2-17-2014

Designing a Clean, Quiet, Fuel Efficient High Performance Four- Stroke Flex Fuel Snowmobile

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ABSTRACT

The University of Wisconsin-Platteville Clean Snowmobile Challenge (CSC) Team has successfully designed and constructed a quiet, efficient, and environmentally friendly snowmobile. The snowmobile is designed for the 2014 Society of Automotive Engineers (SAE) Clean Snowmobile Challenge, held at the Keweenaw Research Center, in Houghton, Michigan, March 3rd - 8th 2014. The snowmobile for this year's competition is built on the 2014 Arctic Cat ZR 7000 LXR chassis, which features a 1049cc, three cylinder, 4-stroke engine. The engine control system, from Performance Electronics (PE), is a stand-alone engine control unit (ECU). This gives our team complete control over the engine parameters to achieve a decrease in exhaust emissions and an improvement in fuel economy. The muffler system is modified to further reduce the emissions by utilizing a pre-burn catalytic system, custom made by Tikka Race (TR). Driveline improvements were another significant factor for improving fuel economy; these modifications helped to achieve UW-Platteville's goal in producing a quiet, reliable, and efficient snowmobile.

INTRODUCTION

It is crucial to design snowmobiles to utilize the best available technology. With total 2013's sales increasing by 12%, to a total of 144,600 units worldwide, it is clear that snowmobiling is becoming more popular [1]. As the sport grows, it is met with pressure from the Environmental Protection Agency (EPA) to lessen these machines' environmental impact. This is broken into categories such as: carbon footprint, noise pollution, and fuel efficiency. The most notable of these new regulations was the Yellowstone National Park's ban of snowmobiles in the year 2000.

In an effort to lessen the negative environmental impact caused by the snowmobile industry, SAE teamed up with Teton County Wyoming Commissioner, Bill Paddleford, along with environmental engineer, Lori Fussell, to start working on an innovative solution. Their combined efforts resulted in the first SAE Clean Snowmobile Challenge, in 2000 [2]. The CSC was, and still is, an international collegiate event, aimed at improving on the designs of current snowmobiles, with the best available technology. After a year of hard work, teams gather in Houghton, MI to showcase their efforts. The CSC competition standards are more stringent than those currently set by the EPA, the National Parks Service (NPS), and the Department of Energy.

The competition is continuously improved from year to year. This year's notable change is the specification of corn-based bio-isobutanol fuel, within the range of 16% to 32%. Bio-isobutanol is a renewable additive that can replace petroleum based fossil fuels. A benefit of isobutanol is that it contains approximately 30% higher energy content compared to ethanol. According to the bio-fuel company GEVO, "[Isobutanol] has a lower propensity for phase separation in the presence of water and has no stress corrosion cracking compatibility or elastomer incompatibility issues."[5] These characteristics indicate that isobutanol is a better alternative fuel than ethanol, due to the fact that it is less harsh on fuel systems.

Implementation of new flex-fuel systems and efficient design strategies, the CSC is grooming the way for future snowmobiles. Design objectives are as follows: improving emissions, fuel economy, noise, ride comfort, handling, acceleration, and cold starting abilities. This CSC event has encouraged the recent ruling on snowmobile use in Yellowstone National Park, which allows up to 500 snowmobiles into the park each day [6]. The following paper outlines the UW-Platteville CSC Team's efforts for designing and building such a snowmobile.

DESIGN OBJECTIVES

To be an elite competitor in the 2014 Clean Snowmobile Challenge, the UW-Platteville CSC Team has refined the best 4-stroke snowmobile technology the industry has to offer. The team's main goal is to improve fuel efficiency. Competitors participate in two different events to gauge fuel economy. The first test coincides with the 100 mile (160 km) endurance event. 100 points will be awarded to each team that successfully completes the mileage requirement. Points beyond 100 will be awarded to teams based on their comparative fuel economy. These additional points are awarded relative to the performance of other teams, which completed the event. The additional points are calculated by Equation 1 [3]:

$$\text{Team Score} = 100 * \left[\frac{\left(\frac{\text{G}_{\text{max}}}{\text{G}_{\text{team}}}\right)^2 - 1}{\left(\frac{\text{G}_{\text{max}}}{\text{G}_{\text{min}}}\right)^2 - 1} \right] \quad (\mathbf{1})$$

