# University of Idaho's Reduced Speed Isobutanol Flex Fuel Direct-Injected 797cc Two-Stroke Snowmobile

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## ABSTRACT

The University of Idaho's entry into the 2014 SAE Clean Snowmobile Challenge is a 2013 Ski-Doo MXZ-TNT chassis with a low speed 797 cc direct-injected two-stroke engine modified for flex fuel use with blended isobutanol/gasoline fuel. A battery-less direct injection system was used to improve fuel economy and decrease emissions while maintaining a high power-to-weight ratio. Noise was reduced by operating the engine at a lower speed, and by strategically placed sound absorbing/deadening materials within the engine compartment. A muffler was modified to incorporate a three-way catalyst, which reduced engine emissions without greatly reducing power output or increasing sound output. The 2014 configuration implements a fuel economy switch which creates a powerful "sport" and efficient "eco" mode. Pre-competition testing had the snowmobile entering the 2014 SAE CSC competition weighing 263 kg (580 lb) wet, achieving 12.99 l/100km (18.11 mpg) or 21.00 miles per gallon gasoline equivalent using B32 fuel in mountainous terrain. The snowmobile was tuned to be operable in either a "power" mode or an increased fuel economy and reduced power "eco" mode. When in eco-mode and using B32 fuel the snowmobile had an EPA five mode emissions test score of 203, and a J-192 sound magnitude score of 71.5 dBA under light powder conditions.

## INTRODUCTION

Snowmobiling offers a great opportunity for winter recreation and exploration. Snowmobiles have traditionally been loud, with high levels of toxic exhaust emissions and poor fuel economy. Snowmobiles are often ridden in environmentally sensitive areas such as Yellowstone National Park where the adverse effects of snowmobiles can be substantial. To counter the potentially negative impact of snowmobiles a partnership between industry, conservationists, and the snowmobiling community was created. As part of this partnership, a competition was created for college students to design a cleaner, quieter snowmobile. 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) supported the effort and began the Clean Snowmobile Challenge (CSC) in 2000. Traditionally, the competition has been to develop a touring snowmobile which meets NPS standards. In part, due to the efforts of all involved with the CSC, manufacturers now produce touring snowmobiles that meet both noise and exhaust emissions standards. The University of Idaho Clean Snowmobile Challenge (UICSC) team recognizes that the problem has shifted to technologies that are not currently meeting these standards. Once these technologies are improved, they can be implemented on snowmobiles and other high-performance vehicles raising the industry standard.

The 2014 CSC continued to encourage snowmobile development by mandating use of blended isobutanol/gasoline fuel in gasoline engines. The required blend ranged from 16 to 32 percent isobutanol by volume (B16-B32) [1]. Isobutanol is a renewable fuel that has lower energy content per unit volume than gasoline but has greater energy density than ethanol. Exhaust emissions from burning blended isobutanol fuels differ from those of gasoline, typically with lower total hydrocarbons (HC) and carbon monoxide (CO) quantities. A twenty percent isobutanol/gasoline blend behaves very similarly to a ten percent ethanol/gasoline blend, but is a higher concentration of biofuel [2]. Other challenges associated with blended isobutanol fuels include creating flexible engine calibrations. The rules allow for a possible user input switch that creates an optional fuel economy mode which was implemented in the 2014 configuration. This paper outlines the design strategies of the University of Idaho in engineering a solution that meets and exceeds industry standards for regulated emissions, improves efficiency, and maintains performance and reliability.

## UICSC SNOWMOBILE DESIGN

### *Engine Selection*

For 2014, the UICSC team chose to use a direct-injected (DI) 797 cc Rotax two-stroke engine mounted in a 2014 Ski-Doo MXZ-TNT Chassis. This selection was based on the better power-to-weight ratio, suspension, and handling, and reduced cost and complexity of two-stroke engines. The characteristics that make two-stroke engines mechanically simple typically result in lower thermal efficiency, poor part-load operation, and high exhaust emissions compared to four-stroke engines of similar output. To counteract these issues, the UICSC team reduced the maximum engine speed, making the power output comparable to a 600 cc DI two-stroke while increasing efficiency and reducing emissions. This configuration has proven that a DI two-stroke powered snowmobile can meet and exceed the demands of the Clean Snowmobile Challenge [3]. Our goal is to design a snowmobile that meets the performance demands of enthusiasts, while simultaneously being clean, quiet, fuel efficient, and conscientious for use in sensitive areas, effectively creating two snowmobiles in one.

## *Ergonomics (Human Factors)*

Building on research from the 2013 competition, the UICSC team further addressed ergonomics in the snowmobile's design. To reduce the risk of injury while riding the snowmobile, the team replaced the stock 11.4 cm (4.5 in) handlebar riser with a 20.3 cm (8.0 in) riser. This keeps the average male of height 176.0 cm (69.3 in) in the optimal position while riding [4]. The riser achieves this by keeping the rider's wrists in the neutral position. This is where the plane of the wrist is unbroken as to prevent flexion or extension. The new riser, unlike the stock one, allows for the forearm to be kept parallel to the ground, which keeps the elbow at a position of nearly 90 degrees. Since they are major factors of cumulative trauma disorders (CTD), reducing extension and flexion of the wrist reduces risks of injuries such as carpal tunnel syndrome [5]. According to the CTD risk index, in a typical five hour riding period where the user will release and press the throttle every ten seconds the risk factor while using the stock riser is 1.486 and while using the 20.3 cm (8 in) riser is 1.424. The risk factor is reduced by 4.14 percent and the rider is less likely to develop a CTD.

