Development of Testing Methods and Solutions to Reduce Environmental Impacts of a Reduced Speed, Direct Injection, Two-Stroke Snowmobile

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Innovations

The University of Idaho's entry to the 2019 Clean Snowmobile Challenge (CSC) is a 2017 Ski-Doo MXZ-TNT 850 E-TEC two-stroke with throttle body and direct injection (DI). Performance in the last several years indicated that the University of Idaho CSC (UICSC) team would benefit from updated testing methods. Engine testing was addressed with improved dynamometer data acquisition, development of combustion analysis capabilities, and ramped modal cycle (RMC) testing. On-chassis testing was updated with in-service data collection and order analysis. To reduce sound, a new intake design was explored and the Ski-Doo Silent Drive system was implemented.

Data Acquisition

During engine testing, engine inputs, outputs, and operating conditions are measured (Table 1). Previously, information was visually read from various displays and manually recorded into a spreadsheet. This method of data collection required five points of interaction, was time consuming, and yielded unsynchronized data.

Table 1. Data collected during dynamometer testing. Asterisks indicate new equipment.

Measurement	Equipment
Emissions	Horiba Mexa-584L 5 Gas Analyzer
Air-to-Fuel Ratio (AFR)	Bosch wideband 02 sensor, Innovate LM-2
Fuel flow	MAX Machinery 710 Series Fuel Measurement System
Engine speed and torque	Borghi & Saveri eddy current dynamometer
Cylinder pressure*	PCB 111A24 ICP transducer
Crankshaft position*	Encoder Products Company model 15S
Temperatures: coolant inlet & exit, exhaust and clutch side exhaust gas temperature (EGT)	Omega K-type thermocouples
Coolant flowrate*	Omega FTB 905 turbine flowmeter & FLSC-61 analog transmitter

To address this, the team's existing SuperFlow sensor box and WinDyn software are now used to record measured data into a single file to be post processed and analyzed. Likelihood of erroneous data entry is reduced, data at discrete operating points can be time averaged, and measurements are time synchronous.

The improvements made to the UICSC's engine test cell also allowed for automation of the dynamometer controls and data acquisition (DAQ), making it possible to perform the RMC test used in the CSC. This allows for evaluation of transient performance at the competition, which has been a challenge for the UICSC team in recent years.

Combustion Analysis

In-cylinder pressure measurements resolved to crankshaft position is being introduced to the UICSC team's testing capabilities and will be operational by the close of the academic year. This will allow combustion to be analyzed on a cycle-to-cycle basis during dynamometer testing.

A National Instruments PCI-6143 is being used to collect signals from an encoder with 0.35 degree resolution and a pressure transducer placed in the engine's cylinder head. To overcome drift characteristic of piezoelectric pressure transducers, it is necessary to peg the transducer output to an absolute reference pressure. An absolute pressure sensor will be added to the crankcase to accomplish this.

Pressure versus volume (p-V) plots will be useful in identifying engine knock which is indicated by high frequency oscillation of the pressure measurement. This helps to identify knock threshold and effects of engine operating parameters on knock development. Figure 1 compares p-V plots with and without knock.

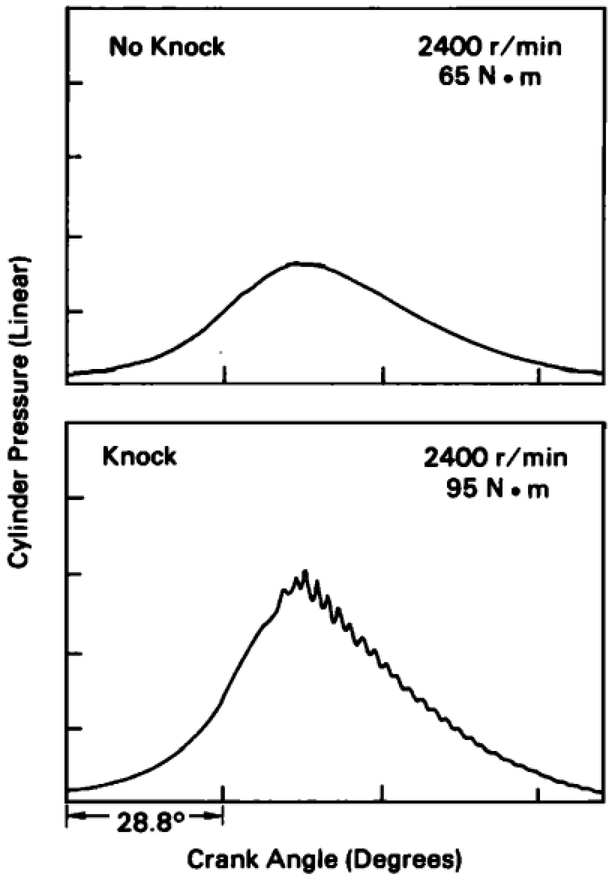

Figure 1. In-cylinder pressure data without (above) and with (below) knock [5], reprinted with permission.

