Incorporating a Ford 1 L. EcoBoost GTDI Engine into an Arctic Cat ZR 7000 LXR

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Abstract

The University of Wisconsin-Platteville Clean Snowmobile Challenge (CSC) Team has successfully developed a quiet, efficient, and environmentally friendly snowmobile. The snowmobile is designed to compete in the 2017 Society of Automotive Engineers (SAE) Clean Snowmobile Challenge, held at the Keweenaw Research Center in Houghton, Michigan, March 6^{th}-11^{th}. The snowmobile for this year's competition is built on the 2017 Arctic Cat ZR 7000 LXR platform, featuring a one-liter, three-cylinder, four-stroke engine. The UW-Platteville CSC snowmobile is home to a GTDI Ford 1.0 L EcoBoost. This engine provides many possibilities for advancements in the areas of performance and emissions through its leading edge technology. Utilizing a MoTeC M142 engine control unit (ECU), the team is able to manage the many engine parameters to reduce exhaust emissions and improve fuel economy. A unique steering design was necessary to accommodate for the increased engine size. Hydraulic steering similar to that of a helm operated marine engine was chosen, as it has a very small footprint in the engine compartment as well as flexible lines to route around the engine. Driveline improvements, such as a lightweight belt drive and larger rear idler wheels, are also incorporated to facilitate increased fuel economy. A variety of sound reduction designs were used, such as undercoating in the tunnel, lower engine rpm through custom gearing and clutching, an anti-stab kit, and a custom track. These modifications, along with many others, have aided the UW-Platteville CSC Team in achieving our goal to produce a quiet, efficient, and environmentally friendly snowmobile.

Introduction

The snowmobiling industry is continuously met with pressure from the Environmental Protection Agency (EPA) to reduce environmental impact. The main concerns are broken into categories including carbon footprint, noise pollution, and fuel efficiency. As a result, environmental regulations have been enacted, including the Yellowstone National Park's ban of snowmobiles in the year 2000. In an effort to diminish 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 [1]. The CSC continues to be an international collegiate event aimed at improving 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. For 2017 the CSC will use a fuel blend of 0-85% ethanol. The CSC is grooming the way for future snowmobiles with the implementation of new flex-fuel systems and efficient design strategies. After the efforts to lessen environmental impact, Yellowstone National Park has implemented a new management approach, which began with the 2014-2015 winter season, changing from the fixed maximum number of snowmobiles per day to a more flexible system based on transportation events [2]. The following paper outlines the UW- Platteville CSC Team's motivations:

1. Chassis selection
2. Engine selection
3. Emissions control and engine calibration
4. Suspension and driveline
5. Sound control
6. Modifications

Chassis Selection

Starting with a chassis that was rider and performance centered was the team's goal. Arctic Cat's ProCross chassis has not only been a rider favorite since its initial release but has also proven itself as a performance machine on the racing circuit. This chassis was developed and tested on the racetrack for two years before it was released for multiple production snowmobile models. These years of development on the ProCross chassis have resulted in a snowmobile that handles extremely well because of its slide action rear suspension and distinctive A-arm architecture. SnowTrax Television's co-host Luke Lester says Arctic Cat's ProCross is, "The best riding ZR I've ever swung a leg over" [3]. Handling directly correlates to the strength of a vehicle's design. According to Brian Dick, Arctic

Cat's Performance Team Manager, "The ProCross chassis is a very strong chassis. It's got a two piece tapered tunnel design that gives you great stiffness as well as good [ergonomics] with the side walls being tipped in, [and it] allows the rider to stand up, sit down, [for a] nice transition" [4]. Furthermore, these key design features of strength and handling do not effect MSRP. With an estimated chassis price of $7,469.40, the ZR 7000 LXR is not only affordable but also extremely capable. For perspective, a comparable snowmobile, the Ski-Doo MXZ Blizzard, has an estimated chassis price of $7,679.40. These estimates were calculated with Equation 1.

$$Estimated\ Chassis\ Price = MSRP * 0.60 \tag{1}$$

Perhaps the largest draw to this chassis was the fact that it could enclose a large engine. This chassis was easily selected because Ford's 1.0L EcoBoost is slightly larger than the OEM Yamaha Genesis engine. Arctic Cat's ProCross chassis' spacious engine compartment presented opportunities for obtaining the goal of implementing an automobile engine into a snowmobile.

