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Design and Validation of the 2018 University of Idaho Clean Snowmobile: Reduced Speed 850cc Direct-Injection Two-Stroke with Tuned Exhaust

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Abstract

The University of Idaho chose a 2017 Ski-Doo MXZ to compete in the 2018 Society of Automotive Engineers Clean Snowmobile Challenge. The snowmobile was modified to be cleaner, quieter, and more fuel efficient while maintaining a high power-to-weight ratio. The engine is a reduced speed 850cc direct injection two-stroke with flex-fuel capability for ethanol-blended fuels. Emissions were improved through engine calibration and the addition of a 3-way catalyst. Noise was mitigated with strategically placed sound absorbing and damping materials as well as a custom Camso track. Drivetrain efficiency was improved with larger rear idler wheels. Pre-competition testing had the 2018 entry weighing 277 kg [611 lb] wet, achieving 13.4 L/100 km [17.5 mpg] on an ungroomed trail, with an emissions score of 172 on ethanol-free gasoline, and a J1161 sound pressure of 67.5 dBA. The final configuration had a 27% increase in fuel economy, a 39-point improvement in emissions score, and an estimated 2.5 dBA decrease in sound pressure over the stock snowmobile. The result is a high-performance snowmobile that can be operated in environmentally sensitive areas.

Introduction

This paper is organized into three sections. The “Innovations” section introduces improvements to the design of the snowmobile. Team structure and project management practices are discussed in “Team Organization and Time Management.” Details on design implementation, testing procedures, and results are presented under “Snowmobile Design.” A major effort of the 2018 University of Idaho Clean Snowmobile Challenge (UICSC) team was to refine components and strategies proven on previous entries and adapt them to a new chassis.

Innovations

The UICSC team transitioned to a Rotax 850cc direct injection (DI) engine in the 2017 Ski-Doo Rev Gen4 chassis. Innovations developed by the 2018 UICSC team include a reduced speed engine, a modified tuned pipe, a custom muffler, and larger rear idler wheels.

Engine

Growing concerns over the environmental impacts of internal combustion (IC) engines have caused increased regulation of the fuel efficiency and exhaust emissions of modern engines. Current trends in the automotive industry are to reduce displacement and utilize forced induction to comply with stricter regulations [1]. In contrast, the UICSC team has chosen a larger displacement engine operating at lower engine speeds to reduce environmental impact.

The power limit at the Society of Automotive Engineers (SAE) Clean Snowmobile Challenge (CSC) is 97 kW [130 hp]. A Rotax 600cc engine produces 93 kW [125 hp] at 8100 RPM [2]. Alternatively, the UICSC reduced speed 850cc engine produces a comparable 88 kW [118 hp] at 6800 RPM with increased torque at all operating speeds. With respect to the 600cc engine, the higher torque of the 850cc engine allows for lower engine speeds and reduced throttle position to achieve the same ground speed at most operating conditions.

Two-stroke engines with direct injection produce minimal nitrogen oxides (NO_x), but high carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions as they approach peak operating speeds [3]. By reducing peak engine speed from 7900 RPM to 6800 RPM, the mode points for the Ramped Modal Cycle (RMC) are shifted to areas of lower engine speed and throttle position. This reduces emissions and brake specific fuel consumption (BSFC) at the mode points. BSFC is a measure of fuel consumption normalized by engine-out power.

In addition to reducing emissions and BSFC, the reduced speed engine produces a lower dBA reading during the J1161 sound test. Due to the higher torque of the reduced speed 850cc engine, the snowmobile is able to achieve the 56 kmph [35 mph] of the J1161 at a lower engine speed and throttle position than a 600cc engine. This reduces both the frequency and amplitude of sound produced. The test uses the A-weighted scale, which weighs higher frequencies more heavily in evaluating sound pressure [4]. This means a reduction in firing frequency will reduce sound pressure readings on the A-weighted scale. Additionally, a lower throttle position will reduce both in-cylinder and exhaust pressures, decreasing the amplitude of sound produced [3].

Tuned Pipe

Two-stroke engines require a tuned pipe, shown in Figure 1, to generate a pressure wave that aids in scavenging exhaust from the cylinders and trapping the fresh air-fuel mixture in. After combustion, the piston is driven down, opening the exhaust port. High-pressure exhaust gases are drawn into the tuned pipe through the header (L1) and expanded through the diverging cones (L2-L4) to create a low-pressure region in the dwell (L5). When the exhaust gases reach the converging cone (L6), a high-pressure exhaust wave is formed and reflected toward the engine. The geometries of the diverging cones and converging cone determine the intensity of the exhaust wave, while the overall length of the tuned pipe affects the timing of the wave [5].

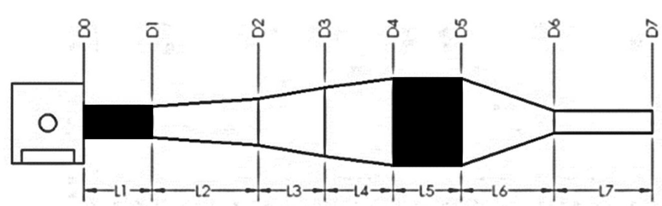

Figure 1. Locations of tuned pipe length increases.

The reflected exhaust wave increases pressure at the exhaust port to trap fresh charge in-cylinder. A tuned pipe is typically designed so that, at peak engine speed, the pressure wave reaches the exhaust port just before it closes [6]. The UICSC team extended the tuned pipe to delay the exhaust wave, accommodating the reduced speed of the engine. The lengthened tuned pipe has the additional benefit of lowering the frequency of exhaust waves, producing a lower sound pressure reading on the A-weighted scale.

The intake, engine, and exhaust components were analyzed using the GT-Suite Direct Optimizer. The goal of the model was to minimize BSFC by altering the length of the header and dwell. The cones were unaltered to avoid changing the intensity of the pressure wave. The model parameters can be seen in Table 1. Intake and exhaust geometries of the 850cc engine were incorporated into the model and in-cylinder pressure and burn rates were approximated using a Wiebe combustion model. Changes to header and dwell length have similar effects on wave timing, so a 1-D optimization of only dwell length was chosen for simplicity and faster run times [5].

Table 1. GT model parameters.

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.]

The results of the simulation are shown in Figure 2, with a local minimum occurring at a dwell length increase of 10.4 cm [4.1 in.]. Due to combustion approximations and manufacturing tolerances, there was no need for higher resolution of the tuned length. To fit the extensions in chassis, the dwell was extended by 6.4 cm [2.5 in.] and the header was lengthened by 4.0 cm [1.6 in.].

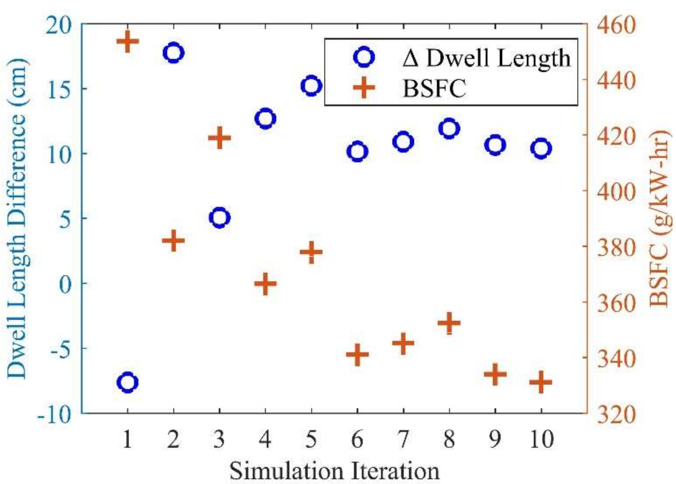

Figure 2. BSFC optimization at mode 1.

