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Design and Validation of the 2016 University of Idaho Clean Snowmobile: A Reduced Speed 797cc Flex-Fueled Direct-Injection Two-Stroke with Active and Passive Noise Cancellation

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Abstract

The University of Idaho's entry into the 2016 SAE Clean Snowmobile Challenge is a 2013 Ski-Doo MXZ-TNT chassis with a reduced-speed 797cc direct injected two-stroke engine, modified for flex fuel use on blended ethanol fuel. A battery-less direct injection system was used to improve fuel economy and decrease emissions while maintaining a high power-to-weight ratio. A new tuned exhaust was designed to accommodate the lowered operating speed of the engine while improving the peak power output from 65.6 kW (88 hp) to 77.6 kW (104 hp). Noise was reduced through the implementation of a mechanically active quarter-wave resonator, Helmholtz resonator, strategically placed sound absorbing/deadening materials, and by operating the engine at a lower speed. A muffler was modified to incorporate a three-way catalyst, which reduces engine emissions while not significantly reducing power output or increasing sound output. Pre-competition testing had the snowmobile entering the 2016 SAE CSC weighing 267 kg (588 lb) wet, achieving 13.5 L/100km (21 mpg), with an EPA five mode test score of 186 on E0 gasoline, and a J1161 sound magnitude of 71 dBA.

Introduction

Snowmobiling offers a recreational opportunity during the winter months for families and enthusiasts alike to enjoy and explore the snow packed wilderness. This winter fun comes at a cost as snowmobiles are known for being loud, having toxic emissions, and low fuel economy. Snowmobiles are often operated in environmentally sensitive areas, such as Yellowstone National Park. To counter this negative impact, a partnership between industry, conservationists, and the snowmobiling community was created in 2000 [1]. As part of this, a competition was created for college students to develop a cleaner, quieter, and more fuel efficient snowmobile.

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's focus has been developing a trail snowmobile that meets NPS standards. Currently manufacturers produce NPS certified trail snowmobiles. Approximately 60,000 snowmobiles are sold annually; of these purchases 12,000 or 20% are mountain snowmobiles. Mountain snowmobiles are typically high powered two-stroke snowmobiles. The University of Idaho CSC team recognizes that the need for development has shifted from NPS certified four strokes, to those mountain platforms that do not meet NPS standards [2].

Unlike the West, the Midwest has little land for public use as shown in table 1 [3].In the Midwest most public land that is available is only accessible through private properties, and many popular snowmobiles are not NPS certified meaning they are often loud and have the "two-stroke" exhaust smell. This often leads to land access closures, drastically reducing available riding areas.

Table 1: Percentage of land available for public use by state

Western States	Percent Public Land in State	Eastern States	Percent Public Land in State
Idaho	66.55	Michigan	22.47
Utah	70.40	Minnesota	17.57
Wyoming	54.65	Wisconsin	16.21

The 2016 CSC continued to encourage snowmobile development by mandating the use of an ethanol/gasoline fuel blend. The required range varies from 0 to 85 percent ethanol per unit volume. The option of an economy mode switch was eliminated [1].

The three foci for improvement for the 2016 team were: noise, fuel efficiency, and refinement of past technologies. The goals set to accomplish this were being comfortably below the NPS sound level at 66 dBA and achieving an E-score of 185 while maintaining over 74.5 kW (100 hp). These goals were pursued with cost and weight as a consideration.

This paper introduces the multifaceted projects initially then shares results in the appropriate sections.

UICSC Snowmobile Design

Chassis and Engine Selection

The 2016 UICSC team continued the use of a direct injected 797cc Rotax two-stroke engine with a 2013 MXZ TNT chassis. This selection is based on the higher power-to-weight ratio, proven rider comfort, low cost, and mechanical simplicity, which weighs heavily into consumer purchasing decisions. The Rotax engine is also extremely low maintenance requiring only the cleaning of the exhaust valves annually, which weighed heavily in the power plant choice.

Calibration

UICSC has traditionally implemented a four step calibration strategy. All steps below are altered with some relative maximum or minimum value as a goal, meaning depending on the operating point the objective is different. The objective for cruising speeds and throttle positions is to minimize brake specific fuel consumption (BSFC). While at high speeds and loads the 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.
- 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 penalty.
- Step four (calibration interpolation): after tuning the 5 mode points the values were interpolated between these points, and then roughly verified for runability. This was done to keep consistency in the calibration and address the transition points of the map.

Equation 1 is a representation of measured air-to-fuel ratio (AFR) to stoichiometric AFR. The stoichiometric AFR is exactly enough air is available to completely burn all the fuel that was injected into the cylinder achieving complete combustion, leaving only exhaust gasses, no excess fuel or air. The goal during calibration is often to minimize the emissions score. To do this a penalty function equation 2 was developed by the UICSC where F(x) is how many E-score points will be lost at the design point.

$$\phi = \frac{1}{\lambda} = \frac{AFR_{Stoich}}{AFR_{Measured}} \qquad (1)$$

$$F(x) = W_m * \frac{\left(\frac{6*UHC+NO_X}{150}+\frac{CO}{400}\right)}{P} \qquad (2)$$

Figure 1 and 2 show two of the steps of calibration. A fishhook sweep is performed, looking for the minimum F(x) value shown on the vertical axis. Figure 1 shows step one of the calibration process, where equivalence ratio is held constant, while sweeping when the fuel enters the cylinder. Figure 2 shows the second step in the process where the ideal injection timing that is found in step one is held constant, while sweeping AFR's.

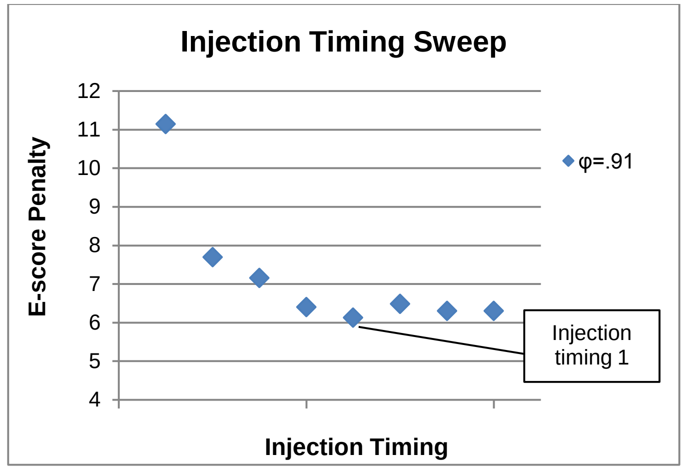


Figure 1: Penalty function vs. injection timing at a constant equivalence ratio.