G is the number of gallons of fuel consumed

The second measurement for fuel economy is conducted during the in-service emissions event, described later. Scores for this event range from zero to 50; similar to the endurance run scores and are based on the performance of other teams. Points for this event are awarded according to Equation 2 [3].

$$\text{Team Score} = 50 * \left[\frac{\left(\frac{\text{FE}_{\text{max}}}{\text{FE}_{\text{team}}}\right)^2 - 1}{\left(\frac{\text{FE}_{\text{max}}}{\text{FE}_{\text{min}}}\right)^2 - 1} \right] \quad (\mathbf{2})$$

FE is the Fuel Economy measured in the event.

The team's second goal was to reduce Hydrocarbon (HC) and Carbon Monoxide (CO) emissions, without increasing the emission of Nitrous Oxides (NO_x). The fuel, chosen by CSC staff, is an unknown blend ranging from 16% to 32% of isobutanol and gasoline. Emission testing is performed during two events, the first of which is an in-service emissions test. During this procedure, a test sled is coupled behind the snowmobile and tailpipe emissions are recorded by the sled. The event effectively determines the total gaseous emissions of the snowmobile during a realistic trail ride. Competition organizers operate the snowmobiles on a three mile course (4.8 km), while the test trailer records grams of HC, CO, CO_2, and NO_x produced. The total weights of emissions are compared between the best and worst competitors to determine a score, based on a range of 0-50 points.

The second emissions event is a lab test performed when the snowmobile is connected to a dynamometer. This is a static test, where the engine is operated under predetermined conditions and emission levels are recorded. The test modes for the lab emissions follow a five-mode test cycle, as published by Southwest Research Institute (SwRI) [4]. Table 1 shows the speeds, loads, and weighting factors for the five-mode test.

Table 1: The five-mode snowmobile test procedure used by the EPA and NPS.

Mode Point	Speed [% of Rated]	Torque [% of Rated]	Weighting [% of total]
1	100	100	12
2	85	51	27
3	75	33	25
4	65	19	31
5	Idle	0	5

From the lab measured emissions, an EPA snowmobile emission number (E) can be calculated. This E-score is determined from the operating points of **Error! Reference source not found.** by calculations using Equation 3 [4]. A minimum E-score of 100 is required to meet the corporate 2012 and later snowmobile emission standards. Points in excess of 100 are awarded to teams who beat the minimum EPA requirements. The E-score is calculated as follows.

$$E = \left[1 - \frac{(HC + NOx) - 15}{150}\right] * 100 + \left[1 - \left(\frac{CO}{400}\right)\right] * 100 \quad (\mathbf{3})$$

Further requirements state that the average weighted emissions for $HC+NO_x$ must be less than 90 g/kW-hr and less than 275 g/kW-hr for CO. As an incentive to meet the harsher National Parks standards, E-scores beating 170 are given additional points based on a linear scale. Lastly, soot will be accounted for and must never exceed 100 mg/kW-hr.

Noise emissions were also a high priority for the team, as both objective and subjective events are conducted at the competition. The objective noise test procedure follows the SAE J192 recommended practice. During the test, sound pressure created by the snowmobile cannot exceed 78 dB, which is the standard set by the International Snowmobile Manufacturers Association (ISMA). To account for environmental variations, a control sled will be used to adjust the 78 dB pass/fail limit if necessary. Teams receive points based on an exponential scale of 0 to 150, which corresponds with the control sled and the best performing machine.

For the subjective noise test, recordings of the snowmobiles taken during the objective test are played back and reviewed by a jury of CSC volunteers. The team with the most favorable subjective noise is awarded 150 points, while the least favorable score receives zero points.

Achieving the main goals of economy, emissions and noise, would be a hollow victory if the cost, performance, or comfort of the snowmobile were unreasonably compromised. Although they are not the main focus of the CSC; teams compete in acceleration, subjective and objective handling, and cold start events. These parameters are used to gauge performance and handling characteristics of the snowmobiles.

In the acceleration event, all snowmobiles must complete a 500 ft. (152 m) course in less than twelve seconds. Based on two attempts, each team's fastest time is used for scoring this event. The quickest team is awarded 50 points, while the other teams receive points based on their relative performance.

