Implementation of a Small High-Performance Clean Turbo Diesel Engine in a Snowmobile Chassis

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ABSTRACT

For 2010, the University at Buffalo Team has designed and implemented a high performance, turbocharged clean diesel powered snowmobile for the SAE Clean Snowmobile Challenge. Residing in a 2005 Polaris IQ chassis, this 980cc four stroke three cylinder indirect injection Daihatsu diesel engine has been significantly modified to meet the performance and emissions demands of the competition. An all new intake and exhaust manifold system has been implemented with a ported cylinder head, along with a larger variable geometry turbocharger and intercooler, in order to supply the engine with an adequate mass flow of air. The injection pump governor has been modified to allow engine speeds up to 6000 revolutions per minute. The engine displacement has been increased from 953cc to 980cc to allow higher specific power output. The compression ratio has been lowered to facilitate the higher boost pressures that the new turbo can generate as well as lowering peak combustion temperatures for reduced NO_x emissions. In order to handle the additional component forces of the new engine, the connecting rods and pistons have been upgraded. Forged steel h-beam connecting rods and forged aluminum pistons specifically have been designed for our new engine. Due to mechanical fuel injection, the engine can safely run on all blends of diesel and biodiesel fuels. A prototype exhaust after-treatment system has been fitted to reduce UHC, CO, and soot emissions. Significant weight reduction has been performed in order to offset the heavier engine design. The above modifications close the performance gap between a diesel-powered snowmobile and those available today, while meeting the strict emissions standards of the EPA.

INTRODUCTION

Due to the increasing regulations on exhaust and noise emissions on modern snowmobiles, there is an ever-growing need for further development of new technologies that assist in making snowmobiles cleaner and quieter. The Clean Snowmobile Challenge is a collegiate design competition for student members of the Society of Automotive Engineers (SAE). “The intent of the competition is to develop a snowmobile that is acceptable for use in environmentally sensitive areas. The modified snowmobiles are expected to be quiet, emit significantly less unburned hydrocarbons, carbon monoxide and particulate matter than conventional snowmobiles, without significantly increasing oxides of nitrogen emissions (1).” The modified snowmobiles are also expected to be cost effective. The intent of the competition is to design a touring snowmobile that will primarily be ridden on groomed snowmobile trails. Guidelines for the 2010 SAE Clean Snowmobile Competition state that this year’s entries into the competition must exceed the EPA 2012 emissions standards just as the manufacturers must do. Additionally, entries must pass the current Snowmobile Industry noise test minus two decibels. Our team has chosen a diesel engine as the engine of choice for this competition as it has great potential that has yet to be exploited in the recreational vehicle market. The diesel engine is vastly superior to gasoline two and four stroke engines with respect to efficiency, emissions, and torque output, all of which are required of modern snowmobiles.

DESIGN INTENT

For the past three years our team has attempted to prove the viability of a diesel engine in a snowmobile chassis. We have succeeded in winning not only the emissions event with this diesel engine, but scoring second in the noise event of the 2009 CSC. The lacking performance of the diesel engine has hindered our team’s ability to succeed and thus is our main focus for the 2010 CSC. Realizing that our options for a higher performance small diesel engine were almost non-existent, we decided to extensively modify the Daihatsu three cylinder turbo diesel we have used in the past competitions.

CHASSIS SELECTION

For the 2010 Clean Snowmobile competition the team has utilized a 2005 Polaris Fusion as a base snowmobile. This is a modern chassis that uses A-Arm front suspension as well as rider forward position while reducing overall weight. This chassis was selected due to its large engine bulkhead and excellent cooling capacity. Even with the relatively large engine compartment on the Polaris IQ chassis, significant modification and relocation to engine systems was required. The oil filter was relocated remotely through the use of a custom adapter. The oil pan was also cut down ¾" to allow clearance for steering linkages. A single v-belt accessory drive was replaced by a custom multi-belt design to avoid interference with the side of the bulkhead.

ENGINE PERFORMANCE

Photo of completed engine for 2010 CSC.

The 2010 CSC team has decided to extensively re-engineer the small three cylinder diesel engine that we have used in previous competitions. In order to improve the performance of the engine while maintaining clean emissions, the air flow through the engine needed to be improved. Flow tests of the cylinder head and stock manifolds were performed in order to gain insight into potential improvement areas. The results show very little flow increase for valve lifts past 75%, indicating either flow choking at the valve stem openings or in the ports. Due to ease of machining and availability of parts the cylinder head ports were ported and polished in order to increase volumetric efficiency and minimize frictional losses. The results of the ported flow test can be seen in Figure 1 of the appendix.

