Sound Level Measurements of an Electric Snowmobile and an Internal Combustion Engine Snowmobile on Various Snow Surfaces

by

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Abstract

Snowmobile noise is a major issue affecting the perception and regulation of the snowmobile industry and community. Snowmobile producers and original equipment manufacturers have invested in the design, testing and implementation of noise reducing technologies. Other groups have studied snowmobile noise and its effects to expand the understanding of this subject.

Electric vehicles (EVs) are slowly becoming more popular in the automotive space. Along with the rise of EV automobiles, some groups have successfully added electric powertrains to other traditionally internal combustion (IC) engine propelled vehicles including snowmobiles. An example of this type of vehicle modification is an EV snowmobile built for utility purposes at a glacial arctic research station.

For many IC vehicles , the IC components (the engine, intake and exhaust for example) represent a significant source of noise. A number of researchers have studied the acoustic differences between IC and EV or hybrid EV automobiles and have found EVs significantly quieter than IC automobiles in a number of scenarios. To date, this research has not yet extended to off road electric vehicles. This thesis examines the potential noise-related benefits of electrification of the snowmobile powertrain by comparing a converted EV snowmobile with the IC snowmobile model it was converted from. Testing was done using a variation of the constant speed snowmobile pass-by noise measurement standard (SAE J1161).

Additionally, this thesis aims to consider the effect of ground hardness on this standard based on previous research on the subject. To accomplish this goal, these vehicles were tested on both hard and soft snow types. This thesis also examines reductions in snowmobile noise over the past decade. The most popular snowmobile of 2003 in Quebec and the most popular snowmobile of the 2014-2015 winter season were tested concurrently using the SAE J1161 standard and a full throttle pass-by noise measurement standard (SAE J192).

Testing on these vehicles demonstrated that the EV snowmobile was quieter than the IC snowmobile by close to 7 dB on soft snow but that this number reduced on harder snow types. In testing of the most popular snowmobiles of 2003 and winter 2014-2015, the newer snowmobile was considerably quieter than the older snowmobile (greater than 10 dB quieter) for both full speed and constant speed acceleration tests though the vehicles were only tested on soft snow. Although the results obtained with the EV snowmobile were not remarkable compared to the old versus new comparison, further testing is required to fully understand the possibilities of an EV snowmobile.

Sommaire

Le bruit de la motoneige est un problème majeur qui affecte la perception et la réglementation de l'industrie de motoneige et la communauté motoneigiste. Les producteurs de motoneige et leurs fournisseurs investissent toujours dans la conception, expérimentation et mise en œuvre des technologies de réduction de bruit. D'autres groupes ont étudié le bruit de la motoneige et ses effets pour élargir la compréhension de ce sujet.

Les véhicules électriques (VE) sont en train de devenir plus en plus populaire dans l'espace automobile. Avec la montée de VE, certains groupes ont ajouté avec succès des motopropulseurs électriques à d’autres types de véhicules, incluant des motoneiges. Un exemple de ce type de modification est une motoneige VE conçue pour une station de recherche arctique.

Pour de nombreux véhicules à combustion interne (CI), les composants CI (moteur, admission et échappement par exemple) représentent une source considérable de bruit. Un certain nombre de chercheurs ont étudié les différences acoustiques entre voiture CI et VE (ou voitures VE-hybrides) et ont trouvé que les voitures VE sont beaucoup plus silencieuses que les voitures CI dans certain scénarios. À ce jour, ce type de recherche n'a pas encore inclus les véhicules électriques hors route. Cette thèse examine les avantages potentiels de l'électrification d’une motoneige en termes de bruit. Une motoneige CI et une motoneige VE presque pareil en forme ont été testées ensemble. Les tests ont été effectués en utilisant une variante de la norme de mesure de bruit de motoneige à vitesse constante (SAE J1161).

En outre, cette thèse vise à examiner l'effet de la dureté du sol sur cette norme basée sur des recherches antérieures sur le sujet. Pour atteindre cet objectif, ces véhicules ont été testés sur deux types de neige (durs et mous). Cette thèse examine également des réductions dans le bruit de la motoneige durant la dernière décennie. La motoneige la plus populaire de l'année 2003 au Québec et la motoneige la plus populaire d’hiver 2014-2015 ont été testées simultanément en utilisant la norme SAE J1161 et un la norme de mesure de bruit en accélération plein régime (SAE J192).

Les essais sur ces véhicules ont démontré que la motoneige VE fait moins de bruit que la motoneige CI de près de 7 dB sur la neige molle, mais que ce nombre réduit sur la neige plus dure. Dans les essais des motoneiges les plus populaires de 2003 et de l'hiver 2014-2015, la motoneige plus récente était considérablement plus silencieuse que la motoneige plus âgée (plus de 10 dB plus silencieuse) pour les essais à plein régime et à vitesse constante. Bien que les résultats obtenus avec la motoneige VE ne

fussent pas remarquable par rapport à la comparaison ancienne-nouvelle, des essais supplémentaires sont nécessaires pour comprendre pleinement les possibilités d'une motoneige VE.

Table of Contents

List of Figures

Research Context

The following research is the result of an FQRNT BMP – Industrial Innovation Scholarship Master's project with industrial partner CrossChasm Technologies Inc. and in collaboration with Mogile Technologies. CrossChasm and Mogile Tech. are companies in the electric vehicle space, specializing in both on- and off-road applications.

CrossChasm Technologies, headquartered in Waterloo, Ontario, specializes in capturing, analyzing, and simulating on-road vehicle data. Mogile Technologies is based in Montreal and has developed an expertise in building off-road prototype electric vehicles such as snowmobiles.

Acknowledgements

Firstly, I would like to thank all of the people and groups who directly made this thesis possible. I would like to thank CrossChasm Technologies, NSERC and the FQRNT fund for sponsoring my thesis. I am extremely grateful for the wonderful support of the Mogile Tech. staff who have helped me immensely in the fulfillment of my thesis. This group includes Francis De Broux, Simon Ouellete, Olivier Proulx and Ramtin Parvizi. Without both their expertise in electric vehicles and their unending academic support this document would not exist today. All of the testing described in this document occurred on McGill University's MacDonald campus farm. I would like to additionally thank the management of MacDonald campus for providing the space for testing.

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Lastly I would like to thank my academic supervisor, Professor Peter Radziszewski, for his guidance and support.

1 Introduction

1.1 Snowmobile Noise

This research concerns the noise produced by over-snow vehicles known as snowmobiles. Snowmobiles enjoy tremendous popularity in North America, Northern Europe and Russia[1]. Although snowmobile ridership is high, conflict between riders and non-riders often threatens to bar snowmobile use from certain public or private spaces. These sources of conflict include noise, combustion-related emissions and safety, among other issues.

Snowmobile noise is a major source of conflict between snowmobile riders and non-riders. The American Council of Snowmobile Associations has said of snowmobile noise “that few other factors contribute more to misunderstanding and prejudice against the snowmobiling community than excessively noisy snowmobiles” [2]. In rural areas, snowmobile trails are often placed along highways and can pass nearby to country homes. Often this placement provides easy access to fueling, services and transportation to and from trails. Because of this proximity, however, non-riders may be exposed to unwanted noise from passing snowmobiles. Furthermore, snowmobile riders enjoy access to many public parks which experience wintertime snow cover. The presence of snowmobiles in public parks means that many snowmobile riders get to experience these parks in wintertime. However, some non-riders feel the presence of snowmobiles ruins the expected tranquility of these parks.

With electric vehicles (EV) gaining traction in the automotive industry and technologies constantly improving, it is not outside of the realm of possibilities to one day see a commercially available EV snowmobile. The limiting factor today is the cost and energy density of available electric batteries. However, even today, limited range electric snowmobiles designed for utility purposes are already in use [3]. With improving battery technologies, an EV snowmobile with the range of a traditional snowmobile and having an acceptable cost could be an appealing choice for a future snowmobile buyer.

A potential benefit of a fleet of EV snowmobiles is that EVs enjoy a reputation as being both cleaner and quieter than IC vehicles. EV automobiles can be so quiet that there is a field of research concerning adding noise to EVs to make them safer around pedestrians. Multiple studies have shown that at low speeds EVs or hybrid EVs in EV mode are significantly quieter than other IC automobiles [4][5]. At very low speeds the tested EVs could be up to 20 dB quieter than their IC counterparts.

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[1] Roughly 150,000 snowmobile units were sold worldwide during the 2013-2014 winter season [1].

To date, there has been little research into the possible noise reduction gains of an EV snowmobile except for the work of a number of undergraduate design teams in the Clean Snowmobile Challenge, a yearly student design competition.

The primary goal of this research is to determine what gains in noise reduction are possible through EV conversion of a snowmobile. That is to say, the goal of this research is to determine whether an electric snowmobile is quieter than its equivalent IC powered snowmobile and if so to what degree. To make this comparison, snowmobile noise measurement standards will be used as a basis for testing. However, following the works of Dilworth and Blough [7] on the effects of ground hardness on snowmobile noise measurement standards, this research will also consider the effects of ground cover type on any apparent noise level improvements related to EV conversion.

Testing under the primary goal will include a third snowmobile with differing characteristics compared to the first two snowmobiles (e.g. shorter track). The goal of this inclusion is to compare ground and speed noise-related effects on snowmobiles with different components. This vehicle will also be included to show the effect of speed on the snowmobile noise level and spectrum based on the work of Menge and Ross [8].

Snowmobile manufacturers are continuously improving their vehicles for noise, vibration and harshness. Another goal of this research is to put the comparison of the EV and IC snowmobiles in the context of improving snowmobile noise levels. This thesis will consider the improvements achieved by the snowmobile industry over the last decade in noise reduction. As a secondary goal this study will compare the most purchased snowmobile models in Quebec in 2003 and 2014.

To restate, the goals and sub-goals of this research are as follows:

1. determine whether an EV snowmobile is quieter than an equivalent IC snowmobile and if so to what degree
    a. consider the effect of snow type on the noise level of test vehicles
    b. include a third snowmobile in testing for context
    c. determine the noise level of these vehicles (the EV snowmobile and the third snowmobile) at different speeds
2. determine whether the most purchased snowmobile in Quebec from 2014 is quieter than the most purchased snowmobile from 2003 and if so to what degree

    a. compare the potential noise-reduction improvements between these vehicles to potential improvements in *1.*

These goals will be achieved through the following means:

- test a 2012 Ski-Doo Skandic WT (referred to as Vehicle 1 in this paper) with an EV-converted 2012 Ski-Doo Skandic WT (referred to as Vehicle 2 in this paper) using the SAE J1161 measurement standard as a rough guide
- test both Vehicle 1 and Vehicle 2 with an additional snowmobile having different characteristics (a 2009 Yamaha RS Venture; referred to as Vehicle 3 in this paper) using the SAE J1161 measurement standard as a rough guide
- test Vehicle 2 and Vehicle 3 using a modified SAE J1161 measurement standard at different speeds
- test a 2003 Arctic Cat ZL 800 (the most purchased snowmobile in Quebec in 2003; referred to as Vehicle 4 in this paper) and a 2015 Ski-Doo Grand Touring LE (the most purchased snowmobile in Quebec in 2014; referred to as Vehicle 5 in this paper) using the SAE J192 and SAE J1161 measurement standards as rough guides
- when possible, repeat testing on a variety of snow types (powder, wet, icy, etc.)

1.2 Snowmobiles

Broadly put, snowmobiles are vehicles designed for travel over snow. They are generally single or two person vehicles propelled by a rotating track and steered by one or two skis at the front of the vehicle. The legal definition of a snowmobile can vary by governing jurisdiction, but the State of Michigan provides a typical definition:

'"Snowmobile" means any motor-driven vehicle designed for travel primarily on snow or ice of a type that utilizes sled-type runners or skis, an endless belt tread, or any combination of these or other similar means of contact with the surface upon which it is operated…' [9]

Figure 1 - A typical modern snowmobile (Vehicle 5).

Today, snowmobiles are mostly used as off-road recreational vehicles. However, they remain essential tools in certain niche domains: isolated northern communities, hunting cultures, search and rescue, in the skiing and snowboarding industry and in the military.

1.3 Snowmobiling Popularity and Economic Impact in North America

Snowmobiles enjoy an immense popularity in areas of the world with wintertime or permanent snow cover. In the 2013-2014 winter season, 157,105 new snowmobile units were sold worldwide according to the International Snowmobile Manufacturers Association [1]. This number represents an increase of 9 % from the previous year and a 21 % increase from the 2012-2011 season [10]. Snowmobiles are used predominantly in the United States (particularly in the northern states), in Canada, in northern Europe and in Russia. Of the total worldwide snowmobile purchases in 2014, roughly 58,000 were sold in the US and 49,000 were sold in Canada [11]. Furthermore, for the 2013-2014 season, 1.4 million snowmobiles were registered in the US and roughly 594,000 snowmobiles were registered in Canada [11].

The three most popular provinces for snowmobiling in Canada are Quebec, Ontario and Newfoundland & Labrador (184,900, 150,000, and 101,400 registered snowmobiles, respectively) [11]. Quebec, the province with the most registered snowmobiles, has almost a third of the registered snowmobiles in Canada (31.1 %). The snowmobiling industry has a pronounced effect on Quebec's economy. The nearly 32,000 Km of groomed trails [12] across the province bring in approximately $2 billion, of which the provincial and federal governments receive roughly $250 million in tax revenue [13]. One of the ways that snowmobiling adds to this region's economy is through tourism. Approximately 30,000 tourists go to Quebec every year to ride on public trails [13]. Additionally, Quebec is home to one of the top four snowmobile manufacturers in the world, Bombardier Recreational Products & Vehicles (BRP) owner of the Ski-Doo brand. BRP had revenues of $1.2 billion in 2014 and currently employs 6,500 employees [14].

Ontario is the second most popular province for snowmobiling with roughly 11 registered snowmobile for every 1000 persons (compared with Quebec's 23 snowmobiles for every 1000 persons). Beating worldwide numbers, the province saw a gain of roughly 21 % in both participation and snowmobile sales in the 2013-2014 season compared to the previous year [15]. Furthermore the 2013-2014 season was the most popular snowmobiling season of the previous ten years in Ontario. Like Quebec, the snowmobiling industry has significant economic impact for Ontario. The industry brings in approximately $1.7 billion annually through winter tourism in Ontario [15].

The third most popular snowmobiling province is Newfoundland & Labrador. Although it lags the top two provinces in registered snowmobiles, it is by far the most snowmobile driven province per capita. With a population of 527,000, Newfoundland & Labrador has more than one registered snowmobile for every 5 persons.

America's three states which have the most snowmobile ridership roughly double Canada's top three. In the 2013-2014 season, Michigan, Minnesota and Wisconsin had 205,400, 258,000 and 237,800 registered snowmobiles, respectively [11]. Michigan's Department of Natural Resources reported that spending in that state related to snowmobiling was $412 million for spending on excursions and spending on equipment. Of those dollars, the state captured roughly $254 million [16].

Beyond having over 250,000 registered snowmobiles, Minnesota is home to two of the world's top snowmobile producers, Arctic Cat and Polaris Industries. Arctic Cat employs 1,369 production personnel (as of 2012) [12] while Polaris Industries employs roughly 3,000 full-time persons (as of 2010) [18]. With two of the top snowmobile manufacturers in this state, the snowmobiling industry has a significant effect on the state of Minnesota's economy.

Snowmobiling is also an important source of revenue for public parks. Yellowstone National Park has seen as many as +80,000 snowmobilers in the early 2000s and currently sees approximately 25,000 snowmobilers each year [19] (restrictions on number of snowmobilers were added in between these periods). Snowmobilers can visit the park by joining sanctioned tours which lead a single file pass along predetermined tour routes. Without snowmobiles, Yellowstone, like many other national and state/provincial parks in northern states and provinces, would remain largely unvisited during winter months. Snowmobiling creates a more even revenue stream for these parks since snowmobiles tend to be more practical than skis or snowshoes for average park visitors who might otherwise only visit during the spring, summer and fall months. According to *Yellowstone in Winter: The Role of Snowmobiles and Snowcoaches*, the presence of snowmobiles in public parks helps to diminish the ‘feast and famine cycle’ for parks and communities in adjoining areas [20].

2 Theory

2.1 Snowmobile Design

Figure 2 is an image of a typical modern snowmobile. The main components of a snowmobile are a chassis, skis, continuous track, suspension systems (at the skis and at the track), internal combustion engine, transmission and intake and exhaust systems. Snowmobile’s can be designed for 1 or 2 riders. The vehicle in Figure 2 has a second seat for an additional passenger.

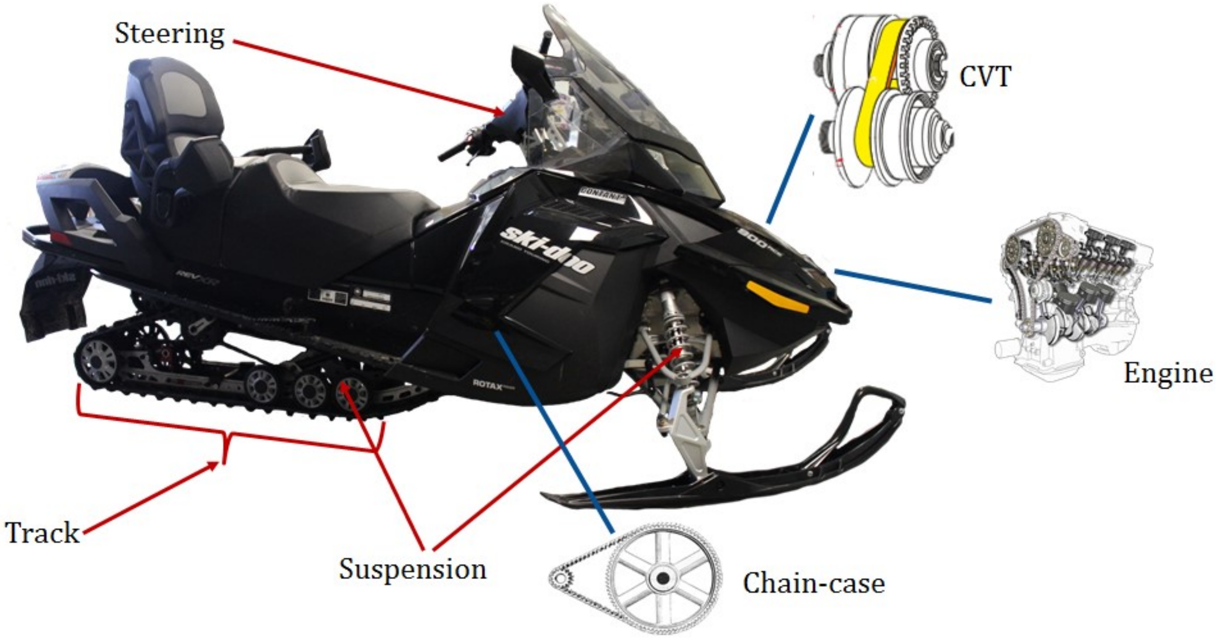

Figure 2 – A typical modern snowmobile (Vehicle 5) with various components highlighted.

The vehicle powertrain can vary snowmobile to snowmobile, but the basic components are often similar. Snowmobiles are propelled by a 2- or 4-stroke engine in the front compartment (a hollow cavity enclosed by the black panels at the head of the snowmobile in Figure 2). The engine is coupled to a belt-type continuous variable transmission (CVT) at the crankshaft with pressure clutches at either end of the CVT[2]. The secondary shaft of the CVT is connected to the track drive axle through a chain drive with a fixed gear reduction. The track drive axle turns the track using one or more paddle wheels also known as a drive sprockets. These drive sprockets have a number of plastic or rubber teeth which either fit into slots along the track or are set to receive inward facing teeth from the track (see Figure 3).

Figure 3 - Drive sprocket with both horizontal and vertical teeth types (removed from drive shaft).

The engine, 12 V battery, crankshaft, clutch, CVT, secondary shaft and the chain case are housed within the compartment at the front of the snowmobile. This compartment is often enclosed by several removable plastic covers for easy access to mechanical components. A long folded sheet metal structure (known as the tunnel) provides the base for a seat for the driver and, in many snowmobiles, a passenger. The frame is folded in a way that partially houses the track, protects the riders' legs from spinning parts and provides a foothold for the riders (see Figure 4). The front of the frame provides the base for the engine.

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[2] Variable terrain and highly fluctuating torque and speed requirements make CVTs the ideal transmission system for snowmobiles.

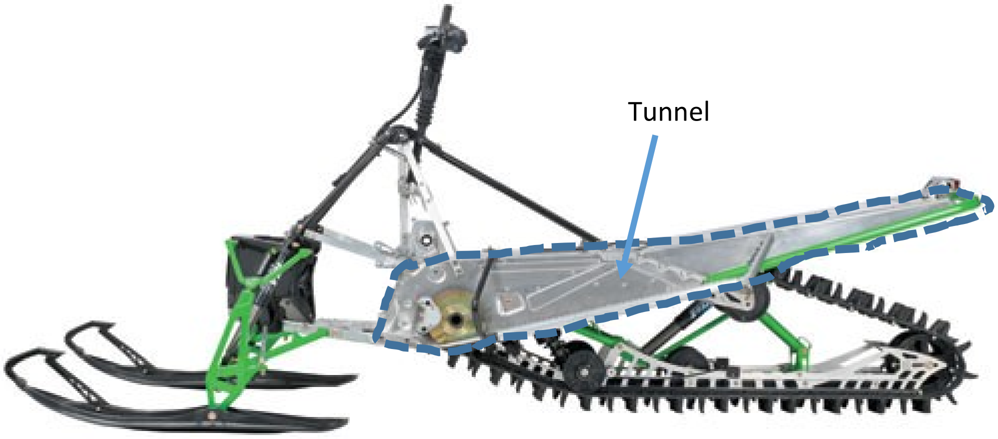

Figure 4 – Snowmobile chassis (image: [17]), tunnel highlighted.

The engine, CVT and to some degree the exhaust system are principally cooled by vents in the compartment covers. These vents are meshes, grates or simple openings in the plastic covers that allow for free flow of outside air into the compartment. The engine intake can either be directly coupled to a vent on the panel cover or be located within the compartment. The exhaust system configuration depends on the make and model of the snowmobile. Some configurations have the exhaust at the rear of the snowmobile while others have the exhaust in front of the foot holds, pointed towards the ground. Some configurations have a single exhaust with one muffler while others have a symmetrical design with two exhausts (see Figure 5).

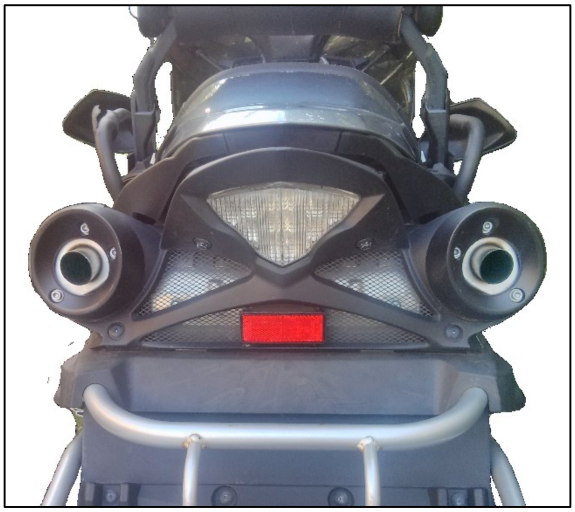

Figure 5 - Twin rear exhaust of a 2009 Yamaha RS Venture.

There are two separate sets of suspension in a snowmobile. A front suspension dampens impact and vibration between the skis and the frame. Generally there is one spring and shock absorber for each ski. The support for the skis can have a number of setups, one of which is the A-arm configuration (see Figure 6). A rear suspension (see Figure 7) dampens vibration and impact between the track and the frame. The amount of travel and stiffness of each suspension depends on the intended use of the snowmobile and is sometimes adjustable.

Figure 6 - A-arm suspension design.

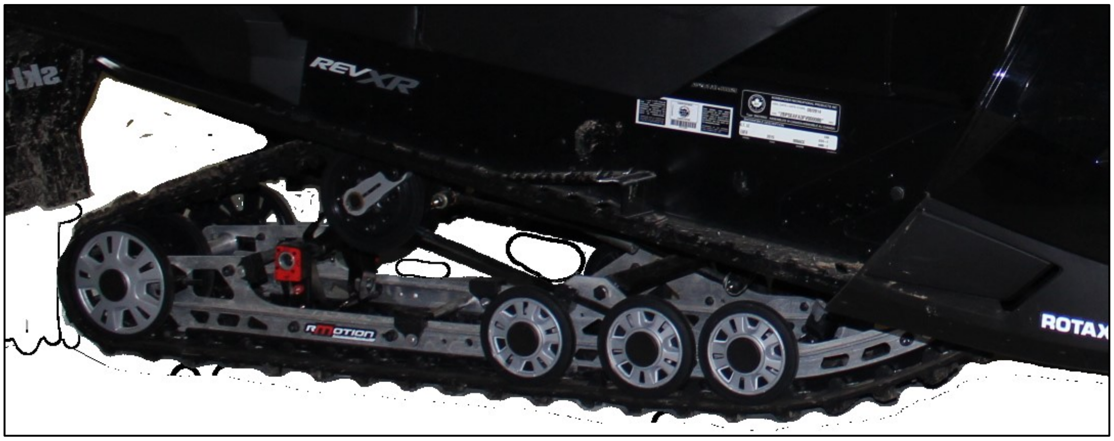

Figure 7 – Track frame (including rear suspension), track and section of tunnel.