The handling events are closely related and used to gauge the snowmobile's agility and maneuverability. For the objective test, a team member completes individually timed, consecutive laps on a designated course. The fastest team receives 75 points. During the subjective handling event, professional snowmobile riders drive each vehicle and evaluate ride quality and comfort. The winning team will receive 50 points, with the other teams receiving points based on their relative scores.

A cold start test is also performed at competition; this event is performed to keep design solutions appropriate for the harsh environments which consumer snowmobiles must experience. In order to pass the event, and receive 50 points, snowmobiles need to start in twenty seconds. After starting, machines have two minutes to traverse 100 feet (30.5 m) without stalling.

An oral presentation and static display event are hosted by student teams in order to explain their particular solutions. The presentations explain how the teams met the requirements of the environment, the dealer, and the consumer. They are a showcase of the design process and highlight how the teams were able to overcome the challenges which they were given.

ENGINE SELECTION

The UW-Platteville CSC Team decided to modify a snowmobile that would excel in performance and handling. The efficiency of the modern 4-stroke fuel injected engines compelled the team to investigate ways to make them even cleaner while retaining a high level of performance. In previous events 4-stroke engines have proven to have lower emissions and to be fuel efficient. While these engines have established themselves firmly in the competition, to the UW-Platteville team has seen them as lacking the most important quality, “the fun factor.”

The search led the team toward the Yamaha Genesis 130FI, a 1049cc fuel injected, three cylinder, 4-stroke, as seen in Figure 1. With throttle body electronic fuel injection precise fuel metering delivers fuel efficiency. Furthermore this engine’s power and torque delivery exceeded the team’s definition of fun.

Figure 1: Yamaha Genesis 130FI Engine

The Genesis 130FI is equipped with three separate throttle bodies, which allows for near-instant off-idle throttle response. The use of fuel injection allowed Yamaha to develop an Engine Braking Reduction System (E.B.R.S), which permits the snowmobile to coast when the throttle is released, performing similar to a 2-stroke snowmobile. The E.B.R.S. is imperative to a smooth deceleration and a traditional snowmobile feel. The E.B.R.S works by allowing small amounts of air to pass through the fuel injection system, therefore reducing engine braking. Although the Genesis 130FI is new to the ProCross chassis, it has been proven to be reliable and durable in the Yamaha Nytro models.

The Genesis 130FI has a great balance of power, fuel efficiency, and weight which make it one of the most dominant 4-stroke engines on the market. This engine was a great platform to build modify.

Engine Management

The Arctic Cat ECU was replaced by the PE3-8400, from Performance Electronics. The ECU works with almost any engine, and has the ability to adjust fuel and ignition parameters. The team elected to work with this system because it is a stand-alone unit, enabling 100% tune-ability. Parameters were set to compensate for flex-fuel along with other engine operating conditions. An example of the PE system is shown in Figure 2.

Figure 2: Performance Electronics PE3 ECU

Implementing the PE required re-wiring the snowmobile. This also allowed the team to add a wireless router. The router connected with the PE, allowing the snowmobile to be tuned. This added convenience enabled real-time tuning during operation.

CHASSIS SELECTION

The UW-Platteville CSC Team has selected the Arctic Cat ProCross chassis as a base for the 2014 competition. See Figure 3 for chassis illustration. The ProCross chassis is made up of an inner and outer-formed shell with a boxed support structure. This makes up a two-piece tunnel, saving weight and giving additional strength [7]. The ProCross chassis has large running boards to accommodate different riders and massive holes to keep snow from building up. For strength Arctic Cat used a triangular design, which also reduced weight.

Figure 3: Arctic Cat ProCross Chassis

BRAKE SYSTEM

To increase stopping efficiency and safety, an aftermarket brake was installed. The Hayes *Trail Trac 1.0* functions as an Antilock Braking System (ABS). The system uses an electronically controlled single hydraulic cylinder to modulate brake line pressure. The computer determines when slip is likely to occur and adjust brake pressure accordingly. The result is an improved braking performance and vehicle control. In addition to improved deceleration, Continuously Variable Transmission (CVT) disengagement is prevented, allowing for quicker throttle response by keeping the driveline in motion. To validate the brake system modification, the UW-Platteville CSC Team conducted straight line deceleration tests on two different types of surfaces, sugar snow and ice, to compare the stopping distance with and without the ABS activated. It was determined that the Hayes system improved stopping distance by an average of 12 percent. The team's overall opinion was that the braking feel was improved.

