Development of a Simplified Drive System to Ease in the Operation and Maintenance of a Quarter Scale Pulling Tractor

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Final Report
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1. Introduction

1.1 What is a Drivetrain?

OxfordDictionaries.com defines a drivetrain as the system in a motor vehicle that connects the transmission to the drive axles. In terms more agreeable to the scope of this project, Popular Mechanics includes both the engine and transmission when they define and explain the several types of drivetrains.

Drivetrains come in four general configurations: rear-wheel drive, front-wheel drive, four-wheel drive, and all-wheel drive. Despite these variations, all drivetrains share the same goal: to transfer power from the engine to the drive wheels as efficiently as possible.

1.2 Drivetrain Components

1.2.1 Engine

The engine is the power source of any motorized vehicle. Internal combustion (IC) engines convert chemical energy into mechanical energy, more specifically into linear then rotary motion, through a controlled burning of a fuel/air mixture. IC engine types currently in use include inline engines (all cylinders are arranged in a straight line), V-type engines (cylinders are arranged in a V-pattern which allows more cylinders and more power to be concentrated into a specific volume), and rotary engines. Rotary engines are uncommon and differ greatly from inline and V-type engines. IC engines burn a variety of fuels including gasoline, diesel fuel, compressed natural gas, propane, biodiesel, and ethanol.

1.2.2 Transmission

A mechanical transmission consists of a set of gears, whether spur, helical, or planetary, that reside inside a housing and allow the vehicle operator to select specific gear ratios which result in high speed or high torque outputs, or any combination in between. A transmission is usually mounted directly to the engine, but not always, and is available in a variety of types.

A manual transmission uses the simplest principle of operation of all the transmission types, but also takes the most skill to operate. This transmission is used in conjunction with a manual clutch and is made up primarily of a metal housing, input gears, output gears, and input and output shafts. The input and output gears are mounted on various shafts within the transmission and are meshed together to achieve specific gear ratios. These ratios, along with engine speed, vary the speed of the rotating output shaft exiting the transmission. The reverse gear in a manual transmission must rest on its own shaft in order to reverse the direction of the output shaft. The clutch for a manual transmission must be disengaged for the transmission to be shifted (Chaikin, 2004).

Automatic transmissions were developed after manual transmissions. They allow a vehicle to travel in a variety of gear ratios and speeds while eliminating the need to manually select those ratios by the operator. This allows a multitude of users, including those lacking the experience to operate a manual transmission, the freedom to drive a motorized vehicle.

The main components of an automatic transmission are the torque converter and several planetary gears set with differing gear ratios. The torque converter is mounted between the engine and actual transmission housing and allows the vehicle to come to a stop without shifting out of the forward gear. It does this by adjusting the slip between the input and output shafts using adjustable flow rates of fluid into the torque converter (Nice, 2013). Once power has reached the transmission itself, various components of the planetary gear sets are held stationary by clutch bands or allowed to move. By creating different combinations of stationary and moving components, an automatic transmission can create multiple gear ratios and output speeds (Chaikin, 2004).

Another common type of transmission that is gaining popularity among automobile and heavy equipment manufacturers is the continuously variable transmission, commonly referred to as a CVT. A typical CVT uses two pulleys, a primary and secondary, whose halves can be positioned closer together or farther apart via control from hydraulic pistons or electric solenoids (WeberAuto, 2010). By doing this, the belt connecting the pulleys can ride higher or lower in the pulleys, which fluctuates the effective speed ratio between the input and output shafts. Many variations of this type of CVT have been developed along with radically different designs, but automobile CVTs tend to use the general principle described above.

1.2.3 Ring and Pinion

The ring and pinion gears are located in the rear axle housing of a vehicle. The pinion gear is a small diameter helical gear that meshes with a larger diameter ring gear that features a matching helical pattern. These gears, which create the final-drive ratio, are offset 90° from each other. This offset, combined with the unique design of each gear, transfers rotary motion and power from the longitudinally mounted driveshaft to the transversely mounted axles (Chaikin, 2004).

1.2.4 Differential

When a vehicle turns, the wheels toward the outside of the turning radius must travel in a longer arc than the inside wheels and therefore, must rotate faster. Because of this, a differential is placed between the two wheels on a single axle and delivers power to them via two separate axle shafts. An open differential, the most commonly used type of differential, features a carrier that is connected directly to the ring gear in the rear axle housing. This carrier holds two sets of spider gears, each of which is connected to an axle shaft, that are able to rotate independently of each other which allows the axle shafts to rotate independently also (Chaikin, 2004). This also eliminates excess torque and stress on the shafts that otherwise shorten component life. A differential mechanism, as well as the ring and pinion gears, can be seen in Figure 1.

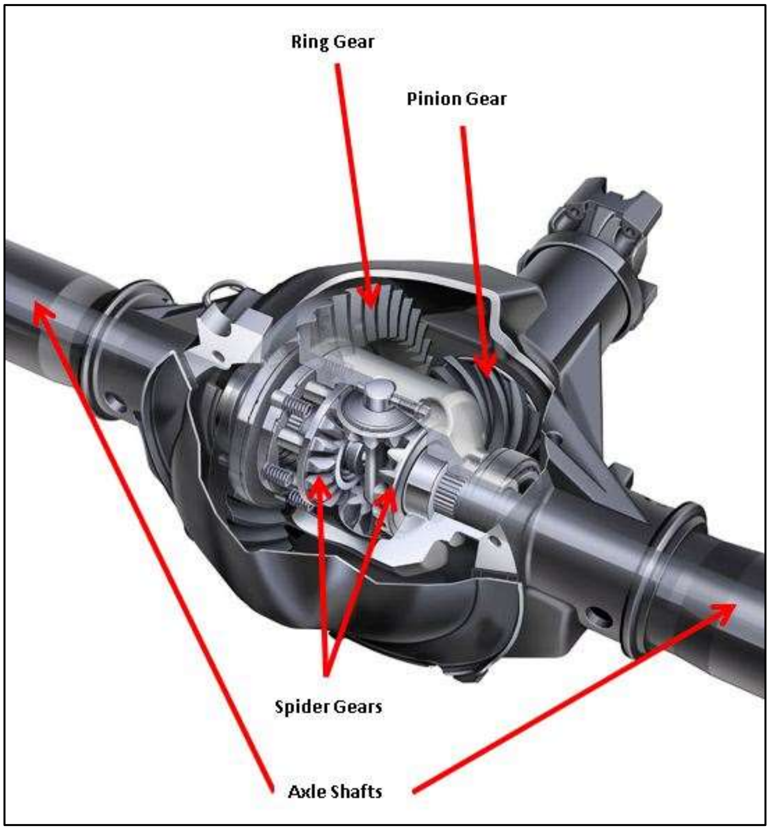


Figure 1: Rear Axle Housing (Cutaway View) Ring, Pinion, and Spider Gears are shown. (Levine, 2009)

In addition to the open differential, limited-slip and locking differentials are also available. These types allow the vehicle operator to partially or fully lock the axle shafts together. This is done to improve traction in poor conditions. Even more differential types, which differ greatly in their design and operating principles from those stated above, are available for additional applications.

1.3 Rear-Wheel Drive

The rear-wheel drive (RWD) drivetrain is the least complex of all the drivetrains. In this configuration, the engine is mounted with the crankshaft running front-to-back, and the transmission is mounted directly to the rear of the engine. A driveshaft, equipped with universal joints and an expansion joint to allow for suspension motion, delivers power to the ring and pinion gears as well as the differential located within the rear axle housing. The differential then delivers power to both rear axle shafts and wheels. The RWD configuration, shown in Figure 2, is used in compact and full-size pickup trucks, muscle cars, and sports cars.

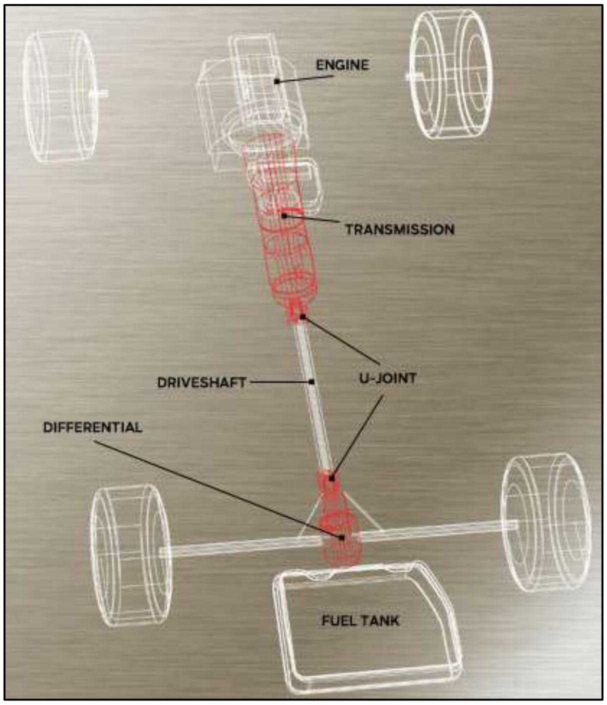


Figure 2: Rear-Wheel Drive Layout (Chaikin, 2004)

1.4 Tractor Drivetrains

Based on observation, one can see that the most popular tractor drivetrain during much of the 20th century most closely resembled the RWD automobile configuration discussed above. The John Deere 4020 shown in Figure 3, one of the company's bestselling tractors, utilized this type of drivetrain.

Figure 3: John Deere 4020, which uses the basic Independent Rear-Wheel Drive system. (Swope, 2010)

In the 4020 and tractors like it, the engine is mounted longitudinally towards the front of the frame and the transmission is mounted directly behind it. The output shaft of the transmission is coupled directly to the pinion and ring gears, without use of a driveshaft, and a differential delivers power to the rear wheels.

In addition to its basic principle of allowing the drive wheels to rotate at different speeds, the differential in a tractor allows the operator to take advantage of independent brakes; often referred to as split brakes. Tractors often operate on awkward or rough terrain, and because early tractors did not have power steering, split brakes made it much easier to maneuver the tractor during sharp turns or in poor traction conditions. Even with today's technological advances and modern power steering, independent brakes are still featured on many tractors to make steering easier when towing large implements or operating in confined areas.

The primary goal of a tractor's drivetrain is to produce as much torque as possible, usually at low speeds. This is different from an automobile, whose primary focus is to transport people and their goods as fast and safely as possible. An automobile's drivetrain must also produce sufficient horsepower and torque, but must produce both of these at a wide variety of speeds. The other noticeable difference is that most automobiles are designed to mainly operate alone whereas tractors are designed to operate almost exclusively with an implement connected to them. The high-torque low-speed conditions that tractors must operate under produce the need for a specialized drivetrain.

Because tractor drivetrains operate at these high-torque low-speed conditions, their individual components must be larger and stronger to survive the high stresses to which they are subjected. Shafts, couplings, gears, and bearings are often many times the size of those found in automobiles. These bulkier components increase both weight and cost, but engineers have developed a possible solution to this dilemma. Placing the final drive as near to the drive wheels as possible allows engineers to place smaller components between the engine and drive wheels because those components now operate at higher speeds and are subjected to lower torques.

The complex systems within the drivetrain of a tractor also differ substantially from those found in automobiles. One main difference is related to the tractor's transmission. A manual tractor transmission, in general, features several large, low speed working gears. These gears are designed to be used when the tractor is operating in the field at speeds up to 10 miles per hour (mph). Several working gears are provided so the tractor can pull a multitude of implements at a variety of speeds, for a variety of purposes. These include planting, plowing, and spraying. In addition to the lower working gears, a tractor features at least one high, or road, gear. Road gear is used when traveling at higher speeds (up to 25 mph) between fields or when returning to the farmyard.

