UMSAE Baja Transmission Design

Company Name: UMSAE Baja

Project Advisors: Malcolm Symonds & Paul Labossiere

Final Design Report

Team # 19

Team Name: Trans-Formers

2011-12-05

Names of Team Members:

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Letter of Transmittal

Dec 6th, 2011

Dr. Paul E. Labossiere
Room E1-546 EITC, University of Manitoba
Winnipeg, Manitoba, Canada
R3T 2N2

Dear Dr. Labossiere,

We are submitting to you this report, due December 6th, 2011, which outlines our final design for the UMSAE Baja transmission. The report focuses on the features of our design, as well as cost and technical analysis. The design is the result of considering a number of alternatives, which were carefully screened based on our clients' needs. If you should have any questions concerning our report or project, please feel free to contact me, John Bais, at .

Sincerely,

John Bais
Team Leader

Abstract

The University of Manitoba SAE (UMSAE) Baja team is a school group that designs, builds and races an off-road vehicle every year. The team has requested a re-design of their powertrain system, as they have had problems with the operation of the vehicle at last year's competition. This report describes the final design that will best meet the needs of the Baja team. The design was chosen by narrowing down a list of concepts based on the needs of the Baja team and the required technical specifications of the car's powertrain. Four designs met those needs and were researched further after which a final design was selected.

The design selected is an Infinitely Variable Transmission (IVT) system, which is created by modifying a Continuously Variable Transmission (CVT) system by adding a planetary gear set. The sun gear of the planetary set is driven directly by the engine and the ring gear is driven through the CVT which is attached to the engine. Changing the CVT ratio changes the speed of the ring gear which, in turn, creates a difference in the speed of the ring and sun gears. This difference causes the planet gears to displace, which is the output of the system to the wheels. A pair of gears reverses the direction of rotation of the ring gear and a sprocket set is added to give the ability to easily change the overall reduction ratio of the system. This system offers high low-speed torque while still providing a high top speed and, for this reason, an IVT system will be the best option for the Baja team.

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1 Introduction

The UMSAE Baja team competes in an annual competition with a student-designed off-road vehicle and has requested a redesign of its powertrain system. The current powertrain system consists of a Polaris CVT clutch and a UMSAE Baja custom made gear box. The custom gear box has high, low, and reverse settings, as well as a lockable differential. The problems with the current system are as follows:

- The gearbox will not stay in gear and slips into neutral when strong torque loads are applied.
- The differential within the gearbox will not unlock.
- The hand controls are not ergonomic.

The UMSAE Baja team has a powertrain system design that goes from the stock engine to the rear axle. The design should also include the driver controls for the system to improve the ergonomics of the shifting system. The transmission system that will be designed should allow for the tires to spin independently thus improving the vehicle's manoeuvrability. At the same time, the system developed should have the versatility to handle events such as the rock crawl where all four tires will not always be in contact with the ground. The SAE competition rules state that a Briggs & Stratton Intek 20 engine must be used by all teams, therefore the design is limited by those operating specifications [**1**]. In order to remain competitive, however, the performance efficiency must be increased while reducing the system's weight, these are often contradictory objectives.

1.1 Project Objectives

The goal of this project is to improve the performance of the 2011 Baja powertrain design. This project will focus on the analysis of the current system and the design of a new transmission system for the Baja vehicle. The design will also include analyses, calculations, and full justification of all components involved in the final design.

To achieve success at international competition the design must be

- Capable of transferring motion from the engine to the wheels
- Designed/optimized for each dynamic event at the Baja competition
- Able to provide gearing to keep the engine within the optimum power band
- Capable of spinning each driven wheel independently, as well as coupling each wheel to spin at the same rate
- Capable of forward and reverse drives
- Able to operate in a variety of terrains
- Able to withstand prolonged adverse conditions
- Easy for students to service, repair and troubleshoot
- Easy for an amateur driver to operate under dynamic events
- Packaged to keep the center of mass as low as possible
- Small enough to fit within the frame's backend
- Able to adapt to different frame mounting configurations
- Designed to keep the wheelbase as short as possible
- Relatively light (not more than 80 lbs.)
- Cost effective (team's powertrain budget is approximately $5000)

- Manufactured from as many standard components as possible
- Efficient by maximizing performance output with minimal power losses
- Compatible with SAE Briggs & Stratton Intek 20 Baja engine
- Compliant with SAE safety requirements
- Designed to follow Baja's competition rules

The aim is to produce a design that meets all of the above requirements so that the Baja team can achieve success at the 2012 competition.

1.2 Target Specifications

To optimize the design of a new Baja transmission system and aid in the selection of feasible power transmitting alternatives, a table of customer needs has been made according to the corresponding technical specifications. The metrics associated with the technical specifications are identified and listed, as well as their current and target values.

1.2.1 Analysis of Customer Needs

The transmission design must satisfy the customer needs in Table I below. Each customer need has a corresponding importance value ranging from 1 to 3, with 1 being the most important, based on suggestions from the client.

TABLE I - CUSTOMER NEEDS

Need #	Need	Importance (1-Highest, 3-Lowest)
1	Must transfer motion from the engine to the wheels	1
2	Must be optimized for each dynamic event at the Baja competition	1
3	Must be durable	2
4	Must provide different gear ratios	2
5	Must be easy to manufacture	3
6	Must be able to operate in a variety of terrains	2
7	Must be packaged to keep the center of mass as low as possible	2
8	Must have minimal power losses	2
9	Must be cost effective	3
10	Must be relatively small	2
11	Must be relatively light	1

1.2.2 Technical Specifications

The technical requirements of our design, based on the needs of our customer, are summarized and provided as target values in Table II below.