**CTD Risk Index**

| | | |
|---|---|---|
| Job Title: | VCR Counter No.: | Date: |
| Job Description: | Department: | Analyst: |

| | | |
|---|---|---|
| Cycle Time (in minutes; obtain from videotape) | | |
| # Cycle/Day = (480 - Lunch - Breaks) / CycleTime = 300 / .10 | 3000 | Larger of 2a or 2b: |
| # Parts / Day (if known) | | |
| # Handmotions / Cycle | | 1 |
| # Handmotions / Day (3 x 4) | | 3000 |
| Frequency Factor (Divide by 10,000) = | | .3 |

| (Circle appropriate condition) | Points 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| Working Posture | (Sit) | Stand | | |
| Hand Posture 1: Pulp Pinch | (No) | Yes | | |
| Hand Posture 2: Lateral Pinch | (No) | Yes | | |
| Hand Posture 3: Palm Pinch | No | Yes | | |
| Hand Posture 4: Finger Press | No | Yes | | |
| Hand Posture 5: Power Grip | (Yes) | No | | |
| Type of Reach | (Horizontal) | Up/Down | | |
| Hand Deviation 1: Flexion | No | (Yes) | | |
| Hand Deviation 2: Extension | No | (Yes) | | |
| Hand Deviation 3: Radial Dev. | (No) | Yes | | |
| Hand Deviation 4: Ulnar Dev. | (No) | Yes | | |
| Forearm Rotation | Neutral | In/Out | | |
| Elbow Angle | -90° | (≠90) | | |
| Shoulder Abduction | 0 | (<45°) | <90° | >90° |
| Shoulder Flexion | (0) | <90° | <180° | >180° |
| Back/Neck Angle | (0) | <45° | <90° | >90° |
| Balance | (Yes) | No | | |
| Total the Points for the Circled Conditions | | | | 4 |
| Posture Factor (Divide by 10) = | | | | .4 |

| | | |
|---|---|---|
| Grip or Pinch Force Used on Task | 2 lbs. | Divide by: |
| Max Grip or Pinch Force | 3.5 lbs. | |
| Force Factor (Divide by .15) = | | .57 |

| (Circle appropriate condition) | Points 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| Sharp Edge | (No) | Yes | | |
| Glove | No | (Yes) | | |
| Vibration | No | (Yes) | | |
| Type of Action | Dynamic | (Intermittent) | Static | |
| Temperature | Warm | (Cold) | | |
| Total the Points for the Circled Conditions | | | | 4 |
| Miscellaneous Factor (Divide by 3) = | | | | 1.33 |

*CTD Risk Index = .3 x (Frequency + Posture + Force Factors) + .1 x (Miscellaneous Factor)*

**CTD Risk Index = .3 x ( .3 + .4 + .57 ) + .1 x ( 1.33 ) = 1.486**

Figure 1. CTD Risk Index form evaluating the stock riser.


Figure 2. Rider position on the 2014 UICSC snowmobile (stationary).

## *Fuel Delivery System*

In the 2014 CSC, all gasoline spark ignition engines are fueled with blended isobutanol fuel. Consequently a major design goal for the competition was to tune and modify the UICSC DI snowmobile to run on a blended isobutanol fuel [1]. The challenge rules state 32 percent isobutanol as the upper limit and 16 percent as the lower limit (B16 –B32). Using isobutanol as a fuel has some drawbacks, such as slightly increased fuel flow requirements, shorter shelf life, lower viscosity, and extremely limited availability. Even though the UICSC engine closely resembles the 600 H.O. as opposed to the 800 R, it is still necessary to use the higher capacity 800 E-TEC injectors to compensate for higher fuel flows associated with alcohol blended fuels. The fuel lines and O-rings used are compatible with alcohol blend fuels [6].

## *Calibration*

A Borghi & Saveri (SRL) eddy current dynamometer, model FE-260-S, was used for all flex-fuel calibration work. A Max Machinery 710 Series Fuel Measurement system allowed fuel flow to be measured. Emissions data were collected with a Horiba MEXA-584L emissions analyzer. An Innovate LM-2 wide band oxygen sensor provided information about the air/fuel ratio (AFR) of the engine. Since the two-stroke cycle allows fresh charge to short circuit out the exhaust, the oxygen value measured in the exhaust does not represent the actual fuel air charge trapped in the cylinder. As a result, the trapped equivalence ratio is unknown during calibration and cannot be used as a calibration objective. Equivalence ratio is stoichiometric AFR divided by actual AFR. The wide band oxygen sensor does provide relative data, which were used to replicate an unburned oxygen concentration. This is useful when fuel injection timing and quantities are changed while engine speed and throttle position remain constant.

An E-score based function was used to optimize engine calibration for the maximum emissions score. The objective function was equation 1 below. In this function, $W_m$ is the mode weight, unburned hydrocarbons (UHC) is in g/hr hexane equivalent, oxides of nitrogen ($NO_x$) and carbon monoxide

(CO) are in g/hr, and P is power measured in kW. When calibrating at a mode point, this function allows us to compute the points contributing to the total E-score at a single mode. Fuel injection timing and quantity must be calibrated simultaneously due to their strong interaction. Alterations in injection timing have two main effects: mixing time, and short-circuiting control. Earlier injection results in cleaner combustion, but may also result in the short-circuiting of fuel. Injection quantity must be altered to control trapped AFR.

$$F(x) = W_m * \frac{\left(\frac{6*UHC+NO_x}{150}+\frac{CO}{400}\right)}{P} \quad (1)$$

The strategy to minimize the objective function is shown in figures 3 and 4.

- 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. Step two completes the iteration. In order to achieve the optimal setting, multiple iterations must be completed.
- Step three (tune interpolation): after tuning the ten mode points (accounting for eco and sport mode) the values were interpolated between these points. This was done to keep consistency in the tune and address the transition points of the map.