This showed only a small difference in optimal tuned length from equation 1, a correlation-based equation used in previous tuned pipe extensions. L_T is the tuned length in mm, and ED is the duration in degrees that the exhaust port is open [5].

$$L_T = \frac{ED \times 42545}{RPM} \quad (1)$$

The final result of the simulation differs from that of equation 1 by 1.2%, validating the model. The project learning from this simulation allows for more advanced simulation-based design in the future.

The improved trapping efficiency of the lengthened tuned pipe led to higher torque output across the operating range of the engine, as shown in Figure 3. Torque at the peak speed of 6800 RPM was increased by 6.8 N-m [5 ft-lb].

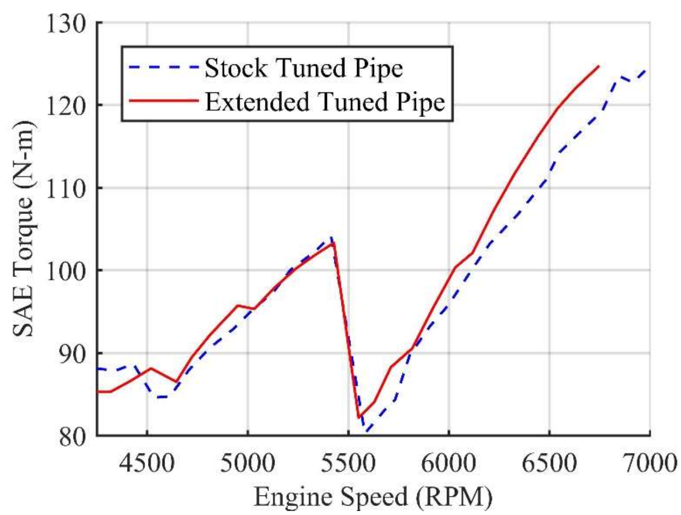

Figure 3. Torque comparison with stock tuned pipe and extended tuned pipe.

Muffler

A custom muffler, based on the 2017 UICSC muffler, was designed to reduce backpressure and increase durability. Alternative design configurations were tested but the final configuration was not implemented. Individual design changes and the final configuration were validated using SolidWorks flow simulations. The results are shown in Table 2 and Figure 4.

Table 2. Design revisions to the 2017 UICSC muffler.

Revision	Label	Calculated Back-pressure	Back-pressure Reduction
2017 UICSC	-	0.043 bar [0.62 psi]	0
Removed small flap	1	0.040 bar [0.57 psi]	9%
Increased diameter from 2 in. to 2.5 in.	2	0.037 bar [0.54 psi]	14%
80 mm outlet diameter	3	0.032 bar [0.47 psi]	26%
Final configuration	-	0.021 bar [0.31 psi]	51%

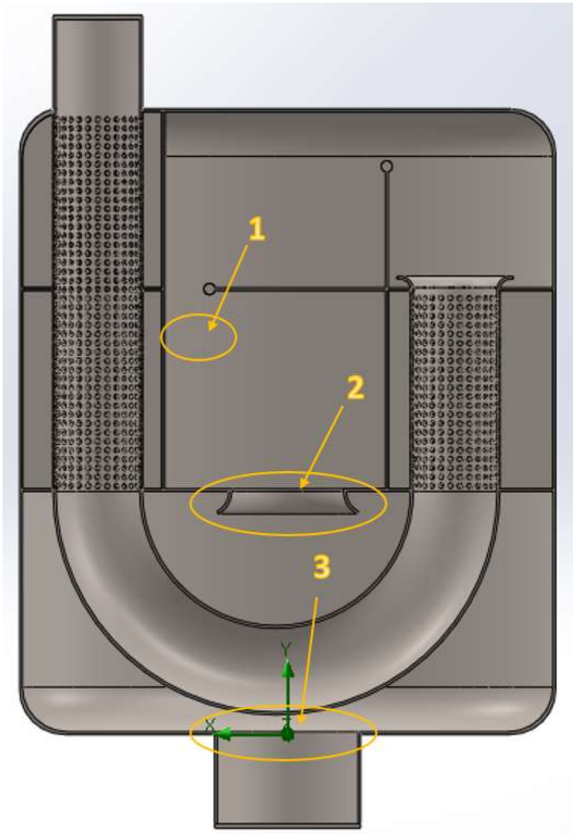

Figure 4. Diagram of muffler design changes.

To verify a decrease in backpressure, the 2018 muffler was measured on a flow bench and compared to the 2017 muffler. The new muffler's backpressure measured 0.057 bar [0.82 psi], which was a 2.4% reduction from the previous revision. Both methods of determining backpressure showed a decrease compared to the previous muffler iteration. However, further testing is required to determine the magnitude of backpressure reduction.

To increase the durability of the muffler, ceramic fiber with a temperature rating of 1430 °C [2600 °F] was placed in the sound absorbing chambers. Another ceramic material rated to 1260 °C [2300 °F] encases the muffler to maintain exhaust temperatures and aid in catalyst light-off. Comparatively, the last iteration utilized a 1260 °C [2300 °F] rated fiber in the muffler chambers and a 650 °C [1200 °F] rated fiberglass blanket encasing the muffler. The manufacturing process was refined to fully seal the three insulated expansion chambers within the muffler, reducing material blow-by and maintaining sound reduction performance over time.

Drivetrain

The UICSC team defines drivetrain efficiency as the effectiveness of power transmission from the crankshaft to the track. Components in the drivetrain include the primary and secondary clutches, chain case, and suspension. To improve drivetrain efficiency, the diameter of the rear idler wheels was increased from 17.8 cm [7 in.] to 25.4 cm [10 in.]. A new axle assembly was designed to accommodate the larger wheels. This design is shown in Figure 5.

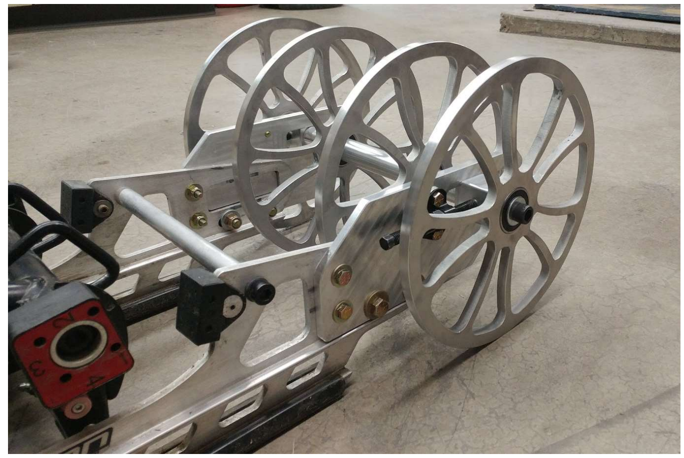

Figure 5. UICSC designed rear idler wheels.

The design allowed testing of multiple idler wheel configurations, shown in Figure 6. To accommodate the larger idler wheels, a new 348 cm [137 in.] Camso track replaced the stock 328 cm [129 in.] track.

