SAE 2008-xx-xxxx

McGill University Hybrid Snowmobile Design Implementation of a Series Hybrid Powertrain

Albert Mathews, Christian Wassmer, Jean-Simon Lavallee, Louis-Philippe Morin, Alexandre Masse
SAE Student Members, McGill University

Prof. Peter Radziszewski
Mech. Eng. Dept., McGill University

Abstract

2004 was the first year that McGill University proposed competing with an electric snowmobile at the SAE Clean Snowmobile Competition with the ambition that a "clean snowmobile" could first be made completely clean and then performance could be developed from that point on. After 3 years of development and participation at the CSC with an electric snowmobile, the realization has been made that a zero emissions snowmobile cannot adequately match the performance of the average recreational snowmobiler. With continued ambition for innovation, the McGill team has chosen to further develop the prototype hybrid snowmobile first introduced at the CSC 2007. The 2008 hybrid design incorporates a more powerful engine and reduced battery capacity. The main goal for 2008 is to compete with a reliable hybrid snowmobile capable completing all CSC I.C. category events.

Introduction

For the past 8 years the SAE CSC has being giving university students the opportunity to find innovative ways of enhancing the environmental and social compatibility of leisure snowmobiles (1). In the past decade, the EPA, State Governments and other regulating bodies have introduced into the snowmobile scene mandates focusing on limiting snowmobile emissions and noise (2) (3).

Table 1: EPA New Off Road Engine Emissions Regulations (2)

Model Year	Emissions Standards		Phase-in
	HC	CO	
	g/kW-h	g/kW-h	
2006	100	275	50%
2007-2009	100	275	100%
2010	75	275	
2012	75	200	

As these regulations were introduced into an industry that had seen little regulations on such performance specifications in the past, snowmobile manufacturers responded by implementing technologies from the automotive industry which could be applied to snowmobiles. Some of these technologies include: four-stroke engines, fuel injection, alternate fuels, and electronic timing. McGill University attempts to take this one step further by implementing a bio-diesel series hybrid powertrain for the 2008 SAE CSC.

The hybrid snowmobile powertrain design is based on the theory that for a given drive cycle, the engine design of a hybrid drive train can be optimized based on the time average power requirement for the drive cycle. However, for the same drive cycle, the engine design of a conventional powertrain will have to meet the time average power requirement, the maximum power requirement, and maximum torque requirement. These added constrains on design performance of the engine hinder the ability to generally operate the engine in its high efficiency regime (4). However, since power peaks and torque peaks can be buffered out by the battery electric drive system of the series hybrid powertrain the operation of the engine can, in general be kept within high efficiency operating regimes. Added advantage of a narrower operating regime is the increased ability to optimize noise and emissions reduction equipment (5) (6).

For the CSC 2008, the McGill University Team hopes to demonstrate how this technology can increase fuel economy and decrease emissions while maintaining base performance requirements. It is understood that such powertrains bring about complications when emissions testing is performed on a modal basis. However, the team hopes that with the experience gained from participation in the CSC emissions event this year, testing standards for alternate powertrains can be developed.

This report will cover design considerations including design goals, strategy & theory, and qualitative powertrain simulation results; followed by design implementation and component selection.

Hybrid Snowmobile Design

DESIGN CONSIDERATIONS – This section discusses the theoretical aspect of design involved in the development of 2008 hybrid snowmobile and outlines the goals and constraints for the project.

Design Goals - Due to fact that the 2007 and 2008 McGill Hybrid snowmobile prototypes are unique in their design, it is difficult to establish base line performance standards and design goals for the 2008 Hybrid snowmobile. This year the team has decided to focus primarily on reliability, specifically directed at completing the endurance/fuel economy and the emissions event while satisfying the CSC baseline requirements for the I.C. category. At this stage, the 2008 SAE CSC rules state that *"After review of the design the organizers will determine if the entry can be included in the IC category or on an "Exhibition" basis."*

Design Goals for CSC 2008:

- Complete Fuel Economy Event
- Complete Emissions Event
- Maintain Baseline Performance Requirements of IC Category

Design Strategy - Hybrid powertrains come in 3 different configurations:

- Series
- Parallel
- Series-Parallel

Each configuration can have either one of two control strategies:

- Charge Sustaining
- Charge Depleting

The design of the hybrid powertrain for the McGill University prototype snowmobile is a bio-diesel and electric direct current series hybrid set up, see figure 1.

The team chose a series hybrid powertrain setup to minimize the amount of active control the system would need to operate. Parallel and series-parallel designs typically require complex active control systems to maintain appropriate power balance between the engine and the batteries (6). The 2008 diesel electric series prototype uses the diesel engine governor as the sole element of active control to manage the power split between the engine and the batteries.

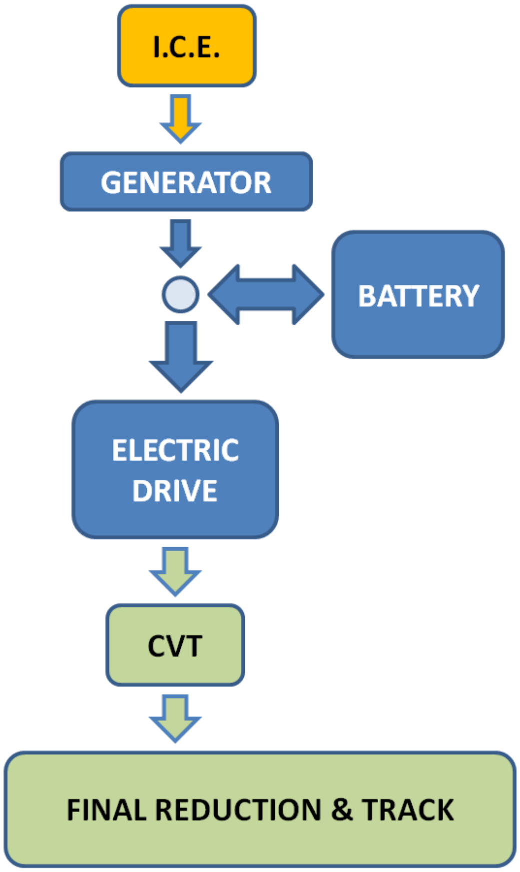

Figure 1: McGill University Series Hybrid Snowmobile Powertrain Flow Diagram

The hybrid system functions according to the following principles:

- The governor sets maximum voltage that the generator can produce, which limits charging voltage
- When operating below this voltage, the generator outputs maximum current at all times
- This current can be used to power the electric drive directly, or charge the batteries
- If the current demand of the electric drive is smaller than the generator supply, the excess will go charging the batteries
- If the current demand of the electric drive is greater than the generator supply, the batteries will provide the necessary supplemental current

The current split taking place according to these rules occurs naturally. This simplified control strategy requires careful selection of the voltage and current capabilities of both the battery and the engine.

