Development of a 1st Generation Series Hybrid Snowmobile

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ABSTRACT

The McGill University Electric Snowmobile Team, returns to the Society of Automotive Engineers Clean Snowmobile Challenge (SAE CSC) in 2007 with a revised electric snowmobile prototype and an all new hybrid prototype. This paper covers the design and development of the hybrid snowmobile prototype.

This completely new design uses the team's experience in the electric snowmobile domain to assemble a snowmobile which can have all the advantages of electric drive systems while at the same time not being too limited by the battery's energy density. The goals for this initial design were to make a simple and reliable prototype which can serve as a baseline for further refinement of the hybrid concept in the future.

This design paper covers the challenges of hybrid snowmobile design as well as the possible advantages of such a vehicle. The design decisions made by the team in the conception of this 1st generation prototype are reviewed and, when available, preliminary results are given .

INTRODUCTION

In recent years, snowmobile exhaust emissions and vehicle noise levels have been the focus of new legislation which aims to gradually reduce both of these over the next few years.

The SAE Clean Snowmobile Challenge has, since its inception, given an opportunity for students to tackle the real world challenges of lowering touring snowmobile noise and exhaust emissions while at the same time ensuring that the vehicle can satisfy the end user needs and maintain a fair level of profitability for the manufacturers.

Over the years the competition format has evolved and even a new category for zero emission snowmobiles to serve the need of the research community has emerged. McGill University has been active in the zero emission snowmobile world even prior to the inception of such a category at the SAE CSC. For the 2007 competition, the McGill Electric Snowmobile Team has designed a simple hybrid snowmobile in an attempt to bring to the winter touring world some of the advantages which are currently only available to zero emission utility snow vehicles.

This first generation hybrid snowmobile is a series hybrid. In essence, it operates exactly like an electric snowmobile except that, when needed, an internal combustion engine (ICE) coupled to a DC generator, can supplement the battery power. Also the ICE generator makes it possible to recharge the battery pack via the use of the on board fuel tank and thus the snowmobile is not limited to outlet power in order to recharge its battery pack.

Since the design of this new snowmobile is being done by the same students who are designing the 2007 electric snowmobile, the team's funds, man power and resources had to be divided between the two vehicles. Thus, in order to design, assemble and test both vehicles in 6 months, some priority choices had to be made.

For the 2007 SAE CSC, electric snowmobiles have their own category with distinct sets of rules and requirement. Hybrid snowmobiles however do not have such a well defined framework to work with. The method for comparing hybrid and ICE snowmobile in certain events at the competition has yet to be defined and SAE CSC organizers will take these decisions during the competition.

Thus, given the status of the electric and hybrid snowmobiles at the 2007 competition, it was decided that the team's hybrid snowmobile would be designed with the simple goal of being able to participate in all the events of the ICE branch of the SAE CSC 2007 without actual emphasis on winning the events.

The team believed that the goal of participating in every event at the 2007 SAE CSC with the hybrid snowmobile. was the limit of what was reasonably attainable without compromising the chances of the electric snowmobile of winning its category due to the sharing of available resources.

The following pages, look at the reasons which motivated the team to design and assemble a hybrid prototype, the challenges of hybrid snowmobile design, the design decisions the team made in the creation of this 1st generation prototype and some preliminary results obtained from the hybrid drive system.

HYBRID VEHICLE BASICS

WHAT IS A HYBRID VEHICLE?

A hybrid is a vehicle which uses more than one source of power to move. While some may think that hybrids are a result of recent technology, historically hybrid vehicles were around thousands of years ago. One example of this is the Greek warships which used both sails and oars to propel the ship. Such a vehicle is a hybrid vehicle since it combined two distinct sources of power: Wind and Human. Nowadays, there are several different combinations of power sources which are used to make hybrid vehicle.[1 & 2]

Some of the most widely known hybrid vehicles are the Hybrid-Electric Vehicles (HEV). In a majority of cases the two sources of power used in HEV are an energy converting unit and an energy storing unit. For example, a ICE engine coupled to a DC motor can convert mechanical energy into electrical energy. This energy can then be stored in batteries (storing unit). Another example is a hydrogen fuel cell paired with capacitors. In this case the energy conversion unit is the fuel cells, which use hydrogen as fuel, and the energy storing units are the capacitors. The reasoning behind this pairing is to use a very energy-dense fuel with the highest possible efficiency. By pairing the energy converting unit with an energy storing unit which can serve as a buffer to regulate peak power demands, the efficiency of the energy converting unit can be optimized. [1]

WHAT ARE SOME COMMON TYPES OF HEV?

HEV have two basic configurations: series and parallel. It is also possible to combine both configurations in what can be termed a series-parallel hybrid.

For the case of a HEV using an ICE and batteries all 3 possible HEV configurations will use the same basic components: ICE, batteries, drive motor, driving unit (ex: wheel).

In a series HEV configuration, the ICE is used only to generate electricity via a generator; it cannot move the vehicle directly. The power output of the ICE must absolutely pass through the drive motor in order to make it to the driving unit. Illustration 1[1] below shows a block diagram of a series HEV.

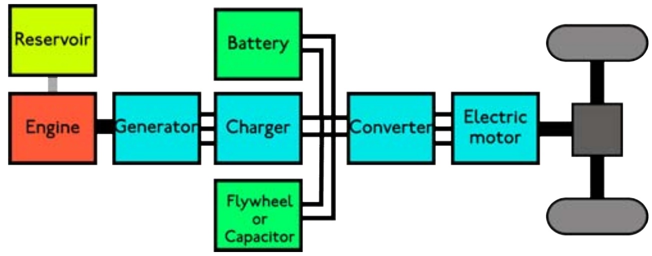

Illustration 1: Seried Hybrid Diagram

In a parallel HEV configuration, the ICE is used to drive the vehicle directly via a mechanical connection to the driving unit (ex: gearing system). However, it cannot directly supply the electric drive motor with power to propel the vehicle. Illustration X[1] belox shows a block diagram of a parallel HEV.