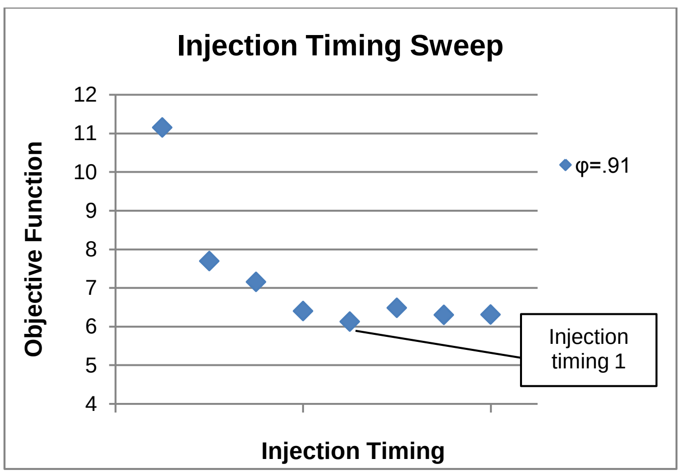


Figure 3. Objective function vs. injection timing at a constant equivalence ratio.

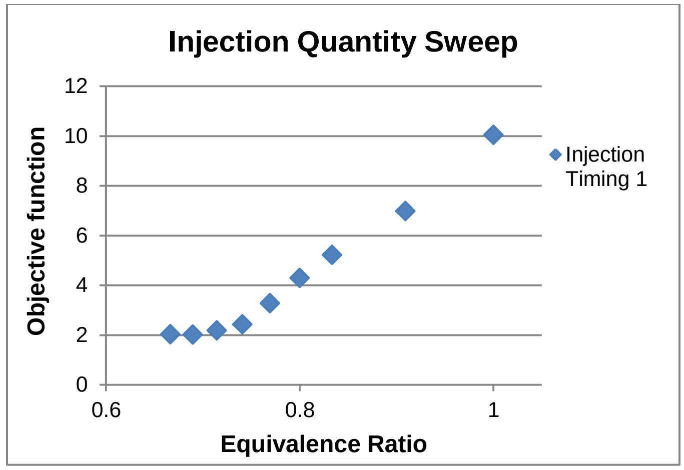


Figure 4. Objective function vs. equivalence ratio at a constant injection timing.

The calibration strategy was employed using the 800cc engine with the same throttle bodies, intake reeds, tuned pipe, and muffler that would be used at the 2014 CSC. The base map in the engine management module (EMM) was calibrated using 0% isobutanol fuel, with an uncoated catalyst substrate installed in the exhaust stream. This was done to replicate the backpressure caused by the catalyst without risking damage to a catalyst during use of an unrefined EMM map. After the initial calibration was complete, isobutanol compensation calibration was done using a similar strategy to find optimal injection timing, quantity, and ignition timing.

## *Flex Fuel System*

For 2014 the UICSC team used a Continental flex fuel sensor and custom analog circuit to send information about the isobutanol content of the fuel to the EMM. This was tested and calibrated to ensure proper identification of isobutanol content. The analog circuit converts a frequency signal from the Continental flex fuel sensor into an analog signal that is accepted by the EMM. The CSC has been incorporating flex fuel since 2009. Figure 5 displays the final circuit design, which is on a compact printed circuit board approximately 4.8 cm x 5 cm x 1.9 cm (1.9 in x 2 in x .75 in). The altered flex fuel signal is connected to an existing input on the EMM, allowing for multidimensional compensations in the EMM for a wide range of alcohol contents with no user input and low price increase.

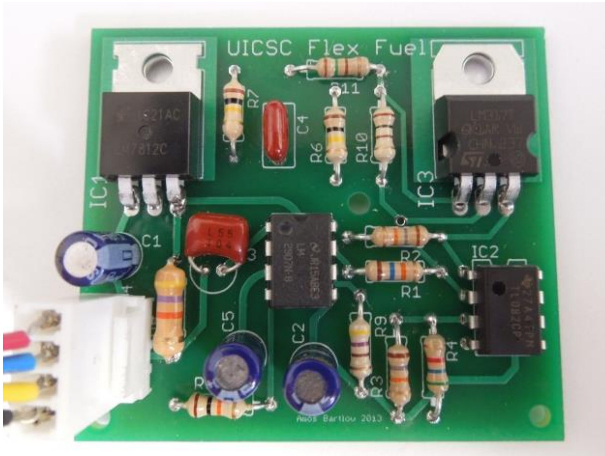


Figure 5. The UICSC printed flex fuel circuit.

Injection quantity was compensated first. A mathematical compensation was calculated based on the stoichiometric AFR of the fuels and their respective densities. With this theoretical compensation entered into the EMM, engine testing was done to determine if the mixture was rich or lean, then adjustments were made accordingly. Figure 6 shows the theoretical compensation. Increases in fuel quantity were required in part to reduce secondary combustion in the exhaust system. To switch between the alcohol fuels (ethanol and isobutanol) the only information required is the AFR of the fuel being used. After this it is a simple change in compensation values based on the percentage of alcohol in the fuel. All compensations are achieved on a fuel composition basis, requiring only a coefficient change for each fuel type.

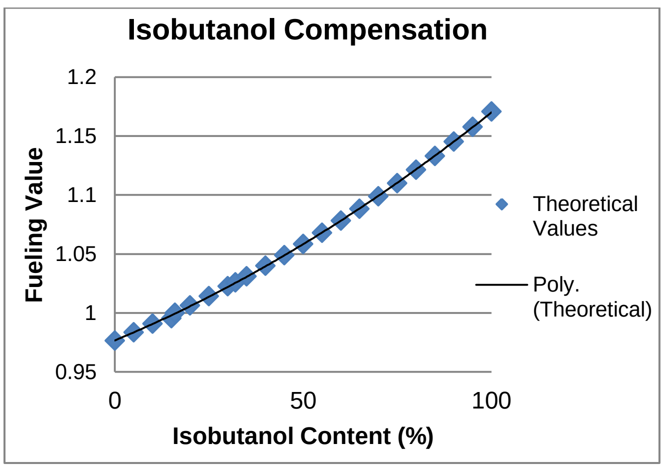


Figure 6. Theoretical and calibrated compensation for blended isobutanol fuels.