The rules regarding the endurance event state that a total of approximately 100 mile must be completed at an average of 30 miles per hour (7). Since rules regarding hybrid design control strategies are not yet defined, this leaves the option open to both charge sustaining and charge depleting control strategies. Charge sustaining hybrids will finish the endurance event with a battery SOC (State Of Charge) identical to that at the beginning. However, depending on charge depleting strategy, these hybrids would finish the endurance event with battery SOC lower than the SOC at the beginning of the event. It is suggested by McGill University that any hybrid design demonstrating a charge depleting strategy be required to use the on-board I.C.E. to return the battery to its SOC as measured at the beginning of the endurance event. In addition to this, all hybrid designs should provide a clear means by which the battery SOC can be measured to establish in a fair manner that hybrid designs do NOT make use of pre-stored electric energy to supplement the fuel used in completing the event. For the 2008 McGill prototype, it is suggested that the voltage and charge current be recorded while stopped at the beginning of the endurance event and that the generator be left to charge the batteries at the end of the event until the same voltage and current are attained assuming that voltage is below that at the beginning of the event.

Considering CSC events only, the team has used data generated from McGill University's Electric Snowmobile Prototype to estimate the time average required power for the CSC endurance event. This requirement was used to select the continuous power capability of the direct current generator. Because of uncertainties of snow condition and total time needed for the conduct of the endurance event, it is difficult to be sure whether this power requirement will indeed prove to be charge sustaining or depleting. If the snow is sticky, and the average speed for the event is greater than 30 miles per hour with a relatively high amount of stopping and starting, this will increase the time average power requirement. In this situation the hybrid snowmobile will rely on the energy stored in the battery. It must be noted that for a given hybrid design, if the time average power requirement becomes great enough the battery could be depleted before the end of the endurance event. This situation should be considered similar to running out of fuel or having technical difficulties for standard I.C. sleds. In the absence of high fidelity powertrain simulations, range estimates for charge depleting strategies can be evaluated using the flowing equations (8):

$$Range = Time \times V_{ave}$$

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

Where:

- V_{ave} is the average speed of the snowmobile
- Time is total amount of time to reach destination
- $E_{battery}$ is the amount of energy stored in the battery
- $P_{generator}$ is the average electrical power supplied by the generator
- η is the average efficiency of the electric drive
- P_{ave} is the average power output from the electrical drive required to propel the snowmobile at V_{ave}

The design values resulting from an analysis using these equations and estimates for inputs from the electric snowmobile are:

- V_{ave} = 30 miles per hour
- Time = 3.33 hours
- P_{ave} = 11 kilowatts
- η = 0.8
- $E_{battery}$ = 0 kilowatt-hours, (for charge sustaining)
- $P_{generator}$ = 13.75 kilowatts

If we increase the average speed but keep the generator power constant, we can estimate the minimum amount of battery energy required to complete the 100 miles with a charge depleting strategy:

- V_{ave} = 33 mile per hour
- Time = 3 hours
- P_{ave} = 12 kilowatts
- $E_{battery}$ = 3.75 kilowatt-hours

Starting with these design values, the team explored what options were available for the I.C.E., battery, and electric drive system. It was found that due to this power requirement and space constraints, more spatially compact direct current components were chosen over the alternating current counter parts; also lithium-ion batteries were chosen for their preferable voltage/current characteristics and energy/power density. The decision to use a diesel engine was based on the CSC 2009 rules. The rules state that all I.C.E. entrants are required to be flex-fuel for combinations of either Gasoline/E85, or Diesel/B10. The team established that when one is starting from limited experience with engines, it would be less difficult to convert a diesel to B10 and then further to B20 flex-fuel, than a gasoline engine to E85 and then further to E85 flex-fuel. This decision and the selection process for all components will be reviewed in greater detail in the practical selection section of this paper.

Fuel Economy – Fuel economy of an I.C.E. powered vehicle depends on the operating efficiency. As mentioned above, the series hybrid powertrain allows the engine to be operated at higher efficiencies in general.

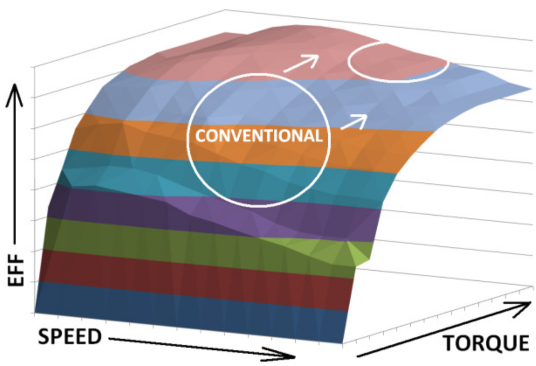

Figure 2: Efficiency of Typical Diesel Engine.

Figure 2 represents graphically how the operating regimes for cruising power requirements differ between a conventional powertrain and the series hybrid powertrain of the McGill prototype. It must be noted that a series hybrid setup does in fact introduce two efficiency factors between the engine and the input into the transmissions:

- Conversion of mechanical power into electrical power at the generator
- Conversion of electrical power into mechanical power at the electric drive

Calculations of fuel consumption can be made from the manufacturer data (*note: the team is not authorized to publish the performance charts*) and continuous power requirement of the snowmobile, which gives approximately 3510 grams of diesel per hour (9). If we assume 48.3 km/h (30 mph) with 160.9 km (100 mile) range for the fuel economy event and approximately 0.833 kg/L (10) (note: all attempts to contact Gage Products for B10 density were unsuccessful) we can predict that the hybrid snowmobile could achieve a fuel economy of 6.06 L per 100km (38.8 MPG)

However, using vehicle powertrain simulation software such as Argonne National Laboratory's PSAT (Power System Analysis Tool), one can show on a qualitative basis how a series hybrid setup can benefit total drive cycle fuel efficiency for many different types of drive cycles. Appendix A shows and discusses in detail PSAT results from a comparison of 5 different simulations of vehicles all driving a cycle made up of standard UDDS (Urban Dynamometer Driving Schedule) drive cycle followed by a standard HWFET (Highway Fuel Economy Test). All 5 vehicles are *diesel powered* Ford Explorers with differing powertrains as shown in table 2:

Table 2: PSAT simulations fuel economy results.

