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DESIGN, DEVELOPMENT AND TESTING OF HYBRID-ELECTRIC SNOWMOBILE FOR REDUCED NOISE APPLICATIONS

Simon Ouellette
CrossChasm Technologies
Waterloo, Ontario

Jared Giesbrecht
Defence R&D Canada - Suffield
Medecine Hat, Alberta

David Kuyek
Francis De Broux
Olivier Proulx
CrossChasm Technologies
Waterloo, Ontario

ABSTRACT

Defence R&D Canada – Suffield has undertaken a research project to investigate the practicality of an operationally quiet hybrid-electric snowmobile.

This paper reports on the design of, and the testing conducted with, a prototype noise-reduced hybrid-electric snowmobile. The project goals were to ascertain the practicality of such a design and to determine the baseline achievable noise reduction prior to any optimization. The project has overcome most of the technological hurdles, producing a solid basis for future work. The vehicle performed well in military user testing.

INTRODUCTION

Given the geographic size of the Arctic, motorized transport for military operations is a necessity. Currently, the military of many northern countries rely on snowmobiles to patrol the Arctic and other snow covered regions during the winter months. Traditional snowmobile engines produce a significant amount of noise that can be reduced to some extent through the use of careful design. However, the noise level of an internal combustion engine cannot be reduced to an acceptable level for missions where covertness may be required, especially given the increased propagation of sound in cold, dry, Arctic air.

Electric snowmobiles are a potential solution to this problem, eliminating the internal combustion engine and using a much quieter electric motor to drive the track system. However, a purely electric snowmobile must carry all of its power in the form of batteries, which have a much lower energy density than fossil fuels, limiting electric snowmobile range to tens of kilometers, rather than the hundreds of kilometers required for Arctic operations.

Hybrid-electric snowmobiles offer a potential alternative to both pure electric and pure internal combustion systems.

In a “series” hybrid-electric vehicle, a fossil fuel engine functioning as an electric generator is used to provide energy to an electric motor which powers the vehicle drivetrain. Extra electricity generated by the engine is stored in battery packs on the vehicle. Using this design, a hybrid electric vehicle, can have a “silent” mode where the internal combustion engine is turned off and the system runs entirely on electric power for a period of time. Such a system can have the features of both types of vehicles: a noise reduced mode for short ranges as required, while still maintaining long range endurance. Furthermore, such a powertrain topology, when designed in a modular fashion, can power a remote base camp and share power loads between a healthy and an incapacitated vehicle to ensure all can return to base.

PROJECT GOALS

This project was undertaken in order to answer two key questions:

1- Is it feasible to design and build a hybrid snowmobile which could suit military operational requirements?
2- Does a snowmobile driven by an electric powertrain provide a substantial noise level advantage over an identical one powered by an internal combustion engine (ICE)?

This paper looks at how, in a 15 month time frame, CrossChasm Technologies demonstrated that:

1- YES, it is feasible to design and build a hybrid snowmobile which could suit military operational requirements.
2- YES, a snowmobile driven by an electric powertrain provides a substantial noise level advantage over an identical one powered by an ICE.

However before looking at the design and performance of the prototype developed for this project and some of the noise level results obtained, it is important to put into perspective some of the key challenges at hand in electric and/or hybrid vehicle design.

THE ENERGY DENSITY CHALLENGE

Electric vehicles (EVs) have a large disadvantage when compared to their ICE counterparts in terms of energy density of their energy storage system (ESS). Even the most energy dense battery technology commercially available today can only hold a small fraction of the energy that gasoline contains per unit mass.

Table 1 below illustrates the consequence of this by comparing equivalent energy storage system mass which would be required for an electric snowmobile to have the same amount of on-board energy as a stock ICE utility snowmobile.

Table 1: Energy Storage System Comparison

Energy Storage System (ESS)	Gasoline	Batteries (Lithium Ion @ 108 Wh/kg)
Vehicle	Ski-Doo Skandic WT	
Dry Weight	278kg (613 lbs)	
Energy On-Board	408 kWh	
ESS Volume	45 liters (12gallons)	1447 liters (382 gallons)
ESS Mass	33 kg (73 lbs)	3778 kg (8334 lbs)
Ratio ESS Mass / Vehicle Dry Mass	0.12 : 1	13.6 : 1

As can be seen in Table 1, the electric snowmobile would need 3778 kg (8334 lbs) of batteries in order to carry an equivalent amount of energy as what a standard ICE utility snowmobile can carry in its gasoline tank. Furthermore, the volume of batteries would take ~32 times the space currently available for fuel.