Intake and Exhaust Manifold

Two areas in need of vast improvement were the intake and exhaust manifolds. The stock design intent of this engine was for its use as an industrial power generator and thus these systems were not optimal for our intentions. The turbo manifold was a cast iron, constant pressure log type with restrictive geometry that did not allow for optimal use of exhaust gas velocity. After researching various types of manifolds, a pulse style design was chosen. In this way, the high velocity exhaust gasses are passed though individual tubes that merge at the inlet of the turbine, thereby creating a train of pulses that quickly spool the compressor. The volume of the system was optimized such that the volume of combustion gasses could be expelled with excellent scavenging efficiency, while keeping the exhaust length short enough to minimize energy losses. Through research, a design goal for a pipe volume to cylinder volume ratio of 0.5 was established, which maximizes the available energy to the turbine (2). Due to other design constraints a ratio of 1.15 was achieved and thus only 87% of the exhaust kinetic energy is available in our designed system. See appendix figure 2 for the pipe volume to cylinder volume chart. A solid model of the exhaust can be found in appendix figure 3 as well as a picture of the actual exhaust. Grade 304 stainless steel was used for its excellent heat retention, strength, and corrosion resistance. The turbocharger requires a gravity fed oil drain which dictated its elevated location above the engine block. The stock intake manifold was a small-volume, log type cast aluminum design with numerous flow obstructions. We designed a larger volume intake manifold that fits within the tight special constraints of the engine bay. The larger volume will ensure an adequate supply of air even at high engine speeds. See appendix figure 4 for the solid model design and actual design picture for comparison.

Turbocharger and Intercooler

The addition of a Garrett GT15 variable nozzle turbocharger and intercooler is a major design change for this year. By matching our engine flow rate and desired intake pressure ratio to the compressor maps of various turbochargers, the GT15 VNT was chosen as the best match (5). The compressor and turbine maps can be found in appendix figure 6 which indicates our operating point on the map with a red asterisk. This turbocharger is designed for use on the Volkswagen 1.9L TDI engine and thus is desirable for use in our diesel engine. The variable nozzle design allows for a more dynamic operating range which can spool quickly when the vanes are closed and flow a greater amount of air at fully open. A diagram of the turbocharger can be seen in appendix figure 7. An intercooler was chosen in order to cool the intake charge air in an effort to maximize the density of air and thus increase the engines ability to cleanly and efficiently burn the fuel.

Displacement Increase

Increasing the displacement of the engine will allow higher power and torque output to be reached, both of which were lacking in the previous year's snowmobile. Boring the engines cylinders 0.040" over resulted in a displacement increase of 27cc. This increases the area upon which the combustion pressures will act thereby increasing the torque of the engine.

Governed Speed

The low governed speed of a diesel engine is due to the slow burn rate of diesel fuel during the combustion process, and also the peak torque of our engine is made at 2500 rpm. For ease of clutching and a higher achievable top speed the governed limit of our engine was raised from 3950 rpm to 5000 rpm.

Engine Durability

With all of the above performance additions, the durability of the engine needed to be considered. By using higher strength connecting rods and pistons, the lifetime of the engine would not be shortened. High strength h-beam connecting rods are used with custom forged aluminum pistons with extreme duty wrist pins. The connecting rods were made by Carrillo and the pistons manufactured by Arias and both were specifically designed for our engine operating conditions.

EMISSIONS CONTROL

A diesel engine suffers from two disadvantages with respect to emissions when compared with two and four stroke gasoline engines. These are the emission of NO_x and particulates. Due to the extensive modification of the engines performance characteristics, an all-new exhaust aftermarket treatment system was fitted and specifically designed for our new operating conditions. The prototype system was generously donated by Emitec and includes a oxidizing catalyst and a PM filter. The diesel oxidizing catalyst utilizes the excess oxygen in the exhaust stream to oxidize CO to CO_2 and unburned hydrocarbons to H_2O and CO_2 (4). The particulate filter can absorb the carbon particles emitted from a diesel engine and thus eliminate any black smoke that often gives diesel engines a poor reputation. The restriction of NO_x emissions from a diesel engine is a challenge that was tackled by our team by lowering the compression ratio of the engine. This reduces the peak in cylinder combustion temperatures which give rise to the NO_x formation. The compression ratio was lowered from 24.8:1 to 20:1 to reduce temperatures but still ensure the cold start ability and running quality of the engine. A strict monitoring and tuning of the engine can result in decreased emissions as well, particularly with the full load fuel setting and injection timing, both of which are controlled mechanically by the injection pump. The full load air fuel ratio must stay near 23:1 to maintain "smoke-free" performance, which can be ensured by a properly functioning turbocharger and air intake system (2). The use of NGK ceramic glow plugs will aid in cold start emissions as well as they reach and maintain a temperature 200ºC greater than the stock glow plugs.