Sim #	Powertrain	Engine max Power	Miles per Gallon	% Battery Depletion
1	Conventional	160 kW	28.72	0
2	Series Hybrid	60kW	33.01	-0.41
3	Series Hybrid	30kW	31.2	1.02
4	Series Hybrid	20kW	34.5	23.72

Note: In order to make valid comparisons of powertrain efficiency, regenerative braking was effectively disabled on all vehicles.

Comparing these simulation results demonstrates how the fuel economy of a series hybrid powertrain increases as the power of the engine at its peak efficiency becomes closer to the average power requirement for the specified drive cycle. Sim 2 had a better fuel economy than Sim 3 while at the same time charging the battery by an extra 0.41% while Sim 3 used up 1.02% of its battery capacity. Furthermore, Sim 4 did not have adequate engine power alone to match the power demand of the drive cycle; therefore required supplemental battery energy which produced a final state of charge of 23.72% below the original value. This supplementary energy input contributes to the better fuel economy of Sim 4. As mentioned above, Appendix A presents the full set of results, graphs and a detailed discussion.

These results are not directly applicable to the snowmobile prototype but can be used in a qualitative way to show that for the same vehicle and drive cycle, the fuel economy can be increased by implementing a series hybrid powertrain with the engine closely matched to the continuous power demand of the vehicle.

Emissions – Improvements in emissions per distance traveled in general follow improvements made to fuel economy (10). For 2008 the team has implemented a diesel oxidation catalyst after treatment system with 25 grams of platinum loading in addition to the emission reductions from estimated increase in fuel economy.

Noise – Comparison of the results from the CSC 2007 sound event shows that the diesel series setup has the potential to record relatively low sound levels in the J-192 sound test, see table 3; note that team #8 SUNY-Buffalo ran a 3 cylinder diesel engine (11) and team #18 McGill ran a series setup with the generator un-loaded in this sound test. However, the continuous roar of the generator can be irritating to bystanders therefore the outcome of the subjective noise event is difficult to predict.

Table 3: CSC 2007 Objective Noise results (12)

TEAM	**J192 Level**
#1University of Wisconsin-Madison	73
#2University of Minnesota-Duluth	74
#3Kettering Univ	73
#5University of Maine	67
#6Michigan Tech Univ	DNF
#7University of Wisconsin-Platteville	DNF
#8SUNY-Buffalo	**61**
#10University of Idaho	73
#11Minnesota State University - Mankato	78
#18McGill Univ (Exhibition only)	**64**

PRACTICAL DEISGN CONSIDERATIONS - This section addresses the selection criteria and selection process for the major components which make up the Hybrid snowmobile.

System Design – The decision to implement a series setup as opposed to a parallel setup for the second iteration of the hybrid snowmobile prototype was based on operating efficiency, capability of all electric range, reliability and simplicity. In terms of efficiency, the I.C.E. in a series powertrain is further isolated from the vehicle’s power demand than in a parallel setup. For this reason, the idea illustrated by figure 2 can in general be taken further for a series setup than for a parallel setup. Second, since a series powertrain propels the vehicle solely with the electric motor it is possible to operate the vehicle without the I.C.E. Although the CSC noise events do not take this major advantage into account, the ability to run without the I.C.E. in sound sensitive areas reduces the negative social and environmental impact of recreational snowmobiling. Finally, parallel setups typically require highly active control of the engine throttle (6) where in a series setup the engine can be controlled by a mechanical governor similar to that of a typical lawn mower.

The ability of hybrids to perform regenerative braking is considered a major advantage over conventional powertrains in the automotive industry (4). However, due to the greater powertrain drag to mass ratio of snowmobiles (i.e. the track and skis) compared to road vehicles, preliminary estimates show that the marginal gains from regenerative braking on a snowmobile do not outweigh the costs or complications. Note: CSC 2008 rule number 4.4.3, “In stopping snowmobiles, usually the brakes lock up and the snowmobile slides on the snow….”, this re-enforces the point above.

Electric Drive - The electric drive for the 2008 hybrid snowmobile consists of 2 components:

- Advanced Motors & Drives, DC Series Wound Motor, 203-06-4001A
- Navitas TSE600-96 Series Motor Controller

The Advanced DC motor selected for the 2007 was selected based on estimates for the continuous power requirement using experience from the electric snowmobile and a weighted decision matrix, see appendix B, for various motor types. The Advanced-DC motor was chosen for its availability and popularity on the market. The motor is rated at 14kW continuous at a nominal voltage of 96V. The data gathered from the 2007 prototype along with CSC acceleration event results indicate that this motor can indeed provide the necessary power to pass CSC base performance requirements. The acceleration runs for the 2007 prototype were 10.86 and 11.17 seconds.

The Navitas controller was chosen to power the Advanced-DC motor based on the necessity of a 96 volt controller to ensure full use of the motor's capabilities. Other controllers available capable of the same performance are Curtis Controllers' PMC-1221C-7401 and Cafe Electric's Zilla line of controllers. The Navitas was chosen for its cost benefits and availability.

In this paper the motor and controller will be referred to as one working unit called the electric drive.

<u>Engine</u> - The I.C.E. chosen for the 2008 hybrid snowmobile is a Yanmar 2V750. It is a vertical output shaft V-twin, 750 cubic centimetre diesel engine originally intended for a lawn tractor. The B10 versus E85 decision was based on criteria for the both the CSC 2008 and CSC 2009, meaning that the engine chosen for 2008 would be used again in 2009 as a flex fuel engine. The team consulted professors and the McGill SAE Formula on the complications involved bio-fuel and flex fuel conversions. A decision matrix was constructed, see table 4.