To put these numbers into perspective: the Saturn V rocket that put Neil Armstrong on the moon had a fuel mass to vehicle dry mass ratio of ~14.8 : 1 and the bed of a standard full size pick-up truck has a typical volume of ~2000 liters

Fortunately electric powertrains have at least one advantage powerwise over ICE powertrains. They generally have much higher efficiency. This higher efficiency translates in two advantages:

1- They have a lower heat signature at a given power output
2- They don’t require that as much energy be inputted into the system to give the same performance as an ICE powertrain

This second point, even though it is non-negligible, still doesn’t come close to offsetting the energy density gap between batteries and gasoline.

This is clearly illustrated in Table 2 below which shows that even if an electric powertrain was 100% efficient (***which it is not***), ICE powertrain would have to be only

0.88% efficient on average for the two technologies to be on par. Given this, it is obvious that the higher efficiency of electric powertrains does not come close to making up the difference in energy density.

Table 2: Hypothetical Efficiency of Different Powertrains for Equivlent Performance

Energy Storage System (ESS)	Gasoline	Batteries (Lithium Ion)
Vehicle	Ski-Doo Skandic WT	
Dry Weight	278kg (613 lbs)	
ESS Mass	33 kg (73 lbs)	
Energy On Board	408 kWh	3.6 kWh
Hypothetical Efficiency for Equivalent Performances	**0.88%**	**100%**

Therefore clearly, the design of a vehicle that includes a sizeable electric powertrain is a considerable challenge. The energy density issue makes it very challenging to design and build a small, nimble, light weight tracked vehicle that can provide meaningful range at usable speeds.

The design of a hybrid vehicle instead of an EV helps reduce the severity of the energy density issue by replacing some low energy density energy storage system (ESS) (aka. batteries) by a high energy density ESS (aka. gasoline). Unfortunately, this comes at a substantial cost. Two complete powertrains and their respective ESS now have to be carried by the vehicle.

CONCEPT

The chosen concept for this new and innovative vehicle is a modular series hybrid design.

One of the main challenges of building an electric and/or series hybrid snowmobile is the very limited amount of space available for all the components. More so in the hybrid case, since both batteries and a fossil fuel powered generator must be housed.

Given this, it was decided to modularize the design by placing the generator setup (genset) in a trailer sled. This makes the snowmobile fully capable of operating without the trailer sled in all-electric mode while having the option of adding the range extender when required.

The trailer sled is attached/detached without tools, making it easy for an operator to add the hybrid capability and range extension to the vehicle in any environment. Electronics seamlessly handle the control of the genset. The user can also turn off the generator enabling the vehicle to still be used in all-electric silent mode at any time without disconnecting the genset.

Below is a list of points which helped steer the design direction for the concept:

1. A trailer sled is already used in most of the most operations in the arctic for carrying equipment. It was estimated that a compact genset would increase the mass of a loaded trailer sled by approximately 10-12%. Impact on space would be of the same order but easily counteracted by increasing trailer sled volume.
2. The trailer sled can be used as a generator to power the mission's electrical equipment both during travel as well as at the campsite. It is estimated that a single one of these trailer genset units would be able to provide enough power to run most arctic camps.
3. In case of a genset issue on a multi-snowmobile mission, a team can easily reach their next destination by alternating the use of a single trailer sled genset from snowmobile to snowmobile.
4. In case of a genset issue near base camp, the vehicle can easily swap its trailer sled for a different one thus avoiding complete vehicle downtime.
5. The trailer sled genset is not specific to this vehicle. Thus they can be used with the current internal combustion engine snowmobile fleet and power electric equipment on the go or at camp site without the need for the electric snowmobile.
6. The ability to detach the vehicle's prime heat producer and leave it behind on final approach to target can be a substantial advantage to avoid detection.
7. Splitting the mass of the hybrid powertrain over a larger surface area has significant advantages on energy consumption and maneuverability.
8. This modular approach keeps the center of gravity of the entire vehicle-trailer system as low as possible thus improving stability.
9. Having the ability to shed the genset weight in silent/all electric mode gives the vehicle maximum handling and performance when used in "snowmobile only" configuration.
10. Having the electric powertrain physically separate from the genset unit makes it possible to take up a maximum amount of space inside the electric snowmobile for batteries. On top of freeing up the volume of the genset itself, even more space is gained due to the fact that heat issues and cooling of the engine can be dealt separately from heat management of the electrical powertrain.