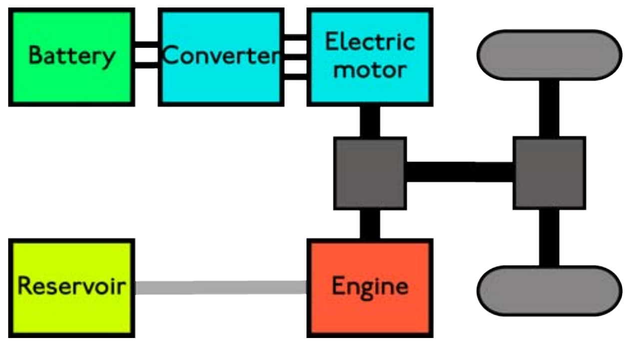

Illustration 2: Parallel Hybrid Diagram

A series/parallel hybrid is a combination of both of the aforementionned scenarios. Thus in a series/parallel configuration the ICE can either generate electricity to charge batteries and power the electric drive motor or power the driving unit directly. If needed, the ICE can actually do all of these at once. Illustration 3[3] belox shows a block diagram of a series/parallel HEV.

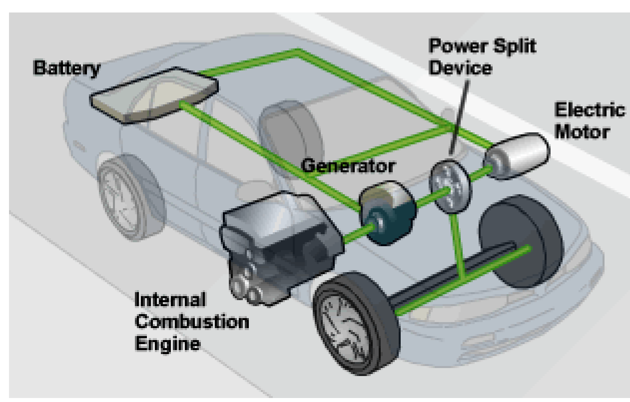

Illustration 3: Full Hybrid Diagram

WHY DESIGN A HYBRID SNOWMOBILE?

By using two different energy sources (batteries and gasoline), a wide array of different possibilities for energy usage are available.

Prior to looking at the different possibilities which a hybrid system opens up, it is important to take the time to look in more detail at some of the main differences between the two energy carriers on board a gasoline-electric hybrid.

ENERGY DENSITY

A hybrid snowmobile can be viewed as a crossover between an electric and an ICE powered snowmobile. Both types of snowmobiles have their advantages and disadvantages. In making a hybrid snowmobile, the goal is to try and overcome the disadvantages of one technology by exploiting the advantages of the other. One such characteristic is the energy density of each technology. As it will be demonstrated in this section, energy density is the main reason why electric snowmobiles cannot compete performance wise with ICE snowmobiles in the touring snowmobile sector.

First off, the state of today's snowmobiles must be quantified energy wise. By using a value of 8760 Wh/l as the energy available in gasoline and looking at the size of the fuel tanks offered by the 4 main snowmobile manufacturers on some of their utility/touring models it can be seen in Table 1 that, on average, by taking the fuel tank size of one snowmobile model from each manufacturer, their snowmobiles on average carry 358,722 Wh of energy on-board. As a basis for comparison, the 2006 McGill Electric Snowmobile Team's prototype carried 6480Wh of energy.

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

Table 1: On-board energy of gasoline powered utility/touring snowmobiles

Using a mass of 0.73 kg/l (6.1 lb/gal) as the volumetric mass of gasoline, the weight of the average 358,722 Wh of energy carried on-board those snowmobiles is 29.9 kg (65.8lbs).

In comparison to the gasoline numbers, Table 2 looks at the energy density of 4 of the main battery technologies mature enough for use in electric snowmobiles: lead-acid (Pb-A), Nickel Cadmium (Ni-Cd), Nickel Metal Hydride (NiMH), Lithium-Ion (Li-ion).

Battery Technology	Gravimetric Energy Density (Wh/kg)	Volumetric Energy Density (Wh/l)
Pb-A	33.5	76.2
Ni-Cd	54	95
NiMH	60	155
Li-Ion	105	284

Table 2: Energy Density of Common Battery Technologies

As table 2 shows, the “raw” energy density of battery technologies is nowhere near the “raw” energy density of gasoline.

Why is it termed the “raw” energy density? Because the numbers in Table 2 only looks at the energy density of the batteries themselves. For a very accurate comparison between energy density of batteries and gasoline one should take into account weight and volume of the containment chamber or other means of holding the gasoline and batteries on board. To that must be added the difference in weight and volume of energy transfer systems (i.e. Fuel pump and tube vs. battery management system and heavy gage copper wire). Lastly, the drop in battery energy density related to temperature and discharge rate should be taken into account for a true comparison between battery technology and gasoline. In general, the “net” energy density comparison will be worst for the batteries than the “raw” energy density comparison.

In a best case scenario, as seen in 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. With new utility/touring snowmobiles such as Ski-Doo's Tundra weighting 172kg (379lbs) (dry weight), this represents a “fuel” weight 16.5 times larger than the weight of the vehicle itself. Adding to that the fact that 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 suited for a snowmobile.