TABLE II - TECHNICAL SPECIFICATIONS

Need #	Metrics	Imp	Units	Current Value	Target Value
11	Weight	1	Lbs.	65	<80
5,10	Size	1	In^3	1000	<2000
1,2,3	Input RPM range	1	RPM	1800-3800	1800-3800
2,4	Target speeds	1	km/hr	65	60-80
2,4,6	Min/Max gear ratios	1	times	6-40	5.46-38.1
8	Efficiency	3	%	Unknown	>60%
5	Manufacturability	3	Easy/Medium/Difficult	Medium	Easy
9	Cost	2	CAD $	$3000	<$5000
3	Running life	3	Km	Unknown	10000 km

Thirteen concepts were developed, and the team then screened those concepts on how well they met the basic needs of our customer. This produced four design concepts which were then scored based on their technical abilities. The final design concept was chosen based on the highest ranked score from the technical specifications.

2 Details of the Design

After doing an in-depth concept analysis on the designs that were being considered, the team decided that an Infinitely Variable Transmission (IVT) system would be the best choice, as it scored well in all of the technical specification categories. An IVT powertrain consists of a modified Continuously Variable Transmission (CVT) with the addition of a planetary gear set [**2**].

A CVT is essentially a pair of pulleys with tapered walls that are able to move in and out. This allows for a continuous range of gear ratios where no gear shifting occurs. This is beneficial when compared to gears which can only provide a small number of different ratios. Gears are relatively inefficient when it comes to reductions as the engine is not kept within its optimum power band, but rather fluctuates around the optimum operating point. A CVT however, provides this continuous range in the forward direction only and the reduction is only available from a certain minimum speed. This is due to the fact that the weights in the pulleys control the ratio. A continuous range is not offered in reverse. It would be beneficial for the forward range to be available from the instant the car starts to move. Therefore, converting a CVT to an IVT will provide the benefits of a CVT while reducing the deficiencies of the CVT system.

In order to convert a CVT into an IVT, a planetary gear set must be used and the engine must also operate differently. A planetary set is made up of a sun gear, a ring gear, and multiple planet gears. The planet gears mesh with the ring and sun gears, which spin in opposite directions. When the angular velocity of the ring and sun gears are equal, the displacement of the planet gears, and therefore the output of the system, will be zero. By changing the ratio of the CVT, the ring and sun gears rotate at different speeds relative to each other which produce an output at the planetary.

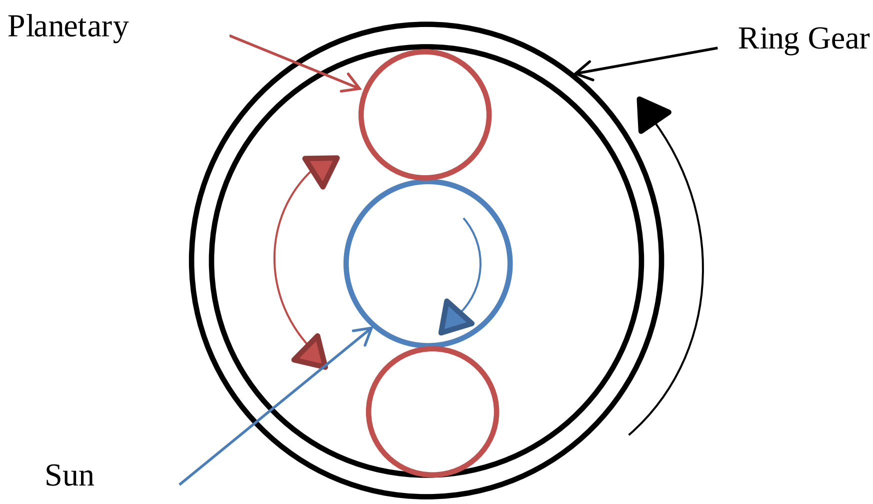


Figure 1: Planetary gear set

In a typical CVT system, the speed of the engine would be controlled by the driver and the pulleys would be controlled by weights that would change the ratio as the speed increases. For an IVT, the engine runs at the desired optimum point at all times, which would keep the sun gear and the CVT primary clutch rotating at a constant speed. The CVT controls the speed of the ring gear. The difference in the speed of the two gears is what displaces the planet gears, thus producing a shaft output.

2.1 Features of the Design

As discussed in the last section, an IVT can be built using a CVT and a planetary gear set. This section details the features of an IVT system as well as methods of controlling it.

A render of the IVT powertrain system can be seen in Figure 2 and Figure 3.