DRIVELINE

To increase driveline efficiency, the seven inch diameter stock rear idler wheels were replaced with ten inch wheels, as seen in Figure 4.

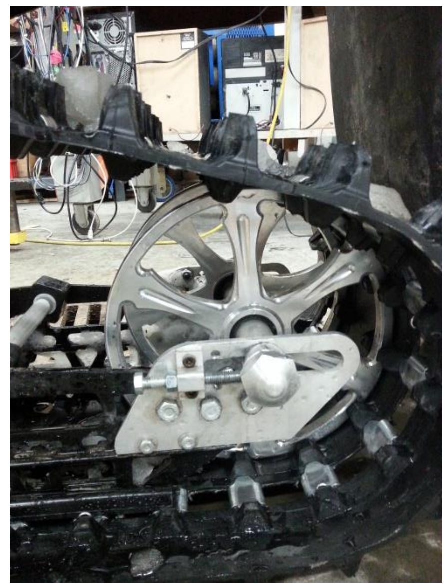

Figure 4: Ten inch wheels with 136 inch track

The larger diameter wheels reduce the angular acceleration of the track since it follows a larger radius. By following the enlarged radius the amount of track deflection is reduced, minimizing the energy consumed to bend the track. Based on the same principle the team also installed a set of larger ten tooth track drivers to replace the stock nine tooth drivers. To compensate for the larger geometry, a 136 inch track replaced the stock 129 inch track. A survey was conducted which asked participants what features would be preferred in a new snowmobile. The results, shown below in Figure 5, indicate the most desired track size. The 136 inch track was most popular with 56 percent of the vote. This information supported the decision to implement a 136 inch track.

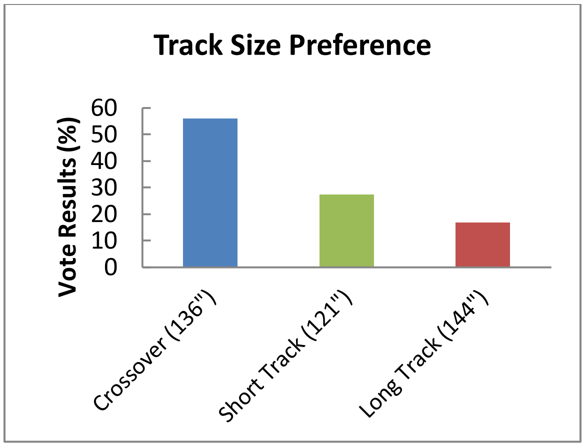

Figure 5: Survey results for track size preference.

In replacement of the conventional chain case, a belt and pulley drive system from C3 Powersports was tested and utilized. The advantages of the belt drive system include an eleven pound overall weight reduction, an eight pound decrease in inertia without requiring lubrication. This resulted in overall maintenance and environmental savings. A 2.5:1 gear ratio was chosen to maintain near stock gear ratios, while allowing for the largest pulley diameters possible so as to decrease the angular acceleration of the belt. In addition, Polaris claims that their comparable belt drive system will reduce the required gyroscopic force by 21 percent. This shows that the industry is starting to switch from the traditional chain case system to a more efficient belt drive. [9]

Last year a chassis pull test was conducted to measure rolling resistance through the driveline. For this test, the snowmobile was pulled on asphalt by a winch, for a specified distance, while the force required to pull the sled was measured. The skis were removed and replaced with wheels so that the effect of the skis would not compromise driveline data. Upon analyzing the data, shown in Figure 6 in the Appendix, it was found that under stock conditions the force required to maintain motion was 82 lbs. The greatest reduction in force from a single modification came with replacing the stock chain and gears with a belt and pulley combination. This modification resulted in a force of 53 lbs. required for motion.

A second driveline test was to connect a handheld drill to the snowmobile driveline. By turning the jackshaft, the amperage draw of the drill was measured. Hoisting the chassis up, the track was held off of the ground, and the free hanging system was analyzed. With this approach any change in the friction of the driveline would change the amount of power drawn by the drill. A series of measurements were recorded when the track reached steady state conditions. Experimental values of each set up are shown below in Table 2.