From the matrix, the conclusion was that it would involve fewer complications to start with a diesel engine converted to bio-diesel and then convert that to flex fuel for 2009.

The team conducted a thorough search of diesel engines within the power, size and weight ranges which were required for the design and also conformed to CSC 2008 and 2009 rules. Very few engines fit within all of these constraints, and from these the Yanmar 2V750 was the only one which was available on the market within the time constraints of the 2008 CSC.

Table 4: Engine Decision Matrix

Modifications		**Approx. Relative Difficulty**	
Description	**Weight**	**Gas-E85**	**Diesel-B10**
Convert to Bio-Fuel			
Change Fuel Hoses	10	yes	yes
Modify Air - Fuel Ratio	7	yes	no
Modify Compression Ratio	7	yes	no
Change Timing	5	no	no
Convert to Flex Fuel			
Electronic Fuel Injection	10	yes	no

The 2V750 has a maximum output of 13.3 kW at 3200 RPM producing 40 Nm of torque. The 2007 prototype had a Robin-Subaru EX21 as primary power supply. For comparison, the engine was measured to be capable of approximately 5.5 kW at 5000 RPM.

For emissions testing of the diesel engine at the CSC, the team proposes the values in table 6.

Table 5: Speed and torque value for modes 1 - 4

Mode	Speed RPM	Torque N-m
1	3200	40
2	2720	20.9
3	2400	14
4	2080	8.7

Generator - There are two options to be explored when selecting an electrical generator for a hybrid system: AC and DC. Since the hybrid snowmobile generator is connected directly to the DC power bus between the battery and the electric drive, the choices are narrowed down to a DC generator or an AC generator with a rectifier. For this project the AC option is eliminated because of the complications, cost and power loss associated with the rectifier.

Within the continuous power range required, there are 3 permanent magnet DC motors available:

- Etek, 48 volt, 110 amp
- Perm PMG 132, 72 volt, 110 amp
- Lemco, LEM, 60 volt, 200 amp

These motors can be used alone or coupled with one another in series or parallel configurations to meet the voltage range and continuous power requirements of a given design. Since the DC bus on the 2008 Hybrid Snowmobile is 96V nominal, one can find 2 or 3 configurations which could suffice. However, it is not recommended to couple two unlike motors together in a system because of the uncertainty of their compatibility at all required operating points. With this in mind, the team chose to couple 2 Eteks, mechanically in parallel, and electrically in series, see appendix C for a detailed flow diagram. The 2007 hybrid snowmobile used a Perm PMG as a generator; again, this shows how the strategy for 2008 prototype is more heavily reliant on the I.C.E.

From here on, the term Genset will be used to describe the 2V750 and the Eteks as one working unit.

Battery Pack – A 93.6 V nominal pack is used as the secondary energy storage on the hybrid snowmobile. This pack is made up of 26 3.6 V nominal 45 amp-hour lithium-ion cells is series. These cells are made by Lithium Technologies Corporation (LTC). The safety of the pack is managed by LTC's own battery management system (BMS). This system monitors individual cell voltage and state of charge (SOC), pack current, and cell wall temperature in strategic areas. Using this information, the system can balance the cells by "bleeding" current through the systems intended resistors, and can open a relay connecting the pack to the snowmobile power bus if the system concludes that the pack has reached an unsafe condition (13).

Lithium-ion was chosen over other battery chemistries because of the advantages of power and energy density with respect to both space and weight. They are rated at 90 amp continuous discharge and 23 amps continuous charge with maximum charge voltage of 4.2 volts. At the maximum charge voltage the BMS will isolate the pack. Because of this reason, the Genset is designed to never produce a voltage higher than 4.2 volts per cell which makes a total of 109.2 volts. The pack is configured to fit in the engine bay of the chassis as shown in figure 3.

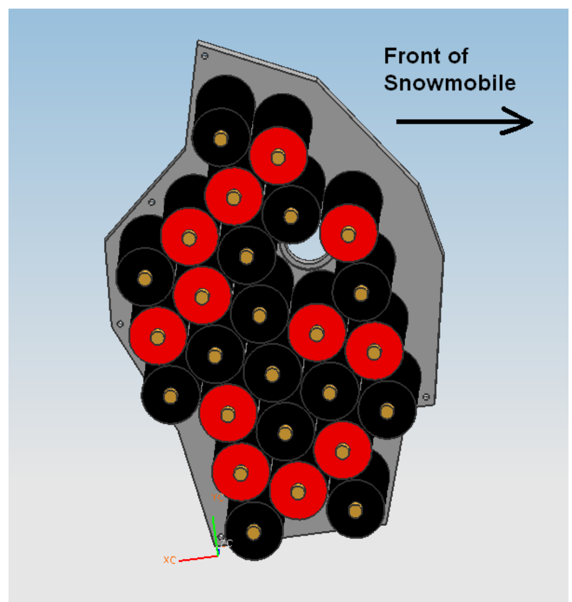

Figure 3: Battery pack for 2008 Hybrid Snowmobile

All together including BMS the pack weighs 44 kilograms and the amount of energy stored at full charge is equivalent to approximately 0.416 litres of gasoline or 4kW-h (13) compared with the 2007 hybrid pack which weighed 100 kg containing 0.96 equivalent litres of gasoline or 9kW-h (13). This demonstrates the difference in strategy between 2007 and 2008, with more powerful generator and smaller battery, the design has been made closer to a charge sustaining hybrid for the purpose of the CSC endurance event.

Capacitors were not chosen for this application for the following two reasons. First, energy stored in capacitors is proportional to the square of the voltage across the terminals. This means that to make use of the full range of energy storage of a capacitor, its terminal voltage must change by a large amount compared to its nominal voltage (14). To incorporate this large swing in terminal voltage, complex and costly power electronics must be included between the capacitor bank and any load or source of power. Second, capacitors do have relatively good energy storage per unit weight, but not per unit of volume, this makes them ineffective for charge depleting hybrids because of the space requirement for adequate energy storage (14).