Energy Carrier (EC)	Gasoline	Batteries (Li-Ion)
Vehicle	Ski-Doo Tundra	
Dry Weight	172 kg	
Energy On-Board	297,840 Wh	
EC Volume	34 l	1049 l
EC Weight	24.8 kg	2837 kg
EC/Dry Weight Ratio	0.144	16.5

Table 3: Head-to-head energy carrier comparison

Thus, in making a hybrid snowmobile, one of the design goal is to minimize the impact of the low energy density of the batteries on the performances of the vehicle relative to what users require.

ENERGY EFFICIENCY

Another main advantage of a hybrid system is the energy efficiency of the electric drive system. An electric drive system produces much less waste heat than its ICE counterpart. For example, when comparing BRP's most efficient snowmobile with McGill's electric 2006 prototype, one can notice that the electric prototype is 3.5 times more efficient.

Snowmobile	Efficiency (km/kWh)
BRP Rotax, 4-TEC, V-800	1,26
McGill Electric 2006	4.629

Table 4: Efficiency Comparison

OTHER ADVANTAGES OF HYBRIDS

<u>Energy Intake</u>

By offering the possibility of recharging their battery pack from different sources, hybrids enable owners, in any given location, to select the energy input which best suits the environment and their wallet.

One way of recharging the battery is from the vehicle's ICE. Another way is via regenerative braking. While this method of recharging is very attractive in road vehicles especially when driven in start-stop applications, it is unfortunately not as attractive in a touring snowmobile application. The lack of start-stop driving and the high risk of the track locking up or plowing through the snow on braking greatly diminish the possible returns of energy during braking relative to road vehicles. A third way of recharging the battery is to plug it into any suitable electrical outlet. This third method of recharge has the advantage of allowing the batteries to be charged from renewable energy sources and high efficiency energy sources when these are available. Furthermore, it makes it possible to recharge the vehicle at low power demand hours and can, in some places, have the potential of saving substantial operating costs both to the snowmobile users and the electric power provider.

<u>Noise</u>

In the case where the electric drivetrain is quieter than the ICE, hybrids which can operate for certain periods of time solely on battery power (i.e. ICE turned off) can be very attractive when areas particularly sensitive to noise must be traversed. This is especially true if the area is traversed by a group of many snowmobiles which is often the case in touring activities. Furthermore, it can enable a snowmobile to "electrically idle" in complete silence.

<u>Emissions</u>

Provided that the hybrid snowmobile has sufficient all electric range, a hybrid can turn off its ICE prior to entering an environmentally sensitive area to minimize the vehicle's impact on this area. Once the sensitive area has been passed hybrid powering of the snowmobile can be resumed.

Also, in applications which do not require extensive distances to be driven all the time, if desired, the hybrid can be used as an electric snowmobile for most if not all of its mileage during regular day-to-day operations. However, unlike the true electric snowmobile, it is not restricted to this short radius of operation if, for any reason, longer range is occasionally required.

SELECTION OF HYBRID CONFIGURATION

After having reviewed some of the possible advantages of hybrid snowmobiles over both ICE and electric snowmobiles, the team's task was to decide which hybrid configuration it would implement in its 2007 hybrid prototype. While a fair amount of time was spent debating the pros and cons of each configuration relative to the SAE CSC 2007 requirements, in the end, most of these ended up being secondary issues as the team agreed that only one configuration allowed it to achieve its primary goal which is to making a simple and reliable prototype that can serve as a baseline for further refinement of the hybrid concept in future years.

In order to make it reliable and simple to build, the team believed that, technology wise, the hybrid prototype should remain fairly close to an electric snowmobile; the type of vehicle the team has experience with. Thus, the team selected to build a series hybrid snowmobile as the 2007 McGill University Hybrid Snowmobile Prototype.

SELECTION OF SERIES HYBRID COMPONENTS

MOTOR SELECTION

There are many criteria to be looked at when selecting a traction motor for any electric vehicle. A firm understanding of the loads and dynamics of the vehicle in question are crucial for this process. There are several ways by which one can attain such an understanding of their vehicle, here are 3 of them:

- Before dismantling, the vehicle is out fitted with a data acquisition system consisting of various sensors and a recording device. The vehicle is then operated for a standard drive cycle while the data acquisition system records parameters such as power, speed, torque, acceleration, etc.

- Knowledge and experience are gained through basic load tests. Examples of these would be towing the vehicle with a load cell or using a torque wrench on input shaft to the transmission. A few calculations can then provide some useful estimates for power, speed and torque. This method would also require the construction and testing of preliminary electric prototypes to validate the estimates.

- Obtain operating load data from vehicle manufacturer.

Over the years the electric snowmobile team has gone through method two numerous times. In addition to this knowledge and experience, the past 2 prototypes have been equipped with data acquisition systems from Isaac® Instruments[4]. This allows the team to monitor parameters such as voltage, current, RPM and temperature while the snowmobile is operating and then analyze the data afterwards with the drive motor power and torque curves as reference. We have also spoken to after market snowmobile track manufacturers about average power requirement of the track and suspension system at various operating speeds. From all this we feel that we have a firm understanding of the loads and dynamics of the stock snowmobile chassis that we are using as a basis for our prototypes.

