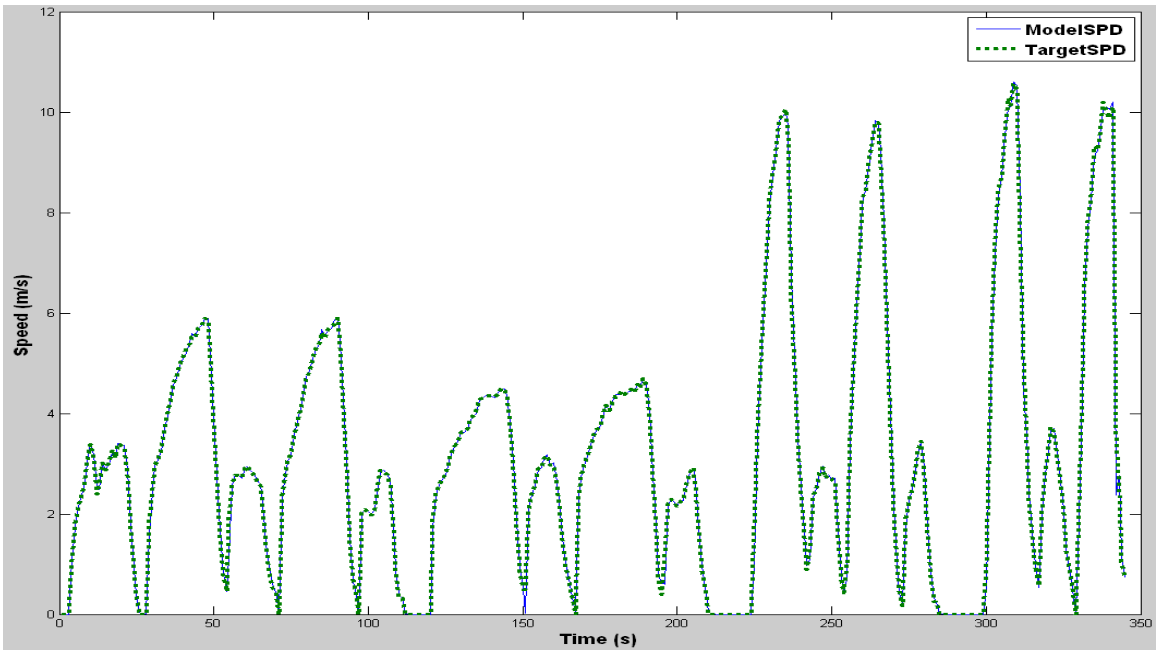

Figure 29: Target Speed Trace Overlapping Electric Snowmobile Model Speed Trace on Acceleration Test

3.1.6.2 Instantaneous Power Use

The power used at each time step by the electric snowmobile model is plotted along with the data gathered from the actual electric snowmobile for both the application duty cycle and the acceleration test.

Figure 30 below shows the results for the application duty cycle.

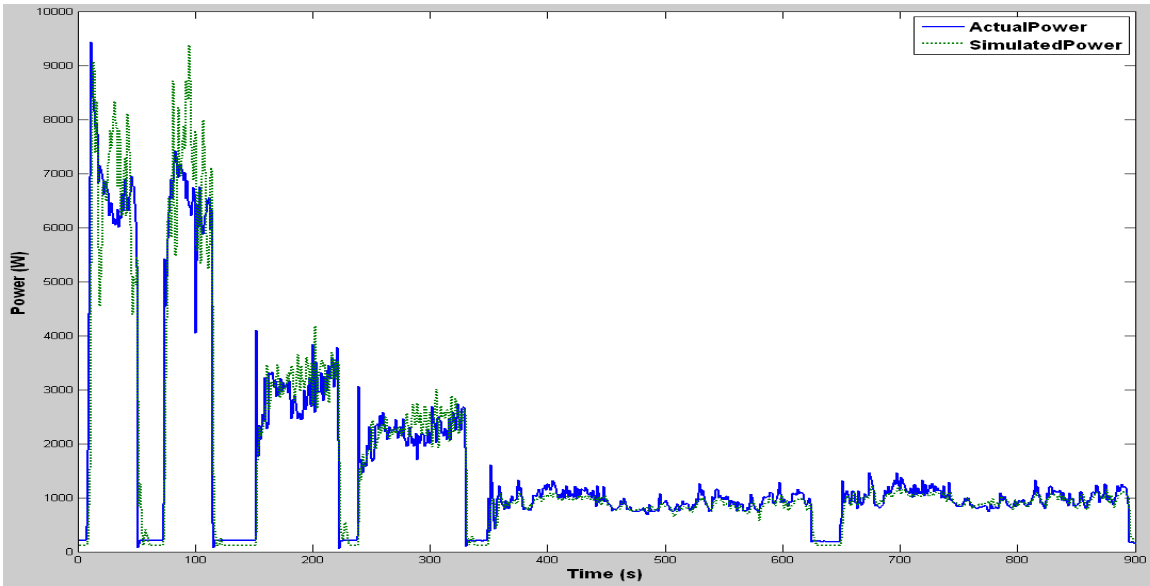

Figure 30: Electric Snowmobile Model Simulation Power Use Results and Actual Electric Snowmobile Power Use Data for Application Duty Cycle

Correlation at low speeds is very good; unfortunately, simulated power at high speed is noisy. Interestingly, as seen in the following section, this noise has almost no impact on the energy required by the electric snowmobile model.

Figure 31 below shows the power results for the acceleration test.