FUEL SYSTEM

The fuel system on the Daihatsu diesel is relatively simple because it is mechanically injected. The four parts to the fuel system are the injector pump, fuel filter/water separator, injectors, and the fuel tank all of which are connected via fuel lines. A schematic of the fuel system can be seen in Appendix figure 8. The fuel pump internal to the stock Polaris Fusion fuel tank was removed and replaced with a custom plug. This unit was designed to accept hose barb fittings on both the inside and outside of the tank. These fuel lines serve as fuel pickup and fuel return feeding between the engine and the fuel tank. Since diesels are typically 10 - 15 percent more thermally efficient than two and four stroke engines we will be able to traverse more miles than other CSC teams on a gallon of fuel. In last year's competition, while not being officially recorded, the mileage of our snowmobile exceeded 42 mpg. Appendix Figure 3 displays our fuel efficiency, weight, and fuel range in comparison to current market offerings as well as the winner of last year's CSC. Due to the simplicity of mechanical injection, our engine can efficiently run on any blend of biodiesel, enhancing its appeal for alternative fuel usage.

COOLING SYSTEM

The cooling system was an initial concern for this year's design due to the increased heat rejection rates expected from this year's modified engine. The Polaris Fusion stock cooling system was determined to exceed the necessary heat rejection of the turbo diesel engine, and thus the elimination of the small front radiator allowed for placement of the turbo intercooler. Using the stock cooling system saves weight and allows for easy fitment to the diesel engine. Additionally the largest of the heat exchangers has excellent placement on the underside of the tunnel and is therefore exposed to cool ambient air and snow. The hood will not be sealed for this year's competition to allow for convection currents to cool the engine and turbocharger. Two coolant hoses had to be routed to mate with the system with the new engine. Using a filler neck and overflow bottle allows us room to put the filler at the very top of the engine and thus avoid air bubbles which could potentially lock up the system.

ELECTRICAL SYSTEM

A major concern of our simple electrical system is reliability and neatness. In order for the engine to stay running, a small current must be supplied to the fuel shut-off solenoid. Since there is no electrical ignition system in a diesel engine, the engine is shut off by simply cutting power to this solenoid. In order to prevent failure of this system, redundancy will be incorporated into the wiring to ensure engine operation. All electrical accessories are wired in a loom and tucked safely out of the range of moving engine components, heat sources and weather exposed areas. The electric power supplied for engine startup will be a 12V, AGM battery supplied by Braille Battery. This battery is very lightweight at 18 lb. considering its pulse cranking amp rating of 1164A. The battery will be housed in a non conductive, Lexan battery box under the seat of the Fusion. This allows for a stock look and also a more evenly distributed weight and more room under the cowl of the snowmobile. The tunnel of the Polaris Fusion also has inset grooves that increase rigidity of the tunnel and also allow for the wiring to be run to the engine and components under the seat. Another addition to this year's snowmobile is a mechanical speedometer and analog tachometer from a different Polaris snowmobile, as the stock gauges were inadequate. We will also be utilizing additional gauges for oil pressure, turbocharger boost pressure, coolant temperature and EGT's. The exhaust gasses and water temperatures into and out of the engine will be monitored by a Hot Tach Pro digital readout system. This system will monitor pre-turbo and both pre- and post- Cat/PM exhaust temperature. Additionally, lights are mounted on the snowmobile to alert the rider of coolant overheat, oil pressure, and a charge light to insure the alternator is working correctly.

COLD START PERFORMANCE

Cold starting has historically been a perceived disadvantage of diesel engines. However, we have made changes to enable the engine to start easier in cold weather. The major cold start aid for this engine is the use of glow plugs. This year we have chosen ceramic glow plugs as opposed to the sheathed glow plugs that are stock on the engine. The advantages of these are quicker heat up time, and a higher absolute temperature. While it is one task to get the engine started, it is another to keep the engine running when it is first started. Due to this engine being an indirect injected design, there is a lot of heat transfer out of the pre-combustion chamber when the engine is cold and may cause the engine to run rough at first due to the compression ignition temperature not being able to be reached. An aid that is utilized is the use of afterglow. Afterglow is simply running the glow plugs after the engine is started in order to aid in the combustion when the engine block is still cold. Also, fuel gelling is a known problem with diesels in cold areas. An aid is for this problem is designed in from the manufacturer, and is also an inherent feature of the injection pump. Due to the mechanics of the injection pump, it needs to be lubricated and cooled by the fuel it uses. This is accomplished by having excess fuel flow through the injection pump back to the fuel tank. When the tank is cold, the warm return fuel will help to reverse any gelling that may have occurred. In the past, the diesel engine has started quickly in cold weather situations evidenced by our passing the cold start even every year at the CSC.

MAINTENANCE AND SERVICEABILITY

Maintenance and service on a diesel snowmobile is as easy as that of a conventional gas powered snowmobile. Engine oil needs to be changed approximately every 7500 miles or every year at minimum. Long drain periods are possible due to the robustness of the oil used for compression ignition engines and the synthetic properties needed for cold temperature operation. Engine oil changes are aided by the addition of a remote oil drain hose and a remote oil filter located in the space under the clutches. The fuel and ignition system needs very little maintenance due to the face that fueling and ignition are both controlled by the injection pump.