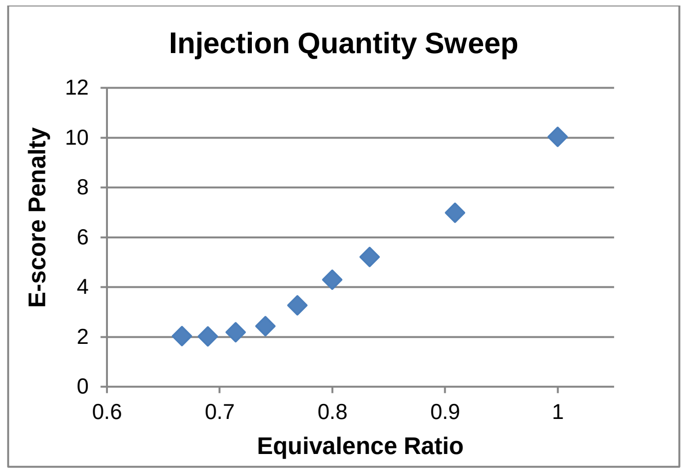


Figure 2: Penalty function vs. equivalence ratio at a constant injection timing.

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 2016 CSC. The base map in the engine control unit (ECU) was calibrated using 0% ethanol 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, ethanol compensation calibration was done using a similar strategy to find optimal injection timing, injection quantity, and ignition timing.

Flex Fuel

For 2016 the UICSC team used a Continental flex fuel sensor and a custom analog circuit to send ethanol content of the fuel to the ECU. The analog circuit converts a frequency signal from the sensor into an analog signal that is readable by the ECU. The CSC has been incorporating flex fuel since 2009. The flex fuel system designed in 2015 has proved to be reliable and no hardware changes were needed for the switch from butanol to ethanol. The flex fuel signal is connected to an existing input on the ECU, allowing for compensation of injection timing, quantity, and ignition timing.

Injection timing compensation was explored for the timing when the fuel is injected into the cylinder, but was not implemented in 2016 as it did not provide any improvement during testing. Ignition timing was only slightly modified. It is necessary to retard ignition timing when using 87 octane gasoline since original equipment manufacturing (OEM) snowmobiles are calibrated for 91 octane. This is done to reduce knock at wide open throttle (WOT). There is potential to greatly increase the performance of the vehicle using ethanol as a fuel source, due to the high octane rating of ethanol fuels. E85, for example, has an octane rating of 97 (average of research octane and motor octane) [4]. The UICSC team took advantage of this to increase power output. The full potential, however, could not be realized due to the power limit of the competition [5].

Exhaust Valve Calibration

An area that has not been pursued by the UI team before is the adjustment of when the Rotax Adjustable Variable Exhaust (RAVE) valves open. This need arose because of the reduced engine speed. The purpose of these valves is to change the height of the exhaust ports. At low loads and speeds the valves decrease the port height decreasing the airflow to improve idle quality and low load operation. While at high loads and speeds the port height is increased maximizing air flow. There are three potential positions that the RAVEs can attain, low, mid, and high largely correlating to the relative speeds and loads desired. Lowering the valves means that the exhaust port closes sooner and opens later during the piston stroke. This allows for better air control through the engine. During an acceleration event on the dynamometer there is a significant drop in power where these valves change position, this occurs because of the sudden change in airflow. Once fully opened the increased airflow results in power gains. These valves were swept similarly to the rest of the calibration, with smoothness of transition being the objective.

Tuned Exhaust Redesign

Unlike a four-stroke, two-stroke engines do not have poppet valves to control intake and exhaust flows, thus need a way to expel exhaust while keeping fresh charge in the cylinder. Two-stroke engines use a tuned exhaust pipe to create exhaust pulses that aid in trapping and scavenging. Scavenging refers to the process of pulling the fresh air/fuel mixture into the cylinder, while trapping is the pulse that pushes any short-circuited air/fuel mixture back into the cylinder [6].

By reducing the speed of the engine the operational speed moved away from the effective tuned length of the tuned pipe. When operating at speeds farther from the effective tuned length of the pipe, power and efficiency are decreased. Due to these decreases development on the tuned pipe was a focus. Due to the nature of these exhaust pulses, a tuned pipe operates most effectively across a specific frequency band that depends on its overall length, given by equation 3. To mitigate the effect of lowering maximum operational engine speed, the 2015 configuration included an extension in the header, (L1 in Figure 3) and some benefits in torque and efficiency were seen [6].

$$L_T = \frac{ED \times 42545}{RPM} \qquad (3)$$

During pipe design each section is designed based on the previous section. Thus, care must be taken in choosing which sections are modified. There is potential to negatively shift the power band if the cone angles are changed drastically. If a change in tuned length is desired, rather than a shift in power band profile, extending both the header and dwell, (L1 and L5 in Figure 3) is an effective solution. These two portions of the pipe mainly effect the timing of the pulse, where the tapered sections effect the aggressiveness of the pulse [8]. Rather than extending the stock pipe, the team worked with a performance pipe company to utilize OEM quality designs, and to achieve a lower RPM power band rather than the higher band preferred by OEM's.

Figure 3 illustrates the seven sections of the tuned exhaust pipe. The sections, beginning at L1 are: the header, three diverging cones, the dwell, the converging cone, and the stinger. This image does not correspond exactly with the hardware on the snowmobile, as it is common practice to use an internal stinger (L7). This helps to keep the overall length of the pipe down without reducing the effectiveness. Equation 3 represents the tuned length L_T of the pipe. The individual sections of the pipe are designed using numerous equations [8] [9]. As there are many design equations, they are not all included here. Utilization of these equations resulted in an overall increase in length of 14%. This would time the pulse to return ideally at 6800 RPM rather than the stock 8000 RPM.