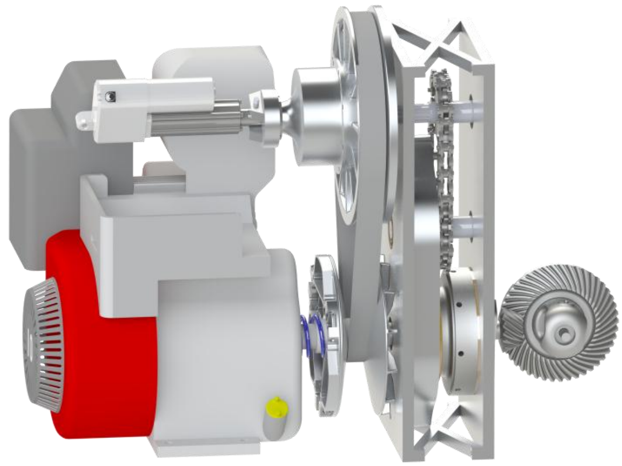


Figure 2: The IVT powertrain system assembly by Team Trans-Formers

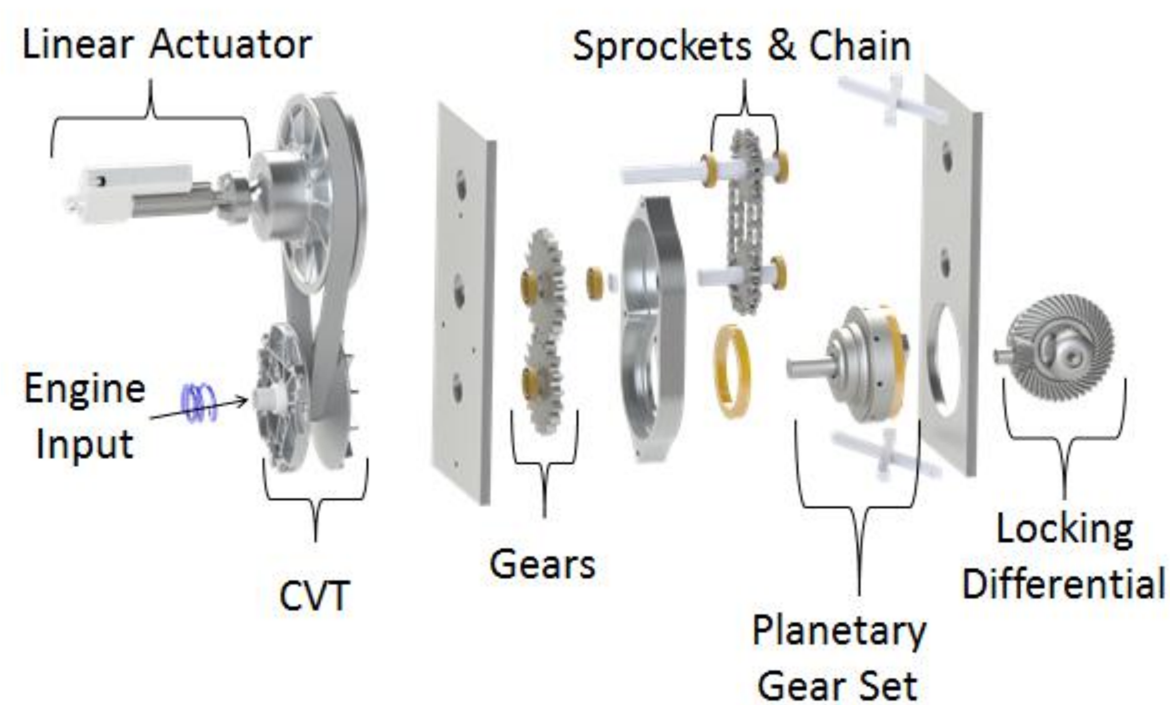


Figure 3: The IVT powertrain system exploded view of assembly by Team Trans-Formers

2.1.1 Performance

The powertrain system directly affects the performance of the vehicle. The IVT powertrain system is designed to maximize the potential of the engine. It is similar to a CVT system in the sense that there is no need to shift between gears while accelerating. In the CVT system the engine RPM follows a linear curve. The IVT holds the engine at a constant RPM from the neutral position to the maximum velocity. Figure 4 shows the profiles of the engine RPM verses velocity for a powertrain system using gears, CVT and IVT.

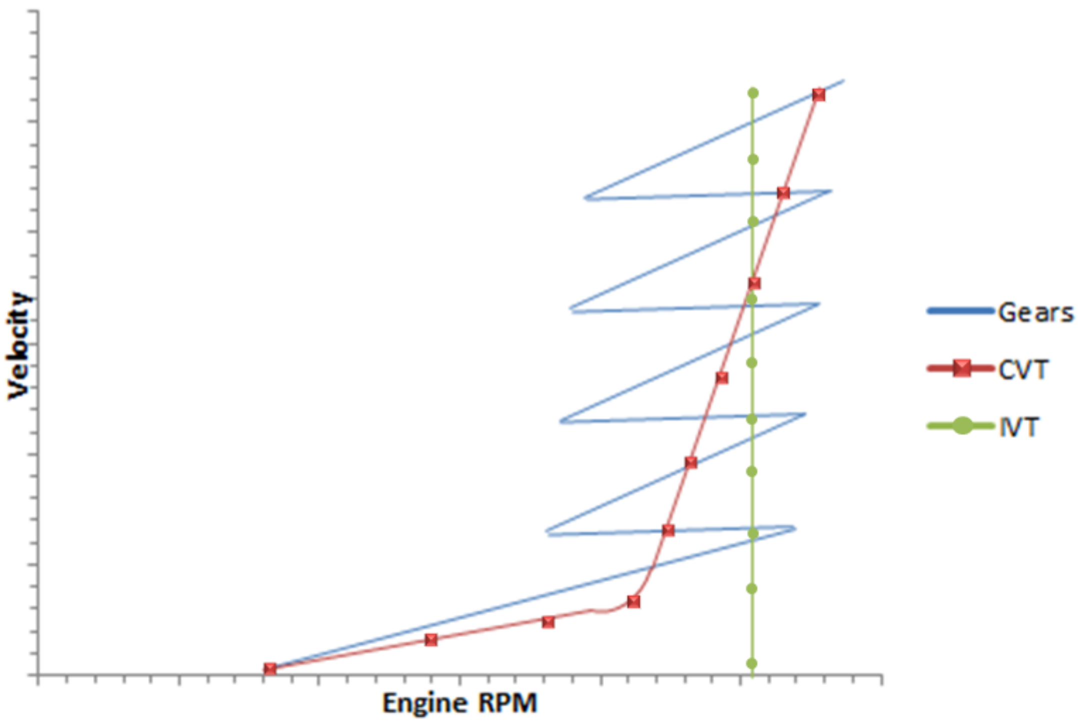


Figure 4: Engine RPM vs. velocity profiles for gears, CVT and IVT systems

Since the engine can be held at a constant RPM, which can easily be adjusted by the driver, the maximum power from the engine can always be obtained. Having the engine produce maximum power at virtually all times means that not only will the IVT powertrain system deliver substantial low end torque and high end top speed, but it will also deliver full mid-range performance. Also, the IVT system places less stress on the engine, as it is held at a constant RPM and doesn`t fluctuate. Consistent RPM is ideal for the Brigg`s and Stratton engine which is not designed for racing applications.