Transmission – The transmission and secondary reduction used to couple the electric drive with the track shaft is comprised of a permanently engaged continuously variable transmission (CVT) and a synchronous cog belt (sometimes referred to as a timing belt). Similar to the Advanced DC drive motor these components have not changed since 2007. This setup was kept for the 2008 prototype because it proved to be robust and capable of transferring the power necessary to meet CSC baseline performance requirements.

Chassis – The Ski-Doo MXZ chassis used in 2007 and 2008 is light and while at the same time has adequate space available to house the extra component required for a hybrid powertrain.

The team uses anti-ratchet track wheels on the track shaft which permit reduced track tension, thus decreasing the drag of the chassis.

COLD START - 2007 McGill electric and hybrid prototypes displayed robust behaviour with respect to this event. The McGill electric snowmobile which is equipped with the same basic electrical powertrain has proven this robustness on the Greenland glacier where temperatures are equal to or lower than those in a typical CSC cold start event.

WEIGHT, HANDLING & MSRP – As a proof of concept second iteration prototype, the 2008 hybrid snowmobile is hoped to bring another level of interest to the CSC I.C. category. Being inherently different from other competitors, it is difficult to compare it on all levels. Noting that the CSC is more than anything else a competition for marketable and environmentally friendly touring/sport snowmobiles; McGill has chosen to investigate the capabilities of alternative technologies which are just now appearing in the automotive world. Since the implementation of these technologies to snowmobiles has not yet been done on an industrial scale, certain expectations of performance and cost which can attained by student team modifying a stock snowmobile become more difficult to fulfill. Still today in the automotive industry, increases in fuel economy from the implementation of a hybrid powertrain typically come with an increase of vehicle cost and complexity. With this in mind the McGill hybrid snowmobile should be viewed as an example of a possible stepping stone on the path towards more sustainable snowmobile propulsion.

Conclusion

The McGill University hybrid snowmobile is one of very few of its kind in existence. This proof of concept prototype is based on a mix of theory, simulation and data from previous years. As a second iteration, performance goals for the hybrid snowmobile have been established in a conservative manner. The McGill team hopes that with the completion of all CSC events in 2008, the experience gained by the team and the CSC organizational staff benefits the development of alternative snowmobile powertrains and helps clearly define their inclusion in the CSC.

References

1. **SAE.** students.sae.org/competitions/snowmobile/cdshistory.htm. [Online]

2. **EPA.** *Emissions Standars for New Nonroad Engines.* 2002.

3. **Maine, Government of.** www.maine.gov/ifw/laws rules/snowlaws.htm. [Online]

4. *A Critical Examination of Hybrid Vehicle Benefits and Possibly Better Alternatives.* **Talbert, Joshua (Mechanical Engineering Department, Union College), Wicks, Frank and Wilk, Richard.** s.l. : Proceedings of the Intersociety Energy Conversion Engineering Conference, 2001.

5. *Hybrid vehicle engine size optimization.* **Triger, L., Paterson, J. and Drozdz, P.** s.l. : SAE Special Publications, 1993.

6. *Design methodology of drive train for a series-parallel hybrid electric vehicle (SP-HEV) and its power flow control strategy.* **Halvai Niasar, A., Moghbelli, H. and Vahedi, A.** s.l. : IEEE, 2005.

7. **SAE.** *CSC rules 2008.* 2008.

8. **Mathews, Albert.** *Hybrid Snwomobile Project.* 2006.

9. *2V750-CV Engine performance curve.* **Yanmar.**

10. *DOE HYBRID TEST VEHICLE - RESULTS OF FUEL ECONOMY EMISSIONS AND ENGINEERING CHARACTERIZATION TESTING.* **Trummel, Marc C., et al.** s.l. : SAE Technical Paper Series, 1984.

11. **Chris Battaglia, Steve Battaglia, Jake Ennis, Kevin Gastle.** *The UB Approach to a Diesel Powered Snowmobile.* s.l. : SAE International, 2007.

12. **University, Keweenaw Research Center / Michigan Technological.** http://www.mtukrc.org/snowmobile.htm. [Online] 2008.

13. **Lithium Technologies Corporation.** *http://www.lithiumtech.com/.* [Online]