As can be inferred, tractor drivetrains are similar to automobile drivetrains, but many differences are apparent. All tractor components, not just their drivetrains, must be built larger and stronger because tractors are designed for working, not merely driving.

1.5 International Quarter Scale Tractor Student Design Competition

The Bison Pullers Quarter Scale Tractor Team, who is the design team's sponsor for this project, is a student-managed club within the Agricultural and Biosystems Engineering Department of North Dakota State University (NDSU). Each year, the Bison Pullers research, design, and build a quarter scale tractor. This tractor is then taken to Peoria, Illinois and to the annual International Quarter Scale (IQS) Tractor Student Design Competition. This event is sponsored by the American Society of Agricultural and Biological Engineers (ASABE) as well as many equipment manufacturers. Teams and their tractors are judged on the basis of overall design, manufacturability, safety, maneuverability, sound, written report, oral presentation, technical inspection, and performance (actual tractor pulling). The competition, in addition to being fun, offers students a glimpse of what can be expected of them when they begin employment as full-time engineers. Students learn researching, marketing, design, and testing techniques while they attempt to build the winning tractor.

Tractors entered into the IQS competition must meet the strict guidelines described in the competition's *Rules and Regulations* and *Handbook* (ASABE, 2013) These references, which total 91 pages for the 2013 competition, are reviewed and updated annually to ensure that competition is kept fair amongst the teams.

The major guidelines of the competition (not necessarily related to the drivetrain) are as follows:

- Tractor will have a maximum weight of 800 lbs. without an operator
- Tractor must utilize one 31-hp Briggs and Stratton Vanguard engine or two 16-hp Briggs and Stratton Vanguard engines
- Tractor can have a maximum of four drive wheels, whether using MFWD or duals
- Tractor must have an originally designed frame each year, not one reused from a previous tractor
- Tractor cannot use skid, rear-wheel, or articulated steering
- Tractor , when utilizing MFWD, must use Titan 26x12-12 tires on one axle and the other axle must utilize tires with a 20% smaller diameter than the Titan 26x12-12
- Tractor can have a maximum hitch height of 13 inches

1.6 Problem statement

In recent years, failures of the tractor's drivetrain components have led to poor pulling performances by the sponsor team at the IQS competition. These tractors have generally used experimental technology that was only minimally tested by the sponsor. The pursuit of a reliable yet simple drivetrain that can be maintained throughout the tractors' life remains a top priority for the sponsor. As a result, the sponsor has charged the design team with developing such a drivetrain.

1.7 Rationale

1.7.1 IQS Competition Rules

The main motivation behind the development of a lightweight drivetrain was the set of guidelines put forth for the IQS competition. These rules are established to ensure that competition is fair amongst the teams and encourages them to visualize and then innovative designs into their tractors. Although the rules provide restrictions on the tractor's weight, encouraging the design team to focus on incorporating lightweight components into their design; there was also another reason behind choosing this exact drivetrain layout.

During recent IQS competitions, the design team and their sponsor have noticed a trend towards the use of 2WD tractors that pull at higher speeds than the 4WDs. These 2WD tractors, which commonly also feature a TA, pull well by using the concept of momentum to their advantage. By gaining a higher speed at the beginning of the pull, the tractor can use its built-up kinetic energy to carry it farther down the track once the weights on the progressive-load sled advance. A progressive-load sled is one that becomes more difficult to move because it creates more down-force on the tractor’s rear wheels as the pull progresses.

The sponsor has been developing a powerful 2WD system for several years now and feels that the design team’s current drivetrain may be just what they need. This design does not feature a TA right now, but was designed for one to be included later on.

1.7.2 Compact Tractors

During development of this drivetrain, the design brainstormed techniques to simplify the controls that would be used to operate the new drivetrain. One idea was to use similar controls and a similar control layout to the ones found on compact tractors. By doing this, the design team was able to ensure that anyone would be able to operate their tractor, not just the more experienced members of the sponsor team.

Hydrostatic drive systems are becoming increasingly popular on compact tractors. This system is controlled using a throttle pedal for the right foot and one or two brake pedals for the left foot. This layout is similar to those used in automobiles and makes operators feel comfortable when they are on the machine. When operators feel comfortable, they are less likely to make errors while attempting to understand their machine.

1.8 Design Objectives

In order to provide a solution to the sponsor's problem, the design team formulated several specific goals that needed to be met in order to properly develop the solution. With the rationale explained above in mind and some additional guidelines given to them by their sponsor, the design team created the following goals:

- Design a lightweight drivetrain weighing no more than 300 lbs.
- Design a drivetrain that is reliable and can be serviced by the owner
- Design a drivetrain that is simple to operate and requires few controls
- Design a drivetrain that can be further developed by the sponsor in future years

1.9 Impacts on Society and Industry

During the engineering process, engineers must evaluate design alternatives and decide which one will be the best for their company, for the environment, and for their customers. When deciding what is best for their company, engineers must focus on what components and materials to use to keep costs low and attain their target profit margin, but also how retain the quality that their company is known for. Utilizing a simplified drivetrain in automobiles and off-road equipment is a great way to positively impact the success of one's company.

When concerned with the environmental impacts of their products, engineers must avoid hazardous material usage and manufacturing techniques. Using biodegradable materials when possible and disposing of manufacturing byproducts properly are steps that can be taking to ensure a company is not adversely affecting the environment. Lawsuits concerning environmental degradation can lead to lost profits, lost jobs, and a company that may never recover. By using simplified drivetrains comprised of modern materials, engineers can impact the environment in a good way by limiting material waste and manufacturing byproducts.

Engineers are always focused on their customers. Keeping customers safe, comfortable, and happy are all goals of every engineer. Researching what customers want in a machine and then deciding what they actually need are difficult tasks. Whether during operation or maintenance, the implementation of a simplified drivetrain guarantees engineers that their customers will be satisfied with the product they receive.

During the IQS competition, students establish contact with company representatives and industry professionals. Through this contact, the sharing of ideas and discussion of technologies flourishes between engineering students and professional engineers. This two-way communication benefits both sides. Students can see the established technologies that they will be dealing with once they enter the workplace and those in industry can observe radically new and innovative technologies that may one day be implemented at their engineering firms.

2. Literature Review

2.1 Background

To develop the best drivetrain possible, the design team researched several papers written by other quarter scale tractor teams. The focus of these papers was the transmissions used by those teams in their tractors. The design team felt these papers would be excellent resources since their authors are familiar with the IQS competition and they relate so well to the design team's current endeavor.

In addition to journal articles, the design team also examined past tractors built by their sponsor. Because they only have one year to design and build an entire tractor, the sponsors like to take a basic concept and develop it over several years among several tractors. Since recent tractors built by the sponsor have all shared a general frame/drivetrain layout, the design team felt it would be possible to build upon positive attributes of those tractors and re-engineer the negative ones.

2.2 Previous Works

2.2.1 Oklahoma State University (IVT Transmission)

In 2004 the Oklahoma State University ¼ scale tractor team, Cowboy Motorsports (CMS), used knowledge gained from their previous tractors to design, build, and test a custom-built infinitely variable transmission (IVT). An infinitely variable transmission allows the tractor operator to select from an infinite number of transmission output speeds. CMS achieved this by using a planetary gear set in which the ring gear speed could be varied by a hydraulic motor. A planetary gear set is comprised of three main components: the outermost ring gear, the innermost sun gear, and the planets which reside between the sun and ring gear. These components can be seen, in detail, in Figure 4.

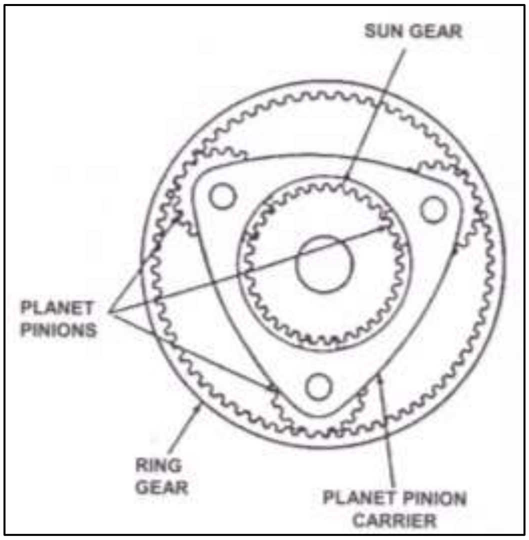


Figure 4: Planetary Gear Set (Goering, 2006)

The CMS team's design consisted of a pre-manufactured Parker 3:1 planetary gear set which saved time and money by allowing the team to focus their efforts on other drivetrain components and reducing development costs. By inputting power into the sun gear, varying the speed of the ring gear, and outputting power through the planet carrier, the team was able to vary transmission output speeds. Using Equation 1 (Oberg), the team created a spreadsheet model to simulate various output speeds and calculate the power delivered to the wheels.

Equation for relating speeds of planetary gear sets:

$$n_s N_s = (n_s + n_r) N_{pc} - n_r N_r \qquad (1)$$

Where:

$n_s = Number\ of\ teeth\ (sun\ gear)$

$n_r = Number\ of\ teeth\ (ring\ gear)$

$N_s = Rotational\ speed, rpm\ (sun\ gear)$

$N_{pc} = Rotational\ speed, rpm\ (planet\ carrier)$

$N_r = Rotational\ speed, rpm\ (ring\ gear)$

In both dynamometer and track testing of the drivetrain, the team members of CMS found that a 20% average increase in performance was seen between earlier pilot models and the 2004 model (Crossley). The engineers at CMS found that advanced drivetrains, such as the IVT, need large amounts of testing and calibration to fine tune the system. Drivetrains that are not tuned properly can rapidly become inefficient and introduce many parasitic losses to the system.

The design team feels that advanced systems design, such as an IVT transmission, would require a multi-year study of design, implementation, and redesign to perfect.

2.2.2 North Dakota State University (Belt CVT Transmission)

In 2009, NDSU Bison Pullers set out to design, build, and implement a four wheel drive tractor with the heart of the drivetrain being a continuously variable transmission (CVT). The team decided to modify a stock CVT system from a Polaris all-terrain vehicle. Traditionally, CVT systems are actuated through a centrifugal weight system, which involves opening and closing the sheaves of the CVT to vary speed ranges; ranges vary from a 3:1 reduction to 1:1.125 overdrive.

A belt-driven CVT, like the one seen in Figure 5, utilizes two pulleys, a primary and secondary, which are connected via the drive belt. Most commonly, the pulleys are controlled through centrifugal forces that vary with engine speed. Through this method, variable speeds can be produced, but are dependent on engine speed and loading.