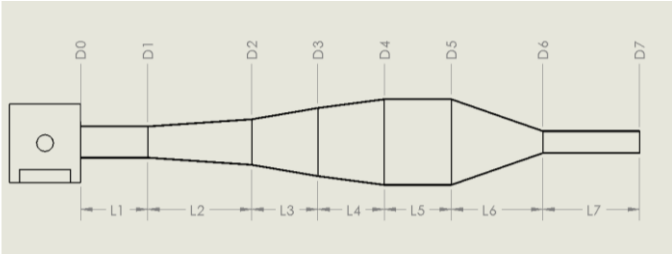


Figure 3: Visual representation of a tuned exhaust

The tuned length (L_T) is equivalent to all seven of the sections of the pipe added together and is determined using exhaust duration (ED) and the engine speed where the designer wishes to see peak power.

Figure 4 shows the packaged tuned pipe in chassis. When a pipe is being built for chassis it needs to be curved for packaging purposes. The two circles in Figure 4 show the two locations where the pipe was extended and fit in chassis. The line across the front represents the location where the stock pipe reached, showing issues in packaging. This led to a need to modify the belly pan of the snowmobile.

Figure 4: Extended tuned pipe in chassis

Mechanically Active Quarter Wave Resonator (MAQR)

To further interdisciplinary work, the UI team continued to pursue a project that requires mechanical, computer, and electrical engineers. This project is the MAQR. The robustness and calibration of this technology needed improvement.

The MAQR is a form of active noise cancellation similar to many headphones that are commercially available today. This is achieved by creating a destructive sound wave in the exhaust that is 90 degrees out of phase with the noise that is being produced in the exhaust at the design point [10]. The targeted frequency is found by using equation 4 and the design frequency is found by using equation 5 [9] [11]. The MAQR is able to actively change its targeted frequency by changing the effective length, L in equation 5. By decreasing the length of the resonator, the time it takes for the wave to travel through the tube is reduced, creating a higher frequency destructive wave. This means when the engine is operating at a higher RPM the MAQR has a shorter effective length.

$$f_e = \frac{RPM \times N_c}{N_R \times 60} \quad (4)$$

$$f = \frac{c}{4 \times L} \quad (5)$$

The main foci for this year's improvements on the MAQR were to develop a robust system that can handle the extreme exhaust temperatures and to increase the speed of the system to match changes in engine speed. To handle the exhaust temperatures the housing was constructed from aluminum. This also created a more robust system over the previous plastic iteration. To increase the speed, the ratio of the gear train was increased from 3.65 to 4.0. A motor with a higher RPM range was used to further increase the speed of the system. These changes allow the resonator to maintain a phase shift of 90 degrees out of phase during typical trail riding conditions, able to travel at a speed of 7.62 cm/sec (3 in/sec). The travel time from min to max positon, or 17.78 cm (7 in) of travel, is 2.33 seconds. This system is designed to attenuate, or reduce, the noise between 4500 to 5800 RPM.

Consumer considerations when shopping for a recreational vehicle typically include power, weight, cost, and maintenance. The MAQR does not largely impact any of these, while having a considerable effect on the exhaust noise of the snowmobile.

Noise Reduction

A drawback to the two-stroke platform is that it is typically noisier than its four-stroke counterpart. This is due to two-strokes having a power stroke every cycle, which means that N_R in equation 4 is equal to one while in a four-strokes it is equal to two [11]. Due to the higher frequency, on the A weighted sound scale the engine noise is louder. There are three primary contributors to overall vehicle noise; intake, exhaust, and mechanical noise. These were each approached separately, and will be discussed here. Reducing the operational speed of the engine affects all three noise sources by shifting the frequency of the engine lower, which results in less overall noise on the A weighted sound scale used at competition. Also, by not operating the engine at full speed, noise is reduced due to reduced power, and less vibrations.

Intake Noise

The 2016 UI configuration took a four step approach to mitigate intake noise. The first was the implementation of open cell foam in the intake which resulted in a reduction in noise of 0.5 dBA on both sides of the snowmobile. The second was in the application of a damping material coating on the air box and associated plumbing. The third step was in the use of a Helmholtz resonator targeted at a cruising speed of 56 kph (35 mph) which resulted in a loss of 0.5dBA, on the clutch side. The final step was in the addition of intake noise deflectors. As it is difficult to measure noise independently from the rest of the vehicle, all noise data were gathered using the J1161 sound test that will be used in the competition and compared relative to a baseline [12].

The intake can be a significant contributor to noise as well as affect the volumetric efficiency of the engine. By using Helmholtz principles, a volume can be added between the two air boxes to not only reduce noise, but also increase volumetric efficiency [13] [14]. The basic geometry is displayed in Figure 5. The resonator was designed using equation 6. The Helmholtz resonator is effective at the same engine speed that the UI platform will be operating at during the J1161 sound test. A common application of the Helmholtz resonator is in the muffler to reduce exhaust noise, this typically results in a loss in overall power of the engine. This was not seen during development of the intake resonator, although power gains and noise loss was observed.

$$f_H = \frac{V}{2*\pi}\sqrt{\frac{A}{V \times L}} \quad (6)$$

The variables in equation 6 are equivalent to the variables in Figure 5. Displayed in Figure 5, V is the volume of the main chamber, A is the cross sectional area of the neck, and L is the length of the neck.

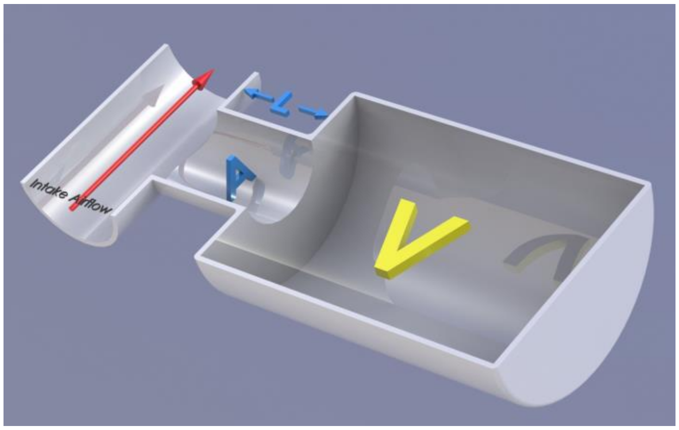


Figure 5: Visual representation of Helmholtz configuration chosen

There are two common styles of Helmholtz resonators, series and side branch. A series resonator is put inline, often looking like an expansion in the plumbing. The side branch Helmholtz resonator is attached to the side of the stock intake plumbing. Three side branch configurations were designed and tested. Table 2 describes the configurations and a short justification of the design choice. The physical response of a Helmholtz resonator is to create a notch at the design point, reducing the noise at that frequency. This is analogous to notch filters used in electrical engineering.