The track wraps around a frame support structure. This structure provides a link between the snowmobile chassis and the track. The frame has two plastic runners, known as skids, which allows the track to slide beneath it (see Figure 8). It also has a set of wheels which maintain the track's form and tension. The skids have a smooth plastic surface which minimizes friction between the sliding track and the track frame. During normal snowmobile operation the skids are lubricated by melting snow passing between the skids and the track. This feature is essential to the track operation; without lubrication the normal force of the weight of the snowmobile and passenger would create extreme friction forces between the track and skids[3].

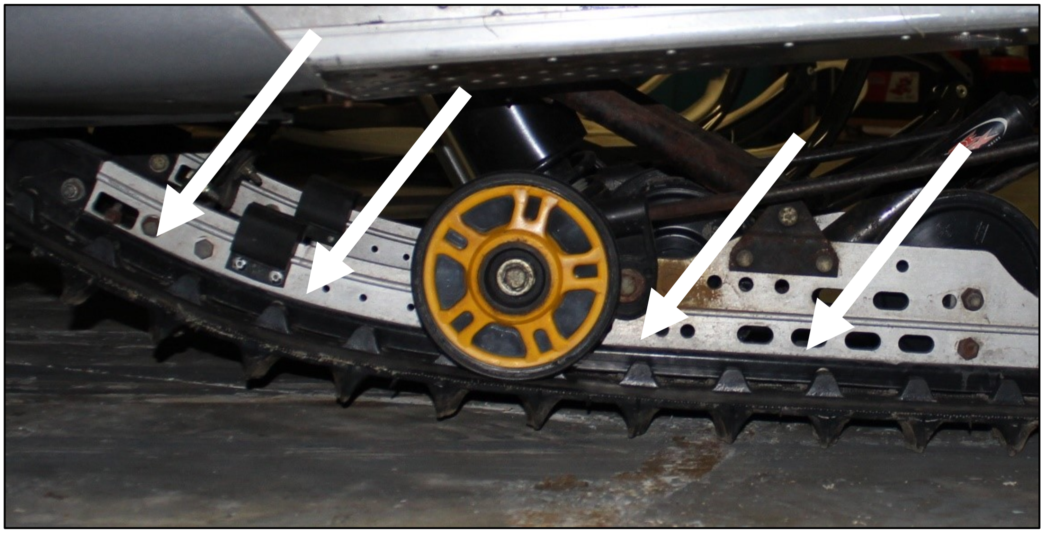

Figure 8 - Section of track length; arrows highlighting portion of a skid along the track frame.

Some of the wheels on the track frame are for maintaining the shape, tension and position of the track. Some snowmobiles allow the position of these wheels to be adjusted to control the tension of the track. Depending on the intended use of the snowmobile a looser or tighter track may be beneficial to the rider. In addition to these adjustable wheels, extra wheels (known as bogie wheels) provide further support for the runner frame.

Other features of the track include widthwise imbedded support rods and track lugs. The support rods provide rigidity to the track. The lugs provide traction for the vehicle in loose snow. The length of the lugs vary by track. Different conditions or riding styles call for different lugs. Shorter lugs provide more maneuverability while longer lugs are more suited to deep powder. In some cases, pointed metal lug inserts are used to provide traction on ice.

2.2 Design Aspects of an EV-Converted Snowmobile

Typically a snowmobile consists of a chassis, an IC engine, a suspension system, a continuous track, a transmission system and intake and exhaust systems. The EV version of a snowmobile will need to include a battery pack (in addition to- or in place of- the 12 V battery), an electric motor, a battery

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[3] The track must be lubricated manually if a snowmobile is driven on surfaces other than snow.

management system (BMS) and a motor controller in place of the fuel tank, engine and engine control unit of the IC snowmobile.

As the McGill University Electric Snowmobile Team explains in their 2007 competition design paper, the principal reason why the design of a practical electric snowmobile is such a challenge is energy density [22]. The mass-wise energy density of gasoline is over 100 times[4] that of lithium ion batteries (like the ones used for the EV snowmobile in this research. In terms of space, the volumetric energy density of gasoline is approximately 30 times that of lithium ion batteries. These numbers do not take into account the differing weights of management and housing components (gasoline tank and fuel pump versus wires, BMS, etc.) or the negatively affected battery performance in the cold. Taking these differences into account will further swing the pendulum in gasoline's favor [22]. However, the differences in efficiencies between an internal combustion system and an electric propulsive system does favor the electric system. The 2007 design paper presents a highly optimistic scenario where the electric system has a 95% efficiency and the internal combustion system has a 15% efficiency. Even in this optimistic scenario, they write that there would need to be 18 times the equivalent weight of gasoline in lithium ion batteries on board. They conclude that an electric snowmobile is not ideal for every snowmobile application and that some snowmobile applications are better suited to an electric vehicle.[5] A key design challenge is bringing the efficiency of the EV snowmobile as high as possible.

The space in the engine compartment of a modern snowmobile is limited. Four-stroke engines in new snowmobiles are almost twice the size of a comparable two-stroke engine and so snowmobile manufacturers must employ clever placement techniques to be able to utilize the already limited space. Some motors may be cheaper or lighter than an equivalent engine. However, limited gains from the switch to these motors would be overshadowed by the drastic energy storage requirements already outlined. To utilize the existing transmission infrastructure, the motor should be installed in line with one of the already existing shafts of either the CVT (if including) or the chain drive or gear box. Vibration dampers may have use at mounting points for reducing vibration from the motor. It is essential that the motor is sized to take into account all of the other components [25].

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[4] Gasoline Energy Density: 12,930 Wh/kg, 9,300 Wh/l [23]
Lithium Ion battery Energy Density: 105 Wh/kg, 284 Wh/l [24]

[5] Ski trail grooming requires a snowmobile trail a heavy sled. This sled could hypothetically house the batteries and connect to an electric snowmobile.

As previously explained, the EV snowmobile's battery will take away any possible (minor) gains in reduced power plant weight and size. Lithium ion battery packs, like the one used in Vehicle 2, must be large and heavy in order to house enough charge for typical snowmobiling applications. The modularity of lithium-ion batteries, however, allows the designer to utilize the remaining space in interesting ways, storing the battery pack in the space that used to be the gas tank or separating the pack into two parts, for example.

CVTs, which are useful for the fluctuating torque requirements of snowmobiling, are less useful for EV snowmobiles. Since electric motors have roughly flat torque-speed curves compared to IC engines, a variable transmission system in an EV is not required. The motor in a converted EV snowmobile can be directly coupled to the stock fixed-gear gear box or chain case. Removing the variable transmission frees up more space and reduces the overall weight of the snowmobile.

Additionally, the cooling system can be removed and the motor could potentially be sealed. The reason this removal is possible is because an electric motor requires significantly less cooling than an IC engine. For example, an impressive thermal efficiency of a typical automobile engine is 35% [26] while the Chevrolet Volt's electric motors can achieve operating efficiencies of 76-82% [27]. With less waste heat, the electric motor requires less cooling. Other thermal losses in the electrical system are not enough to warrant additional cooling.

The goal of improving the efficiency of the vehicle overall to minimize the power requirements (and thus battery weight required) is imperative. Therefore, it may be worthwhile to replace certain stock components with more expensive lighter parts. For McGill's 2007 competition electric snowmobile, the team replaced the steel driveshafts, chain drive and brake system with aluminum shafts, a synchronous belt system and a lightweight brake system [22].

Mechanically, these differences are the major ones between an IC snowmobile and a converted EV snowmobile. Additionally, an EV snowmobile requires a motor controller, a BMS, a DCDC converter or ACDC converter (depending on motor type), an on or off board charger and extensive wiring. Furthermore, safety considerations, powertrain modeling, electrical design, software design and validation are required for the successful electric conversion of a snowmobile. These other design aspects will not be considered in detail since this research focuses on noise and the potential mechanisms behind it. For further readings on the topic of EV snowmobiles and their design, [22] and [28] are suggested further reading.

2.3 Sound

2.3.1 Sound and Psychoacoustics

Acoustic waves, or sounds, are pressure vibrations which propagate through solids, liquids or gasses. In the physiological sense, sounds are acoustic waves which can be perceived and interpreted. Typically, humans perceive sound through the transmission of pressure waves in air from a source to the human ear. Pressure waves are interpreted by a nerve in the inner ear which transmits the acoustical information to the brain.

Humans can perceive both loudness and pitch in sounds. Loudness is the human interpretation of the pressure level of a sound. Loudness is measured in units known as Sones. Measuring loudness can be difficult and so typically sounds levels are represented by sound pressure levels. Sound pressure level is typically presented as a measure of the difference between the sound wave pressure and the local pressure of the medium. The range of pressure between audibility and permanent damage is very large (one to several trillion) and so typically sound pressure level (L_P) is given in the logarithmic decibel scale. This decibel value is given in terms of a reference pressure of 20 µPa (an approximation for the lowest sound level perceivable, the lower bound of human hearing). L_P is defined as $L_P = 20 * \log_{10}\left(\frac{p_{rms}}{p_{ref}}\right)$ dB (1).

“Pitch” relates to the perceived frequency of sound. Since it, too, can be difficult to measure, frequency is generally used to describe a sound. Frequency is a measure of the peaks or troughs of a sound wave transmitted per unit time. Humans can typically perceive sound in frequencies between 20 Hz and 20 kHz.

Beyond the bounds of human hearing, there is also a limit to the perception of differences in loudness and frequency that a human can perceive (also known as resolution). This limit is known as the just noticeable difference (JND); it is the limit with which an individual can perceive a change.

For frequency differences, the resolution of the human ear varies by reference value and from person to person. Commonly, a value of 5 cents (100 cents per semitone, 12 semitones per octave and an octave step being a doubling in frequency) is used as a value for the JND of frequency changes [29]. Since the JND of frequency is in fractions of an octave and octave steps are a doubling or halving of a given frequency, the resolution of human hearing of frequency increases logarithmically. For example, the difference between 80 and 90 Hz would be perceived as greater than the difference between 900 and 910 Hz.

Like frequency, the JND of sound pressure level is also dependent on the reference level and varies from person to person (in addition to other factors including frequency). A typical approximation for the JND of sound pressure level is 1 dB [30]. This approximation can be applied to pure tones (sounds consisting of a single frequency), frequencies in the middle range of human hearing and "regular" background noise [31]. This approximation is therefore less accurate for sounds nearing the loudness bounds of human hearing[6].

The human ear is more adept at hearing certain frequencies than others. As frequency approaches the upper and lower limits of human hearing, the loudness decreases. In other words, two sounds of equal sound pressure level but different frequency will not necessarily sound the same loudness to a listener. Human hearing can be approximated by an equal-loudness curve which provides the gain or loss required for pure tones to appear equal in loudness across the frequency spectrum.

To take this phenomenon into account, a variety of weighting schemes have been developed to better characterize sound as it is interpreted by humans. The most common is the A-weighting scheme (see Figure 9). A-weighting adds a negative gain to the actual L value of frequency bands near the lower and upper bounds of human hearing and adds a positive gain in the frequencies bands that humans are most able to hear. Though weighting schemes more analogous to human hearing have been developed since A-weighting was created, this weighting scheme is still the most commonly used for reasons of consistency.

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[6] In terms of sound level the upper 'bound' of human hearing is the threshold of pain. In this way it differs from the other bounds of perception.

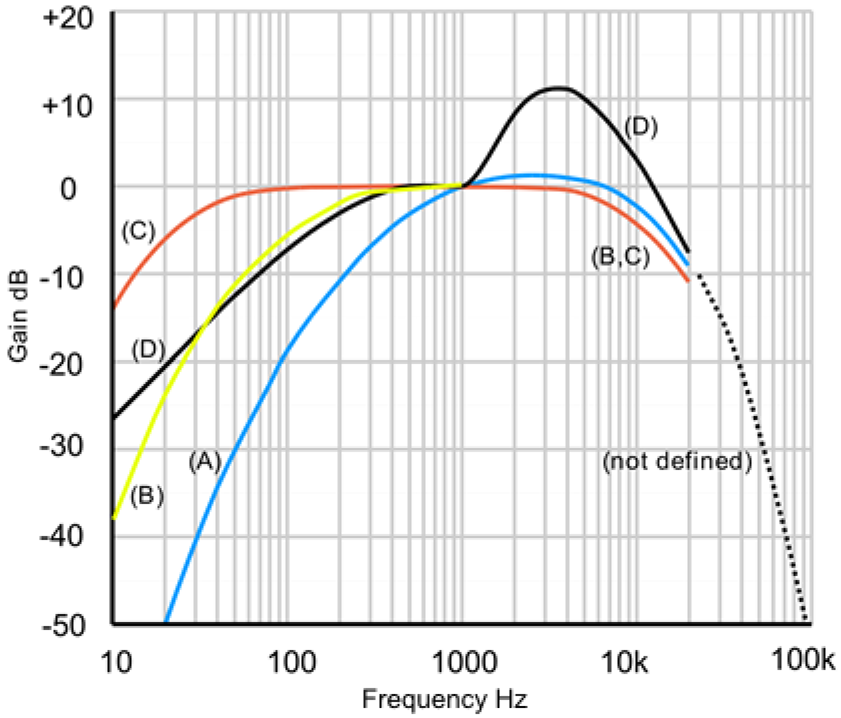

Figure 9 - Various weighting schemes. A-weighting in blue (image: [32]).

2.3.2 Fast Fourier Transforms and Octave Bands

There are a variety of different means of representing the frequency content of sound. For an instantaneous sound or sound that is relatively constant, it is common to display a single snapshot or average of the frequency content over a given length of time. Fast Fourier Transforms and single or fractional octave band charts are two examples of this type of representation. In both charts, frequency (usually in Hz) is on the x-axis and sound level (usually in dB) is on the y-axis.

An FFT converts a signal (in this case a sound wave or pressure versus time) from the time domain to the frequency domain. Signals can be analyzed in real-time or in post processing using the FFT. The x-axis on this type of chart can be displayed in the logarithmic scale.

Octave band charts are another way of representing the frequency content of sound. In an octave band chart or a fractional octave band chart, the frequency content of sound is broken down into bands using the average output of a bank of parallel bandpass filters [33]. Commonly, the bands span octaves or fractional octaves (most commonly 1/3 octave bands). In octave bands, the frequency of the upper bound of a band is twice the value of the lower bound. For 1/3 octave bands, every three bands is a doubling of the frequency at the center of the band. In other words the upper bound is the cube root of two times the lower bound. The bands are typically labelled by their center frequency. The center frequency is defined as $f_{center} = 2^{(n/3)}$ Hz (2).

Tones at the intersecting frequency of two adjacent bands will be divided between these bands. Put differently, a tone occurring at the upper limit of one band and the lower limit of the next band will be evenly split between both bands. Additionally, octave bands do not have infinitely steep skirts meaning that there is a transitional section between each band [33]. In this way, even if a tone is not located at the direct intersection of two adjacent bands, it may be divided between the bands in a manner which reflects the tone's relative proximity to either band center. For example a tone at 85 Hz is close to the upper band limit of the 80 Hz and 100 Hz (1/3 octave) band limit of 89.1 Hz. The tone will likely be divided between both bands in an octave band chart with more of the tone being portioned into the 80 Hz band.

The principal advantages of using octave band or 1/3 octave band measurements are that the logarithmic scaling of the bands is more closely analogous to how frequencies are differentiated by humans, the results are more repeatable and analysis is simplified overall. The drawback of this representation is that it is not the most accurate representation of the frequency content of sound.

2.3.3 Time Constants and Windowing

Sound level measurements are often taken with one of a set of parameters informally known as time-weights. These parameters include S (previously known as Slow), F (previously known as Fast), impulse and peak. The S and F parameters are a relic from analogue sound level meters and refer to the reaction time of a sound level measurement. The slow setting gave the analogue meter's needle a rise/fall time of 1,000 ms while the fast setting gave the needle a rise/fall time of 125 ms. For consistency, current digital models maintain this relic with the addition of an impulse and a peak option. The F setting has the advantage of being more reactive to short burst noises while the S setting is easier to read and gives a better indication of the average sound level for a changing or oscillating sound source.

Oscillating or time varying sound sources can be windowed using a simple moving average or through exponential smoothing or averaging. In exponential averaging (as opposed to rectangular averaging) the recorded average is a weighted running average of the sound level. In this type of reading, more weight is given to recent sound level measurements over sound levels further in the past. In other words, the sound level for a specific moment of time will have less and less bearing on the current sound level average as time passes [34].

2.3.4 Sound Propagation

A variety of factors affect the propagation of sound through a medium. One of these factors is distance from sound source to receiver. The intensity of sound as it propagates is governed by the inverse square law. The inverse square law states that intensity (I) is inversely proportional to the distance (r) from the source to the measurement point as $I \propto \frac{1}{r^2}$ (3).

In addition to the inverse square law, the medium also has an effect on the propagation of sound. Most mediums are somewhat viscous and will attenuate sound through thermal consumption.

Environmental factors specific to the medium also affect the propagation of sound. In air, temperature, relative humidity, precipitation and wind (among other factors) can affect propagation and may have other effects (wind causing background noise for example).

Barriers between the source and the receiver will have an effect on sound propagation. Barriers will cause a mix of reflection, refraction, diffraction and attenuation of sound. Barriers will both reflect sound waves and absorb some of their energy. The degree to which each occurs depends on the barrier substance and structure. Outdoor sound propagation theory attempts to model sound propagation using a ground-barrier model. The model is based on the height of the source, the height of the receiver, the distance between them and the impedance (Z) of the ground.

The presence of snow can further complicate the sound propagation model. Nicolas, Berry and Daigle in [6] attempted to model sound propagation over snow by extending the theory of propagation of sound from a point source above a porous half-space to include propagation above a finite thickness layer backed by an acoustically hard material. They found that some results agreed well with the theory (mid-range frequency noise) while low frequency noise better followed the porous ground model. Further complicating the study of sound propagation over snow, the researchers found that snow which had hardened on top did not follow either model but could be approximated by a thinner layer of snow in their model with the acoustically hard backing.

The effect of the ground impedance has been shown to be significant in standard snowmobile pass-by tests depending on the ground cover during the test. Losses could be as high as -6 dB in the 125 Hz to 1000 Hz frequency range according to [7].

2.3.5 Sound Source Addition

Incoherent sound sources measured in decibels must be summed taking into account their logarithmic scale. With the sound level being specified by Equation 1, the sound level of multiple sources is defined by the following equation $L_{\Sigma} = 10 * \log_{10}(10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}} + \cdots + 10^{\frac{Ln}{10}})$ (4) assuming the sources are not coherent.

Subtracting two sound sources works in much the same way. This equation can be used to show the difference between sounds in terms of the actual difference in sound pressure (Ex. the difference between 60 dB and 65 dB is 14,200 Pa or 63.3 dB). Conversely, the difference could also be described in number of decibels (Ex. the difference between 60 dB and 65 dB is +5 dB). The second comparison method is factually incorrect but may be a more useful comparison in terms of the subjective experience of a listener since humans do not interpret sound pressure differences linearly (see *Sound and Psychoacoustics*).

It is additionally important to note that an added noise source which adds less than +3 dB is small enough that it is comparatively insignificant. Likewise, caution is advised when determining a sound source from the sum of two sources and one of their levels. If the sum is greater than +10 dB more than the one known source, the known source will essentially be negligible compared to the greater source.

2.4 Snowmobiling Noise Standards

Quantifying snowmobile noise is of interest for regulators, manufacturers and other parties. In North America, the Society of Automotive engineers has three standards for measuring snowmobile noise, SAE J1161, SAE J192 and SAE J2567A. The first two standards are pass-by sound level measurements. In a pass-by test, the test vehicle is driven past a measurement device which records the vehicle sound level. SAE J2567A is a stationary test in which the sound level of the vehicle exhaust is recorded while the engine is engaged in neutral at a specific engine speed.

In J1161 and J192, the test vehicle is driven past a sound recording instrument which registers the maximum sound level as the vehicle passes. The snowmobile moves along a straight route which runs perpendicular to the direction of the recording instrument. The sound level is recorded in A-weighting and the S setting. The maximum recorded sound level is used as the recorded metric for the test ($L_{S,MAX}$). Jonasson and Frisk, the authors on a Swedish technical report on snowmobile noise [35], were critical of the use of the S setting. These researchers showed that by measuring with the S setting versus the F setting, the maximum sound level recorded could be up to 2 dB quieter during both the J1161 and J192 tests.

Additionally, environmental conditions must meet certain requirements according to the SAE standards. These go/no-go conditions include both atmospheric conditions and certain ground conditions.

This research relies heavily on the SAE J1161 and J192 standards as the basis for testing methodology. For more information on these standards, see *Test Design*. Since J2567A does not apply to EVs, it was not used in the analyses.

2.5 Snowmobile Noise Sources and Modern Mitigation Techniques

Snowmobiles, like other IC vehicles, have many sources of noise: the combustion in the chambers of the engine, the impact of various interlocking parts, the aerodynamics of the vehicle, the interaction between the track and the ground surface, etc. The degree to which each source dominates the overall noise of a snowmobile depends on the specific vehicle and a host of other factors. In *Snowmobile Design and Snowmobile Sound Basics* [37], author Dr. Jason Blough summarized the major sources of snowmobile noise and the design modifications the snowmobile industry has utilized to minimize them.

Though almost any part of a snowmobile is a potential source of noise, Blough’s list of most likely sources includes the engine, the exhaust, the intake, the CVT, the chain case, the chassis and the track and suspension.

Of the potential noise sources, the engine is a major source but ranks below the exhaust and track. During snowmobile operation, the engine block vibrates the chassis and support structure through mounting points. Surface vibration of the chassis and the engine itself radiate outward as noise. This engine surface vibration and vibration of the components within the front compartment pass outward through seams and vents in the plastic panels. Reflected noise which partially absorbs into the panel surfaces of the front compartment can radiate out from the vehicle as surface vibration.

Improvements in engine design for noise, vibration and harshness (NVH) have made inroads in reducing this type of noise. Noise absorbing foam and vibration dampers have been used to attenuate engine noise with some success. Since vents are integral to regulating engine temperature, reducing vent size or significantly covering the engine to seal in this noise and vibration would be difficult to do without affecting safety or performance.

The exhaust is another significant source of noise. Blough writes that it has long been considered the dominant source of noise on a snowmobile but that improvements in the last 10-15 years have made it a secondary source of noise in some new snowmobiles. 2-Stroke engines require precisely tuned exhaust to produce maximum power, often at the expense of noise emissions. The last 15 years have seen significant industry focus on improved exhaust tuning with a focus on noise and a push towards 4-stroke engines. The result of this push is a significantly quieter exhaust. The trade-off in this move is in weight and power. Aftermarket mufflers can offer riders gains in both reduced weight and improved power but come at the expense of noise. For this reason, snowmobile associations and regulators often discourage riders from buying aftermarket mufflers [2].

The intake is another significant source of noise on a snowmobile. Blough writes that the intake noise can be reduced with intake silencers and redesigns of the intake manifold and plenum. According to Blough, the snowmobile industry has achieved significant success in reducing this type of noise but further improvements are limited by the available space in the front compartment.

In addition to the aerodynamic noise of the exhaust and intake, both systems are subject to structural noise caused by the high-speed flow of gases through them. Vibrations caused by this flow radiates off of the sidewalls of the intake and exhaust silencers. The walls of the intake and exhaust silencers are often very thin. Their limited thickness means they are easily vibrated.

The CVT is another source of noise on the snowmobile. The CVT is air cooled and so cannot be fully enclosed. The unfortunate consequence of this exposure is that the CVT is subject to a lot of noise. Like the engine noise, CVT noise escapes the front compartment through the vents or is propagated through vibration of the front panels.

The track can be a major source of noise on a snowmobile and in some cases is the dominant noise source as manufacturers reduce the other sources of noise on their vehicles. A recent article in American Snowmobiler claimed that 50% of current snowmobile noise was caused by the track [38]. The track and suspension create noise through a variety of means. The list of noise sources on the track includes aerodynamic effects of the lugs, drive sprocket-track interaction, impact of the bogie wheels and widthwise track support rods, vibration of the track surface and interactions of the track and the ground surface (specifically the impact of lugs into the ground surface).

These sub-sources are affected by the many, variable characteristics of the track. The list of these characteristics includes:

- track length, width and thickness
- lug length, position and shape
- inclusion of metal lug inserts
- track tension
- number of bogie wheels and position
- position and size of imbedded support rods
- type of drive sprocket, such as number of teeth and tooth direction

These variations will all have an effect on overall track noise. Furthermore, as will be shown in the results of this research, the effect of these characteristics will further vary by ground cover type.