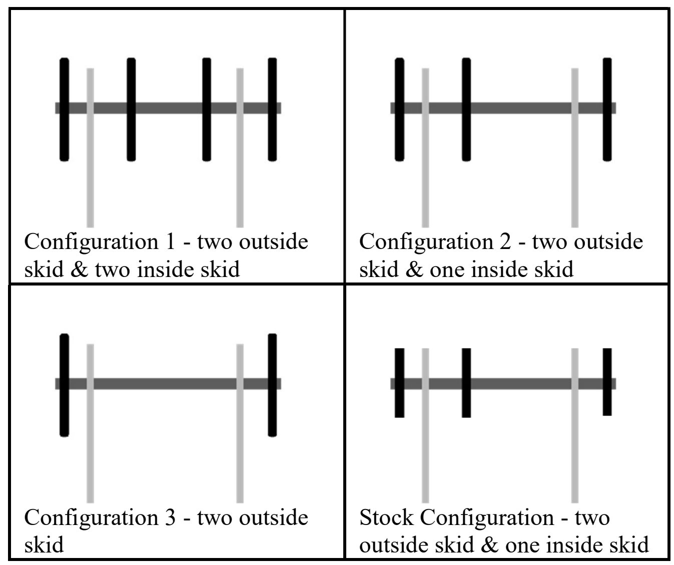

Figure 6. Idler wheel configurations.

The longer track included additional central ports to decrease noise created in the tunnel. It is thought that as the track spins during operation, pressure is built up in the tunnel, increasing noise production. Central ports allow an area for air to escape and relieve pressure [10].

Team Organization and Time Management

The UICSC team attended its first CSC competition in 2000 as a spectator and returned to compete the following year. Since then, the team's structure has continuously evolved to improve project management, knowledge transfer, and accountability among team members.

Team Structure

The team maintains a structure, shown in Figure 7, that prepares members for the design work, project coordination, and leadership roles that they will encounter as engineers.

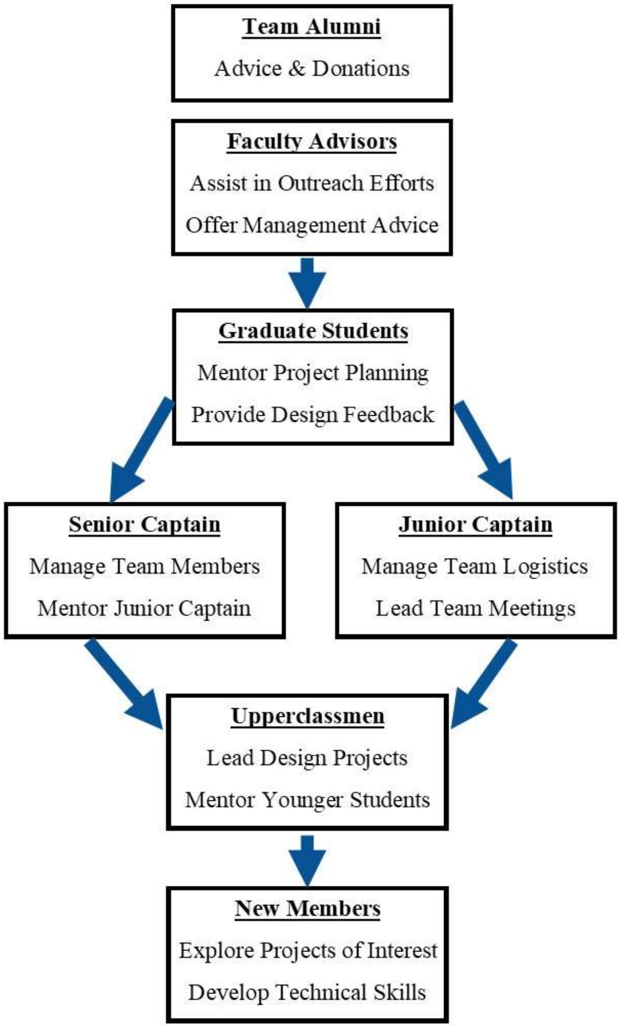

Figure 7. Organizational chart.

Alumni of the team support progress with project suggestions and critique technical papers and presentations. Faculty members offer advice at the request of student leaders and assist in interactions with university administration. Undergraduate team captains are responsible for team and project management. The team typically includes a graduate student, who mentors the team captains and reviews designs. In the absence of graduate students, the senior members assume their responsibilities.

Junior and senior captains share leadership responsibilities. The junior captain manages day-to-day operations such as paperwork and team meetings. The senior captain ensures that work is completed on time and prepares the junior captain for senior leadership [7].

Senior members participate in a year-long design project. This project drives innovation for the UICSC platform. Junior members lead the remaining design and manufacturing work. First- and second-year members join multiple project groups to learn design and testing strategies from older members.

Class Development

Over the last 17 years, the UICSC team has identified recurring challenges regarding team management. The most prevalent was the transfer of knowledge, not only from the upperclassmen to incoming members, but also among members with specialized experience. A lack of knowledge transfer impeded progress when skills and procedures had to be re-learned. To improve team efficiency, members began creating quick reference guides for common assembly and testing operations to be used in a just-in-time manner. These guides could also be deployed as part of a formal orientation process ahead of the competition season. Beginning in the 2015-2016 academic year, an elective class was created for the fall semester to facilitate exploration of these reference materials and improve understanding of snowmobile systems. Over the course of the last year, these resources have been refined, re-sequenced, and packaged on a course website [8].

The course is taught by upperclassmen to enhance their technical leadership skills and to provide peer-to-peer learning opportunities for new team members. The class uses active learning principles and the student instructors review lesson plans with the faculty advisor. The faculty advisor attends selected classes as a coach to the student instructors.

Weekly assignments encourage members to explore available resources such as former members' theses, competition rules, and design papers. Periodic quizzes aid in evaluating understanding of complex but vital project-related knowledge. Students are required to maintain a logbook documenting lessons and project learning. Reading assignments and quizzes are used to encourage classroom discussion and lead into course topics. Table 3 shows a selection of topics covered throughout the course.

Table 3. Course topics.

Main Topic	Resource
Lab Safety Training	Machine shop tour
	Engine test facilities tour
Purchasing (UI)	Purchasing info-session
Project Planning	Milestones and development
Engine Background	2-stroke IC principles
	Combustion regimes
	Sensors
	Calibration overview
Testing and Documentation	Logbook expectations
	Proof-of-concept vs publishable tests, testing procedures, data acquisition
Lab Management/Kaizen Practices	Best practices, kaizen locations, continuous improvement
Technical Communications	Presentations, audience, career pitching
	Technical writing
	Project progress review

Feedback on maintaining quality logbook entries and organization is given at intervals throughout the course. Personal growth, lessons learned, and recommendations for course improvement are captured in end-of-semester papers. These are synthesized for use in planning future course topics.

After implementation of the new course, incoming members absorbed critical knowledge early in the year, encouraging early involvement in design, manufacturing, and testing. New member retention has increased from previous competition years as well.

Project Management

During weekly team meetings, designated speakers from each project sub-group announce status updates and action items for the upcoming week. A Gantt chart, shown in Appendix A, links to a project schedule, Appendix B, that is dynamically updated as sub-groups report weekly progress. Progress and action items are noted in the project schedule to promote accountability.