Table 2: Driveline tests conducted with an electric drill.

Driveline Drill Test Data		
Type of Drive	Chain Drive	Belt Drive
Average Total Amps	4.376	3.432
Horsepower Lost	0.719	0.564
Efficiency vs. Chain Drive	0%	22%

Using the equation below the stock driveline absorbed 0.72 horsepower. The C3 PowerSports' belt drive system was tested under the same conditions and the power was reduced to 0.56 horsepower. As shown in Table 2, the C3 PowerSports' belt drive was 22% more efficient than the chain drive, making it a clear choice for the team to implement.

$$\text{Horsepower Lost} =$$

$$(115\text{ Volts}) * (\text{Amps})\left(0.001341\,\frac{\text{Hp}}{\text{Watts}}\right) \quad \textbf{(4)}$$

As a final test to prove the modifications to the driveline, the team decided to run a real world driveline tests measuring throttle position (TPS). A Logger Pro handheld data acquisition device was connected to the TPS monitoring the change in voltage. The test speed was a constant 25 mph, and a stock control test was performed. The following variations were tested: belt drive system, big wheel kit, and DuPont Teflon slides. Results of the tests can be seen in Table 3. The combination of all these components resulted in a 13% reduction of throttle position, achieving higher efficiency. These results decided the competition setup.

Table 3: Driveline tests at a constant speed measuring throttle position, compared to stock.

Modification	% Reduction of TPS
Belt Drive System	9.26
Big Wheels/10 Tooth Drivers	2.12
DuPont Teflon Slides	1.71
All Modifications Combined	**13.1**

SUSPENSION & HANDLING

Skis, carbides, track selection, and the suspension system all have an impact on the handling of a snowmobile. When all of these components are set up and tuned correctly, the result is a highly tuned, comfortable ride.

The Arctic Cat ZR 7000 LXR chassis is equipped with adjustable front and rear shocks allowing the suspension to be tuned to the rider's preference. Arctic Cat's new Slide-Action Suspension uses a revolutionary design which allows for more traction through rough terrain. When a conventional coupled suspension compresses in the rear of the skid, lost motion occurs causes the front of the skid to lift off the ground, resulting in a loss of traction. The Slide-Action Suspension allows for the total track footprint to reach the ground, even when riding through rough terrain. Since the front arm of the Slide-Action Suspension skid is not coupled, it allows the lost motion to be transferred to the front skid arm. This results in the skid arm sliding back freely and allowing the front of the skid to drop to the ground, achieving maximum traction. The action of this system is shown in Figure 7.

Figure 7: Arctic Cat Slide-Action Rear Suspension [8]

To improve the trail handling of this snowmobile, the stock skis were replaced with C&A RZ skis. These offer V-shaped keels to eliminate darting. A six inch carbide setup was chosen to provide positive steering through corners, increased handling on ice, and aggressive trail riding.

The Camoplast Ice Attak XT track was chosen for the benefits of in-lug studs, which provide added traction without adding weight. This track is single-ply, meaning increased flexibility, and fully clipped windows allow the use of extravert drivers. These drivers help eliminate ratcheting when the track is under low tension.

EMISSIONS

For the first time, the UW-Platteville CSC Team will be using a 4-stroke engine. One of the positive aspects of the 4-stroke engine is the reduced emissions over 2-strokes. A 4-stroke engine burns fuel more efficiently producing less air pollution, while increasing fuel mileage without consuming oil. These are the reasons why the UW-Platteville Team chose a 4-stroke.

Tikka Race supplied a pre-burn catalytic system for the team. In previous years the UW-Platteville CSC Team has had success with Tikka Race's proprietary, unique solutions. Tikka Race specializes in fitting carbureted and fuel injected 2-stroke and 4-stroke engines with pre-burn catalytic systems.

An overview of the new system has an inlet which leads to a pair of pre-burn catalysts. These converge into the main catalyst chamber where ignition of the unburnt fuel takes place.

NOISE

Noise pollution is a very important factor in today's trail system. Strategies for the reduction of noise were the implementation of sound deadening materials, and the development of a post-catalyst muffler. This muffler was developed through an inter-team design competition, the goal of which was to minimize exhaust noise.

