University of Wisconsin – Platteville's Semi-Direct Injected Two Stroke Flex Fuel Snowmobile

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ABSTRACT

The University of Wisconsin-Platteville (UW-P), Society of Automotive Engineers (SAE), Clean Snowmobile Challenge (CSC) team, has re-engineered a snowmobile that is quieter, cleaner, and more fuel efficient while maintaining original equipment manufacturer (OEM) performance and reliability. This recreational vehicle is powered by a 2008 Rotax 600 high output (HO) semi-direct injection (SDI) engine installed in a 2008 Ski-Doo REV-XP chassis. The engine has the ability to operate on fuel ranging from 93 octane containing ten percent ethanol to 93 octane containing 85 percent ethanol. The two-stroke internal combustion engine has been modified with a MicroSquirt Engine Management System to allow for full combustion of any range of fuel from E-10 to E-85, while maintaining nearly the same stock power output of the engine. With the aid of a three way oxidation catalyst found after the exhaust silencer, the team was also able to greatly reduce emissions and noise output. These modifications on the team's snowmobile achieved UW-P's reliability, efficiency and noise goals in a cost-effective manner.

INTRODUCTION

Snowmobiling has proven to be a great winter past time as shown with industry sales reaching 163,753 units sold in 2008, along with the nearly 30 billion dollars generated worldwide annually [1]. The SAE, along with the Environmental Protection Agency (EPA), National Parks Service (NPS) and the Department of Energy (DoE), began the Clean Snowmobile Challenge in 2000 when the U.S. government banned snowmobile usage in National Parks. The CSC is an engineering design competition for university students. Student teams are given the opportunity to help advance the snowmobile industry by providing alternatives to current snowmobiles that have poor fuel economy, high toxic emission levels, and high noise levels. Entries in the CSC are tested on design strategies, emissions (CO, UHC and NO_x), economy, noise, rider comfort, handling, acceleration and cold starting abilities [2]. The 2009 CSC will require competing student teams to modify a production snowmobile to be reliable, efficiently run on any blend of ethanol/gasoline mixture between winter blend E-10 and E-85, and yet be marketable within the current snowmobile industry. Students will be showcasing their re-designed snowmobiles March 16-21, 2009, at the Keweenaw Research Center in Michigan's Upper Peninsula.

To be one of the elite teams to compete in the 2009 competition, the University of Wisconsin-Platteville team has re-engineered the best technology the snowmobile industry currently has to offer. The following paper describes Platteville's design strategy. The first section addresses the chassis and engine selection process. The second describes modifications to the snowmobile's engine and drivetrain and chassis. The third and fourth sections focus on emissions and noise reduction techniques. The paper itself addresses the combined modifications employed to optimize the aforementioned technologies, respectively. Finally, the paper summarizes the cumulative cost corresponding to a comparable stock production snowmobile.

PERFORMANCE

Practicality and simplicity are the guiding principles for UW-Platteville's clean snowmobile design. In order to successfully market to current snowmobile consumers, the team conducted a survey consisting of 105 snowmobile enthusiasts located in the Northern U.S. and Canada. This allowed the team to determine what qualities consumers deemed most important. The poll, which was conducted on the Hardcoresledder (HCS) forum, asked volunteers to rank the attributes important to them when considering the purchase of a new snowmobile. Emissions, fuel economy and performance/handling were the characteristics volunteers were asked to rate based on importance. Based on the results, which can be seen in Figure 1, performance/handling influence a buyer noticeably more than either fuel economy or emissions. The poll results verify the principles guiding the Wisconsin-Platteville Clean Snowmobile Team.