The injectors and injection pump only need to be checked if there is a noticeable change in engine performance. Also, if a problem did arise, the injectors and injection pump can be serviced at any reputable diesel engine shop. One thing that needs to be checked regularly is the fuel filter/ water separator. Due to the very close tolerances in the injection pump and injectors, the fuel must be clear of any debris or water. Changing the fuel filter is facilitated with the filter being located in the open area above the chain case. Bleeding the fuel system is facilitated with a fuel lift pump and a bleed screw on top of the fuel filter. Glow plugs that aid in cold start up only need to be replaced if they have malfunctioned and there is noticeable white/blue exhaust smoke at start up. Obviously, the absence of spark plugs removes the hassle of worn and fuel fouled plugs and reduces maintenance costs and labor. The robustness of the diesel engine increases the time before rebuild or major engine overhaul is necessary, in stark contrast to the conventional gas powered snowmobile. All of the above benefits for ease of maintenance and serviceability highlight the attractiveness of a diesel powered snowmobile for the consumer market.

SUSPENSION AND TRACTION

The rear suspension has been upgraded this year with an M-10 Airwave skid. The suspension is superior in both allowed travel and weight. The suspension allows a more aggressive rider-forward stance and also a higher viewing position to allow proper navigation of snowmobile trails. The front suspension used this year will be a pair of FOX FLOAT Airshox. They eliminate the need for standard shock springs by using an internal floating piston coupled with high-pressure nitrogen gas. There is also a weight savings of about 6 lbs. due to the lack of an external spring. FLOAT Airshox also have a great amount of adjustability via a miniature air pump that changes the internal pressure of the shock. This allows for adjustability from race to trail conditions as well as rider weight in a matter of minutes.

WEIGHT REDUCTION

The addition of a diesel engine into a snowmobile may seem to be a disadvantage due to its high weight when compared to a conventional gasoline engine. The 2010 snowmobile will utilize a lightweight Lexan hood is to save 12 lbs. from the stock design. The larger mold also provides additional clearance for the engine and components. The existing gauge cluster housing a conventional Polaris snowmobile speedometer and tachometer required modification yet maintains the stock appearance of a typical snowmobile. The stock 12 gallon fuel tank is quite excessive considering the fuel mileage of a diesel snowmobile. This year we modified a stock Fusion fuel tank by reducing the internal volume by 3.5 gallons thus saving approximately 28 lbs. The stock flywheel for the engine weighed 26 lbs. and was designed for industrial applications. When sudden load was applied, the high rotating inertia of the wheel would keep the engine running until the turbocharger spooled and could provide adequate boost pressure. For a snowmobile application where sudden throttle pulses and quick acceleration are needed, a less massive flywheel is essential. Using a CNC lathe the excess flywheel material was removed and reduced the weight by 13 lbs. Total weight reduction compared to last year's snowmobile is 66 lb. This reduces the weight of the snowmobile to about 650 lbs, which is comparable to the CSC competition average snowmobile weight.

NOISE REDUCTION

Diesel engines emit lower frequency mechanical noise, and when properly muffled are less of an annoyance than a typical two stroke snowmobile, as proven by our subjective sound results from last year. A vinyl based matting called VE was used to reduce resonating frequencies coming from areas within the snowmobile. VE is used to lower noise heard from a resonating structure, which is perfect for the underside of a snowmobile tunnel. Noise from the moving track and rear suspension components are trapped in this cavity and resonate. With the use of VE on the interior of the tunnel, this will help to absorb unwanted frequencies and reduce audible noise. The hood will also be lined with sound absorbing foam from American Acoustical which has proven successful in years past.

TRACK SELECTION

A Camoplast Hacksaw track combined with 96 Woody's Gold Digger studs are used on the 2010 snowmobile. This track is the lightest available and provides excellent traction on trail conditions.

SKIS

C&A Pro Trail XT skis are used on the 2010 sled. These skis are lightweight and offer a great amount of durability and prolonged wear. The patented design on the bottom of the ski allows for reduced darting and improved cornering because of the big footprint it makes when cutting through the snow. More responsive steering is imperative in this design since the diesel engine adds a significant amount of weight to the front of the snowmobile. Additionally a pair of Woody's carbides will be used to give the snowmobile good traction in unfavorable conditions.

MSRP

The addition of the performance parts in this engine is necessary for the proper operation of a diesel engine in a snowmobile. Since no such engine is currently available, our team has pioneered the market with such an offering in order to show manufacturers the need for a small performance oriented diesel engine. An estimated MSRP of $11,710.01 has been determined and justified according to the 2010 CSC rules. The average price of a snowmobile in 2009 was $8,800.00 (3). The premium cost of a diesel snowmobile would be offset by the dramatic increase in fuel mileage, and would be returned in 2-3 years based on diesel prices remaining at $3.00/gallon. Since the lifetime of diesel engine in a snowmobile would also be greater than that of a two stroke, a user would be able to see this repayment period. If current fuel price trends continue, this repayment period will shrink and buyers will look to more fuel efficient forms of recreation, and a diesel powered snowmobile would be an attractive option. Within the next five years, the diesel snowmobile could be seen on showroom floors.