Starting with an understanding of the vehicle one must look at all the options available that match the performance requirements of the vehicle. An average snowmobile for example needs approximately 10 kW to move at 60 km/h on flat packed snow, if we break that down into RPM's and torque we get 1736 RPM and 55 N-m. Some types of electric motors that can provide this kind of power are:

- DC Motors, which includes series, series parallel and shunt wound
- Permanent Magnet DC motors
- Brushless DC motors
- AC Induction motors

These all have their pros and cons and therefore, it is up to the designer to select the most appropriate one based on power, torque, speed, cost (including the required controller), weight, physical size, efficiency, availability etc. From here, "one may be tempted to use some of the more powerful compact motors available. However, one must make sure that all other electrical components in the snowmobile can feed the motor the amount of power it can output for a suitable period of time as well as fit into a target chassis. Failure to do this will in most cases result in a loss of efficiency, both on a performance and a cost basis."[5] With this in mind we can take a closer look at the motors in our list.

DC Motor

There is many ways in which a DC motor can be configured; here we will only look at four of the more common configurations that best fit our application. The four types differ from each other in the way they are wired which gives each of them a different characteristic curve (figure 4). Although they tend to be less efficient than the others in the list, these motors can be built to fit almost any application, they have a competitive power weight ratio and can be produced at low cost which makes them the motors of choice in the electric vehicle industry today. From figure 4 we see that only shunt, compound and series will provide stable speed control, and that in fact series will provide the most stable speed control of all four.

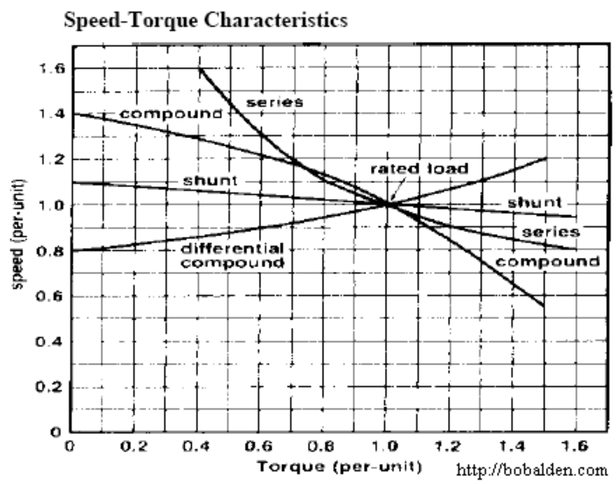

Illustration 4: Speed and Torque Characteristic of DC motors

Permanent Magnet DC motors

These motors are very similar to the DC motor discussed above except for that their stator field is created by permanent magnets rather than electro-magnets. This feature allows them to be fairly efficient and produces a nice linear power curve which is attractive from a design point of view; however, most permanent magnet motors are rated under 15kW. The Wendigo is currently equipped with a PMG 132 permanent magnet DC motor for which a 72 volt graph is shown in figure 5.

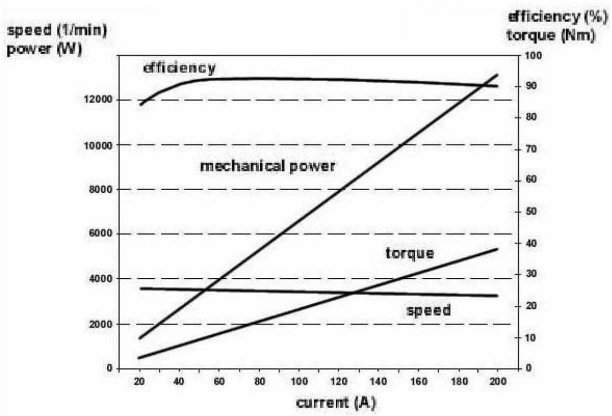

Illustration 5: Characterisitics of Permanent Magnet DC motors

Brushless DC motors

A Brushless DC (BLDC) motor typically uses permanent magnets as well; however, they are electronically commutated rather than mechanically commutated. This process requires high power circuitry that monitors the action of the rotor using Hall Effect sensors and produces 3-phase AC power creating a rotating magnetic field in the stator. These motors have the potential to be more efficient than other DC motors and require less maintenance because they do not have brushes. The power curve of a BLDC is similar to that of a permanent magnet DC motor (figure 6). BLDC motors are generally more expensive than other DC motors and from our experience are less reliable due to the electronics which are required to operate at high power density. In previous electric prototypes BLDC motors have been the dominant choice; however, due to the poor reliability of the electronics and high cost of BLDC motors, we have chosen not to use them in either the electric or hybrid snowmobiles this year.

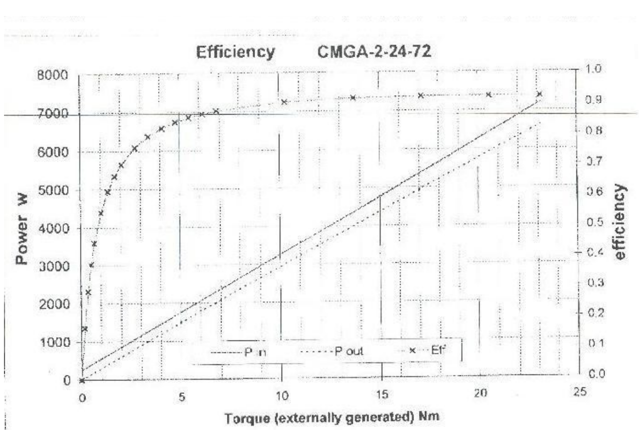

Illustration 6: Power curve DC brushless motor

AC Induction Motos

As suggested by the name these motors operate using 3-phase AC power. Their operation is similar to the BLDC motor, meaning that to operate in a DC system it would require similar high power electronics. AC motors are very efficient however they tend to be heavy compared to DC motors of the same power rating. Complexity and poor power to weight ratio are the major draw backs that kept AC motors from being competitive as a prime mover in small electric vehicles.