Table 2: Various Helmholtz configurations tested

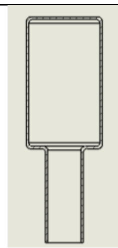
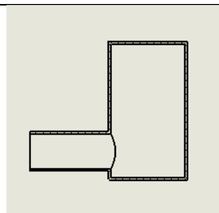
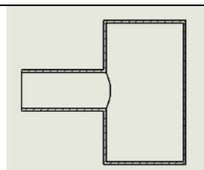
Name	Configuration	Effectiveness
Configuration 1		Most effective, created the deepest notch at the targeted frequency.
Configuration 2		Nearly as effective as configuration 1, more difficult to package for on chassis application.
Configuration 3		Not effective, amplified noise at target frequency.

Figure 6 shows the noise loss due to the application of the Helmholtz on the intake. Zero represents the baseline, where any point below is a loss in noise and a point above is noise amplification. The target frequency is 300 Hz. This target frequency is found using equation 4 above, with idealized temperature and pressure conditions. The test cell conditions were approximated in the design, but during testing the real values varied from the approximations. These changes are likely the reason that the peak loss is skewed slightly to the side.

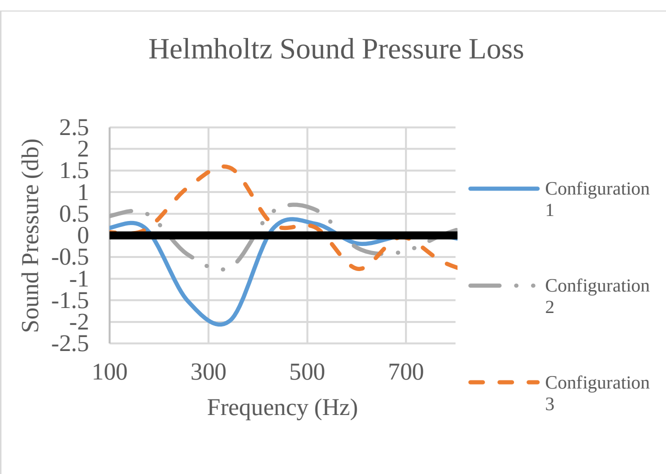


Figure 6: Comparison of various Helmholtz configurations

Exhaust Noise

Exhaust noise was approached with two main technologies. The first was with the redesign of the tuned pipe. This effectively reduces the frequency that the exhaust is pulsing. By lengthening the pipe, the amount of time that it takes for the pressure wave in the exhaust to travel through the pipe is increased. This results in a lower sound pressure on the A weighted sound scale. It has a secondary benefit of increasing the engine's torque, which means that a lower throttle position and engine speed are required to maintain speed during the sound test.

The second was through the implementation of the MAQR. The MAQR reduces target frequencies in the exhaust by sending a destructive frequency through the exhaust which reduces the noise in a J1161 test by 0.5 dBA.

Mechanical Noise

Mechanical noise was approached similarly as it has been in the past by the UI team. One approach was to target noise through the use of damping materials. These damping materials in essence reduce the speed and severity of vibrations in the base material. In mechanical systems vibrations are a contributor to noise. A secondary effect of damping materials is a shift of the resonance of the base material to a lower frequency. Much like lengthening the exhaust pipe, this results in a lower reading on the A weighted scale.

Another approach to reduce this noise is to implement sound barriers and diffusion materials in the belly pan and side panels in strategic locations. A barrier works by reflecting certain frequencies back toward their source, in this case not allowing them to escape the engine compartment. A diffusion material causes the sound wave to bounce around through the material losing energy each time it bounces. This idea is very similar to bouncing a ball, where it bounces less each time it hits the floor.

Fuel Efficiency and Performance

Two-strokes are not as efficient as their four-stroke counterparts due to high trapping losses. To improve this efficiency the UI implemented a custom tuned pipe and intake resonator.

Figure 7 represents the brake specific fuel consumption over most of the operational band of the engine. The vertical axis contains brake mean effective pressure (BMEP) which is a representation of engine load. BMEP can be converted to torque in N-m using equation 7 below. The horizontal axis is engine speed, and the contours are BSFC. The lower BSFC is the better the engine is performing. BSFC is essentially how efficiently the engine is producing power with a given amount of fuel. The majority of the engine's operating range during cruise, between 6-12 bar BMEP, is extremely low at or below 300 g/kW-hr. The dots in Figure 7 represent the weighted operation at each mode point in the 5-mode emissions test. The size of the dot represents the relative weight, while the location represents the load and speed point. Two of the mode points fall in the island that is 280 g/kW-hr and WOT operation achieves a BSFC of 320 g/kW-hr. Not shown on the graph is mode 5 which is a warm idle.