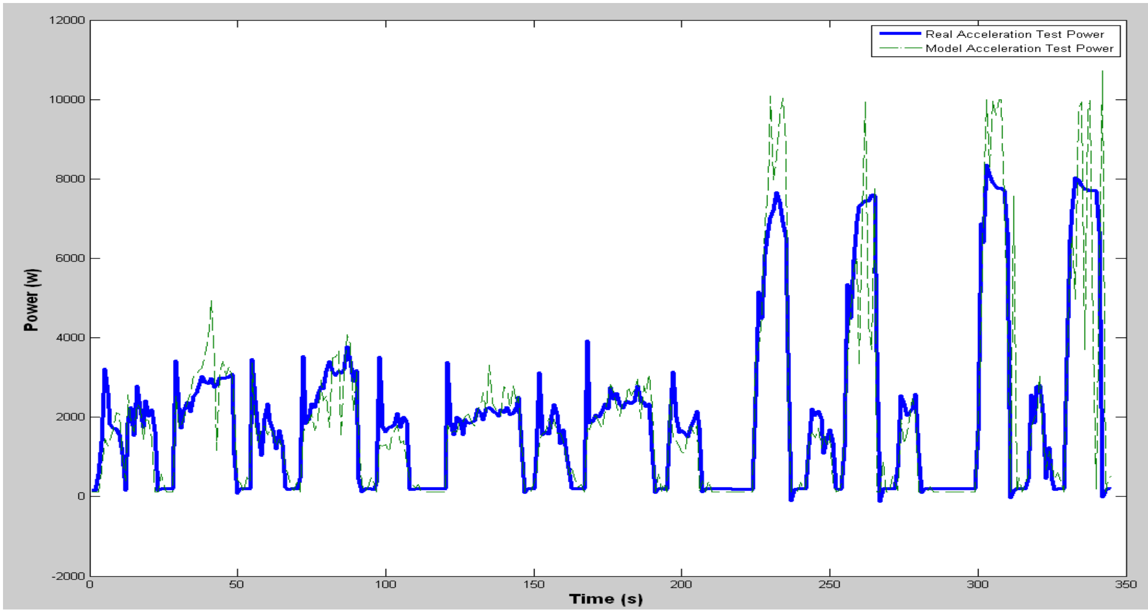

Figure 31: Electric Snowmobile Model Simulation Power Use Results and Actual Electric Snowmobile Power Use Data for Acceleration Test

The results in the acceleration test are similar to those of the application duty cycle test. Very good correlation is obtained at low power levels but higher powers have substantial noise associated with them.

Applying a 5point moving average to the simulation results reveals some interesting information. Figure 32 below shows this result.

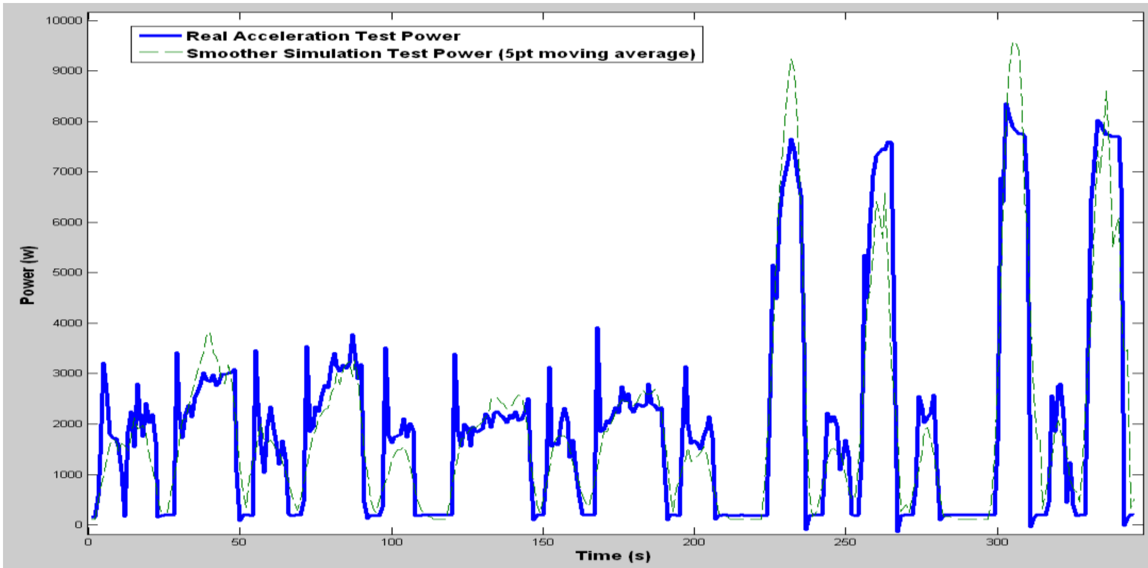

Figure 32: Electric Snowmobile Model Simulation Power Use Results (5pt moving average) and Actual Electric Snowmobile Power Use Data for Acceleration Test

It can be seen from Figure 32 that the model alternately overshoots and undershoots the acceleration run results. Given the way this test was performed, this is most likely due to the assumption that the test run was flat. Based on this result, most likely the test run had a small inclination which caused this phenomenon.

Another interesting piece of information is that the model constantly undershoots the "turnaround" of the snowmobile between acceleration runs. This could indicate that a compensation factor might be needed in future simulation in order to compensate for a possible supplemental load during turns.

A smoothing (10 point moving average) was also applied to the results from the application duty cycle simulation. This can be seen in Figure 33 below.

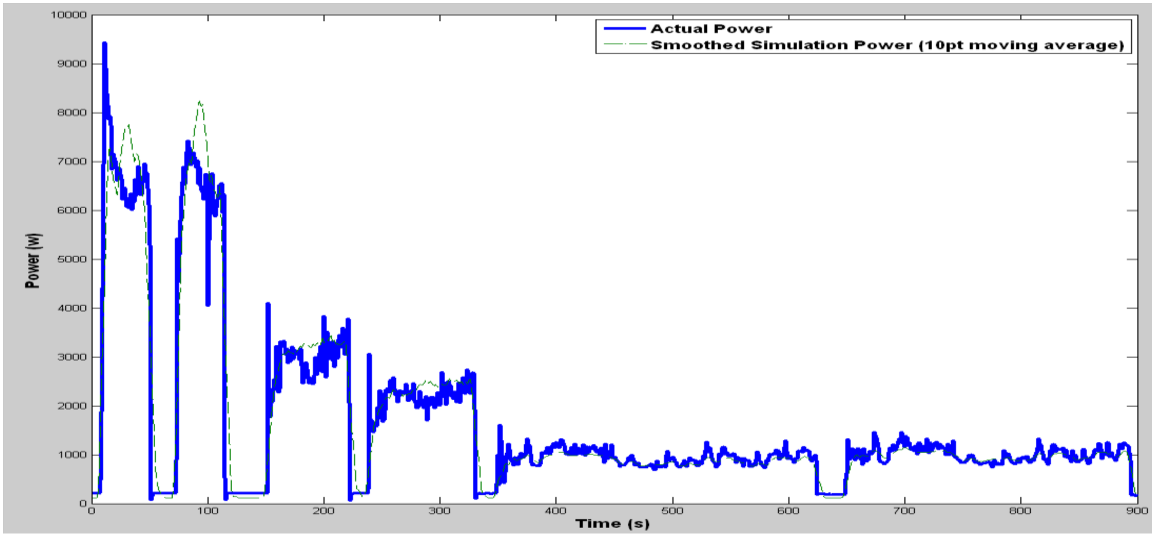

Figure 33: Electric Snowmobile Model Simulation Power Use Results (10pt moving average) and Actual Electric Snowmobile Power Use Data for Application Duty Cycle

Figure 33 shows good correlation between the actual electric snowmobile data and the simulation results. Detailed analysis of the results suggests that the lower fidelity of the power model at higher speeds is in part due to an underestimation of slope in the test circuit and that the impact of this increases as vehicle speed increases. However, since the vehicle is performing on a closed loop, and thus completes its circuit at the same elevation as it has started, the overall energy consumption is not greatly affected by it.