Ignition timing was only slightly modified. It is required to retard ignition timing when using standard 87 octane gasoline. Isobutanol also has a lower knock threshold than ethanol which required a slight retarding of timing compared to the ethanol ideal tune. This is done to reduce knock at wide open throttle (WOT). The octane number listed at gas stations is the average of the research octane and motor octane numbers. The fuel at the CSC 2014 will have a minimum octane rating of 91 which allowed the UICSC team to increase power slightly due to the increase in octane over standard E10 pump gas. The full potential, however, could not be realized due to the power limit of the competition snowmobiles [1].

### *Exhaust Emissions*

In the CSC 2014 the option of a fuel economy switch was allowed and the UICSC team took advantage of this. A dual mode snowmobile was developed. These modes were named sport-mode and eco-mode. The sport or power mode allows for increased horsepower and survivability at the cost of fuel economy. In the economy or eco-mode the power of the engine is limited to 60 hp, and the air/fuel ratio is increased to reduce BSFC. Through this testing and implementation other benefits of the eco-switch were found. Figures 7 and 8 show the power sweep for sport-mode and eco-mode respectively.

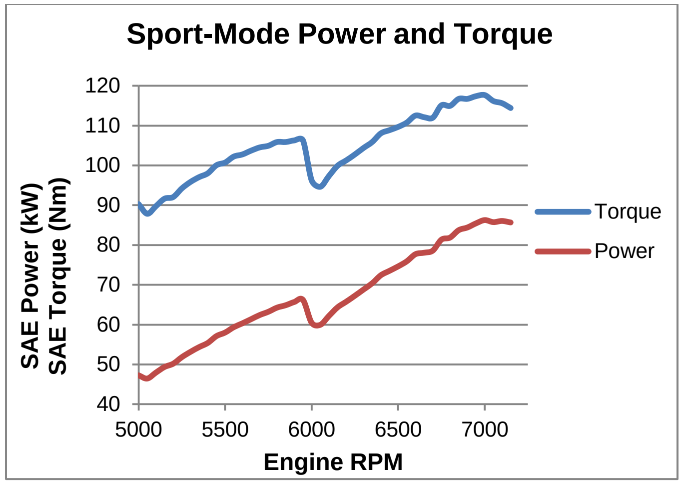


Figure 7. Power sweep for sport-mode (measured horsepower).

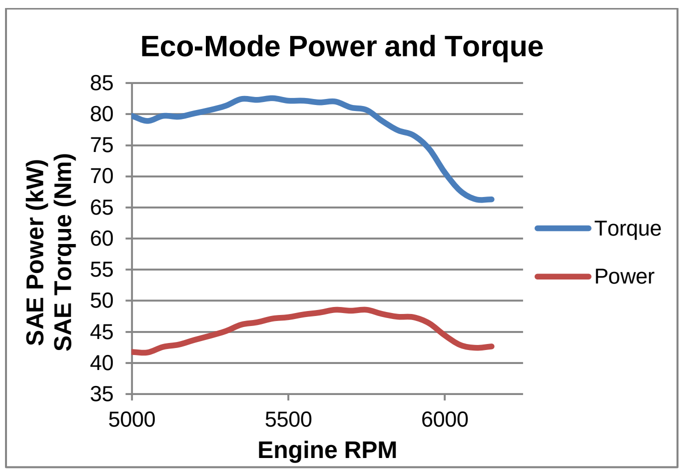


Figure 8. Power sweep for eco-mode (measured horsepower).

The EPA five-mode emissions test was performed for eco-mode to ensure that the lean tune of the engine did not sacrifice emissions for fuel economy. Figure 9 below shows a comparison of the 2013 design to the 2014 design. There was no significant change in the E-score.

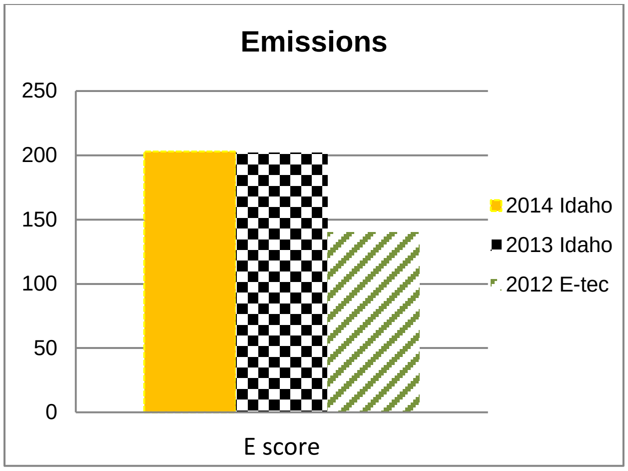


Figure 9. A comparison of the EPA 5-mode emissions E-score.

### Catalyst Aging

In 2012, the UICSC team researched catalyst break-in cycles to get more consistent emission results. A fresh catalyst will convert HC and CO constituents at a much higher efficiency than one that has been used on an engine for an extended period of time. While there may be a short-term benefit to running a fresh catalyst, a seasoned catalyst reflects the type of emissions reduction likely over the life of the snowmobile [7]. Therefore, the UICSC team decided to perform an experiment to test different aging techniques that would mimic on-engine aging practices. The results from that experiment showed that a catalyst broken-in on an engine has lower HC conversion than other methods, and is therefore further aged. The other methods tested were thermal aging at 760 °C (1400 F) for 24 hours and hydrothermal aging at 760 °C (1400 F) for 24 hours. The hydrothermal aging process involves flowing gaseous water through the substrate while at high temperature, while the thermal process uses static high temperature air. Figure 11 shows the results of the tests. For 2014, the UICSC team used thermal aging prior to engine aging to ensure catalyst aging and reduce the possibility of catalyst failure.