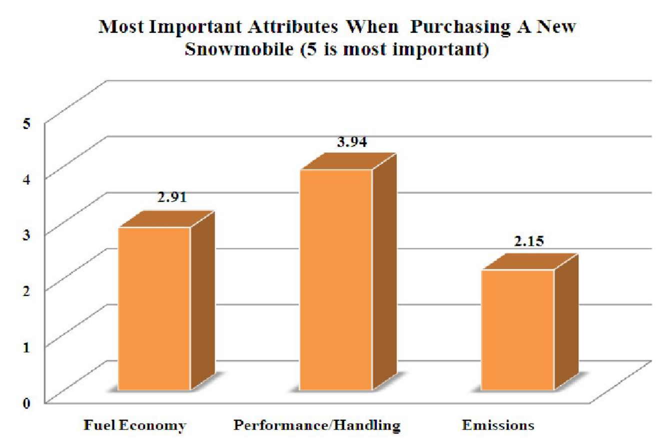

Figure 1: Results from a survey conducted on the Hardcoresledder website showing performance/handling is the most important attribute when purchasing a new snowmobile.

Snowmobile industry sales numbers for the 2007 model year further verify the poll results. Ski-Doo, a division of, Bombardier Recreational Products (BRP), exclusively builds high performance, lightweight two-stroke snowmobiles that have excellent handling and performance characteristics. As seen in Figure 2, Ski-Doo showed superior dominance in the market with 12.5% more total sales than Polaris, Arctic Cat or Yamaha [3].

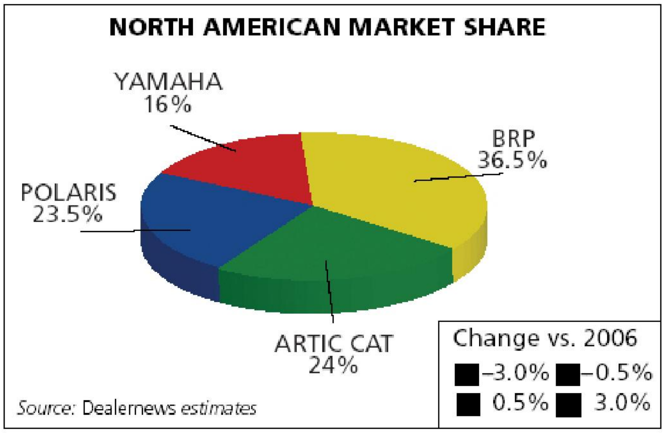

Figure 2: 2007 industry market share in US between the four snowmobile manufactures.

Engine Selection

Given that the market survey results showed that consumers demand a snowmobile that excels in performance and handling areas, the team searched for engines that had superior power to weight ratios. To assist in the engine selection process, the team conducted a second survey on Hardcoresledder, which had 120 volunteers share what powertrain arrangement their current snowmobile has, and the powertrain option they would most likely purchase as their next snowmobile. The options listed in the poll included: two-stroke carbureted, two-stroke fuel injected, four-stroke carbureted and four-stroke fuel injected. As seen in Figure 3, 49% of the participating volunteers stated their next snowmobile would be powered by a two-stroke, fuel injected engine.

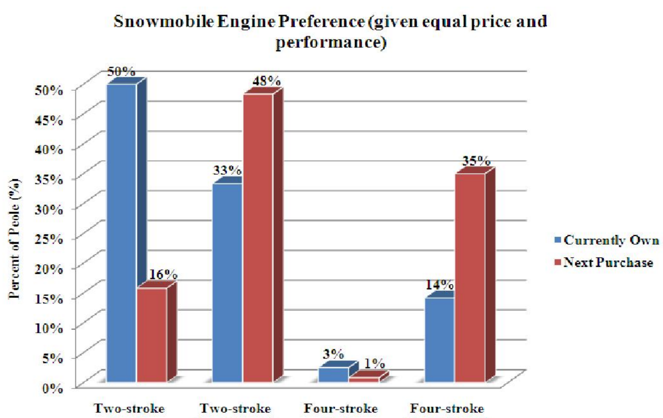

Figure 3: Results from a survey conducted on the Hardcoresledder website showing enthusiasts would prefer a two stroke fuel injected engine as their next snowmobile.