Final Decision

Drive configuration for the hybrid snowmobile has been examined in detail for both permanent magnet and DC motors. In addition to the requirements that the selected drive motor be 72 volts nominal with a peak power rating between 25kW and 35kW, the following weighted decision matrix was used as a guide for motor selection. To meet the continuous power rating using permanent magnet motor the design would have to include two 15kW units working together. The final decision is a custom modified DC series wound motor from High-Torque Electric[6].

Weighted Decision Matrix	Importance of criteria rated with 1,2 or 3 Motor rating Scale: 1(poor) to 5(good)						
Criteria	Power to weight ratio	Cost	Reliability	Eff.	Design Simplicity	Power Curve	
Importance Factor	2	3	3	1	2	2	
Motor Type							Total
Perm. Mag.	5	4	5	5	2	5	56
Series	4	5	5	3	5	4	59
Shunt	4	5	5	4	5	2	56

Table 5: Motor Decision Table

The results from the team's dynamometer testing of this motor is available below.

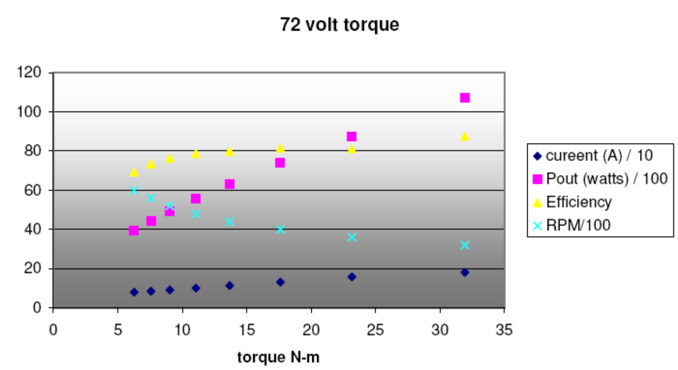

Illustration 7: Dynamometer test results

Chassis Selection

The chassis selected for the hybrid snowmobile comes from a Bombardier Recreational Products[12] (BRP) 2006 MXZ Renegade 800 HO. This chassis was chosen mainly for the two following reasons. First, the MXZ chassis is a REV platform from which the RF chassis, used for the electric snowmobile, originated and therefore they share many aspects in common including the location of mounting holes in and around the engine compartment. Second, the REV platform widely considered amongst the snowmobile community to be superior in terms of weight distribution and rider position.

Energy Storage Device

As previously mentioned, the specific energy is much greater for gasoline than for batteries. The following table shows approximate values of specific energy for some typical energy storage methods.

From this table we can see that vehicles using either gaseous or liquid fuels have a significant advantage over vehicles relying on other types of energy storage. For this reason the energy storage system for an electric or plug-in hybrid must be carefully selected and sized to optimize its usefulness.

In the case of a plug-in hybrid, electrical energy can be stored using either chemical batteries or capacitors. Currently batteries dominate this application in industry for two reasons. First, from the table we see that the specific energy of capacitors is far below that of any of the chemical batteries, and second "for maximum storage, the voltage [of a capacitor] must vary wildly from V max at full charge to V min at full discharge. So high power and very efficient power conversion electronics"[8] are required. Capacitors however, are less expensive to produce than chemical batteries and generally have many more charge-discharge cycles to their lifetime which makes them an attractive solution economically. There are several companies doing research to improve the usefulness of capacitors but have yet to produce any commercially available systems.

Storage Type	Specific Energy Wh/kg
Gasoline	12222
Gasohol (10% ethanol 90% gasoline)	12094
Diesel	13055
Ethanol	6281
Bio-diesel	11722
Compressed natural gas at 200 bar	14889
Lithium Ion	175
Lead Acid	30.6
Nickel Metal Hydride	61.1
Wendigo Lithium Ion from LTC	105
Compressed Air at 20 bar (near compression limit)	75
Flywheel	139
Capacitor	0.6
Ultra Capacitor	5.7

http://en.wikipedia.org/wiki/Energy_density

Table 6: Specific Energy of different fuels

The lithium-ion battery pack in the team's Wendigo Electric Snowmobile Prototype is a custom pack from LTC which consists of twenty 3.6 volt, 45 amp-hour high power cells in series and protected by a LTC Battery Management System (BMS). These cells have very good resistance to temperature fluctuations ranging from -30ºC to 60ºC. The high power refers to their rated discharge rates; other cell cells are classified as high energy and have between 55 and 60 amp-hours of capacity for the same size and weight; however they cannot discharge at the rates required by the snowmobile. Since the hybrid snowmobile is intended to travel much further than the electric it will require more batteries.

The team has decided to stack 3 packs similar to the electric snowmobile pack in parallel to compose the hybrid battery pack. The result is added efficiency at the battery pack level on high discharges since the 3 packs share the load of the current draw. This large pack also serves as an ideal buffer to the ICE engine since due to its large size it can easily buffer large engines without overcurrenting the pack since the cells share the load on recharge.

Unfortunately, cost in terms of size, weight and dollar figures are considerable for such a pack. Given the cells were readily available to the team, only the first two obstacles had to be overcome.