CONCLUSION

The University at Buffalo 2010 CSC team has successfully designed and implemented a high performance clean burning turbo diesel engine for use in a snowmobile chassis. The engine is a highly efficient alternative to a traditional gasoline powered snowmobile. With fuel mileage at least twice that of the competition and the performance that snowmobilers come to expect, our entry for this year exceeds the expectations of the CSC. With currently available technology, the diesel snowmobile can meet the demands of snowmobilers, the EPA, and manufacturers.

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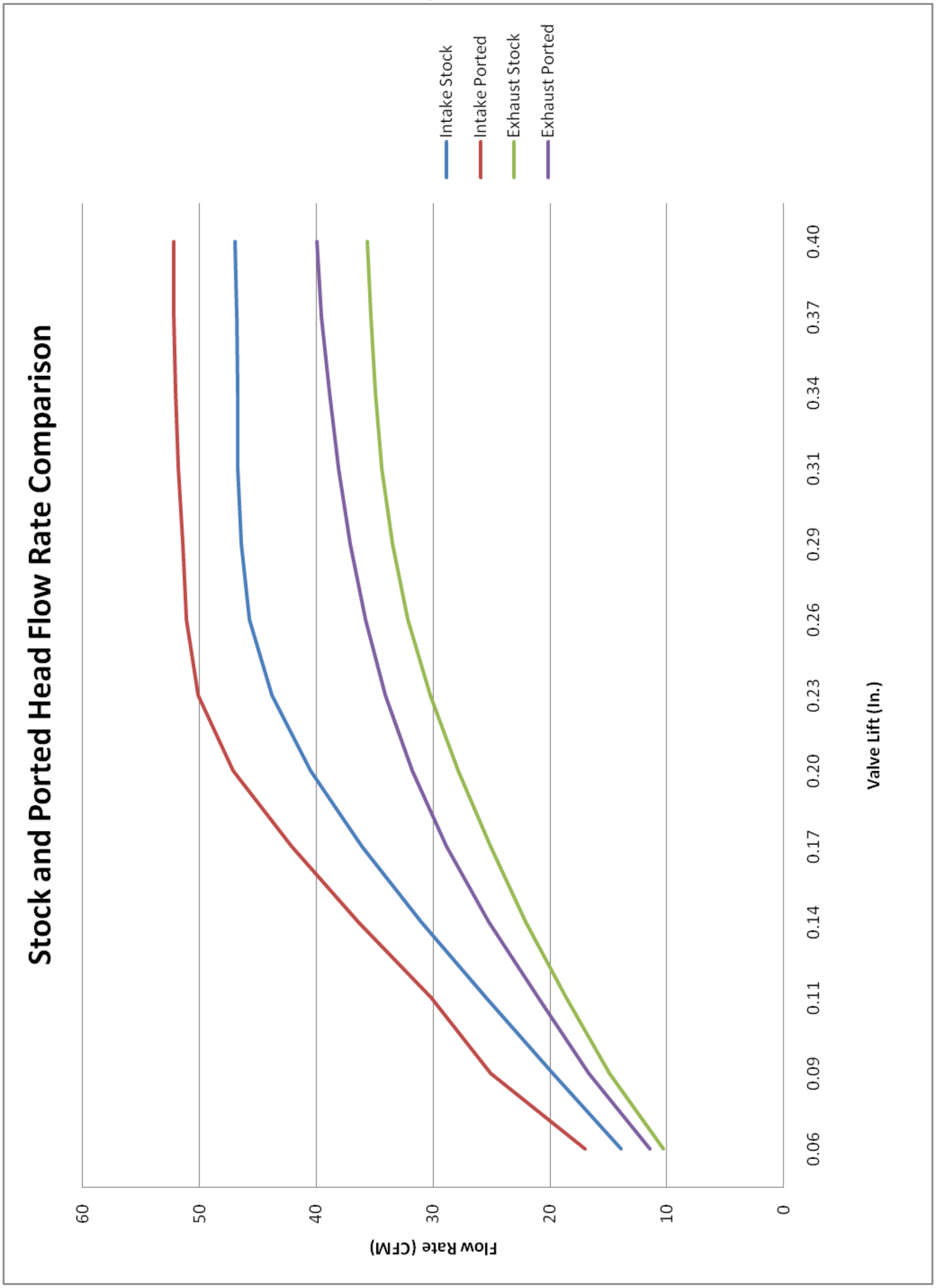
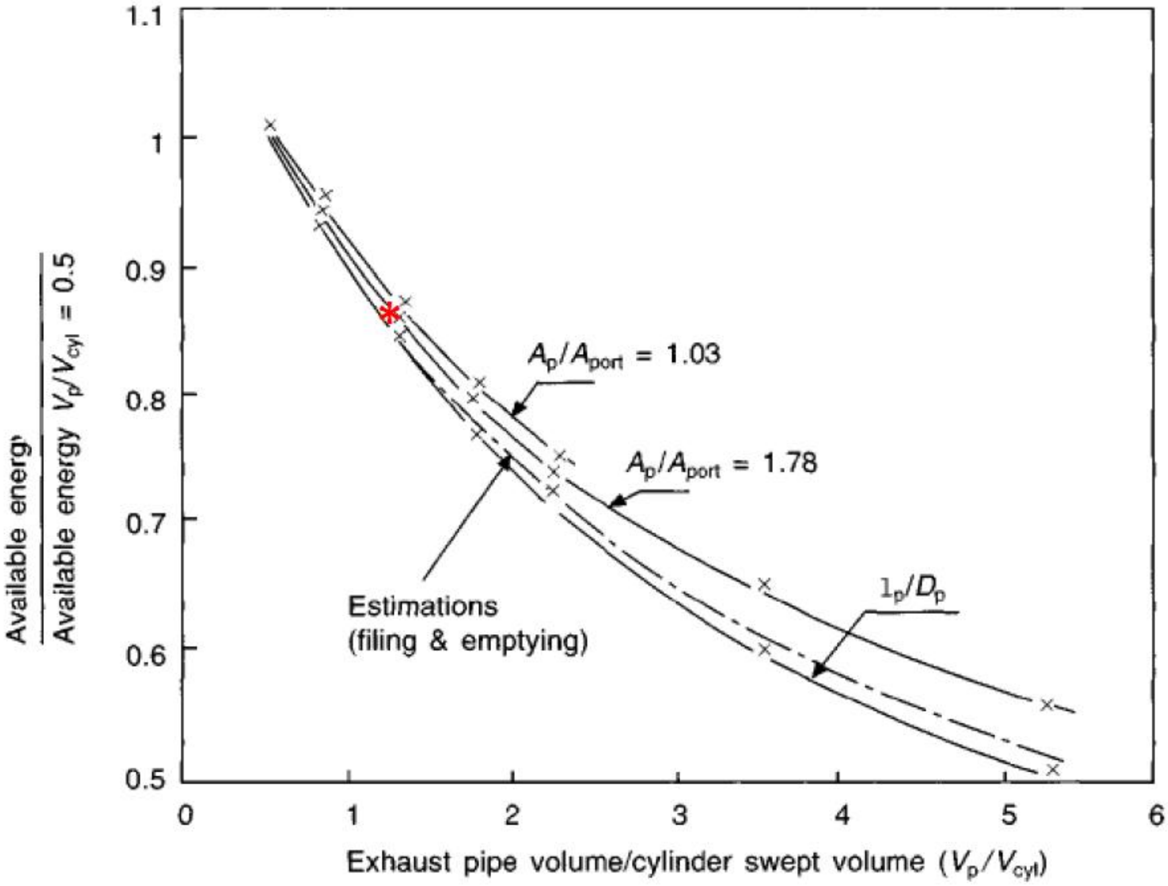
6. ski-doo. *Supertrax*. Feb. 2010, 2009, Vol. 21, 2.