Indicated mean effective pressure (IMEP) is found by calculating the mean cylinder pressure measured over each cycle and indicates the efficiency of work production within the combustion chamber. IMEP will be used as a metric of performance during the calibration process. The coefficient of variance of IMEP is used to quantify cycle-to-cycle variations in combustion; the team seeks to minimize this value, to ensure consistent engine performance. Pumping mean effective pressure (PMEP) is measured similarly, using pressure data from the crankcase and characterizes the work required to pump air into and out of the engine. Brake mean effective pressure (BMEP) is calculated with Equation (1) and is a measure of the efficiency of work production relative to engine displacement. $\dot{W}_b$ is the brake power output of the engine, V_{sv} and rps are the swept volume and engine speed, respectively.

$$BMEP = \frac{\dot{W}_b}{V_{sv} \cdot rps} \quad (1)$$

Friction mean effective pressure (FMEP) indicates the work required to overcome frictional losses within the engine and is found with Equation **Error! Reference source not found.**, using the measured mean effective pressures introduced above [1]. Determining these four mean effective pressures allows the engine efficiency to be characterized and will guide future UICSC engine projects.

$$FMEP = IMEP - BMEP - PMEP \quad (2)$$

The mass fraction burned (MFB) is a measure of the fraction of fuel burned by the engine and is calculated according to Equation (3) [3]. In this equation, p and V represent pressure and volume, subscripts o and f represent start and end of combustion, respectively.

$$MFB = \frac{p^{1/n}V - {p_0}^{1/n}V_o}{{p_f}^{1/n}V_f - {p_0}^{1/n}V_o} \quad (3)$$

MFB data are then used to generate combustion phase information of crank angle (CA) relative to MFB. CA10, CA50, and CA90 (crank angle at which MFB is respectively 10%, 50%, and 90%) are useful indicators of appropriate spark timing and fuel injection timing. Optimal CA50 values typically range from 5-10 degrees after top dead center [1].

In-Service Data Collection

Previously, in-service testing has been inaccurate and inconsistent due to a lack of data recording capability. For 2019, the UICSC team began logging engine and vehicle data in the field. These data allowed the team to identify areas of operation on which to focus outside of the 5 discrete modes, measure real-time fuel consumption to quantify changes in efficiency, and characterize the operation of the Continuously Variable Transmission (CVT).

A histogram of the engine's operation while attempting to maintain an average trail speed of 45 mph can be seen in Figure 2.

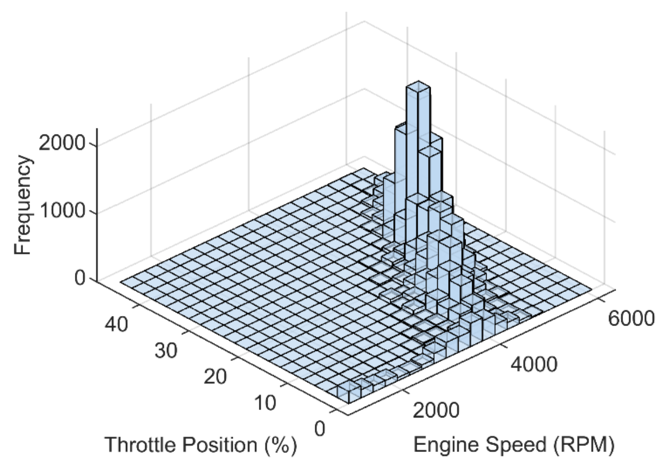

Figure 2. Histogram of engine operation during trail riding similar to the CSC endurance event.

With this information, engine calibration was revisited and decreased brake specific fuel consumption (BSFC) was targeted in the regions of high frequency.

Order Analysis

Order analysis test procedures were developed to determine the main contributors to noise and allow more informative comparisons after changing parts of the snowmobile. The analysis works by decomposing a noise signal into its frequency components over a time range. In most vehicles, the prominent noise frequencies are proportional to the rotational frequencies of shafts in the drivetrain. This proportion is called an order, computed as in Equation (4) where f is the frequency of a component and ω_{shaft} is the frequency of the source shaft. For example, the primary firing frequency of a two-cylinder two stroke should have an order of 2.0 with respect to the crankshaft.

$$N_{order} = {}^{f}/_{\omega_{shaft}} \tag{4}$$

The UICSC team performed order analysis on vibration and acoustic data. For vibration testing, the snowmobile was kept stationary with the track lifted while the engine was taken from idle to wide open throttle (WOT) and back. An accelerometer was placed near the front of the PTO-side running board to provide information on the front and rear sections of the vehicle. Figure 3 shows order magnitude versus time as well as driveshaft speed as measured by a laser tachometer.

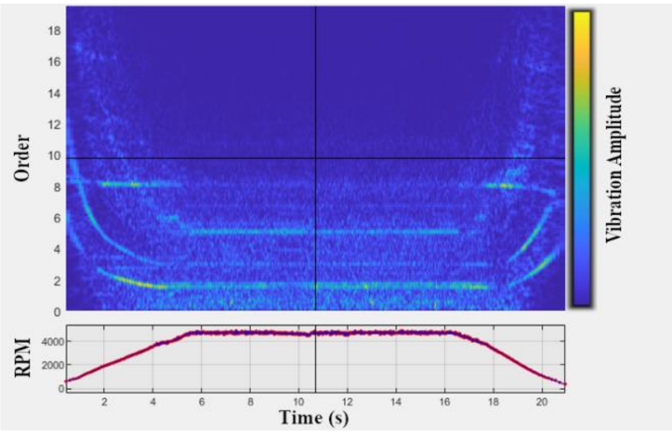

Figure 3. Vibration order with respect to driveshaft RPM.

One of the most prominent orders, a constant 8.0, was linked to the stock drivers, which have eight teeth. Because the track had no load at steady state in the middle of the test, the contact forces on the track lugs dropped, prompting the development of an on-snow acoustic test. A discussion of the strategy to target the drivers can be found in the Drivetrain section that follows. The other main orders are theorized to be related to combustion, crankshaft vibration, and the CVT pulleys. Analyzing these order curves is difficult because of the changing CVT gear ratio, which flattens at steady state. The team is developing a method to compute orders with respect to both drivetrain and crankshaft speed to fully understand the system and quantify noise reductions more easily.

For acoustic testing, a microphone measured unweighted sound pressure from 50 ft. away in the J1161 test, where the snowmobile was driven at about 35 mph. Shaft speeds were not recorded, but an approximate driveshaft speed was calculated based on groundspeed to help locate orders of interest. Order analysis is useful in this setting because environmental noise is usually separate from sound produced by vehicle components, so the results are not drastically affected by ambient sound level changes. The J1161 test is better for determining final A-weighted sound output, but order analysis allows more direct comparisons of the noise contributions of individual components. Results from this testing are presented in the Drivetrain section.