Weekly meetings within the sub-groups are held to organize project work. All brain-storming, research, and design work are discussed and delegated to individuals in these meetings.

Outreach and Public Relations

The UICSC team attends snowmobile shows around Idaho and Washington State and the Engineering Design EXPO at the University of Idaho. At these events, team members network with vendors, raise awareness about university programs, and improve public speaking skills.

New members are recruited through facility tours, classroom presentations, and university functions. Individuals interested in joining the team submit applications that address their interests, availability, and skillsets.

The UICSC team works with over thirty companies and individuals who provide material and technical support. Maintaining relationships with these contacts teaches members to communicate professionally.

Snowmobile Design

The goals for the 2018 UICSC team were to reduce noise and pollutant emissions while increasing fuel economy and preserving the appeal of the two-stroke platform. Modifications made to reach these goals are summarized in the build sheet, Table 4.

Table 4. Modification build sheet.

Chassis	2017 Ski-Doo MXZ-TNT with strategically placed sound damping and absorbing materials
Engine	Rotax, reduced speed, spark ignition (SI), 850cc 2-stroke E-TEC. 88 kW [118 hp] measured peak power
Track	Camso Ice Attak XT 328 cm [137 in.] with port windows
Exhaust piping/muffler	Extended tuned pipe, stock muffler modified to accept catalyst
Catalytic converter	Heraeus 3-way catalyst, 1:20:1 Platinum:Palladium:Rhodium coating
Skis	Stock
Skid	Custom 25.4 cm [10 in.] idler wheels

Engine Calibration

The main goal of calibration was to maximize the engine's emission score (E-score), while increasing fuel economy and maintaining engine survivability and torque output throughout the operating range.

Calibration Equipment

The base map was calibrated using an uncoated catalyst to emulate the expected backpressure and 0% ethanol fuel. Test equipment is shown in Table 5. An eddy-current dynamometer was used for engine calibration and a waterbrake dynamometer was used for validation.

Table 5. Test equipment used for calibration.

Calibration software	ETAS Inca
Eddy-current dynamometer	Borghi & Saveri model FE-260-S
Waterbrake dynamometer	Land & Sea 9 in.
Fuel delivery	Max Machinery 710 Series
Emissions analyzer	Horiba MEXA-584L 5-gas
Oxygen sensor	Innovate LM-2

Calibration Strategy

The UICSC team used an objective function, equation 2, which approximates how many E-score points would be lost at each mode depending on measured emissions. Primary emissions of interest were UHC, NO_x, and CO, as they are the emissions measured during the in-lab emissions event at the CSC. P is the power produced by the engine, and W_m is the scoring weight of the mode during the RMC.

$$f(x) = W_m * \frac{\left(\frac{(UHC + NO_x)}{1.5} + \frac{CO}{4}\right)}{P} \tag{2}$$

The excess air coefficient λ, shown in equation 3, relates measured air-to-fuel ratio (AFR) to stoichiometric AFR. Stoichiometric AFR is achieved when the exact amounts of air and fuel are present in the cylinder to completely burn all fuel and oxygen, leaving no excess oxygen or fuel in the exhaust gases.

$$\lambda = \frac{AFR_{Measured}}{AFR_{Stoic}} \tag{3}$$

At heavily weighted points of the RMC, the engine was calibrated to minimize E-score penalty. At cruising speeds, values were chosen to minimize BSFC. At high engine loads and speeds, engine survivability and power were prioritized. The UICSC team implemented a 5-step process for engine calibration.

- Step one (injection timing sweep): fuel injection timing was swept while holding λ constant. Figure 8 shows injection timing plotted against the penalty function. The timing that produced the lowest penalty was chosen.
- Step two (λ sweep): the amount of fuel injected was varied to sweep λ while maintaining the timing found in step one.
- Step three (injection ratio sweep): the ratio of fuel injected between the throttle body injectors and in-cylinder injectors was adjusted while λ and injection timing were held constant.

- Step four (ignition timing sweep): ignition timing was altered with previous parameters held constant to determine optimal timing to maximize E-score. This step required special attention to prevent engine knock.
- Step five (calibration interpolation): after vital sections of the map were calibrated, values were interpolated to populate the remainder of the map. This maintains consistency in transition areas.

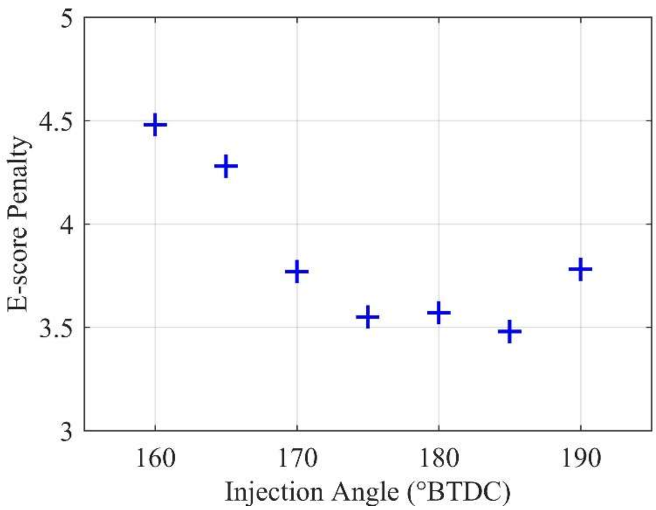

Figure 8. Sample injection timing sweep.

Time constraints do not allow the team to perform steps one through four of the process at every point in the map, necessitating the interpolation step of the calibration process. The calibration was validated on chassis for runability by measuring λ during on-snow operation in various conditions.

RAVE Valves

The Rotax adjustable variable exhaust (RAVE) valves were recalibrated to produce a smoother torque curve and improve transient response.

These guillotine valves, located above the exhaust port, change the height of the port as they move from positions of high, mid, and low. Lower positions decrease air flow through the combustion chamber and advance the closing of the exhaust port. This improves trapping effectiveness and volumetric efficiency at low engine speeds. Table 6 shows position changes from stock in the RAVE calibration map. A plus sign indicates a higher position and a minus sign a lower position than on the stock map. Only the transition regions of the map are shown as all other areas of the RAVE position map remain the same.

Table 6. RAVE valve positions compared to stock.

%TPS	4500 RPM	5000 RPM	5500 RPM
15			
20			+
25			+
30	-		
35	-		
40	-		
50	-		-
60	-		-
90			-
100			-

Flex-fuel

The 2018 competition requires the use of ethanol-gasoline mixtures ranging from 0% to 85% ethanol. To accommodate this, the UICSC team continued to use the system developed in 2012. This includes a Continental flex-fuel sensor coupled with a UICSC-designed analog circuit [9]. Due to the reliability of the system, no alterations were made.

Emissions Control

In addition to engine calibration, emissions that contribute to E-score were reduced using a three-way catalytic converter. The catalyst was relocated from the inlet to the outlet of the muffler to avoid the heat fatigue seen on the 2017 muffler.

Catalyst Selection

Four catalysts were compared using the 5-mode test to approximate their performance during the RMC. The results are shown in Figure 9. Two styles of catalytic converter were tested. The first had a single substrate (SS) while the second had dual substrates separated by a small gap (DS). Two catalysts of each style were tested, one uncoated (UNC) and the other with a 1:20:1 Platinum:Palladium:Rhodium coating.