APPENDIX FIGURE 1: Stock vs. Ported Head Comparison

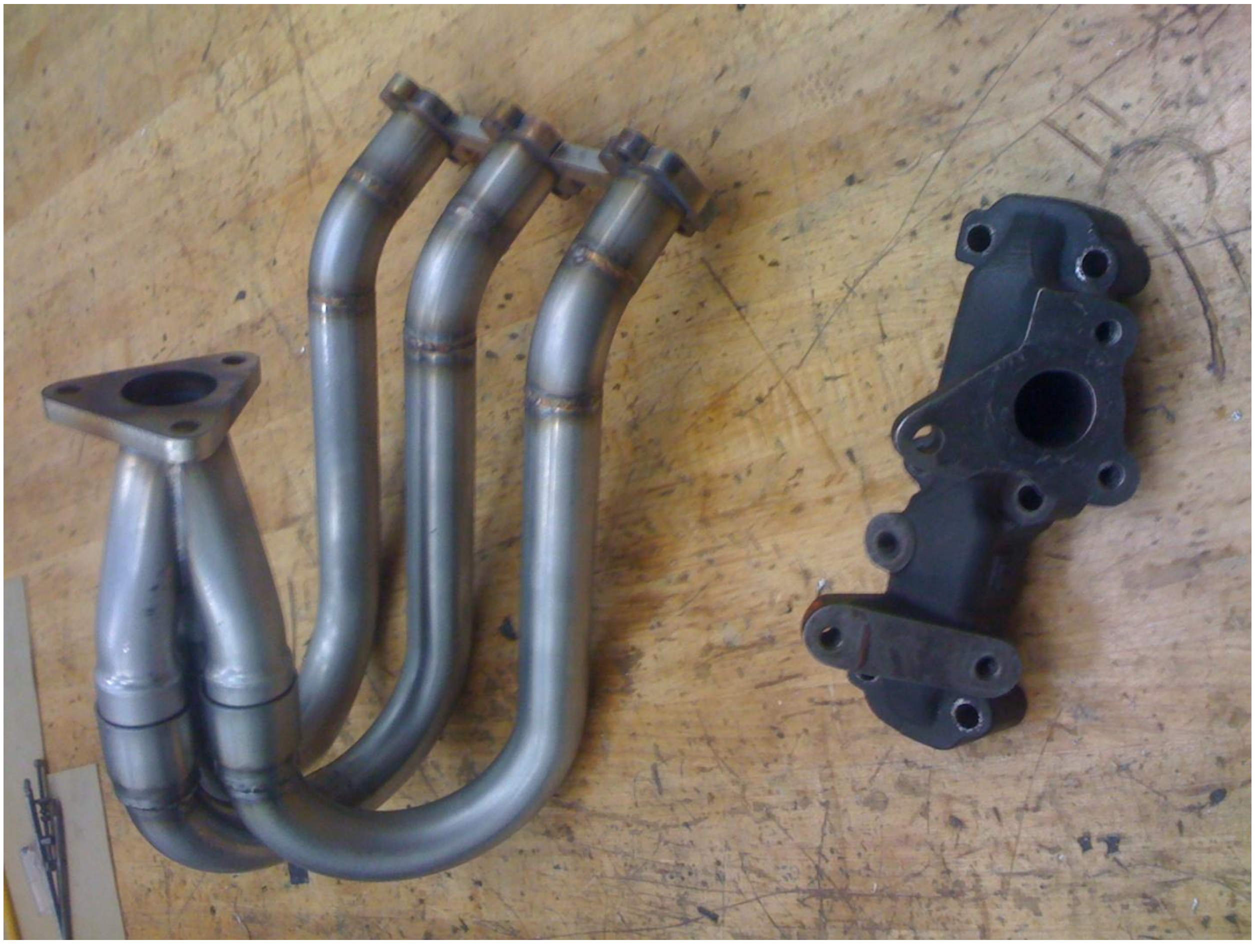


APPENDIX FIGURE 2: Pipe Volume to Cylinder Volume Chart (2)



APPENDIX FIGURE 3: Solid model of exhaust manifold