Appendix A

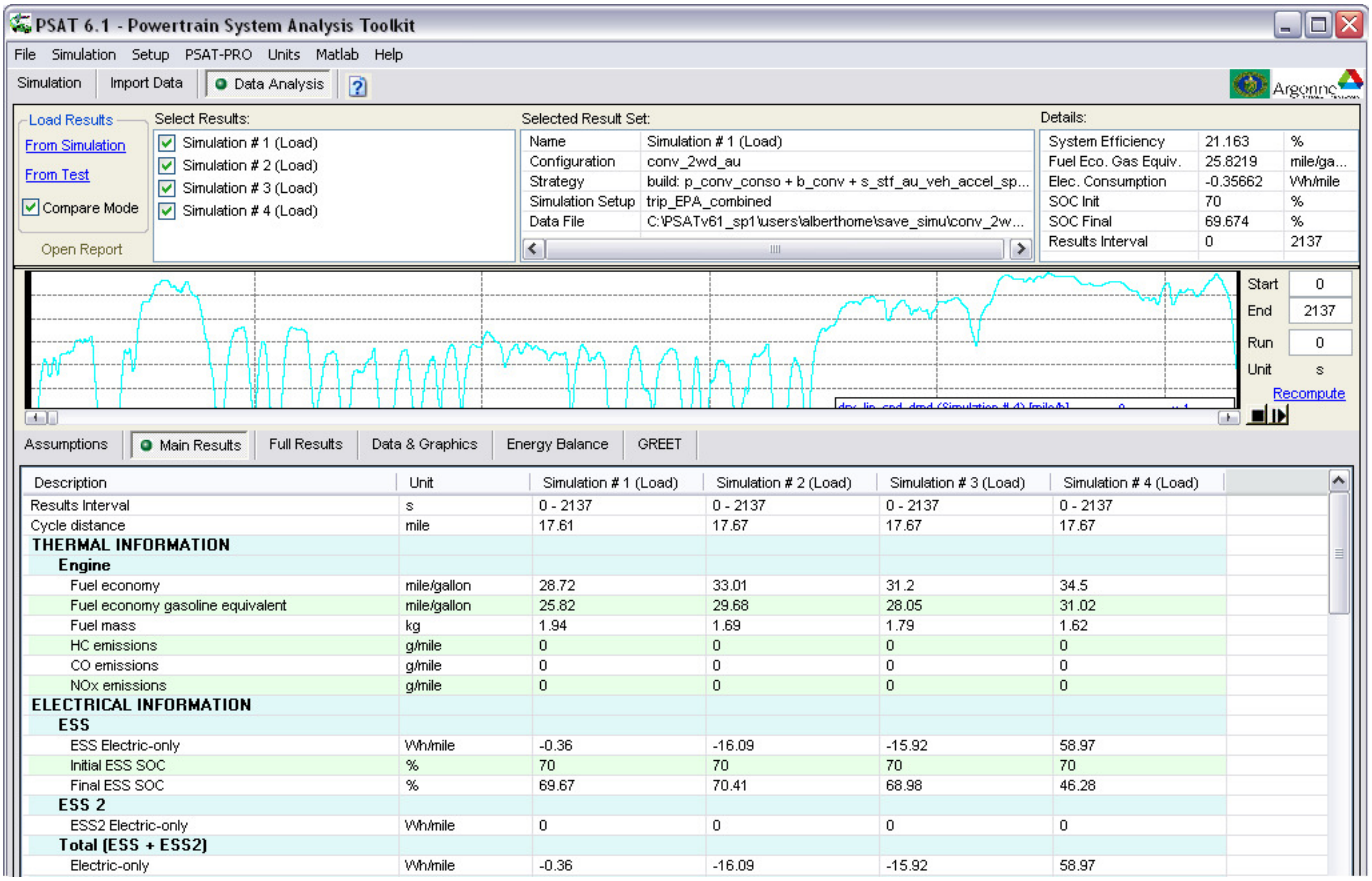

Figure 4: PSAT results showing drive cycle and fuel economy.

The graph in figure 4 is the speed profile of the drive cycle used for the simulations. Numerical results are tabulated at the bottom and continue in figure 5. PSAT does yet have the information required to produce emissions results for these simulations. Here we see that the charge sustaining hybrids, Sim 2 and Sim 3, have respectively a 14.9% and 8.6% increase in fuel economy with respect to Sim 1. Detailed discussion of results is continued following figure 5.

Description	Unit	Simulation # 1 (Load)	Simulation # 2 (Run)	Simulation # 3 (Run)	Simulation # 4 (Run)
ENERGY SUMMARY					
Energy loss accmech	Wh	293.88			
Energy loss cpl	Wh	514.52			
Energy loss gb	Wh	282.25			
Energy loss fd	Wh	155.1			
Energy loss wh	Wh	2661.38			
Energy loss veh	Wh	1912.36			
Energy loss ess	Wh	8.98			
Energy loss gc	Wh	-20.17			
Energy loss tc_gc	Wh	4.03			
Energy loss accelec	Wh	148.4			
Energy loss eng	Wh	16931.1	12550.28	13590.4	12831.92
Energy loss accmech	Wh		186.93	207.53	232.47
Energy loss tc_gc	Wh		219.12	223.3	186.99
Energy loss gc	Wh		598.06	516.58	406.75
Energy loss ess	Wh		288.56	368.2	380.85
Energy loss mc	Wh		811.08	811	811.06
Energy loss tc_mc	Wh		183.38	183.36	183.37
Energy loss fd	Wh		414.97	414.92	414.95
Energy loss wh	Wh		3552.3	3552.3	3552.3
Energy loss veh	Wh		1917.86	1917.86	1917.86
Energy loss pc_accelec	Wh		0	0	0
Energy loss accelec	Wh		415.53	415.53	415.53
Energy loss aero	Wh	1912.36	1917.86	1917.86	1917.86
Energy loss drag	Wh	1785.25	2186.96	2186.96	2186.96
Energy loss grade	Wh	0	0	0	0
Total Energy loss	Wh	26589.45	25242.91	26305.81	25438.85
Total Energy used @ vehicle	Wh	1907.86	2334.81	2334.42	2334.5
Engine Fuel Energy Use	Wh	22897.37	20006.35	21148.37	19127.04
Fuel Cell Fuel Energy Use	Wh		0	0	0
Total Fuel Energy Use	Wh		20006.35	21148.37	19127.04
ESS Net Energy Use (propel + regen)	Wh	2.7	4.2	86.81	1423.09
ESS2 Net Energy Use (propel + regen)	Wh		0	0	0
Total Net Energy Use (propel + regen)	Wh		4.2	86.81	1423.09
Combined Power Source Energy Use	Wh	22900.07	20010.55	21235.18	20550.13
Powertrain Energy Use In @ wheel (w/regen)	Wh	22939.43	21275.03	22808.76	21652
Powertrain Energy Use Out @ wheel (w/regen)	Wh	4854.63	7035.56	7423.68	6964.9
Percentage Braking Energy Recuperated at Battery	%	0	0.69	0.69	0.69
Percentage Braking Energy Recuperated at Wheel	%	0	1.1	1.1	1.1
COMPONENT AVERAGE EFFICIENCIES					
Engine efficiency	%	26.34	37.3	35.8	33.03
Motor efficiency	%		88.28	88.28	88.28
Motor efficiency during acceleration	%		88.3	88.3	88.3
Motor efficiency during deceleration	%		87.26	87.26	87.26
Generator Efficiency	%	115	92.14	93.2	93.54
Transmission efficiency	%	94.77			
OTHER INFORMATION					
Engine					
Weight Specific Fuel Consumption Gas Eq. (WSF...	gallon/100mile/ton	1.88	1.34	1.42	1.29
Mass of fuel needed to travel 320 miles	kg	35.22	30.64	32.42	29.32
STATISTICS					
Absolute average difference on vehicle speeds	mile/h	0.17	0.07	0.07	0.07
Percentage of the time the trace is missed by 2mph	%	0.12	0	0	0
Total time the trace is missed by 2mph	s	2.5	0	0	0
Greatest percentage deviation from the trace in mph	%	11.35	15.63	15.63	15.63
At time	s	453.3	163.7	163.7	163.7
Absolute deviation from the trace	mile/h	2.36	0.77	0.77	0.77
At time	s	453.3	196	196	196

Figure 5: PSAT results showing energy summary, component efficiencies and drive cycle speed match statistics.