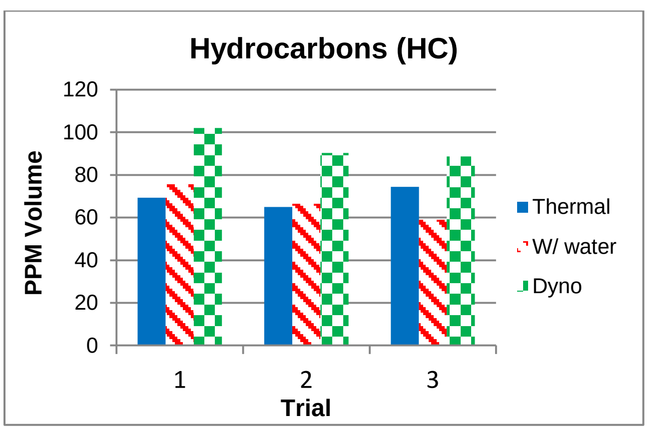


Figure 10. Hydrocarbon emissions after catalyst aging.

### Fuel Economy

For 2014, fuel economy was measured during on-snow testing with B16-B32 isobutanol blends, the same that could be used in the 2014 competition. In 2014 fuel economy was one of the main foci of the UICSC team. One of the main contributors to fuel economy drop identified by the UICSC team was poor clutching, which is discussed later in this paper. The cruise operating range was identified by recording throttle position and engine RPM while traveling at speeds between 48 kph (30 mph) and 80 kph (50 mph).

Recognizing that the cruise range does not coincide with any of the five modes tested, the engine was calibrated for minimum brake specific fuel consumption (BSFC) rather than maximum E-Score. This calibration was accomplished using the same strategy as the emissions calibration, with the objective function being the BSFC. Therefore, calibrating for minimum BSFC will result in improved fuel economy. During on-snow testing for fuel economy, the UICSC team achieved economy numbers of 12.99 l/100km (18.11 mpg) or 21.00 miles per gallon gasoline gallon equivalent using B32 fuel.

### Noise Reduction

In past years, the UICSC team's method for reducing noise emissions involved adding sound deadening material wherever possible. This method, while somewhat successful, added weight to the chassis and did not address the sources of the noise. For 2014 the UICSC design team began by first identifying the contributing sources. The sources explored were mechanical noise, intake noise, and exhaust noise from the engine and drivetrain. Strategies were then developed to address each area using a variety of techniques to reduce the overall noise emissions.

In 2014 a new sound box was constructed in an attempt to improve the quality of data acquisition. Past tests the UICSC team used were the airfoil and standing wave tube tests. The sound box test was chosen over these for simplicity of design and repeatability. The UICSC sound box design allows for fast changeover of materials and adjusts for different sizes using spring clamps. Box hardware included: ¾ inch dense particle board, a Pioneer speaker (14.0 cm (5.5 in)), two omni-directional Audio-Technica microphones (frequency response:50-13000 Hz, sensitivity: -48 dB), plastic material resembling the Ski-Doo body panels, steel spring clamps, metal stripping to reduce auxiliary vibrations in the box, and Liquid Nails used for sealing box seams and microphone mounting. The first microphone was placed 25.4 cm (10 in) from the speaker, with the outside wall being the plastic material. A second microphone was placed outside the box 5.1 cm (2 in) away from the plastic material.

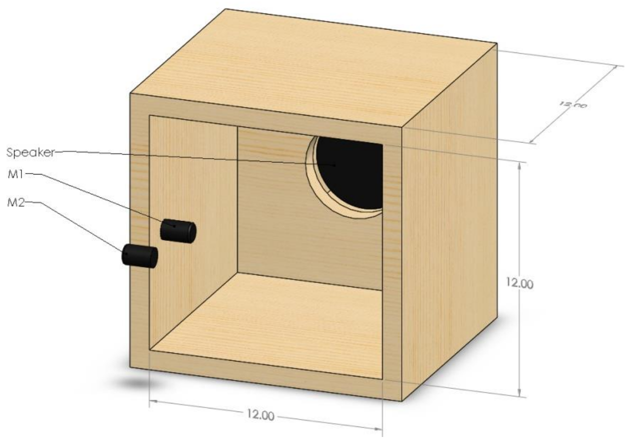


Figure 11. Sound box, materials testing apparatus

White noise tests were used in the UICSC sound materials testing to observe the noise deadening characteristics of the materials. White noise was chosen because it is an equal distribution of all frequencies from 0-20000 Hz. The analyzed frequencies were between 0-12000 Hz, because they are typically the most audible, and 1000-7000Hz are weighted heavily on the dBA scale.

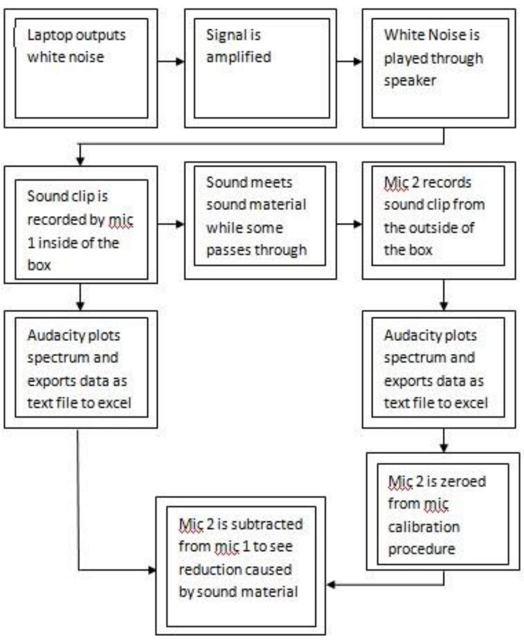


Figure 12. Test setup flow chart

Test setup involved a laptop which output a default white noise sample to an amplifier, the amplified signal went to a speaker mounted inside the box, where white noise was directed at the first microphone and test material. Both microphones recorded the sound, clipping it into useable data with the Audacity™ software installed on two computers each connected to a microphone.