Another advantage the IVT system has over a traditional transmission where gears are used is that there is no impact to the system that is normally associated with shifting from one gear to the next. Also, without a need to shift gears into reverse, there is no chance that the powertrain system can ever be engaged in two settings at the same time.

In addition to the overall performance of the vehicle, the IVT system also allows the engine to be lowered to the bottom of the frame. The engine contributes a large portion of the overall weight of the powertrain system, and by keeping the engine lower, the center of gravity will also be lowered which will improve the handling of the Baja vehicle.

2.1.2 Component Features

The final gear ratio reduction of an IVT system occurs through a series of reductions from each component. Changing one component can greatly affect the final ratio. However the variance in overall ratios can be preserved or tailored by using easily interchangeable components. The features of the IVT system, as well as how other components in the powertrain are affected by the IVT will be explained it the following sections. The equation for the final ratio of the system and the description of the variable used is given below. Descriptions of the variables in the equation for the final output ratio are outlined in TABLE III.

TABLE III - TERMS USED TO DETERMINE THE FINAL RATIO OF IVT OUTPUT

Variable	Details
Ns	# of teeth on sun gear
Nr	# of teeth on ring gear
Ae	Angular displacement of the engine
Rcvt	Ratio delivered from the CVT
Rsp	Ratio delivered from the sprockets
Rg	Ratio delivered from the gear and pinion
Rd	Ratio delivered from the differential
Rf	Overall angular displacement of the engine to the rear axle

$$Rf = Ae * Rd \left\{ \frac{Rcvt * Rsp * Rg}{1 + \frac{Ns}{Nr}} - \frac{1}{1 + \frac{Nr}{Ns}} \right\}$$

The above equation's derivation is shown in APPENDIX B.-.

2.1.2.1 Clutch and differential Upgradability

The design of this powertrain system is unique in the sense that the overall ratios can be easily adjusted. As a result, many different CVTs and differentials can be used and interchanged with the current ones used. The accommodation of different CVTs and differentials is possible because the ratio of the sprockets within the powertrain system plays a large a role in the ratio of the entire system. A small change to the ratio in the sprockets generates a large change in the maximum and minimum ratios seen from the input to output of the powertrain system. The sprockets are easily accessible and new sprockets are readily available on the market. An example of how the system could be updated by adjusting the sprockets is seen in TABLE IV. If the current Polaris CVT was replaced with the CVTech clutch, the maximum speed theoretically achievable would be an unrealistic 166.7 km/hr. However, the ratio is corrected with only a small change in the number of teeth on the sprockets, as shown in TABLE IV.

TABLE IV – THEORETICAL VELOCITIES CAPABLE BY ADJUSTING THE SPROCKETS OF THE IVT SYSTEM

Variables	Current system Polaris CVT	CVTech clutch same sprockets	CVTech clutch adjusted sprockets
1st Sprocket # of teeth	18	18	22
2nd Sprocket # of teeth	18	18	16
Max Speed [km/hr]	84.5	166.7	88.6
Min Speed [km/hr]	-1.2	-4.5	-6.7

The ability of the system to accommodate the exchange of the clutch and differential means that the system can be progressed as better components become available.

2.1.2.2 Differential

The engine within the IVT powertrain system has been rotated by 90 degrees so that the input shaft from the engine now rotates perpendicular to the rear axle. The previous UMSAE Baja vehicles have always had the engine positioned so that the input shaft of the engine was parallel to the rear axle. Having the input shaft of the engine perpendicular to the rear axle is an attractive feature because there is a greater variety of locking differentials available on the market that have this orientation. The Baja team currently has a locking differential from a Polaris Ranger, as shown in Figure 5.

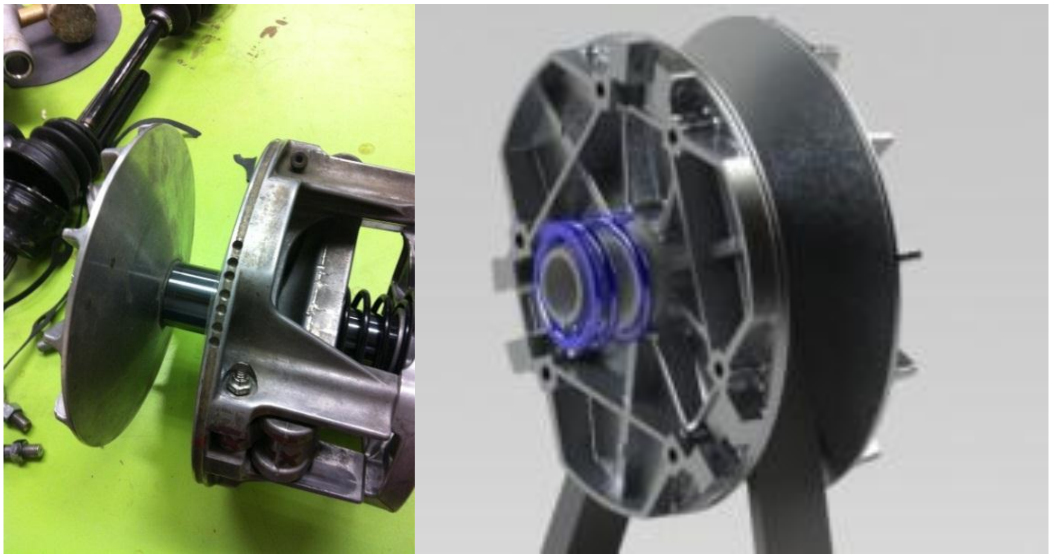
Figure 5: Polaris Ranger rear end locking differential

The Polaris Ranger rear locking differential is used for this design because of its availability to the Baja team. This differential is designed to handle a larger amount of torque and is therefore heavier and bulkier than what is needed for the Baja vehicle. Nevertheless, as previously stated the differential can be interchanged for a new model as other differentials become available to the team.