Note: the row titled “Percentage Braking Energy Recuperated at Battery” marked with blue marker shows that only 0.7% of braking energy was recuperated to the battery for re-use with for all hybrid vehicles simulated.

At the bottom of figure 5 under the “Statistics” heading, we can see that each vehicle adequately attained the speeds and accelerations required by the drive cycle; therefore any difference in fuel economy or component efficiency can be attributed to powertrain architecture and/or proper component sizing. If we look at the rows titled “Energy loss eng”, “Engine Fuel Energy Use” and “Engine efficiency” marked with red markers, we can see clearly that Sim 2 with its 60kW diesel engine had an overall better performance on the specified drive cycle than the other three simulations.

The effect of added weight for the hybrid set up can seen by comparing the rows marked by green markers. Aerodynamic losses for all 4 vehicles were identical as expected while losses attributed to the final drive (fd), the wheels (wh) and rolling resistance (drag) are larger for the heavier hybrids compared to the conventional vehicle.

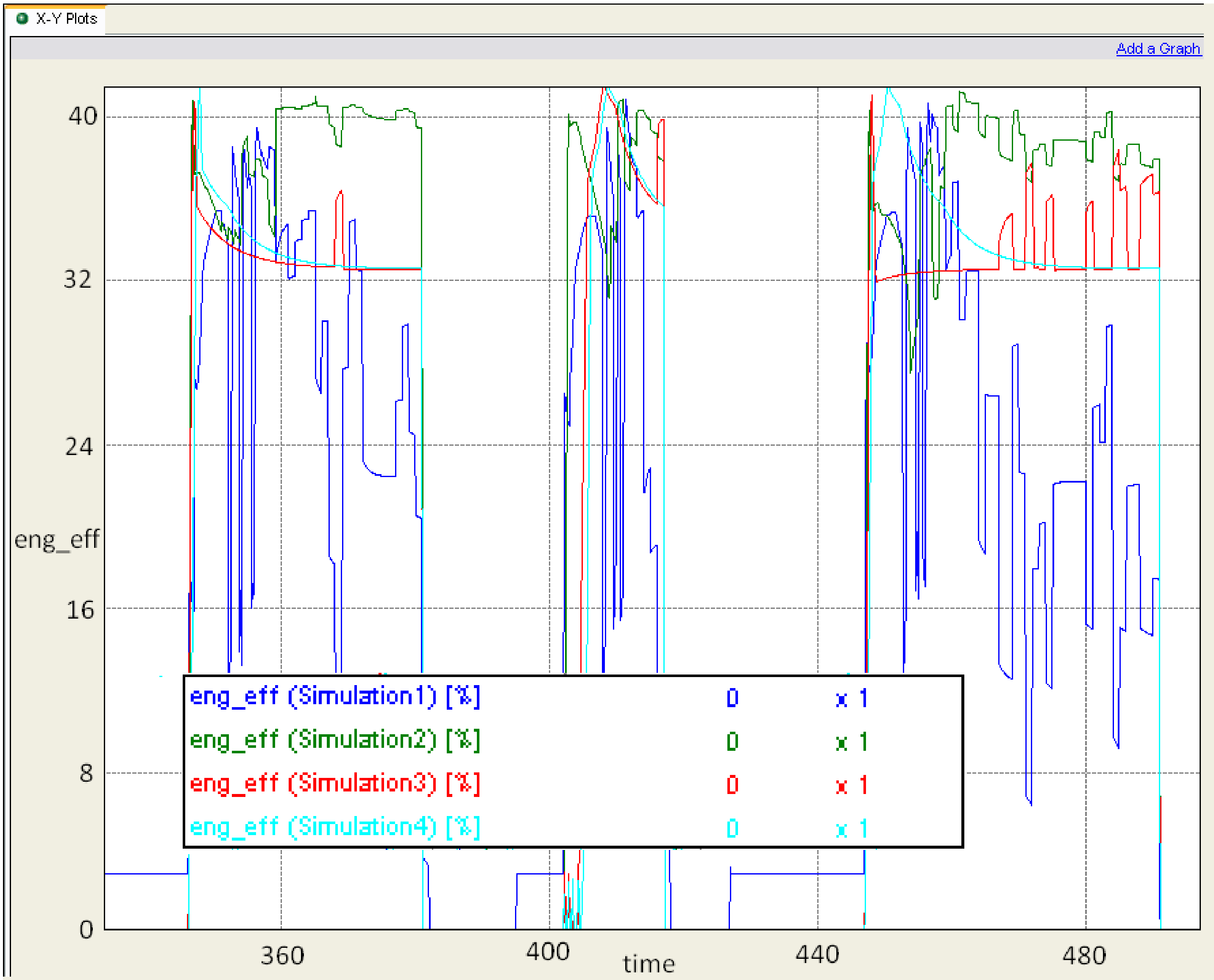

Figure 6: Graph of simulated engine efficiency over selected time interval.

Figure 6 is a graph of simulated engine efficiency versus time for a selected descriptive section of the drive cycle. For this section we can see that engine efficiency for Sim 2 is generally greater than the others as expected. What is interesting to note is the levelling out of characteristic of Sim 4 and to some extent Sim 3. This occurs because once a power demand is given by the vehicle controller, the engine in Sim 4 attempts to run at its point of maximum efficiency; however, at this point, since the engine cannot provide adequate power to the system, the controller raises the power output of the engine to its maximum where its efficiency is approximately 32.5%.