Other than 2007, in which a direct injected two-stroke proved to be more efficient, the past CSC competitions have proven a four-stroke engine can be used in snowmobiles to produce a clean, quiet, fuel efficient snowmobile [4, 5, 6, 7, 8, 9, 10]. Snowmobile emissions testing, performed by Southwest Research Institute (SwRI), also proves this point by stating that commercially available four-strokes "…emit 98-95 percent less HC, 85 percent less CO, and 90-96 percent less PM" than conventional two stroke snowmobile engines [11]. However, the demand for two-stroke powered snowmobiles is still very high due to their excellent power-to-weight ratio, and new technology continues to emerge.

With the recent development of semi-direct fuel injection, two-stroke snowmobiles have become capable of attaining fuel economy that matches or exceeds that of current production four-stroke snowmobiles, while still maintaining their light weight [7]. However, from an emissions standpoint, SDI two-strokes are still subpar in comparison to four-stroke engines. Table 1 shows the difference in emissions produced and fuel economy between carbureted two-stroke, electronic fuel injection (EFI) four-stroke, and semi-direct injection two-stroke snowmobile engines.

CSC Year Engine Type	C0 [g/kW-hr]	UHC [g/kW-hr]	NO_x [g/kW-hr]	Fuel Econ. [MPH]
'03 Two-Stroke Carbureted*	319.94	125.50	0.73	8.7
'04 Four-Stroke EFI*	99.84	11.48	23.33	15.3
'05 Two-Stroke SDI*	215.38	63.53	2.39	19.1

* Indicates snowmobile was control snowmobile

Table 1: Emissions and fuel economy of two and four-stroke snowmobiles at CSC [5, 6, 7].

The high specific outputs that exist in significantly less mechanically complex two-stroke engines allows for them to have higher performance qualities than comparable four-strokes. These higher performance qualities also allow for a more suitable torque curve for the belt-type continuously variable transmission (CVT) currently used in the snowmobile industry [11].

Final Engine Choice

Taking into account the previous information and the apparent potential to vastly improve emissions over production two-stroke engines, the Wisconsin-Platteville team decided to build a clean, quiet, high performance two stroke powered snowmobile. The most important part of the teams design was to maintain the engine's simplicity, low cost and excellent power-to-weight ratio while methodically reducing emissions and increasing fuel economy.

The engine the Platteville Clean Snowmobile Team decided to modify was a loop scavenged, semi-direct injection reed valve, 594 cubic centimeter (cc) Rotax engine. This engine is factory equipped with a tuned pipe and Rotax's Electronic Automatic Variable Exhaust (R.A.V.E.) system.

The Wisconsin-Platteville team chose this engine for multiple reasons. The powerplant is within the constraints of competition guidelines, delivers performance characteristics indicative of two-stroke snowmobiles, and is manufactured with parts that are readily available.

Final Chassis Selection

A 2008 Rev-XP chassis has been selected by the University of Wisconsin-Platteville CSC Team for the 2009 competition. Other than accepting the selected engine without hindrance, it is an extremely lightweight chassis with incredible trail ergonomics and excellent rider positioning. This rider forward position allows for eight additional inches of foot clearance over the 2007 Rev chassis. This is obtained by moving the secondary clutch and jackshaft from beside the tunnel to above the tunnel as shown in Figure 4. The additional foot room gives the rider better bump isolation and rider control.

Figure 4: Rider forward positioning of 2008 Rev-XP (outlined in blue) verses 2007 Rev (outlined in red) [12].

SYSTEM MODIFICATIONS

Engine

Our Rotax 2-Tec Semi Direct Injected (SDI) engine has a 72mm bore, 73mm stroke, and 46mm throttle bodies to provide optimum performance while staying within the 600cc displacement limit for two-strokes. Due to the naturally aspirated, twin-cylinder, Rotax 600 H.O. SDI's high power output and excellent reliability in stock configuration, the team concluded that the internal components of the engine need not be modified for the Clean Snowmobile Challenge.