Drivetrain

Sound vectoring performed on the 2018 UICSC snowmobile identified the track region as one of the loudest areas on the snowmobile [4]. Order analysis was used in conjunction with known groundspeed and mechanical relationships on the snowmobile to identify the track-driver interaction as being a significant source of sound

Of several options considered, the Ski-Doo Silent Drive system was chosen to address this. The irregular contact pattern between the drive cogs and the track's inner lugs was expected to reduce a pure tone into interacting frequencies of lower amplitude. Additionally, transitioning from plastic-on-metal contact to plastic-on-rubber contact between the drivers and the track was also expected to reduce sound pressure [7]. The Silent Track II and driver combination is shown in Figure 4.

Figure 4. Silent Drive and Silent Track II [8].

To measure the effect of the Silent Drive system on sound production, J1161 tests were conducted. The Silent Drive system afforded an average decrease of 0.9 dBA from the 2018 configuration.

Order analysis was performed on sound data gathered during the J1161 tests to generate frequency versus time plots. Processing the microphone recording yielded data that represent sound pressure. While no absolute units can be used, the root mean square (RMS) amplitudes can be compared, because the microphone had a constant gain in testing. These are shown for both the 2018 configuration and the 2019 Silent Drive configuration in Figure 5 and Figure 6, respectively.

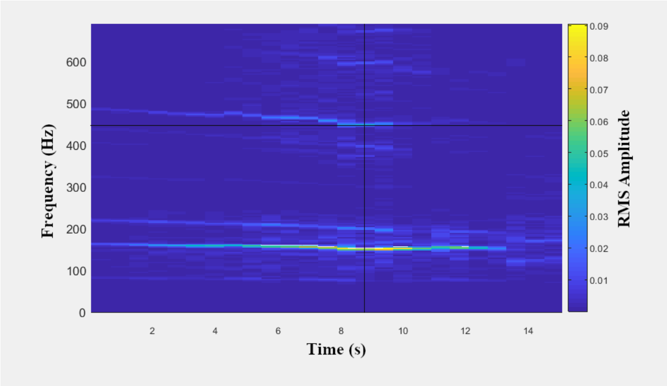

Figure 5. Frequency versus time plot with 2018 track and driver configuration measured on the clutch side. Crosshairs indicate frequency identified as the track and driver interaction.

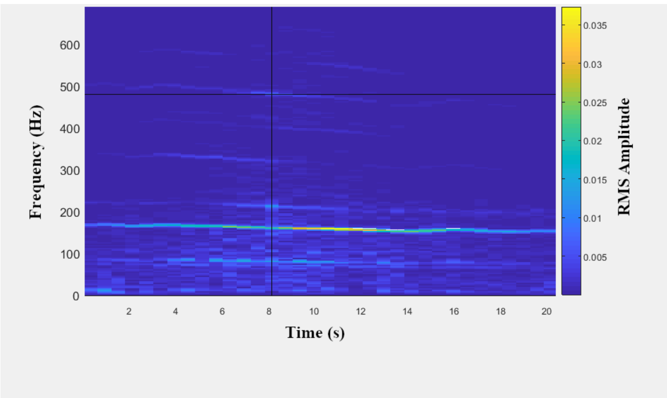

Figure 6. Frequency versus time plot with Silent Track II installed measured on the clutch side. Crosshairs indicate frequency identified as the track and driver interaction.

Based on estimated ground speed, the approximate frequency of the driveshaft was calculated to be 60 Hz. For the 2018 configuration, significant average sound pressures, identified with a relatively high RMS value of .033, were identified at approximately 446 Hz. This is an order of 7.4 relative to the driveshaft and was identified as likely being the interaction between the track and driver, based on the 8 points of contact. Similarly, a RMS value of .013 was identified at a frequency of 479 Hz; this is an order of 7.9 relative to the approximated driveshaft frequency. The variation over time visible in all order lines is likely a result of inconsistent ground speed that is assumed constant. The slight increase of frequency between the configurations may be a result of differing ground speeds or the slight increase in driver-track contact frequency imparted by the irregular lug pattern. The decrease in RMS magnitude represents a 69% reduction in the sound pressure developed at these frequencies. It was extrapolated that the Silent Drive system is responsible for this reduction in sound.

Intake Design

The stock configuration of the intake design includes an under-hood flow path that directs airflow across a series of Helmholtz resonators. Because there was no measurable difference in power when removing this intake, shown in Figure 7, it was assumed that these resonators are designed to reduce intake noise.

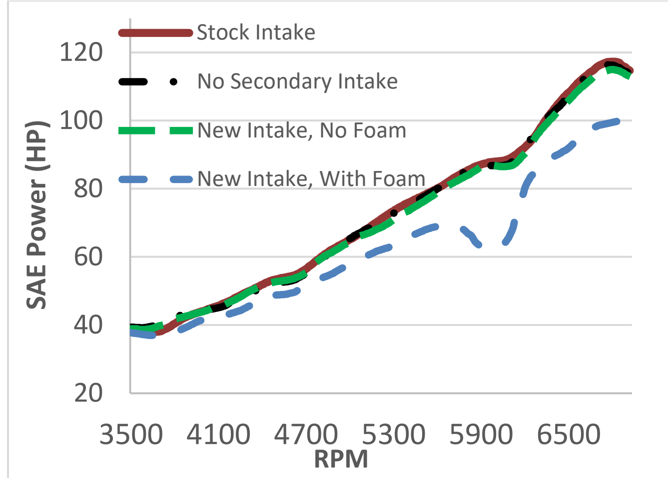

Figure 7. Power sweeps comparing intake configurations.