3.1.6.3 Overall Energy Consumption

Below, Figure 34 compares the energy consumption simulation results with the data obtained during application duty cycle testing.

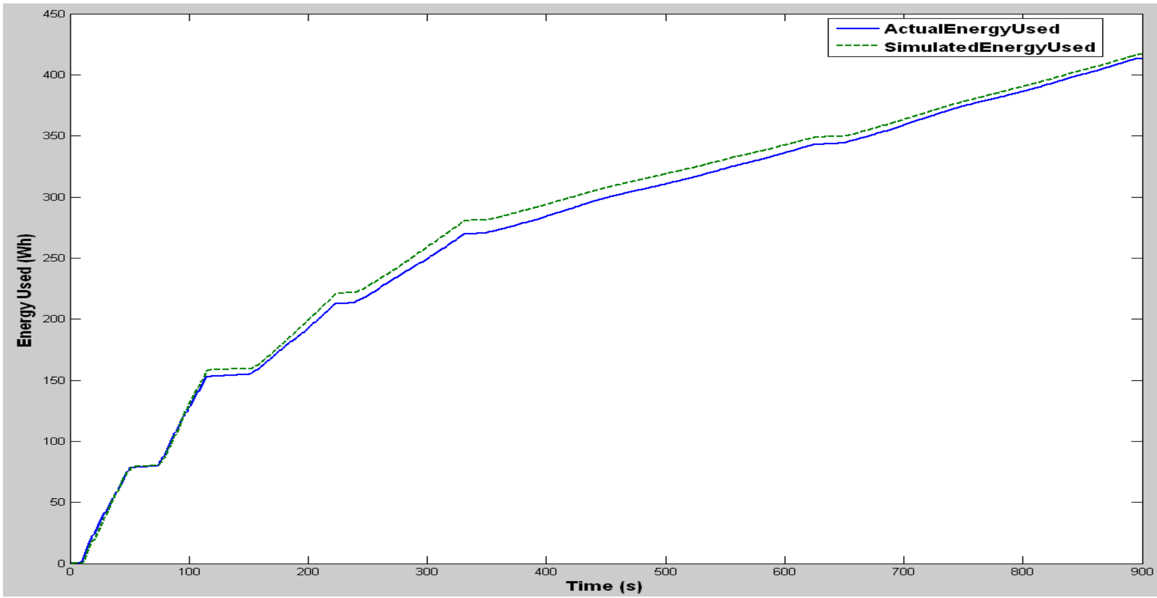

Figure 34: Electric Snowmobile Model Simulation Cumulative Energy Use Results and Actual Electric Snowmobile Cumulative Energy Use Data

Figure 34 shows that the model accurately predicts energy consumption. The maximum error is 11.25Wh. The final error at the end of the drive cycle is only 3.25Wh (approximately 0.8% of the total energy used).

3.2 Conclusion

The goal of this exercise was to see if it was possible, using a standard powertrain simulation software platform, to create an electric snowmobile model which could be used to predict snowmobile performance for a given duty cycle in a potential application. The idea behind this is to enable designers to rapidly, and cost efficiently, custom design an electric snowmobile for specific applications while simultaneously assuring the end user that the electric snowmobile will meet the application's needs.

Even though the model obtained in this first attempt is not a high fidelity model, the data obtained shows that such a simulation does yield results which should ensure an end user that the electric snowmobile will adequately perform on a specific application duty cycle. At the same time, the modular approach used by simulating with PSAT is perfectly suited to fine tune motor power and battery pack energy to a specific application duty cycle without having to go to remote locations in order to do full scale trials on site.

That being said, a number of issues still need attention in order for electric snowmobile powertrain modeling to reach its full potential. These issues are discussed in section 6.

In the end, it is believed that this section has shown that, electric snowmobile powertrain modeling and simulation can potentially be a key tool in making viable electric snowmobiles. The use of this tool eases electric snowmobile implementation in specific applications. Furthermore, there is no reason why this type of modeling could not be used in order to try to improve current gasoline snowmobile emissions and energy use.

4. Electric Snowmobile Fuel Cycle Emissions, Energy Use and Resource Use

So far in this investigation on the development of a zero-emission electric utility snowmobile it has been established that:

- Energy density is a major technological hurdle to the regular use of electric utility snowmobiles
- Modeling and simulation can be useful tools in the advancement of commercially viable electric snowmobiles towards utility snowmobile markets since they can allow designers to rapidly tailor an electric snowmobile to a client's needs

Since electric snowmobiles do not produce significant in-use emissions, they are often perceived by some as being the best "global" solution when compared to gasoline snowmobiles. However, the lack of in-use emissions only makes electric snowmobiles the best "local" solution in terms of emissions. In order to be the best "global" solution, electric snowmobiles must be superior to gasoline snowmobiles not only during vehicle use, but also during the whole product life cycle and the whole fuel cycle.

This last section focuses on the snowmobile's fuel cycle. In it, the actual and relative environmental impact of snowmobiles (gasoline and electric) in Canada, in terms of fuel cycle emissions, energy use and resource use will be investigated.

4.1 Overview of Fuel Cycle Simulation Software Platform

The Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model (Version 1.7) was used in order to complete the electric snowmobile fuel cycle investigation.

The GREET model has been designed to compare road vehicles, using different drivetrain technologies, against each other, on a standard drive cycle. In order to do this, it calculates energy consumption and emissions both during the vehicle use and the fuel production process. Calculations are based on an extensive fuel cycle information database and a number of user selected inputs.