2.1.2.3 CVT Clutch

The CVT clutch is used to change the output ratio of the powertrain system. However, since the engine is always held at a constant rpm, instead of the position of the CVT being automatically adjusted by the rpm of the engine, the CVT position will be adjusted by driver input. The CVT can be adjusted by the use of either a linear actuator or by mechanical linkages. For the scope of this project the linear actuator is recommended because of its simplicity of manufacturing and integration into the system. The linear actuator will be further explained in the Controls section of this report.

The weights and spring on the CVT that normally control the position of the tapered walls are not needed for the IVT powertrain system and can therefore be removed as seen in Figure 6.



a) Stock primary clutch b) Modified primary clutch

a) Stock secondary clutch b) Modified secondary clutch

Figure 6: Modifications to Polaris P90 CVT clutch

The modifications to the Polaris P90 CVT can easily be performed by a hand milling operation. The Polaris P90 CVT clutch has been recommended for the IVT powertrain system because the Baja team currently has access to one. The Polaris P90 CVT clutch is designed to handle a greater torque and horsepower then the Baja engine can produce. A CVTech clutch would be an alternative that would offer a smaller and lighter option in the future for the IVT system.

2.1.3 Controls

The output of an engine in a normal vehicle is controlled by a foot pedal that has a direct effect on the speed of the vehicle. However, because an IVT does not produce an output the same way as a normal vehicle would, the methods of controlling it are different as well. To control the IVT powertrain system the foot petal, throttle control and hand controls must be considered.

2.1.3.1 Foot Pedal

The IVT powertrain is controlled in a very different way than most automotive powertrain systems. The "gas pedal" of the system will not control the throttle position. Instead the foot pedal will control the Polaris P90 secondary clutch position through a linear actuator. In other words, the driver would be in control of the overall power train ratio not the engine power. The IVT system would require more driver-training than a traditional system, but there are a greater number of benefits in performance.

2.1.3.2 Throttle Position

Since the throttle to the engine is held at a constant position, the control can be independent of the foot controlled "gas pedal". The throttle control will be on the dash board of the vehicle and will hold its position after the driver has selected the desired position. To maximise power during racing applications, the throttle can be set to the optimum limit. To conserve fuel and reduce noise, a lower throttle position can be selected. While in forward drive, the only input from the driver to the IVT system is through the "gas pedal", allowing the driver to keep both hands on the wheel to increase performance.

2.1.3.3 Hand Control Lever

To reverse the vehicle with the IVT system, the driver will need to remove their foot from the "gas pedal" and pull the reverse lever. The reverse lever moves the CVT position past the neutral zone and into the reverse zone. Since very little time is spent in reverse, coupled with the slow associated speeds, it was determined that the reverse lever would be held to engage motion and spring back to neutral upon release. When the reverse lever is released, the car will be instantly ready to drive forward without the need for additional driver input.

A lever that controls the locking and unlocking of the differential is also required. There is a switch directly on the differential that controls the locking mechanism. A simple mechanical linkage consisting of a push pull cable will be used to complete this task.

It is recommended that the reverse lever and the differential lever be placed on opposite sides of the driver for ease of manufacturability as well as driver ergonomics.

2.2 Operation

The IVT system designed for the UMSAE Baja team uses the planetary system to achieve an infinite range in ratio output between maximum speed in the forward direction and reverse direction. A simplified schematic of the IVT system can be seen in Figure 7.