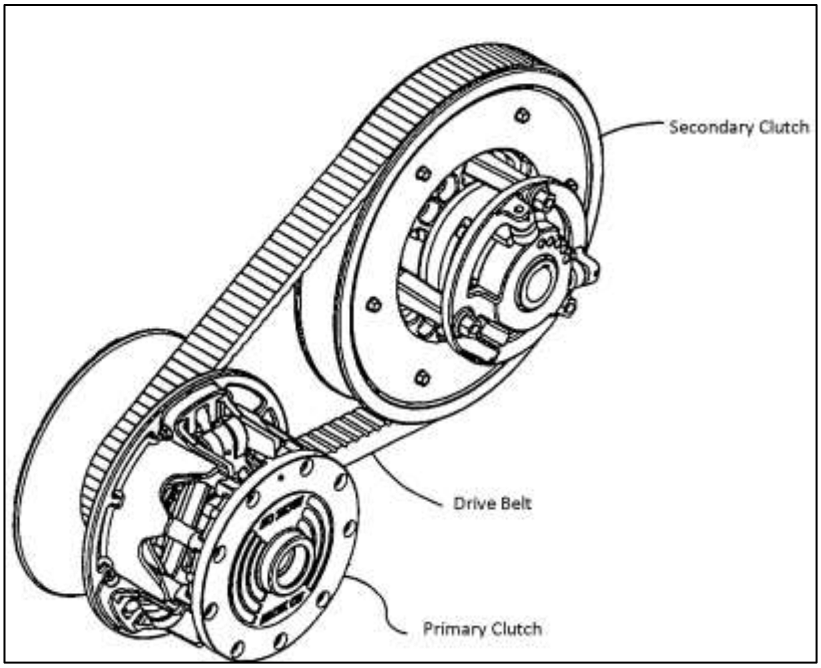


Figure 5: Polaris CVT Belt System (Polaris Industries 2008)

To improve efficiency of this system and directly control the gear ratio of the CVT system, the Bison Pullers developed an electronically actuated CVT (Figure 6). This system utilized an electronic actuator to manually close the primary clutch of the CVT system. By doing this, manual control of the speed within the 3:1 reduction to 1:1.125 overdrive range could be achieved independent of engine speed.

Figure 6: Bison Pullers Forced CVT Design (Bon, 2009)

The primary and secondary clutches, being from an ATV application, were designed for higher engine speed ranges (1800 to 6500 rpm), thus performance of the secondary clutch was less than optimal since the Bison Pullers' application operated at speeds from 1500 to 3200 rpm. In addition to this, the worn parts in the system caused the drive belt to slip and form a glaze on the surface of the clutches, severely degrading the performance of the system. It was also found that the efficiency of the CVT was roughly 78% at best and declined severely as the glaze formed on the clutches. Bison Pullers engineers discovered that proper tuning of the system takes many hours of testing and can have large impacts on efficiency.

For these reasons, the design team has decided not to pursue a belt-driven CVT drivetrain because testing methods such as a dynamometer and functioning load-sled are not currently available.

2.2.3 Bison Pullers Model 1131

With the combination of lower weight restrictions and the disappointing performance of the Bison Pullers' CVT-driven four-wheel drive tractor during the 2010 IQS Competition, club members decided to pursue a simpler two-wheel drive machine the following year. This 2011 tractor used the same 31 horsepower Briggs and Stratton Vanguard engine, NORAM centrifugal clutch, and Toro six-speed transaxle that are included in the design team's current drivetrain.

The centrifugal clutch on the Model 1131 was mounted midway back on the tractor, directly beneath the steering column, on a fully supported shaft independent of the engine. This shaft was then coupled to the engine via a flexible Lovejoy coupler that allowed for slight angular and radial misalignments of the shaft. The clutch provided excellent engagement under load, but due to its poor location and small housing, it was difficult to access the clutch itself.

The belt and tensioning system used in conjunction with the clutch were also housed in the same area which made the problem even worse.

The Toro transaxle performed well while pulling, but the shifting mechanism used to actuate the transmission was less-than-desirable. The shifter handle itself was a purchased component and was well designed, but the team decided to mount it to the steering column and connected it to the transmission using two push-pull cables. The stiffness of the cables, combined with loose and inadequate mounting, led to a system that sometimes could not actuate the transmission at all.

The main components of the 1131 were well designed and built, but the failure of smaller intermediate components led to a poor performance during heavy pulling. One main area of concern was the use of Lovejoy's *jaw in-shear* type coupling. This style of coupling is designed to be the weak point in any application, ensuring that critical more expensive components remain undamaged. In the design of the 1131, the Lovejoy coupling connected the engine's crankshaft to an input shaft which had a pulley mounted to it. The two shafts were misaligned causing the external retaining ring on the coupling to wobble and migrate from its intended position. When this happened, the spider came free from the coupling and was damaged. The team attempted to secure the retaining ring using adhesives, but the high frequency vibrations developed as result a of the crankshaft speed overcame the adhesive's strength and led to failure.

Another coupler problem that caused problems during the 2011 was the rear axle coupler. The coupler utilized rectangular tubing welded to drawn over mandrel (DOM) round tubing. The rectangular tubing was cut into a three sided shape so it could effectively slip over an existing splined cast coupler that was available to the Bison Pullers. Bolts were then used to fasten it to the cast coupler. This configuration placed an overwhelming amount of normal stress on the bolts. This resulted in plastic deformation and elongation which caused the coupler to fail. This failure can be seen in Figure 7.

Figure 7: Failed Axle Coupling System from the Bison Pullers Model 1131 Tractor

This failure occurred under normal operating conditions during the heavy pull of the competition. It ultimately led to a redesigned coupling system that was utilized on the Bison Pullers' 1231 tractor and in the design team's current drivetrain as well. This redesigned system, illustrated in Figure 8, eliminated the weaker cast coupler and instead used a spline shaft coupler welded directly to the axle shaft, eliminating the weak design flaw of using bolts. With the redesigned configuration, the entire axle assembly could be case-hardened to eliminate localized hard spots throughout the weldment.

Figure 8: Redesigned Axle Shaft Coupler System used to repair the Model 1131 Tractor

2.2.4 Bison Pullers Model 1231

Although the Bison Pullers' Model 1131 tractor had a series of major and minor failures and design flaws, the club decided to build another two-wheel drive tractor. Their goal was to enhance the components that did work well the previous year and modify or remove those that did not perform so well.

The Bison Pullers focused a majority of their attention on how to mount the shifter for the transmission so it would provide smooth and consistent shifts time and again. They decided to mount the shifter directly above and slightly ahead of the transmission. The shifter was not mounted to the transmission, but instead to the deck plate. A straight adjustable link was used to connect each side of the shifter to either of the two rotating mechanisms used to shift the transmission. These links easily disconnected from the shifter; this attribute, combined with the shifter being mounted to the deck plate, meant that the entire mechanism could be removed to allow access to the drivetrain components beneath the deck plate.

One portion of the 2012 tractor that led the design team to initially pursue a powershift transmission equipped drivetrain this year was the implementation of a belt-driven torque amplifier (TA), which acted as a primitive powershift transmission. A lighter weight and reduced cost were the reasons that the Bison Pullers chose to go with a more experimental belt-driven TA instead of a traditional mechanical one which uses a series of gears to boost torque.

Poor tensioning and controls ultimately led to the downfall of the belt-driven TA on the 1231. The TA was actuated using a push-pull cable, but this cable was difficult to mount in a way so that the outer cable housing would stay in place. Also, the Bison Pullers could not find a way to get the handle and inner cable to remain motionless once the TA was actuated, which put significant tension on the cable.

Another major drivetrain difference for the 1231 was the integration of a manually controlled single plate friction clutch. This clutch is used in the same Toro Workman utility vehicle as the transaxle being used, so the Bison Pullers' assumed it would be an easy way to couple their drivetrain components, since both components were designed to be used together by their manufacturer.

Some slight modifications of the clutch had to be made to ensure it would fit within the limited space available on the 1231 tractor. A large portion of the bell-housing had to be removed to decrease the overall length of the clutch. Then, a cover made of ¼ inch aluminum was mounted to the front. This cover included a tubular outer shafting and two roller bearings that fully supported the input shaft running from the TA to the clutch. These bearings fully supported the shaft in the radial direction but did not provide adequate axial stability.

The problem with the aluminum cover for the clutch was that it did not provide enough strength to keep the internal components in place when the clutch pedal was pressed to disengage the clutch, resulting in significant axial deflection. Because of this, there were times when the clutch plates would not separate and the tractor could not be stopped unless it was shut off entirely. The deflection of this aluminum cover caused problems for the Bison Pullers throughout the 2012 competition, including premature failure of the internal-spider type couplers the team chose to use.

2. Materials and Methodology

The development of the design team's final design took an unorthodox path to its final conclusion. The original focus of the project was to design a drivetrain that included powershift transmission technology. The reasoning behind this was the need for on-the-fly shifting during the competitive pulls at the IQS competition. Teams that performed well at recent competitions have made use of this technology and the design team's sponsor felt that including it in their latest tractor was a logical step in the development of a high-performance two-wheel drive tractor.

Approximately halfway through the development stage the sponsor decided to halt the development of a powershift drivetrain due to a lack of financial and labor resources. The sponsor instead decided to pursue the development of a drivetrain that was as simple to operate and maintain as possible. The following sections include descriptions and evaluations of five initial designs, all of which included powershift technology, and three latter designs whose focus was simplicity. Ultimately, a simplified drivetrain was chosen as the one to pursue.

3.1 Initial Designs

The five initial designs all included powershift technology, but the means of providing it varied greatly amongst the designs.

3.1.1 Design 1 - Racing Transmission with Quick-Change Rear Axle

This design utilizes a 2-speed transmission with reverse (B&J Racing Transmissions: Lindon, UT) and a rear differential (Winters Performance Products: York, PA) that features quick-change gears which allow the user to select different final drive ratios for various conditions. Both of these units are capable of withstanding up to 500 horsepower meaning that durability and maintenance concerns are nearly nonexistent. The transmission is actuated using a pressurized air system and push-button controls. The need for this air system and its maintenance requirements were reasons why this design may not be worth pursuing. An area where this design does stand out is the ability to swap the gears in the rear axle to select optimal gear ratios for various situations. Also, another housing and gear set can be added to the transmission to upgrade it to a three-speed unit.

The main areas of concern for this setup are its tremendous cost and the fact that it operates using a high pressure air system. High pressure air can be very dangerous to the operator and others close by. A noticeable advantage to this design is its light weight. This would allow the design team more freedom to experiment with other components and systems on the tractor. This design is a two-wheel drive configuration.

3.1.2 Design 2 - Transaxle with Manual Clutch and Mechanical Torque Amplifier

This design uses a transaxle (The Toro Company: Bloomington, MN), manual clutch, and mechanical TA. The transaxle has three forward gears and one reverse gear in both high and low range. It also has a lockable differential that can be disengaged at any time.

The TA gives this design the ability to shift on-the-fly. For this design, the TA consists of a planetary gear set contained inside a sheetmetal housing. This housing allows the TA to be immersed in fluid for cooling and lubrication purposes. Attached to the ring gear of the planetary gear set is a rotor from a disc brake system.

When the brake is not engaged, the TA operates at a 1:1 gear ratio and does not produce a torque increase. When the brake is engaged and the ring gear is held stationary, the TA produces a gear reduction and corresponding torque amplification whose values are dependent upon the planetary gear set chosen. The brake actuation takes place using a hand lever and traditional braking system, which includes a master cylinder and steel tubing for brake lines.

The drawbacks of this system include increased weight and increased complexity over Design 1. Both the housing and fluid for this system add significant weight which is a concern because the tractor can only weigh 800 lbs. total. Having to actuate the TA requires the driver to operate yet another lever or pedal; and he or she already has to deal with a throttle, clutch, brake, and steering wheel. The pros for this design are its high efficiency and relatively low cost. This design is again two-wheel drive.

3.1.3 Design 3 - Worm Gear Rear Axle with Mechanical Torque Amplifier

This design's two areas of interest are a worm gear differential and two independent final drives; each consisting of a planetary gear set. The worm gear takes the rotary power from the transmission and transposes it 90° to the rear axle. The torque from the rear axle is then increased through the gear reduction of the planetary gears located in the rear wheel hubs. This provides more useful power to the rear wheels. The drawback to this design is that most worm gears are for horsepower ratings lower than the 31 horsepower that will be running through it, and they also are only rated for 1800 maximum rpm, usually. The transmission for this design is simply the mechanical TA system described in Design 2. This design is a two-wheel drive configuration.