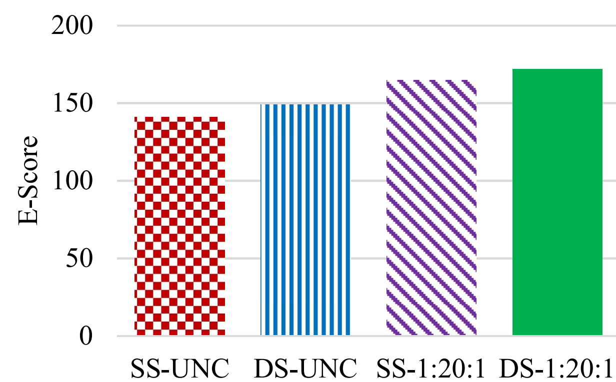

Figure 9. Catalyst comparison.

The coated catalyst with two substrates was implemented on the final configuration because it produced the highest E-score.

Emissions Results

Emissions data were collected at the 5 mode points from the RMC in the final 2018 configuration. Total weighted emissions measured were 126 g/kW-hr of CO, 7.2 g/kW-hr of UHC, and 2.5 g/kW-hr of NO_x, a reduction of 19% CO, 86% UHC, and 58% NO_x from the stock snowmobile. Figure 10 shows the anticipated E-scores for the 2018 entry compared to the stock 850cc Rotax as measured by the UICSC team. The results from the in-lab emissions event are also included for the 2017 UICSC entry, an ultra-low emission four-stroke, and a four-stroke of similar power output.

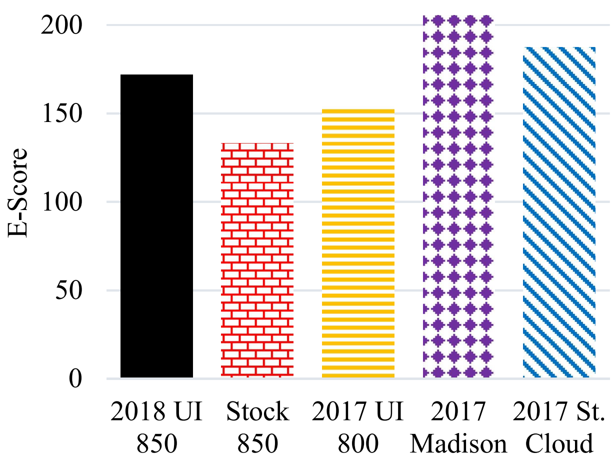

Figure 10. E-score comparison.

Noise Reduction

In the 2017 CSC, the UICSC snowmobile passed National Park Service sound standards and was the third-quietest SI vehicle in the competition. Similar noise reduction strategies were applied to the 2018 snowmobile, including damping material on the tunnel, a ported track, and engine compartment sound absorbing material.

Acoustic Damping Materials

The 2017 UICSC team created an anechoic sound box to quantify the sound-attenuation performance of various materials and components. The sound box, shown in Figure 11, includes a speaker that produces a tone at a range of frequencies from 80 to 4000 Hz at one end of a tube. These frequencies were held constant from 2017 testing. Microphones were placed in the tube before and after the test component. Power transmission coefficients (PTCs) were found by measuring sound pressure and phase at each microphone. [9]

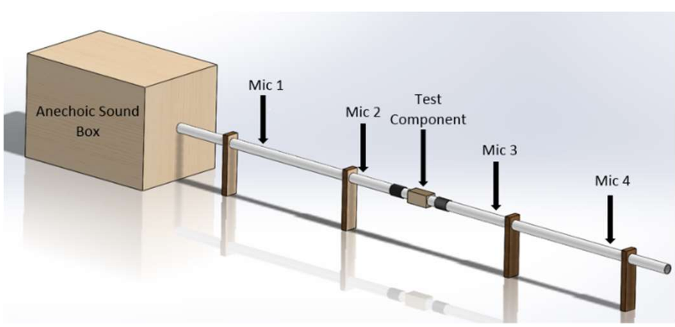

Figure 11. Sound box.

A PTC represents the percent reduction in sound power through a material. For example, a 0.2 PTC correlates to a 20% reduction in sound power. A negative PTC corresponds to an amplification of sound power, which can be caused by a natural resonance in the material or sound reflection. Results from sound box testing are shown in Figure 12. The melamine three-layer material outperformed the other materials overall and was applied to the snowmobile's body panels.

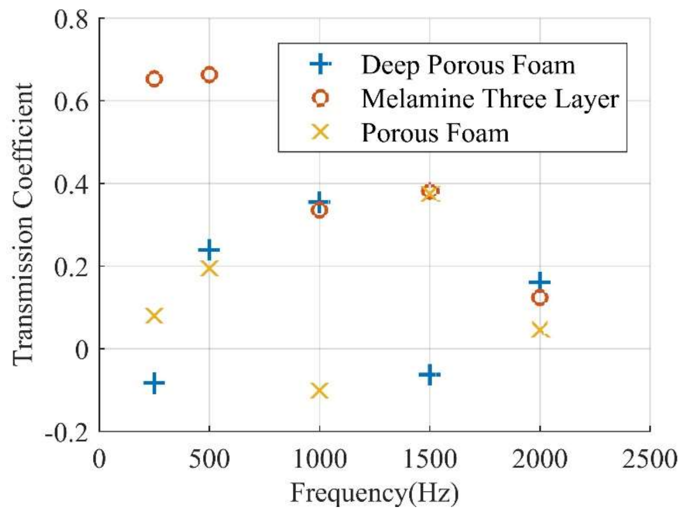

Figure 12. Power transmission coefficients of acoustic foam.

Tunnel Resonance Damping

Mechanical resonance of the tunnel caused by engine and chassis vibration contributes to noise production. To reduce vibration, the UICSC team tested two different vibration-damping materials, Polydamp and Silent Running. Z-channels were constructed with a similar shape and material as the tunnel. Impact tests were conducted using the apparatus shown in Figure 13 with an accelerometer attached opposite the point of impact to measure vibration.

Figure 13. Tunnel resonance test apparatus.

Damping ratio ζ quantifies the rate at which oscillation is removed from a second-order system [11]. A material with a higher damping ratio reduces vibration more quickly, minimizing noise production.

Damping ratios were calculated using the logarithmic decrement method, equation 4, where x_1 and x_2 are two consecutive peaks of the accelerometer signal. A sample plot of data used to determine the damping ratios is shown in Figure 14.

$$\zeta = \frac{\ln \frac{x_1}{x_2}}{2\pi} \tag{4}$$

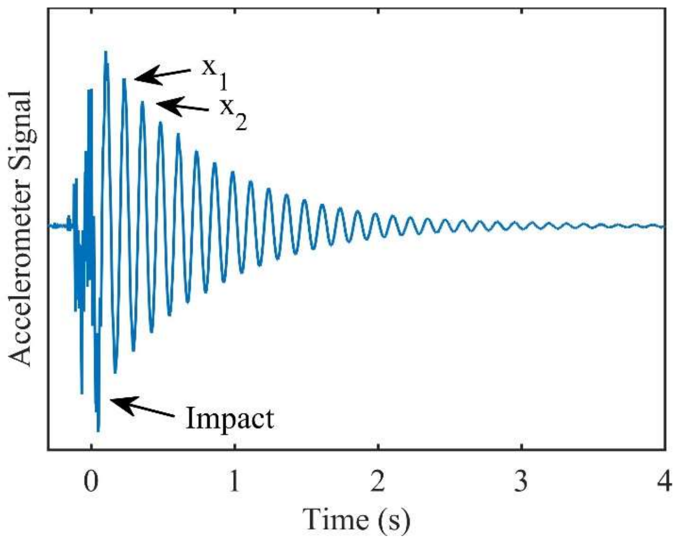

Figure 14. Z-channel test example.