11. In the future, the use of this modular system will allow the development of either new electric snowmobiles or new genset trailer sleds without having to completely re-package an entire hybrid vehicle thus saving substantial time and funds.

12. Since packaging constraints are much lower for the genset in the trailer sled than in a fully contained hybrid snowmobile, over time, different trailer sleds can easily be developed for specific needs. Ex: change of engine for higher power, change of engine for use of different fuel.

PROTOTYPE

A first lab-level proof of concept of the modular series hybrid vehicle was completed in March 2012. The vehicle was nicknamed "Loki" after the mythological Norse shape-shifting god.

Figure 1: Loki Prototype with optional modular genset / cargo trailer sled attached

Over the next ten months the prototype underwent extensive testing and improvement. This development culminated with multi day testing of the prototype with a group of military users.

Figure 2: Testing of Loki in silent mode during vehicle development

User testing was conducted to provide feedback which can orient future development of the technology. Most of the testing was conducted in an informal fashion in February 2013 alongside two other snowmobile models: some Ski-Doo Tundra 550F and a Yamaha RS Venture.

Figure 3: Military user testing with Loki + Yamaha RS Venture + Ski-Doo Tundra 550F

Acceleration and top speed

From the user feedback gathered it was apparent that Loki's acceleration was adequate. However, the users agreed that the top speed was not, although no particular number could be put to a top speed that would be adequate. It was felt that the Tundra vehicle was probably in the right category for speed and acceleration (having a 57 HP engine), while the RS Venture had more power than would generally be required (having a 120 HP engine).

It should be noted that the speed and acceleration produced by Loki was not detectably different between silent mode and hybrid mode, as the limitation is primarily the electrical current that can be consumed by the drivetrain motor to produce mechanical power.

Towing

The users were asked to bring a representative vehicle load to tow behind the snowmobile. Unfortunately, the load provided was not realistic as it contained some camping gear, but did not contain some large, heavy items such as fuel, drinking water, ammunition, etc., and was therefore too light and small to be realistic. As such, the Loki prototype had no problem towing this load.

In order to test the towing capacity further, one of the Tundra snowmobiles was put in neutral and towed behind Loki (Figure 4). Loki had no problem towing this load (over 300 kg of vehicle and operator weight). It could start and accelerate smoothly, and seemed to function as well or better than the other snowmobiles in this capacity.

Figure 4: Loki towing a Ski-Doo Tundra 550F

Hill Climbing

The limit of Loki's climbing ability was a hill of about 70% grade (approximately 35◦ slope).

Figure 5: Loki with genset/cargo trailer being tested for hill climbing capability

Range

The vehicle's silent range was tested at a speed of 24km/h on mixed types of surfaces and terrain including flat areas and hilly snow covered roads. In these conditions, Loki provided 8.1km of silent mode operation before needing to have its genset unit powered up.

Mobility

There are very few metrics available to test snowmobile mobility. However, with use on a variety of terrains, it was possible to compare Loki to the other snowmobiles.

Loki's electric drivetrain provides steady low-speed torque and is great for maneuvering slowly around obstacles. This is in stark contrast to the ICE snowmobiles that use a belt-driven continuously variable transmission (CVT), with which the user must rev the engine to engage the CVT. This makes it difficult to carefully maneuver an ICE snowmobile at slow speeds, and often causes them to dig themselves into the snow when starting from a stopped position. In this sense, Loki has much better mobility than a regular machine.

The Loki/Skandic platform was deemed easier to drive than the other snowmobiles. Having a wider chassis with a wider track than either the Tundra or the Venture made it more stable and more forgiving to handle on rough terrain. However, the extra size and weight also meant that it was somewhat more cumbersome to maneuver around obstacles. The extra weight is mostly a function of the base platform chosen for the prototype, and not an effect of the drivetrain itself.

One might think that the batteries on Loki would cause it to be heavier than a similar ICE snowmobile but the innovative modular design actually yields an electric snowmobile similar in mass to its ICE counterpart. Loki does have a gen-set and fuel in the towed trailer, but this is distributed weight which has much less effect on mobility and stability.

Usability and Robustness

Overall, the users deemed Loki to be well constructed, reliable and easy to use.

The genset started reliably and automatically with the switch from silent to hybrid mode.

