SAE 2015-xx-xxxx

Design and Validation of the 2015 University of Idaho Clean Snowmobile Challenge Entry, Featuring a Dual Mode 797cc Two-Stroke Direct-Injection Engine with Active Noise Cancelation

Savage,D., Green,C. Smith,C.,Keys,T.,Lipple,Z.,Woodland,M.,Eliason,A.

ABSTRACT

The University of Idaho's entry into the 2015 SAE Clean Snowmobile Challenge is a 2014 Ski-Doo MXZ-TNT chassis with a reduced-speed 797 cc direct injected two-stroke engine, modified for flex fuel use with blended isobutanol/gasoline fuel. A battery-less direct injection system was used to improve fuel economy and decrease emissions while maintaining a high power-to-weight ratio. Noise was reduced by operating the engine at a lower speed, reducing the throttle opening via an electronic throttle control, a mechanically active quarter-wave resonator, and by strategically placing sound absorbing/deadening materials throughout the chassis. A muffler was modified to incorporate a three-way catalyst, which reduces engine emissions without significantly reducing power or increasing sound output. The 2015 configuration implements a fuel economy switch which creates a powerful "sport" and an efficient "eco" mode. Pre-competition testing had the snowmobile entering the 2015 SAE CSC weighing 265 kg (585 lb) wet and achieving 10.2 l/100km (23 mpg) in mountainous terrain. The snowmobile had an EPA five mode emissions test score of 204 and 199, in eco and sport-mode respectively. Additionally, a J192 sound magnitude score of 73.5 dBA was measured under wet and heavy snow conditions in eco-mode.

INTRODUCTION

Snowmobiling offers a great opportunity for winter recreation, exploration, and transportation. Snowmobiles have traditionally been loud, with high levels of toxic exhaust emissions and poor fuel economy. Snowmobiles are often ridden in environmentally sensitive areas such as Yellowstone National Park where the adverse effects of snowmobiles can be substantial. To counter the potentially negative impact of snowmobiles a partnership between industry, conservationists, and the snowmobiling community was created. As part of this partnership, a competition was developed for college students to design a cleaner, quieter snowmobile.

In 2000, the Clean Snowmobile Challenge (CSC) was created through support of the Society of Automotive Engineers (SAE), the Montana Department of Environmental Quality, the Environmental Protection Agency (EPA), National Park Service (NPS), and the Department of Energy (DOE). Historically, the competition goal has been to develop a touring snowmobile which meets NPS standards. As a result of regulation changes, customer demand, and technologies displayed in CSC events, manufacturers now produce touring snowmobiles that meet both NPS noise and exhaust emissions standards.

With commercially available snowmobiles meeting NPS standards, the University of Idaho Clean Snowmobile Challenge (UICSC) team recognizes the need to develop and test innovations that would be applicable to models that do not currently meet these standards. Land access is a major problem for snowmobilers across the United States and many riding areas must be accessed through private lands. However, many landowners are unappreciative of overly loud and dirty snowmobiles traveling through their property. In many cases this leads to a closure of land access which can greatly reduce the amount of public land available for power sports use. Hence, the UICSC team has focused its research on technologies that can be easily adapted to two-stroke engines which reduce noise and exhaust emissions while maintaining the riding experience that enthusiasts have come to expect and love.

The designs technologies to improve these vehicles is an attempt to foster innovation in industry. The 2015 CSC continued to drive technology, design, and engineering by making several rule changes while still allowing an economy, or "eco-mode" switch. The most significant change is emissions will be measured in the mode with the worst E-score. That mode's brake specific fuel consumption (BSFC) will also contribute to the overall points for in lab emissions [1]. For many teams the logical decision is to utilize a single mode vehicle. Doing this sacrifices power for lower noise and emissions since a performance mode (sport-mode) will typically be dirtier and louder than that of an eco-mode. The UICSC team chose to continue development of a dual-mode design. This strategy focuses on improving the efficiency and fuel economy, while reducing noise and exhaust emissions in eco-mode. Improvements to noise, emissions, and fuel economy will also be experienced in sport-mode, but the rider will notice a significant increase in performance. Snowmobilers desire handling, acceleration, and cost above all else in their purchasing decisions. Developing a powerful vehicle, maintaining performance, and modifying it to be environmentally responsible is the strategy the UICSC team has chosen to pursue [2].

Equipment

An SRL eddy current dynamometer, model FE-260-S, was used for all flex-fuel calibration work. A Max Machinery 710 Series fuel measurement system determined fuel consumption. Emissions data were collected with a Horiba MEXA-584L emissions analyzer. An Innovate LM-2 wide band oxygen sensor provided information about the air/fuel ratio (AFR) of the engine.

Summary of 2014 Configuration

The University of Idaho's entry into the 2014 SAE CSC was a 2014 Ski-Doo MXZ-TNT chassis with a low speed 797 cc, direct-injected, two-stroke engine modified for flex fuel use with blended isobutanol/gasoline fuel. This was achieved with a Continental flex fuel sensor and a custom analog circuit. A battery-less direct injection system was used to improve fuel economy and decrease emissions while maintaining a high power-to-weight ratio. Noise was reduced by operating the engine at a lower speed and by strategically placed sound absorbing/deadening materials within the engine compartment. A muffler was modified to incorporate a three-way aged catalyst, which reduced engine emissions without greatly reducing power output or increasing noise [3]. The 2014 configuration implemented a fuel economy switch which created a powerful "sport" and efficient "eco" mode. Competition testing showed the snowmobile weighed 271 kg (597lb) wet, and achieved 12.45 l/100km (18.9 mpg) on a 161 km (100 mile) endurance run. When in eco-mode and using B16 fuel, the snowmobile received an EPA five mode emissions test score of 203.The snowmobile also obtained a J192 sound magnitude score of 78dBA under icy conditions.

The vehicle also included the technology of a quarter-wave resonator to reduce noise emissions. Adjustments to the primary clutch were also tested to improve drivetrain efficiency of the snowmobile. Improvements to the testing set-up for sound material selection were also achieved. The past human factors and ergonomics work included raising the handlebars and relocating the throttle to increase control and reduce risk of injury. Many of the design elements from the 2014 vehicle have been augmented, redesigned, and refined as part of the 2015 vehicle configuration described in the rest of the paper. [4]

UICSC SNOWMOBILE DESIGN

Engine & Chassis Selection

The 2015 UICSC continued use of a direct injection (DI) 797 cc Rotax two-stroke engine used in conjunction with a 2014 Ski-Doo MXZ-TNT chassis. This selection is based on the high power-to-weight ratio, rider comfort, low cost, and mechanical simplicity which weigh heavily into consumer purchasing decisions. The characteristics that make two-stroke engines mechanically simple typically result in lower thermal efficiency, poor part-load operation, and high exhaust emissions compared to four-stroke engines of similar output. In response to these relative deficiencies, the UICSC team has chosen to reduce the maximum operating speed of the engine which improves overall efficiency and decreases emissions while maintaining performance comparable to that of the Rotax 600 cc two-stroke engine. This configuration has proven that it can meet and exceed the expectations of the 2015 Clean Snowmobile Challenge [5]. The UICSC design goal is to create a snowmobile that power sports enthusiasts' desire while meeting and exceeding NPS standards on exhaust and noise emissions.