The GREET Model 1.7 is essentially a multi-layered spreadsheet equipped with a "user-friendly" interface. Running a simulation with the model involves three steps:

1. Input from the user
2. Spreadsheet calculations
3. Output: Creation of two files, "filenameIN.xls" and "filenameOUT.xls".

The following block diagram illustrates these steps.

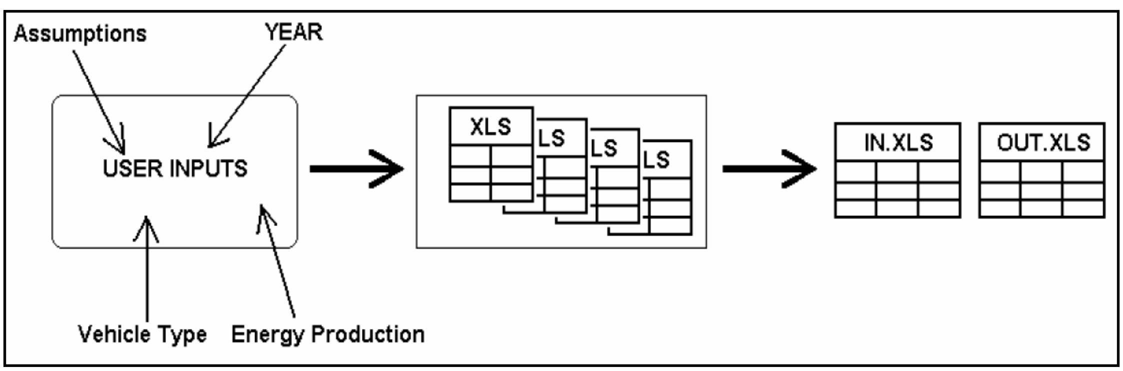

Figure 35: GREET model 1.7 Block Diagram

4.1.1 Input from the User

The model's user interface separates the input step into two sections:

1. Scenario options
2. Parametric assumptions

4.1.1.1 Scenario Options

The scenario options section is a sequence of dialogue boxes where the user defines the elements of the scenario they wish to simulate. The following list is an example of some of the options in this section:

- Vehicle Technology
- The Year(s) desired (Certain assumptions are built in to GREET based on the year being simulated.)
- Fuel Types (including electricity)
- Fuel Characteristics
- Electricity Production Source Mix

4.1.1.2 Parametric Assumptions

In the parametric assumptions section the options available serve to modify the function of the elements defined in the scenario options. Here, the user can change things such as the relative efficiencies of the vehicle technologies or fuel type refinement efficiencies.

4.1.2 Spreadsheet Calculations

The GREET calculations are done based on a combination of the user's input and the GREET's built-in database.

4.1.3 Output

The created output files contain the results of the simulation as well as a record of all the input settings for that simulation. The output results are organized onto three sheets in the following manner:

1. Well to Pump Results - energy costs and efficiencies of the fuel/electricity supply path

2. Relative Change Results - relative performance of technologies compared to the baseline vehicle(s)
3. Well to Wheel Results - energy costs and emissions on a per mile basis for the technologies of interest

4.2 Limitations of Fuel Cycle Simulation Software Platform

The GREET 1.7 model has been developed mainly for road vehicles. Because of this, it is not suitable for use as a snowmobile simulation platform unless some modifications are done to the GREET 1.7 model and/or the snowmobile parameters are carefully transformed to fit the GREET 1.7 model's strict input definitions.

For this snowmobile simulation it was assumed that in general the GREET model's results from "well-to-pump" (from the extraction/production of energy all the way to the input of energy into the vehicle) were valid for any snowmobile application. In other words, it was assumed that the production of gasoline and electricity within a geographical region was the same for road vehicles and snowmobiles.

However, the same general assumption is not valid for the use of this energy in the vehicle. The GREET model 1.7 built-in fuel consumption and emission values for the baseline vehicle during use are not valid for the snowmobile. Thus, in order to use the GREET model 1.7 for this exercise, a snowmobile drive cycle must be defined and both fuel consumption and emission values for this defined cycle must be compiled.

4.3 Methodology

Unfortunately, unlike passenger cars, snowmobiles do not have standard drive cycles specifying vehicle speed over time. Thus, a snowmobile drive cycle must be defined in order to begin the analysis.

4.3.1 Drive Cycle Definition

The main standard cycle used in the snowmobile industry is the one used for emission testing. This cycle is a modal cycle. Measurement of emissions is done at five different pre-defined engine load cases (given as percentages of engine rated speed and torque) and emissions are measured for each engine load case. Emissions from each load case are then multiplied by a percentage factor (all five factors adding up to 100%) and the emissions values obtained for each load case are then summed up. Table 10 below shows the torque, the speed and the weight factor for each of the five modes of the snowmobile emissions testing modal test.

Table 10: Snowmobile Emission Testing Modal Test Specifications

Mode	**1**	**2**	**3**	**4**	**5**
Torque (% of engine rated max)	100	85	75	65	Idle
Speed (% of engine rated max)	100	51	33	19	0
Weight factor (%)	12	27	25	31	5

The GREET Model's key inputs in terms of vehicle use are

- Fuel consumption (in miles per gallon)
- Emissions (in grams per mile)

Unfortunately, the snowmobile standard modal method of measuring emissions does not yield fuel consumption and emission values on a per distance basis. Thus, a valid methodology in order to obtain fuel consumption and emissions on a per mile basis needs to be determined. Also, valid data needs to be found to implement the chosen methodology and obtain valid fuel consumption and emissions values for snowmobiles on a per mile basis.

The chosen methodology was to use the standard snowmobile emissions modal test and correlate each mode with a vehicle speed. Then, using the speed of each mode and the weight factor of each mode, the time to travel a mile was calculated. Once the time required to travel a mile was known, fuel consumption and emissions on a per distance basis could be computed provided that one had valid values for the emissions and the fuel flow per mode.