Engine Selection

While researching engines, the gasoline, turbocharged, direct injection (GTDI) Ford 1.0 L EcoBoost engine, stood out as a clear leader in the automotive industry. For three years in a row this engine was recognized as International Engine of the Year [5]. A variety of features such as variable cam timing, direct injection, turbo charging, a variable displacement oil pump, and fly-by-wire were influential in choosing this engine.

Variable cam timing provides benefits well beyond any other feature of this engine. For instance, this technology provides the ability to instantly change the performance and emissions characteristics of the engine. Through tuning, it is possible to realize Exhaust Gas Recirculation (EGR) results. This technique could result in lower Nitrogen Oxide (NO_x) emissions. Improvements can be made not only in emissions and fuel economy, but also torque. A wider torque curve provides smoother and stronger power delivery. Power curves are also affected and can be modified for a less dramatic drop after peak power is reached.

The second most notable feature of this engine is direct injection. The primary benefit of direct injection is the precise fuel injection timing. With correct tuning less fuel is needed compared to traditional port injection. Direct injection is also capable of multiple injections per stroke resulting in a more efficient combustion of fuel and a quieter running engine [6].

Equipped with a small low-inertia turbo, this engine minimizes lag in response during the acceleration process [7]. Because of the turbine's blade design this engine runs quieter with less exhaust noise and turbo whistle. The spinning impellor creates a uniform exhaust flow compared to an engine not equipped with a turbo. This is because engines not fitted with a turbo have larger fluctuations in exhaust gas velocity resulting in additional exhaust noise.

Other unique features of this engine provide many advantages. For instance, the variable oil pump provides a precise amount of oil pressure for a given operating condition. This helps overall engine efficiency by reducing unnecessary pumping losses.

Engine losses are further minimized through the oil bathed timing belt which reduces weight and friction over a traditional timing chain.

Fly-by-wire provides the ability to have multiple throttle modes, rapid engine response, and smoother accessory function. Fly-by-wire also presents the opportunity for the implementation of cruise control.

Engine balancing is necessary on a three-cylinder engine due to inherent rocking. Ford solved this issue by incorporating a unique balancing system. Utilizing an unbalanced flywheel and harmonic balancer, this engine eliminates the need for a countershaft. Without a counter balancing shaft, a chain is eliminated which results in less overall friction loss.

Ford's Split Cooling System, with two thermostats, allows critical engine components to reach operating temperature faster. Once the coolant within the block reaches operating temperature the rest of the engine begins circulating. This is beneficial because the oil heats up more quickly while keeping head and exhaust temperatures down, thereby reducing emissions.

In addition to the split cooling system, the exhaust manifold is integrated into the head. This reduces weight and lowers exhaust temperature. NO_x emissions are reduced by keeping the exhaust temperatures low.

Yet another benefit to the 1.0L EcoBoost is the advanced alternator. This enables charging control well beyond that of any current production snowmobile. The ECU control of this alternator allows for complete alternator disengagement for optimum fuel economy in the appropriate operating conditions. Furthermore, in combination with the fly-by-wire throttle body, the engine can actively compensate for the extra torque required for the charging load. This provides smoother transitions between charging cycles.

Engine Calibration and Emission Control

The Motec M142 ECU was chosen for its ability to manage many pulse width modulated (PWM) actuators, as well as direct injection. This platform allows for innovative projects related to the 1.0L EcoBoost engine. It is anticipated that these capabilities will be further utilized in future competitions.

To further reduce emissions, the catalytic converter, shown in Figure 1, chosen was the Ford 3-way catalyst developed for use with the 1.0L EcoBoost in the Fiesta line. The Ford catalyst was chosen due to the fact that it was designed for the 1.0L EcoBoost and is cost efficient. The catalytic converter was placed near the exit of the turbo in order to rapidly achieve operating catalyst temperature.

Figure 1: Ford Three-Way Catalytic Converter

Driveline & Suspension

From Camso, the team installed a custom ported 137in in-lug-stud track with a 2.86in pitch. The change from a 2.52in pitch to a 2.86in was for gains related to rolling resistance and noise. The track was ported with a unique 1.5in rectangular cutout to reduce noise and to increase efficiency. After testing the Ice Attack XT in two variations, ported and un-ported, the efficiency advantages to a ported track were clearly visible, as seen in Figure 2. The pull force test consisted of a winch and a force meter. The snowmobiles were pulled over a smooth consistent surface and the pull force was recorded. The data was then analyzed and the results indicate a 57% reduction in pull force compared to an un-ported track.