Flex Fuel System

In the 2015 CSC, all gasoline spark ignition engines are fueled with blended isobutanol. Consequently, a major design goal for the competition was to tune and modify the UICSC DI snowmobile to operate effectively using this fuel. The challenge rules state that a range of 16 percent to 32 percent isobutanol (B16 –B32) is to be used [1]. This is the same range as the 2014 CSC which requires no further recalibration of the engine.

While alternative fuels, like isobutanol, are environmentally friendly, there are some drawbacks to their use. Isobutanol requires slightly increased fuel flow requirements, has a shorter shelf life, higher viscosity, and extremely limited availability. Alcohol based fuels typically have detrimental effects on rubber and plastic components, but the fuel lines and o-rings used are compatible [6].

For the 2015 CSC a new model Continental flex fuel sensor and custom analog circuit were used to send information about the isobutanol content of the fuel to the Engine Control Unit (ECU). The new flex fuel sensor implements identical circuitry, but is significantly smaller and less expensive. The small size made packaging much easier and used already limited space more efficiently. The analog circuit was tested and calibrated to ensure proper transfer of isobutanol content information. The circuit converts the signal from the flex fuel sensor to a signal that can be used by the ECU.

Calibration

UICSC has traditionally implemented a four step tuning strategy. As no additional major tuning was done for the 2015 CSC the strategies are not explicitly explained. If more information is desired, reference the 2014 UICSC design paper [4]. All steps below are altered with some relative maximum or minimum value as a goal. Depending on the point the objective is different. At cruise speeds and throttle positions BSFC is the minimum value, while the top end's objective is peak power and survivability.

- Step one (injection timing sweep): change the fuel injection timing while adjusting the injection quantity in order to replicate the equivalence ratio ϕ from the initial point. This will obtain the optimal injection timing for that equivalence ratio. Equivalence ratio is shown in equation 1.

- Step two (injection quantity sweep): change the equivalence ratio by adjusting the injection quantity while using the same injection timing found in step one. In order to achieve the optimal setting, multiple iterations must be completed.
- Step three (spark timing): after tuning steps one and two ignition must also be adjusted. The map requires this dimension to find an ideal value for the objective.
- Step four (tune interpolation): after tuning the ten mode points (accounting for eco and sport-mode) the values were interpolated between these points, and then roughly verified for runability. This was done to keep consistency in the tune and address the transition points of the map.

$$\varphi = \frac{AFR_{act}}{AFR_{Stoich}} \quad (1)$$

All calibration was performed using the 797cc engine with the same throttle bodies, intake reeds, tuned pipe, and muffler that will be used at the 2015 CSC. The base map in the ECU was calibrated using 0% isobutanol fuel with an uncoated catalyst installed in the exhaust system. This was done to replicate the backpressure caused by the catalyst. It also reduces catalyst wear during use of an unrefined fueling map. After the initial calibration, isobutanol compensation calibration was done using a similar strategy to find optimal injection timing, injection quantity, and ignition timing.

Electromechanical Development

In the 2015 UICSC configuration, two interdisciplinary projects were pursued; the electronic throttle control (ETC) and the mechanically active quarter wave resonator (MAQR). The goal of the ETC is to increase efficiency of the vehicle at cruise speed operating points in eco-mode while maintaining stock performance in sport-mode. High-load efficiency is typically low in a two-stroke engine, while low load operation is often more efficient than a four stroke due to reduced pumping losses [7].

The UICSC continued development of past quarter-wave technology by developing a MAQR. A quarter-wave resonator creates a destructive sound wave that propagates through the exhaust to reduce noise at a target frequency based off of engine speed. In many cases riding conditions for snowmobiles are not consistent. This causes the cruise RPM of the vehicle to vary. There is risk of noise amplification when the engine RPM shifts away from the design point of the quarter-wave. This is the driving force behind the MAQR since it is a form of active noise cancellation. The MAQR effectively creates an infinitely variable band of frequencies that are quieted while having little to no effect on the power output.

Both systems are controlled using a Tiva-C TM4C123GX Launchpad. The processor runs at 80 MHz with a floating point unit and 12 bit analog to digital converter (ADC) [8]. The Launchpad has sufficient processing power for both applications.

The motor used with the MAQR is a motor operating at 14 V with gear head output of 700 RPM. The motor drive circuit is an H-Bridge LM298N, and the control feedback is a 10 kΩ continuous rotation potentiometer. The gear head has a gear ratio of 1:3.6. The required distance of travel is 23 cm (9 in) in 6 seconds. With the selected gearing the 23 cm (9 in) can be traversed in approximately 5 seconds. Due to the distance that the MAQR is required to travel a current location is vital. This is achieved by implementing a virtual encoder and a system that homes on a limit switch. The drive system for the quarter wave is shown in figure 1.

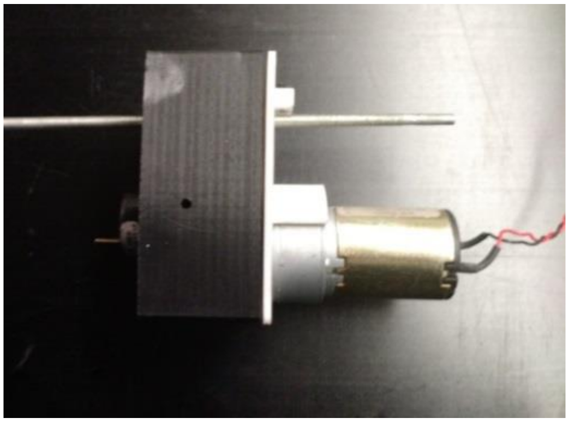

Figure 1.Geared drive box for the MAQR.

The ETC is actuated by a servo on the throttle bodies and the throttle position is referenced by a 300 degree dual potentiometer. A dual potentiometer is used to add redundancy to the system, increasing the safety. The potentiometer is coupled to the throttle lever through a gear train with a 1:3 ratio. This utilizes nearly the full travel of the potentiometer, maximizing the resolution of the system. This is shown in figure 2. The throttle bodies are driven by a servo and pulley system. The pulley is attached to the throttle bodies with a cable. The servo responds to user input from the throttle lever potentiometer. The control system can be seen in figure 3.