4.3.2 Implementation

In order to implement this methodology and obtain complete fuel cycle results for the snowmobiles, data and assumptions must be inputted into the GREET model 1.7 for:

- Vehicle use
- Energy production and distribution

4.3.2.1 Vehicle Use

Yellowstone National Park and the Montana Dept. of Environmental Quality ordered a number of tests on snowmobiles in 2002[22]. Among those tests, the standard modal emissions test was performed on two different 4-stroke stock snowmobiles (2002 Arctic Cat 4-Stroke Touring & 2002 Polaris Frontier 4-stroke). An attempt was made to correlate a vehicle speed with each test mode for both vehicles. By using this data and the methodology previously outlined, fuel consumption and emissions per distance traveled were obtained. The results for both snowmobiles were averaged out and the resulting fuel efficiency and emission results were used as the values for the baseline vehicle in the GREET model simulation for the snowmobile.

These inputs into the GREET 1.7 model can be viewed in Table 11 below.

Table 11: Snowmobile Fuel Consumption and Emissions per Distance Travelled

	Fuel Consumption in MPG	13.22
Emissions in grams per mile	Hydrocarbons (HC)	2.50
	Carbon Monoxide (CO)	42.82
	Nitrous Oxides (NOx)	4.71
	Particulate Matter (PM)	0.05
	Carbon Dioxide (CO_2)	599.36

4.3.2.2 Energy Production and Distribution

The assumptions used for all vehicle simulations were the GREET 1.7 model built in assumptions for simulation year 2010 with the following modifications:

Fuel: 99.9% of fuel used was conventional gasoline (GREET would not let reformulated gasoline % drop to 0 so it had to be at least a minimum of 0.1%.)

Electricity production was changed to "User Defined". The GREET model divides possible electricity production methods into 6 categories. Hydroelectric power production does not have its own category; thus, in the context of a production which has a high amount hydroelectric power, the "other" category accounts for a large percentage of electricity production. The values used are given in Table 12 below. They reflect Canadian electricity production in 2003 based on statistics from the International Energy Agency[23].

Table 12: Canadian Electric Production by Type

Oil	Natural Gas	Coal	Nuclear	Biomass	Other	Total
3%	6%	19%	13%	2%	57%	100%

4.4 Simulation Results

In order to put the electric and gasoline snowmobile results in context a third simulation was performed using the GREET model 1.7 built-in values for fuel consumption and emissions of a gasoline powered car (with the same energy production and distribution assumptions as the snowmobiles).

A result summary of the GREET analysis is presented in the Tables 13, 14 and 15 for the car, the gasoline snowmobile and the electric snowmobile respectively. Tables 16 and 17 follow with relative results. First, to put things into context, Table 16 shows the results of the gasoline snowmobile relative to the car. Following this, Table 17 presents the results of the electric snowmobile relative to the gasoline snowmobile.

4.4.1 Notes on Results

Prior to presenting the result summary tables, the following notes must be made regarding their preparation:

- During vehicle operation, the GREET model calculates CO_2 emissions based on the vehicle's fuel consumption. However, since the amount of unburnt fuel in the snowmobile is much higher than in a car, the model overestimates the CO_2 emissions. Thus, the CO_2 emissions values during snowmobile use in the result table are not the GREET results, they are values found using the same methodology as the other emissions values (methodology described in section 4.3.2.1).
- The GREET model divides volatile organic compounds (VOC) into 2 categories: exhaust and evaporative. The result tables above only shows exhaust VOC. It is also worth noting that snowmobiles will normally operate on winter blend fuel. This factor was not taken into account in this analysis.
- The GREET model classifies particulate matter (PM) in 2 different size categories. It also normally looks at PM produced from tire and brakes separately from PM

produced by fuel combustion. The data available for the snowmobile did not look at PM from brake and track. Also, it did not differentiate between the sizes of the particles. Thus, the presented PM values represent the sum of the fuel combustion PM of both sizes from the model.

- The electricity production distribution used in the model looks at all of Canada. Thus, the model gives projected values for fuel consumption and emissions as if electric snowmobiles were in use at a greater scale and their distribution followed distribution of power across the country. In other words, for this model to be exact, if a province produces 10% of all of Canada's electricity, then it would need to have 10% of all of Canada's electric snowmobiles, and so on for each province. (It must be noted that electricity production varies from province to province. Thus, some provinces with a high percentage of hydro power such as Quebec, would have much "cleaner" electric snowmobiles over their entire fuel cycle than the Canadian average.)

4.4.2 Results

Table 13: Gas Car Energy Use, Resource Use and Emissions per Distance Travelled

	GAS CAR Wh/km or *grams/km*		
Item	**Well to Pump**	**Vehicle Operation**	**Total**
TOTAL ENERGY	**184**	**853**	**1037**
Fossil Fuels	176	853	1029
Coal	24	0	24
Natural Gas	61	0	61
Petroleum	91	853	943
CO2	*47*	*224*	*271*
VOC	*0.077*	*0.076*	*0.153*
CO	*0.040*	*2,328*	*2.367*
NOx	*0.132*	*0.088*	*0.220*
PM	*0.036*	*0.009*	*0.045*

Table 14: Gas Snowmobile Energy Use, Resource Use and Emissions per Distance Travelled

	GAS SNOWMOBILE Wh/km or *grams/km*		
Item	**Well to Pump**	**Vehicle Operation**	**Total**
TOTAL ENERGY	**345**	**1599**	**1945**
Fossil Fuels	330	1599	1929
Coal	45	0	45
Natural Gas	114	0	114
Petroleum	170	1599	1770
CO2	*89*	*372*	*461*
VOC	*0.145*	*1.554*	*1.698*
CO	*0.074*	*26.613*	*26.687*
NOx	*0.248*	*2.927*	*3.175*
PM	*0.067*	*0.031*	*0.098*

Table 15: Electric Snowmobile Energy Use, Resource Use and Emissions per Distance Travelled

	ELECTRIC SNOWMOBILE Wh/km or *grams/km*		
Item	**Well to Pump**	**Vehicle Operation**	**Total**
TOTAL ENERGY	**333**	**457**	**790**
Fossil Fuels	173	237	410
Coal	117	161	279
Natural Gas	34	47	81
Petroleum	21	29	50
CO2	*134*	*0*	*134*
VOC	*0.013*	*0.000*	*0.013*
CO	*0.042*	*0.000*	*0.042*
NOx	*0.168*	*0.000*	*0.168*
PM	*0.216*	*0.000*	*0.216*

Table 16: Gas Snowmobile Energy Use, Resource Use and Emissions per Distance Travelled Relative to Gas Car