Control Hardware

Considering Ski-Doo would not supply the proper interface to reprogram the stock SDI Electronic Control Unit (ECU) for flex fuel operation, Platteville is utilizing a MicroSquirt EFI controller with a closed loop feedback system to optimize fuel delivery. MicroSquirt is a fully assembled Surface Mount Technology (SMT) fuel injection controller designed solely for automotive applications. It utilizes a 35 pin AMPSEAL weatherproof connector and is also sealed in a weatherproof case. With an Ingress Protection (IP) rating of 54, the processor is protected against dust ingestion and liquid spray from any direction, respectively [13]. These characteristics; the MicroSquirt's physical size of 2.4" by 3.5", shown in Figure 5, and its ability to withstand temperatures from -40°C to 105°C make it quite suitable for under-hood installation.

Figure 5: MicroSquirt fuel controller.

MicroSquirt is equipped with an operating system developed by Bowling and Grippo, however, initial tuning parameters must be set for the particular engine that the MicroSquirt is installed on. MegaTune, a graphical software application, will run on any windows based computer and is used to configure, tune, and monitor the engine during the set up and testing period.

The stock ECU for the SDI engine was retained so that the OEM premium gauge package can be utilized. The team deemed the information provided by the factory gauge set to be necessary to any potential rider of the snowmobile. The stock ECU also incorporates a fail-safe mode, which enriches the air-to-fuel mixture when signals from one of several different sensors are outside of their normal operating range. This is a highly desired feature that can prevent catastrophic engine failure. The ECU also signals the possible problem by flashing an amber check engine light on the instrument panel in a coded sequence. This operation is supplemented by a loud "beep" which helps notify the rider that the engine has entered fail-safe mode [14].

Fuel System Modifications

In order to successfully run on any blend of ethanol based fuel as high as winter blend E-85, fuel system testing and modifications were required. Ski-Doo verified that the in-tank fuel pump installed in the team's 2008 chassis was ethanol compatible. Throughout the rest of the fuel system the fuel lines were changed to a SAE 30R9 ethanol approved line. Stainless mesh was wrapped around the new lines to reduce fuel line expansion during fuel system pressurization, i.e. while the sled is running. All other fuel system components were soak tested to verify compatibility with the blended ethanol fuel.

In order to achieve successful flex fuel operation the UWP CSC Team opted to install a Continental Flex Fuel Sensor, as seen in Figure 6. The sensor measures alcohol content in the fuel by utilizing a dielectric measuring principle [15]. The robust case and sensor element make it suitable for under-hood, off road use.

Figure 6: Picture of Continental Flex Fuel Sensor.

The fuel characteristics analyzed by the Continental Flex Fuel Sensor are supplied to the MicroSquirt controller. Instead of attempting to use fuel map correction tables to adjust fuel delivery, the engine management system bases its operations on the physics of combustion. Platteville configured the MicroSquirt controller to provide the 600 SDI engine with the proper air-to-fuel ratio (AFR) at all times.

While running an E-10 blend fuel, normally aspirated engines operate with a stoichiometric AFR near 14.7 to 1. E-85 has a smaller, lower heating value than gasoline resulting in a stoichiometric AFR around 10.7 to 1 [22]. The MicroSquirt controller continuously calculates the correct fuel injector duty cycle and resultant injection amount based on values it receives from the Manifold Absolute Pressure (MAP) Sensor, Intake Air Temperature (IAT) Sensor, Coolant Temperature Sensor, Throttle Position Sensor (TPS) and Continental Flex Fuel Sensor. Once the engine is base tuned using an engine dynamometer, the fuel system runs in a closed-loop configuration. At this point in time, the heated NTK Exhaust Oxygen Sensor, or lambda sensor, is activated, and becomes responsible for tuning the engine to run at a stoichiometric level. Using the Continental Flex Fuel Sensor's fuel density and alcohol content input values, optimal air-to-fuel ratios could be set and stored, making it possible to run the engine on any commercially available ethanol blend. From that point forward, the NTK heated wideband oxygen sensor could be used to adjust fuel injection amounts to provide stoichiometric values. This provided clean, efficient flex fuel power while reducing emissions.