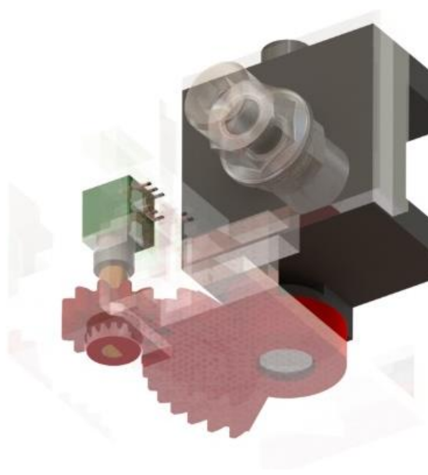

Figure 2. ETC throttle configuration.

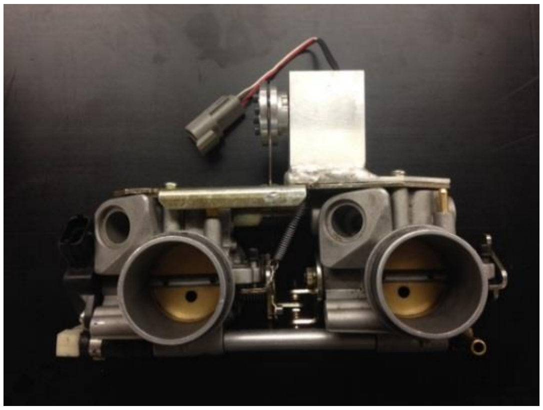

Figure 3. ETC servo, installed on throttle bodies.

The ETC was designed to have response characteristics similar to the mechanical throttle and enough torque from the servo to completely open the throttle bodies due to its application on a high performance vehicle. The throttle bodies are coupled to a servo with a cable and pulley system ratio of 1:1.5. This allows for a travel speed of approximately 0.5 seconds from closed to wide open throttle (WOT). This opening time is achieved while having a return spring in place that easily closes the throttle when power to the servo is removed. This configuration gives a very similar feel to that of a mechanical throttle.

Efficiency

This year an ETC was designed and implemented. The control system consists of two modes, economy and sport. The economy mode limits maximum throttle opening to 50%, and reduces butterfly response time to decrease fluctuations in throttle position while traveling over rough terrain. This limit chosen was based off of criteria determined by the UICSC. The vehicle is required to climb a steep hill at 97 kph (60 mph), with a large rider. Limiting throttle is a common method to increase efficiency and has added benefits of reducing noise. By using an ETC developing throttle profiles and limits becomes very safe and easy.

The UICSC team has known that reducing the speed of the engine has the adverse effect of moving the engine RPM away from the effective tuned length of the tuned pipe. When operating at speeds nearer to the effective tuned length of the pipe, mid-range power and efficiency are increased in addition to increasing power at the top end.

Exhausts are designed as entire systems and as a result each individual component relies on other components for their own design. This is especially true in a two-stroke engine since engine operation depends heavily on advanced fluid mechanics involved in trapping and scavenging. As shown in equation 2 below, D_2 which is not shown in figure 4, is the second diameter of the pipe which is reliant upon the header length, header taper (H), and the diameter of the header (D_1). This is one of several equations used in exhaust system design. Figure 4, which is truncated for readability, gives a rough design scheme for tuned pipes. The y-pipe or exhaust header is the variable LH and tuned length is L. Modifying one portion will change the entire tuned length of the pipe [9].It is with this intention that the header length of the exhaust system was modified. It was kept in mind that the extension may have unexpected effects on runability at some points of the engine's power curve. Further discussions with UICSC sponsors gave a general rule for header extension; 5mm (0.2 in) changes the effective tuned length by 100 RPM. Due to the limited space in the engine compartment a maximum of 19 mm (0.75 in) could be added to the header. The engine speed is reduced by 1000 RPM so the addition of the extension approaches the effective length, but does not meet it. Just by shifting the operational band closer to the effective length shows benefits.

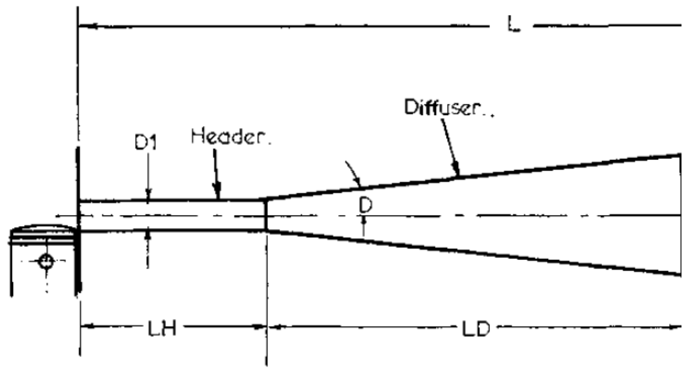

Figure 4. Tuned Pipe Configuration.

$$D_2 = \left(\frac{LH*2}{\cot H}\right) + D_1 \quad (2)$$

Developing BSFC maps for the UICSC platform was necessary to calibrate and tune the ETC, as well as assist in clutching. A reduction in BSFC correlates to less fuel consumed per unit power. This means a gain in BSFC is an unwanted result. During BSFC testing it was shown that in eco-mode the engine makes nearly the same power at 100% throttle position, 84 N-m (62 ft-lb), as at 55% throttle, 81 N-m (60 ft-lb). This allows the UICSC team to reduce maximum throttle in eco-mode by a minimum of 45% across the entire operational band while having no detriment to performance and increasing efficiency. To develop BSFC maps the UICSC team analyzed nearly 60 points based on the 5 mode tests used in emissions testing, excluding mode five (idle) [10].

Improvements to BSFC were achieved using the ETC and y-pipe extensions. Throttle limits are necessary in eco-mode to further increase fuel efficiency. By limiting the throttle to 50% the BSFC in eco-mode was decreased by a minimum of 56 g/kW-hr across the entire RPM band while reducing BSFC by 117 g/kW-hr at full power. Figure 5 shows the BSFC map of the y-pipe extension. The bands shown in the figure were filled using regression, instead of a high number of points which is the industry standard. The bands show an approximation of what real time BSFC would be when attempting to reach a certain torque at a given RPM. With the implementation of the y-pipe extension the engine sees a peak BSFC reduction of 48 g/kW-hr, and the largest gain is only 5.7 g/kW-hr.