Original equipment manufacturers and snowmobile makers have taken steps to reduce track noise in recent years. A first generation of reduced noise tracks (like the Arctic Cat-Camoplast Ripsaw Quiet Track or the Ski-Doo SilenTrack) included small ramps along the track length which reduced the impact of the bogie wheels on the imbedded widthwise support rods. Since 2014, BRP has introduced another quiet track system, the SilentDrive (Figure 10). They claim that the SilentDrive system reduces noise at the track[7] by up to 65% and reduces vibration at the driver's feet by up to 70% [39]. The SilentDrive system involves a redesigned series of drive sprockets, a new track design and a modified suspension. Highlights of the SilentDrive system include a doubling of the number of sprocket teeth, internal teeth meshing, pushed forward bogie wheels (for reduced track vibration during suspension compression) and a thicker middle section of the track for more rigidity. This system is implemented in Vehicle 5.

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[7] They do not specify exactly where "at the track" sound level measurements were taken

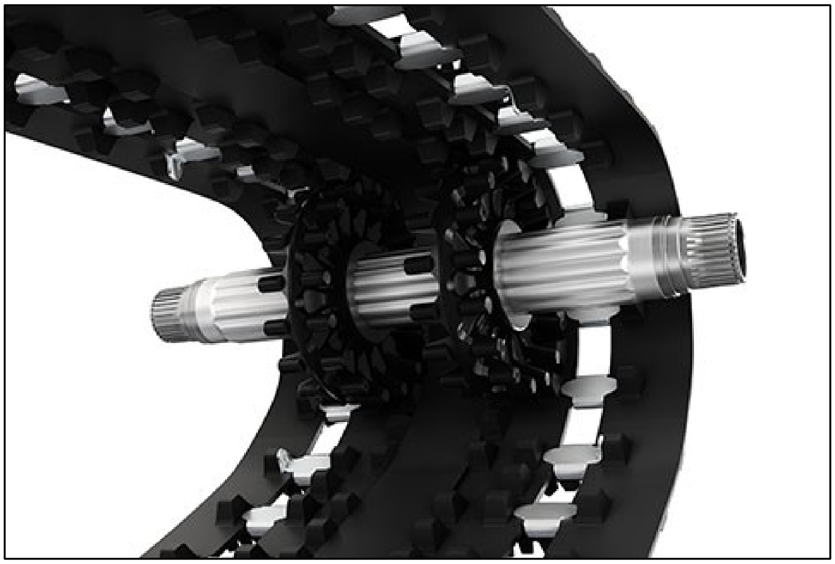

Figure 10 – Close-up of the Ski-Doo SilentDrive system (image: [10]).

The final notable source of noise is the snowmobile chassis. Surface vibration of the tunnel, caused by propagation of other vibration sources, radiates outward as noise. Blough writes that the snowmobile industry has taken large steps in the last decade to reduce this noise through implementation of NVH techniques from the automobile industry. Each new chassis is designed using "…finite element method modeling of prototype or concept chassis, transfer path analysis of prototype chassis, materials selection, and an understanding of how to design and optimize and engine and powertrain mounting systems to reduce radiated noise and chassis vibration" [37].

2.6 Electrification: A Yet-Unexplored Solution for Reducing Snowmobile Noise

In *Snowmobile Design and Snowmobile Sound Basics*, Blough described how the snowmobile industry has so far reduced the noise of their vehicles. The industry has redesigned their intakes and exhausts, dampened engine vibrations and absorbed radiated noises, designed new chassis' with NVH techniques taken from the automobile industry, adopted 4-stroke engines in some of their vehicles and reduced track noise through a variety of means. For the IC systems, further gains in noise attenuation come at the cost of power and weight. One possible solution, not yet explored by the industry is the electrification of their vehicles.

Leaving aside the practicality of this solution, a snowmobile converted to an EV would eliminate all of the engine, exhaust, intake and CVT noise associated with the IC components. However, a converted snowmobile would gain noise from the electric motor. Electric motors, like the ones in EV automobiles, generally make less noise than IC engines but are known to be tonal at high frequencies [36]. The tonal quality of high frequency motor noise can be annoying to listeners.

Electric motors also require less cooling (see *Design Aspects of an EV-Converted Snowmobile*). With lesser cooling requirements, the front compartment could be further acoustically insulated, potentially negating motor noise in practical terms. In theory, the switch to electric propulsion could offer a significant reduction in snowmobile noise. Among other effects, this research will look at the effect of electrification on snowmobile noise, specifically on the electrification of a 2012 Ski-Doo Skandic WT.

As mentioned in *Snowmobile Noise*, this research is not the first to explore the possible benefits of EV snowmobiles. The CSC has student design teams convert commercial snowmobiles to EVs every year since the first EV competition in 2007. Though Vehicle 2 was designed for another use, it was designed by veterans of the competition and would not exist had it not been for the CSC.

The degree to which electrification will reduce snowmobile noise will depend on how dominant IC noise is for Vehicle 1. As Blough wrote, the snowmobile industry has already had significant success in reducing IC noise. Furthermore, Vehicle 1 and Vehicle 2 are based on the same wide track model, lacking any of the track noise reduction technologies discussed in *Snowmobile Noise Sources and Modern Mitigation Techniques*. If track noise dominates the overall noise output, then electrification will have a limited effect overall.

2.7 Frequency Relationships of Rotating Parts

The previous sections, *Snowmobile Noise Sources and Modern Mitigation Techniques* and *Electrification*: A Yet-Unexplored Solution for Reducing Snowmobile Noise, examined possible noise sources on an IC and EV snowmobile. Some of these sources are rotating parts which are all dynamically connected, the meshing of the drive sprocket and the track for example. These connections may offer insight into the expected fundamental frequencies and harmonics of noise sources based on their rotational speed and other information. It has been shown in [40] that tonal noise below 250 Hz present in snowmobiles can be audible from very far away in quiet environments. For this reason, it may be worth examining component speeds to give a basis for future noise source analyses. This section will examine the governing equations for dynamically connected parts on a typical snowmobile.

With a known vehicle speed, the track rotational speed can easily be deduced using the full belt track length (equivalent to circumference) as $f_{track} = v_{vehicle}/L_{track}$, where f_{track} is the rotational speed or frequency of the track, $v_{vehicle}$ is the velocity of the snowmobile and L_{track} is the track length.

The lugs are generally grouped into single widthwise rows along the track. Knowing the number of lug groupings creates a means of determining the expected fundamental frequency of lugs impacting the ground surface as $f_{lugs} = f_{track} * N_{lugs}$ (5), where f_{lugs} is the dominant frequency of the lug impacts and N_{lugs} is the number of widthwise groupings of track lugs. Widthwise imbedded support rods in the track are often positioned above rows of lugs and in many tracks they are equal in number with lug rows. For this reason, the f_{lugs} can also be used for the frequency of the bogie wheels passing over the support rods.

Knowing the tangential speed of the track[8], the drive sprocket frequency can be determined by $f_{sprocket} = v_{vehicle}/C_{sprocket}$, where $f_{sprocket}$ is the rotational speed of the drive sprocket and $C_{sprocket}$ is the circumference of the drive sprocket. The circumference of the drive sprocket is generally not provided by the manufacturers but can be derived from the pitch of the track and the number of drive sprocket teeth according to $C_{sprocket} = p_{track} * N_{teeth}$, where p_{track} is the pitch of the track and N_{teeth} is the number of teeth on the drive sprocket. So therefore, $f_{sprocket} = \frac{v_{vehicle}}{p_{track} * N_{teeth}}$ (6).

The fundamental frequency of the drive sprocket teeth meshing with the track will also depend on the number of teeth and will therefore be $f_{teeth} = f_{sprocket} * N_{teeth}$, or $f_{teeth} = v_{vehicle}/p_{track}$ (7).

The frequency of the sprocket is also the low side frequency of either the chain drive or the gearbox depending on whether a gearbox has been included. Generally, snowmobile manufacturers do not specify the chain drive ratio and so the high side frequency is unknown. The gearbox ratio is usually provided, though. The gearbox high side frequency is simply $f_{high} = R_{GB} * f_{low}$, where f_{high} is the rotational speed of the gearbox high side, R_{GB} is the gear ratio of the gearbox and f_{low} is the rotational speed of the gearbox low side (which is equivalent to the rotational speed of the drive sprocket if they are directly connected).

Finally, in this direction of flow through the power train, the CVT is a computational dead end. Without the engine speed, the CVT speeds are unknown since the ratio varies depending on the required torque, operational speed and other factors. However, with a direct coupling to the engine/motor, as in Vehicle 2, the motor speed is simply $f_{motor} = f_{high}$, or $f_{motor} = \frac{R * v_{vehicle}}{p_{track}}$ (8).

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[8] The difference in tangential speed of the inside and outside of the track is negligible since the track thickness is under 5 cm and the track length is generally greater than 3 m.

For the exhaust of an IC snowmobile and direct and indirect engine vibration, the dominant frequency of the resultant noise is dependent on the engine speed, the number of cylinders and the number of stokes of the engine cycle. For 2-stroke engines, each cylinder is fired once every revolution (at the speed of the engine). For 4-stroke engines, each cylinder is fired every second revolution (at half the speed of the engine). Furthermore, assuming the firings in each cylinder do not overlap, the fundamental frequency of the resultant noise will be directly proportional to the number of cylinders in the vehicle. These factors will ensure a fundamental frequency related to engine speed according to $f_{IC} = \frac{2}{N_{strokes}} * N_{cylinders} * f_{engine}$ (9), where f_{IC} is the dominant frequency of internal combustion related noise, $N_{strokes}$ is the number of engine strokes per cycle, $N_{cylinders}$ is the number of cylinders and f_{engine} is the engine speed.[9]

The sound source analysis completed with these equations is meant to be preliminary in nature. It is meant as an accompaniment to the spectral results from this research. Further computational analyses could involve finding the natural frequency of the chassis, engine or track frame with FEA tools such as ANSYS or determining the resonant frequency of the exhaust muffler. Beyond computation, sound source analysis using nearfield acoustic holography could present a more accurate means of determining sources of noise and their relative contribution to the overall noise of the vehicle.

2.8 Studies of Snowmobile Noise

This research is not the first study of snowmobile noise. Snowmobile manufacturers, their suppliers, government bodies and independent researchers have studied snowmobile noise in the past. This section will highlight notable works and how they relate to this research.

One of the most influential researchers of snowmobile noise is the Society of Automotive Engineers (SAE). SAE International is responsible for the SAE J1161 and SAE J192 standards for determining the operational sound level of snowmobiles and has published various papers related to snowmobile noise. It is also responsible for the CSC. The EV section of the CSC is the inspiration for the EV snowmobile used in this research and to date the CSC has been the biggest source of research on the noise of EV snowmobiles.

Several notable SAE published papers on snowmobile noise include *Over-Snow Vehicle Sound Level Measurements* [41], *Supplemental Over-Snow Vehicle Sound Level Measurements* [42], *Noise Data from*

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[9] The engine speed here is in rev./s not RPM.

Snowmobile Pass-bys: The Significance of Frequency Content [43], *Determination of Source Contribution in Snowmobile Pass-by Noise Testing* [44], *Quantifying How the Environment Effects SAE-J192 Pass-by Noise Testing of Snowmobiles* [45], *Realization of Ground Effects on Snowmobile Pass-by Noise Testing* [7], and student papers from the yearly CSC design competitions.

In *Noise Data from Snowmobile Passy-bys*, authors Ross and Menge used a sound propagation model and the frequency content of a typical snowmobile at 15.2 m to determine whether the vehicle would be audible at 914.4 m. The authors collected frequency content of over-snow vehicles (including snowmobiles, snow coaches and over-snow-converted vans) taken from measurements at Yellowstone National Park and from competition vehicles at the CSC. The study found that snowmobiles differed in frequency content, some had smooth spectrum while others had distinct tones. The authors concluded that even for quieter vehicles, low frequency tones below 250 Hz (which may be caused by the engine, exhaust or track) could travel long distances and make the vehicles audible from far away in quiet environments. Following this study, the frequency content of pass-by tests has been collected for this research.

The effect of ground conditions and other environmental factors on the SAE J192 pass-by test standard were studied in *Quantifying How the Environment Effects SAE-J192* and *Realization of Ground Effects.* In *Quantifying How the Environment Effects SAE-J192*, Blough et. al. measured weather conditions such as wind speed and direction, temperature, humidity, snow depth and in some tests ground hardness to determine the effect of these conditions on the SAE J192 test and to determine which factor had the greatest effect overall. The study found that of all factors temperature had the greatest effect on snowmobile noise but that further testing of ground effects would be necessary to increase the understanding of how a snowmobile track interacts with the ground. *In Realization of Ground Effects*, authors Dilworth and Blough continued the research from *Quantifying How the Environment Effects SAE-J192* by studying how ground hardness affects the SAE J192 test. They determined that ground hardness could substantially affect the recorded noise level in the SAE J192 test. The authors tested a number of snowmobiles on a variety of snow and grass types in Northern Michigan, Wisconsin and Northwest Minnesota over 2 years. The paper concluded that with this array of ground covers, the recorded noise level could differ by up to 8 dB for their test vehicles and that the ground surface could pass or fail any of the test vehicles in the study by the widely mandated 78 dB_A limit for the SAE J192 test. The authors suggested that varying ground acoustical impedances and differing vehicle performance (related to track slip) on ice, snow types and grass could explain the difference between recorded sound levels on these surfaces. The research in this paper will add to Dilworth and Blough's study into ground effects by testing snowmobiles (including two snowmobiles with identical bodies but differing power plants) using the SAE J1161 standard on a variety of snow surfaces.

Finally, the CSC competition has provided a number of documents related to the noise of EV-converted snowmobiles. However, in the CSC, IC and EV snowmobiles are not tested in the same way. The IC vehicles are tested with the SAE J192 standard while the EV snowmobiles are tested with the SAE J1161 standard [46] [47]. This research will expand on their data by directly comparing an EV and an IC snowmobile.

Another major researcher of snowmobile noise is the National Park Service of America. Largely due to a longstanding controversy surrounding the use of snowmobiles and snow coaches in Yellowstone National Park [20], the National Park Service have commissioned a number of studies related to snowmobile noise to create a permanent winter park use management guide. These studies include yearly reports of *Natural Soundscape Monitoring in Yellowstone National Park*, yearly best-available-technologies (BAT) lists for snowmobiles admissible to Yellowstone and Grand Teton National Parks, sound modeling reports and studies into the effect of winter park use on wildlife. Much of their research is intended to assist the evolution of the Winter Use Planning program for the National Park Service. Of note is that the research completed by the National Park Service has resulted in a 2013 Winter Use Plan that both environmental groups and pro-snowmobiling groups have agreed upon [49].

As *Snowmobile Noise Sources and Modern Mitigation Techniques* has discussed, snowmobile manufacturers have been actively researching ways to reduce snowmobile noise and pollution since the 1970s. From the institution of vehicle noise regulations, snowmobile manufacturers have actively sought to clean and quieten their vehicles. Today snowmobiles are designed with NVH techniques from the automobile and heavy equipment industries. Manufacturers use "finite element analysis, rigid body dynamics, boundary element analysis, transfer path analysis, sound intensity and nearfield acoustic holography to optimize their designs" [37]. Currently, snowmobile manufacturers must research and develop new noise reduction technologies with parts suppliers because elements like the track and CVT are manufactured by outside companies [37].

Research on snowmobile noise is not limited to North America. Two relevant studies on snowmobiling noise from European researchers include the Swedish report *Noise Emissions from Snowmobiles* [35] and the Finnish report *Snowmobile Noise* [48]. *Noise Emissions from Snowmobiles* was commissioned by the Swedish government with the aim of having snowmobiles included in the European Commission's Directive on Noise in the Environment by Equipment for Use Outdoors. The study compared 4 snowmobiles (2 2-stroke and 2 4-stroke snowmobiles) through a variety of means. The researchers compared measurement distances, measurement height, accelerating, cruising and stationary speeds, S and F time settings and ground impedances. The study was very critical of the SAE J192 noise standard and of the Snowmobile Manufacturers Association. The study took issue with revisions to the J192 standard for starting from 24 km/h versus starting from rest and using the S setting over the F setting, suggesting that snowmobile manufacturers were able to boast on reduced snowmobile noise when in fact the changes to the measurement standard had contributed to lower recorded noise levels. Additionally, none of their test snowmobiles passed the widely used 78 dB_A maximum for SAE J192[11]. Other notable conclusions of the study include:

- The F setting adds approximately 2 dB over the S setting in the SAE J192 test.
- A 50 km/h cruising speed makes considerably more noise than 24 km/h for constant speed pass-by tests.
- Snow depth is not critical as long as it exceeds 7.5 cm.
- The practice of removing 2 dB to account for measurement error was unacceptable.

Snowmobile noise is another relevant study by a researcher outside of North America. The report was published by the Finnish Ministry of the Environment. Like *Noise Emissions from Snowmobiles*, this study measured the sound level of passing snowmobiles at a variety of speeds and from a variety of distances. In *Snowmobile Noise*, researchers also measured the noise level of safaris of snowmobiles, or groups of snowmobiles travelling in a line. The researchers found that the snowmobile noise around snowmobile trails would not surpass Finnish noise guidelines so long as the trails did not pass close by noise sensitive areas. However, it concluded that noise in quiet areas could be received with malice regardless of whether or not the noise passes guidelines.

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[11] Some of these test snowmobiles were included in the National Parks Service's BAT list of that year which makes their failure to meet the sound level maximum all the more surprising.

3 Methodology

3.1 Test Design

3.1.1 SAE Pass-By Noise Standards

SAE J1161 [50] and SAE J192 [51] are two standards created by SAE International for determining the operational sound level of a snowmobile. In both standards, a snowmobile is driven along a straight path (laneway) while a sound level meter or microphone records the maximum sound level as the snowmobile passes. These standards form the basis for most of the testing included in this research and the basis for other tests performed (see *Constant Speed Pass-By Tests at Other Speeds*).

SAE J1161 and SAE J192 are variations of each other. Each has the same setup but slightly different procedure. Both standards describe the instrumentation, test site, environmental requirements and procedure required for the test. This section will outline these common aspects.

In both pass-by tests the snowmobile is driven along a 45.6 m laneway (labeled in Figure 11 as "ACCELERATION LANE"). The snowmobile driver must stay within 1 m of the centerline in either direction. The recording device is positioned 15.2 m from the widthwise center and in line with the lengthwise center of the laneway. The start point, end point and microphone location are at least 30.4 m from any obstructions (trees, shrubs, hills, etc.). The recording device measures the sound level as the snowmobile passes from the start point to the end point of the laneway.

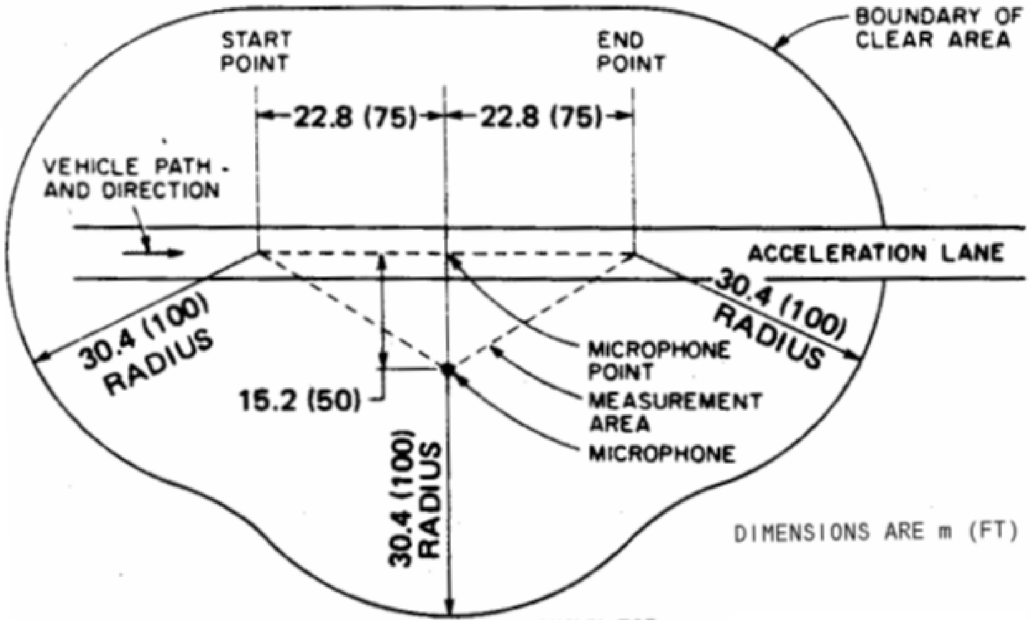

Figure 11 – Positional diagram for the SAE J1161 and SAE J192 standards highlighting the laneway length, the boundary of the test area and the recording device position (image: [50])

SAE standards J192 and J1161 specify certain aspects of the ground cover (section 4.2). When travelling over snow, they specify that the ground cover must consist of a maximum cover of 7.5 cm of loose snow and a minimum base of 5 cm of compact snow. According to the SAE's definition, compact snow is snow that may "support the snowmobile without penetration" (section 4.4). The standards also allow for testing on grass cover provided that the grass is visibly dry and is of maximum length of 7.5 cm.

SAE J1161 and J192 specify environmental conditions including wind speed, barometric pressure and background noise. According to the standards, wind speeds must not be in excess of 19 km/h while the absolute pressure must be between 93 and 103 kPa (section 7.4). The A-weighted ambient background noise must be 10 dB less than the recorded sound level of the snowmobile (section 4.7). However, it is not stated what type of sound level reading (weighting, setting, reading time, etc.) the ambient sound level is to be measured with. Since the background sound level can fluctuate even over short periods of time, an equivalent continuous sound level (L_{eq}, comparable to an overall average) was taken with a measurement period of 1 minute. The standards also suggest measuring temperature, humidity and wind direction but do not specify any bounds for these readings. All environmental measurements must be retaken every hour (section 6.3).

The maximum A-weighted, S setting sound level ($L_{AS,\ MAX}$) is recorded as the snowmobile passes from the start point to the end point in each test. Tests are repeated until 3 consecutives tests are within 2 dB of each other. Both sides are tested. A series of tests is performed with the snowmobile passing by the microphone at its left and then at its right (or vice versa). The three consecutives tests on a given side are averaged and then the louder of the two sides is taken as the result (section 6.4). The standards also include a 2 dB tolerance for these measurements to take into account "variations in test sites, temperature gradients, wind velocity gradients, test equipment and inherent difference in nominally identical vehicles."[12]

Measurement devices must meet Type 1 requirements of the American National Standard Specification for Sound Level Meters. The measurement device must be calibrated (with a calibration device within ±0.5 dB) in the field before use. In addition, a windscreen must be installed and it must not affect the response by more than ±1 dB for frequencies in the 20 Hz to 4 kHz range and ±1.5 dB for frequencies in the 4-10 kHz range with no wind.

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[12] This practice was criticised by one author of a study related to snowmobile noise [35] who accused the snowmobile industry of abusing the 2 dB tolerance.

For further information on these standards see *SAE J1161* and *SAE J192*.

3.1.2 SAE J192

The SAE J192 standard is the first of two SAE pass by tests used for characterizing snowmobile noise. Historically, it is the first of the two created. (SAE J1161 was created as an addition to SAE J192.) The SAE J192 standard is intended to characterize the full-throttle sound level of a snowmobile. In SAE J192, a test snowmobile is accelerated at full-throttle through the laneway. The intention of SAE J192 is to characterize the maximum sound level of the test vehicle.

In SAE J192 the snowmobile driver approaches the start point with a speed of 24 km/h[13]. When the start point is reached, the driver engages the throttle to full in a rapidly but smooth fashion. The driver maintains full throttle (within the limits of safety) until they reach the laneway endpoint. The maximum sound level ($L_{S,MAX}$) registered from start to end point is recorded as the result for this test. The maximum engine speed achieved during the test should also be recorded.

3.1.3 SAE J1161

The SAE J1161 standard was created as an addition to SAE J192. SAE J1161 is used to characterize the constant speed sound level of a snowmobile. In SAE J1161, a test snowmobile is driven at a constant speed through the laneway. The intention of SAE J1161 is to characterize the operational sound level of a test vehicle.

In SAE J1161 the snowmobile driver approaches the start point with a speed of 24 km/h. The driver must maintain this speed ±3 km/h until the end point is reached. The maximum sound level ($L_{S,\,MAX}$) registered from start to end point is returned as the result for this test.

A calibrated vehicle speed indication system with an accuracy within ±5% at test speed is required.