3.1.4 Design 4 - 3-Speed Automatic Transmission with Garden Tractor Rear Axle

This design consists of a 3-speed automatic transmission from a compact car connected to the rear axle from a garden tractor (Cub Cadet: Cleveland, OH). By using the automatic transmission, the tractor will be able to shift on-the-fly. The main drawback of this design is the immense weight of the transmission. When filled with fluid, it weighs more than 150 lbs. This is a significant problem due to the weight restriction on the tractor. Using the rear axle out of a garden tractor is ideal because no design, manufacturing, or machining has to be done. It can be purchased off the shelf from a supplier. Design 4 is also a two-wheel drive configuration.

3.1.5 Design 5 - 2-Speed Powerglide Transmission with Garden Tractor Rear Axle

Design 5 is similar to Design 4, but uses a 2-speed Powerglide transmission instead of the 3-speed automatic transmission out of an automobile. The Powerglide is also an automatic transmission, but is designed for high-horsepower applications in racing. Using this transmission reduces weight and is attractive because it can be purchased as a complete unit. This design uses the same garden tractor rear axle at Design 4 which can be purchased off the shelf. This final design is also a two-wheel drive configuration.

3.1.6 Evaluation of Initial Designs

3.1.6.1 Overview

In an attempt to determine the optimal design to pursue, the design team felt it was wise to evaluate each design be comparing various aspects of engineering designs. This allowed the team to compare the designs on a more accurate level. Only criteria that the design team felt were most critical were included. The criteria used were not weighted in any way because the design team had no basis for placing weighted values and could therefore, not rate them accurately.

3.1.6.2 Criteria

- **Safety**: The safety of the operator and potential bystanders are the most important items when designing a product. In an ideal world, all hazardous components would be engineered out of a system. This, of course, cannot be done in reality so if the hazards cannot be eliminated, they must be guarded against, or at the very least, warning signs and decals must be present to warn of possible dangers.
- **Manufacturability**: Designing an efficient and productive machine can easily be done on a computer, but if it cannot be built at a cost effective rate, then the design is not worth

considering. Welding, forming, laser-cutting, and bending limitations must be taken into account during development.

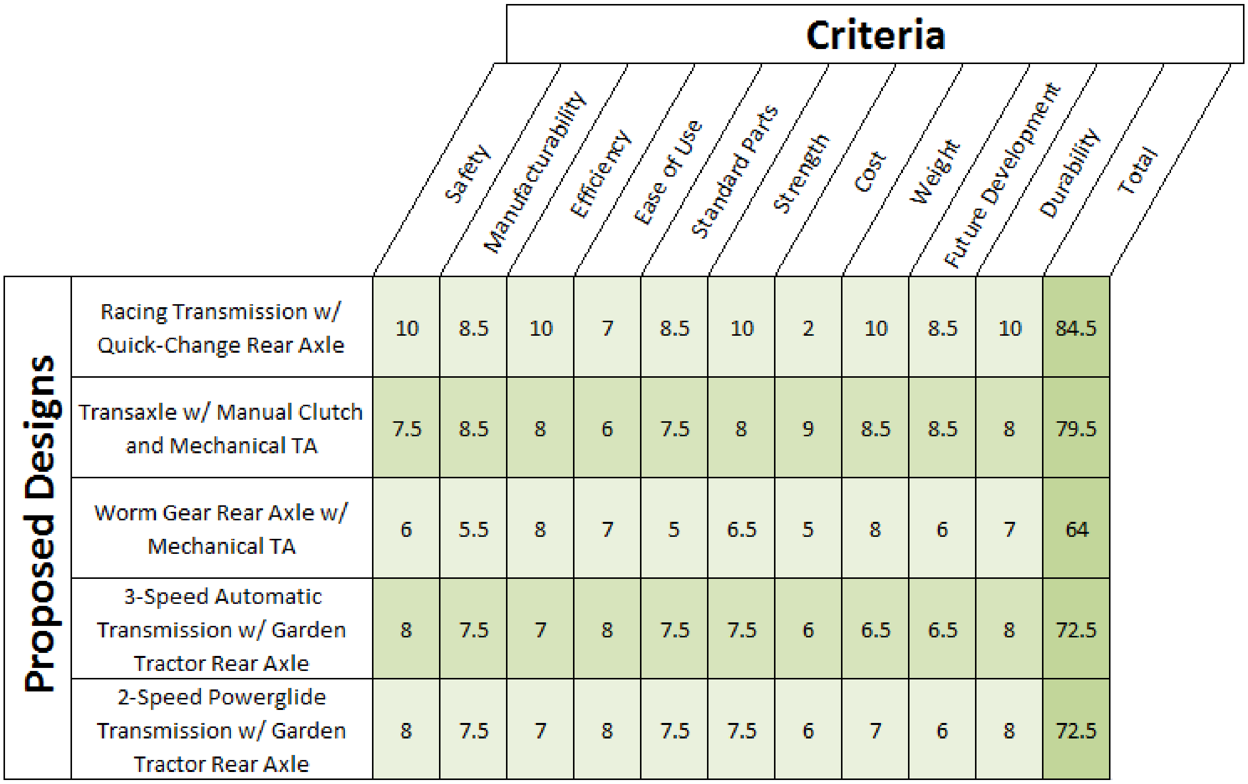
- **Efficiency**: With today’s emissions regulations, engine and driveline efficiencies are becoming increasingly important. Being able to transmit a greater percentage of engine horsepower to the drive wheels allows the operator to increase productivity without increasing pollution.
- **Ease of Use**: Operator comfort is always a major concern for customers. Operators often spend all day in a machine and being able to control the machine with minimal effort can be a deciding factor when purchasing a new product. No matter now efficient and durable a design is; if it is difficult and tiresome to use, nobody will want to buy it.
- **Standard Parts**: Industry professionals, as well as the design team, are constantly trying to incorporate the use of common parts across all their product lines in an effort to reduce cost and boost productivity. Use of standard parts relates closely with ease of use, but this time during maintenance. If only a few tools are needed to perform all of the common repair and maintenance operations on a machine, that machine will be very appealing to a potential customer. Examples of standard parts include: bolts, fasteners, cooling components, hoses, pedals and levers, etc.
- **Strength**: Manufacturers occasionally sacrifice quality and strength in an attempt to save cost. Sometimes this works in their favor; sometimes it does not. Companies build their reputations by manufacturing quality high strength machines at a reasonable price. In the agricultural and construction equipment industries, strength is paramount because these machines must operate for several decades in the harshest of conditions.

- **Cost**: Economics play a critical role in the engineering design process. Today, design engineers have extremely advanced technologies such as carbon fiber and fuel cells at their disposal, but the problem is that engineers cannot include them in their designs because they are simply too expensive. Finding the right combination of what to include and what to eliminate is what engineers are paid to do. This often comes down to determining what the customer wants and what he or she really needs.
- **Weight**: This criterion is critically important during the design process of a quarter scale tractor because the competition requires that the tractor weight no more than 800 lbs. without an operator. In the agricultural industry, soil compaction has become an item of concern because it can reduce soil productivity which ultimately leads to lost profits. Determining the optimum combination of weight and distribution of that weight has become a key aspect in engineering agricultural equipment.
- **Future Development**: Brainstorming during the engineering design process always produces a multitude of ideas; some are outlandish, but some are worth pursuing. Sometimes an idea may be viable, but just not at the present time. Limits on funding and current technology may be reasons that some ideas are postponed until future years. Designing a system that can be expanded upon and improved makes future designing simpler and easier.
- **Durability**: Durability is closely related to strength. Consumers will be much more likely to buy a product if they know that it can withstand abuse over a long period of time. Agricultural equipment is usually in use for an extended period of time so durability is definitely an item to think about.

3.1.6.3 Selection of a Powershift Drivetrain Design

Table 1 was used to assist the design team in choosing a design to pursue. All criteria explained above are listed, along with the point values and totals that each design was given. The point range was from 0 to 10 for each criterion.

Table 1: The table below assisted the design team in evaluating each initial design using 10 individual criteria. These criteria focus on the aspects of the designs that the team felt were most important.



		Criteria										
		Safety	Manufacturability	Efficiency	Ease of Use	Standard Parts	Strength	Cost	Weight	Future Development	Durability	Total
Proposed Designs	Racing Transmission w/ Quick-Change Rear Axle	10	8.5	10	7	8.5	10	2	10	8.5	10	84.5
	Transaxle w/ Manual Clutch and Mechanical TA	7.5	8.5	8	6	7.5	8	9	8.5	8.5	8	79.5
	Worm Gear Rear Axle w/ Mechanical TA	6	5.5	8	7	5	6.5	5	8	6	7	64
	3-Speed Automatic Transmission w/ Garden Tractor Rear Axle	8	7.5	7	8	7.5	7.5	6	6.5	6.5	8	72.5
	2-Speed Powerglide Transmission w/ Garden Tractor Rear Axle	8	7.5	7	8	7.5	7.5	6	7	6	8	72.5

After the initial designs were thoroughly evaluated, the design team decided to pursue Design 2 which uses a Toro Transaxle, friction clutch, and mechanical (TA). When looking at the table above, one would think that Design 1 should be chosen due to its higher total score. This could not be done because the racing transmission it uses costs $3400 alone and the design team's sponsor could not afford to invest that much money in a transmission alone. Only minimal progress was made on Design 2 before the sponsor chose to halt its development in favor of designing a simplified drivetrain that was easy to operate and maintain.

3.2 New Designs

Once the sponsor decided to pursue development of a simplified drivetrain, the design team again came up with several alternative designs. These were then individually evaluated to determine which one would provide the best solution for the sponsor's application.

3.2.1 Design A - Transaxle with Manual Clutch

This design utilizes the same six-speed transaxle and clutch as Design 2, but lacks the TA. The transaxle is shifted manually using a shift lever and appropriate linkage; the clutch is also manually operated, either with a foot pedal or hand lever. This design is nice because it keeps complexity to a minimum. Both primary components are used in industry today and have proven that they can perform well in a multitude of conditions. The main disadvantages of this system are its significant weight, it complex controls, and the major modifications that must be made to the clutch to allow it to operate well in the tractor.

Along with the clutch and transaxle, an arrangement of pulleys, shafts, and bearings are utilized to transmit power through the system. A small diameter pulley is mounted on the engine's rearward facing driveshaft. Via a double-rib V belt or cogged HTD belt, the rotational torque is then increased by coupling the small pulley to one with a larger diameter. This pulley is attached to a shaft that runs to the clutch, which operates using a traditional dry friction plate setup. The clutch is mounted directly to the transmission, which transfers power from the input shaft to the output shafts, through a 30:1 maximum gear reduction, and finally to the rear axles and tires. This design is a two-wheel drive configuration.

3.2.2 Design B - Transaxle with Centrifugal Clutch

This drivetrain is very similar to the Bison Pullers 1131 tractor mentioned earlier, but its clutch location and belt-tensioning system are what make it vastly superior to the 1131. With this design, the centrifugal clutch (NORAM: Milwaukee, WI) is mounted directly to the engine's crankshaft and immediately transfers power to a common shaft via a double-band B-belt and compatible pulley. This shaft couples directly to the transaxle, delivering power to the rear axle shafts and drive wheels. This drivetrain uses an automotive-style belt tensioner that can be easily adjusted with a spanner wrench or standard ¾ inch wrench.

The most noticeable difference and largest benefit of this system over the 1131 is that the clutch and tensioner are located above the frame of the tractor and are guarded by large removable shields to allow easy access during service or adjustment.