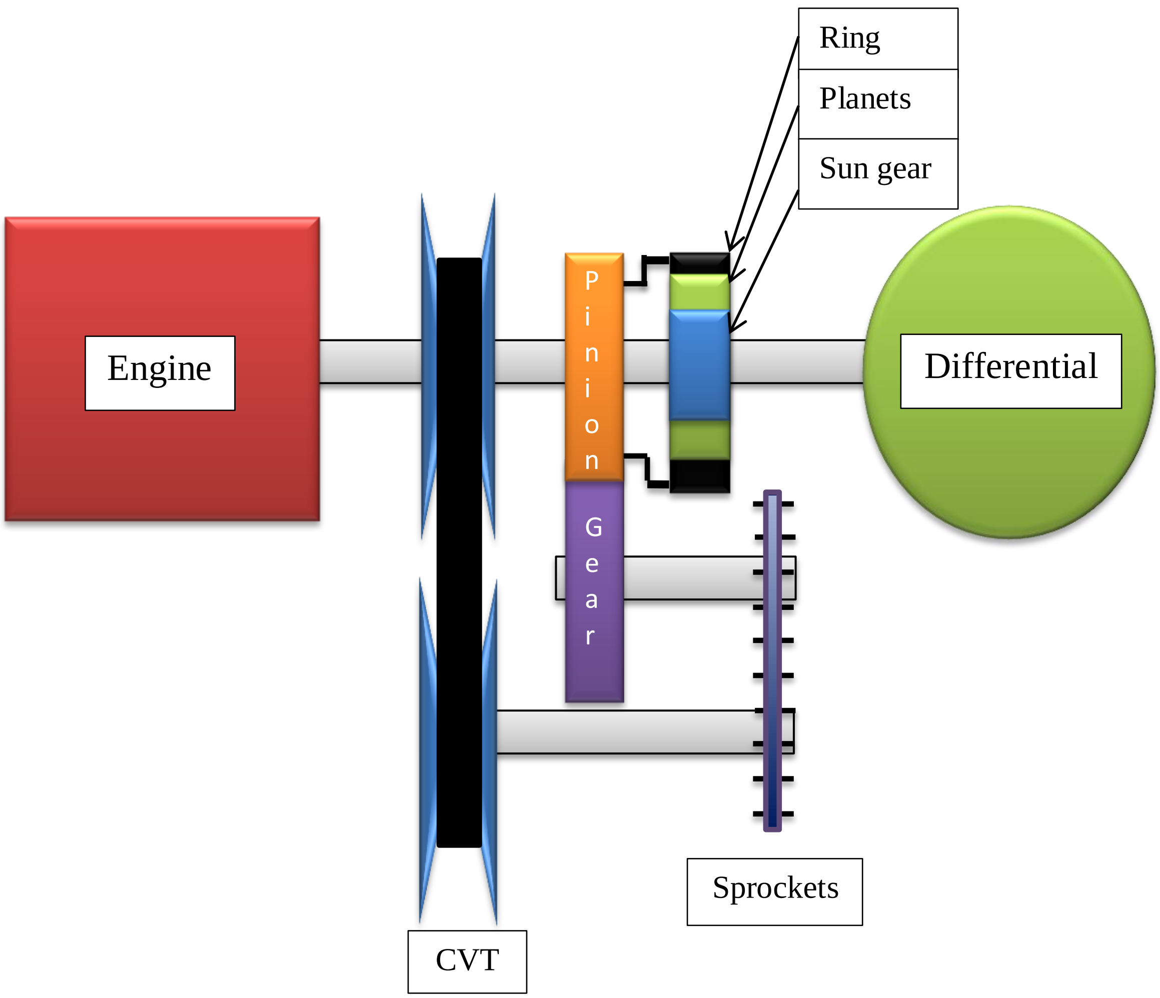


Figure 7: Simplified IVT system powertrain system

The rotational output of the engine is in the counter clockwise direction. Connected to the output shaft of the engine are the primary CVT pulley and the sun gear of the planetary system. The primary and secondary pulleys of the CVT are connected through the belt of the CVT and as a result the output of the CVT is still rotating in a counter clockwise direction. From the output shaft of the CVT the first sprocket is connected. The first and second sprockets are connected via chain and are both spinning in the counter clockwise direction. The shaft that holds the second sprocket also holds the first gear. The second gear transfers the rotation from the first gear to the case of the ring gear. The second gear provides the change in rotation for the ring gear necessary for the IVT to operate. The sun gear and the ring gear work together to control the output of the planetary gear carrier. The planetary gear carrier can rotate either in a clockwise or counter clockwise direction depending on the relative speeds of the ring and sun gears. The planetary gear carrier is directly connected to the input of the differential. Finally the differential is connected to the rear wheels of the vehicle via the rear axles.

2.2.1 Gears

A pair of gears is required in the IVT system to transmit power from the sprocket to the ring gear, as well as reverse the direction of rotation. To determine the required size of these gears, a decision was required as to the gear ratio, as well as the diameters of the gears. It was decided that the desired ratio through the gears and sprockets should to be 0.9:1. That ratio was assigned to the gears, meaning the sprockets could then have a ratio of 1:1. The diameters of the gears were limited by the center to center distance between the shaft going from the CVT to the sprocket and the shaft going from the engine to the sun gear. These maximum pitch diameters of 4.5 and 5 inches respectively were noted and, using the desired gear ratio, the appropriate gears were found.

Suitable gears were found on Martin Sprocket's website that will fit within the size limits of the design. The diameter of the driving gear is 5 inches, while the diameter of the driven gear is 4.5 inches. The slowest speed that the gears will experience corresponds to the maximum torque and it was possible to calculate the minimum face width of both gears (calculations shown in Appendix B). The minimum face width was found to be 0.3 inches for both gears, but it was decided a width of 0.5 inches was more appropriate as alignment could be an issue with very thin gears. The gears offered by Martin Sprocket come with face widths of about 3.5 inches. The gears must therefore be cut down to the desired width of 0.5 inches. The final dimensions of the gears are outlined in TABLE V.

TABLE V - SUMMARY OF THE DIMENSIONS FOR THE GEARS

Value	Driving Gear	Driven Gear
Pitch Diameter (in.)	5	4.5
Number of Teeth	20	18
Face width (in.)	0.5	
Bore diameter (in.)	1.125	

2.2.2 Sprockets and Chain

Sprockets and chains are used to transmit power from the output of CVT to the ring gear of the planetary gear set. They are more compact, lighter, and efficient compare to spur gears. Another beneficial feature is that the sprockets and chains can be isolated from the main transmission casing so that they are easily accessible from the outside. Since the overall gear ratio is very sensitive to the change in ratio between the sprockets, the Baja team has the freedom to adjust the overall gear ratio very easily by changing to a different sprocket if needed in the future.

A Briggs & Stratton 10 HP Intek Pro Engine is used for the power source for the system. According to the CVT design, the maximum rpm at front sprocket would be 5000rpm. Based on the gear ratio optimizations, it is determined that a 1:1 ratio for the sprockets and chains system would be optimal. By considering the power rating and maximum rpm it was decided to use 15 teeth 520 steel sprockets from Kawasaki for both front and back sprockets and a DID 520 ATV X-Ring chain. A sprocket and chain system summary is listed in TABLE VI and detailed calculations for the sprocket chain set up are provided in Appendix B page 35.