This standard was the principal test type used for tests involving Vehicle 2. The reasoning behind this choice was because Vehicle 2 is considerably torque limited in comparison to Vehicle 1 and most typical IC snowmobiles. As a comparison between equivalent IC and EV snowmobiles, a full throttle pass-by would be heavily biased against the IC snowmobile. Future EV snowmobiles with equivalent acceleration capabilities may provide a better comparison with IC snowmobiles. Furthermore, the use of a constant

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[13] Originally, SAE J192 involved the driver accelerating the snowmobile from full stop. With this practice, the start point would become quickly worn out because of high slip when opening the throttle from full stop.

speed pass-by test provides more worth to frequency analyses since rotating components should have approximately constant rotational speeds.

3.1.4 Constant Speed Pass-By Tests at Other Speeds

In order to demonstrate the effect of speed on the characteristic constant speed noise level of a snowmobile in SAE J1161, the constant speed pass-by test was also done at other speeds. The setup and requirements of SAE J1161 were met for these tests but the test snowmobile was driven at various other speeds. These speeds include: 16 km/h, 32 km/h and 40 km/h.

3.1.5 Deviations from Pass-by Standards

Limitations in time, access to the test vehicles and access to equipment resulted in some deviation from the SAE snowmobile noise standards. Additionally, some data not considered by these standards was recorded to offer more insight into the test vehicles.

The most notable deviation was caused by a lack of access to the test vehicles and limitations in time. Since many of these vehicles were on loan or in the prototype stage, they were only available on certain days and from certain times. As many tests were done with each vehicle as possible. However, for some tests some vehicles could not be present and for others a limited number of tests could be done with a vehicle (less than the 6 tests required by the standard). Because of this limitation and because of the limited difference in left and right sides of the vehicles (approximately 1 dB as documented in [48] and as experienced in this research), averages were taken from all tests completed including tests with measurements from both sides of the vehicle. This choice will likely have resulted in a lower average in comparison to taking the maximum of the left and right side passes.

Other deviations were caused by limited access to equipment. The SAE pass-by standards require an advanced GPS logging system to ensure the vehicles do not deviate significantly from the path and that they do not deviate significantly from 24 km/h in the case of the SAE J1161 standard. Unfortunately a GPS system with instant feedback and logging in the millisecond scale was not available. For this reason, the onboard speedometer was used as the principal measurement of speed and the position of the snowmobile was directed by a series of cones. On any test date the speedometers of each vehicle were tested against each other by driving the snowmobiles in parallel and recording the speed. The snowmobile driver was then responsible for ensuring the snowmobile remained within ±3 km/h during the course of a test. Furthermore, the speed of Vehicle 2 did not have a speedometer but could be controlled by a speed limiting motor controller. The speed of the motor was determined by Equation to be approximately 3020 RPM and this speed was confirmed using the Vehicle 1 as a speed check at 24 km/h.

The maximum engine speed during a test, required by the SAE J1116 and J192 standards, was not recorded. This omission was an oversight rather than an intentional decision. Future testing should include this value or should include logging of the engine speed as this knowledge could add to spectrum analyses.

Additionally, an advanced weather monitoring system was not available for testing. The weather data from the nearest weather station was recorded for each test along with the background noise level recorded at the test site.

Additional data was collected that was not required by the SAE standards. This addition includes sound level data points outside of the maximum (sound level versus time/position) and the sound spectrum recorded at the instant of maximum sound level. The sound level versus time data was collected at 100 ms intervals and has been included to show the evolution of the snowmobile sound levels as they pass the sound level meter. The sound spectrum at the instant of maximum sound level was recorded to expand on data collected in *Noise Data from Snowmobile Pass-bys* where pass-by spectral data for full throttle pass-by tests was collected.

3.1.6 Summary

SAE standards were used as bases for testing. The following is a summary of the testing methodology:

- The sound level meter is calibrated before each test.
- The weather data (taken from the nearest weather station) and the background noise level (taken at the test location) are recorded at the beginning and at any subsequent hour interval of testing.
    - The background noise level reading is an equivalent sound level (L_{eq}) reading.
    - The reading is sufficiently long as to take into account background noise fluctuations.
    - The ground conditions are given approximate descriptors (hard, soft, icy, powder, wet, etc.) and an estimate for the snow depth is made.
- Cones are used to show the length of the laneway for the snowmobile driver.
- A snowmobile passes over the laneway to set the track and compact the snow somewhat.
- The test vehicle speedometers are compared at 24 km/h to ensure accuracy between vehicles.
- For the full throttle pass-by tests:

    - The snowmobile driver approaches the laneway at 24 km/h.
    - Upon reaching the start cone, the snowmobile driver engages the throttle to full.
    - The driver keeps the throttle engaged until they reach the end cone.
- For the constant speed pass-by tests:
    - The snowmobile driver approaches the laneway at 24 km/h (or other speed depending on the test).
    - The driver maintains their speed until they reach the end cone.
- For each test the following are recorded (with A-weighting):
    - The slow-weighted sound level (L_S) over time (at 100 ms intervals).
    - The maximum sound level during the test ($L_{S,MAX}$).
    - The 1/3 octave band spectrum at the instance of maximum sound level.

3.2 Test Locations

Two locations were used for testing. Both test locations are on fields belonging to McGill University's MacDonald Campus in the town of Ste. Anne-de-Bellevue, Quebec. Location 1 is in an extensive empty field north of the MacDonald Campus Farm (see Figure 13). This area is located between Quebec Autoroute 40 (HWY 40) and Quebec Autoroute 20 (HWY 20). Location 2 is in a set of fields used for research purposes at the Emile A. Lods Agronomy Research Centre (see Figure 15). The Location 2 area is north of QC Autoroute 40.

Figure 12 - Google Maps satellite image of the test location area altered to show QC Autoroute 40 and 20 (HWY 40, HWY 20), MacDonald Campus Farm and Lods Agronomy Research Centre.

Figure 13 is a more zoomed in satellite view of Location 1. The laneway for this location is on an already established path straddling a cornfield (to the west; flat during the winter months) and an empty field (to the east). As per the requirements of SAE standards J1161 and J192, there were no obstructions between the lane and the microphone.

HWY 40 lies north of these fields and was a notable source of noise for testing at this location. The buildings in the south-west corner of the image are livestock-holding buildings and were not a significant source of noise during testing.

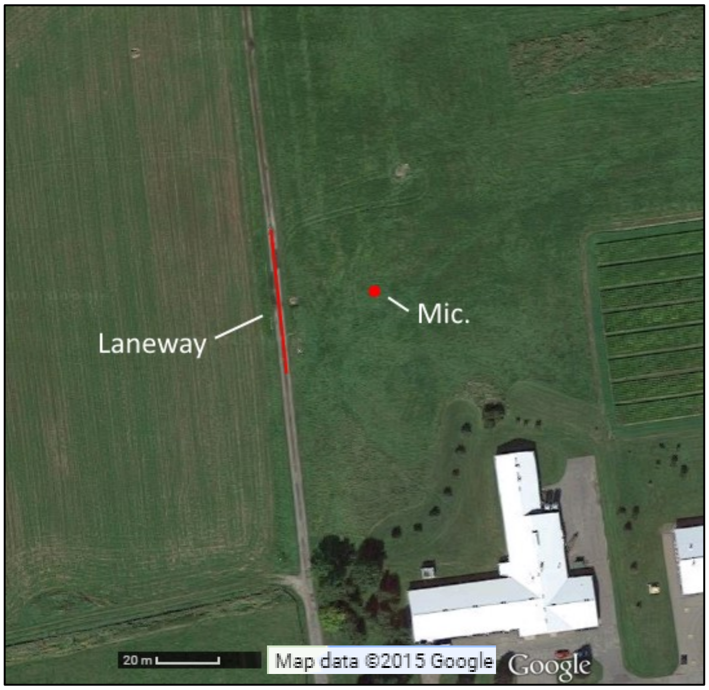

Figure 13 – Google Maps satellite view of Location 1 altered to show approximate location of laneway and microphone (Mic.)

Figure 14 shows the ground view of Location 1 during wintertime with approximate laneway location highlighted in red. During testing, cones (not pictured) were used to denote the exact position of the laneway and relevant points for SAE J1772 and SAE J192 tests.

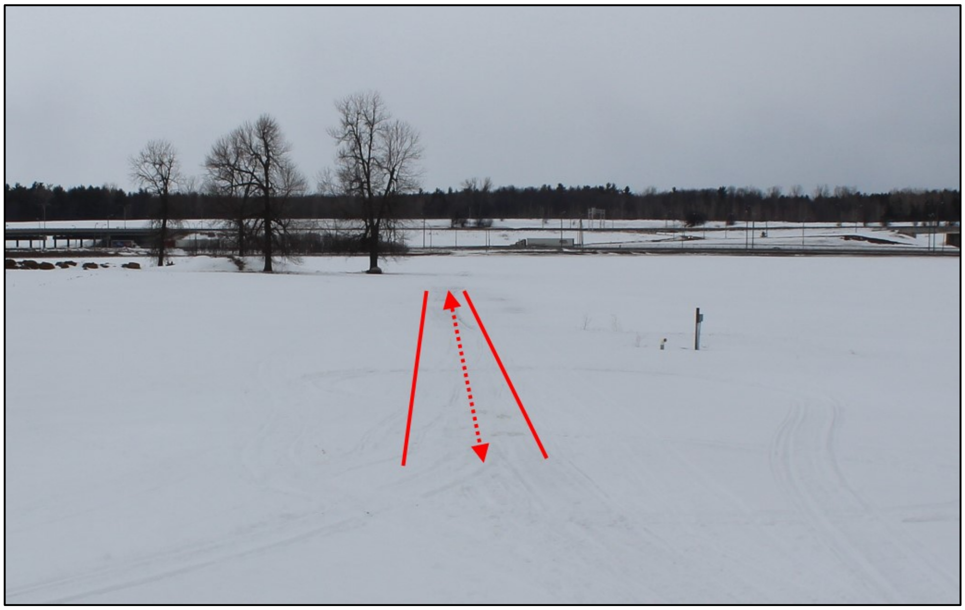

Figure 14 - Ground view of laneway (highlighted) at Location 1.

In the second year of testing, the MacDonald Campus Farm was no longer available for work and storage. The snowmobiles were then transferred to the Lods Agronomy Research Centre. A new location for testing, Location 2, was chosen at the Lods Agronomy Research Centre to keep the testing site close to the snowmobile storage space. Figure 15 is a more zoomed in satellite view of Location 2. As per the requirements of SAE J1161 and SAE J192, there were no obstructions between the laneway and the microphone. The line of trees and shrubs was further than the required 30.2 m from the laneway.

As with Location 1, HWY 40 was a notable source of noise at Location 2. Chemin Ste.-Marie (shown in Figure 15) passes by the Lods Research Centre but was not a major source of noise.

Figure 15 - Google Maps satellite view of Location 2 altered to show approximate location of laneway and recording device (Mic.) (note difference of scale between Figure 13).

Figure 16 shows Location 2 from the ground with the laneway highlighted in red and a storage barn in the distance. Cones were used to mark the 45.6 m laneway and the location of the recording device specified by SAE J1161 and SAE J192.

Figure 16 – Ground view of laneway (highlighted) at Location 2.

3.3 Instrumentation & Test Vehicles

3.3.1 Snowmobiles

This section will discuss some of the details of the snowmobiles used for this research. Five snowmobiles were tested. This list includes a 2012 Ski-Doo Skandic WT (Vehicle 1), an EV-converted 2012 Ski-Doo Skandic WT (Vehicle 2), a 2009 Yamaha RS Venture (Vehicle 3), a 2003 Arctic Cat ZL 800 (Vehicle 4) and a 2015 Ski-Doo Grand Touring (Vehicle 5). These snowmobiles were chosen largely because of their availability and worthiness for testing. Each one was available at some point between 2012 and 2015 and fit into several possible theses.

Vehicle 1 and Vehicle 2 were chosen because they presented a unique opportunity to compare an EV snowmobile with an almost identical IC snowmobile. The principal differences between these vehicles are their power plants and transmissions. Vehicle 1 is a 2-person, wide track utility snowmobile. Vehicle 2 has the same base as Vehicle 1 but has had the engine, CVT and cooling system removed and replaced with an electric drive.

Vehicle 4 and Vehicle 5 were chosen because they were the most popular (most purchased) snowmobiles in Quebec in the year 2003 and the 2014-2015 winter, respectively. This comparison is meant as an indication of noise improvements in the snowmobile industry. The principal differences between both vehicles are their available horse power, their track lengths and number of engine strokes. Other differences include chassis structure and suspension systems.

The final test snowmobile to be listed is Vehicle 3. It was used as a stand in for Vehicle 1 when this vehicle was not available. It has a smaller track in width and length than Vehicle 1 and Vehicle 2. Additionally it is a 4-stroke snowmobile to the 2-stroke of Vehicle 1.

Vehicle 1: Ski-Doo Skandic WT 600 H.O. E-TEC [53]

- Model Year: 2011
- Power Plant: Rotax E-TEC® 600 High Output Engine, 2-stroke, 594.4cc, 2 cylinder, 120 HP
- Track: 20 in x 154 in x 1.5 in (Wide Track)
- Drive System: CVT coupled to 2-speed gear box

Figure 19 – Vehicle 1 (stock; image: [53])

Vehicle 2: EV-converted Ski-Doo Skandic

- Model Year (of base): 2011
- Power Plant: HPEVS AC 15 Motor, 60 HP (peak)
- Track: 20 in x 154 in x 1.5 in (Wide Track)
- Battery: Li-ion, multi-cell
- Drive System: Direct coupling to stock 2-speed gear box

Figure 20 – Vehicle 2 with rider

Vehicle 3: Yamaha RS Venture [54]

- Model Year: 2009
- Power Plant: Yamaha Genesis 120, 4-stroke, 973 cc, 3 cylinder, 120 HP
- Track: Camoplast Ripsaw Track, 15 in. x 144 in. x 1.25 in.
- Drive System: CVT coupled to chain drive

Figure 21 – Vehicle 3 (stock; image: [54])

Vehicle 4: Arctic Cat ZL 800 [52]

- Model Year: 2003
- Power Plant: Liquid Cooled Twin, 2-stroke, 785 cc, 140 HP
- Track: 15 in. x 121 in. x 1.0 in.
- Drive System: CVT coupled to chain drive

Figure 22 – Vehicle 4

Vehicle 5: Ski-Doo Grand Touring LE 900 ACE [39]

- Model Year: 2015
- Power Plant: Rotax ACE 900, 4-stroke, 899 cc, 3 cylinder, 90 HP
- Track: 15 in. x 137 in. x 1.0 in. Ripsaw
- Drive System: CVT coupled to chain drive
- Other: SilentDrive track-drive system, adjustable suspension

Figure 23 – Vehicle 5

3.3.1.1 Other Snowmobile Specifications

Other specifications for these snowmobile which may be relevant to a frequency analysis (see *Frequency Relationships of Rotating Parts*) and sample calculations based on a vehicle speed of 24 km/h are included in Table 1. Some of the specifications were taken from official vehicle websites, some were taken from aggregate websites and others were measured from the vehicles themselves.

Table 1 – Other specifications for test snowmobiles and frequency calculations based on a vehicle speed of 24 km/h

	Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4[14]	Vehicle 5	
Track Length (m)	3.91	3.91	3.66	3.07	3.49	Spec.’s
# Rods/# Lug Rows	53	53	58	Unknown	53	
Pitch (m)	0.073	0.073[15]	0.064	Unknown	0.036	
# Teeth	7	7	9	Unknown	16	
Sprocket Circ. (m)	0.511	0.511	0.576	Unknown	0.581	
G.B. Drive Ratio	3.86	3.86[16]	-	-	-	
Track Rot. Speed (rev./s)	1.71	1.71	1.82	2.17	1.91	Calc.’s at 24 Km/h
Rod/Lug Impact Freq. (Hz)	90.4	90.4	105.6	Unknown	101.3	
Sprocket Speed (rev./s)	13.0	13.0	11.6	Unknown	11.5	
Teeth Impact Freq. (Hz)	91.3	91.3	104.2	Unknown	183.5	
G.B. Low Side Speed (rev./s)	13.0	13.0	-	-	-	
G.B. High Side Speed (rev./s)	50.4	50.4	-	-	-	
Motor/Eng. Speed (RPM)	Unknown	3022	Unknown	Unknown	Unknown	

Table 1 is not meant to be an exhaustive frequency analysis but is meant to give an idea, based on equations in *Frequency Relationships of Rotating Parts*, of possible sources for peaks found in spectral results.

3.4 Measurement Equipment & Software

The following sections describe the relevant specifications and other information for all measurement equipment used during testing.

3.4.1.1 Brüel & Kjær Hand-held Analyzer Type 2270 [55]

- Class 1 sound level meter (conforms to IEC 61672-1:2002; equivalent to ANSI Type 1 specifications)
- dynamic range: > 123 dB
- broadband range: 0.5 Hz to 20 kHz

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[14] Vehicle 4 was returned to owners before measurements were taken. Limited information about the vehicle was available.

[15] The 2011 Ski-Doo Skandic is specified on the official Ski-Doo website as having 8 teeth and a drive sprocket diameter of 0.183 mm (C = 0.575 m). From inspection, Vehicle 1 and Vehicle 2 had drive sprockets with 7 teeth and a circumference of 0.511 m (D=0.163 m) based on a track pitch of 0.073 m.

[16] Gear ratio is for 1st gear of Skandic model. All testing was done in 1st gear.

- windscreen correction (unknown error bounds for windscreen)

3.4.1.2 Brüel & Kjær ½ in. Microphone Type 4189 [56]

- free field
- pre-polarized
- sensitivity: 50 mV/Pa
- dynamic range: 14.6 dB to 146 dB
- frequency range: 6.3 Hz to 20 kHz
- temperature range: -30˚ C to 150˚ C

3.4.1.3 Brüel & Kjær Sound Calibrator Type 4231 [57]

- conforms to EN/IEC 60942 (2003) Class LS and Class 1, and ANSI S1.40 – 1984
- calibration accuracy: ± 0.2 dB

3.4.1.4 Brüel & Kjær BZ-5503 Measurement Partner Suite

- viewing and post-processing toolbox

3.5 List of Tests and Environmental Conditions

Table 2 - List of dates, test types, test vehicles, number of trials, ambient temperature, ambient pressure, relative humidity, background noise level, wind speed and direction, and a description of the ground cover for all tests.

Date	Test Type	Vehicles Involved	Number of Trials	Temp.	Press.	Relative Humidity	Bkgrd. Noise Level (L_{eq})	Wind Speed, Dir.	Ground Cover[17]
19/12/12	-J1161	• Vehicle 1 • Vehicle 2	• 17 • 8	+0.4˚ C	100.9 kPa	93%	52.1 dB_A	6 km/h, DIR: S	Wet snow (5-10 cm cover)
16/01/13	-J1161	• Vehicle 1 • Vehicle 2	• 5 • 2	-0. 6˚ C	100.4 kPa	80%	49.3 dB_A	11 km/h, Dir: NW	Hard/icy layer over soft snow over hard-packed base (2-3 cm crust, ~5 cm soft, ~10 cm base)
21/01/13	-J1161	• Vehicle 1 • Vehicle 2 • Vehicle 3	• 2 • 1 • 1	-17.6˚ C	101.4 kPa	58%	44.0 dB_A	7 km/h, DIR: S	Hard/icy layer over soft snow over hard-packed base (2-3 cm crust, ~5 cm soft, ~10 cm base)
11/02/13	-Varied Const. Speed	• Vehicle 1 • Vehicle 3	• 4 • 4 (each speed)	-6.5˚ C	100.2 kPa	50%	52.2 dB_A	9 km/h, DIR: NE	Powder snow, over mix of hard packed snow and ice (~5cm powder, >15 cm base)
27/02/15	-J116	• Vehicle 4 • Vehicle 5	• 4 • 4	-14.7˚ C	102.5 kPa	49%	41.2 dB_A	13 km/h, DIR: SW	Powder snow over hard-packed snow (5-10 cm powder, ~10 cm base)
“”	-J192	• Vehicle 4 • Vehicle 5	• 4 • 4	“”	“”	“”	“”	“”	“”

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[17] Before each test series, the laneway was passed over several times to create a consistent track. The ground cover information above pertains to unperturbed conditions.

4 Results

In this section, results from all test series have been compiled, tabulated and graphed. An average value for $L_{S,MAX}$, the population standard deviation and the range of results were calculated for each vehicle in a given test. In some sections, sample sound level versus time comparison charts have been included and are based on single tests reflective of the series. 1/3 Octave band charts from the moment of peak noise level during a typical test have also been included in some sections to show the frequency content of the vehicle noise. Observations and discussion relevant to the results have been included as well.

Standard deviation was calculated using $\sigma = \sqrt{\frac{\sum(x-\bar{x})^2}{(n-1)}}$.

4.1 Influence of Power Plant Type (Part 1)

The following results are from a series of 24 km/h constant speed pass-by tests of Vehicle 1 and Vehicle 2 driven over wet snow. Seventeen tests were done with Vehicle 1 while 8 tests were done with Vehicle 2. With Vehicle 1, 9 tests were done on the right side of the microphone and 8 tests were done on the left side. For Vehicle 2, 4 tests were done on the right side of the microphone and 4 tests were done on the left side.

These results are from December 19th, 2012. On this date the ground cover consisted of wet snow with some give but compact enough to support the snowmobiles. At test time, the background noise level was measured to be 52.1 dB_A (not insignificant) and the principal source of background noise was the nearby highway (see *Test Locations*). Other test conditions can be found in *List of Tests and Environmental Conditions*.

Figure 24 shows the average maximum sound level registered during this test series. The averages include test results from both sides of the vehicle. The population standard deviation of these series has been included and is represented as error bars.

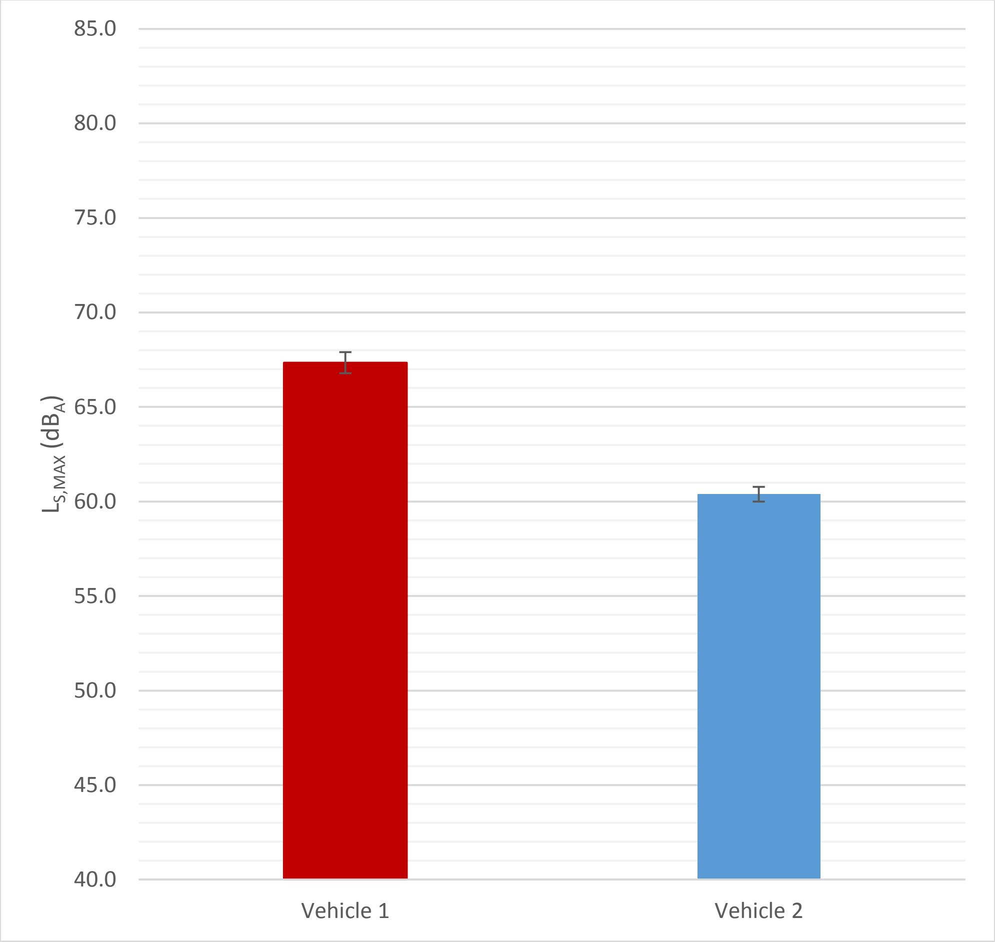

Figure 24 – Average $L_{S,MAX}$ registered during multiple 24 km/h pass-by tests of Vehicle 1 and Vehicle 2 on wet snow.

Vehicle 2 was significantly quieter than Vehicle 1 during these tests. Vehicle 2 registered on average an $L_{S,MAX}$ of 60.4 dB$_A$ while Vehicle 1 produced an average $L_{S,MAX}$ of 67.3 dB$_A$. Vehicle 1 was therefore more than twice as loud as the EV version of this vehicle at 24 km/h on this snow type.