$$BMEP\ [bar] = \frac{T\ [N\!-\!m] \times 2\pi}{100 V_D\ [L]} \quad (7)$$

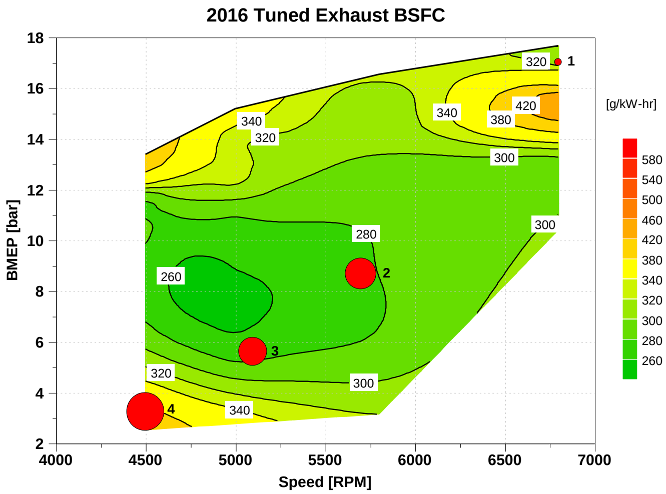


Figure 7: Brake specific fuel consumption map for 2016 exhaust

Figure 8 shows the percent improvement in BSFC from the stock pipe to the modified configuration in 2016. The majority of the map shows a 5-10% improvement, with one small portion at high speed and load showing a slight loss, where operation is limited under normal trail riding. The gains are in the cruising range for the snowmobile, which equates to increased fuel economy. The difference between this plot and Figure 7 is that the contours here represent percent improvement. This means that a positive percentage is a reduction in required fuel.

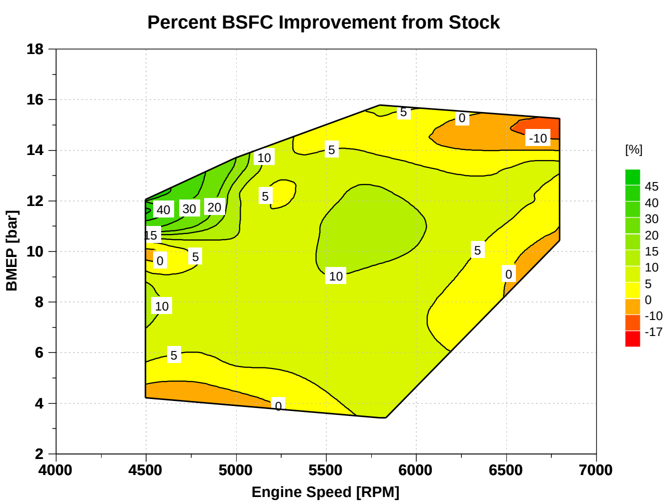


Figure 8: Percent BSFC improvement over stock tuned pipe

Fuel Economy

With the implementation of all of the CSC design changes, the snowmobile achieves a fuel economy of 19.1 L/100km (14.8 mpg), or 13.5 L/100 km (21 mpg) gallon gasoline equivalent (GGE) during heavy snow trail riding in mountainous terrain. GGE is the process of normalizing fuel efficiency based upon the energy content available in the fuels.

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 2016 UICSC design additionally benefit the riding experience of the snowmobile. Every year, UICSC strives to bring a snowmobile that not only is clean and quiet, but that competes with the most powerful competition entries in performance events. A comparison of power and torque for the 2016 configuration to 2015 is shown in Figures 9 and 10 respectively. The 2016 configuration achieves power levels exceeding many past configurations with a power to weight ratio of 0.30 kW/kg (0.18 hp/lb).

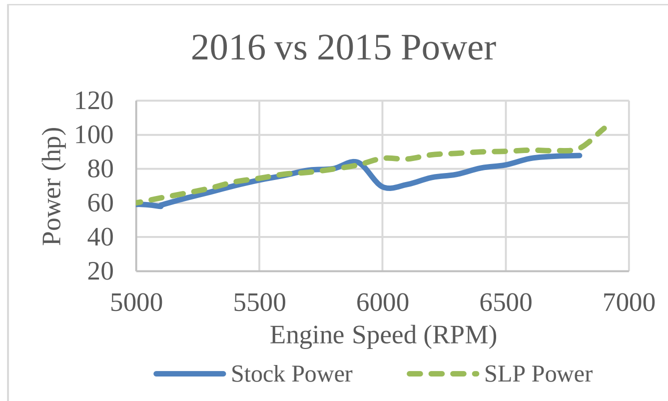


Figure 9: Power comparison

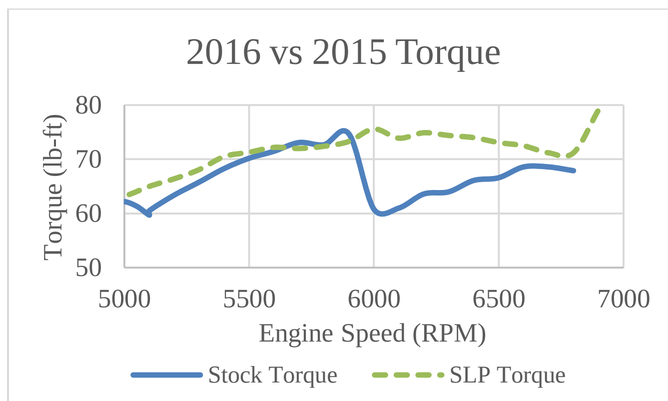


Figure 10: Torque comparison

Emissions

As a two-stroke engine short circuits fuel, especially at high speeds and loads, it requires special attention for reducing engine out emissions. The UICSC team implemented a four part strategy to reduce emissions. These technologies are: aftertreatment via a three way catalyst, an intake resonator, tuned exhaust redesign, and RAVE calibration.

The three-way catalyst, coated with rhodium and palladium, was implemented at the exit of the muffler. One risk of implementing a catalyst is that the added back pressure could reduce overall engine performance, so the catalyst was sized by UICSC sponsors to be large enough that the performance losses are low enough that they are not outside the error of the dyno [6].

The intake resonator improves emissions over a relatively limited RPM band. This is done through the increases in torque of up to 3% at the design point. Contrary to implementation of a Helmholtz chamber on the exhaust, where sound reduction is coupled with power loss, on the intake there are power gains and noise reductions. This is due to the increased pressure developed by the sound wave created by the chamber. This resonator is only designed for a specific frequency of 300 Hz which corresponds to 56 kph (35 mph) on the UI snowmobile. The effects of the resonator diminish the farther away from the design frequency the engine operates, but there are no detrimental effects on engine output.