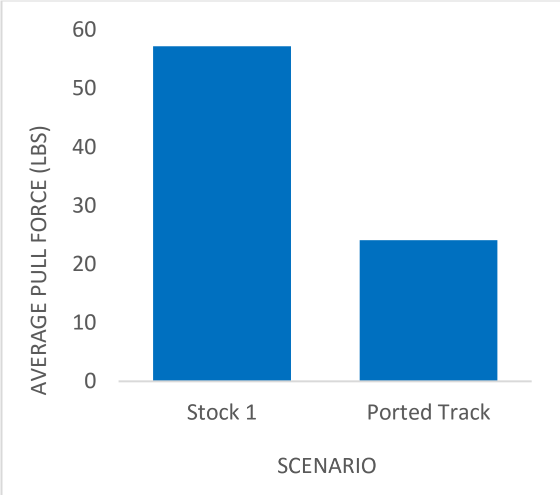

Figure 2: Pull Force Data

The next benefit to the track was the in-lug studs. These provide more traction without the additional weight from traditional studs. Additionally, it also reduces losses associated with flexing a traditionally studded track. This results in better fuel economy and driveline efficiency.

To further improve efficiency, a C3 belt drive system was used, as seen in Figure 3. This system increased efficiency, alleviated friction, and reduced mass. In fact, the belt drive reduces rotating mass by 8 pounds with an overall weight savings of 11 pounds [8]. The belt drive has no need for oil, therefore, it is more environmentally friendly and requires less maintenance. One of the largest benefits to the belt drive is a reduction in noise compared to the traditional chain drive resulting from the materials used.

Figure 3: C3 SyncroDrive Belt Drive

Graphite infused slides were chosen over standard polymer hyfax slides due to their lower coefficient of friction, lower operating temperatures, and increased durability.

One goal agreed upon by the driveline team was to reduce contact with the hyfax and the clips. To do so, bogie wheels were added along the front bend of the rails to create a gap between the track and the slides. Advantages of creating a gap include increased skid frame lubrication and reduced hyfax temperature. The larger diameter rear idler wheels, shown in Figure 4, reduce the torque required by minimizing the angular acceleration of the track. By following the enlarged radius, the amount of track deflection was mitigated, minimizing the energy wasted on bending the track.

In order to attain a reasonable clutch engagement with an automotive engine, modifications were necessary. Custom heavier weights and a lower spring rate were used in order to reach the lower engagement needed for the lower engine speed. The combination of these two modifications resulted in a system that engages smoothly and keeps the engine near optimum torque.

As a result of the narrower engine speed range of the 1.0L EcoBoost, the gearing had to be changed. The belt drive was geared up from the stock ratio which increased the speed attainable for trail cruising. The 1.0L EcoBoost's high torque output allows this gearing change to be made without sacrificing acceleration.

Figure 4: Big Wheel Kit

Sound

For the exhaust system, components from the 2016 Ford Focus were implemented. These parts were chosen as they are tailored to the specific exhaust frequencies, flow requirements, and their relatively inexpensive cost. The decision to purchase a muffler system, seen in Figure 5 and Figure 6, was simple given the effective design already produced by Ford for the 1.0L EcoBoost.

Figure 5: Ford Resonator

Figure 6: Ford Muffler

Sound levels were further reduced through the improvements made to the driveline and track. The track chosen for the 2017 competition was a custom Camso track. It incorporated Arctic Cat's quiet track technology as well as ported pattern. The quiet track technology reduces track noise by mitigating the sound produced by bogie wheels. According to Jason Davis at Camso, "This track has additional geometry on the inside of the track that look like small ramps in order to have the idler wheels span the fiberglass rods in the track and lower the dB of the track," [9]. These features can be seen in Figure 7.