The range of each snowmobile for all tests was within ±0.6 dB for Vehicle 2 and ±1.1 dB for Vehicle 1, sufficiently low to qualify the results for the SAE J1161 standard. However, the background noise level was close enough to the measured sound levels of Vehicle 2 (only 8 dB difference between them) to disqualify the Vehicle 2 results from official use for the SAE J1161 standard. For comparative purposes with Vehicle 1, these Vehicle 2 results still hold merit. When interpreting these results, it should be understood that there is somewhat of a bias towards the louder snowmobile (Vehicle 1) since the background noise contributes more to the decibel sound level of the lesser noise (Equation 4).

Figure 25 shows the sound level of both vehicles as a function of time[18] during a typical test. The chart for the Vehicle 2 test and the Vehicle 1 test have been overlaid in such a way that their maxima are positioned at the same relative time (approximately 6.6 s on the x-axis).

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[18] At a constant speed of 24 km/h, the x-axis could alternatively be the position of the snowmobile relative to the start point or relative to the recording device through calculation. With normal fluctuations in the driver's speed and without an accurate GPS system, time is a more accurate unit to display.

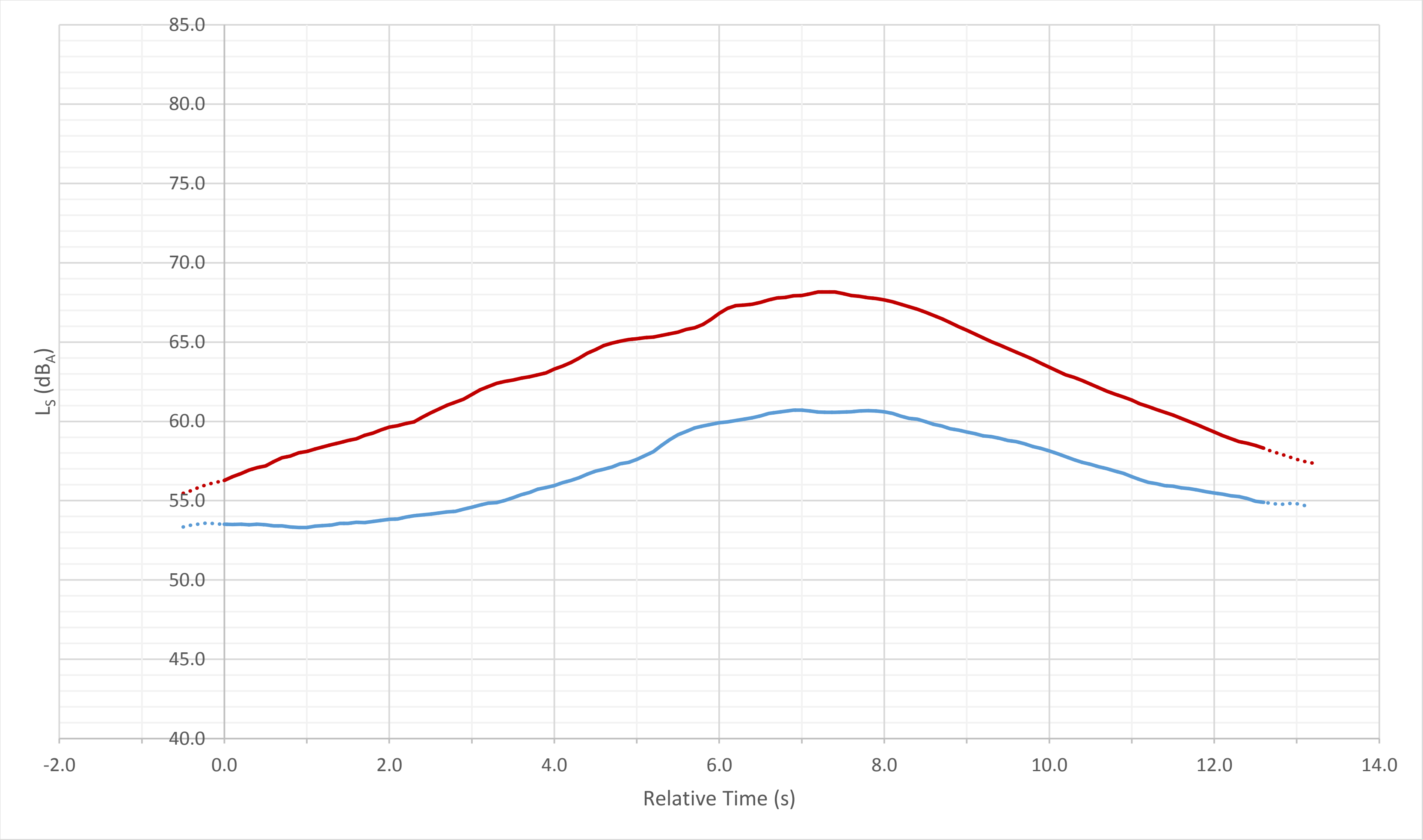

Figure 25 - Sound-level profile over time of typical 24 km/h pass-by tests of Vehicle 1 and Vehicle 2 on wet snow. The red lines represent the Vehicle 1 sound level and blue lines represents the Vehicle 2 sound level.

Over the course of the test, Vehicle 2 was consistently quieter than Vehicle 1. If the start point is considered to be at approximately 4 s on the relative time axis, Vehicle 2 remains at least 5 dB quieter than Vehicle 1 during the entire test (test length should be approximately 6.8 s long at 24 km/h).

Without an accurate GPS and with a short test time, it is difficult to frame the test (signify a start and end point). However, from experience, the maximum sound level occurred consistently with the vehicle closer to the end point of the laneway than to the start point but before the test vehicle had reached the end point. This shift towards the end either signifies that the snowmobiles are louder from the rear or that the S setting creates a delay in the results.[19]

Figure 26 is a 1/3 octave band chart of the moment of maximum sound level for both snowmobiles. The chart ranges from the 12.5 Hz band to 20 kHz band and has the overall sound level ($L_{S,MAX}$) as the right-most bar (labelled “A”). The values were registered using the S setting and appropriate A-weighting gains have been applied to each band.

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[19] S setting will delay noises depending on their strength as compared to the F setting (see *Time Constants and Windowing*).

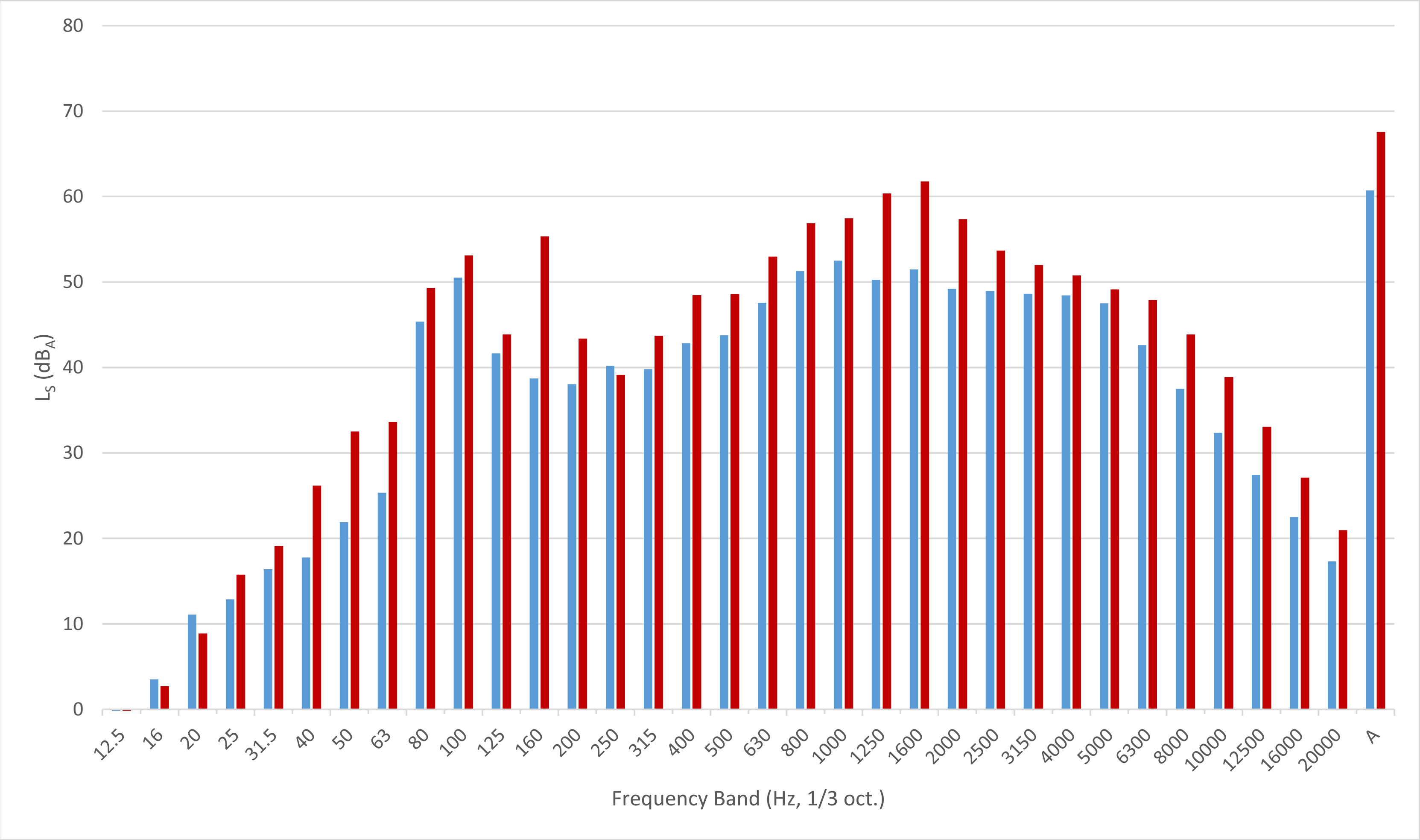

Figure 26 - 1/3 Octave band chart of the peak sound levels registered during a typical 24 km/h pass-by test of Vehicle 1 and Vehicle 2 on wet snow. Red bars represent the Vehicle 1 distribution and blue bars represent the Vehicle 2 distribution.

In most bands Vehicle 1 was louder than Vehicle 2 and there are certain bands where the difference is most pronounced. Vehicle 2 shows a relatively flat, broadband distribution (taking into account the A-weighting) with a notable peak in the 80 to 100 Hz region. Vehicle 1 has a similar response with the same peak in the 80 to 100 Hz region and an additional peak at 160 Hz.

The peak in the 80 to 100 Hz region is common between both snowmobiles (although Vehicle 1 is slightly louder in these bands) which suggests the source might be components common between both vehicles (the track, suspension, chassis, etc.). From the sample calculation table in *Frequency Relationships of Rotating Parts*, the individual rows of track lugs, support rods impacting bogie wheels[20] and meshing drive sprocket teeth should all have a fundamental frequency of about 90 Hz at a vehicle speed of 24 km/h (according to Equation 7). These components are possible causes of the peak in these bands. Having a 2-stroke, 2 cylinder engine, a 160 Hz exhaust noise could correspond to an engine speed of 4800 RPM, which is a reasonable engine speed at the velocity of Vehicle 1.

Because of the broadband nature of the noise distribution, these peaks have a limited contribution to the overall noise levels at 15 m. Most of the noise distribution of both vehicle profiles is in the 300 Hz to 8 kHz range. However, distinct tones at lower frequencies (below 250 Hz) may travel further than higher frequency noise, even if the lower frequency tones represent a small fraction of the overall noise level at 15 m [43]. Recalling that A-weighting is a psychoacoustic concept and thus has no bearing on the propagation of sound, the distinct tones at 80-100 Hz in the Vehicle 1 and Vehicle 2 responses and the 160 Hz tone in the Vehicle 1 response are undervalued in Figure 26 when it comes to their ability to propagate. These distinct tones may cause either vehicle to be audible at significant distances in quiet environments.

A detailed noise source analysis is beyond the scope of this research. A more comprehensive analysis using more vehicle information or noise source identification with an acoustical array are possible future methods that could more conclusively determine noise sources and their contributions to the overall noise of the vehicles.

4.1.1.1 *Summary*

- Vehicle 2 had an average $L_{S,MAX}$ of 60.4 dB_A and Vehicle 1 had an average $L_{S,MAX}$ of 67.3 dB_A at 24 km/h on wet snow.

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[20] The imbedded support rods in the track are lined up with the lug position on the track and so share the same fundamental frequency.

- There was not a significant difference between the maximum sound levels registered from the left and right side passes of each vehicle and there was little variation from test-to-test.
- Both vehicles exhibited a peak during a typical test in the 80 to 100 Hz region which may have been due to track related noises including the track-drive sprocket meshing, the lug-ground impact and imbedded support rod-bogie wheel impacts.
- Vehicle 1 exhibited an additional peak in the 160 Hz band which may be due to the exhaust or other engine related noise.

4.2 Influence of Power Plant Type (Part 2)

The following results are from a series of 24 km/h constant speed pass-by tests of Vehicle 1 and Vehicle 2 on icy snow. Five tests were done with Vehicle 2 while 2 tests were done with Vehicle 1. These results are from a single date. The reason so few tests were completed with Vehicle 1 is because of limited test time on this particular date. That there are so few tests included in the average should be considered when interpreting the results. Although the limitation of these results prohibit their official use according to the SAE J1161 standard, for purposes of a preliminary comparison between Vehicle 1 and Vehicle 2 on wet snow these results still hold merit.

For Vehicle 2, 3 tests were done on the right side of the microphone and 2 tests were done on the left side. For Vehicle 1, 1 test was done on the right side of the microphone and 1 test was done on the left side.

The following results are from January 16th, 2013. On this date the ground cover consisted of icy snow with a base sufficiently compact to support the test snowmobile. The background noise level was recorded at 49.3 dB_A at test time. Other test conditions can be found in *List of Tests and Environmental Conditions*.

Figure 27 shows the average maximum sound level registered during these test series. The averages include tests from both sides of the vehicle. The population standard deviation of these series is included with the average and is represented as error bars.

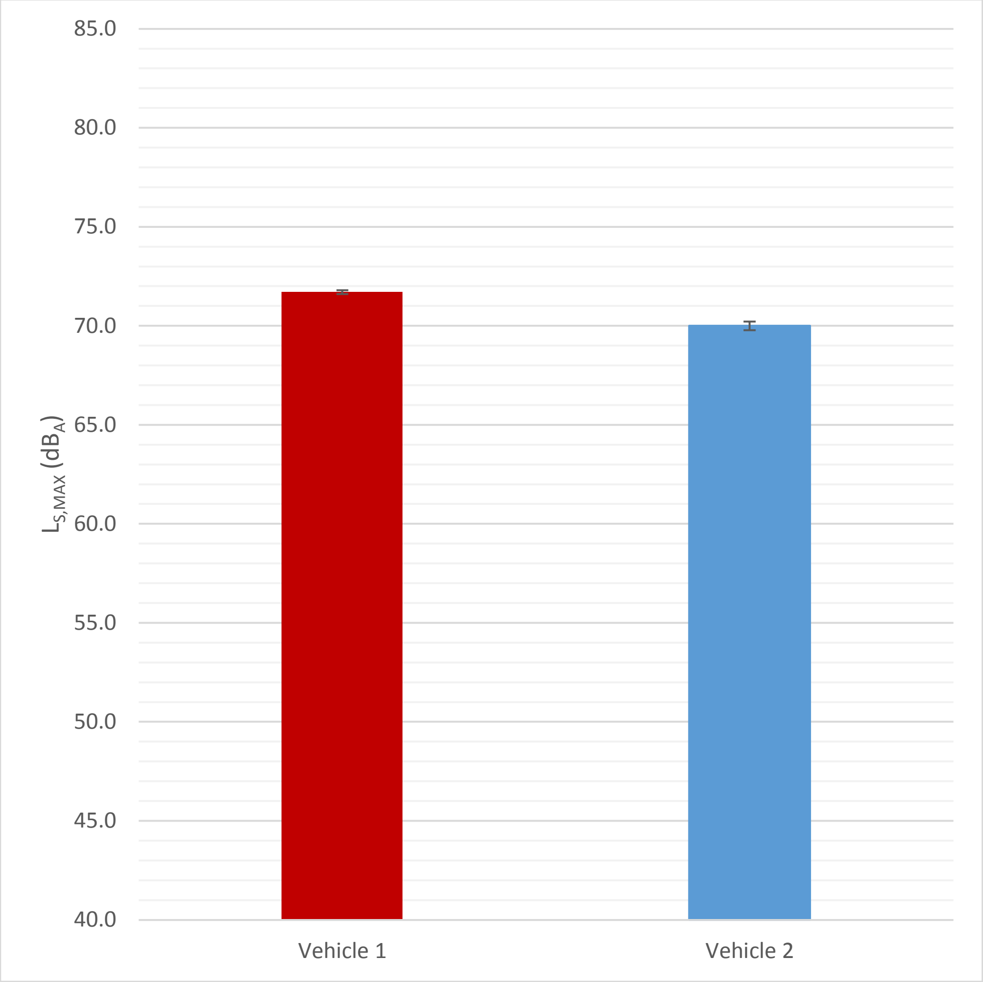

Figure 27 – Average $L_{S,MAX}$ registered during multiple 24 km/h pass-by tests of Vehicle 1 and Vehicle 2 on icy snow.

Vehicle 2 was only slightly quieter than Vehicle 1 during these tests. Vehicle 2 registered on average an $L_{S,MAX}$ of 70.0 dB_A while Vehicle 1 had an average $L_{S,MAX}$ of 71.7 dB_A. Vehicle 1 was within ±2 dB (the measurement error suggested by the SAE J1161 standard) of Vehicle 2. A comparison of these results to the results from *Influence of Power Plant Type (Part 1)* suggests that the difference between both vehicles is significantly dependent on the snow cover. However, if the effect of the decibel scale is considered, this difference between both vehicles on soft snow and hard snow disappears. The difference in sound pressure level between 60.4 dB_A and 67.3 dB_A is roughly +66.3 dB (using Equation 4; for incoherent sound sources) and the difference between 70.0 dB_A and 71.7 dB_A is roughly +66.8 dB. This similarity is an expected result as the principal difference between each snowmobile, the powertrain, should be largely unaffected by the terrain change. Subjectively, though, the snowmobiles should sound closer in loudness on icy terrain compared to soft terrain. Additionally, results show Vehicle 2 and Vehicle 1 are both significantly louder on icy terrain.

The range of each snowmobile for all tests was within ±0.3 dB for Vehicle 2 and ±0.1 dB for Vehicle 1. However, the limited number of tests with Vehicle 1 should induce some caution when considering the Vehicle 1 results. For comparative purposes, the Vehicle 1 results should be taken as a rough measure of the sound level in these conditions.

Figure 28 shows the sound level of both vehicles as a function of time during a typical test. The chart for the Vehicle 2 test and the Vehicle 1 test have been overlaid in such a way that their maxima are positioned at the same relative time (approximately 7 s on the x-axis).

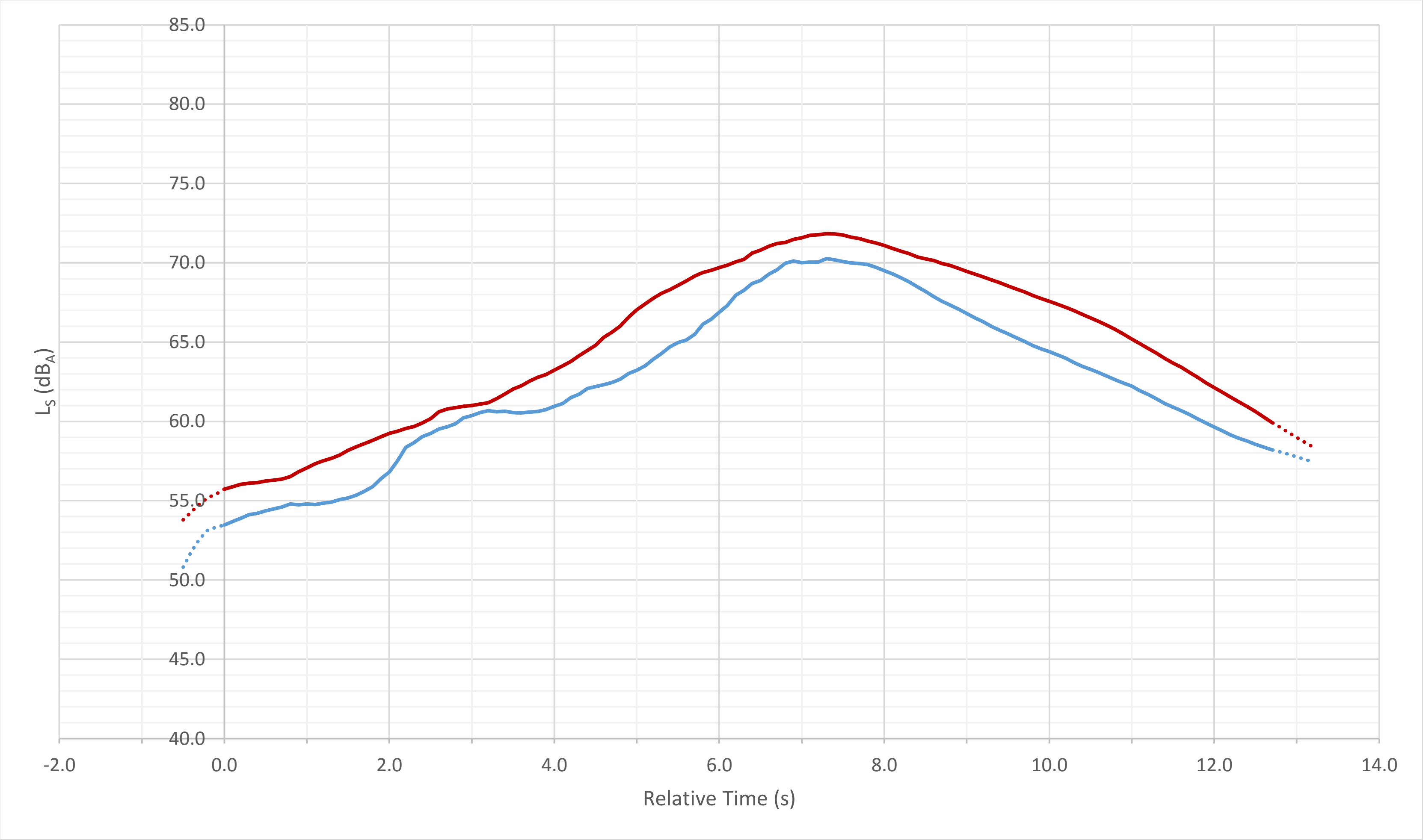

Figure 28 - Sound-level profile over time of a typical 24 km/h pass-by test of Vehicle 1 and Vehicle 2 on icy snow. The red lines represent the Vehicle 1 sound level and blue lines represent the Vehicle 2 sound level.

Over the course of the test Vehicle 2 is consistently quieter than Vehicle 1 but not many dBs quieter. If the start point is considered to be at approximately 3.6 s on the relative time axis, Vehicle 2 remains between 1.5 to 3 dB quieter than Vehicle 1 during the entire test (test length should be approximately 6.8 s long at 24 km/h). The difference, in dB, between both vehicles appears to decrease as the sound levels reach their maxima.

Figure 29 is a 1/3 octave band chart of the moment of maximum sound level for both snowmobiles. The chart ranges from the 12.5 Hz to 20 kHz band and has the overall sound level ($L_{S,MAX}$) as the right-most bar (labelled “A”). The values were registered using the S setting and the appropriate A-weighting gains have been applied to each band.