Results of the z-channel testing are shown in Table 7. The z-channel with Silent Running applied to both sides exhibited the best damping characteristics and was applied to the tunnel of the snowmobile.

Table 7. Average damping ratios for tunnel resonance testing.

Material	Average Damping Ratio
Bare aluminum	0.010
PolyDamp + Silent Running	0.082
PolyDamp both sides	0.045
PolyDamp single side	0.034
Silent Running both sides	0.142
Silent Running single side	0.063

Noise Results

A noise vectoring test was used to determine the loudest areas of the snowmobile and the most prominent frequencies produced. The test was conducted on both sides of the vehicle with a wire grid placed 0.9 m [3 ft] from the respective body panel. The track was lifted and the engine run at 4100 RPM while microphones measured sound at 17 points on the grid. This operating speed was chosen to approximate the engine speed seen in the J1161 sound test. Fast Fourier transforms (FFTs) of the raw sound data were analyzed to yield insertion loss using equation 5, where p_i and p_c are the sound pressures at the point of interest and the control point at the center of the grid, respectively.

$$IL = 20 * \log \frac{p_i}{p_c} \tag{5}$$

Insertion loss compares the sound pressure between two points. This allows for determining the locations of the snowmobile that produce the most noise. Figure 15 and Figure 16 show the insertion loss at each point on the clutch and exhaust sides of the final configuration. The dot on the figures shows the location of the control point. Values between the test points were interpolated to create the contour plot.

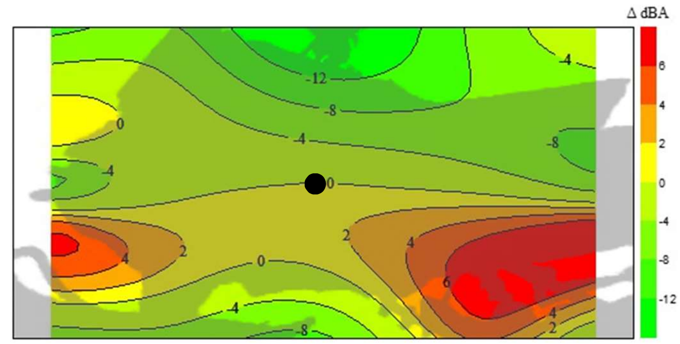

Figure 15. Clutch-side noise vectoring.

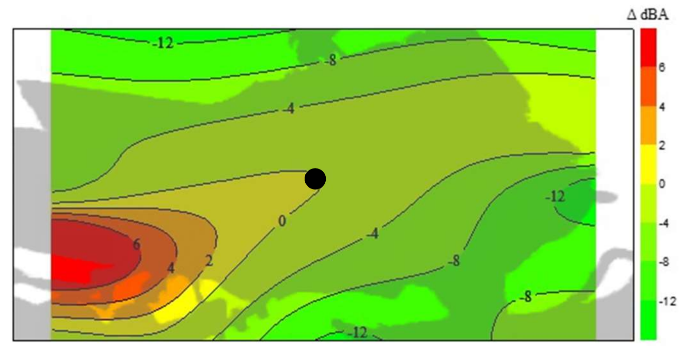

Figure 16. Exhaust-side noise vectoring.

The data were evaluated at 430 Hz, the most significant frequency influencing overall sound output as determined by the FFTs. Louder areas of the snowmobile are shown in red and quieter areas in green. The primary noise sources of the snowmobile were the track and engine compartment. Because most areas on the contour plots correspond to a negative insertion loss, it can be inferred that the control point is also a significant source of noise. The frequencies that contributed most to sound production were found to be 430, 690, 1034, and 2067 Hz. This information will be used to inform the design of components for future competitions.

J1161 Testing

The J1161 test was used to quantify the noise reduction performance of each component compared to stock. Results from individual component testing are shown in Table 8. The ported track and larger idler wheels could not be tested individually as the ported track is longer than the stock track. The final configuration produced a maximum sound pressure of 67.4 dBA on the clutch side and 67.5 dBA on the exhaust.

Table 8. J1161 test results.

Component	Average Sound Pressure Reduction from Stock (dBA)	
	Clutch Side	Exhaust Side
Reduced speed engine, modified exhaust	2.0	1.3
Body panel foam	1.0	-0.5
Ported track, large idler wheels	0.9	0

Performance

The overall efficiency of a vehicle is typically represented as fuel economy. However, fuel economy is a function of several variables including drivetrain resistance, engine performance, and weight. To isolate and quantify the effects of different modifications on powertrain efficiency, separate drivetrain and engine testing procedures were conducted.

Drivetrain Results

A roll-down test was used to quantify the effects of idler wheel configurations, shown in Figure 6, on static resistance. The snowmobile was placed on a platform that was gradually elevated from one end. The angle at which the snowmobile rolled off the platform was recorded for each configuration, shown in Table 9. A lower angle of roll indicates a lower static resistance.

Table 9. Roll-down test results.

Component		Roll-Down Angle (°)
Stock idler wheels		11.4
Large idler wheels	Configuration 1	11.5
	Configuration 2	11.6
	Configuration 3	12.2

The differing resistance may be due to the distribution of force on the track and resistance of idler wheels to rotation. Configuration one exhibited similar static resistance to the stock configuration and outperformed the other configurations.

A roll-out test was used to compare the rolling resistance of the larger idler wheels to the stock idler wheels. In the past, the UICSC team has seen close correlation between roll-down and roll-out performance [9]. Thus, configurations two and three were not tested on snow due to their lesser performance during the roll-down test. The test was conducted on a large, flat area with hard-packed snow. The snowmobile was allowed to coast to a stop from 80 kmph [50 mph], 64 kmph [40 mph] and 48 kmph [30 mph]. The distances the snowmobile travelled before stopping at each starting speed were recorded and averaged. Average roll-out values are shown in Table 10.

Table 10. Roll-out test results.

Tested Component	Roll-Out Distance (m [ft])		
	80 kmph [50 mph]	64 kmph [40 mph]	48 kmph [30 mph]
Stock idler wheels	94.8 [311]	62.2 [204]	43.9 [144]
Large idler wheels – Configuration 1	95.1 [312]	69.2 [227]	44.8 [147]

Clutching

A snowmobile's CVT consists of two pulleys that actively change diameter in response to the rotational speed of the engine. Propulsion is achieved when the primary, or driving, clutch grips and rotates a drive belt, rotating the driven clutch as well. The changing-diameter pulleys of a CVT allow for infinite gear ratios from the output of the engine to the track. The stock clutch had to be adjusted to operate correctly with the reduced-speed engine. An increase of 1 g to each ramp decreases peak RPM by 75 [12]. On-snow testing determined that 17 g added to each ramp resulted in the desired peak RPM. This allowed the primary clutch to fully compress on the drive belt, minimizing the gear ratio at 6800 RPM as opposed to 7900 RPM on the stock vehicle.