Calibration

Engine calibration for Platteville's flex fuel 600 SDI was performed using a Land and Sea water brake dynamometer, NTK exhaust oxygen sensor, Digitron exhaust gas temperature sensors, and piston wash monitoring. Due to the total loss lubricating system used in this engine, two-cycle oil is burned with the gasoline and expelled via the exhaust system. This action reduced the initial accuracy of the lambda sensor. However, once rich/lean parameters were found, the lambda sensor provided valuable data that greatly assisted in the creation of a smooth flex fuel, fuel map and lower emissions.

Continuously Variable Transmission

A large factor in driveline efficiency with a variable ratio belt transmission is tuning the clutches to efficiently transmit maximum power from the engine to the track. The first thing that must be considered in clutch tuning is the engagement speed, which is shown as segment "A" in Figure 7. The engagement speed should at the lowest speed possible, without creating an engine bog. If the engagement speed is set too high, damage to drive components can occur and controlling the snowmobile can be very difficult.

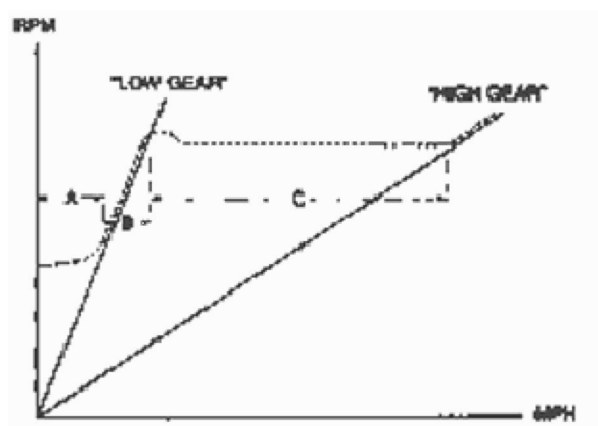

Figure 7: Properly Tuned Clutches (MPH vs. RPM) [16]

The secondary clutch, which is mounted on the jackshaft, uses a steeper initial angle on the helix, causing the secondary clutch to reach a full shift-out condition sooner. This allows for a higher top speed, lowers cruising engine rpm, and when adjusted properly improves fuel mileage. Subsequently, these two segments must also be adjusted in order to achieve the quickest acceleration. Segment "B" in Figure 7 is the low gear acceleration, and segment "C" is the up-shifting acceleration.

The most important aspect of clutch tuning is keeping the engine operating at a speed where it is the most efficient. With a reed valve, variable exhaust two-stroke engine, maximum efficiency occurs over a very short range of rpm's. In order for the engine to remain running in this range, the weights and springs on the crank shaft mounted primary clutch must be properly selected. Supplementing the adjustment of the primary clutch, the spring and cam angle on the secondary clutch must also be carefully selected to keep the engine operating at maximum efficiency during normal cruising and throughout the entire acceleration run [16].

Through trial testing and acceleration runs, the University of Wisconsin-Platteville Clean Snowmobile Challenge Team determined the stock 600 gearing and clutching to be sufficient for the competition.

Chassis and Body

A longer USI snow flap was installed in place of the OEM Ski-Doo snow flap. It was chosen for three reasons, the first being to comply with the challenge guidelines. The second was for safety. The longer, wider snow flap drastically reduces the possible deflection of trail debris and ice chunks, which could be thrown at other challenge competitors or enthusiasts. The final benefit is reflected by lowering engine coolant temperatures. Since there is no gap underneath the snow flap with a rider positioned on the sled, any snow kicked up by the track will bounce off the snow flap and promptly be returned into the tunnel, resulting in more efficient cooling and lower coolant temperatures.

The Platteville CSC Team also created a non-conductive battery box. Produced on a rapid prototype machine, this material is a thermoset plastic with increased strength and rigidity due to an epoxy coating applied after the molding process. The battery box was designed with safety in mind, with the objective being to completely eliminate any possibility of arcing between the battery and chassis. The battery box insulates and protects both terminals from any outside contact. The SolidWorks drawing used to produce this part by the rapid prototyping machine can be seen in Figure 8.