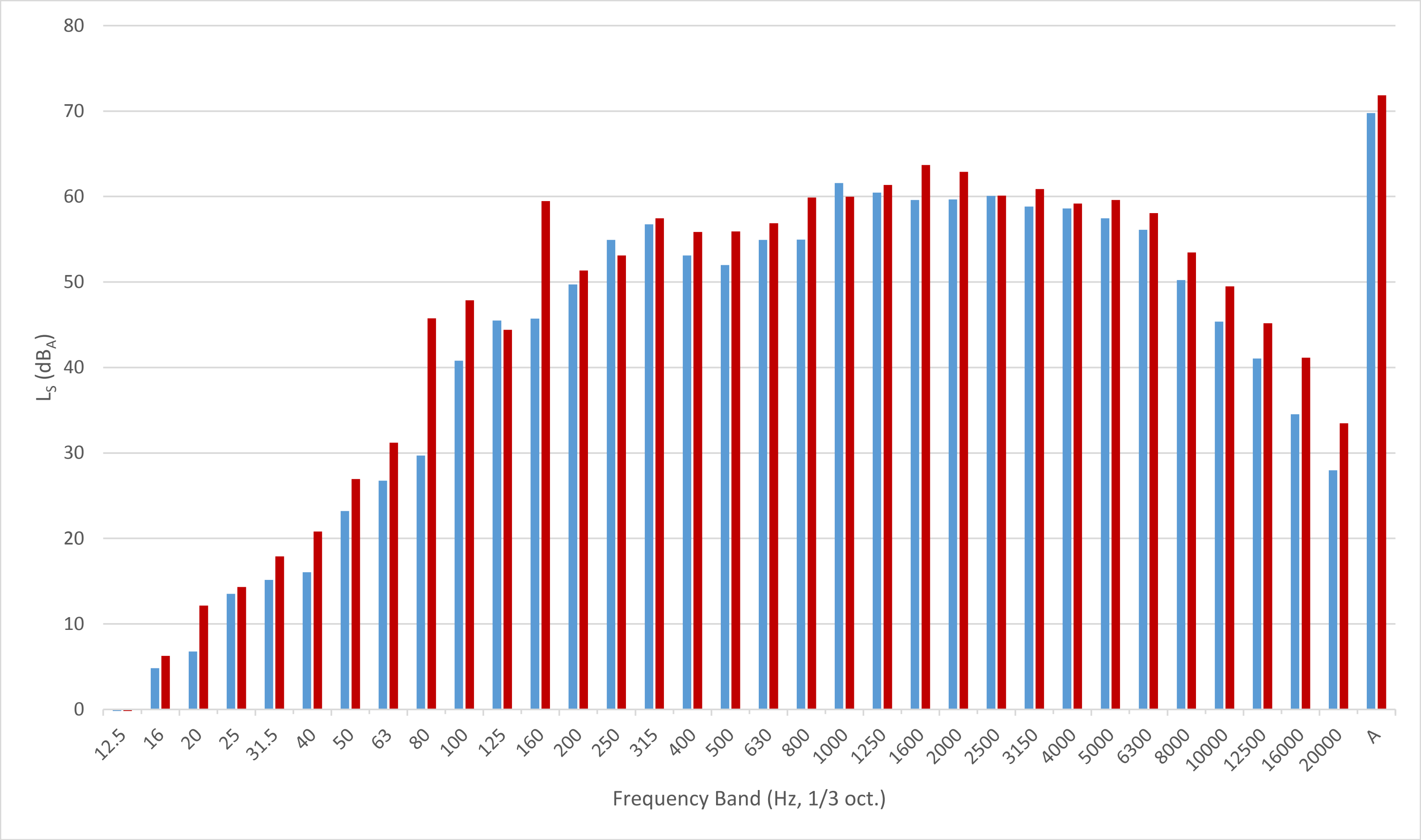

Figure 29 - 1/3 Octave band chart of the peak sound level registered during a typical 24 km/h pass-by test of Vehicle 1 and Vehicle 2 on icy snow. Red bars represent the Vehicle 1 distribution and blue bars represent the Vehicle 2 distribution.

In most bands from 315 Hz to 8 kHz, the difference between each vehicle is minimal and in some bands Vehicle 2 was louder. The increase in noise in these bands is likely due to the previously mentioned track-ground related noise since it is expected that a harder surface would induce more impact, would cause a greater transfer of vibration to the suspension and chassis and would dampen sound and vibration less. The Vehicle 1 spectrum exhibits a notable peak at 160 Hz, in common with the wet snow results. Distinct low frequency tones like this one may be audible at greater distances than higher frequency noise. Additionally, the peak at 80 to 100 Hz from the wet snow results have seemingly disappeared for the Vehicle 2 results but is still somewhat visible in the Vehicle 1 spectrum.

4.2.1.1 Summary

- A limited number of tests were done with Vehicle 1 and Vehicle 2 on icy snow (2 and 5, respectively).
- Vehicle 2 had an average $L_{S,MAX}$ of 70.0 dB_A and Vehicle 1 had an average $L_{S,MAX}$ of 71.1 dB_A at 24 km/h on icy snow.
- There was not a significant difference between the maximum sound levels registered from the left and right side passes of each vehicle and there was little variation from test-to-test.
- Both snowmobiles were substantially louder on icy snow as compared to wet snow (close to 10 dB difference for Vehicle 2 between snow types).
- In terms of decibels, the vehicles were closer in sound level (within 2 dB) as compared to their wet snow results.
- In terms of sound pressure, the difference between both vehicles remained at a similar level switching from wet to icy snow.
- Besides a peak at 160 Hz for Vehicle 1, both vehicles produced a mostly broadband noise distribution at the moment of maximum sound level.
- As with the wet snow results, Vehicle 1 exhibited a peak in the 160 Hz band which may have been due to the exhaust or other engine related noise sources.

4.3 Influence of Vehicle Speed

The following results are from a series of constant speed pass-by tests of Vehicle 2 and Vehicle 3 at 16, 24, 32 and 40 km/h on sticky snow. Four tests were done with each vehicle at each speed, 2 tests for each side. These results are from a single date.

The following results are from February 11th, 2013. On this date the ground cover consisted of sticky snow, snow that was in the process of freezing from a wet state and was nearly frozen. This snow type could be considered a soft snow type similar to wet or powder snow in firmness. The snow base was sufficiently compact to support the snowmobiles. The background noise level was recorded at 43.5 dB_A at test time. Other test conditions can be found in *List of Tests and Environmental Conditions*.

Figure 30 shows the average maximum sound level registered during these test series. The averages includes both left and right passes. The population standard deviation has been included with the average and is represented as error bars.

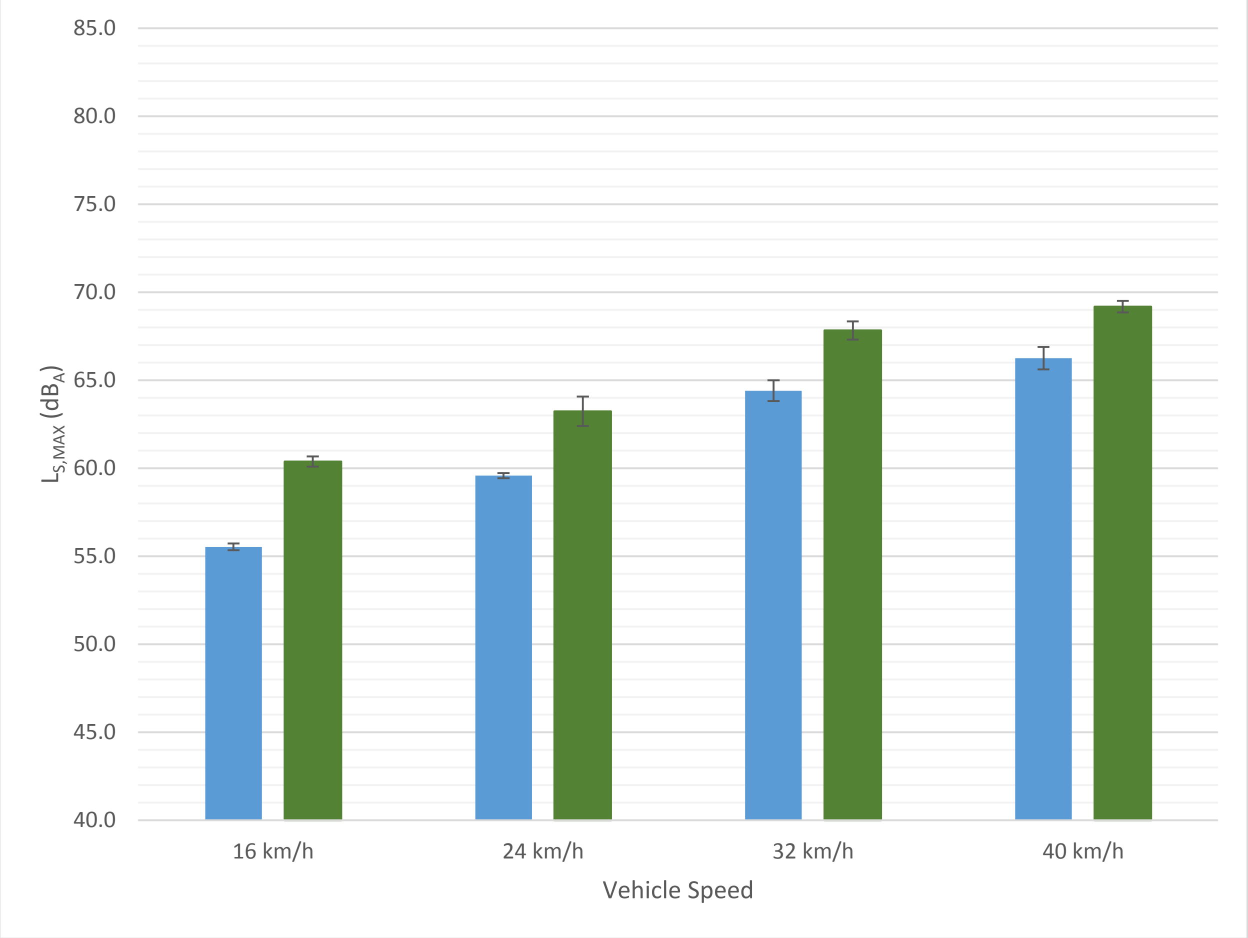

Figure 30 – Averages of maximum sound levels registered during multiple pass-by tests of Vehicle 2 and Vehicle 3 at 16, 24, 32 and 40 km/h on sticky snow. Blue bars represent the Vehicle 2 sound levels and green bars represent Vehicle 3 sound levels.

Vehicle 3 was consistently louder than Vehicle 2 at all four speeds. The difference between their sound levels appears to decrease with speed (4.8 dB difference at 16 km/h, 3.6 dB at 24 km/h, 3.4 dB at 32 km/h, 2.9 dB at 40 km/h). However, if accounting for the decibel scaling, the difference between the vehicles' sound level, in terms of sound pressure, increases with speed (described by Equation 4). So, although the vehicles may appear to be converging in sound level at higher speeds, they are actually diverging somewhat.

The ranges for the Vehicle 2 tests were within ±0.3, ±0.2, ±0.75 and ±0.8 dB for the 16, 24, 32 and 40 km/h pass-by series, respectively. The range for the Vehicle 3 tests were within ±0.4, ±1.2, ±0.7 and ±0.5 dB for the 16, 24, 32 and 40 km/h pass-by series, respectively.

Structurally and mechanically, both vehicles have significant differences. Vehicle 2 is a wide track model. It has a wider and longer track with longer lugs than Vehicle 3 (20 in x 154 in x 1.5 in vs. 15 in. x 144 in. x 1.25 in.). Vehicle 2 has a 2-speed gear box transmission while Vehicle 3 has a sealed chain drive. Vehicle 2 is powered by an electric motor while Vehicle 3 is powered by a 4-stroke engine. They also have different chassis. With so many differences between the vehicles it is inadvisable to draw any conclusions related to any individual noise source based on these results.

The simple conclusion from these results is that both vehicles become louder as speed increases and that their noise levels increase in differing amounts.

The comparison may have differed on another snow surface type. A single pass-by test done with Vehicle 3 at 24 km/h on January 21st, 2013 (icy snow) produced an $L_{S,MAX}$ of 61.5 dB_A, while on the same day Vehicle 2 produced an $L_{S,Max}$ of 65.4 dB_A (see *Influence of Snow Type*). It may be worth retrying these varying constant speed tests on icy snow to compare with results from this section.

Figure 31 and Figure 32 are 1/3 octave band charts (a chart and a line chart) of the moment of maximum sound level for Vehicle 2 for typical tests for each speed. The charts range from the 12.5 Hz to 20 kHz band and have the overall sound level ($L_{S,MAX}$) as the right-most bar (labelled "A"). The values were registered using the S setting and the appropriate A-weighting gains have been applied to each band.

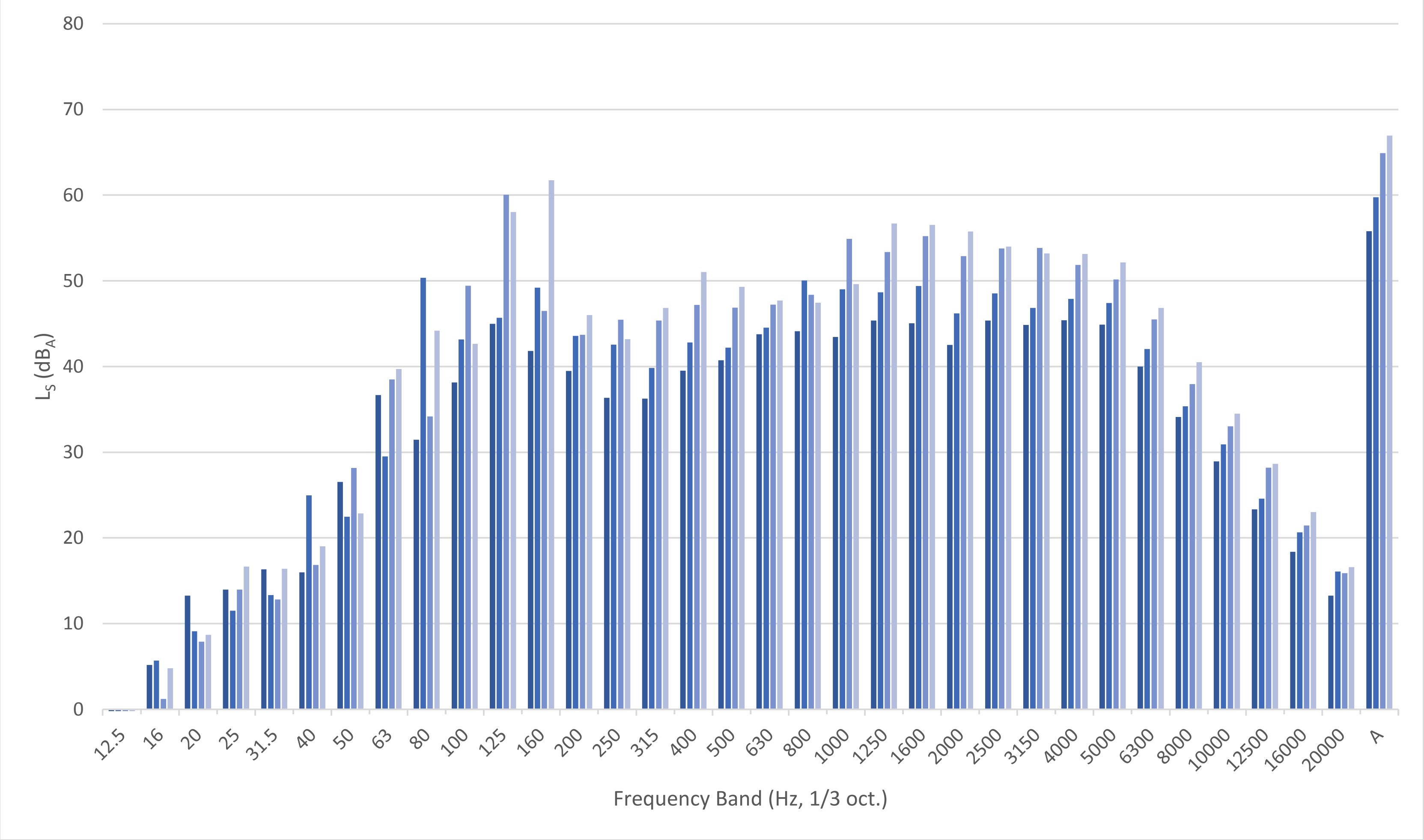

Figure 31 – 1/3 Octave band chart of the peak sound level recorded during typical pass-by tests of Vehicle 2 at 16, 24, 32 and 40 km/h on sticky snow. Results are ordered by speed; darkest blue represent the 16 km/h results while lightest represent 40 km/h.

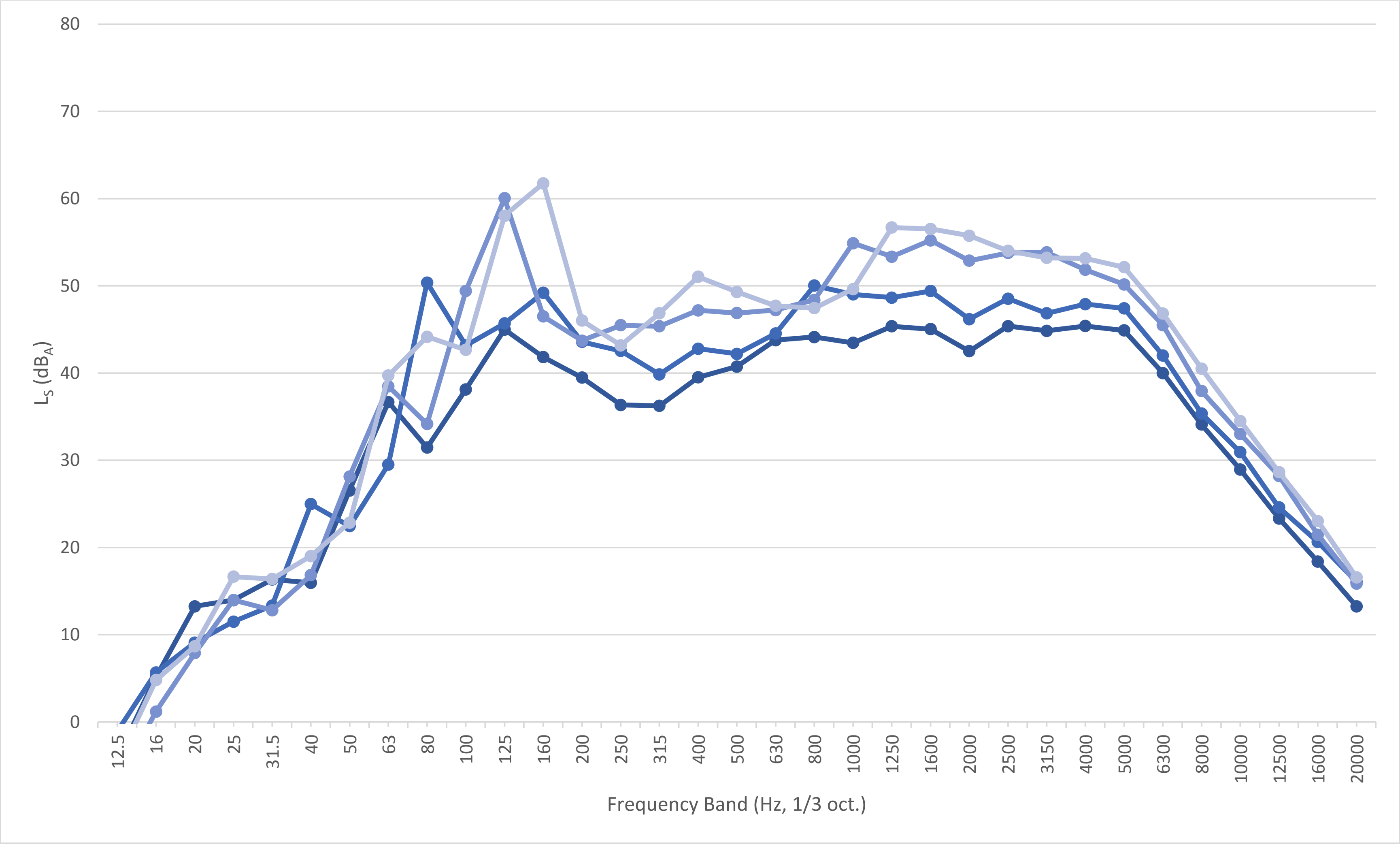

Figure 32 - 1/3 Octave band line chart of the peak sound level recorded during typical pass-by tests of Vehicle 2 at 16, 24, 32 and 40 km/h on sticky snow. Results are ordered by darkness; darkest blue represent 16 km/h results while lightest represent 40 km/h.

In most bands, the sound level increases with each increase in speed, particularly in certain regions of the frequency profile. The peak at 80-100 Hz at 24 km/h (which also appears in testing on wet snow at 24 km/h) appears to exist at 63 Hz at 16 km/h; pass to 80-100 Hz bands at 24 km/h, to 100-125 Hz at 32 km/h and to 125-160 Hz at 40 km/h. As stated in *Influence of Power Plant Type (Part 1)*, this peak may be due to track rod-bogie wheel impact, drive sprocket-track meshing or lug-ground impact as fundamental frequencies of all three occurrences would fit into these frequency bands at these test speeds. As stated in other sections, the low frequency peaks may impact the audibility of the vehicle over extended distances. Lastly, as the vehicle increases in speed, the bands in the 1.25 kHz to 5 kHz range become more prevalent.

Figure 33 and Figure 34 are 1/3 octave band charts (a bar chart and a line chart) of the moment of maximum sound level for typical tests of Vehicle 3 at each speed. The charts range from the 12.5 Hz to 20 kHz band and have the overall sound level ($L_{S,MAX}$) as the right-most bar (labelled “A”). The values were registered using the S setting and the appropriate A-weighting gains have been applied to each band.

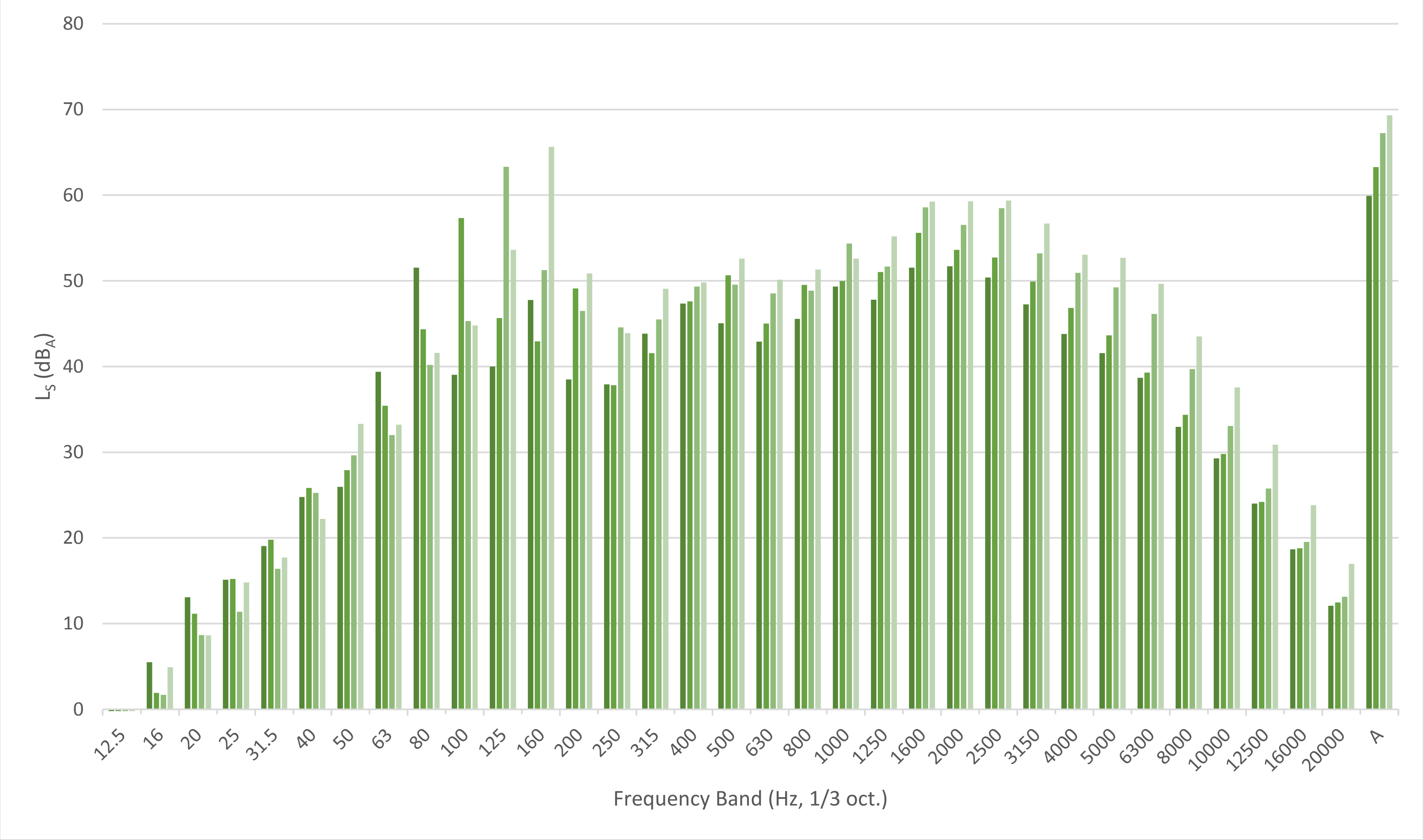

Figure 33 -1/3 Octave band chart of the peak sound level recorded during typical pass-by tests of Vehicle 3 at 16, 24, 32 and 40 km/h on sticky snow. Results are ordered by darkness; darkest green represent 16 km/h results while lightest represent 40 km/h.

Figure 34 -1/3 Octave band line chart of the peak sound level recorded during typical pass-by tests of Vehicle 3 at 16, 24, 32 and 40 km/h on sticky snow. Results are ordered by darkness; darkest green represent 16 km/h results while lightest represent 40 km/h.