To select sound deadening material, a noise sample was taken of the snowmobile at 6000 RPM. This noise sample was played back from a speaker enclosed in a box. This box was covered with various materials and a microphone recorded noise emitted from the box. Figure 8 illustrates the test set up. The UW-Platteville CSC Team ran four decibel tests with the hand held Logger Pro system and selected the quietest material.

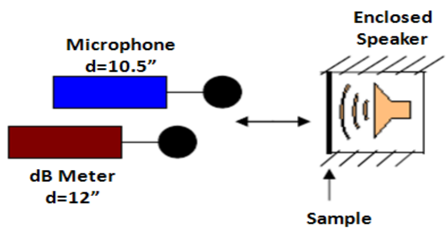

Figure 8: Schematic of the material-sample test configuration

Having selected the best material, additional tests were performed to see how much sound could be mitigated. A set of panels were covered with the sound deadening foam, and set were left untreated. The snowmobile was driven past a decibel meter and a sound recorder at a distance of 50 feet. The resultant frequencies were displayed on a Fast Fourier Transform (FFT) graph, which graphs every frequency picked up by the microphone. By comparing the graphs from each session, there was a noticeable reduction in frequency vs. amplitude with each change. Three tests were performed at 25 mph. The first test was run with the stock exhaust can, and without any side panels. The second test was conducted with the catalyst and secondary muffler, again without side panels. The third test was done with the POLYDAMP® Melamine Foam on the side panels in addition to the catalyst and secondary muffler. Test one was measured to be used as a baseline for the addition of the side panels with the POLYDAMP®. Refer to figures 12, 13 and 14 in the appendix for the graphical representation of the FFT to visually see the reduction in particular frequencies for the three tests.

Noting the results of this controlled test, the UW-Platteville CSC Team chose to place Polymer Technologies POLYDAMP® Melamine Foam inside the panels because of its high heat tolerance and significant sound reduction.

The secondary muffler which won the team competition was designed by creating four distinct chambers in series, inside a three inch exhaust pipe. The muffler incorporated a center dump exhaust inlet from which the exhaust flows through perforated stainless tubing. The second chamber has three resonator cones covering the inlets of three more perforated stainless tubes, which are wrapped with a fiberglass packing material. The third chamber was a larger perforated stainless tube wrapped again with fiberglass packing. The exhaust exits through the fourth chamber where a large diameter perforated tube was wrapped with fiberglass insulation as well as a small diameter tube inside stuffed with insulation. The combination of these different chambers, resonators, and fiberglass packing was sufficient to reduce exhaust noise from a stock sound reading of 80 dB down to a final sound reading of 76 dB. Sound readings were comparable but muffler fitment was an issue.

CONCLUSION

Through extensive research and development, the UW-Platteville CSC Team has produced a snowmobile that is performance oriented and environmentally conscious. The aforementioned modifications have created a snowmobile that meets or exceeds the required standards. The team was able to deliver a snowmobile consisting of ample power, excellent handling and improved economy. Furthermore, this snowmobile not only meets the EPA's emissions standards set in 2012 but surpasses them. The team was able to make these improvements with only an estimated added cost of $3,412 over the stock snowmobile for a total of $15,411.

ABBERIVATION

Clean Snowmobile Challenge (CSC)

Society of Automotive Engineers (SAE)

Performance Electronics (PE)

Engine Control Unit (ECU)

Tikka Race (TR)

Environmental Protection Agency (EPA)

National Parks Service (NPS)

Hydrocarbons (HC)

Carbon Monoxide (CO)

Nitrous Oxides (NO_x)

Southwest Research Institute (SwRI)

International Snowmobile Manufacturers Association (ISMA)

Engine Braking Reduction System (E.B.R.S)

Antilock Braking System (ABS)

Continuously Variable Transmission (CVT)

Throttle Position (TPS)

Fast Fourier Transform (FFT)

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ACKNOWLEDGEMENTS

The University of Wisconsin-Platteville Clean Snowmobile Challenge Team would like to thank our sponsors: Wisconsin Bio-Industry Alliance, University Of Wisconsin-Platteville SUFAC, University of Wisconsin-Platteville SAE-Baja, University of Wisconsin-Platteville SAE-Formula, Nick's Powersports, Millennium Technologies, Kohn's Auto Body, Fastenal, Goodwin Performance, HMK, Signs-to-Go, University of Wisconsin-Platteville Mechanical Engineering Department, University of Wisconsin-Platteville Electrical Engineering Department, University of Wisconsin-Platteville Physics Department, R & R Trailers, CVTech-AAB, Association of Wisconsin Snowmobile Clubs, Tikka Race, and many others who made this project possible.