Although the UICSC team has had success using Helmholtz resonators to reduce sound, it was decided to reinvestigate other solutions from the team's history. In 2010, the UICSC team implemented Melamine 3-layer foam to reduce sound caused by panel vibration. In 2006, the use of sound material to line the air intake was also successful [2]. In 2019, these ideas were revisited by designing an intake without Helmholtz resonators, allowing room to apply sound material to the hood. This intake also allowed for the placement of open cell foam in the flow path.

Preliminary sound testing was conducted on a flow bench operating at 0.099 m^3 /s [3.5 ft^3/s] to simulate the average volumetric flowrate of the engine at peak engine speed. A reduction of 4.6 dBA was measured when placing foam in the intake. However, it was found that pressure drop increased from 1.52 kPa [0.22 psi] to 12.69 kPa [1.84 psi]. Dynamometer testing with the open cell foam in place confirmed this flow restriction caused issues with engine operation too significant to be used (Figure 7). The J1161 pass-by test was used to compare the stock configuration to the new intake with Melamine 3-layer foam installed on the hood; sound pressure increased from 67.7 dBA to 70.3 dBA.

This suggests that the Helmholtz resonators effectively reduce overall sound. In the future, the effectiveness of Helmholtz resonators at varying engine speed and load could be explored. These results indicated that the stock configuration was the most effective at attenuating sound; this is the configuration used for the 2019 UICSC entry.

Team Organization and Time Management

Member Roles and Responsibilities

The overall structure of the team, shown in Figure 8, has gone unchanged from last year. Current members maintain contact with alumni who offer valuable feedback on projects and support the team via donations. The faculty advisor is a non-student position critical to the team's success, acting as the point of contact between the team and university administration. In addition, the faculty advisor provides project management guidance and technical expertise.

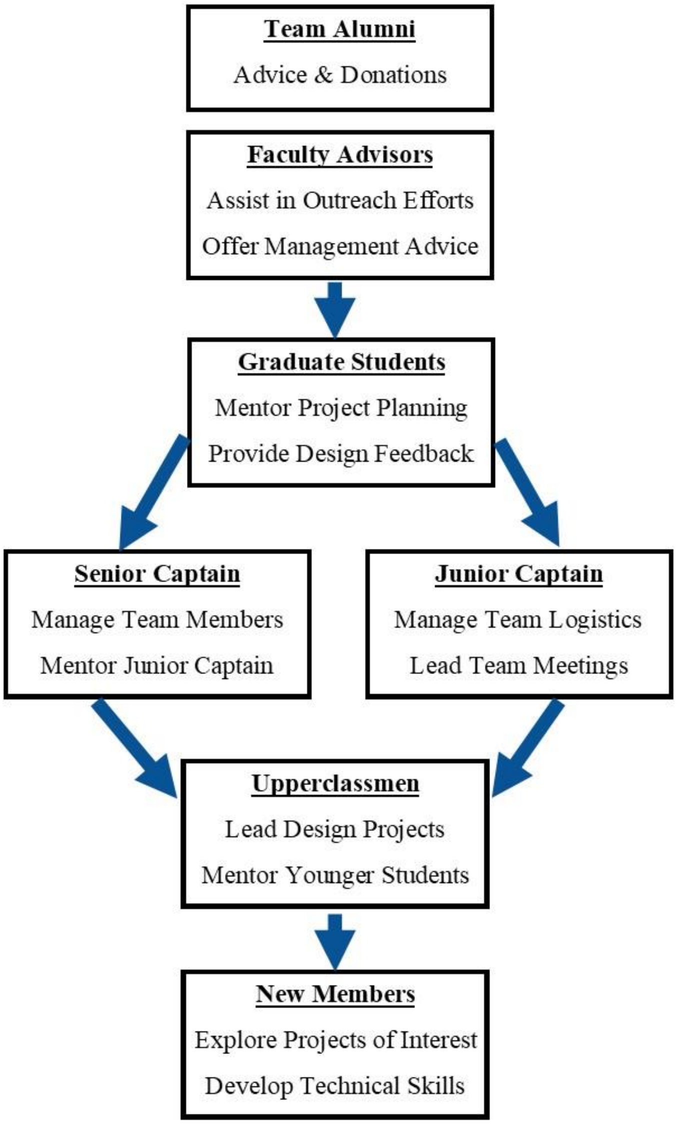

Figure 8. Team structure.

Students are responsible for managing the team's operation and budget, in addition to selecting and completing projects. Members are divided into graduate students, captains, upperclassmen, and new members. Graduate students guide project selection and mentor upperclassmen; they act as a source of tribal knowledge that would otherwise be lost and alleviates challenges of leadership transitions. The lack of a graduate student for the previous two years has placed these responsibilities with the captains and upperclassmen. The senior captain manages deadlines and tracks the status of all projects. They are also responsible for mentoring the junior captain and the other team members. The junior captain's responsibilities include logistics, managing the team's budget, and ensuring accounts are updated. Upperclassmen lead projects, oversee manufacturing, and mentor new members. The new members are encouraged to gain knowledge as quickly as possible and have the opportunity to work on a variety of projects to explore their interests. With mentorship, they complete design, manufacturing, and testing projects from the time they join the team.

Team Education

The team offers a weekly class consisting of presentations, assignments, and quizzes designed to improve knowledge transfer and develop engineering skills. Each lecture is delivered by an upperclassmen with experience in the subject. By teaching, they build on existing knowledge and develop presentation skills.

Course curriculum is as follows:

- Introduction to the CSC
- Logbook Expectations
- Project Management
- Legacy Projects
- Building a Resume
- Sensors
- Continuously Variable Transmissions
- Machining
- Ethanol Compensation
- Acoustics
- Engine Calibration
- Technical Writing

New members take a 200-level version of the course focused on building knowledge. Assignments are based on the course curriculum, general snowmobile information, UICSC theses and design papers, CSC rules, and manufacturing skills. Experienced members take a 400-level version of the course with more rigorous assignments and required project leadership. All members are required to maintain an updated logbook, documenting their current project work and creating a resource for the team in the future.