Direct Current Generator Design

The DC generator in the hybrid snowmobile provides a constant source of current that can be utilized to either propel the snowmobile or charge the batteries. Increasing the design horse power of the generator increases the snowmobiles range according the following relations:

T = Total operating time in hours

V_{ave} = Ave. Speed in km/h

$E_{battery}$ = Battery Energy in kWh

$P_{generator}$ = Power from Generator in kW

P_{av} = Average Power in kW required at the track to move at V_{ave}

η = Drive train efficiency

$$Range(km) = T \times V_{ave}$$

$$T = \left[E_{battery} + \left(T \times P_{generator}\right)\right] \times \left[\frac{\eta}{P_{ave}}\right]$$

Much like 120V 60Hz AC generators available from companies such as Honda, DC generators can be purchased as a ready to run item from companies such as Polar Power Inc[14]. One difference is the lack of a voltage standard in DC systems, which causes a problem for designers seeking a DC generator with a specific voltage. At 72 volts nominal, there are very few options that fit the requirements. For example, eCycle makes 4kW auxiliary power units by coupling their CMG motor with a 7HP Robin Subaru[15] EX 21. If we compare the EX 21 power curve (figure 9) with curves for the CMG and PMG we see that with the PMG coupled to the EX 21 we can squeeze a bit more power out of it because the PMG has a higher RPM/volt constant. In fact, using a PMG in place of the CMG has more benefits than this. The PMG cost less than a third what the CMG costs. From experience, the team feels that the PMG more likely to perform well in the snowmobile application. The CMG is slightly more efficient than the PMG but only by a few percent. For these reasons, we have decided to use the EX 21 coupled with a PMG. The combined technical data for the PMG , CMG and the EX 21 can be found below.

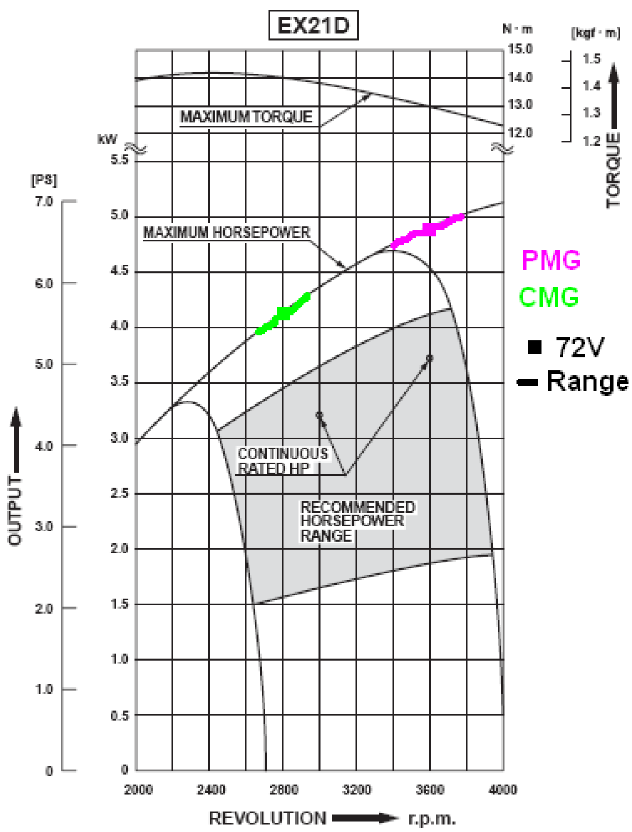

Illustration 8: EX21 technical data

VEHICLE MANAGEMENT SYSTEM

The vehicle management system (VMS) chosen is the same one made for the electric prototype. Since the system was custom made by the team, it was relatively easy to add the features needed in the hybrid. Following is a description of the basic system and then the added features for the hybrid.

The main feature of this system is that it is able to communicate with the user via a Vacuum Fluorescent Display (VFD). Therefore, if the system detects an error condition, it can immediately inform the user of the problem and even turn off stop the snowmobile if required. The Matrix Orbital VFD2041-E was specifically selected for cold and rugged snowmobiling conditions. The characters it displays are very bright and can be seen clearly up to 2.75m (9ft) away. The Matrix Orbital VFD2041-E is rated for temperatures from -40C to 80C. Thcombination of the VMS and the VFD can monitor temperature, voltage, current, RPM and speed and, if any of these reach a critical condition, the system can advise the user and take proper actions to avoid or limit damages.

The VMS also takes care of the “precharging” (charging of capacitors to avoid current spikes at start-up) of the Alltrax controller. To do this, the VMS monitors the voltage levels and closes contactors when the voltage levels are such that they will not cause a current spike. This feature increases the useful life of the contactors. It also provides means to detect faulty conditions (a bad connection for example) and prevents the contactors from closing in this event. Another important safety aspect of the VMS is that is ensures that the snowmobile cannot be turned on while it is being charged. This prevents damage to the charger and to the charging facility.

Some of the added features are the possibility of turning off the generator via a user accessible switch. This enables the driver to go in “electric only” mode. As previously mentioned, this may be very useful for reducing noise and emissions in sensitive areas, while leaving the possibility to turn the generator back on if the batteries are getting too low.

Another added feature is the control of the generator voltage output via a DC-servo motor. By attaching the servo motor to the throttle of the generator, the RPM of the generator can be controlled electronically. A high-voltage sensor senses the voltage level of the generator and adjusts the servo to keep it at the target level.

COMPONENT LAYOUT

Before describing the exact layout for the components in the 2007 prototype, it is important to mention the challenge the team faced for this project. One way to look at this is to imagine fitting an entire new electric drive system in a conventional ICE snowmobile. This means that the team had to find volume space and safe mounting points for an electric motor, a motor controller, a battery pack, a battery charger and miscellaneous electronics. If you look at any snowmobile on the market, you soon realize that this is not easy. The illustration below shows the MXZ 800 HO chassis used by the team prior to disassembly.

Illustration 9: MXZ 800 HO engine bay

Faced with this challenge, the team decided early on that weight distribution and stability would be ignored in this 1st generation prototype.