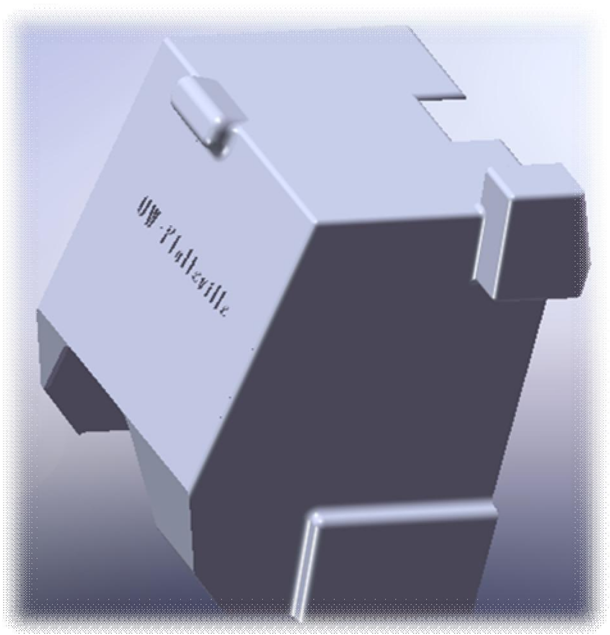

Figure 8: Plastic Rapid Prototyped Battery Box

Track and Suspension

The Ski-doo SC-5 suspension features the use of aftermarket slides. Hiperfax slides utilize Teflon inserts that improve driveline performance by reducing friction between the rails of the skid frame and the track. This reduction of friction is accomplished by the Teflon coating spreading onto the track clips in order to create a Teflon-to-Teflon contact area while rotating. Most standard plastic slides have a melting point near 150°C. Hiperfax claims their slides maintain the structural integrity, until around 375°C [17]. The lower kinetic friction and higher melting point of the slides reduces the possibility of material failure in poor snow conditions.

To make the effective kinetic friction between the slides and rails as insignificant as possible, the team is running Slydog idler wheels. As seen in Figure 9, this fan blade design allows the front two idler wheels to direct snow and air onto the slides, providing lubrication and cooling. Reversing the fan blade direction in the track tensioning rear wheels allows for the dismissal of snow and warm air from the skid to greatly reduce unwanted snow and ice build-up [18].

Figure 9: Slydog Fan Blade Design (Left shows rear wheel, right shows front wheel) [18].

The combined effort of the Hiperfax slides and the Slydog idler wheels minimizes kinetic friction and heat buildup, therefore increasing driveline efficiency. Minimal fuel mileage gains were recorded by the team due to a smaller coefficient of friction.

EMISSIONS

The two-stroke engine is used to power recreational vehicles such as snowmobiles. As previously stated in this paper, two-stroke engines have a much higher power-to-weight ratio than comparable four-stroke engines. However due to the mechanics of the two-stroke, it can have a much larger carbon footprint compared to a similar powered four-stroke.

Over the years many design modifications have been made to improve efficiency as well as emission output of two-stroke engines. However, simultaneous introduction of fuel and release of exhaust gases leads to loss of unburned hydrocarbons, and ultimately higher emissions output than comparable four-stroke engines. This problem is enhanced because two-stroke engine fuel normally consists of a mixture of gasoline and a petroleum lubricant. The latter material has a higher average molar mass, and is therefore less efficiently oxidized during the combustion process than the lighter gasoline.

A positive aspect of the two-stroke engine design is that combustion takes place at a lower temperature than a conventional four-stroke engine. The lower combustion temperature, leads to an exhaust gas composition that is relatively low in nitric oxide emissions, but high in oxygen and hydrocarbons emissions.

Some two and four-stroke engines are now being manufactured with similar power output and therefore it has become possible to make comparisons of emissions between different stroke engines under similar operating conditions. Table 2 shows exhaust composition on 7.3 kW outboard engines.

Outboard Motor Exhaust Gas Output (10^{-8}g J^{-1})			
Engine Type	CO	NO_X	Hydrocarbons
Two-Stroke Engine	165	0.3	89
Four-Stroke Engine	127	0.7	7

Table 2: Comparison of two-stroke engine verses four-stroke engine exhaust gas output [19].