Fuel Economy

Fuel economy was measured by driving the snowmobile 80.5 km [50 mi] on an ungroomed trail at an average speed of 72.4 kmph [45 mph]. The fuel tank was filled prior to departure and refilled on return. The fuel volume required to refill the tank was divided by the distance travelled to determine fuel mileage. A chase vehicle with a known fuel consumption was used as a reference to account for any variability due to trail conditions.

The stock snowmobile produced an average fuel economy of 17.0 L/100 km [13.8 mpg], and the final vehicle configuration achieved 13.4 L/100 km [17.5 mpg]. This is an improvement in fuel economy of 27% over the stock configuration.

Power

Alterations affecting power production included the recalibrated engine and RAVE valves, extended tuned pipe, and modified muffler with catalyst. These changes resulted in a measured peak power of 88 kW [118 hp] at 6800 RPM. As shown in Figure 17 below, torque output of the engine was increased from the stock engine through the majority of its operating range. The dips in torque are a result of the RAVE valves changing position. The RAVE calibration shifted a transition point to a higher RPM, smoothing the torque curve at full throttle for a smoother riding experience.

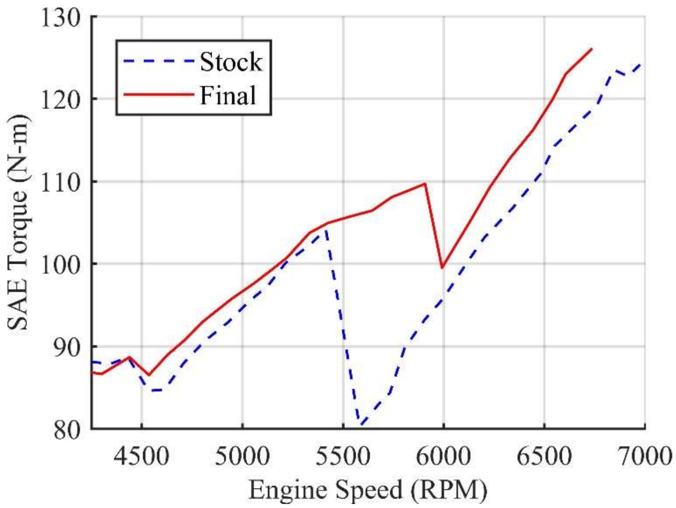

Figure 17. Torque comparison of stock to the UICSC calibrated engine.

Weight

Two-stroke snowmobiles are valued for their high power-to-weight ratio, a property the UICSC team strives to maintain. The UICSC entry into the 2018 competition weighed 277 kg [611 lb] wet. Table 11 compares the weight and power-to-weight ratio of the 2018 entry to the previous entry and a four-stroke of similar power output.

Table 11. Weight and power-to-weight comparisons.

Vehicle Weights			
	2018 UI	**2017 UI**	**2017 St. Cloud**
Total measured weight	277 kg [611 lb]	266 kg [587 lb]	281 kg [619 lb]
Power-to-weight ratio	3.1 kg/kW [5.1 lb/hp]	4.1 kg/kW [6.7 lb/hp]	3.4 kg/kW [5.6 lb/hp]

Manufacturer's Suggested Retail Price

A 2018 Ski-Doo MXZ-TNT with an 850cc Rotax E-TEC engine is $12,549. With the inclusion of all modifications, the UICSC 2018 manufacturer's suggested retail price (MSRP) totals $13,705. The cost increase is justified by improvements in fuel economy and a reduction in noise and exhaust emissions.

Conclusions

The University of Idaho's entry into the 2018 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. Emissions were reduced through the addition of an inline catalyst, modified muffler, and extended tuned pipe. The E-Score measured during the 5-mode test increased by 29%, from 133 to 172 over the stock configuration. Fuel economy was increased by 27% to 13.4 L/100 km [17.5 mpg] with the addition of larger idler wheels, engine calibration, and clutch adjustment. Sound materials, a ported track, and reduced engine speed resulted in an estimated 2.5 dBA reduction from the stock snowmobile, producing 67.5 dBA in the J1161 test.