TABLE VI - SPROCKET AND CHAIN SYSTEM SUMMARY

Sprockets and Chain Properties	Description
Chain Material	Alloy Steel
Chain Length (in)	22
Chain Pitch (in)	0.625
Sprockets Diameter (in)	3.01
Sprockets Teeth	15
Angle of Warp	180°
Sprockets Material	Chromoly Steel
Rated Life(Miles)	20000 [**3**]
Lubrication Method	Chain Lube Spray

2.3 Overall Cost & Bill of Materials

To make the IVT transmission system cost effective, it was decided to purchase parts that that are commercially available. Since the UMSAE Baja team consists of student volunteers, the manufacturing and labour cost to implement the design will not be a factor. This means that only cost to develop this IVT transmission system will be the cost of parts and material. Since the Baja team is a non-profit student organization, most of the parts required are either donated or discounted through sponsors. Therefore, the team will be able to implement the whole IVT transmission system for an estimated cost of less than $1900 CAD. A detailed cost breakdown is listed in Appendix C page 39 and the bill of materials is listed in TABLE VII.

TABLE VII - BILL OF MATERIALS

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Actuator Assembly	DuffNorton-LT25-2-50PN	1
2	Bearing 7905c	NSK bearing	6
3	Bearing 6818vv	NSK Bearing	1
4	Cross braces	Laser Cut Plate 6061 Aluminum 3"x8"x0.25"	6
5	Planetary Gear Set	Anaheim Automation	1
6	Polaris CVT	CVT + Belt	1
7	Briggs and Stratton Engine	Engine	1
8	CVT Secondary Splined Shaft	0.9” OD 4340 x 8”	1
9	15T-N520 Sprocket	3" Pd - 4340	2
10	18T 4Pd 4.5Dp Pinon Gear	Thickness: 0.5"	1
11	Linear Actuator to CVT Adaptor	2.85" x 5.125"OD 6061Aluminum	1
12	20T_4Pd_5Dp Gear	Thickness: 0.5"	1
13	Rotating Output Flange	Anaheim Automation	1
14	6061 Plate 17inx8inx0.5in	CNC Aluminum Plate	1
15	6061 Plate 17inx8inx0.5in(2)	CNC Aluminum Plate	1
16	Gear Case	Gear Oil Housing 6061_ Aluminum 6.5”x11.25”x1.25”	1
17	Sprocket to Gear Splined Shaft -	0.9" OD x 4" 4340	1
18	520_chain	Approximately 2’	1
19	Spring	Between Engine and CVT	1

2.4 Manufacturing

The IVT system will be largely comprised of purchased parts. Many of the major components for the IVT powertrain system will be purchased and modified to work with the system. The modification and manufacturing of the main components will be explained in this section of the report. It should be noted that the UMSAE Baja team has access to most standard forms of machining and metal facilities.

The P90 Polaris CVT will have the weights that control the automatic shifting removed and an adapter will connect it to the linear actuator. This can be seen in Figure 8.

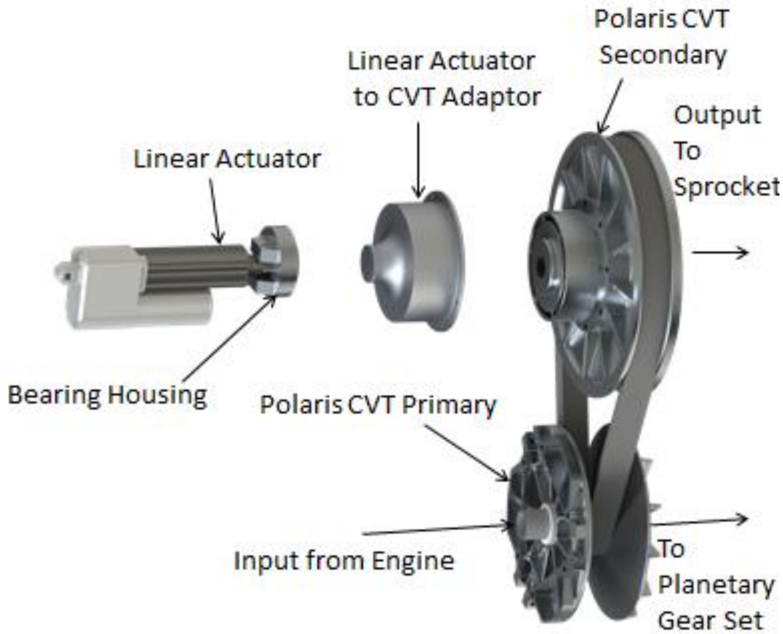


Figure 8: Actuator assembly and modified Polaris P90 CVT

The actuator assembly will have a bearing housing and adaptor attached to the end of its shaft. The housing connects the actuator to CVT adaptor and allows the CVT to spin freely. The housing and adaptor will need to be custom made. It is not a complicated part and can be produced on a standard lathe and milling machine. The actuator housing and adaptor can be seen in Figure 8.

The planetary gear system will be bought and will only require a small modification. The second gear in the IVT system must be connected to the ring gear concentrically. This is accomplished by making the rotating output flange. The rotating output flange can also be produced with a standard lathe and drilling operations. The rotating output flange can be seen in Figure 9.