Similar to the Vehicle 2 results, the Vehicle 3 results show a peak that seems to shift frequency with vehicle speed. The peak appears at 80 Hz at 16 km/h and passes to 100 Hz at 24 km/h, 125 Hz at 32 km/h and 160 Hz at 40 km/h. The 16 km/h and 24 km/h results show a possible second harmonic peak at 160 Hz and 200 Hz, respectively. As stated in other sections, the low frequency peaks may impact the audibility of the vehicle over extended distances. The sound level does not uniformly increase across all bands as the vehicle speed increases. The increases mostly occur in the bands from 1.25 to 20 kHz as the vehicle speed increases.

With a 4-stroke, 2 cylinder engine, Vehicle 3 should have a fundamental frequency of combustion related noise at roughly the speed of the engine (Equation 9). Although the speed of the engine is unknown, the aforementioned peak (at 100 Hz at vehicle speed of 24 km/h) is unlikely to have been caused by the exhaust or other combustion related components since this would correspond to an engine speed of 6000 RPM (a very fast speed) with a fundamental frequency of 100 Hz at 24 km/h (it could be a second harmonic of the engine firing). The track or drive sprocket is a more likely source of the noise since the expected frequency for noise related to these sources follows this peak (see Table 1).

A detailed noise source analysis is beyond the scope of this research. A more comprehensive analysis using more vehicle information or noise source identification with an acoustical array are possible future methods that could more conclusively determine noise sources and their contributions to the overall noise of the vehicles.

4.3.1.1 Summary

- Vehicle 2 had an average $L_{S,MAX}$ of 55.5, 59.6, 64.4 and 66.3 dB_A at 16, 24, 32 and 40 km/h, respectively.
- Vehicle 3 had an average $L_{S,MAX}$ of 60.4, 63.2, 67.8 and 69.2 dB_A at 16, 24, 32 and 40 km/h, respectively.
- In terms of dBs, their sound level converges with increasing speed while in terms of sound pressure their sound level diverges with increasing speed.
- Both vehicles have distinct tones at low frequencies which appear to shift in frequency with changes in vehicle speed.
    - Vehicle 2 has a distinct peak that migrates from the 63 Hz band to the 125-160 Hz bands from 16 km/h to 40 km/h.
    - Vehicle 3 has a distinct peak that migrates from the 80 Hz band to the 160 Hz band.

4.4 Influence of Snow Type

The following results are from a series of constant speed 24 km/h pass-by tests of Vehicle 1, Vehicle 2 and Vehicle 3 on powder snow, wet snow, sticky snow and icy snow. Some of these results have already been presented, including the results from test dates with wet snow, sticky snow and one of the icy snow dates. More information on these series can be found in *Influence of Power Plant Type (Part 1)*, *Influence of Power Plant Type (Part 2)* and *Influence of Vehicle Speed*. Tests done on powder snow and a second, preliminary, set of tests on another icy snow date have been added. These additional tests were each from single dates.

The previously undiscussed series of tests on powder snow are from February 11th, 2013. On this date the ground cover consisted of powder snow with a base sufficiently compact to support the test snowmobile. The background noise level was measured to be 52.2 dB_A at test time. Other test conditions can be found in *List of Tests and Environmental Conditions*.

The previously undiscussed series of tests on icy snow are from January 21st, 2013. This "preliminary" set of tests on icy snow is so-called because only 1 test was performed with Vehicle 3 and Vehicle 1 and only 2 tests were performed with Vehicle 2. This detail must be taken into account when interpreting results from this date. The background noise level was measured to be 44.0 dB_A at test time. Other test conditions can be found in *List of Tests and Environmental Conditions*.

Figure 35 shows the average maximum sound level registered during these test series. The average includes both sides. The population standard deviation of these series has been included and is represented as error bars. The faded bars with hashed outlines indicate single-test results. Missing bars (example: Vehicle 1 on powder snow) indicate test data that has not been collected for these dates/conditions.

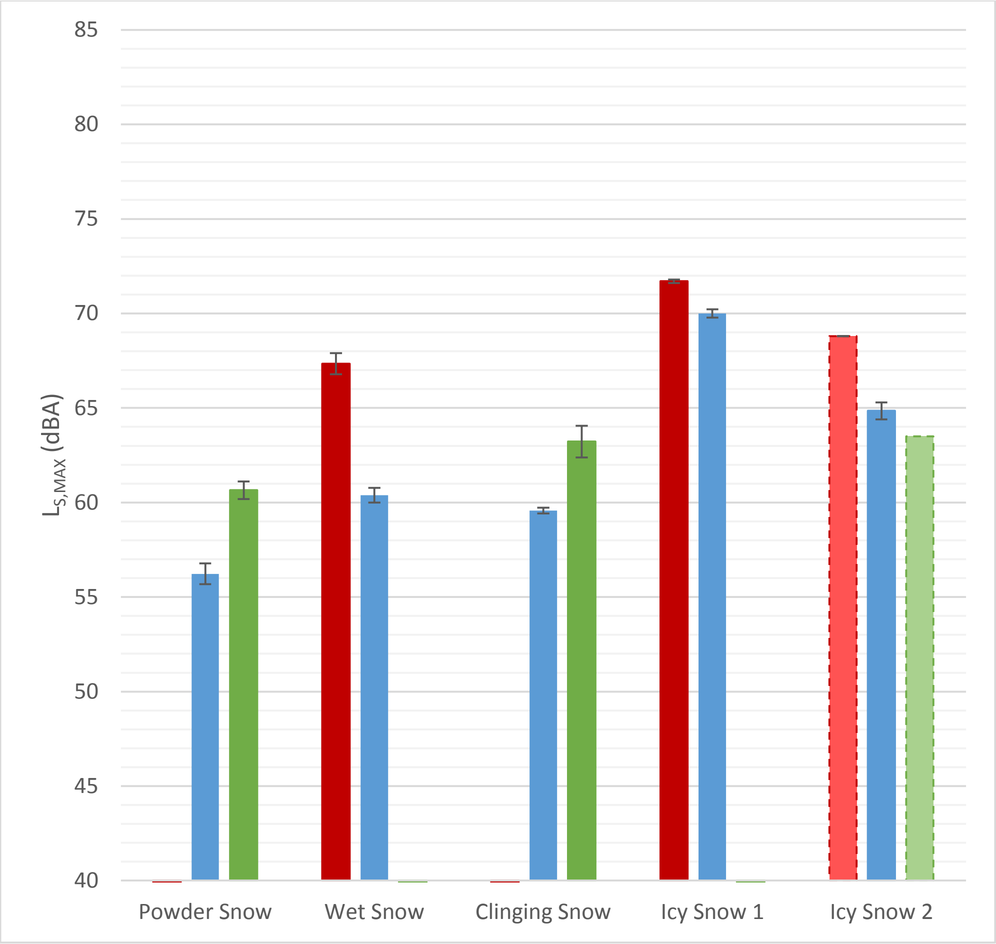

Figure 35 – Results of 24 km/h pass-by tests (some averaged, some single tests) on a variety of surface types. Red bars represent Vehicle 1 results, blue bars represent Vehicle 2 results and green bars represent Vehicle 3 results. Bars with dashed lines indicate single tests.

From the combined results it is clear that snow type has a substantial effect on these vehicles' sound level at 24 km/h. On powder snow Vehicle 2 produced an average $L_{S,MAX}$ of 56.2 dB_A at 24 km/h compared with 60.4 dB_A on wet snow and both 70.0 dB_A and 64.9 dB_A on icy snow. Vehicle 2 can therefore be over 4 times louder (+12 dB) depending on the snow cover. Although there is less data for Vehicle 1, the test results have shown that snow condition has an effect on sound level for this vehicle as well. For Vehicle 1, the difference between a soft snow type (wet snow) and a hard snow type[21] (icy snow; "Icy Snow 1" in Figure 35) is roughly 4.4 dB. The snow type seems to have less of an effect on Vehicle 3. The difference between a soft snow type (wet snow) and a hard snow type (icy snow, "Icy Snow 2" in Figure 35) was roughly 2.5 dB. Although Vehicle 1 and Vehicle 3 were only tested together on

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[21] The Vehicle 1 average from the first icy snow date (Icy Snow 1) consists of only 2 runs, see *Influence of Power Plant Type (Part 2)*.

the second icy snow date ("Icy Snow 2" in Figure 35; based on only 1 test) Vehicle 3 seems to be the quieter snowmobile regardless of snow type. Interestingly, Vehicle 3 appears quieter than Vehicle 2 on icy snow, when it is louder than Vehicle 2 on soft snow types. Unfortunately, not enough tests were completed on the Icy Snow 2 date to insure that these results were not an anomaly. However, if test-to-test fluctuations in $L_{S,MAX}$ of other dates are an indication of typical ranges to expect, the Vehicle 1 and Vehicle 3 averages would have been within ±1 to 2 dB of these preliminary values had more tests been completed.

The range for Vehicle 2 tests on powder snow was within ±0.8 dB and the range for the second set of tests on icy snow (Icy Snow 2) was within ±0.5 dB (but the average consists of only 2 tests). The range for Vehicle 3 tests on powder snow was within ±0.6 dB. Range information for other ground cover type/dates can be found in the appropriate sections.

The 2012 Ski-Doo Skandic WT (the model of Vehicle 1 and the base of Vehicle 2) is a wide track snowmobile. The Skandic track is wider and longer and its track has longer lugs than Vehicle 3. The greater effect of the ground cover type on Vehicle 1 and Vehicle 2 as compared to Vehicle 3 is possibly due to the differences in their tracks. Furthermore, Vehicle 3 has a 4-stroke engine while Vehicle 1 has a 2-stroke engine among other mechanical and structural differences. These vehicles are different enough that it would be inadvisable to suggest any one component is the cause of the noise level differences of Vehicle 1 and Vehicle 3.

4.4.1.1 Summary

- Depending on the ground cover, Vehicle 2 could range in $L_{S,MAX}$ from approximately 56 to 70 dB_A during a 24 km/h pass-by test but on any specific date each set of tests would generally be within ±1 dB.
- A limited number of tests were done with Vehicle 3 and Vehicle 1 on some of the ground surface types.
    - Further testing on hard snow surfaces (icy snow) would be required to expand this research from the preliminary stage.
- Depending on the ground cover, Vehicle 1 could range in $L_{S,MAX}$ from approximately 67 to 72 dB_A during a 24 km/h pass-by test but on any specific date each set of tests would generally be within ±1 dB.

- Depending on the ground cover, Vehicle 3 could range in $L_{S,MAX}$ from approximately 61 to 64 dB_A during a 24 km/h pass-by test but on any specific date each set of tests would generally be within ±1.25 dB.
- All three snowmobiles were louder on hard snow conditions (icy snow) as compared to soft snow conditions, such as powder snow.

4.5 Steady Speed Comparison of 2014 Vehicle with 2003 Vehicle

The following results are from a series of 24 km/h constant speed pass-by tests performed with Vehicle 4, a more than decade old snowmobile, and Vehicle 5, a new snowmobile a number of noise reduction technologies, on powder snow. Four tests were performed with Vehicle 4 and Vehicle 5 each. The number of tests is limited (enough to disqualify it from official use for the SAE J1161 standard) but is enough to offer insight into each snowmobile. The deviation in results for individual tests was limited. For each snowmobile, 2 tests were completed with the microphone at the right of the vehicle and 2 tests were completed with the microphone at the left of the vehicle.

These results are from February 27th, 2015. On this date the ground cover consisted of powder snow, with some give, but with a firm enough base to support the snowmobiles. At test time, the background noise level was measured to be 41.2 dB_A and the principal sources of background noise were the nearby highway (see *Test Locations*) and wind. Other test conditions can be found in *List of Tests and Environmental Conditions*.

Figure 36 shows the average maximum sound levels registered during this test series. This average includes results from both sides (see *Deviations from Pass-by Standards*). The population standard deviation of these series is included with the average $L_{S,MAX}$ and is represented as error bars.

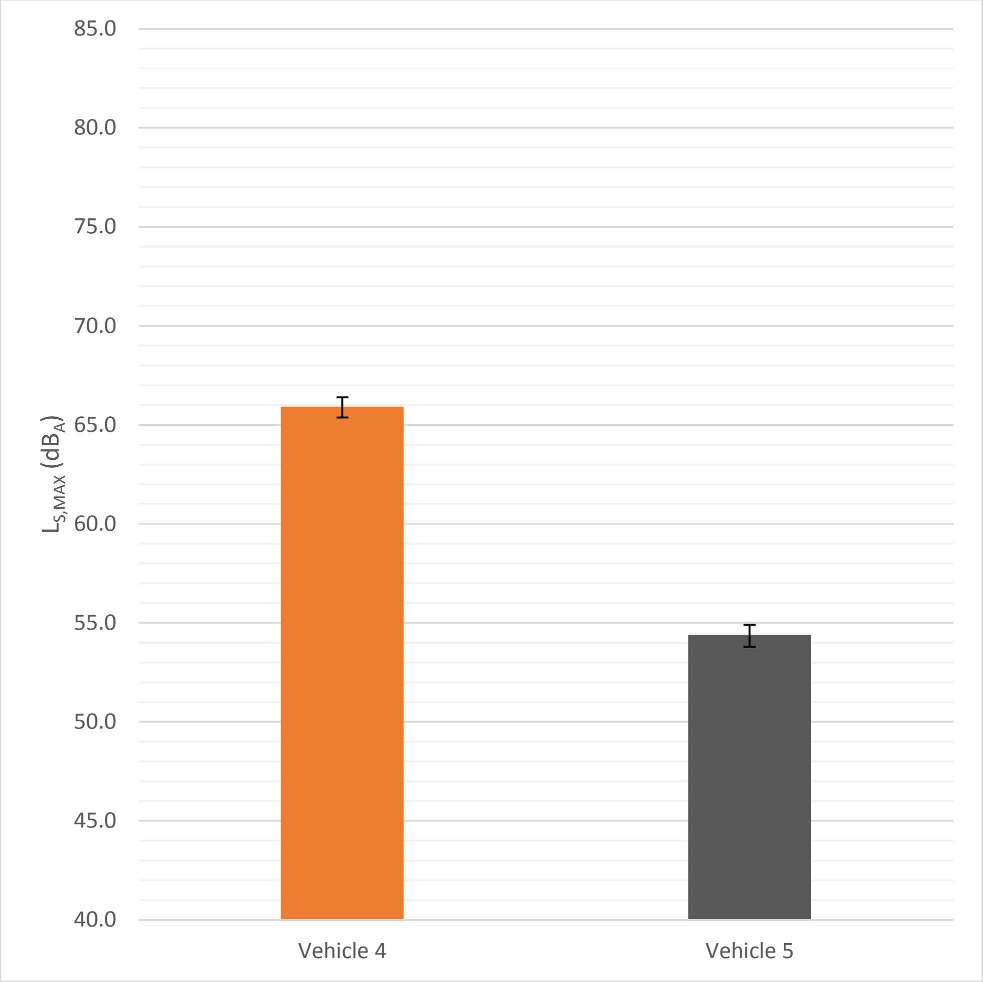

Figure 36 - Average $L_{S,MAX}$ registered during multiple 24 km/h pass-by tests of Vehicle 4 and Vehicle 5 on powder snow.

At this speed there is a significant difference in sound level between each snowmobile. On average, Vehicle 4 had 65.9 dB$_A$ while Vehicle 5 had an $L_{S,MAX}$ of 54.4 dB$_A$. The difference between each vehicle was greater than 10 dB, Vehicle 4 having more than double the sound level of Vehicle 5.

The ranges for the Vehicle 4 and Vehicle 5 series were each within ±0.7 dB. With such a close range, the additional test required on either side for the SAE J1161 standard would likely not have significantly influenced the results (if the standard deviation is used as an indication). Additionally, the difference between an average of the left and right sides was less than 1 dB for both vehicles in line with the findings of [48]. Since there is a difference between an average of the left and right sides, however, it should be noted that the inclusion of both sides in the average has resulted in a slightly lower value than if the greater of averages of the left and right side passes was presented as the result (as the SAE standards require).

Figure 37 shows the sound level of both vehicles as a function of time during a typical test. The graphs of typical tests performed by Vehicle 4 and Vehicle 5 were overlaid in such a way that their maxima are positioned at the same relative time (at approximately 6.9 s).

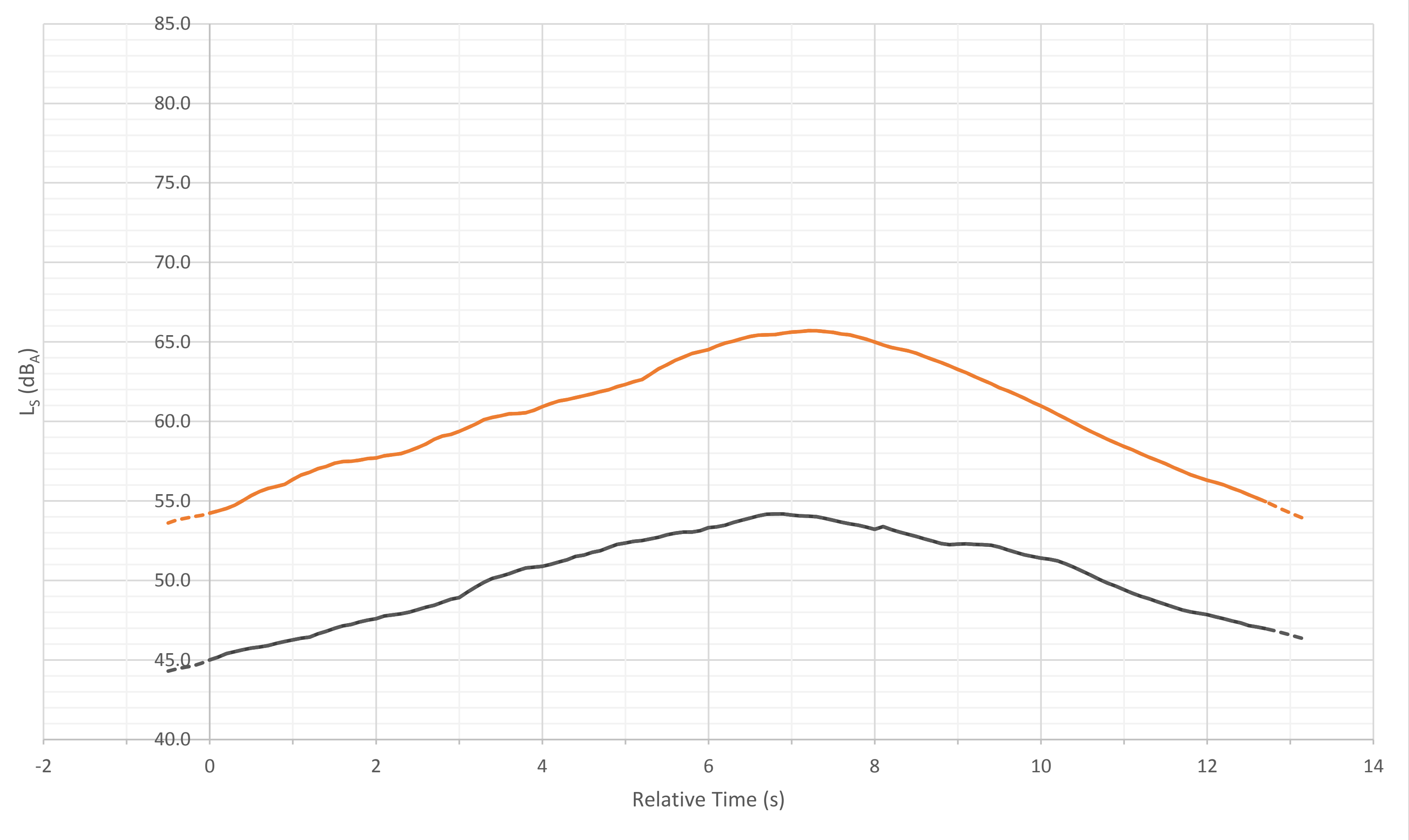

Figure 37 – Sound level versus time line chart of typical 24 km/h pass-by tests of Vehicle 4 and Vehicle 5 on powder snow. The orange lines represent the Vehicle 4 sound level and black lines represents Vehicle 5.

Over the course of these tests, Vehicle 5 was consistently quieter than Vehicle 4. If the start point is considered to be at approximately 4 s on the relative time axis, Vehicle 5 remains at least 9 dB quieter than Vehicle 4 during the entire test.

Figure 38 is a 1/3 octave band chart of the moment of maximum sound level for both snowmobiles. The chart ranges from the 12.5 Hz band to the 20 kHz band and has the overall sound level ($L_{S,MAX}$) as the right-most bar (labelled “A”). The values were registered using the S setting and the appropriate A-weighting gains have been applied to each band.

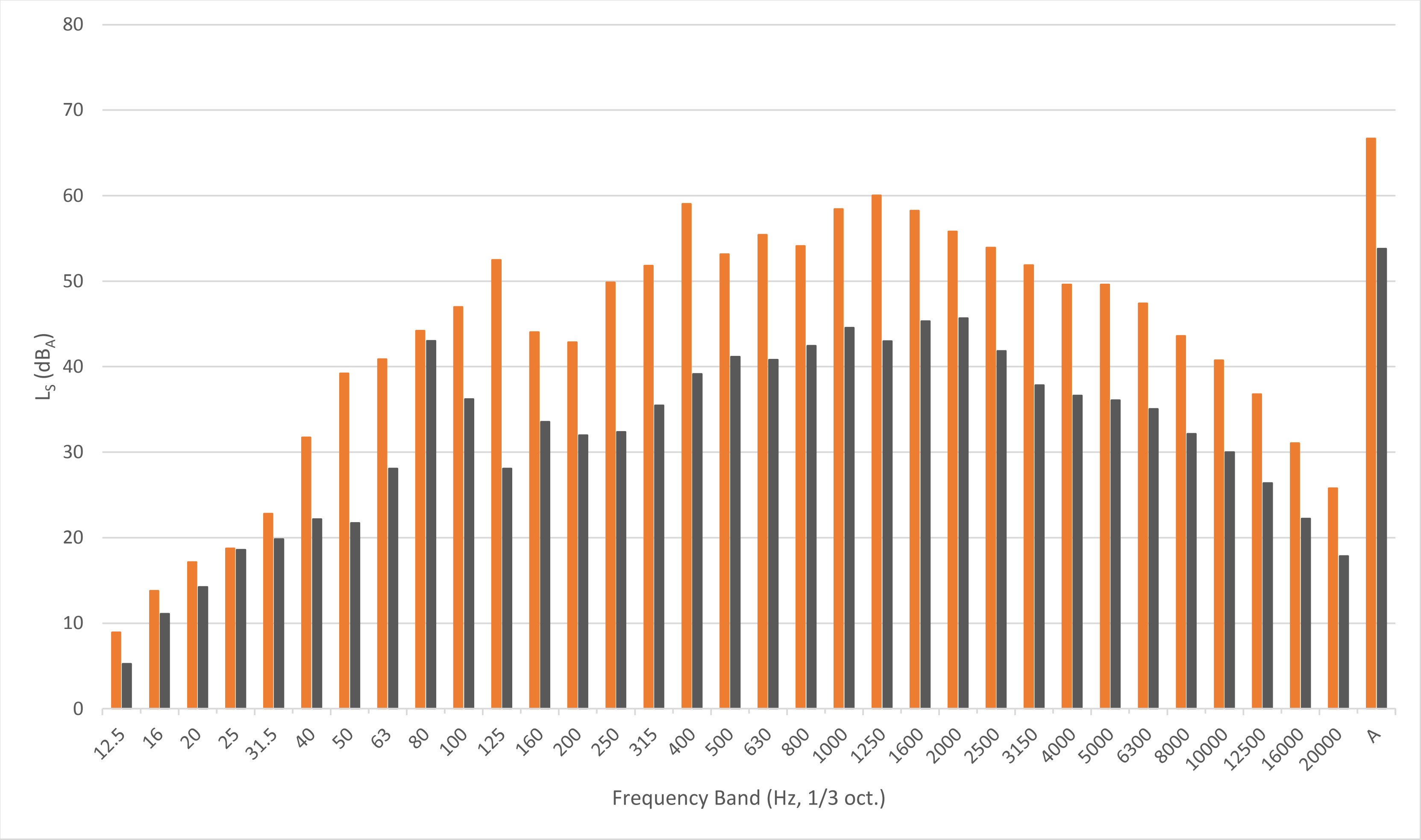

Figure 38 - 1/3 Octave band chart of the peak sound level registered during a typical 24 km/h pass-by test of Vehicle 4 and Vehicle 5 on powder snow. The orange bars represent the Vehicle 4 distribution and black bars represent the Vehicle 5 distribution.

In all bands Vehicle 4 was louder than Vehicle 5. There are certain bands where the difference between each profile is most pronounced. Vehicle 4 has notable peaks at 125 Hz and 400 Hz. Otherwise, it has a relatively flat response with a broadband distribution (taking into account the applied A-weighting gains). Vehicle 5 has a peak in the 80 Hz band but is otherwise relatively broadband in distribution. Besides Vehicle 5's 80 Hz peak, Vehicle 4 is considerably louder than Vehicle 5 from 40 Hz to 20 kHz.