As mentioned above, redesigning the tuned exhaust helps to time the pulses with the reduced engine speed. This does several things for efficiency. It allows more fresh air to enter the cylinder across the entire operating band, but it also forces a higher percentage of short circuited fuel back into the cylinder. This equates to higher trapping, scavenging, and fuel efficiency. Not only does it reduce the amount of short circuited fuel, it can increase the amount of exhaust gas residuals (EGR). Many engines, particularly four-strokes, utilize exhaust gas recirculation valves to increase the amount of EGR in cylinder. Increased EGR results in a higher threshold for detonation in cylinder as well as a general reduction in NO_x emissions [11].

Figure 11 shows the efficiency at which unburned hydrocarbons (UHC) are produced by the UI snowmobile at many operating points. Across the majority of the operating band, there is so little UHC being produced it essentially reads as zero, which means very little fuel is being short circuited relative to the power being produced. This does not equate to zero UHC being emitted, it just shows that when normalized by power, they are extremely low. These data were collected with no aftertreatment to show the low engine out emissions.

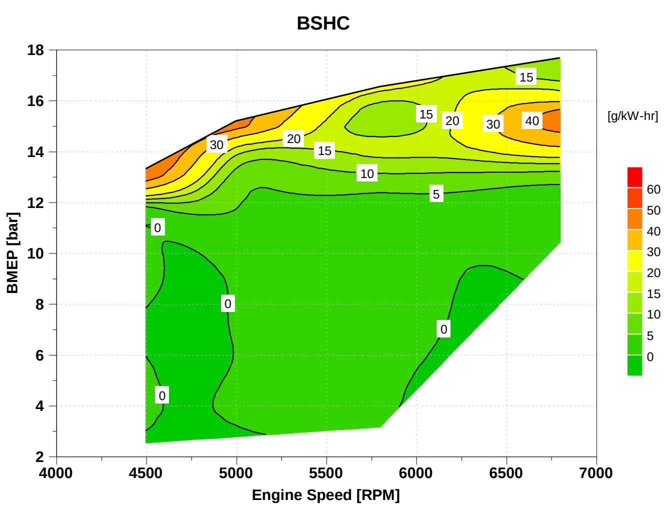


Figure 11: Brake specific UHC production

Figure 12 shows the brake specific CO production. Brake specific NO_x is not shown because the two-stroke platform produces very low amounts of this emission due to lower combustion temperatures [6].

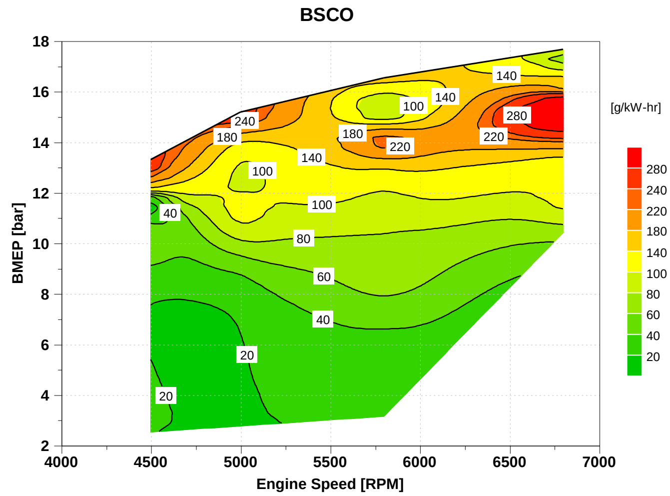


Figure 12: Brake specific CO production

Figure 13 shows the brake specific CO_2 production. The application of aftertreatment increases CO_2 production due to the chemical reactions that occur. CO_2 is a greenhouse gas, and is a consideration during calibration, but it does not weigh into the E-score [6].

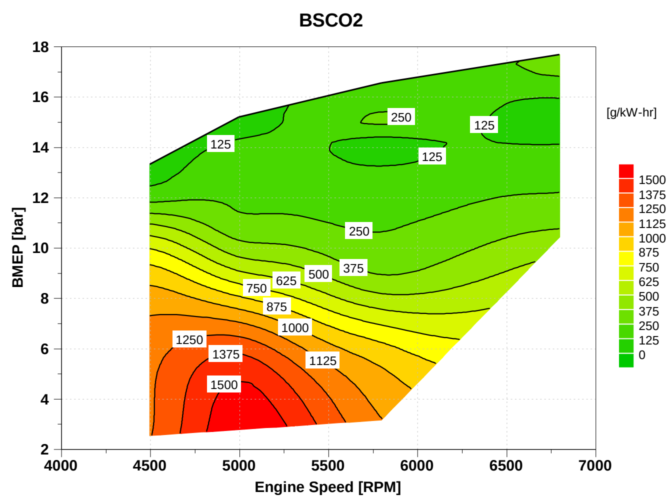


Figure 13: Brake specific CO_2 production

Calibration of the RAVE valves improved transient run quality and decreased emissions. This is especially useful since the competition is utilizing the ramped modal cycle (RMC) emissions test. During the RMC emissions are collected at each of the 5 mode points as well as at the transients between them. This general effect before and after calibration is shown in Figure 14.

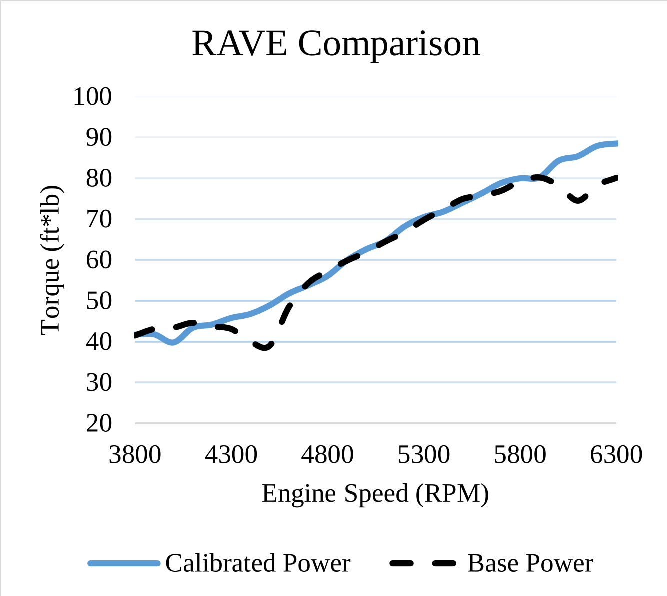


Figure 14: Comparison of power drops accelerating through RAVE openings

The variable exhaust valve calibration and tuned exhaust pipe do not change the fueling values for the engine, but they do increase the amount of trapped fuel in the cylinder. This means that a higher percentage of the fuel that is injected into the cylinder is being utilized to create power. Measuring trapping efficiency is difficult, but increases in torque with no change in fueling are indicative of increased trapping efficiencies.