The previously noted effects are confirmed in this data, showing that the two-stroke engine emits a comparatively high amount of hydrocarbons but a relatively low amount of nitrogen oxides.

The University of Wisconsin-Platteville Clean Snowmobile Team lowered these emissions through use a of a three-way emission catalyst. The three-way emission catalyst, supplied to the Team by Aristo Inc., is capable of reducing three types of emission products namely, hydrocarbons, carbon monoxide, and nitric oxide. For max reduction of exhaust gas outputs, this system requires the combustion process to occur at stoichiometric conditions. Exhaust gases then pass through and interact with two catalysts working in series with one another.

The exhaust gas will first pass through a Rhodium catalyst. This facilitates the reduction of the nitrogen oxides to maximize the formation di-nitrogen. The exhaust gas is then passed over a second catalyst made of Palladium. This part of the catalyst reduces the residual hydrocarbon and carbon monoxide gas remaining after passing through the first Rhodium catalyst. The use of efficient three-way catalyst systems serves to reduce emissions of the three problem gases by 80% or more.

The effects of engine optimization and catalysts on release of CO, NO_X, and hydrocarbons from a 125cc two-stroke motorcycle engine output (g*km^{-1})			
Engine	CO	NO_X	Hydrocarbons
Production Engine	21.7	0.01	16.9
Optimized Engine	1.7	0.03	10.4
Engine with Catalyst	0.8	0.02	1.9

Table 3: Two-stroke engine output [20].

BONX Process Formulation Technology, used in our catalyst, allows for an innovative proprietary washcoat, which provides for more consistent coating characteristics. Aristo also uses MISO Process Coating Technology, effectively minimizing part handling through the innovative use of automation and robotics, leading to the most consistent and predictable loadings. The density of the catalyst used on Platteville's snowmobile is 200 cells per square inch (cpsi). This allows for consistent airflow through the catalyst and minimal back pressure, allowing consistently smooth engine operation.

Emission numbers for the 2009 Platteville CSC snowmobile were not finalized at the point the design paper was submitted. However, Wisconsin-Platteville CSC Team assures they will be competitive in the emissions event no matter what petroleum based ethanol blend fuel is selected.

NOISE

Implementing SAE test procedure J192, the team noted an average dBA score of 81.3 through the stock exhaust and noise damping materials provided. After the additional exhaust pipe was installed to incorporate the Aristo catalyst results were yielding an average J192 score of 79.6 dBA. Sound deadening materials have since been strategically placed throughout the engine bay to reduce mechanical noise. Optimizing the outlet location and angle of our exhaust system should also aid in noise reduction. Unfortunately, further testing was not completed with the addition of these sound damping techniques prior to the submission of this paper.

COST ESTIMATE

Advancements in technology currently implemented in the automotive industry are finally making their way into the snowmobile and recreational vehicle industry. However, utilizing these advancements have continued to increase the cost of snowmobiles on a yearly basis. The Manufactures Suggested Retail Price (MSRP) for a stock 2009 Ski-Doo MX-Z TNT Rotax 600 H.O. E-TEC is $9,649.99. After the modifications the Wisconsin-Platteville Team did the MSRP would be raised $3,447.64 to a total of $13,097.63. Justification on the increase in the MSRP is shown in its flex fuel capability, chassis modifications to improve safety, and additional components used to reduce emission and noise outputs.

CONCLUSION

Through extended research and development, the University of Wisconsin-Platteville has produced an economical and environmental friendly snowmobile with the ability to run on any production ethanol blended fuel. While maintaining the manufacturer's performance and durability, the team was able to surpass the EPA's 2012 emission standards with the aid of a three-way catalyst. Additionally, the Rotax 600 SDI two-stroke maintains its fuel economy of up to 18 mpg by utilizing a MicroSquirt Engine Management System in conjunction with a Continental Flex Fuel sensor. With the modifications the University implemented, the 2008 SnowGoer Magazine Snowmobile of the year now not only emits fewer combustion byproducts but allows consumers to run it on any combination of fossil and ethanol fuels [21].

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