APPENDIX FIGURE 4: Actual picture of old and new exhaust manifolds



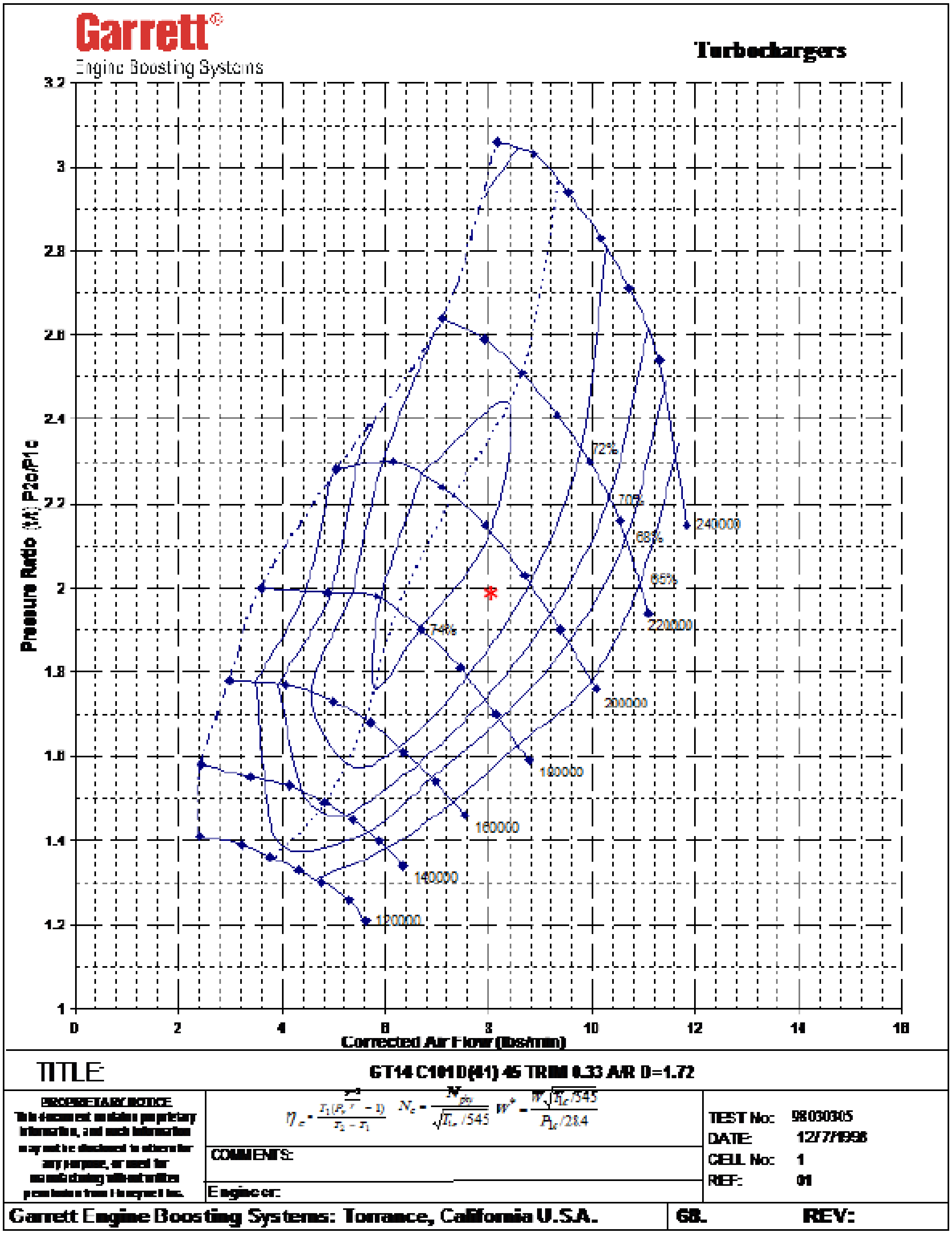
APPENDIX FIGURE 5: Snowmobile Market Analysis (6)