The microphones had slightly different calibrations. To correct this offset the microphones were exposed to the same white noise sample and calibrated relative to each other. The baseline resembling the panel with no material was created by measuring the frequencies on the second microphone of the white noise with the panel as the medium between the microphones. Data were then collected using Audacity's™ plot spectrum function from the sound clip then a Fast Fourier Transform (FFT) was performed. The data were normalized and then the two microphone readings were plotted to show the difference at the points of interest. Audacity™ outputs the data on a negative dB scale, so to interpret the data properly the following equation was used:

$$\text{Insertion Loss(dB)} = 20\text{LOG}\left(\frac{m_2}{m_1}\right) \quad (2)$$

Where $m_2$ is the microphone outside of the box and $m_1$ is the microphone inside the box. In the insertion loss equation, $m_2$ and $m_1$ are the microphone spectra as recorded and computed by Audacity™. Insertion loss is the reduction of noise across the medium between the two microphones relative to the noise source [8,9].

Table 1. Materials tested in the experiment.

| | |
|---|---|
| Composite (Melamine .635cm (1/4 in) , Plastic, Melamine .635 cm (1/4 in), Thermal | Material 1 |
| Composite (EDM, Plastic, Melamine 2.54 cm (1in), Thermal) | Material 2 |

This year material 2 was tested relative to material 1, which was used in the 2013 configuration. The thickness of melamine is a large contributor to the effectiveness of the material. The UICSC team compared ½ inch thick melamine and 1 inch thick melamine. This showed an average reduction of 5 dB across the frequency range.

Human hearing is most sensitive to frequencies ranging from 2000-4000 Hz. The graph below displays the insertion loss between the microphones for both material 1 and 2 over 100-5000 Hz. As the height of the curve increases, so does the reduction in noise levels at that frequency. Over the 2000-4000 Hz range, material 2 was an average of 1.4 dB higher in noise reduction than material 1. The greatest differences between material 1 and 2 within the desired frequency range were between 2-4 dB. A pronounced increase in sound reduction with material 2 also occurred just above 600 Hz, which made that frequency a point of interest even though it was not in the original range of focus. As seen in figure 13, there were a few frequencies at which material 1 had a slight decrease in noise than material 2, but the gains in the desired range outweighed these minor losses.

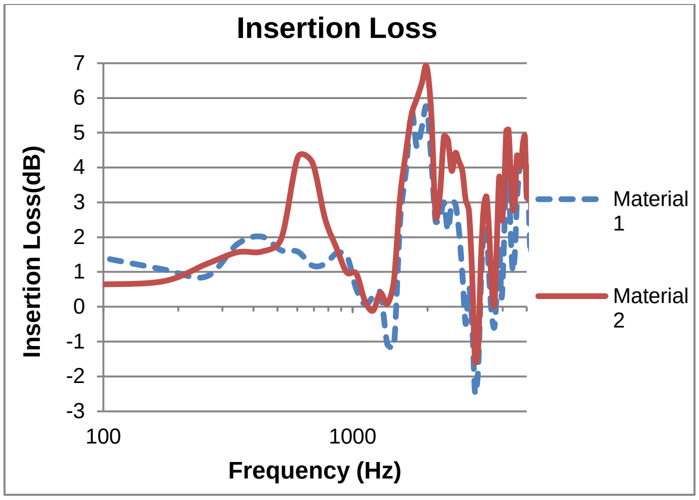


Figure 13. Insertion loss comparison of Material 1 and Material 2.

### Mechanical Noise

To contain and redirect noise, all hood and side panel vents not necessary for engine compartment cooling were sealed. Vents that could not be eliminated were fitted with fore and aft directional vents to reduce direct noise emission and maintain airflow through the engine compartment. During J192 testing the directional vents provided a 1 dBA reduction in the snowmobile's J192 score, along with a noticeable reduction in engine noise directed at the rider.

While testing, a frequency was emitted from the injectors on the engine. The strategy of adding Polydamp sound material was taken to reduce the noise from the injectors. A J192 was performed and a 2.5 dBA reduction in eco-mode was noted.

### Intake Noise

Due to the selection of the MXZ-TNT chassis, there are two intake openings instead of one. In order to reduce intake noise an aft directional deflector was designed for both intake openings and a foam pre-filter was added to the airbox on both sides. A J192 was performed on both the deflectors and the foam. A 0.5 dBA reduction was seen on the exhaust side due to the deflectors and a 1.3 dBA reduction was seen on the exhaust side with the foam pre-filter.

### Exhaust Noise

The 2014 UICSC design team decided to further the two-step approach taken in 2013 to reduce exhaust noise emissions. The first step consists of reducing the engine's overall operating speed from 8000 RPM to 7000 RPM and having both a sport and an eco-mode. In eco-mode the maximum engine operating speed is reduced to 6000 RPM. The second step is the use of a quarter wave resonator. The design team chose to further reduce the noise emissions in eco-mode due to the greater likelihood of operating in that mode within sensitive areas. The resonator is designed for the eco-mode maximum operation speed of 6000 RPM. For the 2013 CSC, the resonator was designed to reduce the second, fourth and sixth harmonic of the exhaust due to ease of manufacturing and installation. The 2014 resonator was designed to reduce the first, third and fifth harmonic.

Difficulties in packaging come from the increase in length associated with reducing the first harmonic. The previous resonator that reduced the second harmonic was 33 cm (13 in) long and the new resonator is 66 cm (26 in) long. This resulted in the secondary bend shown in figure 14. The UICSC team performed experiments to ensure that bending the resonator into this geometry had no effect on the resonator's effectiveness. These experiments consisted of using an unbent pipe, the pipe bent once, and the final configuration shown in figure 14. Packaging of the resonator is show in figure 15.

Figure 14. Quarter wave resonator comparison. Previous design in front, new design in the rear.

Figure 15. The Quarter wave resonator packaged in chassis.