	Relative Energy Use and Emissions (Gasoline Snowmobile Relative to Car)		
Item	**Well to Pump**	**Vehicle Operation**	**Total**
TOTAL ENERGY	**188%**	**188%**	**188%**
Fossil Fuels	188%	188%	188%
Coal	188%	100%	188%
Natural Gas	188%	100%	188%
Petroleum	188%	188%	188%
CO2	188%	*167%*	*170%*
VOC	188%	*2049%*	*1111%*
CO	188%	*1143%*	*1127%*
NOx	188%	*3340%*	*1444%*
PM	188%	*333%*	*218%*

Table 17: Electric Snowmobile Energy Use, Resource Use and Emissions per Distance Travelled Relative to Gas Snowmobile

	Relative Energy Use and Emissions (Electric Snowmobile Relative to Gasoline Snowmobile)		
Item	**Well to Pump**	**Vehicle Operation**	**Total**
TOTAL ENERGY	**96%**	**29%**	**41%**
Fossil Fuels	52%	15%	21%
Coal	259%	INF	613%
Natural Gas	30%	INF	71%
Petroleum	12%	2%	3%
CO2	150%	*0%*	*29%*
VOC	9%	*0%*	*1%*
CO	57%	*0%*	*0%*
NOx	68%	*0%*	*5%*
PM	320%	*0%*	*219%*

4.5 Discussion on the Results

Prior to looking at the details of the results obtained in the two fuel cycle comparative analysis, a quick note must be made to emphasize that this analysis should not be confused with a complete life cycle analysis. In order to have a complete life cycle analysis one needs to add another dimension to the fuel cycle analysis: energy use and emissions due to the making, maintaining and discarding of the vehicles themselves and the infrastructure for fuel production and delivery.

In the case of a relative comparison between two similar vehicles some aspects of the complete life cycle can be assumed to be equal for both vehicles. For example, one can reasonably assume that a substantial number of components (steering, track, seat, etc) in the chassis of both snowmobiles will have the same complete life cycle impact. Nevertheless, there are a few issues in this comparison which one would need to account for if doing a complete life cycle comparative analysis of gasoline vs. electric snowmobiles.

Some key differences would be energy use and emissions produced from battery manufacture and disposal vs. oil and coolant manufacture and disposal. Another one would be the manufacture and disposal of the electric motor and wires vs. the gasoline engine and all its sub systems (exhaust, fuel delivery, ignition, etc). Lastly, the relative amount of electronic components used in each vehicles and their nature should be assessed in a complete life cycle analysis.

4.5.1 Gas Snowmobile Relative to Gas Car

Since it was assumed that the same "well-to-pump" analysis could apply to both the car and the snowmobile, one must concentrate on the differences during vehicle use of Table 16 to get a feel for the differences between both types of vehicles.

Right away, at the top of Table 16, the higher power demand of snowmobiles compared to road vehicles is visible in the total energy used per driven distance. The snowmobile uses almost twice the amount of energy per distance traveled despite the fact that the snowmobiles weight roughly a quarter of the weight of a sub-compact car.

In terms of emissions, the snowmobile produces more of all the emissions under investigation than the car on a per distance basis with the highest one being NOx production with more than 30 times the emissions of a car for the same distance.

While they are unlikely to be interchangeable vehicles in a given application, it can be interesting to use this per distance data to compare emissions from the regular use of these vehicles over a year as a way of putting into context the amount of emissions a gasoline snowmobile typically produces in a year. Using the values from Table 16 and statistical information from the International Snowmobile Manufacturer Association (ISMA)[24] and the U.S. Department of Energy[25] (snowmobile average travel of 2,178 km/yr & car average travel of 12,374 km/yr), a 4-stroke snowmobiles actually emit less CO2 and PM than a conventional car on average per year. But even when viewed on a per year basis, a 4-stroke snowmobile still emits much more VOC, CO and NOx than a conventional car even though the snowmobile travels on average close to 6 times less distance yearly.

4.5.2 Electric Snowmobile Relative to Gasoline Snowmobile

On a well-to-pump basis, the electric snowmobile uses almost the same amount of energy as the gasoline snowmobile. However, on a vehicle use basis, it uses 3.5 times less energy. As a result of this, over the complete fuel cycle the electric snowmobile uses almost 2.5 times less energy than its gasoline counterpart.

Overall, if enough snowmobiles were distributed proportionally to electrical power generation all over Canada, the electric snowmobiles would use close to 5 times less energy from fossil fuels than the gasoline snowmobile. The types of fossil fuels used by each vehicle throughout their fuel cycle vary largely in quantity. The use of natural gas is relatively similar for both cases with the electric snowmobile using 71% the amount of the gasoline snowmobile. However, the use of coal and petroleum is very different for each vehicle.

The electric snowmobile is the biggest user of coal with just over 6 times the amount used per driven distance, but the gasoline snowmobile uses up over 33 time more petroleum than the electric snowmobile per driven distance!

The amount of energy used by each vehicle, and the different energy production methods used, have a direct impact on the emissions results. Thus, given the large amount of coal used in the production of electricity to power the electric snowmobile, it is no surprise to see that the electric snowmobile's complete fuel cycle produced over twice the amount of particulate matter when compared to the gasoline snowmobile's fuel cycle.

However, the heavy reliance of the gasoline snowmobile on burning petroleum products throughout its fuel cycle made it produce 3.5 times more carbon dioxide than the electric snowmobile. It also produced 20 times more NOx, 100 times more VOC and many hundreds of times more CO than the electric snowmobile per driven distance on a complete fuel cycle basis.

4.6 Conclusion

The fact that electric snowmobiles produce little to no in-use emissions makes them a very interesting vehicle for applications which require minimal amount of emissions to be produced within certain boundaries. Furthermore, the higher efficiency of their drivetrain makes them more energy efficient than their gasoline counterpart for the end user.

The fact that electric snowmobiles use substantially less energy and produce infinitely less emissions than gasoline snowmobiles while in use, means that they are “locally” superior to gasoline snowmobiles on these two important environmental aspects. This “local” superiority is critical in certain applications (ex: clean air research zones), and desirable in others (ex: high snowmobile and human density areas such as the base of ski resorts).

While being “locally” more environmentally friendly is good, being both “locally” and “globally” more environmentally friendly is much better. In order to be “globally” more environmentally friendly an electric snowmobile needs to demonstrate that it is superior to gasoline snowmobiles during the whole product life cycle and the whole fuel cycle.