Appendix

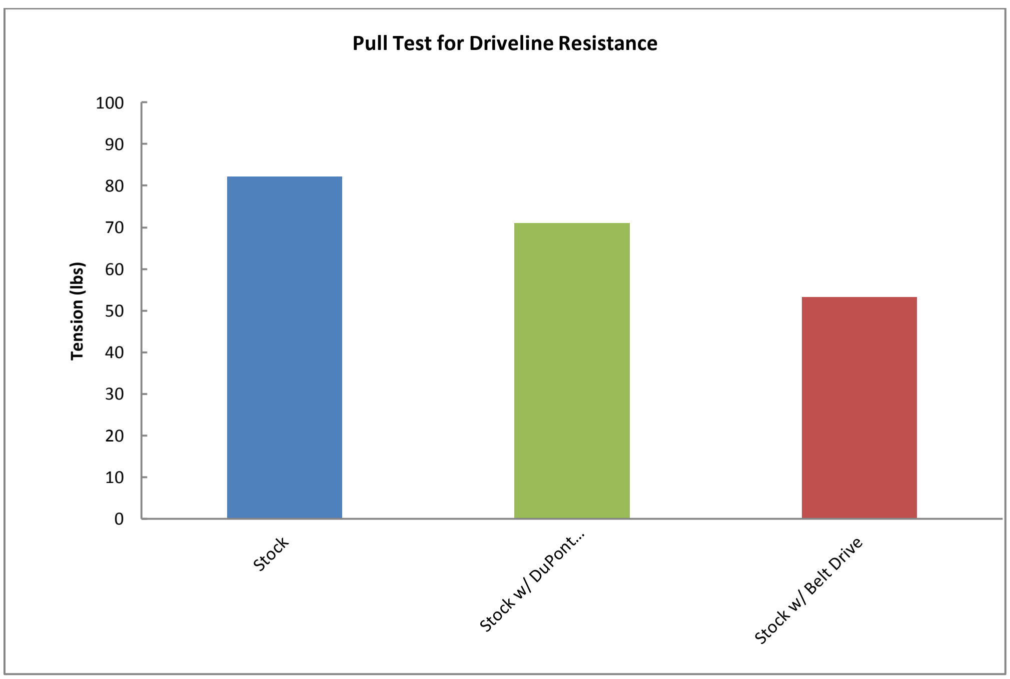

Figure 6: Chassis Pull Test results with multiple setups contrasting with stock setup.