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Acknowledgements

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Definitions/Abbreviations

AFR Air-to-fuel ratio

BSFC Brake specific fuel consumption

CO Carbon monoxide

CSC Clean Snowmobile Challenge

CVT Continuously variable transmission

DI Direct injection

FFTs Fast Fourier transforms

IC Internal combustion

MSRP Manufacturer's suggested retail price

NO_x Nitrous oxides

PTC Power transmission coefficient

RAVE Rotax adjustable variable exhaust

RMC Ramped Modal Cycle

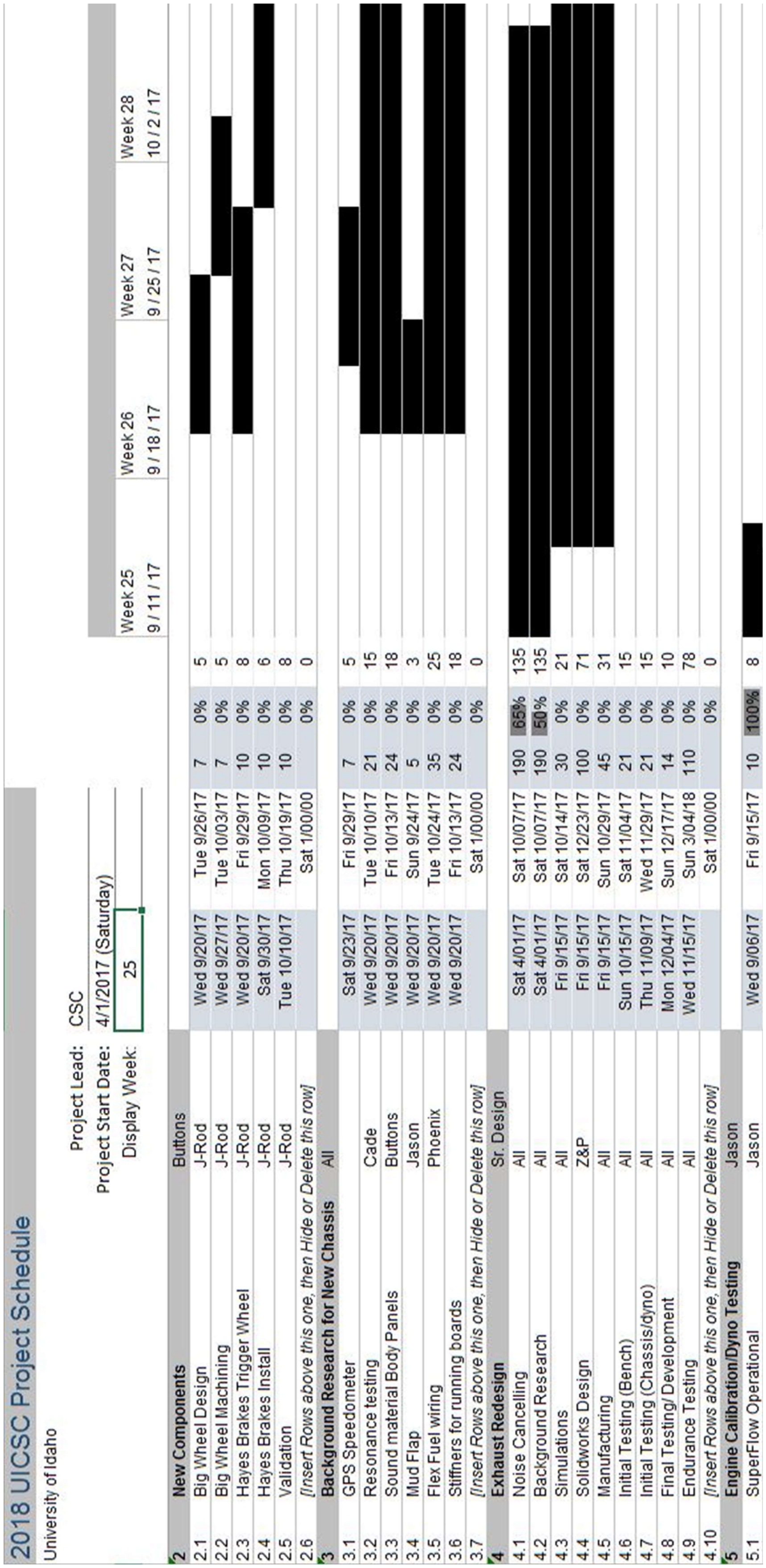
SAE Society of Automotive Engineers

SI Spark ignition

UHC Unburned hydrocarbons

UICSC University of Idaho Clean Snowmobile Challenge

Appendix A – Gantt Chart Snapshot



2018 UICSC Project Schedule

University of Idaho

Project Lead: CSC

Project Start Date: 4/1/2017 (Saturday)

Display Week: 25

Week 25 9/11/17 | Week 26 9/18/17 | Week 27 9/25/17 | Week 28 10/2/17

2	New Components	Buttons					
2.1	Big Wheel Design	J-Rod	Wed 9/20/17	Tue 9/26/17	7	0%	5
2.2	Big Wheel Machining	J-Rod	Wed 9/27/17	Tue 10/03/17	7	0%	5
2.3	Hayes Brakes Trigger Wheel	J-Rod	Wed 9/20/17	Fri 9/29/17	10	0%	8
2.4	Hayes Brakes Install	J-Rod	Sat 9/30/17	Mon 10/09/17	10	0%	6
2.5	Validation	J-Rod	Tue 10/10/17	Thu 10/19/17	10	0%	8
2.6	[Insert Rows above this one, then Hide or Delete this row]			Sat 1/00/00		0%	0
3	Background Research for New Chassis	All					
3.1	GPS Speedometer		Sat 9/23/17	Fri 9/29/17	7	0%	5
3.2	Resonance testing	Cade	Wed 9/20/17	Tue 10/10/17	21	0%	15
3.3	Sound material Body Panels	Buttons	Wed 9/20/17	Fri 10/13/17	24	0%	18
3.4	Mud Flap	Jason	Wed 9/20/17	Sun 9/24/17	5	0%	3
3.5	Flex Fuel wiring	Phoenix	Wed 9/20/17	Tue 10/24/17	35	0%	25
3.6	Stiffners for running boards		Wed 9/20/17	Fri 10/13/17	24	0%	18
3.7	[Insert Rows above this one, then Hide or Delete this row]			Sat 1/00/00		0%	0
4	Exhaust Redesign	Sr. Design					
4.1	Noise Cancelling	All	Sat 4/01/17	Sat 10/07/17	190	65%	135
4.2	Background Research	All	Sat 4/01/17	Sat 10/07/17	190	50%	135
4.3	Simulations	All	Fri 9/15/17	Sat 10/14/17	30	0%	21
4.4	Solidworks Design	Z&P	Fri 9/15/17	Sat 12/23/17	100	0%	71
4.5	Manufacturing	All	Fri 9/15/17	Sun 10/29/17	45	0%	31
4.6	Initial Testing (Bench)	All	Sun 10/15/17	Sat 11/04/17	21	0%	15
4.7	Initial Testing (Chassis/dyno)	All	Thu 11/09/17	Wed 11/29/17	21	0%	15
4.8	Final Testing/ Development	All	Mon 12/04/17	Sun 12/17/17	14	0%	10
4.9	Endurance Testing	All	Wed 11/15/17	Sun 3/04/18	110	0%	78
4.10	[Insert Rows above this one, then Hide or Delete this row]			Sat 1/00/00		0%	0
5	Engine Calibration/Dyno Testing	Jason					
5.1	SuperFlow Operational	Jason	Wed 9/06/17	Fri 9/15/17	10	100%	8

Appendix B – Project Schedule Snapshot

Weekly Team Meeting Schedule

% Complete	1/25/2018	***Project Names***	***Project Lead***	***Due Date***	***Projected (planned progress)***	***Completed (actual progress)***
74%		**New Components**	**Buttons**	**10/19/2017**		
100%		~~Big Wheel Design~~	~~J-Rod~~	~~9/26/2017~~	~~SolidCAM~~	Reverse engineer the old kit, Design review done
100%		~~Big Wheel Machining~~	~~J-Rod~~	~~10/3/2017~~	~~Contact water jet companies~~	
70%	HOT	Hayes Brakes Trigger Wheel	J-Rod	9/29/2017	working on 4th axis	We got specs for wheel, machine and find placement within the next couple days Make Mastercam. Talked to ETS. Sheet metal designs
0%	HOT	Hayes Brakes Install	J-Rod	10/9/2017	Finish cutting out frame	
100%		~~Validation~~	~~J-Rod~~	~~10/19/2017~~	~~Roll downs for big wheel and stopping distances for hayes brakes~~	
100%		~~**Background Research for New Chassis**~~	~~**All**~~	~~**10/24/2017**~~		
100%		~~GPS Speedometer~~	~~NEEDS ASSIGNED~~	~~9/29/2017~~	~~In the mail~~	~~201 sponsorship people find sources, Wait on word back, send another email by Friday~~
100%		~~Resonance testing~~	~~Cade~~	~~10/10/2017~~	Wheel skis on, testing Friday	~~Begin testing, Working on matlab code and excel sheets, additional sources~~
100%		~~Air box foam and deflectors~~	~~LZ~~	~~10/13/2017~~	~~Done by end of week~~	
100%		~~Sound material Body Panels~~	~~Buttons~~	~~10/13/2017~~		
100%		~~Mud Flap~~	~~Jason~~	~~9/24/2017~~	~~Install - Patch~~	~~Here~~
100%		~~Flex Fuel wiring~~	~~Phoenix~~	~~10/24/2017~~	Test on dyno to determine compensations	~~Calibrated with Ethanol percentages, Contact Contintental for new sensor~~
100%		~~Stiffners for running boards~~	~~NEEDS ASSIGNED~~	~~10/13/2017~~	~~Push to 2019?~~	~~Not released yet, check in future~~
56%		**Exhaust Redesign**	**Sr. Design**	**3/4/2018**		
100%		~~Noise Cancelling~~	~~All~~	~~10/7/2017~~		~~Called modular exhaust, Not an applicable solution if system is only good up to 130C~~
100%		~~Background Research~~	~~All~~	~~10/7/2017~~	~~Figure out the diameter of center section of tuned pipe~~	~~Research mostly done, moving into simulations,Reading SAE papers (Cade call SLP), start requesting parts~~
100%		~~Simulations~~	~~All~~	~~10/14/2017~~	~~Buttons - GT Suite, Cade - Chemkin, Phoenix - SolidWorks~~	~~Full Muffler Simulation Done, GT Model Completed, Muffler change simulations~~
100%		~~Solidworks Design~~	~~Z&P~~	~~12/23/2017~~	~~No PreCAT, manufacture muffler~~	~~Muffler Model Completed~~