The work presented in this section demonstrated that the fuel cycle environmental friendliness of electric snowmobiles relative to gasoline snowmobiles is highly dependent on electricity production methods. In the case under investigation in this section, namely a Canadian perspective where electric snowmobiles are distributed from province to province proportionately to each province’s electricity production with regards to the total Canadian electricity production, energy and emission wise, the electric snowmobile is environmentally friendlier than the gasoline snowmobile on all parameters under investigation with the exception of PM emissions.

5. Conclusion

This thesis tried to bring elements of an answer to the following question: can an electric snowmobile be one of the solutions to help lower snowmobile emissions and energy consumption?

The following conditions were set as needing to be fulfilled in order for the electric snowmobile to be considered one of the possible solutions to help lower snowmobile emissions and energy consumption. The conditions are that it must:

I. Help resolve the problem
II. Be implementable
III. Be viable

It was initially taken as given that an electric snowmobile could help resolve the problem “locally”. Results from section 4 showed that this was a correct assumption. What the results of section 4 also showed was that depending on electrical power generation methods, an electric snowmobile can also “globally” help resolve the problem.

In terms of being implementable, the work in section 2 demonstrated that it is extremely unlikely that electric snowmobiles can be implemented on a large scale in the near future. The main reason for this is the difference in energy density between the gasoline used in almost all of today’s snowmobiles and the batteries which can currently be used in an electric snowmobile. Nevertheless, the electric snowmobile prototypes built in the last decade have demonstrated that in applications where only limited range is required, an electric snowmobile can potentially be implemented.

In order to be viable, end users must be willing to purchase electric snowmobiles at a price higher than the manufacturer’s production cost. As seen in section 2, mass production of electric snowmobiles is unlikely due to the relatively low number of suitable applications. Thus, other means of improving the end user’s perceived cost/benefit ratio for electric snowmobiles must be investigated. Section 3 suggests that electric snowmobile powertrain modeling and simulation can potentially improve the end user’s perceived cost/benefit ratio in two ways:

1. By determining if an electric snowmobile design can perform adequately on a given duty cycle, thus ensuring the end users that the snowmobile will meet their needs without need for potentially expensive on-site trials
2. By being used as a tool to custom design electric snowmobiles for specific applications in order to limit costs associated with expensive energy storage and powertrain components.

In order to test that such a modeling and simulation exercise could perform adequately given the currently available simulation technology, an electric snowmobile model and an application duty cycle model were constructed. Simulated use of the electric snowmobile model on the application duty cycle model was performed and the results from this simulation were validated using data gathered from a real life electric snowmobile.

In the end, it appears that, yes, an electric snowmobile can potentially be considered one of the solutions to help lower snowmobile emissions and energy consumption, since in certain cases all three conditions can be met.

6. Future Work

Two areas of the work presented in this thesis can be improved by future work on the subject:

1. Electric snowmobile modelling and simulation
2. Electric snowmobile environmental impact analysis

6.1 Electric Snowmobile Modelling and Simulation

The presented electric snowmobile model does provide high enough fidelity to meet the basic needs of electric snowmobile “design for viability” presented in this thesis. However, further improvement to this model can potentially bring it to a higher level of fidelity and thus improve its effectiveness as a tool to make electric snowmobiles a viable option for on-snow travel. The list below suggests some areas where future work could be done in order to accomplish this.

- The impact of changing snow conditions on the model must be investigated in order to ensure proper model fidelity in a wide range of locations throughout the snow seasons.
- The application duty cycle parameters in this simulation were limited to speed and grade as a function of time. A more relevant duty cycle for this type of vehicle would also incorporate the charging aspect of the vehicle as a function of time since it is one of the major issues of using an electric snowmobile.
- Since a number of potential applications are utility applications, modelling which can include the effect of cargo weight distribution and towing load prediction would be a benefit in many cases.
- Some of the data suggests that in the case of an electric snowmobile, tight turning radiuses might be the source of non-negligible error during simulation and thus taking this factor into account should improve model fidelity.

- Performing data acquisition on better documented terrain is likely to improve model fidelity. Thus establishing a well documented benchmark test site should be a priority for future work.
- The effect of changing temperature was neglected in this simulation. Future efforts could potentially benefit from the incorporation of these effects in the model and the simulation.

6.2 Electric Snowmobile Environmental Impact Analysis

The analysis done in this thesis in order to look at the emissions and energy consumed by an electric snowmobile is:

A. Only valid if the relative distribution of electric snowmobiles in Canada from Province to Province follows the relative electric production capacity from Province to Province
B. Limited to the fuel cycle emissions and energy consumption

In order to better quantify the environmental impact of electric snowmobiles and especially their relative emissions and energy consumption when compared to gasoline snowmobiles, future work should try and improve the two major limitations of this study.

Doing simulations in different countries (mainly Unites States and Scandinavian countries) would give a better view of the global environmental impact of implementing electric snowmobiles. Combining this with more local simulations would allow one to see where electric snowmobiles can potentially be the most beneficial and where electric snowmobile could potentially be detrimental.

The other item which should be thoroughly investigated is the expansion of the current fuel cycle analysis to also include a complete product life cycle analysis. For a relative product life cycle analysis to be performed between electric and gasoline snowmobiles, items such as the production and disposal of batteries, electronic equipment, engine oil, engine coolant, and other items specific to each vehicle need to be investigated. Only once this is done will a true relative environmental impact analysis be completed.

Annex A: Non-McGill Electric Snowmobile Designs

Some level of documentation has been found on the following 13 electric snowmobiles (all links verified Aug 19th 2008):

1. Electrolight – Garage Busato
    - Location: France
    - Battery type: NiCd
    - *Chassis:* Bombardier-Nordtrac
    - *Production:* Ultra low volume production
    - *More information can be found here:* http://www.mtq.gouv.qc.ca/portal/page/portal/Librairie/Publications/fr/securite/vhr_consultation/memoires/20mai_lacbowker.pdf

2. Green Motorsports
    - *Location:* United Kingdom
    - Battery Type: Unknown
    - *Chassis:* Polaris
    - *Production:* Ultra low volume production
    - *More information can be found here:* http://www.greenmotorsport.com/green_motorsport/products_and_services/3,1,388,17,11392.html

3. C-VELEC (École Nationale Supérieure des Ingénieurs Électriciens de Grenoble)
    - Location: France
    - Battery type: NiCd
    - *Chassis:* Ski-Doo
    - Production: Prototype
    - More information can be found here:
      http://c-velec.etu.inpg.fr/realisations/motoneige/fiche-technique.php