2009/2010 Model Year Comparison

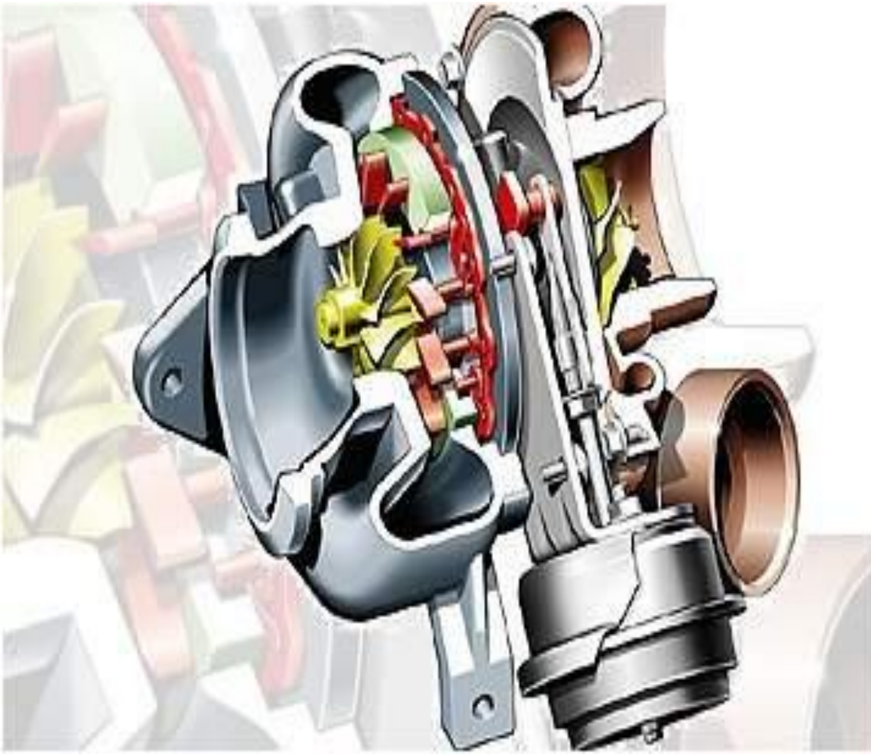
	4-STROKE				2-STROKE		
	2010 Ski-Doo® (GSX LE 4-TEC)	2009 Yamaha™ (RS Vector)	2009 Polaris™ (IQ Dragon Turbo†)	2009 Arctic Cat™ (Z1)	2010 Ski-Doo® (MX Z Adrenaline 600 H.O. E-TEC)	2009 Polaris™ (600 IQ)	2009 Arctic Cat™ (F6 Sno Pro)
Fuel Efficiency U.S. mpg (l/100 km)	18 (12.8)	17.1 (13.8)	15.8 (15)	17 (13.8)	21 (11.3)	15 (15.7)	11 (21.4)
Weight lb (kg)	529 (240)	570 (259)	580 (263)	575 (261)	431 (196)	483 (219)	495 (225)
Oil Efficiency* mi/qt (l/100 km)	470 (0.125)	470 (0.125)	470 (0.125)	470 (0.125)	346 (0.17)	147 (0.4)	101 (0.58)
Fuel Range mi (km)	195 (313)	164 (264)	160 (257)	183 (295)	220 (354)	172 (277)	134 (223)

	UW-Madison (2009 winner) (5)	SUNY Buffalo
Fuel Efficiency (mpg)	11.47	**42.92**
Weight (lbs)	694	**720**
Oil Efficiency (mi/qt)	470	**470**
Fuel Range (miles)	137.64	**515.04**

APPENDIX FIGURE 6: Turbocharger compressor map (5)



APPENDIX FIGURE 7: Garrett GT15VNT Turbocharger cutaway view (5)



APPENDIX FIGURE 8: Fuel System Schematic