Timelines and Project Monitoring

The UICSC team began utilizing the Kanban method of tracking the status of tasks through their conception, execution, and completion. This improved project management and individual accountability. Trello, an online application, was used to facilitate the Kanban approach. For each major project, a board (Appendix A) was created which outlined action items and project deadlines.

A typical Trello board is subjectively more intuitive than the Gantt charts used by the UICSC team prior to 2019. Each project lead develops a layout that works best for their group. Action items, important dates, research, and completed tasks are displayed for each project. Action items are assigned to individual members with due dates, promoting accountability. The Trello app provides easy access to this information and relevant notifications.

Team Building

The UICSC team strives to promote an inclusive and supportive culture. New members are encouraged to participate in the community surrounding the team by organizing team barbeques, holiday meetings, and other social events.

Outreach Activities

Fundraising

Fundraising is crucial to the success of the UICSC team. In-kind donations are the primary form of support received. For existing sponsors, the team works to maintain regular correspondence through email and phone conferences. The responsibility of contacting potential sponsors falls to the members on a given project. Sponsors are recognized in the team's presentation, through branding on the snowmobile, and with a thank you card at the close of each season.

Exposition Events

Each year, the team attends three snowmobile exposition events around the Pacific Northwest. This allows members an opportunity to discuss projects with the public and representatives from industry. The returns on this are twofold, as team members develop public speaking and professional bearing, while also discussing the design decisions made and projects being pursued on the team.

Build Items of the Snowmobile

Table 2. Snowmobile modification and build items.

Chassis	Ski Doo, MXZ REV Gen4, 2017, with 2019 REV Gen4 wide-design bodywork
Engine	Rotax, Gasoline, ETEC DI and throttle body injection, 2-stroke, 849cc, claimed 123 kW [165 hp] at 7900 RPM in stock configuration [6], measured 88 kW [118 hp] at 6850 RPM in UICSC configuration
Track	Camso/BRP, Ice Ripper XT, Silent Track II, pre-studded, used with Silent Drive drivers
Catalytic Converter	Heraeus 1:20:1 Platinum, Palladium, Rhodium Coating, Dual Substrate, 11.5 cm [4.5 in.] long, 7.9 cm [3.1 in.] in diameter
Skis	SLP Mohawk
Exhaust	Student designed, extended tuned pipe
Skid	25.4 cm [10 in.] diameter idler wheel kit designed by students

Snowmobile Design

Reduced Speed Engine

The UICSC team continues to use a reduced speed, 850cc E-TEC engine to meet performance benchmarks of the 600cc class while reducing sound and improving efficiency. For any given road load, engine speed and/or throttle angle will be less in the UICSC engine than in a typical 600cc two stroke. A smaller throttle angle yields lower in-cylinder pressures, which reduces sound pressure at the exhaust outlet. Lower engine speeds result in reduced frictional losses and therefore improved engine efficiency [3].

After benchmarking the stock engine, the UICSC team reduced engine speed such that power output complied with the CSC rules. A peak operating speed of 6800 RPM was chosen, a reduction of approximately 1100 RPM. Fuel injection quantity was reduced and spark timing was delayed to limit engine speed by reducing torque above 6800 RPM. This yielded a power curve that tapered off enough to prevent over-rev in most conditions.

Most two-stroke engines need a tuned exhaust pipe to improve engine operation. A typical tuned pipe is shown in Figure 9. Exhaust gases are first expanded and accelerated through the diverging cones (L2-L4). This draws fresh air through the transfer ports and into the cylinder. When the exhaust gases pass through the converging cone (L6), a pressure pulse is created that reflects back to the exhaust ports, trapping the fresh air and preventing it from exiting the combustion chamber. The intensity of these scavenging and trapping effects is determined by the cone geometry, while the timing is determined by the length of the pipe [1].

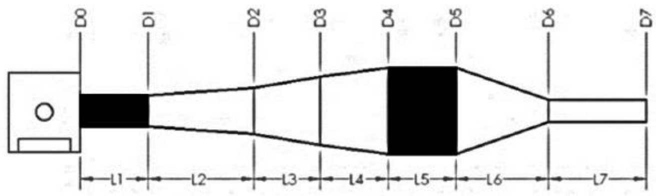

Figure 9. Typical geometry of a tuned pipe. Sections shown in black were extended by the UICSC team.

Two methods were used to determine the change in tuned pipe length to accommodate the reduced engine speed. The first, Equation (5), is an empirical equation presented by Blair, wherein L_T is the tuned pipe length in mm and ED is the duration of the exhaust port opening in degrees.

$$L_T = \frac{ED \cdot 42545}{RPM} \qquad (5)$$

The second method was a GT-Suite Direct Optimizer to find the change in length resulting in the lowest BSFC. The model incorporated internal geometries of the 850cc engine and approximated in-cylinder pressures and burn rates from a Wiebe combustion model. A few of the parameters used for the optimization can be seen in Table 3.

Table 3. Parameters used in GT-Suite Direct Optimizer.

Engine speed	6800 RPM
Optimization method	Local minima
Design variable	Dwell length
Factor range	-10 to 20 cm [-3.9 to 7.9 in.]
Output variable	BSFC
Resolution	0.3 cm [0.1 in.]

Because dwell and header length have similar effects on timing of the trapping pulse, only dwell length (L5) was used in the 1-D simulation. Figure 10 shows the results of the optimization, yielding the lowest predicted BSFC with an additional 10.4 cm [4.1 in.] of length over stock.