The total gain in emissions score from 2015 is 60 points, increasing from 126 to 186. Figure 15 compares emissions scores of 2015 Idaho, a snowmobile of similar power output, and a best available technology four-stroke to the 2016 Idaho configuration.

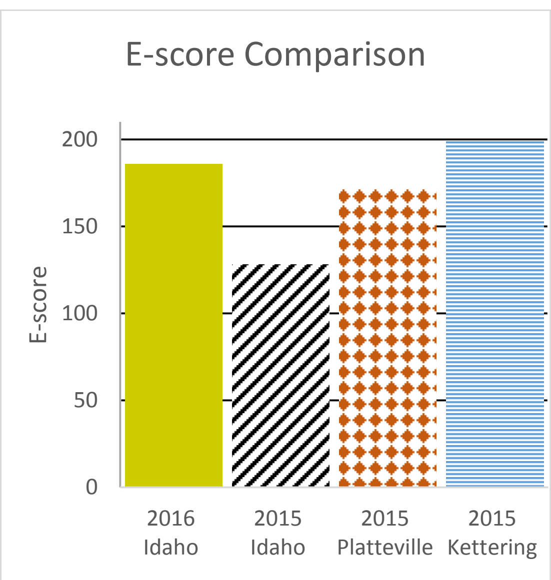


Figure 15: Comparison of emissions scores

Vehicle Dynamics

The UICSC team is attempting to better understand the aerodynamics of the snowmobile. For many years the windshield was removed from the chassis. Experiments were formed to show the effects of removing the windshield. New skis were also tested and implemented on the 2016 configuration.

Computational Fluid Dynamics (CFD)

The UICSC team performed CFD to better understand the aerodynamics of the current snowmobile. CFD was used to compare the vehicle's drag and the effects on the rider at temperatures as low as -18 ℃ (0 °F).

CFD simulation software was used to determine drag of the snowmobile at a velocity of 88.5 kph (55 mph), which is the max speed during the endurance event at competition. The first simulation was with the stock configuration including the windshield, while the second was without a windshield.

With a Coordinate Measuring Machine (CMM), an accurate 3-D computer model of the snowmobile's front end was created. The model was 3-D printed at $1/10^{th}$ scale and tested in a wind tunnel. Dynamic similitude, or the process of scaling the fluid properties, of the snowmobile were computed.

In equation 8, C_d represents the aerodynamic drag coefficient [15]. Due to the small size of the model, a full scale speed of 13 kph (8 mph) was able to be achieved. This resulted in an average coefficient of drag of 1.2.

$$C_d = \left(\frac{2F_d}{\rho A V^2}\right) 32.2 \qquad (8)$$

To verify the CFD visually, smoke-line testing was performed on the scale model. Looking behind the model's windshield, as seen in Figure 16, a circular eddy, or stagnant air flow, forms. Similarly, the CFD model in Figure 17 shows the same effect. This effect results in larger aerodynamic drag. Traveling at these speeds results in a higher wind force on the rider. This just validates the CFD model empirically to show that other results should be accurate.

Figure 16: Wind tunnel test validating simulation

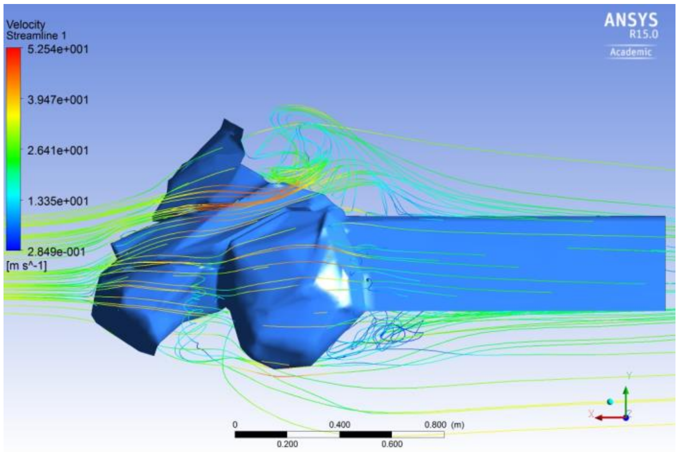


Figure 17: Software simulation showing flow patterns over snowmobile chassis

Use of the windshield, while not greatly affecting the overall drag of the vehicle, has impact on the rider. The rider is represented by the rectangle and circle in the figures below. The windshield helps to divert the airflow toward the rider's helmet, or over them if the they are short enough. With no windshield the airflow is flowing into the rider's chest, which will increase rider fatigue. This effect is shown in Figures 18 and 19. The figures represent the airflow with and without a windshield respectively. The rider representation is an average male standing at 1.8 m (5ft 10 in). The vehicle is travelling at 88.5 kph (55 mph) in the simulation. Once again, the eddy behind the windshield is seen. It is clear that using a windshield improves the comfort for the rider and should be included when designing trail snowmobiles.