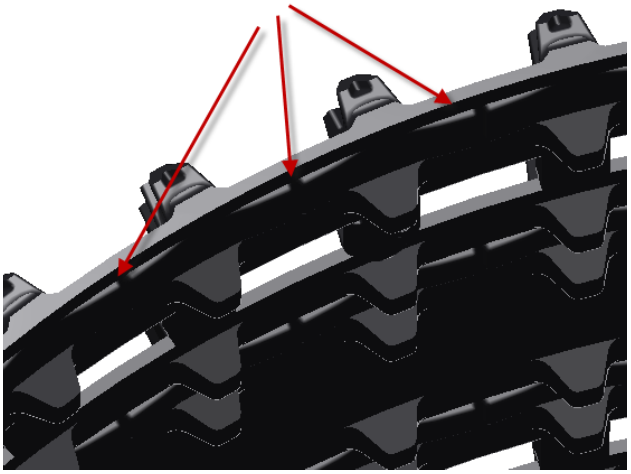
Figure 7: Quiet Track Technology [9].

In regards to the benefits of porting, Camso also stated, “From our past analysis porting of the track does reduce the noise. Also, the larger hole utilized for the clip window allows for lower dB levels from the track,” [9]. See Figure 8.

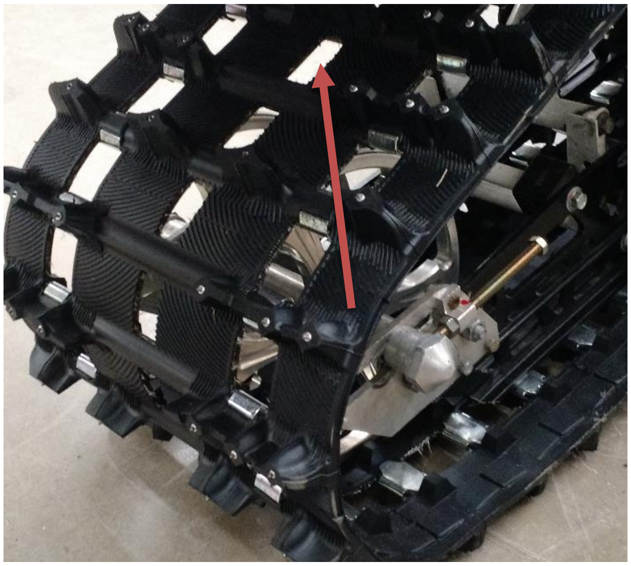
Figure 8: Ported Camso Track

Based upon this reasoning the team decided to switch to a 2.86in pitch track in order to increase the size of the clip windows and therefore reduce noise.

The change in track pitch necessitated different drive sprockets. This year, internal drive sprockets were used instead of aftermarket extroverts. Past data has shown that extrovert drive sprockets result in better efficiency, but the extroverts make contact with the metal clips in the track, increasing sound levels. “From our experience the internal drive sprockets are the best for noise reduction.” [9]. Internal drive sprockets are quieter because of the plastic to rubber interface verses a plastic to metal one. This system has a higher chance of the track ratcheting, however with proper tension, the sound benefits outweigh this potential pitfall. On the slide rails, idler wheels were positioned in order to cancel out the sinusoidal-like wave that occurs while the track is in motion. A staggered pattern was followed so that the wheels were not running in line with each other. This reduces the compression of the track as a wheel passes over, effectively resulting in better rubber compression for the next bogie wheel. The bogie wheels are also placed out of phase so that no two wheels are hitting fiberglass rods within the track at the same time. To reduce vibration noise, more wheels have been added to the system. An anti-stab kit is mounted to the front of the skid and acts as another row of small bogie wheels that eliminates rail tip failure. This helps eliminate vibration caused by the rail tips clicking on track clips as it is guided onto the slide rails.

To reduce tunnel resonation, the chassis was coated with automotive undercoating. This reduces sound levels by adding mass to the system. The additional mass mitigates the amplitude of vibration, which directly correlates to sound level. For similar reasoning, a multilayer foam was strategically utilized to deaden noise in the engine compartment.

After a previous sound requirement failure, a lower engine speed was a focus. The SAE J1161 standard was used to determine ideal engine speed. This was conducted using a PCB Larson Davis 831 sound meter. The specified speed of 35 miles per hour (mph) was set as the target for which engine speed was tuned. This was accomplished through clutching and gearing modifications.

Modifications

The Hayes TrailTrac ABS system was added to improve stopping distance in all situations, specifically icy conditions where the track may lock up. Inexperienced and seasoned riders alike can also see value in the ABS system through better control. This is vital in emergency situations where an inexperienced rider may panic and apply the brakes too firmly, which can cause unexpected movement. This system can also benefit bystanders and wildlife through improved stopping distance.