The first item which was placed was the ICE generator. It was decided to place it where the previous ICE was. The idea behind this decision was that there would be safe mounting points and space for exhaust system. Moreover, given its shape, this is one of the only places where this large component can fit in the snowmobile while still leaving enough room for other required components.

Another large component which must be installed in the hybrid is the the battery pack. Due to the ICE taking up all the space inside the engine bay, it was decided to place the batteries on the tunnel, behind the seat on the cargo area. While this positioning is far from optimal, it is simple to implement and the team has already some experience with this type of installation from a similar placement of the battery pack in the 2006 electric snowmobile. This unit uses 100l of space. Installing it on the cargo rack greatly simplifies the design of the custom made packs.

The electric motor was also forced to the only place where it would hold safely and easily: where the original jack shaft used to be positionned

The fuel tank was left where the original fuel tank was. However, the original tank was replaced with a smaller one in order to leave enough space for all the on board electronics.

Due to the generator placement, the CVT was moved to the right side of the snowmobile (as seen by the driver).

The charger was positioned in the front of the engine bay. Again, this was the last place where the large component would fit. (Note: for the purpose of the SAE CSC competition, for ease of measuring energy equivalence between the ICE snowmobile and the hybrid, the charger will be removed for the duration of the competition so that 100% of the energy input of the hybrid will come from the E10 that the ICE snowmobile are using.)

The last components, which are all smaller electronics, where positioned under the seat. In the space created by the replacement of the gas tank.

An important note here is that this placement facilitated the placement of high power wires. These would go from the batteries in the back, to the electronics under the seat, to the electric motor under the handle bars. This would makes the high power wiring system as short and simple as possible.

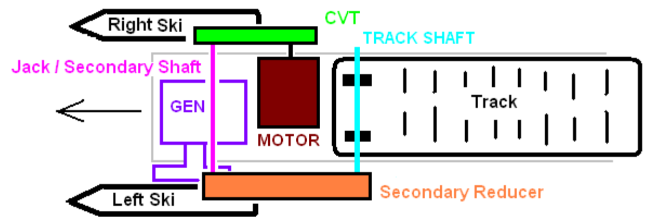

Illustration 10: Component Layout Top View

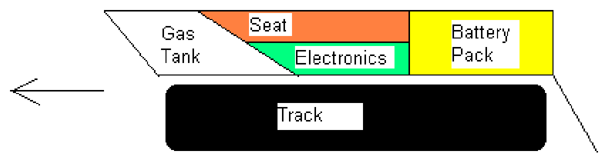

Illustration 11: Component Layout Side View

NOISE REDUCTION

One of the advantages of a series-hybrid drive train is that the alternate power unit can be optimized for a relatively small range of operating conditions. In a typical vehicle, the internal combustion engine must operate at a wide range of speeds depending on the demands of the driver, whereas in a series-hybrid setup, the speed of the gas engine remains relatively constant regardless of throttle inputs from the driver.

One area that can benefit from this steady operating condition is noise control. The noise suppression system can be designed around an engine that operates at a single RPM and can be optimized for the associated sound frequencies. It must be noted however that as the voltage of the system changes from full charge to low charge, the speed of the DC generator must be varied to match this voltage, and therefore the engine speed is not entirely constant. In this particular vehicle, a voltage range of 64V to 80V corresponds to engine speeds of 3200rpm to 4000rpm.

To prove that this was in fact the case, the team tested the EX-21 for the range used in the vehicle. Using a particle zone microphone with a flat frequency response, digital recordings were made of the engine running, saving the data directly to a WAV format sound file on a laptop. This file was then analyzed using MATLAB as well as consumer audio software, and a frequency spectrum of the engine noise was obtained.

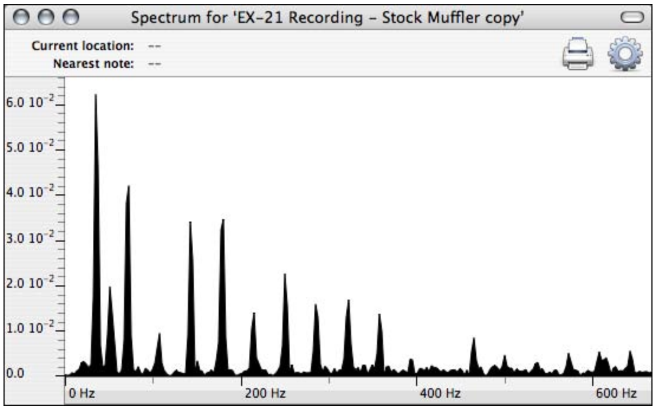

Illustration 12: Frequency analysis of EX-21 sound recording

It was seen that there was one fundamental frequency that was at least 50% stronger than any other notes, and this frequency was in the range of 30 to 35 Hertz. For a four-stroke, single cylinder engine, there is one exhaust stroke for every two rotations of the crankshaft. As had been predicted, the dominant frequency observed in the noise therefore corresponds to the frequency of exhaust strokes (3600 rpm equates to 30 exhaust strokes per second, for example.)

The team research extensively to find an exhaust design which would attenuate the specific frequencies. The design which was most feasible to implement in a snowmobile and which would attenuate the most is based on the Helmholtz resonator. A Helmholtz resonator is a noise suppression device often used in ventilation systems and sometimes in engine intake and exhaust that is tuned to a very specific frequency. It consists of an enclosed volume attached as a side branch to a duct through which there is a flow of gas.