Areas of Improvement

The areas of improvement identified during testing are:

1- Operators noted they would like an increase in Loki's climbing ability and top speed.
2- Although not explicitly tested, it was recognized by all that Loki's hybrid range should only be limited by the amount of fuel it carries. Loki's range extending capabilities need to always be charge sustaining in the future.
3- While it did not directly influence testing during the trials, it was understood by all that the adjustable mounting system for the generator inside the trailer sled was for prototyping purposes only and that future versions of the vehicle would have a rugged purpose built system.
4- Extensive arctic weather testing of the vehicle is required in order to increase confidence in the vehicle under harsh extreme conditions.

For each of these points a straight forward solution approach has been identified and will be implemented in future iterations of the vehicle.

NOISE TESTING RESULTS

Thorough noise testing of the hybrid snowmobile prototype was conducted. For the purpose of this paper, noise results will focus on the comparative results obtained by testing two identical snowmobile chassis. One with the stock BRP Ski-Doo OEM Rotax ICE powertrain and one equipped with CrossChasm's electric powertrain.

More detailed noise results conducted with this prototype in various conditions will be presented at Noise Con 2013.

Background

Analysis on snowmobile noise sources from Dilworth and Blough [1-2] identified some of the main noise sources as the transmission, chaincase, exhaust, engine, air intake, as well as the vibrations the various components can transmit through the body and chassis. Many of the major noise sources can be diminished or completely eliminated by replacing the ICE powertrain by an electric powetrain.

Snowmobile noise reduction has been a focus of many universities participating in the Society of Automotive Engineers (SAE) Clean Snowmobile Challenge. For the past decade, students participating in this engineering design competition have used various means of reducing ICE snowmobile noise. Exhaust and intake silencing plus various forms of noise absorption have been extensively used by the participating students. As a result of this some teams have been able to lower the sound produced by ICE snowmobiles down to 72dBA when tested using SAE J192 procedure. [3,4,5,6]

In recent years the competition has added an electric snowmobile category. Students participating in this category are converting a stock ICE snowmobile by replacing its original powertrain with an electric powertrain. Noise levels as low as 57dBA have been recorded on snowmobiles competing in this category. [7-8] It must be noted however that the electric and ICE categories noise results cannot be directly compared to one another since the electric category uses the SAE J1161 noise standard while the ICE category uses the SAE J192 standard.

Studies performed with other types of vehicles have demonstrated that electric powertrains can have a lower noise signature than their ICE counterparts. Automobile data on this subject has been published by the US Department of Transportation. One result on this study is that hybrid electric vehicles (HEVs) can be 2 to 8 dBA quieter than equivalent ICE vehicles at low speeds. [9-10]

Snowmobile sound detection is another aspect of interest which has previously been investigated. On this front, the U.S. National Park Service has found that the ease of detection of ICE snowmobiles is enhanced when these vehicles has prominent peaks in their noise spectra that rise over the background noise. One of the conclusions of this study is that low frequency broad band noise levels are more important in terms of detection than higher frequencies because higher frequency noise sees more attenuation as it interacts with the snow cover and the atmosphere. [11-12]

Methodology

Data for this paper was gathered according to two standardized tests for snowmobile noise: SAE J1161 and J192 [13-14]. Both tests specify driving the snowmobile down a straight 45 meter runway (Figure 2(a)), with a sound level meter placed 15 meters away, perpendicular to the center of the runway. The J1161 "Operational Sound Level" test specifies that the snowmobile approaches at 24 km/h and maintains its speed from one end of the runway to the other. The J192 "Maximum Exterior Sound Level" test also specifies that the snowmobile approaches at 24 km/h, but in this case accelerates at full throttle from the start of the track to the end of the runway. As expected, the J192 test results in much higher SPL levels than the J1161 test. All results are A-weighted, slow sampling measurements of broadband sound pressure level. The values presented in this paper are the average of three representative passes containing at least one pass from each side of the vehicle, all within +/- 2 dB of each other.

The main test area was a 200-300 meter path along a large open field (Figure 2(b)) located just south of Highway 40 in Ste.-Anne-de-Bellevue, QC, on McGill University's MacDonald campus. The proximity to the highway was responsible for some background noise interference (which varied depending on the date and time of day). However background noise levels remained within the limits stipulated by the SAE standards. The surrounding area was void of any large objects that may have interfered with the propagation of sound.

One of the key difficulties with respect to these tests is the influence of snow cover on repeatability. Dilworth and Blough tested a number of snowmobiles and a speaker system using the J192 standard over two winter and one summer season, and found that there is significant variation in the results obtained between different test days [15]. However, the test can still provide a valid relative comparison of two snowmobiles if they are tested at the same time, as is the case in this paper.