This year the design of our ABS system changed to provide better reliability and consistent track speed readings. This was done by making a more rigid mount for the hall effect sensor and by having the sensor read radially around the tone wheel as opposed to axially. The benefit to reading radially is that the reading is not subject to shaft floating and therefore is less likely to misread.

Due to the space taken by the 1.0L EcoBoost engine, the stock steering column no longer fit in the original position. Research was completed on many new steering options; a hydraulic system similar to an outboard helm controlled boat was chosen. A belt pulley was placed at the end of the steering column,

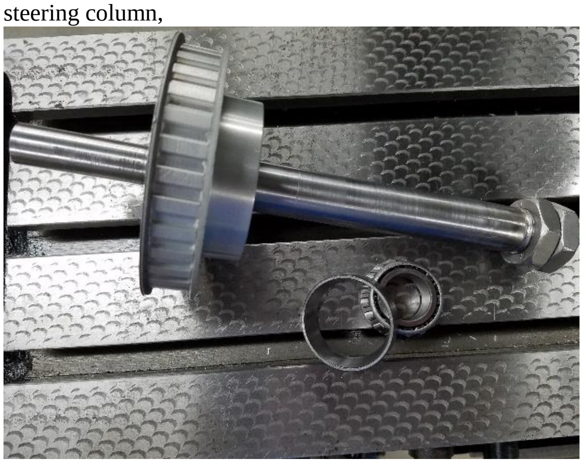

Figure 9, to run the helm pump that powers the hydraulic cylinder, Figure 10, in the front of the snowmobile. To transfer motion from the cylinder to the tie-rods a steering connecting link was designed as shown in Figure 11. The belt-pulley system was used to replicate the steering angles of a snowmobile. This was critical as a typical helm steering wheel would make multiple revolutions before reaching an equal turn radius.

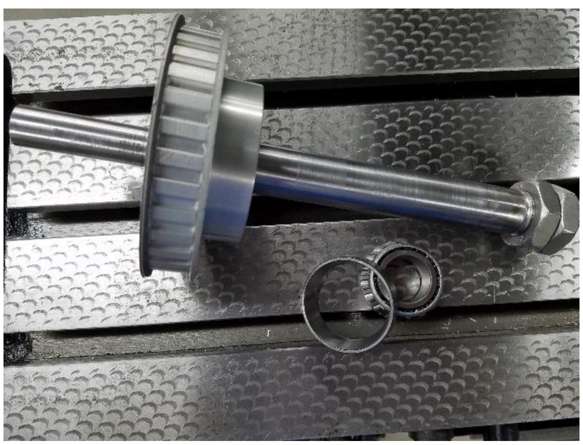

Figure 9: Steering Column

Figure 10: Mercury Steering Actuator

This hydraulic steering setup provides some benefits over traditional linkages. For one, feedback is significantly reduced compared to a traditional snowmobile. Darting and violent bar shake are nearly eliminated, resulting in less rider fatigue; however, there are some drawbacks. For instance, different handling characteristics result from the reduced feedback. The sled will not respond to berms and ruts to the extent a traditional snowmobile would. In many cases this is a benefit, but if a rider expects the snowmobile to initiate the turn they will need to provide more steering input. Secondly, the hydraulic steering will not self-center. The rider would become accustomed to extra required input and may grow to appreciate the reduced feedback after hours of riding.

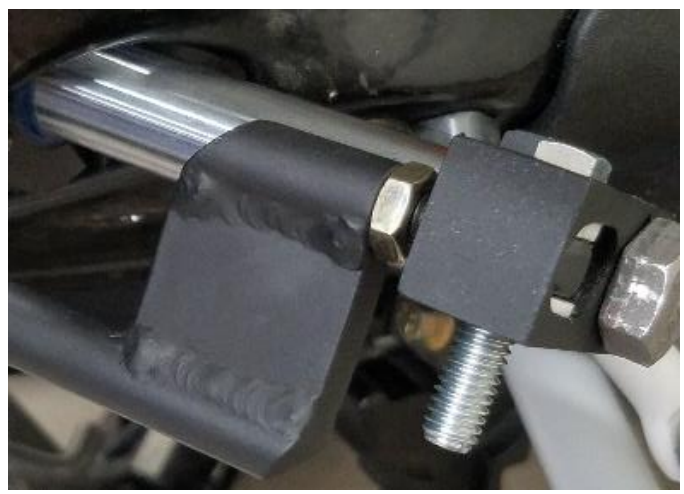

Figure 11: Steering Connecting Link

With the addition of the turbo charger an intercooler was installed to cool the charge of air before it enters the engine. The selected intercooler is designed for an engine with similar displacement, allowing the intercooler to efficiently reduce intake temperatures, Figure 12.