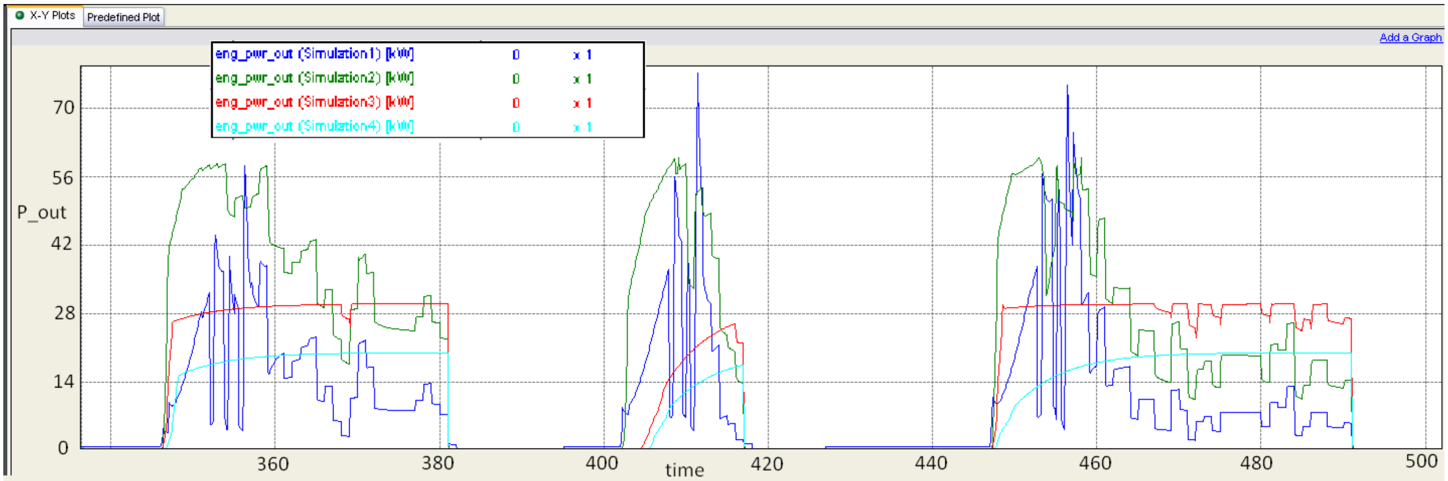

Figure 7: Graph of simulated engine power output over selected time interval.

If we compare the graphs in figures 6 and 7 we see that indeed the engines in Sims 3 & 4 are being operated so that required power dominates over the desire to operate them at their maximum efficiency.

Appendix B

Table 6: Weighted decision matrix for motor selection from 2007.

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

Appendix C

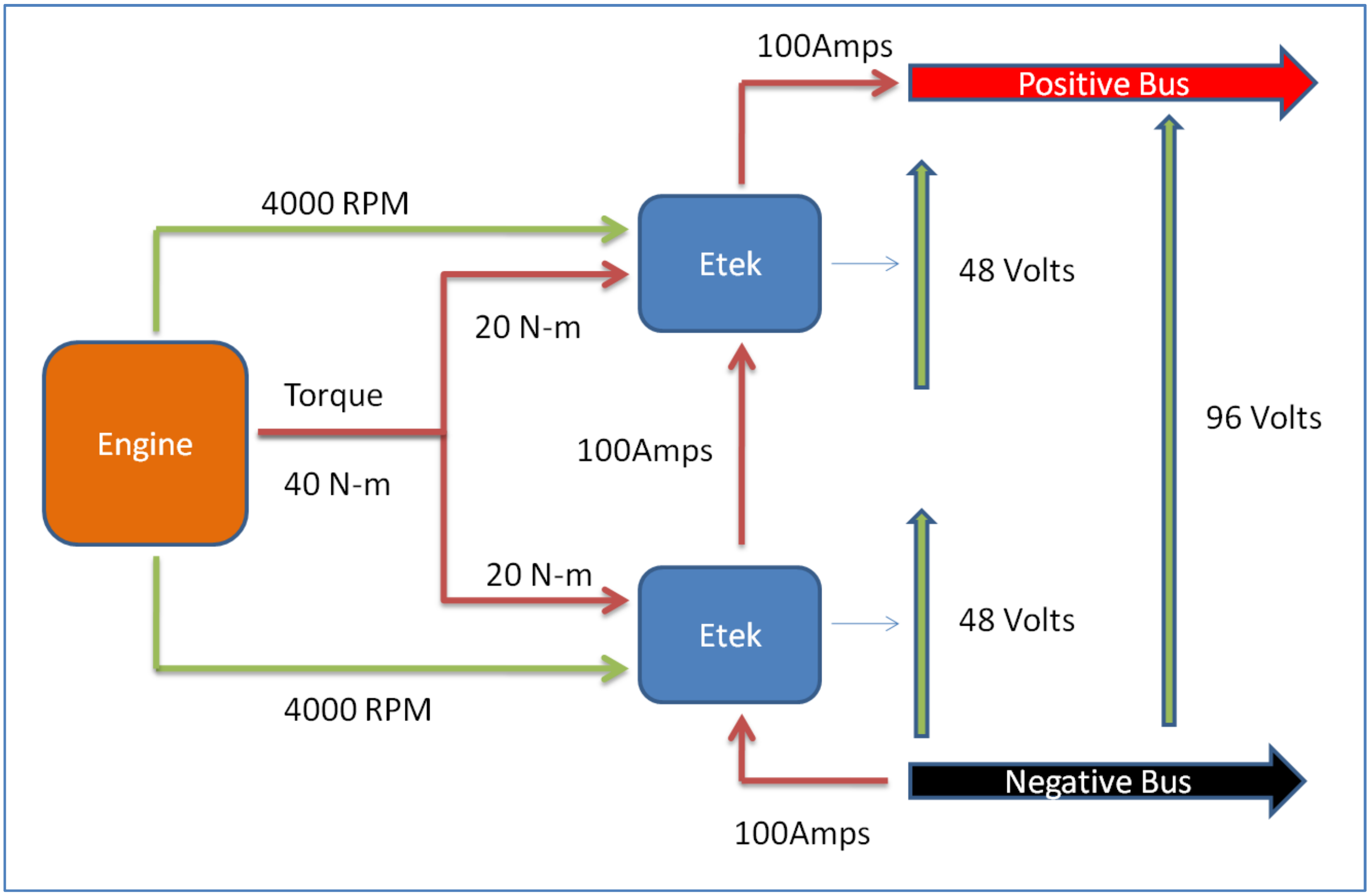

Figure 8: Flow diagram for general operating point of direct current generator.