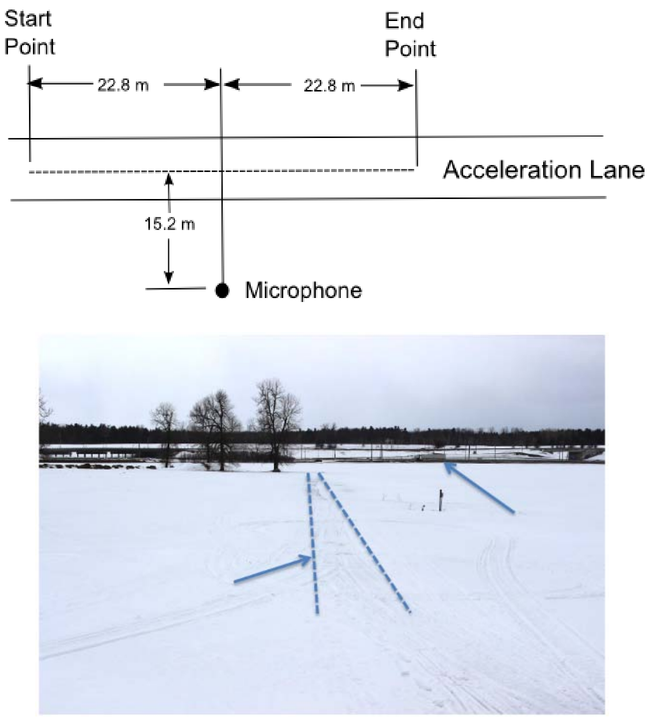

Figure 6: Configuration for the J192 and J1161 tests.

The tests in this paper were conducted using a Bruel and Kjaer 2270 Hand-Held Analyzer, which can gather not only sound pressure levels, but also weighted full octave, 1/3 octave, and FFT analysis of the sounds collected. The ICE snowmobile used for comparison in this report is a 2011 BRP Skandic (the same chassis that the hybrid prototype was based on). It has a 2-stroke E-Tec 594cc engine and a 20" x 154" track. Its engine is rated at 120 horsepower.

A number of different tests have been performed on different surfaces to compare the noise signature of Loki and its ICE counterpart.

SAE J192

J192 testing was performed on January 21st. On that day the snow had a hard "crunchy" top with a softer layer of snow underneath. Beneath the layer of snow was hard packed ice. These conditions were not ideal. However, the results still serve to illustrate the differences between the snowmobiles at full throttle.

Table 3: SAE J192 Comparative Results

Vehicle	LASmax (dBA)	Snow Condition
Loki (Jan. 21, 2013)	67.69	Soft snow with a hard/icy layer over top
Skandic (Jan. 21, 2013)	80.77	Soft snow with a hard/icy layer over top

The SAE J192 standard has the test snowmobile accelerate from the beginning of the runway to the end. Noise making components that rotate and reciprocate, accelerate as the snowmobile moves along the runway. As such, the overall shape of the spectrum changes from one end of the runway to the other. The entire acceleration takes up only just over a second. Therefore it is difficult to observe this phenomenon in the results as the SLM records the spectrum over one second periods. Nevertheless, the spectra corresponding to the LASmax have been included in Figure 7 below. They do not necessarily represent the noise produced by these snowmobiles at full throttle, this noise changes with time.

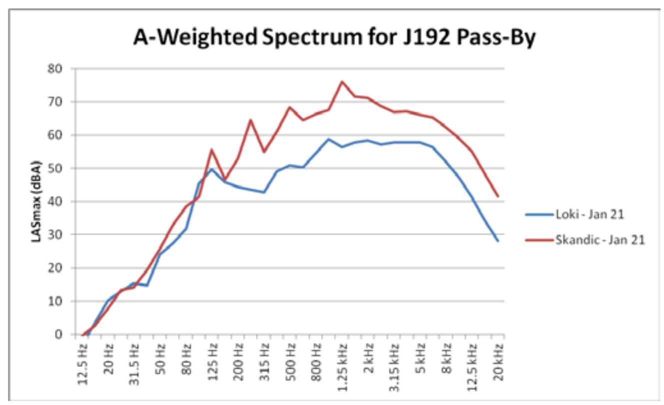

Figure 7: SAE J192 Sound Spectrum Comparison

SAE J1161

SAE J1161 testing results obtained on the same day in identical conditions for both vehicles are presented in Table 4 below. Their respective A-weighted and Z-weighted spectrum during this test are presented in Figures 8 & 9.