3.2.3 Design C - Transaxle with Centrifugal Clutch and Mechanical Torque Amplifier

This design is also similar to Design 2, which utilized the same transaxle and custom-built mechanical TA, but has a centrifugal clutch instead of a manual one. Using a centrifugal clutch eliminates the need for an added clutch pedal. With this design, the tractor incorporates four operator controls; brake pedal, accelerator pedal, TA actuator; and steering wheel. Controlling this drivetrain uses both feet and both hands of the operator and does not require any further control. This design also features the same placement of the clutch and tensioner that were used for Design B, but the tractor would have to be lengthened to allow the TA to fit into the frame ahead of the steering column. This lengthening would negatively impact the maneuverability of the tractor, making this design unfavorable.

3.2.4 Evaluation and Selection of a Simplified Drivetrain Design

Table 2 was used to evaluate the three new designs. The evaluation method and criteria used are identical to those used to evaluate the five initial designs.

Table 2: The table below assisted the design team in evaluating each new design and then selecting the one to pursue.

		Criteria										
		Safety	Manufacturability	Efficiency	Ease of Use	Standard Parts	Strength	Cost	Weight	Future Development	Durability	Total
Proposed Designs	Transaxle w/ Manual Clutch	8	9	8.5	6.5	9	8.5	10	9	9	8.5	86
	Transaxle w/ Centrifugal Clutch	10	9	9	9	9	9	10	9	8	8	90
	Transaxle w/ Centrifugal Clutch and Mechanical TA	8	9	8.5	7.5	9	8	10	9.5	7	7	83.5

Evaluation of the three new designs showed that Design B was the most favorable to pursue. Design B's high factor of safety, low cost, superior ease of use, and its potential for future development set it apart from the other two designs. As a result of all this, the design team decided to pursue the design and implementation of this drivetrain.

3.3 New Drivetrain Development

3.3.1 System Layout

When the development of the new simplified drivetrain began, the design team had already established the general layout of the system. The major components including the engine, transmission, and clutch had already been selected and preliminary placement of them within the drivetrain had been discussed. The engine was placed towards the front of the tractor's frame with the crankshaft facing rearward. The engine was mounted atop the tractor's frame to allow easy access during maintenance or repair. Mounted directly to the engine's crankshaft was a tri-lobe centrifugal clutch which is set to engage at 1800 rpm. The pulley sheaves on the clutch were placed facing forwards. The belt tensioning system was positioned to the lower left of the clutch (when viewed from the operator’s seat). It was mounted to a specially designed bracket intended to keep the design compact.

A double-band B-section belt was chosen to transmit power from the engine and clutch to the lower drive pulley. Once power reached the pulley, a shaft to which it was mounted delivered the power to the input shaft of the transaxle. This shaft was held in place using two pillow block bearings mounted towards the front and rear of the shaft. The transaxle, which was mounted at the rear of the frame; directly under the operator’s seat, altered the direction of motion from the driveshaft 90° to the rear axle shafts. The rear axle shafts, which feature a unique design that is discussed later, delivered power lastly to the rear drive wheels. Figure 9 displays the general drivetrain layout and focuses on several primary and secondary components.

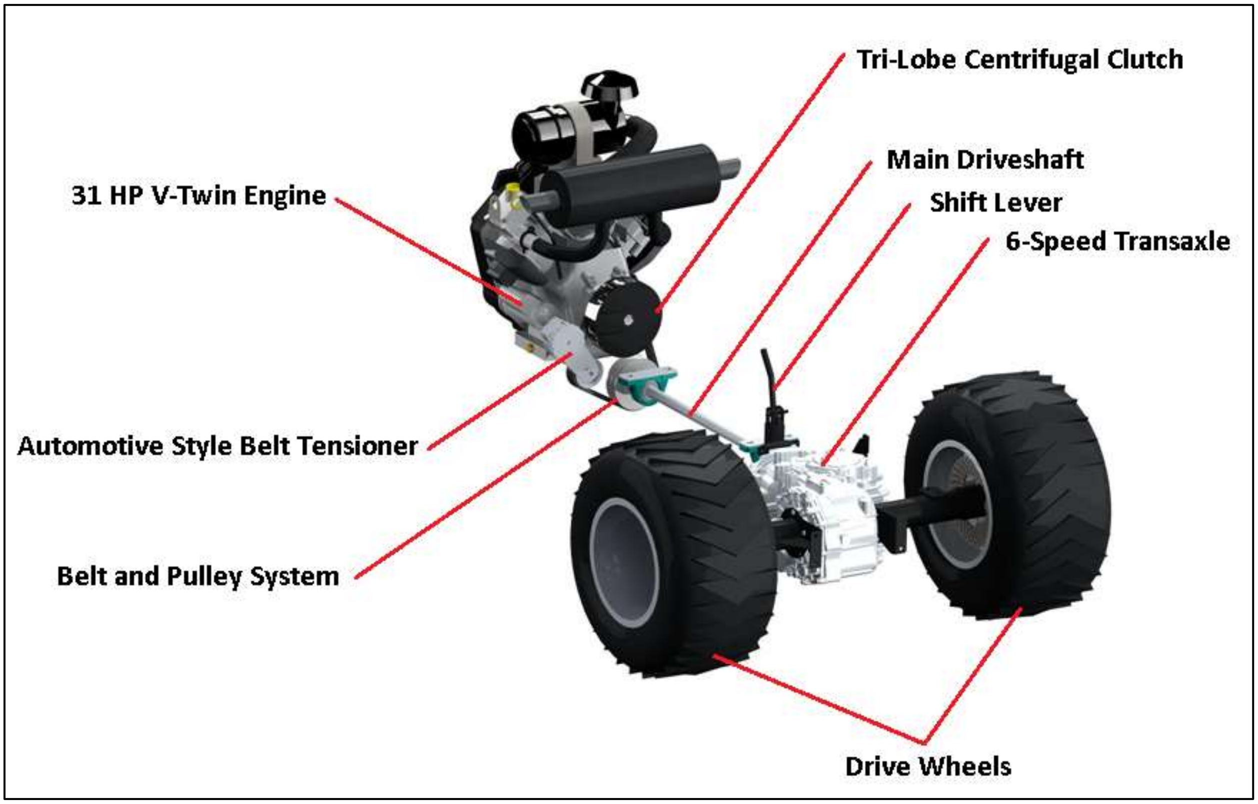


Figure 9: Simplified Drivetrain Layout

3.3.2 Failure Mode and Effects Analysis

Failure modes and effects analysis was utilized to aid in identifying high risks components such as past failed components. An overall drivetrain system analysis yielded that the hub/wheel adapter assembly, and axle shafts were the highest risk components. Table 3 illustrates the re-evaluation of the axle shaft weldment. In this analysis it was determined that a risk priority number (RPN) 240 and 192 out of 1000 was established for each failure mode. Severity, occurrence, and detection are three components that were rated to help identify the failure effects of the system. For both of these items, severity was rated 8-10 indicating these types of failures are severe if they occur. Occurrence was rated lower for both of these items as past failures of axle shafts was not a regular occurrence for the sponsor team. Lastly detection was rated the lowest in this analysis as the detection of these problems has been increased by the sponsor's team.

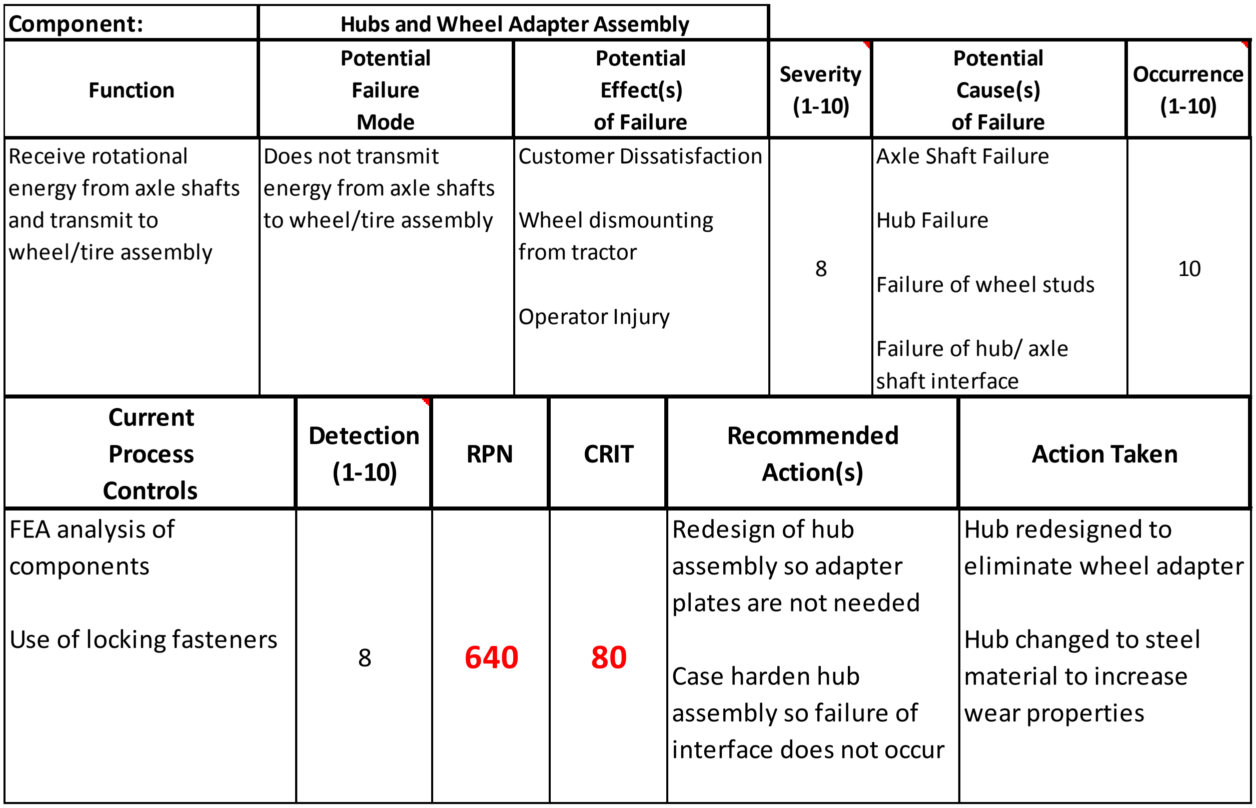
Table 3: FMEA table used to analyze axle shaft weldment

Component:	**Axles Shafts**				
Function	**Potential Failure Mode**	**Potential Effect(s) of Failure**	**Severity (1-10)**	**Potential Cause(s) of Failure**	**Occurrence (1-10)**
Transmit torque from transmission to tires	Does not transmit torque from transmission to wheels	Customer dissatisfaction Possible component failure	8	Axle shaft failure Hub Failure Transmission not in gear	6
	Transmits a fraction of torque from transmission to wheels	Customer dissatisfaction Possible component failure	8	Twisting of axle shafts Failure of axle shafts Failure of hub Differential not locked	6

Current Process Controls	**Detection (1-10)**	**RPN**	**CRIT**	**Recommended Action(s)**	**Action Taken**
FEA Analysis of components Transmission gear plaquard on tractor	5	240	48	Visually inspect welds and fix defects before assembly	Visual inspection process added after welding
FEA Analysis of components Differential normally locked	4	192	48	Visually inspect welds and fix defects before assembly	Visual inspection process added after welding

Analysis of the hub and wheel adapter system was also conducted to rate severity of these components, so they could be rated against the axle shaft weldments. Table 4 illustrates the FMEA analysis of the hub components. As seen in Table 4 the RPN of the hubs is 640, significantly higher than that of the axle shaft weldment. Through this it is determined that the hub assembly was the highest risk component that needed to be reevaluated and redesigned.