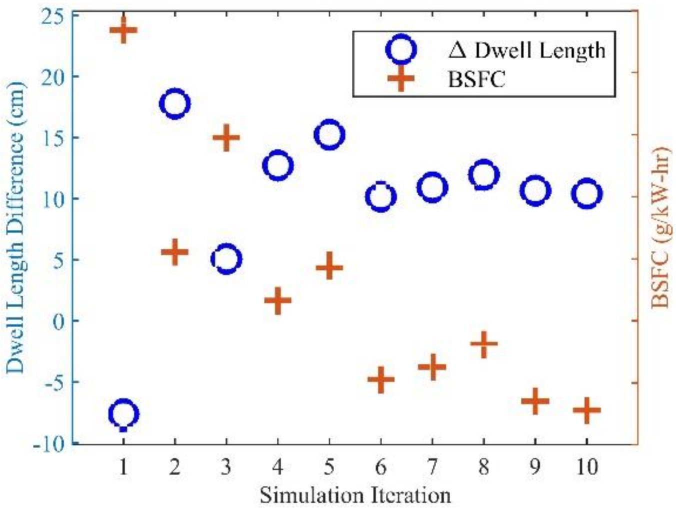

Figure 10. Results of 1-D optimization of tuned pipe length.

The empirical equation and the 1-D optimization yielded similar results of 10.2 cm [4 in] and 10.4 cm [4.1 in], respectively. Packaging space limited extension of the dwell to 6.4 cm [2.5 in.]; the additional 4.0 cm [1.6 in.] was added to the header. Changes to the tuned pipe increased torque, as can be seen in Figure 11.

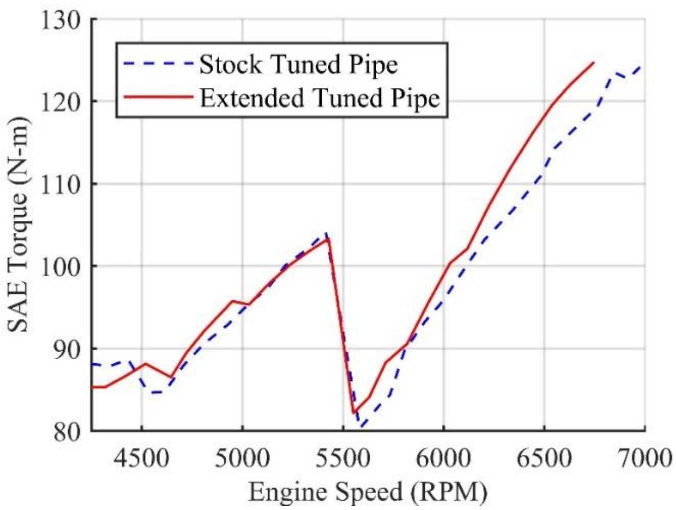

Figure 11. Torque comparison of stock and extended tuned pipes.

Engine Calibration Strategy

After reducing the operating speed, the engine was calibrated to further reduce emissions and improve efficiency while maintaining survivability. Engine efficiency is optimized by minimizing measured BSFC. Emissions can be optimized via the objective function, Equation (6), that determines E-score points lost based on measured carbon monoxide (CO), oxides of nitrogen (NO_x), unburned hydrocarbons (UHC), and power ($\dot{W}$). Relative weighting of the mode point, designated by M, acts as a scaling factor depending on the portion of the map being calibrated.

$$f(x) = M * \frac{\left(\frac{(UHC + NO_x)}{1.5} + \frac{CO}{4}\right)}{\dot{W}} \qquad (6)$$

Survivability is gauged by the excess air coefficient (λ), EGTs, and the presence of knock. λ is the ratio of measured AFR to stoichiometric AFR. Stoichiometric AFR is the theoretical ratio such that no excess oxygen or unburnt fuel remains after combustion. Engine out EGTs should never reach or exceed 650 ºC [1200 ºF] for risk of damaging aluminum engine components. Engine knock is a result of elevated cylinder pressures and adverse operating parameters and can lead to component damage.

Generally, emissions are of primary concern during calibration. At mode points near WOT, survivability takes precedence and operational areas near cruise are calibrated for efficiency with emissions succeeding.

Engine parameters are varied at each operating condition as follows:

- Sweep fuel injection timing of the E-TEC injectors
- Holding the best injection timing constant, sweep the fuel injection quantity
- Vary the ratio of fuel injected by the E-TEC injectors to the fuel injected by the throttle body injectors
- Maintain the value of λ corresponding to the above fueling conditions, while sweeping ignition timing. Care must be taken to prevent knock caused by excessive ignition advance.

Once targeted areas of the map have been calibrated, remaining areas are populated with interpolation. As necessary, transitions between the electronic Rotax Adjustable Variable Exhaust Valve (eRAVE) positions are shifted to linearize torque curves at various throttle openings. After completing the calibration process, on snow validation is conducted. Known λ is compared with measured values during operation to ensure that there are no major discrepancies between engine operation in lab and in chassis.

Ethanol Compensation

The 2019 CSC rules require that the snowmobile must be flex fuel capable (E0-E85). A Continental Flex-Fuel sensor is used to measure ethanol content and this frequency output is conditioned to an analog signal required by the engine control unit. Injection quantity is varied to compensate for ethanol content.

Oversized Rear Idler Wheels

In 2018, the team developed a kit to increase the diameter of the rear idler wheels without modification to the skid (Figure 12). For 2019, this change is again implemented to allow use of the 348 cm [137 in.] Silent Track II.

Figure 12. Increased diameter rear idler wheels installed on the skid.

The idler wheel kit increases the diameter of the wheels from 17.8 cm [7 in.] to 25.4 cm [10 in.] and allows multiple idler wheel configurations [4].