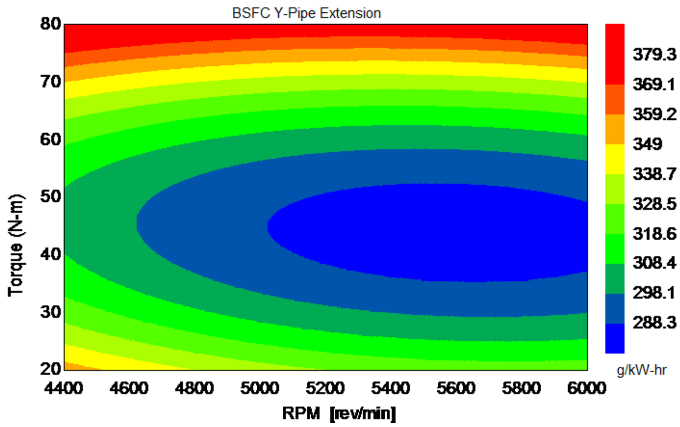

Figure 5. Y-Pipe BSFC Map.

By extending the length of the y-pipe the UICSC shifted the effective tuned length of the pipe closer to the operating speed of the 2015 configuration. This improved average trapping and scavenging which is shown by an increase in power and a decrease in HCx in the exhaust.

The extension was tested using identical fueling values, engine speeds, and throttle positions. In table 1 it is shown that minimum BSFC is decreased by using both of these technologies. The y-pipe extension, used in conjunction with the reduced throttle, achieved an average reduction of 13 g/kW-hr across the entire operational band of the engine. Table 1 shows the decrease in weighted BSFC from the 2014 entry.

Table 1. Weighted BSFCs.

	2014 (g/kW-hr)	2015 (extension/ETC) (g/kW-hr)
Eco	474.5	363.2
Sport	433.2	306.0

During the emissions event BSFC is calculated, and a weighting scale is applied based on the 5 modes. Due to the addition of the y-pipe extension the sport-mode weighted BSFC is lower than the eco-mode. The rules stipulate that if a dual mode vehicle is entered into the competition there must be an economy mode. The lower sport-mode BSFC suggests that sport-mode will get better fuel economy, but that is not the case. Due to the way the 5 mode test is performed there is little difference at low load for sport and eco. Two-stroke engines create power on every revolution which causes the mode points for the emissions test to be tested at low throttle positions. Sport-mode is intended to be a high mode, high throttle configuration and as load is increased, efficiency is significantly decreased. Sport-mode reaches a higher RPM, it shifts the low mode points into a more efficient BSFC band. The clutching of the snowmobile and the mid-range operation that occurs on snow ensures that eco-mode achieves a higher fuel economy.

Computational Fluid Dynamics (CFD)

Research was conducted to determine drag of the snowmobile at max cruise speed 88.5 kph (55 mph). In past years the UICSC snowmobile has run without the stock windshield in place. It was noted that without the windshield the rider was buffeted with air at approximately chest height. Analysis was done using CFD software on the effects of implementing the stock windshield.

Figure 6 shows a two-dimensional simulation of the vehicle traveling at max cruise speed. It is shown that at the front of the vehicle there is a high level of drag, but it is largely unaffected by the addition of the windshield. The next point of interest is at the rear of the vehicle. The large void that is apparent is a low pressure zone that adds down force to the rear of the snowmobile. Due to the simplistic nature of a 2-D simulation the changes in pressure here were also too small to be considered positive or negative. What this simulation does show is by adding the shield there are no negative effects. A 3-D model may show different results, but for the 2015 CSC the 2-D model shows that the addition of a windshield is not harmful. It is also clear a rider with smaller stature would be beneficial, and that there are additional instances of drag due to the visor on the helmet. As such, it would be prudent to utilize a full-face helmet, but this is neglected for the 2015 CSC for sponsor awareness [11].

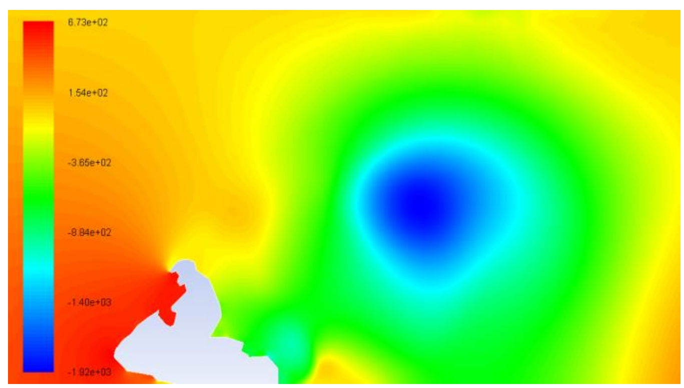

Figure 6. CFD of a rider with a windshield

Power Transmission

Efficiency gains in the drivetrain, from clutching, are achieved through modifications in the secondary clutch. This pulley's purpose is to provide load feedback to the primary clutch via drive belt pressure. Too much pressure leads to frictional heat loss and reduced drive belt life [12]. During low load operation drive belt pressure is reduced with a softer secondary spring [13]. To test for ideal spring pressure UICSC performed a low load cruising speed test. The snowmobile was taken to a speed of 64.4kph (40 mph) for .4km (.25mi), then drive belt temperatures were then measured with an infrared thermometer. Table 2 shows the spring forces tested and the average operating temperatures of each configuration compared to stock.

Table 2. Force of Springs Tested and Drive Belt Temperatures.

Configuration	1	2
Spring Force Reduction From Stock	40%	20%
Average Operating Temperature (°C) (°F)	54 (130)	59 (138)
Temperature Reduction From Stock	6%	3%

The softest spring was chosen for the 2015 CSC configuration based upon the results from table 2, which lacked evidence of drive belt slippage in high load operation.

Through clutching, using the BSFC data, the UICSC team adjusted the engine RPM's in eco-mode to cruise at the most efficient operational band which is near 35% throttle.

The UICSC team experimented with larger drivers and rear bogey wheels to reduce rolling resistance in the drivetrain. A new, similar, longer track was obtained to accommodate the larger drivers and wheels. Size comparisons for the components are shown in table 3.

Table 3. Driver, Wheel and Track Size

	Driver Diameter	Rear Wheels	Track Length
2014 Configuration	7.2	7	121
2015 Configuration	8	10	128

Based on suggestions by UICSC team sponsors, data were collected to record rolling resistance against track break-in. Two tests were conducted to find reductions in rolling resistance. The first utilized a linear force meter to measure the rolling resistance of the track while the snowmobile was suspended. The second consisted of placing the snowmobile on a ramp and increasing the slope until it overcame static friction. Table 4 shows the movement of the track.

.