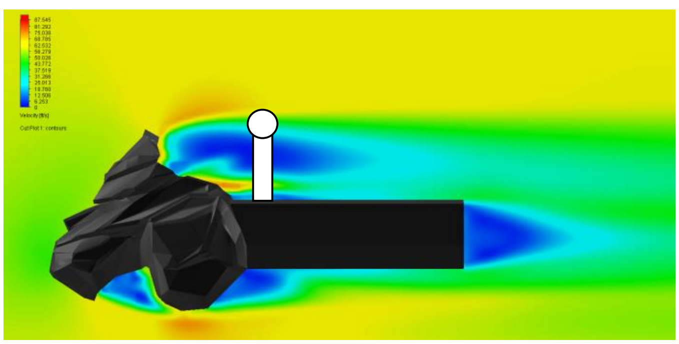


Figure 18: CFD simulation of airflow with windshield

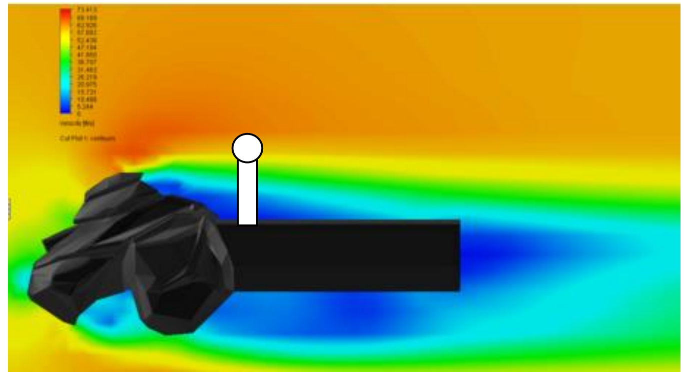


Figure 16: CFD simulation of airflow without windshield.

Ski Coast-Down Test

Two pairs of skis were tested to better understand vehicle drag. SLP Mohawk skis were installed on the snowmobile. These are a high-end aftermarket ski replacement. To ensure that the skis had no detrimental effect on the dynamics of the snowmobile, coast-down tests were performed. This test consisted of entering a gate at a set vehicle speed, then the throttle was released and the vehicle came to a stop after some distance. This distance was measured, then the test was repeated three times, where each repeated test was within 5% of each other. Data were collected at 24 and 57 kph (15 and 35 mph), run 1 and run 2 respectively, and showed a general increase in distance with SLP configuration. The results of this testing are shown in Table 3. The SLP ski results in less drag than the C&A ski, which will increase overall vehicle efficiency.

Table 3: Change in stopping distance from C&A to SLP skis

	C&A Ski	SLP Ski	Distance Change	Percent Change from C&A
Run 1 Average	13 m (42 ft)	14 m (47 ft)	+1.5 m (5 ft)	+11%
Run 2 Average	44 m (145 ft)	46 m (150 ft)	+1.5 m (5 ft)	+3%

Test Equipment

An SRL eddy current dynamometer, model FE-260-S, was used for all flex-fuel, exhaust, and general calibration work. A Max Machinery 710 Series fuel measurement system measured 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 AFR of the engine. Figure 20 shows the flow of information from hardware to software or vice versa. The dashed lines represent the flow of data and the solid lines represent physical measurements from the engine.

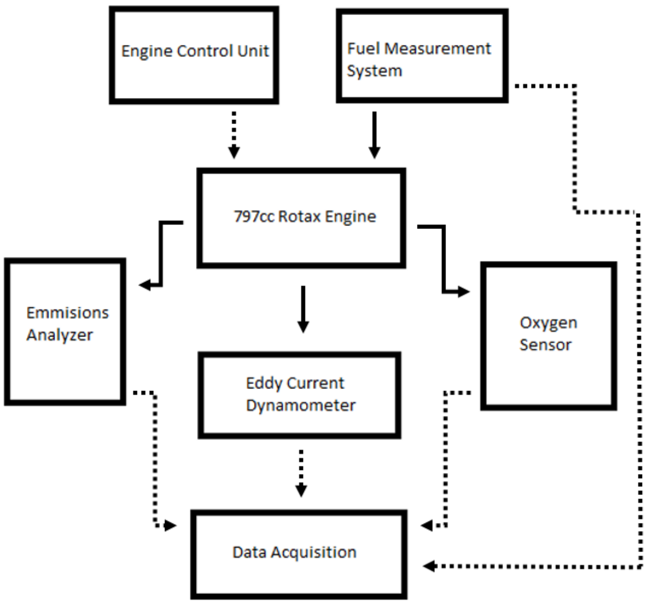


Figure 17: Test equipment data flow.

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 2016 SAE CSC weighing 267 kg (588 lb) wet, three pounds more than the 2015 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, Helmholtz, and extended tuned pipe, which are justified to achieve the goals of the competition. Although this is slightly higher than the production snowmobile which weighs 247 kg (544 lb) wet, it is still competitive with clean four-stroke snowmobiles. Shown in Table 4 is a comparison of measured snowmobile weights at the 2015 CSC competition [16].

Table 4: Comparison of snowmobile weights

University	Measured Total Wet Weight Kg (lb)
Idaho 2016	267 (588)
Madison 2015	251 (553)
Kettering 2015	255 (562)
Michigan Tech 2015	278 (612)

MSRP

The base price for a 2016 Ski-Doo MXZ TNT 600 H.O. E-TEC is $10,949. 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 2016 UICSC configuration totaled $12,172. 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 and Helmholtz are as follows; a reduction of 0.6 dBA/$35 and a reduction of 0.5dBA/$22 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.

Summary/Conclusions

The University of Idaho has developed a cost-effective flex fuel two-stroke snowmobile capable of running on E0 to E85 blended ethanol 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 77.6 kW (104hp), is lightweight at 267 kg (588lbs) wet, and achieves 13.5 L/100km (21 mpg). Overall sound production, measured using the SAE standard J1161, was a magnitude of 71 dBA. The UICSC design achieves NPS emissions with an E-score of 186. Consumers expect snowmobiles that are clean, quiet, fuel-efficient and fun-to-ride. The 2016 UICSC flex-fuel two-stroke reduced engine speed snowmobile is an economical response to that demand.

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Definitions/Abbreviations

CSC	Clean Snowmobile Challenge
SAE	Society of Automotive Engineers
EPA	Environmental Protective Agency
NPS	National Park Service
DOE	Department of Energy
AFR	air to fuel ratio
BSFC	brake specific fuel consumption
ECU	engine control unit
OEM	original equipment manufacturing
WOT	wide open throttle
RAVE	Rotax adjustable variable exhaust
ED	exhaust duration
MAQR	mechanically active quarter-wave resonator
BMEP	brake mean effective pressure
GGE	gallon gasoline equivalent
EGR	exhaust gas residuals
UHC	unburned hydrocarbons
RMC	ramped modal cycle
CFD	computational fluid dynamics
CMM	coordinate measuring machine
MSRP	manufacturer's suggested retail price