Table 4: SAE J1161 Comparative Results

Vehicle	LASmax (dBA)	Snow Condition
Loki (Dec. 19, 2012)	60.37	Wet
Skandic (Dec. 19, 2012)	67.00	Wet

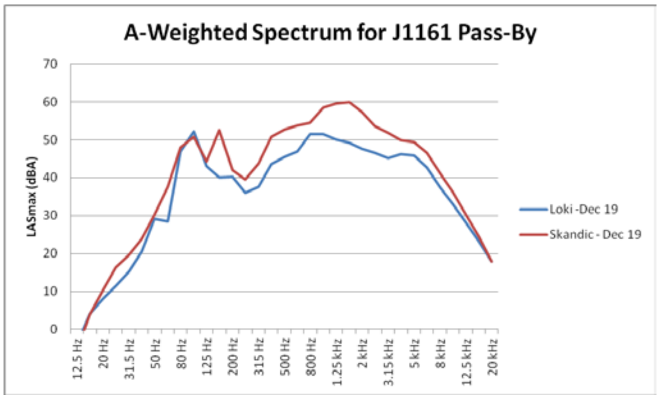

Figure 8: SAE J1161 dBA Sound Spectrum Comparison

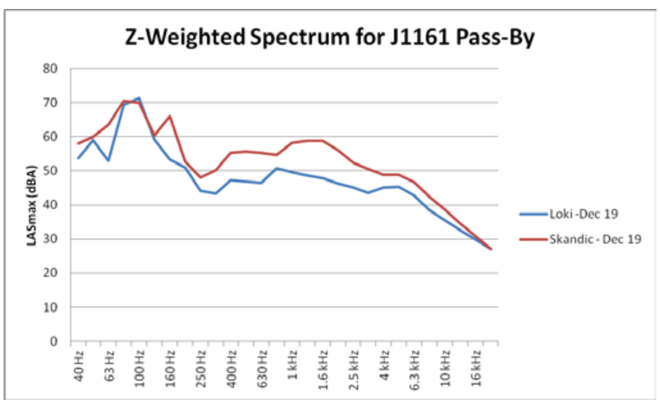

Figure 9: SAE J1161 dBZ Sound Spectrum Comparison

Other Objective Noise Testing

A demonstration video of the prototype was shot during the summer of 2012. During the filming the "surveillance & egress" noise generation of the vehicles was tested from close range (1m). The results of the side by side testing can be seen in Table 5 below.

Ambient/background noise during testing was 48.6 dBA.

Table 5: "Surveillance & Egress" Noise Test Results

Loki	Status	ICE Skandic
48.6 dBA	Start	80.3 dBA
48.6 dBA	Idling	74.2 dBA
84.4 dBA	Acceleration from standstill (mild)	98.7 dBA

Subjective Noise Testing (Detection Test)

A simple test was performed to determine the relative detectability of Loki versus the Skandic. A member of the CrossChasm team stood in a field across from a test snowmobile. The participant faced away from the snowmobiles, with no idea of the order that the snowmobiles would be tested in. The snowmobile was driven at 24km/h towards the listener. The listener was told to turn when the snowmobile became audible and signal the driver. The snowmobile driver would stop immediately and the distance from the snowmobile to the listener would then be measured.

As a comparison the results were impressive: Loki was able to reach 30-50% further than the Skandic without being heard.

Table 6: Comparative Detection Results

Test	Skandic	Loki
Subject 1 (Snow – Jan 21, 2013)	157m	123m
Subject 2 (Snow – Jan 21, 2013)	238m	147m
Subject 3 (Grass – July 5, 2012)	160m	80m

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CONCLUSION

With this first prototype, two important questions have been answered:

1- Q: Is it feasible to design and build a hybrid snowmobile which could suit the operational needs of military users given today's technology?

A: YES

2- Q: Does a snowmobile driven by an electric powertrain provide a substantial noise level advantage over an identical one powered by an internal combustion engine (ICE)?

A: YES

While some areas could benefit from some improvement, overall the prototype was enormously successful and there is a clear development path to rectify its deficiencies.

Without any sound optimization design, the vehicle had a substantial noise advantage over its ICE snowmobile counterparts in almost all usage stages and on all types of terrain.

Plans of a 2nd generation vehicle with double the silent range, three times the power and an optimized sound signature are currently under way. This 2nd generation quiet hybrid snowmobile prototype is scheduled to undergo extensive on snow testing during the 2013-2014 winter season. The first production units based on the 2nd generation prototype are expected to be available for delivery in July 2014.

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