Table 4. Track Rolling Resistance

Test		2014 Configuration	2015 New Track	2015 100 miles on Track
Scale	Force (N) (lb)	92.5 (20.8)	79.6 (17.9)	73.0 (16.42)
	Percent Reduction in Rolling Resistance	0%	-14%	-21%
Ramp	Angle at Roll-out (Degrees)	5.80	5.59	5.38
	Percent Change from Stock	0%	-3.62%	-7.24%

The UICSC team chose to use the new track with larger wheels and drivers due to the reduction in rolling resistance. The results also show that new snowmobile tracks should be put through a break-in cycle.

Human Factors

A concern voiced by many power sports enthusiasts is electronic throttles do not feel like a stock set-up and the throttle response is slower than stock. The UICSC required that in sport-mode the throttle behaved very similar to a stock set-up. Although the travel of the butterfly is not as fast as a stock throttle, it is moving as fast as possible with the current configuration. The main change implemented beyond the deletion of the throttle cable, was a slightly reduced spring rate of the throttle lever return spring. The spring rate was left fairly high to provide haptic, or user feedback, to the rider. This reduces fatigue and decreases reaction time which improves rider safety. The throttle still feels as if the rider is mechanically opening the throttle bodies to accelerate. This was done so experienced riders would have no difficulty in using the ETC.

Emissions

Due to the in-lab emissions event rule change, sport-mode emissions will likely be used for the UICSC's E-score. The y-pipe extension increases the efficiency of sport-mode which directly correlates to a decrease of specific emissions. The maximum possible E-score is 210 and a passing score for NPS is 170. A higher E-score indicate fewer emissions. An E-score of 199 is predicted in sport-mode and a 204 in eco-mode. A three-way catalyst, coated with Palladium and Rhodium, is in use for exhaust after treatment. In sport-mode the E-score without a catalyst is 138. This is a 44% decrease of weighted specific emissions out of the exhaust, thus significantly reducing the snowmobile's environmental impact. Based from the worst E-scores from the top scoring teams in the lab emissions event, figure 7 shows a comparison of the 2015 Idaho configuration to other teams' scores.

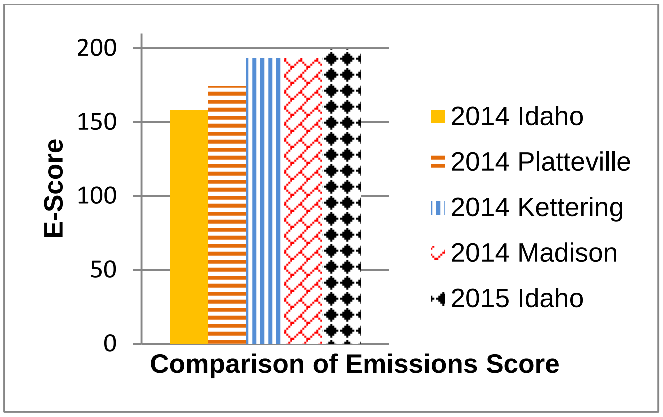

Figure 7. E-Score Comparison Chart.

Fuel Economy

Fuel economy was a major area of focus for the UICSC team. Two-stroke engines have a low thermal efficiency and a typically high amount of short circuited fuel, which results in a relatively low fuel economy. There are two main ways to increase engine efficiency. The first is by increasing thermal efficiency. UICSC has been accomplishing this for many years with the use of direct injection [14]. The second way to increase efficiency is by reducing the amount of fuel that is wasted via short circuiting. Other losses can be found in the drivetrain and over manipulation of the throttle.

UICSC has targeted short circuited fuel reduction in two main ways. The first is by operating the engine at a reduced speed. This allows the fuel to be injected later which reduces the amount short circuited. The second is in the implementation of the y-pipe extension. As mentioned in the BSFC section, this leads to an increase in the trapping efficiency of the engine.

The ETC as described above, limits throttle responsiveness and total opening achieving a reduction in BSFC. This is a common practice in many automobiles and some snowmobiles, such as the Ski-Doo ACE, in industry.

All of the modifications above result in a fuel economy of approximately 10.23 L/100km (23 mpg) which is higher than the UICSC 2014 configuration.

Noise

All noise testing was done in one of two ways. The first is through SAE J192 tests, and the second is done with a standing wave test which is described in the exhaust noise section.

Mechanical Noise

In the 2014 UICSC configuration clutch side noise was the largest contributor to overall snowmobile sound pressure. The main sources of noise on this side were intake, clutch, and mechanical vibrations caused by engine operation. As sound difficult to measure directly at the source all data is measured relatively.

Mechanical resonance, or vibration, in the tunnel is also a significant contributor to noise. In the past UICSC has used adhesive backed damping material to alter the resonance frequency and increase the damping ratio. This year a paint-on damping product was tested. To find the damping ratios a vibrations test was developed and set up as shown in Figure 8.

Figure 8. Tunnel Material Setup.

A z-channel of aluminum was chosen during testing due to the fact that it is a strong representation of the material and shape of the tunnel. Testing was conducted using five different configurations. The configurations are as follows: no damping material, Polydamp on one side, Silent Running, the paint on material on one side, Polydamp on one side with Silent Running on the other (PS), and Silent Running on both sides (SS). A three axis accelerometer was attached to the piece of aluminum and the hammer was released from a specified height each time. A fast Fourier transform (FFT) was performed and is shown in Figure 9.

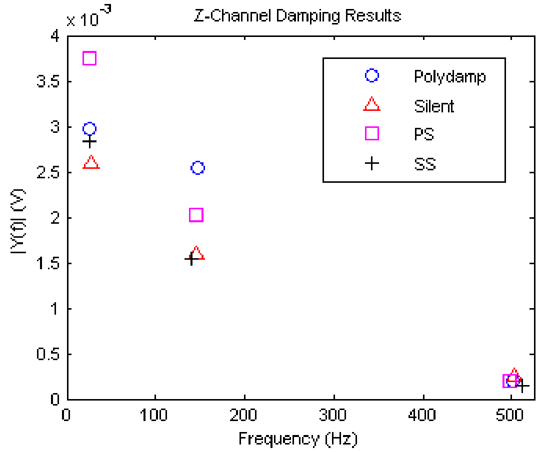

Figure 9. Resonance of the damping material configurations.

The goal of the test is to show an increase in the damping ratio. A lower y-axis value correlates to a higher damping ratio, meaning the material stops making noise sooner. Using the data in the figure and comparing it to the current configuration in use on the tunnel, an overall gain was calculated. It was determined that Silent Running coated on both sides of the tunnel would result in an overall gain of 34% in effective damping ratio.