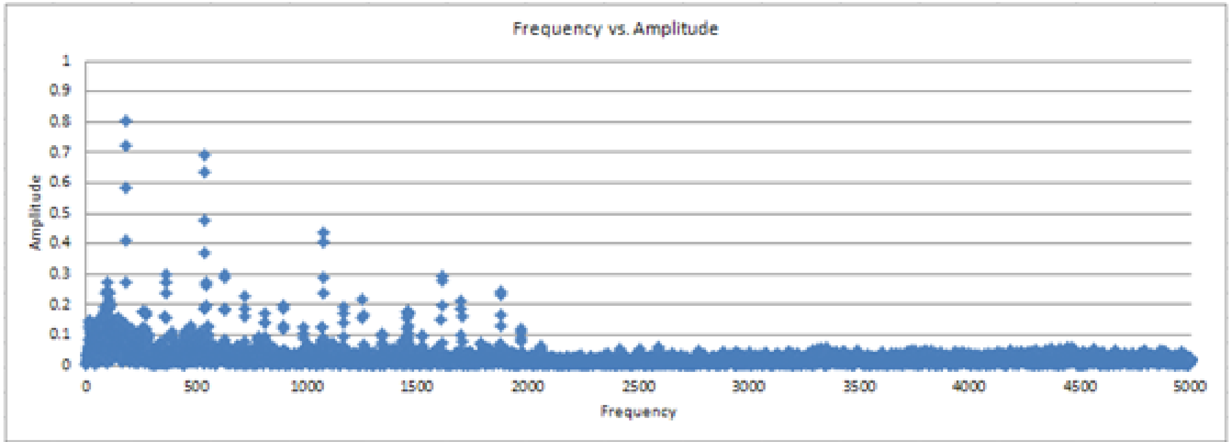

Figure 12: FFT Diagram with no side panels and just the catalyst on exhaust

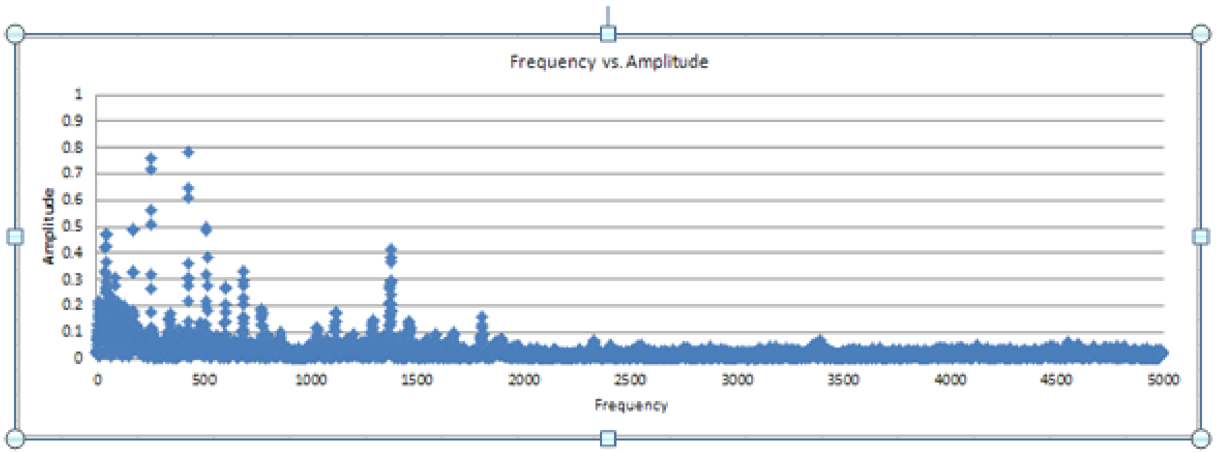

Figure 13: FFT Diagram with no side panels and the catalyst and muffler on exhaust

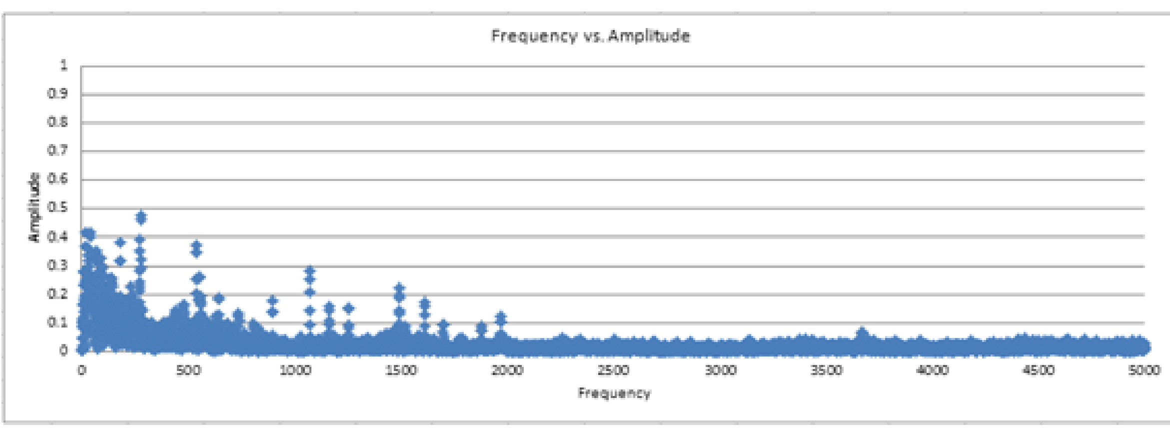

Figure 14: FFT Diagram with side panels and the catalyst and muffler on exhaust