Roll-out testing was used to quantify the change in dynamic rolling resistance imparted by the increased diameter idler wheels in combination with the new Silent Track II. The distance required to coast to a stop from a speed of 80 kmph [50 mph], 64 kmph [40 mph], and 48 kmph [30 mph] on flat, hard-pack snow was measured and is shown in Table 4. Additionally, instantaneous fuel consumption data were collected during steady state operation (Table 5). This indicated that 2019 configuration yielded decreased drivetrain efficiency. It was determined that the reduction in sound afforded by the Silent Track II was worth this decrease in efficiency.

Table 4. Roll-out testing results.

Tested Component	Roll-Out Distance (m [ft.])		
	80 kmph [50 mph]	64 kmph [40 mph]	48 kmph [30 mph]
2018 Configuration	87.0 [285.3]	65.9 [216.3]	45.2 [148.3]
2019 Configuration	80.2 [263.0]	61.6 [202.0]	41.0 [134.7]

Table 5. Calculated instantaneous fuel flow at steady state.

Tested Component	Fuel Consumption (L/100km [mpg])		
	80 kmph [50 mph]	64 kmph [40 mph]	48 kmph [30 mph]
2018 Configuration	14.4 [16.3]	14.0 [16.8]	11.5 [20.4]
2019 Configuration	13.7 [17.2]	14.5 [16.3]	11.2 [21.0]

An 83.7 km [52 mi.] ride on an ungroomed trail was used to measure fuel consumption. In stock form, 17.04 L/100 km [13.80 mpg] was measured. The final configuration achieved 13.42 L/100 km [17.53 mpg].

Emissions

In addition to engine calibration, the UICSC team implements a catalytic converter to reduce emissions. The catalyst placed at the exit of the muffler is a 1:20:1 Platinum:Palladium:Rhodium coated dual substrate configuration. Prior testing comparing varied coatings and single versus dual substrates identified this as the most effective of the tested configurations [4].

The final calculated E-score for the 2019 UICSC entry was found to be 180, increased from 133 in the stock configuration. Presented in the figure below are RMC E-scores for the UICSC team's stock and 2019 configurations in addition to two other CSC teams. The 2018 University of Wisconsin – Madison entry 674cc 4-stroke, producing approximately 34 kW [46 hp]. The University of Wisconsin – Platteville entry is a 4-stroke 1.0L 3 cylinder automotive engine producing approximately 71 kW [95 hp].

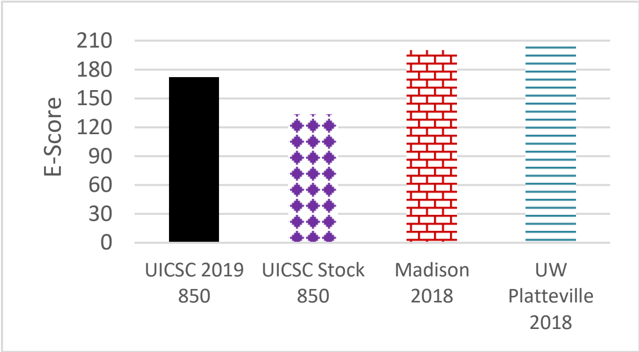

Figure 13. E-Score comparisons.

Sound

Sound reduction is achieved with application of vibration damping and sound absorbing materials in critical locations.

Vibration Damping

To reduce noise produced by chassis vibration, a paint-on damping material called Silent Running was applied to the tunnel based on results from damping ratio tests used in previous years [4]. Polydamp, also tested to decrease oscillation, was adhered to the injectors and chain case because of easier application and no need for cure time.

Engine Bay Sound Material

2019 Ski-Doo Grand Touring 900 body panels were used to replace the stock MXZ-TNT panels, allowing space for additional sound material. Melamine three-layer foam was placed inside the panels as it was shown in previous years' testing to outperform other materials [4]. Where exposed to high temperature, the foam was wrapped with an aluminum-fiberglass heat shielding material. J1161 test results indicating the effectiveness of the Melamine three-layer foam are shown in Table 6.

Table 6. Sound pressures measured during the J1161 test to measure the benefits of Melamine three-layer foam applied to the hood and body panels.

	Average J1161 Sound Pressure (dBA)	
Muffler	Clutch Side	Exhaust Side
No sound material	71.0	70.3

Melamine three-layer installed	69.1	69.7

Sound Vectoring

A sound vectoring test was used to determine the sources and frequency content of noise. A wire grid with a central control mic and 16 outer test mics was placed 0.9 m (3 ft) from either side of the snowmobile with the track lifted as the engine was run at 4100 RPM, the approximate engine speed during the J1161 test. Insertion loss is a measure of sound pressure relative to a control point. It is calculated at each grid point with equation (7), evaluated at each frequency of a fast Fourier transform.

$$IL = 20 \cdot \log\left(\frac{p_i}{p_c}\right) \quad (7)$$

Data processing was further automated to allow a view of insertion loss at all frequencies rather than arbitrary selections, and the data was interpolated linearly to improve visualization. Previous sound vectoring results were processed at a single frequency. Figure 14 and Figure 15 show cumulative insertion loss at each point over a frequency range from 86 to 21964 Hz. Warmer colors represent louder areas. This cumulative metric is only an approximate indicator of relative loudness, because decibel differences do not sum linearly, due to the logarithmic scale. However, it is useful for interpreting data over a large frequency range.

The point with the highest average insertion loss over all frequencies on clutch side was the engine compartment. On exhaust side, the track, chain case, and muffler outlet showed the highest average. Partitioning of the cumulative results into ranges of low, medium, and high frequencies gave the same conclusions. The new data visualization method confirms noise vectoring analysis results of previous years. These results led the team to target track and driver noise as well as add more sound absorbing material to the engine compartment. Future plans also include implementing a belt drive to reduce chain case noise.