Intake Noise

The 2015 configuration uses a two-step approach to reduce intake noise. The first is the implementation of sound reduction foam in the air box, same as the 2014 configuration.

Utilization of the ETC provided an additional benefit of a reduction in noise. By restricting the throttle opening in eco-mode to 50% the noise is reduced by nearly 1 dBA as measured by a J192 sound test. This magnitude of the reduced noise is a result of a lack of barriers between the throttle bodies and atmosphere. Meaning the lack of barriers also made this side louder.

Exhaust Noise

Developing sound reduction technologies to the exhaust is challenging due to the fact that modifying the exhaust can affect the performance of the engine. Equation 3 is how the target or control frequency for the MAQR is determined. Where RPM is engine speed, N_c is the number of cylinders, and N_R is the number of power strokes per revolution [15].

$$f = \frac{(RPM*N_c)}{60*N_R} \quad (3)$$

A simplistic drawing of the experiment is shown in Figure 10. The locations of the microphones are at L1, 25 mm (1 inch), and L2, 25 mm (1 inch). The length L4 is a variable for desired length of the MAQR.

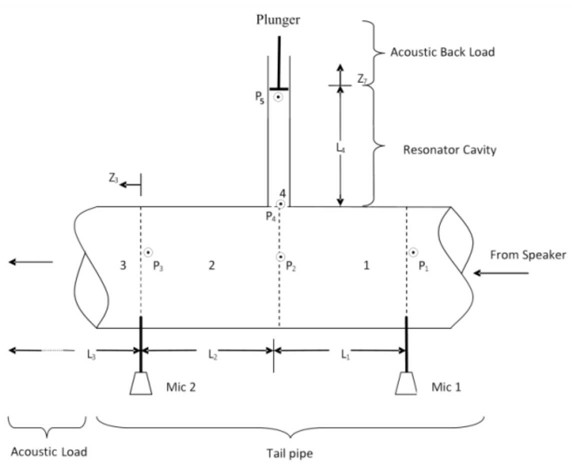

Figure 10. Experimental Setup.

The sound generation box is 0.61 m x 0.61 m x 0.91 m (24 inch x 24 inch x 36 inch). The internal sound chamber is 0.61 m x 0.61 m x 0.61 m (24 inch x 24 inch x 24 inch), containing a 320 W peak set of speakers, and 0.0762 m (3 inch) pyramid foam. The speakers are driven by a 4100 W amplifier. The sound generation box gives accurate results above 560 Hz. The lower limit is due to the sound's wavelength and the size of the internal cavity. A lower frequency results in a larger distance between two peaks meaning the box and the distance between the microphones needs to be increased to accurately measure these data. The experimental setup, with hardware labeled, is shown in figure 11 and the inside of the sound chamber can be seen in figure 12.

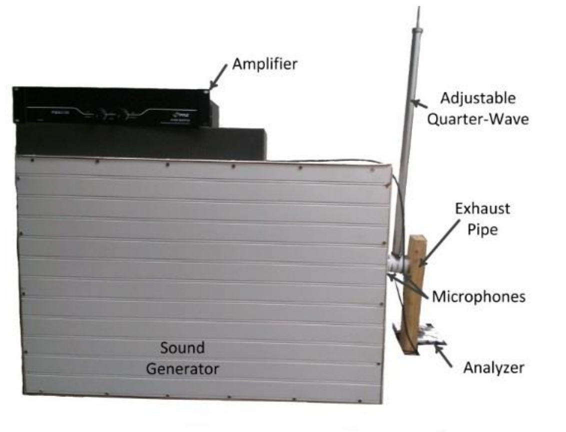

Figure 11. Experimental Setup.

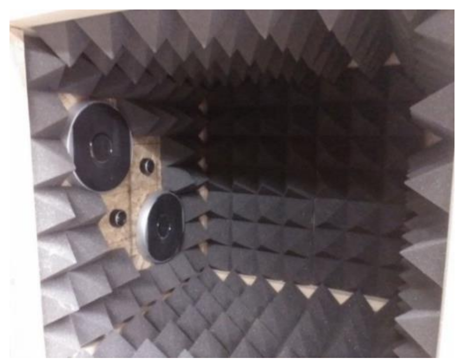

Figure 12. Sound Source internal cavity.

Microphones, Mic 1 and 2 in figure 13 are used to measure the sound pressure. The microphones have a jFET output and frequency range 100-10000 Hz [17]. The circuit to condition the microphone is shown in Figure 12. The jFET amplifier is created using values from the microphone datasheet. This amplifier is conditioned with an instrumentation amplifier, INA129. The conditioned microphone signals are measured using the Network Analyzer tool in the Digilent Electronic Explorer Board [16].

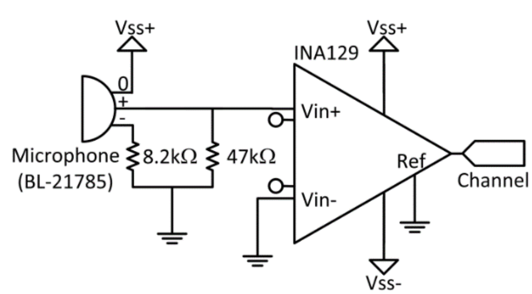

Figure 13. Microphone Circuitry.

The y-pipe extension had an unexpected benefit of reducing exhaust noise which is counterintuitive with a power gain. The reason for this is due to the increased tuned length. Changing the tuned length changes the frequency at which trapping and scavenging pulses travel through the pipe. This lowered the frequency of the exhaust pulse which reduces the noise level in a J192. As sound is measured on the dBA scale higher frequencies are weighted heavier so they contribute more to measured sound pressure. The noise reduction was approximately 1 dBA and 4 dBA on the exhaust and clutch sides respectively. The relatively large reduction on the clutch side is a result of a lack of barriers on this side of the vehicle. Because of this the sound travels through the engine compartment unimpeded. Figure 14 shows the effect of shifting the tuned length. In the graph the x-axis shows the frequency on a logarithmic scale, and the y axis is the magnitude of the peak, but this axis is extraneous. The expected frequency shift is approximately 20 Hz, and that is what is seen using the FFT.