With a variable transmission, unknown ratio of the chain drive and no record of the engine speeds of the vehicles, more information is required to attempt even a preliminary source analysis based on frequency. Although, a few hypotheses include:

- The vehicle exhaust (or another noise source connected to engine combustion) may be the cause of the 80 Hz peak in the Vehicle 5 results since an 80 Hz fundamental frequency of the exhaust corresponds to a reasonable engine speed of 4800 RPM with a 2 cylinder, 4 stroke engine (Equation 9).
- Based on the speed of the vehicle and vehicle characteristics, noise caused by Vehicle 5's track lugs and imbedded support rod-bogie wheel impacts should have a fundamental frequency of roughly 100 Hz while the drive sprocket-track meshing should be at roughly 180 Hz.
    - Neither of these potential peaks are visible in the frequency profile.
- The vehicle exhaust (or another noise source connected to the engine combustion) may be the cause of the 125 Hz peak in the Vehicle 4 results since a 125 Hz dominant frequency of the exhaust would correspond to a reasonable engine speed of 3750 RPM with a 2 cylinder, 2 stroke engine (Equation).

Both frequency responses are sufficiently broadband in distribution that these peaks do not contribute significantly to the overall noise level. However, based on the work of [43] distinct tones at lower frequencies (below 250 Hz) may travel further than higher frequency noise, even if the lower frequency tones represent a small fraction of the overall noise level at 15 m. Recalling that A-weighting is a psychoacoustic concept and thus has no bearing on the propagation of noises, the distinct tones at 125 Hz in the Vehicle 4 response and 80 Hz in the Vehicle 5 response are undervalued in Figure 38 when it comes to their ability to propagate. These distinct tones may cause either vehicle to be audible at significant distances in quiet environments.

A detailed noise source analysis is beyond the scope of this research. A more comprehensive analysis using more vehicle information or noise source identification with an acoustical array are possible future methods that could more conclusively determine noise sources and their contributions to the overall noise of the vehicles.

4.5.1.1 Summary

- Vehicle 4 had an average $L_{S,MAX}$ of 65.9 dB_A and Vehicle 5 had an average $L_{S,MAX}$ of 54.4 dB_A at 24 km/h on powder snow.
- There was no significant difference between the maximum sound levels registered from the left and right side passes of each vehicle and there was little variation between either vehicle, test-to-test.
- The frequency content of typical tests with either snowmobile were mostly broadband in their distribution with spikes at 125 and 400 Hz for Vehicle 4 and 80 Hz for Vehicle 5.
- The exhaust or other engine related noise could conceivably be responsible for the 80 and 125 Hz peaks in the Vehicle 4 and Vehicle 5 respective frequency profiles.

4.6 Full Throttle Comparison of 2014 Vehicle with 2003 Vehicle

Having illustrated and discussed the constant speed noise of Vehicle 4 and Vehicle 5, this section will consider the full throttle noise of both vehicles. The following results are from a series of full throttle pass-by tests performed with Vehicle 4 and Vehicle 5 on powder snow. Four tests each were done with Vehicle 4 and Vehicle 5. The number of tests is limited (enough to disqualify it from official use for the SAE J192 standard) but is enough to offer insight into each snowmobile. For each snowmobile, 2 tests were completed with the microphone at the right of the vehicle and 2 tests were completed with the microphone at the left of the vehicle.

These results are from February 27th, 2015. On this date the ground cover consisted of powder snow, with some give, but with a firm enough base to support the snowmobiles. At test time, the background noise level was recorded at 41.2 dB_A and the principal sources of background noise were the nearby highway (see *Test Locations*) and wind. Other test conditions can be found in *List of Tests and Environmental Conditions*.

Figure 39 shows the average maximum sound level registered during this test series. The displayed average is an average of all tests, left and right passes inclusive. The population standard deviation has been included with the averages and is represented as error bars.

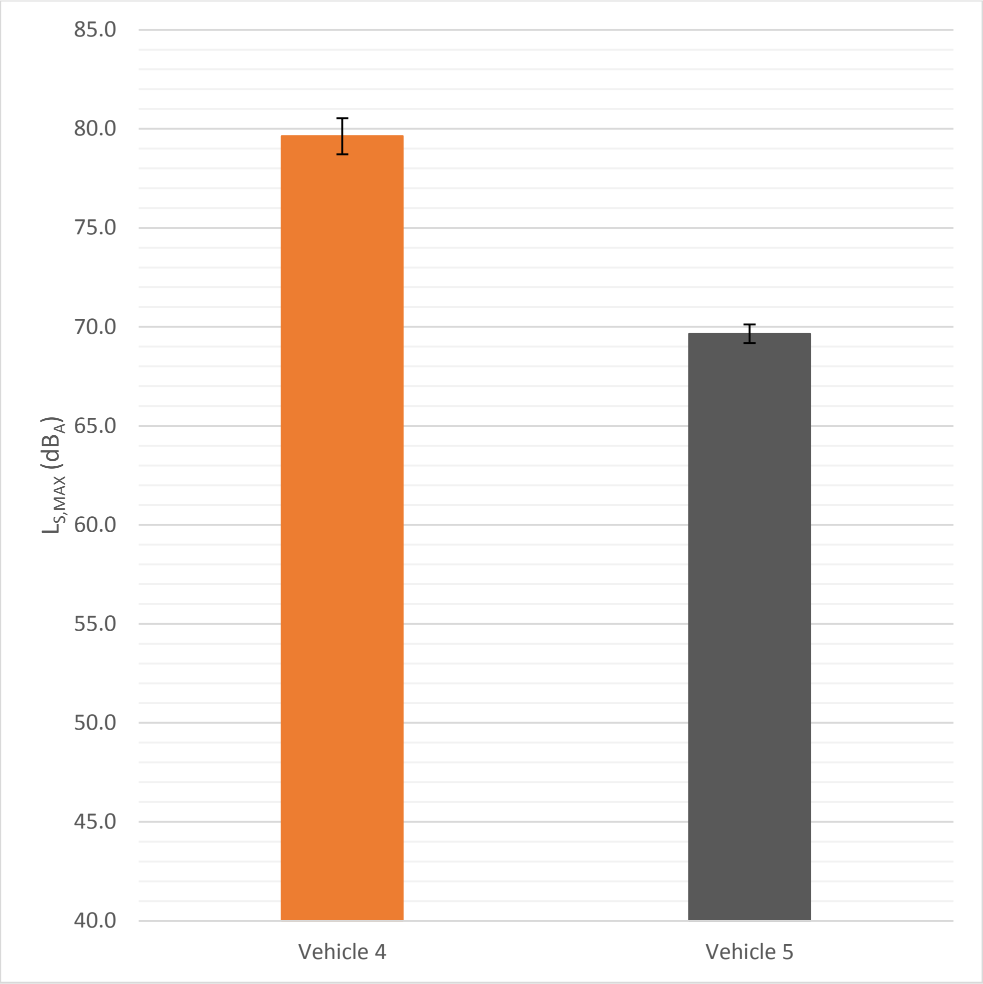

Figure 39 - Average $L_{S,MAX}$ registered during multiple full throttle pass-by tests of Vehicle 4 and Vehicle 5 on powder snow.

At full throttle, as with the 24 km/h constant speed tests, there is a significant difference in sound level between each snowmobile. On average, Vehicle 4 registered an $L_{S,MAX}$ of 79.6 dB$_A$ while Vehicle 5 registered on average 69.7 dB$_A$. The difference between each vehicle is roughly 10 dB, Vehicle 4 having more than double the sound level of Vehicle 5 at full throttle.

The ranges for both sets of tests included in the averages were within ±1.25 dB for Vehicle 4 and ±0.6 dB for Vehicle 5. With a range within ±1.25 dB, the inconsistency of the Vehicle 4 series suggests additional tests may have had a small effect on the Vehicle 4 average. The difference between the averages of either side was less than 1 dB for both vehicles and so choosing an overall average over an average of the louder side did not greatly affect the result.

The extra 50 horsepower of Vehicle 4 over Vehicle 5 may have contributed to the higher noise level of Vehicle 4 at full throttle. However, during testing Vehicle 4 did not have a noticeably greater acceleration than Vehicle 5 despite the +50 HP according to the driver and the technician.

Figure 40 shows the sound level of both vehicles as a function of time during a typical test. The Vehicle 4 test and the Vehicle 5 test were overlaid in such a way that the beginning of each sharp slope (at around 3 s on the chart) were lined up. This point indicates a sharp increase in acceleration or opening of the throttle for both vehicles and should be roughly at the point where the snowmobiles crossed the starting point.

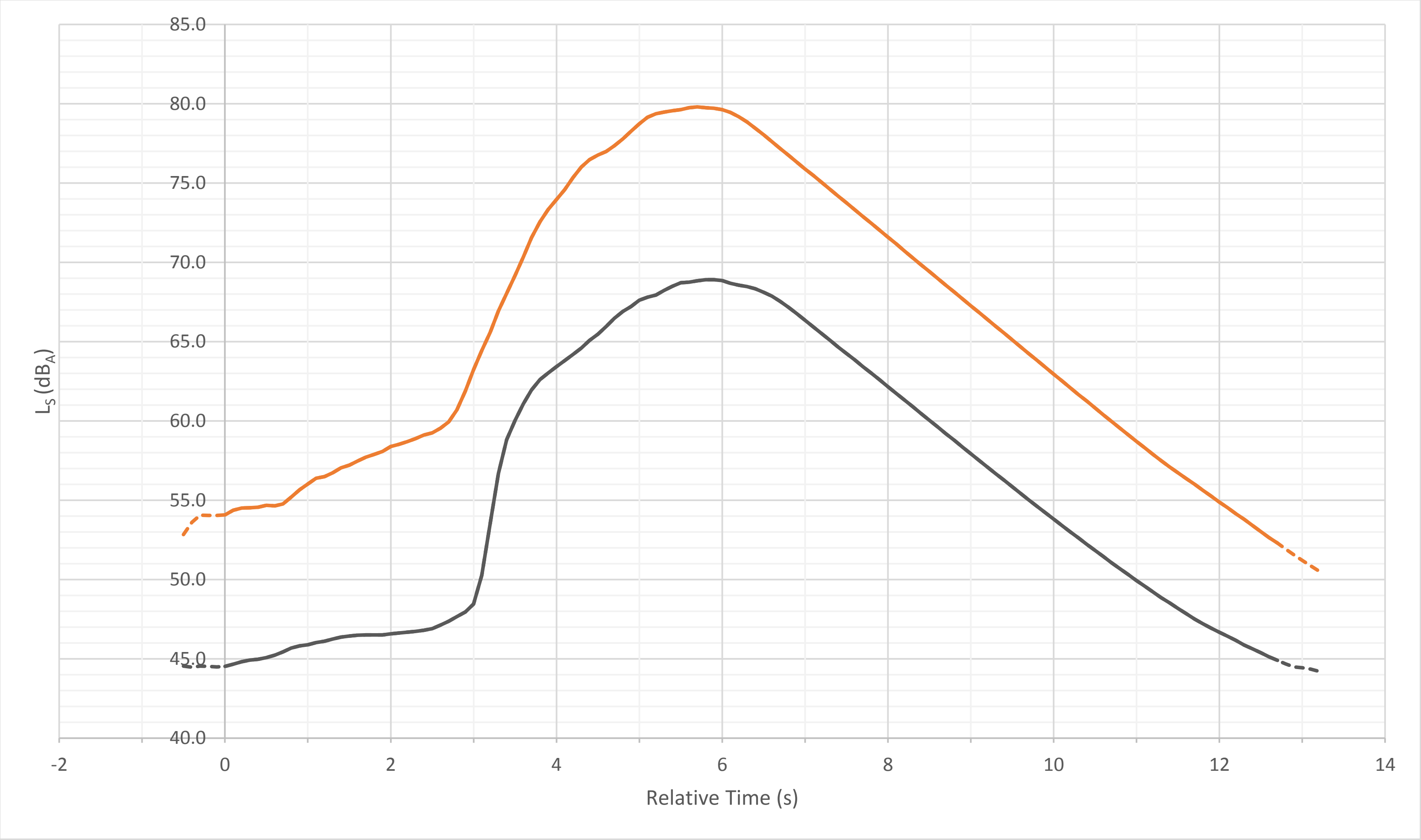

Figure 40 – Sound level profiles of typical full throttle pass-by tests of Vehicle 4 and Vehicle 5 on powder snow. The orange lines represent the Vehicle 4 sound level and black lines represents the Vehicle 5 sound level.

Over the course of the test, Vehicle 5 was consistently quieter than Vehicle 4. If the start point is considered to be at approximately 3 s on the relative time axis, Vehicle 5 remains at least 9 dB quieter than Vehicle 4 during the entire test.

Figure 41 is a 1/3 octave band chart of the instant of maximum sound level for each snowmobile. The chart ranges from the 12.5 Hz to 20 kHz band and has the overall sound level ($L_{S,MAX}$) as the right-most bar (labelled “A”). The values were registered using the S setting and the appropriate A-weighting gains have been applied to each band.

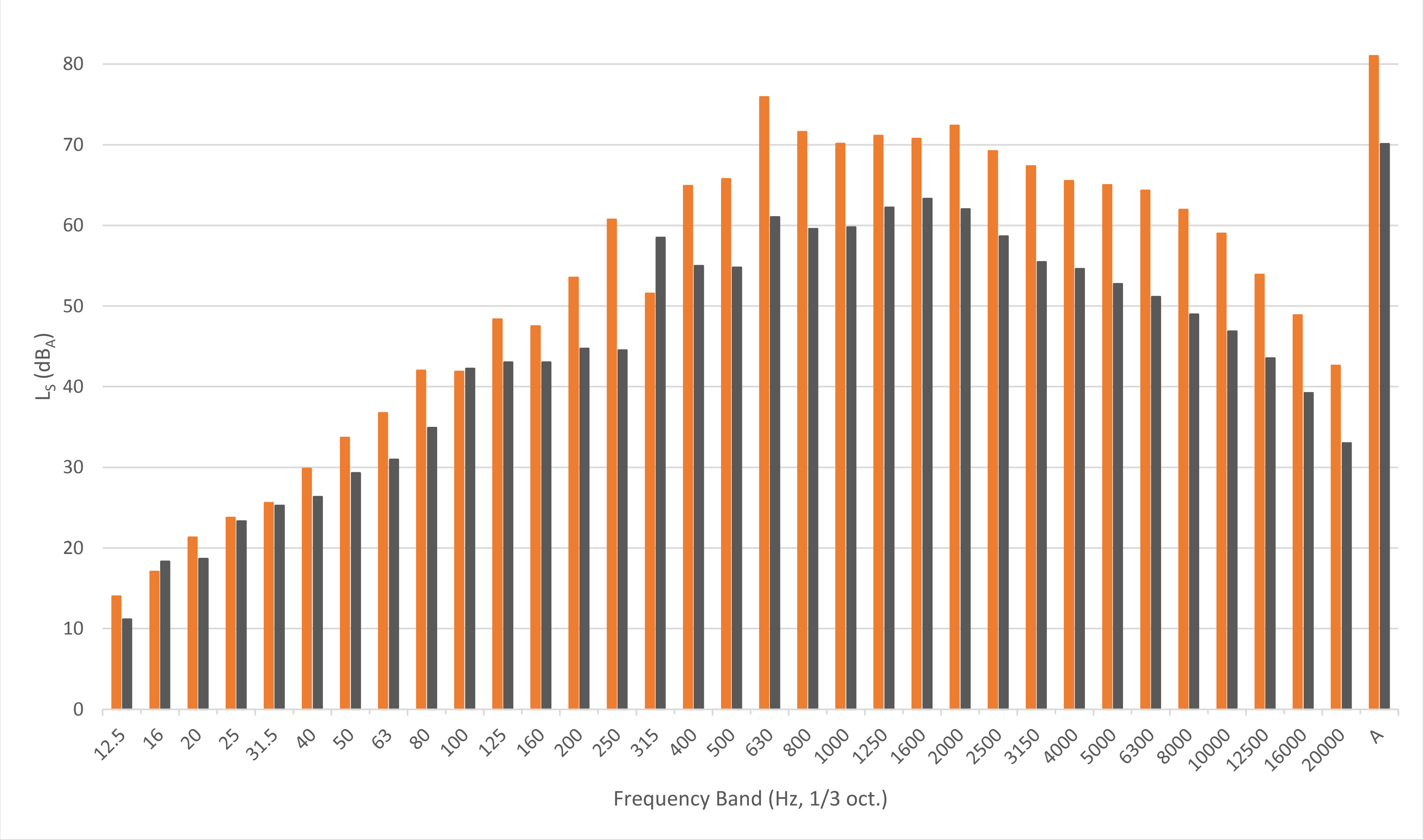

Figure 41 -1/3 Octave band chart of the peak sound level registered during a typical full throttle pass-by test of Vehicle 4 and Vehicle 5 on powder snow. The orange bars represent the Vehicle 4 distribution while the black bars represent the Vehicle 5 distribution.

In most bands Vehicle 4 was louder than Vehicle 5 at the peak sound level point of these tests. There are certain bands where the difference is most pronounced. Vehicle 4 has small peaks at 125 Hz and 400 Hz. Otherwise, it has a relatively flat, broadband distribution (taking into account applied A-weighting). Vehicle 5 has a peak in the 315 Hz band but is otherwise relatively flat as well. Besides Vehicle 5's 315 Hz peak, Vehicle 4 is considerably louder than Vehicle 5 from 40 Hz to 20 kHz.

Since the vehicle and engine speeds are not known, there is not enough information to speculate on the sources of peak bands. Both frequency responses are sufficiently broadband in distribution that these peaks do not contribute significantly to the overall noise level.

A detailed noise source analysis is beyond the scope of this research. A more comprehensive analysis using more vehicle information or noise source identification with an acoustical array are possible future methods that could more conclusively determine noise sources and their contributions to the overall noise of the vehicles.

4.6.1.1 Summary

- Vehicle 4 had an average $L_{S,MAX}$ of 79.6 dB_A and Vehicle 5 had an average $L_{S,MAX}$ of 69.7 dB_A at full throttle on powder snow.
- There was no significant difference between the maximum sound levels registered from the left and right side passes of each vehicle.
- Vehicle 4 had a not-insignificant range of results, values within ±1.25 dB, while Vehicle 5 had little variation from test-to-test.
- The frequency content of typical tests with either snowmobile are broadband in their distribution with a few small peaks at various frequency bands.

5 Conclusion

The primary goals of this research, as presented in *Snowmobile Noise*, was to determine what noise-related improvements were possible through the EV conversion of a snowmobile. The goal was intended to be solved through the use of a pre-existing snowmobile noise measurement standard (SAE J1161) as a base and was intended to have taken into account the effect of ground hardness (testing on multiple snow types).

The primary goal was achieved through simultaneous testing of a 2012 Ski-Doo Skandic WT (Vehicle 1) and an EV-converted version of this vehicle (Vehicle 2). The vehicles were tested on multiple dates, one with wet snow conditions and two with icy snow conditions (a mix of snow, ice and snow crust). On wet snow, Vehicle 2 was on average approximately 60 dB_A loud (at 24 km/h and at 15 m) while the Vehicle 1 was close to 67 dB_A loud. On the first icy snow date, Vehicle 2 was on average approximately 70 dB_A loud (at 24 km/h and at 15 m) while the original Skandic was close to 72 dB_A. On the second icy snow date, Vehicle 2 was on average approximately 65 dB_A loud (at 24 km/h and at 15 m) while the original Skandic was close to 69 dB_A but very few samples were used to determine these numbers (2 and 1, respectively). Seemingly, the difference between the vehicles was significant on a soft snow type and less significant on a hard type. This reduction, however, could be explained through logarithmic manipulation (see *Sound and Psychoacoustics*). 1/3 Octave analyses showed how their frequency contents differed.

A third snowmobile was included within the scope of the first goal. Vehicle 3 was tested alongside Vehicle 2 at a variety of speeds to examine the effects of speed on the noise level of the vehicles (at 15 m). Vehicle 3 was louder than Vehicle 2 (in this test) and the sound level of either vehicle increased with speed. The decibel sound levels of either vehicle converged. However, in terms of sound pressure their levels were actually diverging with increasing speed. The 1/3 octave analyses of either vehicle showed tones within their spectrum which shifted frequency with increasing speed. A preliminary result from testing on another date showed Vehicle 3 as quieter than Vehicle 2 on a hard snow type.

The secondary goal of this research was to examine potential noise improvements of snowmobiles in the last decade. The goal was to test the most purchased snowmobile of 2003 in Quebec (Vehicle 4) alongside the most popular snowmobile of the 2014-2015 snowmobiling season (Vehicle 5) using pre-existing snowmobile noise measurement standards (SAE J1161 and SAE J192).

This goal was achieved through the simultaneous testing of Vehicle 4 and Vehicle 5. Vehicles were tested on a single date and on a soft snow type. Vehicle 5 was considerably quieter than Vehicle 4 at both full speed and at 24 km/h (at 15 m), on average +10 dB quieter. 1/3 Octave analyses showed how their frequency contents differed in both tests. Vehicle 5 was quieter than Vehicle 2 although they were never tested together.

5.1 Sources of Error

Potential sources of error include the number of samples taken for most averages, fluctuating levels of background noise, a lack of GPS logging, driver error and an imprecise language used to describe the snow conditions.

The availability of the snowmobiles or personnel was occasionally a hindrance to testing and so snowmobiles were not always available for very long. In future work, vehicles should be tested by the mandatory 3 tests along each side of the vehicle required by the SAE J1161 and SAE J192 standards. This may have been the largest source of error (some sets contained only a single test).

The standards also require GPS logging for position and speed. A GPS logging system was not used for testing but could ensure the accuracy of future testing. Background noise was a small but not insignificant source of error. It may be hard to find a testing area that is both easily accessible and very quiet but low levels of background noise would improve future testing.

Lastly the imprecise language used to describe the snow type may not have been a source of error, per se, but did not lend to repeatability. It is difficult to describe a snow path that may vary in quality, in depth and with time (melting, refreezing, etc.). Perhaps an overall ground hardness measurement from snow surface to ground (if testing on snow) along with the depth at the point of measurement might add to sound level measurements.

5.2 Future Work

There are a number of future works that could be based off of the results of this research and the research of others. Some of this future work might account for error in this research, some might be for further study of the snowmobile noise measurement standards, some might be for the further study of EV snowmobiles, some might be for the study of other possible noise reduction technologies and others might be for the study of snowmobile noise through different means.

Future work could simply recreate the testing in this research document with a number of improvements. Some of these possibilities have been described in *Sources of Error*. Possibly the most significant source of error was the number of samples taken for most tests. Future work could involve more readily available snowmobiles which could be tested more often and for longer test periods. If the testing is meant to be compared to other SAE J1161 or SAE J192 results then testing should follow the standards to the letter. Standards were deviated from in this research. Deviations include:

- minimum 3 samples along each travel direction
- using average of louder side (rather than overall average)
- GPS logging

Testing with Vehicle 2 in this research was done with the SAE J1161 standard because Vehicle 2 was power limited compared to the original Skandic. Future iterations of an EV snowmobile should have a motor with a comparable power output to the IC snowmobile being tested. With a motor more equivalent to the engine of Vehicle 1, it might be worth making the full throttle comparison between Vehicle 1 and Vehicle 2 in future.

Additionally, another vehicle with less track related noise may be a worthwhile base for a future EV snowmobile if the aim is to have the quietest snowmobile possible. The Skandic model used for Vehicle 2 was a wide track model with none of the Quiet Track technologies outlined in *Snowmobile Noise Sources and Modern Mitigation Techniques*. There may have been more of a noticeable noise difference between the EV and IC snowmobile if the track was not such a significant source of noise for these vehicles.

A track shroud is a mostly untested technology that could potentially be used to reduce the noise of the snowmobile track. Some of the Clean Snowmobile Challenge participants have tried a prototype of some sort of a track shroud in the past (with limited success). However, this type of track noise mitigation technology has not been seriously tested on a vehicle where the track is the most significant source of noise.

The SAE standards allow for testing on grass if snow is not available. In [7], researchers found that this allowance has a significant effect on the noise level of the SAE J192 standard in comparison to values recorded on snow. Future work could include SAE J1161 testing on grass as well.

It is not clear why the SAE J1161 standard, the operational snowmobile noise level standard, is done at 24 km/h as opposed to other speeds (repeatability is a possibility). Determining a speed more closely resembling typical riding speed and then testing at this speed may be worthwhile.

Future work might involve creating a standardized ground hardness test to include with the snowmobile noise measurement standards. As [7] and this research has shown, ground hardness has a significant effect on the snowmobile noise measurement standards. A standard ground hardness test could provide a number or factor to include with the noise level value of the test.

Finally sound source identification analyses may be useful in future for determining noise sources and their relative contributions. These analyses could include acoustic holography or some such acoustic array sound localisation technique. Some of the difficulties of sound source testing of snowmobiles is that snowmobile testing essentially needs to occur in situ whereas other vehicles, cars for example, could be tested on a track or indoors. Other complications include that some of the sound sources are ground level (the track for example).

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