The effect of the 2014 quarter wave resonator was compared with the 2013 design and the stock tuned pipe. This was done with an engine dynamometer operating at the constant speed of 6000 RPM. Sound data were recorded and an FFT was analyzed using equation 2. The FFT of the dynamometer room without the engine running, but all other equipment being powered was used to represent the noise level before the insertion gain. The FFT of the engine running was used to represent the noise level after the insertion gain. The stock configuration of the pipe was used as the control in the testing. Figure 16 below shows the sound pressure reduction of each quarter wave in comparison to the control from 100-700 Hz. As seen in the figure, the 2014 resonator design reduced 0.5dB at the target frequency while the previous design amplified this frequency by 1 dB. As seen at the right edge of the figure, the previous design begins to reduce sound level at the second harmonic of the engine. For this figure a value above the control represents a reduction in dB. The first harmonic of the engine is at 400 Hz and the second harmonic is at 600 Hz. The reduction caused by both of the quarter waves appear to be identical at their respective harmonics. Due to the amplification at the first harmonic by the second harmonic quarter wave the relative loss at the first harmonic is greater than that at the second. This is shown by the difference between the peaks and valleys at the first and second harmonics in figure 16.

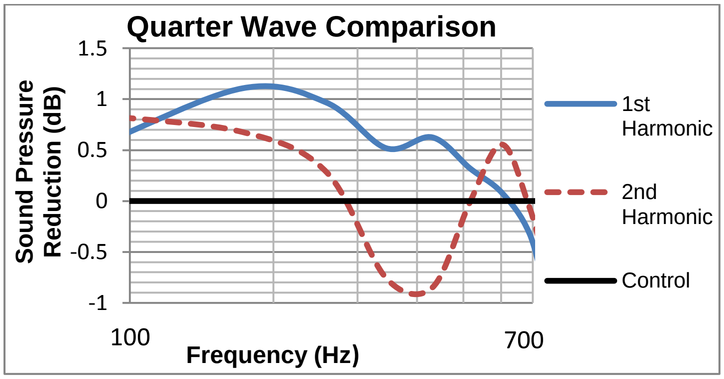


Figure 16. Sound pressure reduced by the 2014 and 2013 quarter wave design in comparison to the stock configuration.

In addition to the steady state comparison test an on-snow J192 test was conducted. A 2009 600 MXZ was used as a control snowmobile while the stock pipe, 2013 resonator design and 2014 design were compared. Table 2 below shows the comparison of the exhaust side measurements of the snowmobile in each configuration while in eco-mode. In total the 2014 design reduced the sound level by 3 dBA.

Table 2. SAE J192 Exhaust side measurements.

| Configuration | SAE J192 Exhaust (dBA) |
|---|---|
| UICSC design with 2014 quarter wave resonator | 71.5 |
| UICSC design with 2013 quarter wave resonator | 73.8 |
| UICSC design without quarter wave resonator | 74.5 |
| Control Snowmobile | 78 |

## Combined Approach

In total, the combination of the UICSC noise reduction strategies yielded a J192 score of 71.5 dBA in eco-mode and 74.9 dBA in sport-mode. Compared to the 2013 UICSC design, the 2014 design achieved a reduction of 3.9 dBA in eco-mode and 3.1 dBA in sport-mode. It is expected that both modes will meet EPA standards at competition and eco-mode will meet NPS standards.

## *Clutching*

The UICSC team determined that clutching had significant impacts on both noise and fuel-economy. This led to optimizing the clutching set-up for the 2014 configuration. The initial testing consisted of roll down experiments to reduce engine braking. Hard engine braking produces high drag, which hinders the snowmobile's ability to coast.

Due to the reduced speed of the UICSC team's engine, the stock clutch had to be modified to reflect the engine's performance. Maximum engine RPM can be reduced using a lower final force primary spring, heavier flyweights or more aggressive ramps [10]. Replacing the factory 1156.5 N (260 lb) final force and 711.7 N (160 lb) initial force spring with a softer 756.2 N (170 lb) final and 444.8 N (100 lb) initial force spring lowered the maximum engine speed to the desired 7000 RPM with an engagement of 3000 RPM. The team found that the shift characteristics were more appropriate, but the low engagement results in a harder engine braking. To study this further, the team conducted a roll out test. The rider entered the test area at 32.2 kph (20 mph) and immediately released the throttle. The coasting distances of three different primary springs are shown in figure 17. The test showed that the medium stiffness and soft springs reduced coasting efficiency by 17% and 28% respectively when compared to stock. This is due to the lower engagement RPM associated with the lower initial spring forces. The flyweights were able to exert more force than the spring and the belt would be engaged to the engine for longer periods of time during the roll out test. This effect showed a drop in fuel efficiency when the stock clutch setup obtained 11.0 l/100km (21.4 mpg) while the soft spring only achieved 12.4 l/100km (19 mpg) in similar conditions.

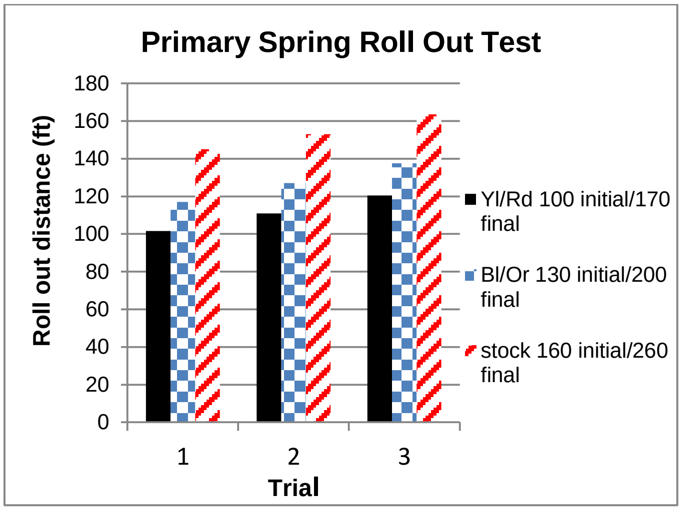


Figure 17. Comparison of three different clutch springs rollout at different speeds

To reduce the engine braking effect, the UICSC team used a more aggressive ramp profile with a higher engagement RPM. The Ski-Doo Summit 441 ramp has a higher engagement and more aggressive shift profile which achieves this effect where the stock 414 ramp does not. The aggressive shift pattern of the 441 ramp also reduces the maximum engine RPM. In figure 18, the ramp is the curved object in the bottom right with the roller of the flyweight in the non-engaged position of the clutch. A more aggressive shift pattern corresponds to the lower angle the roller has to climb. The lower angle allows the flyweight to climb the ramp more easily and shift the clutch into a higher drive ratio. The taller start profile on the 441 ramp tucks the flyweight further to the centerline of the driveshaft lowering the magnitude of force the flyweight applies to shift the clutch into engagement [11].