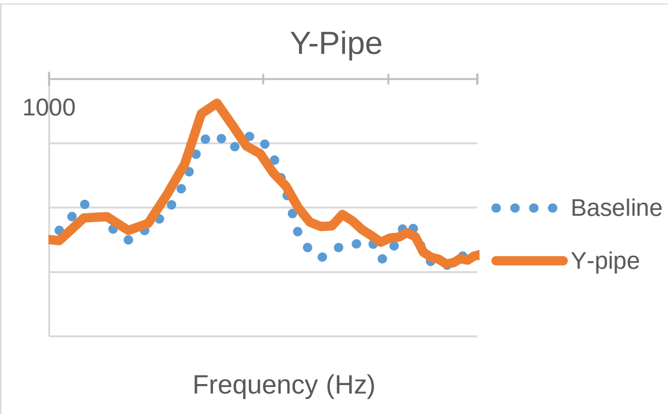

Figure 14. Y-Pipe Frequency Shift

By reducing throttle opening the amount of fluid traveling through the exhaust is reduced. This causes an additional benefit to reducing sound on this side of the vehicle by nearly 1 dBA.

Combined Approach

With the implementation of the y-pipe extension, sound material, intake deflectors, the MAQR, and reduced throttle, the final sound pressures are 73.5 dBA and 72 dBA on the exhaust and clutch sides respectively. These sound pressures were measured in heavy, wet snow conditions.

Performance

As power sports enthusiasts desire an exciting riding experience, performance remains a focal point for the UICSC team. Many of the technologies that target noise and efficiency in the 2015 UICSC design additionally benefit the riding experience of the snowmobile. Every year, UICSC has brought one of the most, if not the most, powerful snowmobiles to the competition. The 2015 configuration achieves power levels exceeding many past configurations with a power to weight ratio of 0.20 kW/N (hp/lb). A major goal was to maintain a high level of performance in both sport and eco-modes, while making gains in the areas of sound and efficiency.

Y-pipe power gain is due to an increase in trapping efficiency. By moving the effective tuned length of the pipe nearer to the engine's operating speed. With identical fueling values the snowmobile produces more power. This causes the vehicle to cruise at speeds and throttle positions closer to peak BSFC. In eco-mode with reduced throttle, the y-pipe extension peak torque increased by 5.4 N-m (4 ft-lb) and average torque increased by 1.4 N-m (1 ft-lb). These gains were highest at low to mid throttle positions. This correlates to increased low end throttle response. Increasing performance in eco-mode leads to increased performance in sport-mode. By adding the y-pipe extension, sport-mode saw an increase in peak torque of nearly 12 N-m (9 ft-lbs) and an average gain of 4.7 N-m (3.5 ft-lbs) across the operational RPM band with negligible losses. Figures 15 and 16 show corrected power and torque curves for the 2015 UICSC configuration in sport and eco-mode.

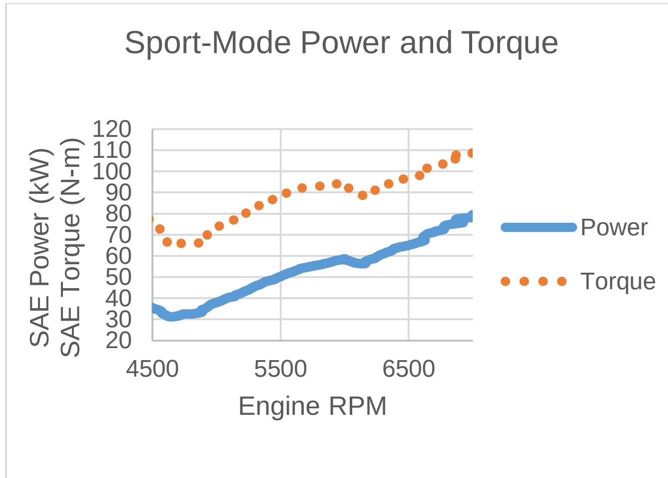

Figure 15. Power Sweep for Sport-Mode.

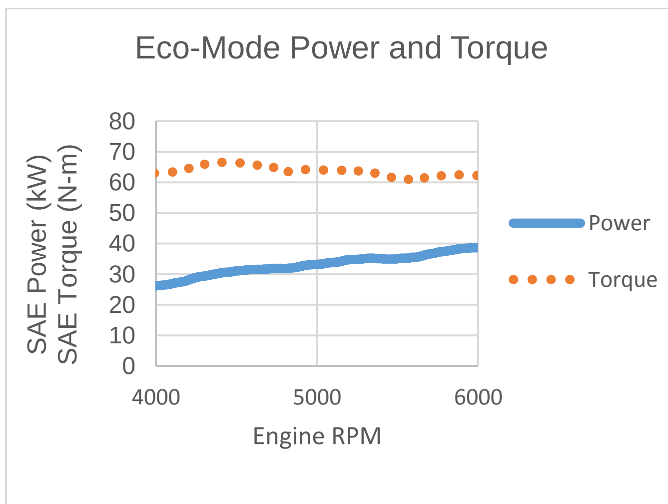

Figure 16. Power Sweep for Eco-Mode.

Figure 17 is a comparison of several competitive team's horsepower at the 2014 competition compared to the 2015 Idaho configuration, which makes 85 kW (115 hp).

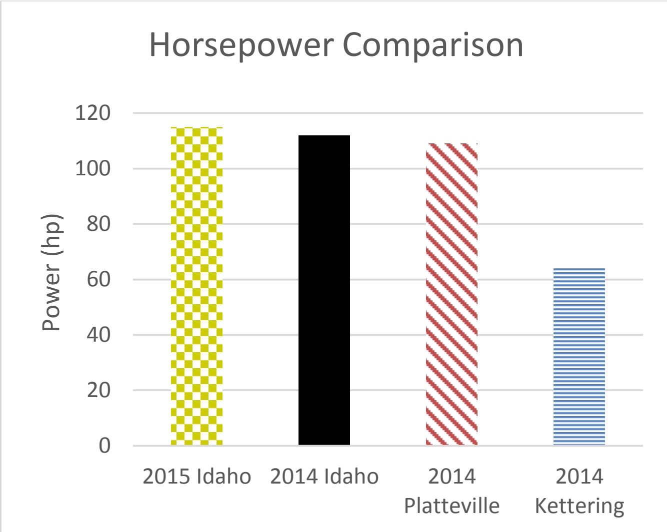

Figure 17. Horsepower Comparison

With a power increase there are often reductions in traction. In order to overcome this an ICE Attak track was chosen. This model was chosen due to being pre-studded with low profile studs and its low durometer rubber. As many events at the CSC are performed on extremely hard packed snow and ice, a lower durometer track will increase traction for events such as noise and acceleration.

Weight

The UICSC team has always strived to keep their machine light. A lighter snowmobile will achieve better fuel economy, improved dynamic performance, and reduced rider fatigue. As snowmobile manufacturers continue to reduce the weight of their machines, the UICSC team needs to follow that trend as well. Pre-competition testing, using UICSC scales, had the snowmobile entering the 2015 SAE CSC weighing 265 kg (585 lb) wet, five pounds more than 2014 configuration. The majority of the additional weight added over stock is sound absorbing material. The rest of the additional weight is due to the MAQR, y-pipe extension, ETC, and big wheel kit, which are justified to achieve the goals of the competition. Although this is slightly higher than the production snowmobile, it is still competitive with clean four-stroke snowmobiles. Shown in table 5 is a comparison of measured snowmobile weights at the 2014 CSC competition [12].