Table 4: FMEA table used to analyze hub and wheel adapter assembly



Component:	**Hubs and Wheel Adapter Assembly**				
Function	**Potential Failure Mode**	**Potential Effect(s) of Failure**	**Severity (1-10)**	**Potential Cause(s) of Failure**	**Occurrence (1-10)**
Receive rotational energy from axle shafts and transmit to wheel/tire assembly	Does not transmit energy from axle shafts to wheel/tire assembly	Customer Dissatisfaction Wheel dismounting from tractor Operator Injury	8	Axle Shaft Failure Hub Failure Failure of wheel studs Failure of hub/ axle shaft interface	10

Current Process Controls	**Detection (1-10)**	**RPN**	**CRIT**	**Recommended Action(s)**	**Action Taken**
FEA analysis of components Use of locking fasteners	8	**640**	**80**	Redesign of hub assembly so adapter plates are not needed Case harden hub assembly so failure of interface does not occur	Hub redesigned to eliminate wheel adapter Hub changed to steel material to increase wear properties

3.3.3 Secondary Component Selection

Once the selection and placement of the primary drivetrain components had taken place, the design team proceeded to evaluate and select the types and sizes of the secondary components which would transmit power between the primary components. These secondary components included shafts, bearings, and wheel hubs.

The final speed ratio of the belt system that connects the clutch and transmission input shaft was determined based on the following criteria:

- The tractor must be capable of driving 4 ± 2 mph at high idle during sound testing as per rule 5.5.4 as specified by the competition (ASABE 2013)
- The tractor must travel at 8 ± 1 mph at high idle to achieve optimum pulling performance based on observations of competitors’ results at past IQS events

Both of these conditions were satisfied by using a 1:1 ratio belt system.

Belt sizing calculations were conducted using Gates *Design IQ* software to verify the use of a double-band B belt would be sufficient. Belt tensions calculated previously were then used to determine shaft side loading, bearing loads, and bearing L_{10} lifespan. Once this was determined sizing of bearings that were able to meet a sufficient service life were selected.

In past years, the design team's sponsor found that using traditional eccentric locking bearings proved troublesome. This was due to the bearing's tendency to seize to the shaft after relatively short periods of operation. Damage to expensive shafts and increased maintenance costs were the ultimate results of choosing these types of bearings because they proved very difficult to remove. To combat this problem the design team researched multiple bearing locking systems, but eventually decided upon the Dodge Grip Tight locking system. This locking system is capable of completely locking shafts without marring the shaft material or the bearing surface.

To improve serviceability of the new design over the sponsor's past tractors, an automotive style belt tensioning system was included. Belt tensioning with this system is accomplished using a single wrench and the risk of over-tightening is completely eliminated. By engineering out the human factor, the drivetrain became more robust and less sensitive to human error.

The driveshaft running longitudinally from the belt system to the input of the transmission is made of turned, ground, and polished (TGP) 1-1/8 inch diameter cold rolled 1045 steel shafting. Tolerances regarding the diameter of TGP shafting as specified by the American Iron and Steel Institute (AISI) are ± 0.0015 inches. This tight tolerance shafting created a more cylindrical mating surface that reduced marring caused by irregular bearing mating surfaces.

The sponsor's previous tractor designs incorporated off-the-shelf hubs from a Polaris Ranger utility vehicle. These hubs utilized a four-bolt design, while the sponsor's wheels utilized a five-bolt pattern. This difference required the sponsor to manufacture hub adapters that converted the hubs from the standard four-bolt pattern to a five-bolt configuration. This adaptation, as seen in Figure 10, was accomplished by bolting an aluminum weldment to the hub that contained the five wheel studs needed to mount the wheel to the hub. Figure 10 also shows that the points at which the adapter and hub were fastened together experienced severely accelerated wear. This eventually caused a wheel to fall off of the tractor at the competition.

The main cause of the accelerated wear was the bolts used to fasten the adapter to the hub. Under high duty cycles, these bolts would stretch and compress causing the nuts to loosen. This allowed the adapter to rotate and quickly wear through the relatively soft aluminum components.

Figure 10: Failed Hub and Hub Adapter used on the Bison Pullers' Model 1231 Tractor

The design team provided a solution to this dilemma by developing a new hub system to implement on the sponsor's latest tractor. This new design eliminated the use of adapters, thus removing excess components and possible failure points from the system. The splined axle shaft used on previous hubs was replaced with a broached hexagonal surface. This hexagonal surface easily mates to the axle shaft featuring an identical pattern which allows for quick removal of the wheel/ hub assembly. This feature can be seen in Figure 11.

Figure 11: Redesigned Five-Bolt Hub with Hexagonal Bore

3.3.4 Cost Analysis

A cost analysis of the drivetrain was conducted to determine the financial impact that would be incurred by the sponsor team. It was determined that the total cost of the system cost was $3452.53 but the total cost would not be incurred by the sponsor team. Donated items included 31-HP Briggs and Stratton Vanguard engine, 6 speed Toro transaxle, two Titan 26 x 12 x 12 tires not including wheels, one NORAM manufacturing 3700 series clutch, and two front tires and wheels. With these items costs deducted from the total price of the drivetrain the total financial responsibility of the sponsor is $665.53.

As seen in Table 5, the design team evaluated the drivetrain in subcomponents that include, engine system, transmission/transaxle, drivetrain, and tires/wheels. These costs were then relayed to the sponsor team for use of their design report.

Table 5: Cost analysis of total drivetrain by subsystems

Sub Assembly:		Engine System				
P/N	Part Name	Purchased	Fabricated	Vendor	Qty	Cost
Fuel Tank	Fuel Tank	$ 10.00	$ -	DL Parts	1	$ 10.00
Fuel Line	1/4" Hose	$ 4.00	$ -	Macs	1	$ 4.00
Gas Pedal		$ 38.00	$ -	Midwest SC	1	$ 38.00
Engine	31HP Briggs	$ 1,360.00	$ -	Briggs & Stratton	1	$ 1,360.00
Total		$ 1,412.00	$ -			$ 1,412.00
Sub Assembly:		Transmission/ Transaxle				
P/N	Part Name	Purchased	Fabricated	Vendor	Qty	Cost
Clutch	Noram Clutch	$ 425.00	$ -	Noram	1	$ 425.00
Transaxle	6 Speed Toro	$ 813.00	$ -	Toro	1	$ 813.00
Total		$ 1,238.00	$ -			$ 1,238.00
Sub Assembly:		Drivetrain				
P/N	Part Name	Purchased	Fabricated	Vendor	Qty	Cost
5.6 Pulley	QD Sheave	$ 23.50	$ -	TB Woods	1	$ 23.50
QD CPLR	QD Coupler	$ 6.50	$ -	TB Woods	1	$ 6.50
Dry Bearing	1.125" Bearing	$ 65.00	$ -	Dodge	2	$ 130.00
Driveshaft	1.125" TGP 1018	$ -	$ 27.50	Bison Pullers	1	$ 27.50
Axle Bearing	1.125" Bearing	$ 52.50	$ -	Polaris	2	$ 105.00
Axle Tube	LH & RH Axle Tube	$ 39.99	$ -	Polaris	2	$ 79.98
Axle Shaft	LH & Rh axle shaft	$ -	$ 65.00	Bison Pullers	2	$ 130.00
Belt	B35	$ 22.05	$ -	Gates	1	$ 22.05
Total		$ 209.54	$ 92.50			$ 524.53
Sub Assembly:		Tires/ Wheels				
P/N	Part Name	Purchased	Fabricated	Vendor	Qty	Cost
Rear Tire	26x12x12	$ 37.50	$ -	Titan	2	$ 75.00
Front Tire	4x8	$ 32.00	$ -	Midwest SC	2	$ 64.00
Rear Wheel	DWT	$ 43.20	$ -	DWT	2	$ 86.40
Front Wheel	DWT	$ 25.00	$ -	DWT	2	$ 50.00
Lug Nuts		$ 0.26	$ -	Fastenal	10	$ 2.60
Total		$ 137.96	$ -			$ 278.00
Total Cost						**$ 3,452.53**

4. Design Calculations

As per the 2013 IQS competition, Rule 3.4.states: “Tractors can use either a maximum of two Briggs & Stratton 16-hp Vanguard engines or one Briggs & Stratton 31-hp Vanguard engine. If used, the multiple engines cannot be connected in series.” The design team’s sponsor chose to again use the 31-hp Vanguard engine. The deciding factor when making this choice were the engine coupling problems during past competitions. The performance characteristics of the engine are illustrated in Figure 12.

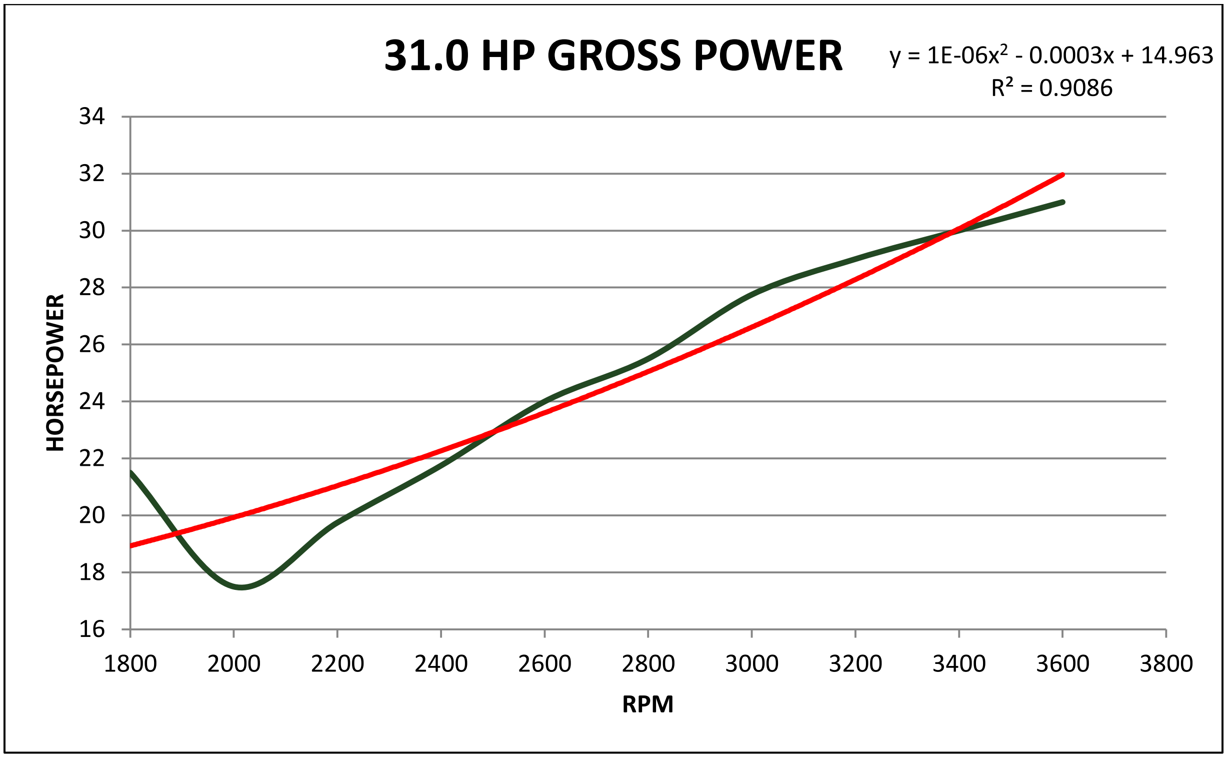


Figure 12: Performance Characteristics of 31-hp Briggs and Stratton V-Twin Engine

Using these performance characteristics, the design team was able to calculate the torque and horsepower through various driveline components. Using this data along with Equation A.8, the team determined the maximum torque output of the engine to be 62 ft-lb at 1800 rpm.

$$HP = \frac{T * N}{5252\,\frac{ft-lb}{\min hp}} \Rightarrow T = \frac{HP * 5252\,\frac{ft-lb}{\min hp}}{N} \Rightarrow T = \frac{21.5 * 5252\,\frac{ft-lb}{\min hp}}{1800\,rpm} = 62ft-lb$$

This data was then used to calculate the size and specifications of driveline components. Table 6 displays the transmission output shaft speeds through all operating gears, including reverse, for the tractor's base configuration. For these calculations, low idle was taken to be 1800 rpm and high idle was set at 3400 rpm. These values are set forth by the rules committee in charge of the competition as well as the engine manufacturer.