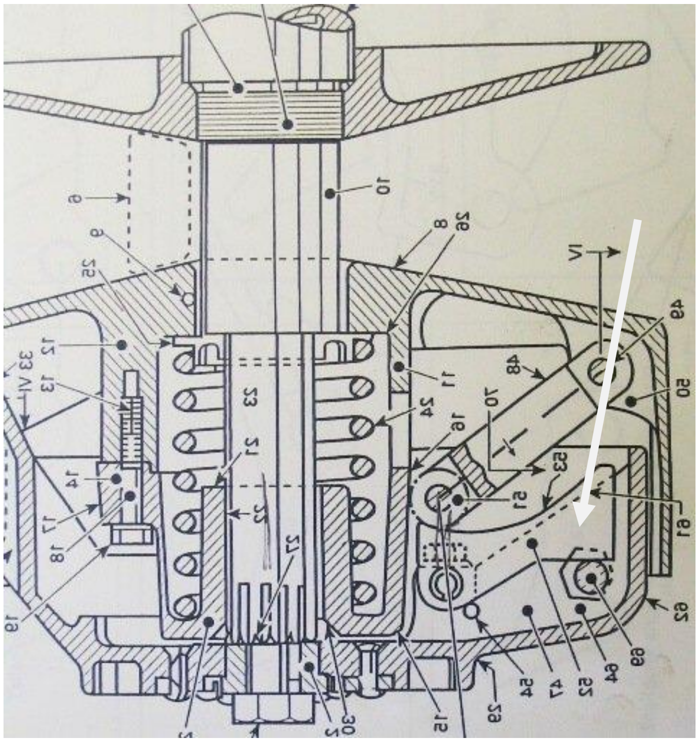

Figure 18. Cutaway of In the TRA clutch cutaway shows the ramp w is the curved object in the bottom right.

The team used the 441 ramp combined with a 889.6 N (200 lb) final force and 578.3 N (130 lb) initial force spring primary spring to minimize the engine braking effect and hold the maximum engine RPM to the peak output of the UICSC team 800 E-tec.

### *Weight*

The UICSC team has always strived to keep their machine light for several reasons. 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 had the snowmobile entering the 2014 SAE CSC competition weighing 263 kg (580 lbs) wet, the same as in 2013. The majority of the additional weight added over stock was sound absorbing material, which was used to meet other competition goals. Due to the implementation of the quarter wave resonator, a less dense sound deadening material was used on the exhaust side of the snowmobile, further reducing weight. Although this is slightly higher than the production snowmobile, it is still competitive with clean four-stroke snowmobiles. Shown in table 3 is a comparison of measured snowmobile weights at the 2013 CSC competition [12].

Table 3. Measured snowmobile weights at 2013 CSC competition

| University | Measured Total Weight<br>kg (lbs) |
|---|---|
| Idaho 2014 | 263 (580) |
| Kettering 2013 | 251 (554) |
| Madison 2013 | 271 (597) |
| Michigan Tech 2013 | 285 (629) |

## MSRP

The base price for a stock 2014 Ski-Doo MX-Z 600 E-TEC is $10,849. With all modifications included, the Manufacturer's Suggested Retail Price (MSRP) of the 2014 UICSC DI totaled $11,765. Chassis components that add to the MSRP were justified by sound reduction, increased performance, reduced exhaust emissions, and sponsor product awareness. The addition of equipment and components is minimal. This strategy allows the UICSC snowmobile to achieve a low MSRP and reliability on par with a stock snowmobile, while still being competitive with other clean snowmobiles.

## SUMMARY/CONCLUSIONS

The University of Idaho has developed a cost-effective flex fuel DI two-stroke snowmobile capable of running on B-16 to B-32 blended isobutanol/gasoline fuel. The DI two-stroke snowmobile maintains the mechanical simplicity and low weight avid riders enjoy, without sacrificing the clean and quiet characteristics necessary to meet current and upcoming standards. The UICSC design produces 85 kW (114 hp), is lightweight at 263 kg (580 lbs) wet, 12.99 l/100km (18.11 mpg) or 21.00 miles per gallon gasoline gallon equivalent using B32 fuel. Overall sound production, measured using the SAE standard J192, was reduced from 74.5 dBA to 71.5 dBA in eco-mode. The UICSC design achieves NPS emissions E-scores in both eco- and sport-mode, with eco-mode having an E-score of 203 while operating on B-32. Consumers expect snowmobiles that are clean, quiet, fuel-efficient and fun-to-ride. The 2014 UICSC dual-mode flex-fuel DI two-stroke reduced engine speed snowmobile is an economical response to that demand.

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## DEFINITIONS/ABBREVIATIONS

| | |
|---|---|
| **AFR** | Air Fuel Ratio |
| **BSFC** | Brake Specific Fuel Consumption |
| **CO** | Carbon Monoxide |
| **CSC** | Clean Snowmobile Challenge |
| **CTD** | Cumulative Trauma Disorder |
| **DI** | Direct Injection |
| **DOE** | Department of Energy |
| **EGT** | Exhaust Gas Temperature |
| **EMM** | Engine Management Module |
| **EPA** | Environmental Protection Agency |
| **FFT** | Fast Fourier Transform |
| **HC** | unburned hydrocarbons |
| **MSRP** | Manufacturer's Suggested Retail Price |
| **$NO_x$** | oxides of nitrogen |
| **NPS** | National Park Service |
| **PPM** | Parts Per Million |
| **RPM** | Revolutions Per Minute |
| **SAE** | Society of Automotive Engineers |
| **UICSC** | University of Idaho Clean Snowmobile Challenge |
| **WOT** | Wide Open Throttle |