Table 5. Measured snowmobile weights at 2014 CSC competition.

University	**Measured Total Weight kg (lb)**
Idaho 2015	265 (585)
Kettering 2014	250 (551)
Madison 2014	268 (591)
Michigan Tech 2014	278 (612)

MSRP

The base price for a 2015 Ski-Doo MXZ TNT 600 H.O. E-TEC is $10,899. The low speed 797 cc direct-injected two-stroke engine can be considered analogous to a 600 H.O. E-TEC due to their equivalent performance characteristics. With all modifications included, the manufacturer's suggested retail price (MSRP) of the 2015 UICSC configuration totaled $11,955. Components that add to the MSRP were justified by sound reduction, increased performance, reduced exhaust emissions, increased efficiency, and sponsor product awareness. The benefit analysis of the MAQR, ETC, and y-pipe extension are as follows; a reduction of 0.6 dBA/$10, a gain of 1.4 l/100km (3 mpg) per $40, and a peak torque gain of 1.4 Nm/$1 (1.1 ft-lb/$1) respectively. The addition of equipment and components is strategic. This allows the UICSC snowmobile to achieve a low MSRP on par with a stock snowmobile, while still delivering exceptional performance, reduced environmental impact, and customer satisfaction.

Conclusions

The University of Idaho has developed a cost-effective flex fuel two-stroke snowmobile capable of running on B-16 to B-32 blended isobutanol/gasoline fuel. The DI two-stroke snowmobile maintains the mechanical simplicity and low weight avid riders enjoy, without sacrificing the clean and quiet characteristics necessary to meet current and upcoming standards. The UICSC design produces 85 kW (115hp), is lightweight at 265 kg (585lbs) wet, and achieves 10.2 l/100km (23 mpg). Overall sound production, measured using the SAE standard J192, was reduced from 76.3 dBA to 73.5 dBA in eco-mode. The UICSC design achieves NPS emissions E-scores in both eco and sport-mode, with eco-mode having an E-score of 204 and 199 in sport-mode. Consumers expect snowmobiles that are clean, quiet, fuel-efficient and fun-to-ride. The 2015 UICSC dual-mode flex-fuel two-stroke reduced engine speed snowmobile is an economical response to that demand.

REFERENCES

1. Society of Automotive Engineers, Inc., the SAE Clean Snowmobile Challenge 2015 Rules, September 2014.
2. Solger M., Blair J., et all., " Flex-Fuel Capability Implementation and Performance and Emissions Improvements of the Rotax ACE 600," Madison Wisconsin *SAE CSC 2014*.
3. Hepburn, J., Chanko, T., McKenzie, J., Jerger, R. et al., "OBD-II Threshold Catalyst Aging Process," SAE
4. Savage D., Green C., et all., " University of Idaho's Reduced Speed Isobutanol Flex Fuel Direct-Injected 797cc Two-Stroke Snowmobile," University of Idaho *SAE CSC 2014*.
5. Society of Automotive Engineers, Inc., SAE Clean Snowmobile Challenge Results, 2007.
6. Wasil J., Johnson J., and Singh R., "Alternative Fuel Butanol: Preliminary Investigation on Performance and Emissions of a Marine Two-Stroke Direct Fuel Injection Engine," *SAE Int. J. Fuels Lubr.* 3(2):1071-1080, 2010, doi:10.4271/2010-32-0054.
7. Nuti, M. (1998). Emissions from Two-Stroke Engines. Warrendale: SAE

8. Texas Instruments. “TMC Microcontrollers,” Microcontroller Selection Guide, 2014
9. Graham Bell A. (1999), Two-Stroke Performance Tuning, Haynes Publishing
10. Lela C.C., White J.J., “Laboratory Testing of Snowmobile Emissions”. Report Number SwRI 08.05486, Southwest Research Institute, San Antonio, July 2002.
11. Sean Quallen M.S.M.E., University of Idaho Mechanical Engineering Department, Personal Communication January-February 2015.
12. AAEN clutch tuning handbook: Aaen Olav, Clutch Tuning Handbook, 1986
13. Ski-Doo Racing Handbook, BRP, 2006
14. G. P. Blair, Design and Simulation of Two-Stroke Engines, Warrendale, PA: Society of Automotive Engineers, 1996.
15. Bosch. *Automotive Handbook 7th Ed.* Robert Bosch GmbH Postfach 2007, pg 565.
16. Dr. Michael J. Santora, University of Idaho Electrical and Computer Engineering Department, Personal Communication August-March, 2014, 2015.
17. Knowles Electronics. “Microphone Outline Drawing,” BL-21785 Datasheet, November 2006.

ACKNOWLEDGMENTS

The University of Idaho CSC Team would like to thank our many supporters: 509, AeroLEDS, Avid Products, BCA, Between the Lines Designs, Biketronics, Bombardier Recreational Products, Boyeson Engineering, C&A Pro, Iron Cupcake, E-Lab, Elk Butte Recreation, Heraeus, HMK, IceAge, Klim, Makita Power Tools, Millennium Technologies, Polymer Technologies, Red Bull, Silent Running, Slednecks, Snowest, Spokane Winter Knights, Stud Boy, Thunder Products, Valley Powersports, Western Power Sports, Washington State Snowmobile Association, the National Institute for Advanced Transportation Technology, Finns, Justin, Nick, Drew, Alex, Sam, Chris, Glen May, Russ Porter, Dr. Dan Cordon, Dr. Karen DenBraven,Dr, Mike Santora and the many others that made this project possible.

Definitions/Abbreviations

ADC	Analog to Digital Converter
AFR	Air Fuel Ratio
BSFC	Brake Specific Fuel Consumption
CFD	Computational Fluid Dynamics
CSC	Clean Snowmobile Challenge
DI	Direct Injection
DOE	Department of Energy
ECU	Engine Control Unit
EPA	Environmental Protection Agency
ETC	Electronic Throttle Control
FFT	Fast Fourier Transform
HC	Unburned Hydrocarbons
MAQR	Mechanically Active Quarter-Wave Resonator
MSRP	Manufacturer's Suggested Retail Price
NPS	National Park Service
RPM	Revolutions Per Minute
SAE	Society of Automotive Engineers
UICSC	University of Idaho Clean Snowmobile Challenge
WOT	Wide Open Throttle