Table 6: Transmission Output RPM and Tire Speed

Transmission Gear		1L	2L	3L	1H	2H	3H	R1	R2
Gear Reduction	:1	89	57	33	34	22	13	92	36
Output RPM Low Idle	(rpm)	20	32	55	53	82	138	20	50
Wheel Speed Low Idle	(mph)	1.6	2.4	4.2	4.1	6.3	10.7	1.5	3.9
Output RPM High Idle	(rpm)	38	60	103	100	155	262	37	94
Wheel Speed High Idle	(mph)	3.0	4.6	8.0	7.7	12.0	20.2	2.9	7.3

Utilizing these values, the design team was able to calculate the torques (ft-lb) that would be transmitted through the transmission input shaft, axle shafts, and the force transmitted to the ground by the tire. The results shown in Table 7 were calculated assuming perfect traction conditions.

Table 7: Torques and Forces Transmitted by Various Shafts

Engine Torque	62	(ft-lb)
Transmission Input Shaft	62	(ft-lb)
Axle Shaft	5518	(ft-lb)
Torque at Wheels	5978	lb_f

Using the values from Table 7, proper shaft sizes were determined by using the following equations (Beer). For the shaft that transmits power from the belt system to the transmission, it was determined that a 1-1/8 inch diameter shaft would work best to provide minimal torsion deflection while also providing a lightweight mode of transmitting the maximum torques.

$$J = \frac{\pi D^4}{32} = \frac{\pi (1.125)^4}{32} = 0.157257$$

$$\emptyset = \frac{TL}{JG} = \frac{62(ft - lb) * \frac{36\ (in)}{12\ (\frac{in}{ft})}}{.157257 * 11.6\ mpsi} = 1.02e^{-4}\ radians = \ 0.0058°$$

A rotational deflection of 0.0058° was found to be acceptable as this value is less than 1% of 1° of deflection along the entire length of the shaft. With a factor of safety equal to 2, the maximum deflection was still below 0.015° degrees of deflection. The same calculations were conducted for the rear axle shafts to determine appropriate sizing of the DOM tubing. It was found that 2.00 inch outer diameter by 1.50 inch inner diameter DOM tubing would provide less than 0.0075° of deflection along the length of the axle shaft, which was adequate.

4.1 Bearing Load Calculations

The transmission input shaft was arranged like the image in Figure 13.

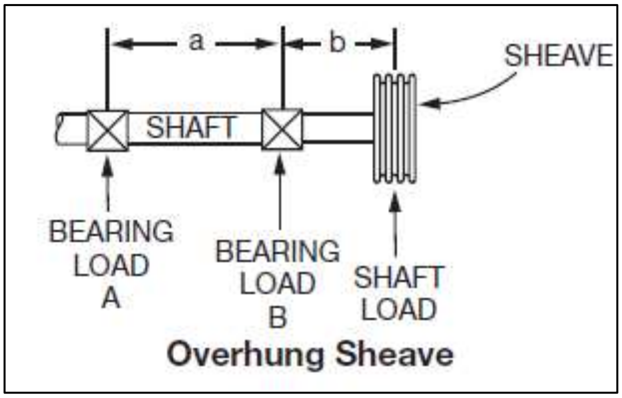


Figure 13: Bearing and Sheave Configuration (Baldor Electric Company, 2013)

The shaft load was calculated by solving for belt tensions on the drive belts. These values were found to be $T_1 = 208\ lb_f$ and $T_2 = 104\ lb_f$, thus the net force on the shaft is 312 lb_f. Dimension A for the current design is 23.5 inches and dimension B is 2.75 inches. From this, the design team was able to calculate the loads on bearings A and B using the following equation.

$Load\ A = Shaft\ Load * \frac{a}{b}$ Where a & b are distances in inches

$$Load\ A = 312\ (lb) * \frac{23.5in}{2.75in} = 2666.18\ lb$$

$$Load\ B = \frac{Shaft\ Load * (a+b)}{a}$$ Where a & b are distances in inches

$$Load\ B = \frac{312\ (lb) * (23.5 + 2.75)in}{2.75\ (in)} = 2978.18\ lb$$

4.2 Relevant Equations

See Appendix A for a complete list of equations and Appendix B for a list of symbols.

5. Results

5.1 Project Evolution

Using the methodology laid out earlier, the design team was able to successfully develop a drivetrain for their sponsor's latest quarter scale tractor that is both durable and easy to use. This drivetrain incorporates several commercially available components, but also uses many original parts that were drafted by the design team. As of now, the drivetrain has been designed using CAD software and has been partially assembled during the preliminary construction of the tractor. Many parts for the drivetrain have been manufactured and purchased, while some are still being fabricated. Full assembly and field testing needs to take place before the design team can fully know if their design was a viable solution to their sponsor's problem or not.

The original intent of this project, set forth by the sponsor, was to develop a quarter scale tractor drivetrain which included powershift transmission technology. Midway through the design process, however, the sponsor and the design team decided to substitute this plan for one that focused on the development of a drivetrain that was as simple to manufacture, maintain, and operate as possible. The reason for this was the limited fiscal and workforce resources that were available to the design team and sponsor. After this decision was made, all five of the original drivetrain configurations which included powershift transmissions or torque amplifiers, were abandoned.

Once the project focus shifted, and because it shifted so radically, the design team completely changed their engineering strategy as well. The project was no longer so much about increasing the tractor's performance as about maintaining the same performance with a drivetrain that was less complicated to operate and service.

Throughout the design process, the design team worked closely with their sponsor; attending their weekly club meetings and discussing possible ideas and solutions frequently. Input from the sponsor club's members was a tremendous help in development of the simplified drivetrain, and help from them will also be needed and appreciated when assembly of the tractor commences.

5.2 Meeting the Design Objectives

The proceeding sections explain how the final drivetrain met each of the four design objectives developed by the design team prior to the start of the project.

5.2.1 Design a Lightweight Drivetrain

Many components of the final design helped lower the weight of the drivetrain. This allowed the sponsor to expand other aspects of their tractor's design in an effort to compete valiantly at this year's IQS competition.

The guidelines of the IQS competition state that a tractor can utilize one 31-hp engine or two 16-hp engine. Since the inception of the 31-hp engine in 2011, the design team's sponsor has chosen to use this engine to reduce weight and eliminate the need for a complicated engine coupling system. The single 31-hp engine weighs 125 lbs. as compared to the combined weight of two 16-hp engines, which total 144 lbs (Briggs and Stratton Corporation, 2013). This results in an immediate savings of 19 lbs. The engine, which is a Briggs and Stratton Horizontal Shaft Air Cooled V-Twin Big Block, can be seen in Figure 14.

Figure 14: Briggs and Stratton Horizontal Shaft Engine chosen by the Design Team (Briggs and Stratton Corporation, 2013)

The Fenner Drives RT 4100 automotive style belt tensioner used in the drivetrain reduced the weight by 3 lbs. Past tensioning systems utilized on the sponsor's tractors were designed by the sponsor. These systems were often crude and bulky due to the limited timeframe they had to develop them. The Fenner Drives tensioner also reduces complexity of the tensioning system by reducing the number of parts and combining them into one compact assemble that can be easy adjusted with simple hand tools. The placement of the Fenner Drives belt-tensioner can be seen in Figures 15 and 16.

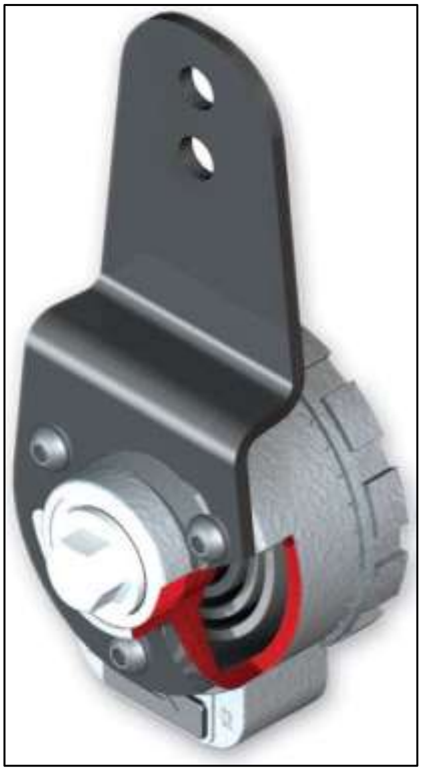


Figure 15: Fenner Drives RT 4100 Belt-Tensioner (Fenner Drives, Inc., 2013)

Figure 16: Mounting location of RT 4100 Belt-Tensioner (Left Side View)

The North American Clutch Corporation (NORAM) 3700 Series Tri-Lobe centrifugal clutch on the drivetrain saves weight in two ways. The weight of the clutch itself is 31 lbs which is four lbs less than the friction-plate clutch used on the sponsor's 1231 tractor. This clutch, which was utilized by the sponsor on their 1131 tractor, is now mounted directly to the engine's crankshaft. Previously, it was mounted on a fully supported shaft positioned further back in the frame, separate from the crankshaft. By eliminating this shaft, the bearings it required, and the housing that accommodated the entire system, the current design reduced weight by 15 lbs. The NORAM clutch can be seen in Figures 17 and 18.

Figure 17: NORAM Tri-Lobe Centrifugal Clutch (North American Clutch Corporation, 2013)

Figure 18: NORAM Clutch mounted in the Tractor

5.2.2 Design a Reliable Drivetrain is Serviceable by Owner

The drivetrain developed by the design team incorporates several means of reducing and simplifying serviceability. The NORAM centrifugal clutch utilizes no fluids that must be checked and replaced regularly like a manual wet clutch. In accordance with manufacturer’s recommendations, replaceable wear components can be installed to rebuild the clutch and bring it back to ideal performance levels.

The drivetrain also features easy access to regular maintenance points such as engine and transmission oil drain ports, engine oil filter, and driveline bearing grease points. Aiding this, the engine oil check and fill points are located on top the engine providing easy access for daily inspection and regular oil changes. The oil filter access and drain port can be seen in Figure 19, while the transmission dipstick, circled in red, can be seen in Figure 20.