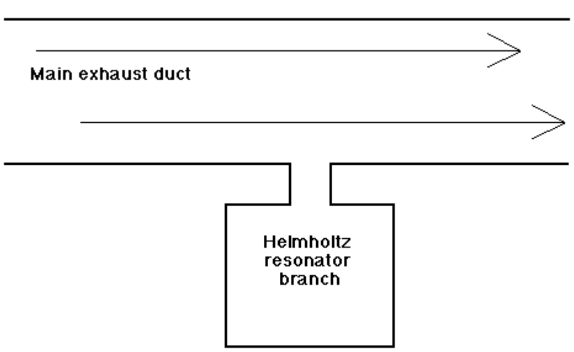

Illustration 13: Basis Heimholtz resonator diagram

The resonator behaves in much the same way as blowing over the top of a bottle; it has an associated sound frequency based on its volume and the dimensions of the neck connecting it to the main duct. When a gas flows over the top of the resonator, the resonator behaves much as a spring-mass-damper system, with the gas inside the neck acting as the mass, the gas inside the resonator acting as a spring, and the damping provided by viscous effects of the gas. The resonator will therefore absorb sound at its specific tuned frequency. The frequency of a resonator is given by

$$f = \frac{c}{2\pi}\sqrt{\frac{S}{L \cdot V}} \qquad \text{Equation 1}$$

where c is the speed of sound in the gas, S is the cross sectional area of the neck, L is the length of the neck, and V is the volume of the resonator.

Helmholtz resonators have been shown to provide very strong noise attenuation over a relatively small bandwidth around the tuned frequency. This is therefore not a very practical means of silencing the broad range of frequencies produced by typical vehicle engines. However, with a series-hybrid vehicle, a Helmholtz type silencer could be tuned to the constant frequency associated with the operating speed of the ICE. The operating speed is not entirely constant, however, and the frequency of exhaust noise would change as the system shifts from full voltage to low voltage.

This system was not fully implemented this year due to time, space and resource constraints. As previously mentioned, since the team was making two snowmobiles, the effort for the hybrid design was to make a simple and reliable working prototype. Given the promising results obtained in preliminary testing, the implementation of this aspects is going to be the priority for the 2nd generation hybrid snowmobile.

EMISSION CONTROL

As mentioned earlier, one of the main reasons for designing a plug-in series hybrid snowmobile is that it offers the possibility to be a full zero emissions vehicle. This means that when a driver is passing by a sensitive area, he/she can simply turn off the generator. This also eliminates the main source of noise.

However, the team cannot simply rely on its zero emissions aspect, since the vehicle would be used in hybrid mode most of the time. Therefore, the team looked into strategies to keep the emissions of the vehicle to a minimum.

The first way by which this was achieved is the selection of the ICE. As mentioned above, the team chose a small motor. By lowering the power output of the generator, the emissions are also lowered.

The EX-21 is usually used for industrial use and therefore does not come with a catalytic converter. Moreover, there are no catalytic converters on the market for this specific engine. Therefore, the team decided to team up with Heraeus. Heraeus took the exact specification from Subaru and made a custom catalytic converter for the EX-21.

The installation of the new catalytic converter forced the team to eliminate the stock exhaust. The team worked very hard to ensure that this change would not result in an increase of the noise. The team also made sure that the total power output of the generator would not suffer from this change.

Also, since the generator is always used at close to constant speed, a custom system could be designed to diminish emissions for that specific speed. This is a possibility the team will investigate extensively next year.

HYBRID SYSTEM PERFORMANCE

The hybrid system was tested on a dynamometer to evaluate its performance prior to installation in the snowmobile.

Results showed that the distribution (between recharging the batteries and powering the motor) of the power produced by the generator varies actively depending on the battery's state of charge, the load applied on the drive motor and the opening of the generator engine's throttle. Since the battery pack and the generator are connected in parallel at the entrance of the electrical box, there is no restriction on the flow of current between the generator and the battery pack. Thus in the case where the drive motor was disconnected from the power sources the flow of current between the generator and the battery pack was a simple function of voltage difference between these 2 units. For example, if the engine was not running the current would flow from the batteries (higher voltage) to the PMG motor of the generator thus cranking the engine in the same way a starter does. At this point, if the engine is given some fuel it turns on. Despite the engine being in operation, the batteries still continue to drive the PMG motor and thus the engine is in compression mode. Current flow can only be reversed if the engine is allowed to rev up to a point at which the angular velocity of the PMG's rotor produces a voltage greater than the battery voltage. If the voltages are equal the engine is idling.

All these principles are also in effect when the drive motor is connected to the power sources however in this case the voltages of the battery pack and the generator vary based on load. One key observation from the tests was that without any regulation between the 2 sources of power, the batteries will react much more rapidly to any peaks in power demand. This is a very good thing since it means that no complicated control systems are required to have a working buffer system between the generator and the drive motor.

While this system can be further refined, its effectiveness and simplicity met the goals the team had set for this 1st generation prototype.

CONCLUSION

As mentioned in the introduction, the goal for the 2007 hybrid system was not to win every category of the CSC. Such a goal would have been unachievable given the available manpower, budget and time of the team had to make its two vehicles. The team's priority was to make the electric prototype simple and reliable.

Having no previous experience working with gasoline engines, no actual resources for guidance of the building of a hybrid snowmobile, and all previously mentioned challenges, the team nevertheless managed to make a working system which can serve as a baseline for further refinement of the hybrid concept in the future.

Although this prototype is only a first proof of concept, the team believes that it is a basis which in due time could set a new standard in innovation and technology in the snowmobile world. With all the benefits of a zero emissions prototype and performances which can approach those of some ICE snowmobiles, the team truly believes that a hybrid design is a winning solution; maybe not a winning solution for the SAE CSC 2007, but eventually a winning solution for the snowmobiling industry in the long run.

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