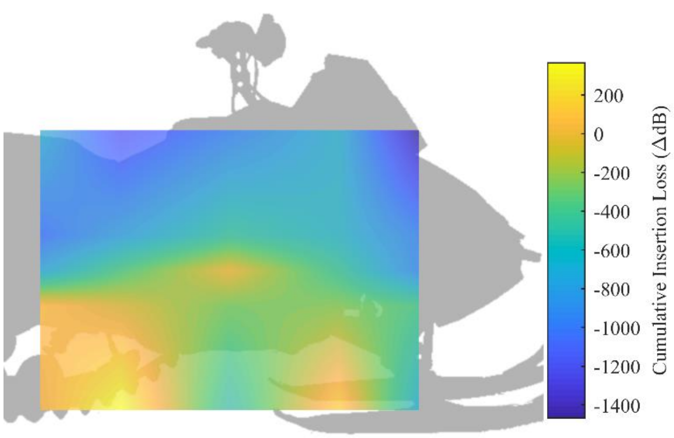

Figure 14. Noise vectoring results from the exhaust side of the snowmobile.

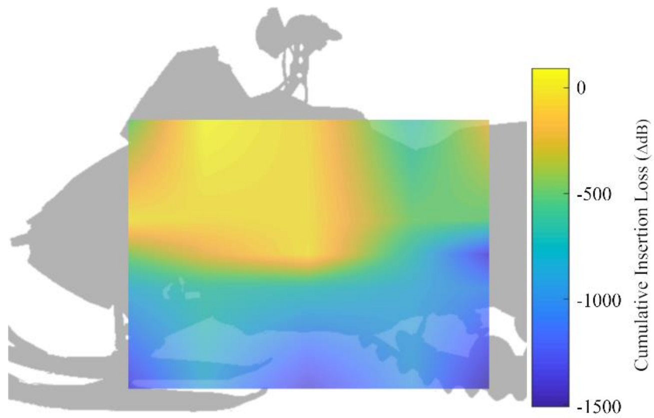

Figure 15. Noise vectoring results from the clutch side of the snowmobile.

J1161 Results

The final snowmobile configuration was measured to produce 67.7 dBA in the J1161 test.

Performance

The CSC encourages student teams to develop solutions to reduce environment impacts of snowmobiles which are practical enough to be adopted by the industry and accepted by consumers. To this end, the UICSC team has set a goal to produce a snowmobile that is clean, quiet and fuel efficient while matching the performance of a 600cc snowmobile. To accomplish this, an 850cc engine is downsped to 6800 RPM, limiting power to 88 kW [118 hp]. Although power is decreased, torque is increased across the remaining operating range, as seen in Figure 11. The 2019 Ski-Doo Grand Touring 600 has been identified as the performance benchmark of comparison for the UICSC entry. According to BRP, the Grand Touring produces 93 kW [125 hp] with a wet weight of approximately 288 kg [634 lbs.] [6], resulting in a power to weight ratio of 0.324 kW/kg [0.197 hp/lb]. The UICSC snowmobile has a wet weight of 280 kg [619 lbs.], yielding a power to weight ratio of 0.314 kW/kg [0.191 hp/lb]. Table 7 compares the power to weight ratios of the top three teams from the 2018 CSC and the 2019 UICSC snowmobile.

Table 7. Overall weight and power to weight ratio comparison.

	UICSC	**Kettering Univ**	**Univ of Minnesota-Duluth**	**Univ of Wisconsin-Madison**
Weight kg [lbs.]	280 [619]	249 [549]	299 [659]	262 [577]
Power-to-Weight ratio kW/kg [hp/lb.]	0.314 [0.191]	0.139 [0.086]	0.074 [0.101]	0.130 [0.080]

The CSC evaluates performance with handling and acceleration events. UICSC has won objective handling five years in a row and acceleration two years in a row following a 2nd place finish in 2016. A UICSC snowmobile has placed in the top two in subjective handling five times in the last seven years.

Despite operating at a higher power output, fuel economy does not necessarily suffer. The UICSC snowmobile has placed top three in fuel economy 3 years in a row, winning in 2016. In the 2018 competition, the only teams to beat UICSC in fuel economy were Kettering and ETS. Kettering produced 35 kW [47 hp] and ETS produced 37 kW [50 hp]. The UICSC snowmobile is competitive in fuel economy while producing substantially more power.

MSRP

The manufacturer's suggested retail price (MSRP) for the 2019 UISCS entry is $13,644.23. The base sled is a 2018 Ski-Doo MXZ-TNT 600 E-TEC with an MSRP of $11,399.00. The increase of 19.7% is justified by the increased fuel economy, reduced emissions and reduced sound output.

Conclusion

The University of Idaho's entry into the 2019 CSC is a 2017 Ski-Doo MXZ Rev Gen 4 chassis with a reduced speed Rotax 850cc DI two stroke engine, modified muffler, extended tuned pipe, and various modifications to reduce noise and increase efficiency. The measured E-Score increased from 133 to 180. Fuel economy improved by 27% to 13.42 L/100 km [17.53 mpg]. Sound output was measured to be 67.7 dBA in the J1161 test. Much of the effort put forth by the 2019 UICSC team was directed towards improved testing capabilities.

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Definitions/Abbreviations

AFR Air-to-fuel ratio

BMEP Brake mean effective pressure

BSFC Brake specific fuel consumption

CA Crank angle

CO Carbon monoxide

CSC Clean Snowmobile Challenge

CVT Continuously variable transmission

DAQ Data acquisition

DI Direct injection

EGT exhaust gas temperature

eRAVE Electronic Rotax Adjustable Variable Exhaust

FMEP Friction Mean Effective Pressure

IMEP Indicated mean effective pressure

MFB Mass fraction burned

MSRP Manufacturer's suggested retail price

NO_x Oxides of nitrogen

PMEP Pumping mean effective pressure

PTC Power transmission coefficient

p-V Pressure versus volume

RMC Ramped Modal Cycle

UHC hydrocarbons

UICSC University of Idaho CSC

WOT Wide open throttle

λ Excess air coefficient

Appendix A – Trello Board Example