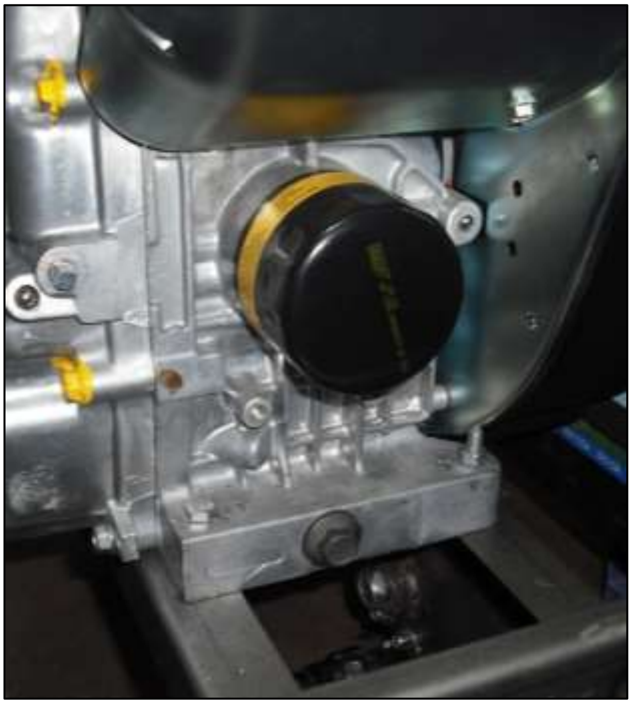


Figure 19: Oil Filter and Drain Plug Accessibility

Figure 20: Transmission Dipstick Access

Figure 20 displays the Dodge GT 206 1-1/8 inch pillow block bearings. These bearing can be accessed for lubrication from underneath the tractor's frame (Figure 21). The sealed bearings feature a service interval of 250 hours per manufacturer instructions. This reduces maintenance considerably.

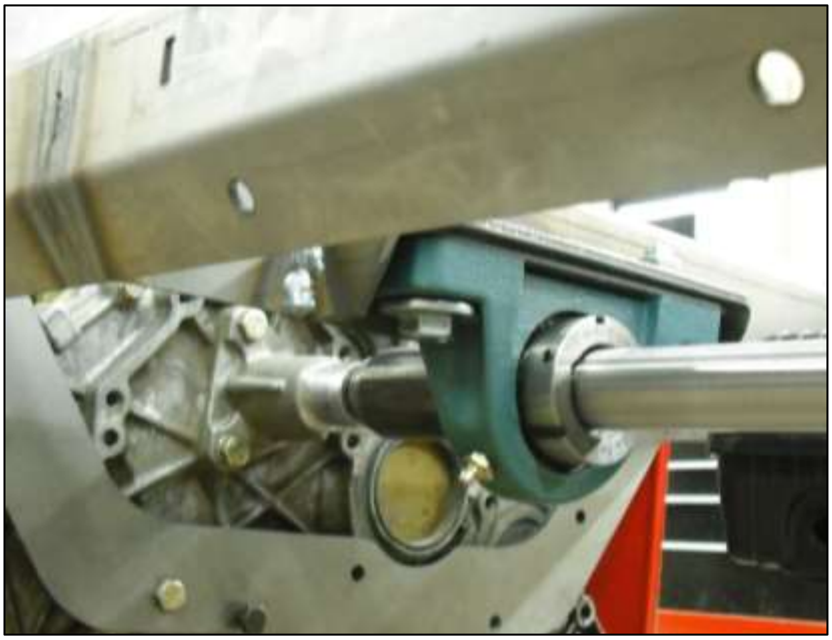


Figure 21: Greased Lubrication Access for Dodge GT 206 Bearings (Baldor Electric Company, 2013)

5.2.3 Design a Drivetrain with Simple Operation Using Few Controls

By using a control configuration similar to those found on compact tractors, the design team was able to simplify the operation of the new drivetrain. The pedals chosen by the design team are commercially available so obtaining replacement parts is not a concern. A Wilwood floor mount aluminum brake pedal (P/N: 340-1285), complete with bias balance bar, controls two Wilwood High Volume Master Cylinders (P/N: 260-6764). This pedal is mounted on the deck plate to the left of the steering column, similar to other tractors. A Midwest Super Cub aluminum throttle pedal kit with cable included easily connects to the throttle mechanism on the engine. The braking control and throttle assembly can be seen in Figures 22 and 23, respectively.

Figure 22: Drivetrain Features one Wilwood Brake Pedal which Controls Two Master Cylinders (Wilwood Engineering, Inc., 2013)

Figure 23: Midwest Super Cub Throttle Pedal Assembly (Midwest Super Cub, 2013)

The shifter for actuating the transaxle uses a standard H-pattern shifting layout and is centered atop the deck plate, between the operator's legs. This location is used on lawn and garden, compact, and many older row crop tractors. The handle for the shifter features a specific orange coloring (Munsell No. 5.0YR6.0/15) which is to be used on all machine ground motion controls in accordance with the Standards of ASABE. The orange coloring and shifter location can be seen in Figure 24.

Figure 24: Location and Coloring of Custom-Built Shifter

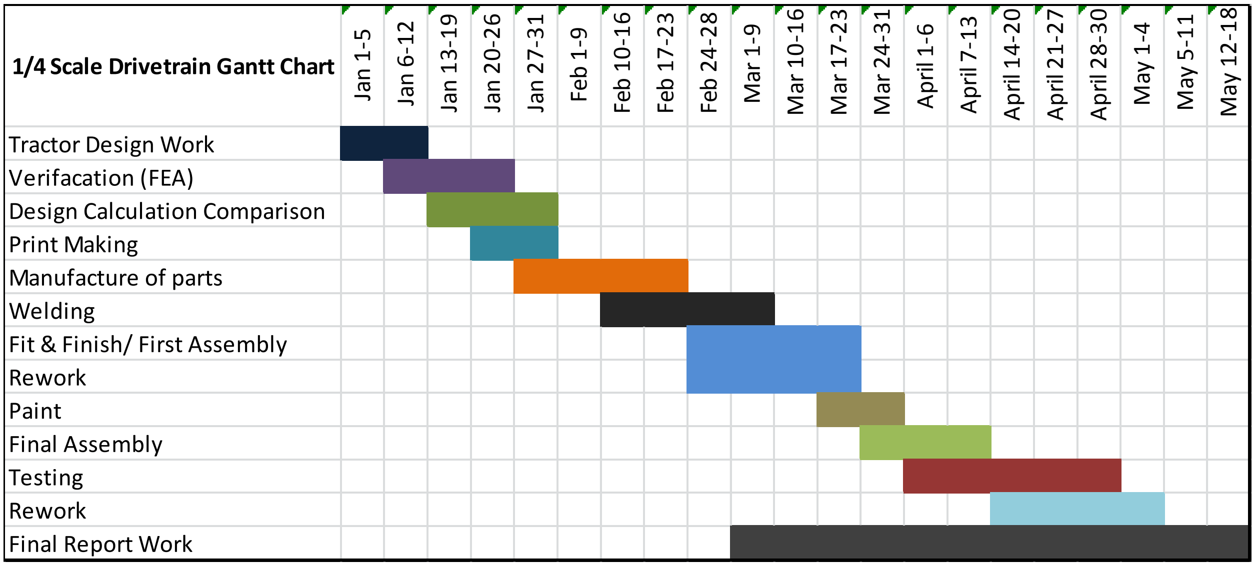
5.2.4 Design a Drivetrain with Capability for Further Development

The sponsor charged the design team to develop and simple lightweight drivetrain to be used on their 2013 tractor, but they also wanted it to be compatible with any future development that may occur in coming years, primarily the integration of a mechanical or belt-driven TA system. By using a centrifugal clutch, the design team made the sponsor’s desire possible. Because this clutch engages at a specific engine speed and requires no operator control, including a TA and the actuation system it requires can be done. Right now during tractor operation, the operator is responsible for handling the steering wheel with one hand, throttle pedal with their right foot, and brake pedal with their left foot. This leaves one hand free to operate the TA.

By housing the clutch, pulley, belt, and tensioner in one area near the engine, there is sufficient room for a TA if the tractor’s frame is lengthened slightly. The TA, if included, would reside low in the frame where the driveshaft now lies. This driveshaft would be split into both an input and output shaft entering and exiting the TA, respectively.

Project Schedule

The design team used a simple Gantt chart to manage project progress and ensure that their intermediate goals were completed on time. This Gantt chart is shown below in Figure 21.



1/4 Scale Drivetrain Gantt Chart	Jan 1-5	Jan 6-12	Jan 13-19	Jan 20-26	Jan 27-31	Feb 1-9	Feb 10-16	Feb 17-23	Feb 24-28	Mar 1-9	Mar 10-16	Mar 17-23	Mar 24-31	April 1-6	April 7-13	April 14-20	April 21-27	April 28-30	May 1-4	May 5-11	May 12-18
Tractor Design Work	■	■																			
Verifacation (FEA)		■	■	■																	
Design Calculation Comparison			■	■	■																
Print Making				■	■																
Manufacture of parts					■	■	■	■													
Welding							■	■	■	■											
Fit & Finish/ First Assembly									■	■	■	■									
Rework									■	■	■	■									
Paint												■	■								
Final Assembly													■	■	■						
Testing														■	■	■	■	■			
Rework																■	■	■	■		
Final Report Work										■	■	■	■	■	■	■	■	■	■	■	■

Figure 25: Gantt Chart utilized by design team to manage project progress

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Appendix A: Design Calculation Equations

Shear Stress on a Circular Shaft

$$\sigma = \frac{TC}{J} \qquad \text{(A1)}$$

Maximum Twisting Moment

$$T_{MAX} = \frac{\sigma_{Max} \times J}{C} \qquad \text{(A2)}$$

Polar Moment of Inertia for a Solid Circular Shaft

$$J = \frac{\pi D^4}{32} \qquad \text{(A3)}$$

Torsional Deflection on a Circular Shaft

$$\emptyset = \frac{TL}{JG} \qquad \text{(A4)}$$

Torque Transmitting Capacity of a Clutch

$$T_C = f * F_C * r_m * n_s \qquad \text{(A5)}$$

Mean Radius of a Clutch

$$r_m = \frac{D_0^3 - D_i^3}{3(D_o^2 - D_i^2)} \qquad \text{(A6)}$$

Torque Transmission between Belt-connected shafts

$$\frac{T_1}{R_1} = \frac{T_2}{R_2} \qquad \text{(A7)}$$

Horsepower (B.C. Units)

$$HorsePower = \frac{T*N}{5252\,\frac{ft-lb}{\min hp}} \qquad \text{(A8)}$$

Bearing Loading Bearing A

$$Load\ A = Shaft\ Load * \frac{a}{b} \qquad \text{(A9)}$$

Bearing Loading Bearing B

$$Load\ B = \frac{Shaft\ Load * (a+b)}{a} \qquad \text{(A10)}$$

Appendix B: List of Symbols

a = center distance between bearing A and bearing B in inches

b = center distance between bearing B and drive sheave in inches

σ=shear stress (MPa, psi)

T = twisting moment (Nm, in lb)

C = distance from center of stressed surface (mm, in)

J = polar moment of inertia for given cross section (mm^4, in^4)

T_{max} = maximum twisting moment to reach maximum stress (Nm, in lb)

Σ_{max} = maximum shear stress (MPa, psi)

D = outside shaft diameter (mm, in)

$\emptyset$= angular shaft deflection (rad)

L = nominal shaft length (mm, in)

G = modulus of rigidity (MPa, psi)

T_c = torque capacity (Nm, in lb)

f = coefficient of friction

F_c = clamping force provided by clutch springs (kN, lbf)

r_m = mean radius of clutch (mm, in)

n_s = number of torque transmitting surfaces = 2 times the number of disks

D_o = outer diameter of clutch disks (mm, in)

D_i = inner diameter of clutch disks (mm, in)

T_1 = torque moment on shaft 1

T_2 = torque moment on shaft 2

R_1 = radius of pulley on shaft 1

R_2 = radius of pulley on shaft 2

N = revolutions per minute