Figure 12: Intercooler

In order for the stock Ford exhaust system to be implemented under the seat of the snowmobile, a new location was needed for the fuel tank, Figure 13. The tank was designed to be located directly behind the seat and carry a similar volume to that of the stock fuel tank. The location of the fuel tank will counteract the added weight from the 1.0L EcoBoost engine. A rubber mount between the chassis and tank was used to decrease the amount of vibrations incurred during operation.

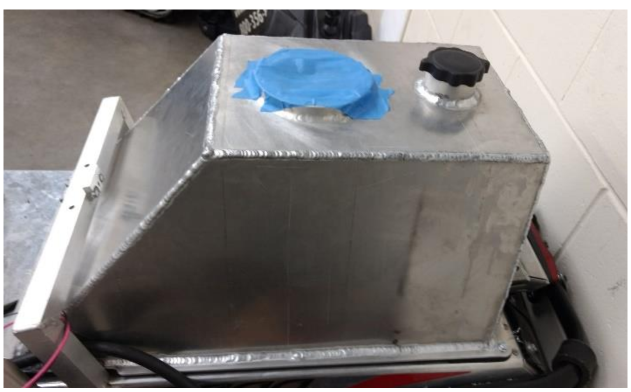
Figure 13: Custom Fuel Tank

The cooling system needed a redesign as the location for the stock radiator was replaced by an intercooler. In order to reach the efficiency of the stock radiator, a much longer, full tunnel length, heat exchanger was added. An aluminum degas bottle was designed and fabricated to replace the stock plastic recovery bottle.

A new design was needed to transition the stock throttle control from being used on a vehicle to a snowmobile. To accommodate the electronic throttle, a fly-by-wire gas pedal system was used. A lighter spring was added to the throttle control to emulate a standard snowmobile thumb throttle. The fly-by-wire system will allow for quick and smooth throttle response.

With the use of the new 1.0L EcoBoost engine it was necessary to come up with a new bracing setup. The custom brace is crucial as it provides rigidity to the entire chassis. This is evident by reinforcing the shock mounts, providing a mounting point for the steering system, as well as sustaining a variety of other lateral forces the chassis experiences. This was fabricated from one-inch diameter 4130 steel tubing to handle these loadings.

A custom air box was designed and fabricated in-house. This allowed for the maximum amount of volume to be utilized. A larger air box allows for better acceleration by creating a reservoir of available air for intake at any time. After flowing through a body panel, air is diverted downwards by a center plate. Moisture is collected, then drained out, as air is pulled back up behind the center plate into the air filter compartment.

Conclusion

The UW-Platteville CSC Team has successfully designed a quiet, efficient, and environmentally friendly snowmobile. The team believes that this could be a marketable solution that will be the new benchmark that all others will be compared to.

The technology of the 1.0L EcoBoost engine presents many opportunities for advancements, but its integration into the snowmobile industry is likely to be a gradual transition. Furthermore, the advanced technology of the 1.0L EcoBoost engine presents complexity and added costs over a similar performing sled.

This competition has played a large role in the improvement of snowmobile design. The implementation of a 1.0L EcoBoost engine is continuing the tradition of engineering excellence in environmental and societal responsibilities.

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Definitions/Abbreviations

Clean Snowmobile Challenge (CSC)
Society of Automotive Engineers (SAE)
Engine control unit (ECU)
Environmental Protection Agency (EPA)
National Parks Service (NPS)
University of Wisconsin (UW)
Gasoline turbocharged direct injection (GTDI)
Exhaust Gas Recirculation (EGR)
Engine control module (ECM)
Pulse width modulated (PWM)
Antilock Braking System (ABS)
Nitrogen Oxides (NO_x)
Miles Per Hour (MPH)