4. Sk-E-doo
    - Location: Canada
    - Battery type: NiCd
    - Chassis: Gilson
    - Production: prototype
    - *More information can be found here:*
      http://www.megawattmotorworks.com/display.asp?dismode=article&artid=66

5. University of Wisconsin–Madison
    - *Location:* United States of America
    - Battery type: Lithium Ion
    - *Chassis:* Polaris
    - Production: prototype
    - *More information can be found here:*
      http://www.mtukrc.org/download/madison/madison_ze_design_paper_2008.pd
      f

6. Snolectric
    - *Location:* United States of America
    - Battery type: Lead-Acid
    - *Chassis:* Polaris
    - Production: prototype
    - *More information can be found here:* http://www.deq.mt.gov/CleanSnowmobile/solutions/engine/hansen.pdf

7. Clarkson University (1)
    - *Location:* United States of America
    - Battery type: NiMH
    - *Chassis:* Arctic Cat
    - Production: prototype
    - *More information can be found here:* http://www.mtukrc.org/download/clarkson/clarkson_electric_design_paper_2007.pdf

8. Clarkson University (2)
    - *Location:* United States of America
    - *Battery type:* Lithium Polymer
    - Chassis: Polaris
    - Production: prototype
    - *More information can be found here:* http://www.mtukrc.org/download/clarkson/clarkson_ze_design_paper_2008.pdf

9. Utah State University (1)
   - *Location:* United States of America
   - Battery type: Lead Acid
   - *Chassis:* Polaris
   - Production: prototype
   - *More information can be found here:* http://www.mtukrc.org/download/utah/utah_design_paper_2006.pdf

10. Utah State University (2)
   - *Location:* United States of America
   - Battery type: Lead-Acid
   - Chassis: Yamaha
   - Production: prototype
   - *More information can be found here:* http://www.mtukrc.org/download/utah/utah_design_paper_2007.pdf

11. South Dakota School of Mines and Technology (1)
   - *Location:* United States of America
   - Battery type: Lead Acid
   - *Chassis:* Polaris
   - Production: prototype
   - *More information can be found here:* http://www.mtukrc.org/download/sdsmt/sdsm&t_design_paper_2007.pdf

12. South Dakota School of Mines and Technology (2)

- *Location:* United States of America
- Battery type: Lithium ion
- *Chassis:* Polaris
- Production: prototype
- *More information can be found here:*

  http://www.mtukrc.org/download/sdsmt/sdsm&t_ze_design_paper_2008.pdf

13. Raser Technologies

- *Location:* United States of America
- Battery type: Lithium
- Chassis: Polaris
- *Production:* electric/gasoline series-hybrid snowmobile prototype
- More information can be found here:

  http://www.rasertech.com/apps_snowmobiles.html

  And in:

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  http://www.allbusiness.com/transportation/motor-vehicle-manufacturing/290735-1.html

Annex B: Overview of McGill Electric Snowmobile Designs

Since year 2002, McGill University students have designed and built 11 different electric and hybrid-electric snowmobile prototypes/variations. Below is an overview of these electric snowmobiles in chronological order:

Figure 36: McGill Electric Snowmobile Prototype 1

- Date: April 2003
- Type: Electric
- Chassis: Bombardier S
- Battery: Lead Acid
- Motor: Brushless DC
- Transmission: Direct
- Track length: 136”

Figure 37: McGill Electric Snowmobile Prototype 2

- Date: March 2004
- Type: Electric
- Chassis: Bombardier S
- Battery: Lead Acid
- Motor: Brushless DC
- Transmission: Direct
- Track length: 136”

Figure 38: McGill Electric Snowmobile Prototype 3

- Date: March 2005
- Type: Electric
- Chassis: Bombardier S
- Battery: Lead Acid
- Motor: Brushless DC
- Transmission: Direct
- Track length: 136”

Figure 39: McGill Electric Snowmobile Prototype 4

- Date: March 2006
- Type: Electric
- Chassis: BRP RF
- Battery: Lithium Ion
- Motor: Brushless DC
- Transmission: CVT
- Track length: 136”

Figure 40: McGill Electric Snowmobile Prototype 4A

- Date: May 2006
- Type: Electric
- Chassis: BRP RF
- Battery: Lithium Ion
- Motor: Brushless DC
- Transmission: CVT
- Track length: 136”

Figure 41: McGill Electric Snowmobile Prototype 5

- Date: March 2007
- Type: Electric
- Chassis: BRP RF
- Battery: Lithium Ion
- Motor: Brushed DC Permanent Magnet
- Transmission: CVT
- Track length: 136”

Figure 42: McGill Hybrid Electric Snowmobile Prototype 1

- Date: March 2007
- Type: Electric/E-10 Gasoline Series Hybrid
- Chassis: BRP REV
- Battery: Lithium ion
- Motor: Series DC
- Transmission: CVT
- Track length: 136”

Figure 43: McGill Electric Snowmobile Prototype 5A

- Date: July 2007
- Type: Electric
- Chassis: BRP RF
- Battery: Lithium Ion
- Motor: Brushed DC Permanent Magnet
- Transmission: CVT
- Track length: 136”

Figure 44: McGill Electric Snowmobile Prototype 5B

- Date: December 2007
- Type: Electric
- Chassis: BRP RF
- Battery: Lithium Ion
- Motor: Brushed DC Permanent Magnet
- Transmission: CVT
- Track length: 121”

Figure 45: McGill Electric Snowmobile Prototype 6

- Date: March 2008
- Type: Electric
- Chassis: BRP RF
- Battery: Lithium Ion
- Motor: Brushed DC Permanent Magnet
- Transmission: CVT
- Track length: 121”

Figure 46: McGill Electric Snowmobile Prototype 6A

- Date: March 2008
- Type: Electric
- Chassis: BRP RF
- Battery: Lithium Ion
- Motor: Brushed DC Permanent Magnet
- Transmission: CVT
- Track length: 121”

Figure 47: McGill Hybrid Electric Snowmobile Prototype 2

- Date: March 2008
- Type: Electric/Biodiesel Series Hybrid
- Chassis: BRP REV
- Battery: Lithium ion
- Motor: Series DC
- Transmission: CVT
- Track length: 136”

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