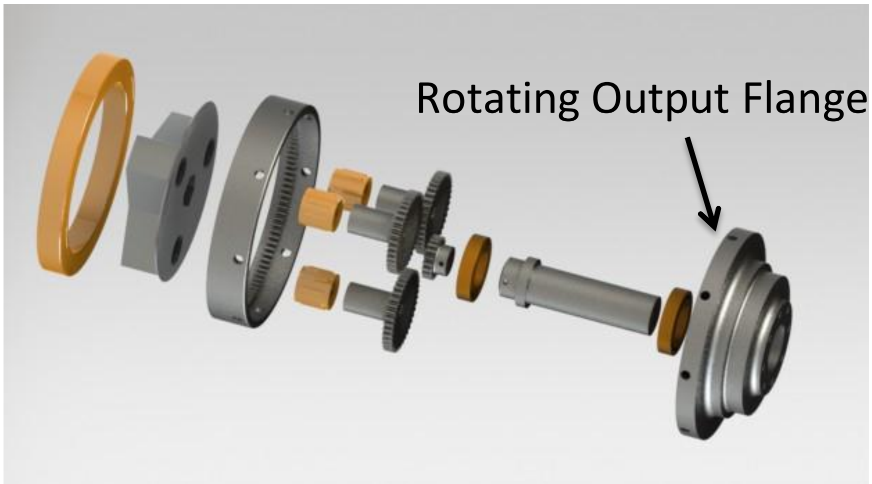


Figure 9: Planetary gear assembly exploded

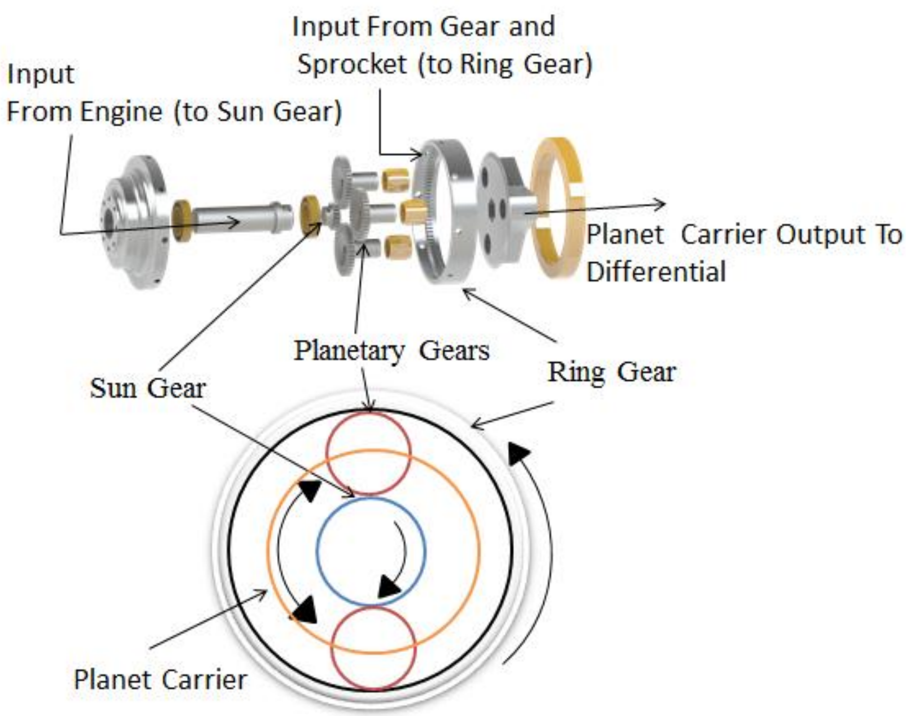


Figure 10: Planet carrier assembly visual explaination

The spur gear and pinion will be produced from Martin Sprocket Inc. gear blanks made of 1144 steel [**4**]. The UMSAE Baja team is sponsored by Martin sprocket and has machined and heat treated gear blanks like these in the past. Therefore there will be no issue with fabrication these gears for the Baja team. The gear and pinion will need to be machined to fit on the shafts and to the appropriate width.

The main support and frame of the IVT planetary system is made from 6061 Al plates as seen in Figure 11. This structural plate can be machined on a 3 axis CNC machine available to the UMSAE Baja team. The gear case enclosure is comprised of two parts: the front plate and the center enclosure seen in Figure 11. The gear case enclosure can be produced in a several different ways. The center pattern of the enclosure can be cut out with a water jet cutter. The critical sections of the gear case, such as bearing locations, would call for additional machining to achieve the needed tolerances. If water jet cutting is not available, the gear case can be machined by a 3 axis CNC machine. The front plate will need to be CNC machined.

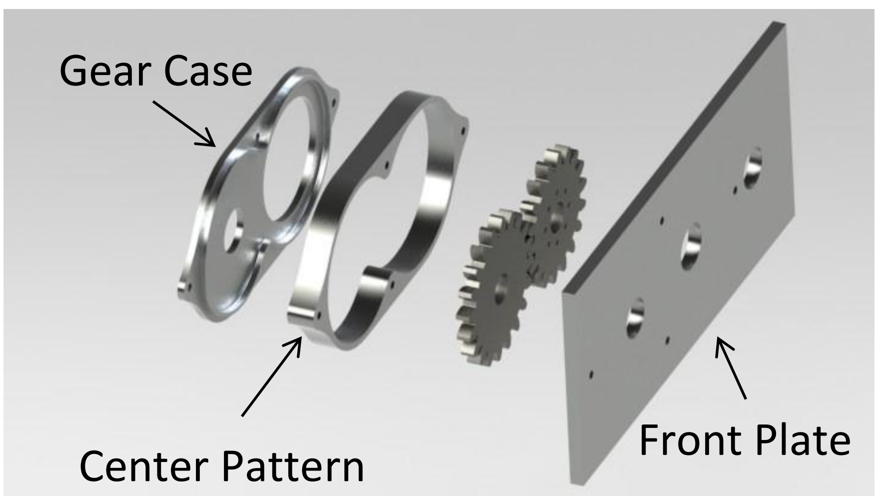


Figure 11: 6160 AL plates, gear and pinion, and gear case enclosure

3 Conclusion

The purpose of this project was to design a powertrain system for the UMSAE Baja team. The request for the redesign of the current powertrain system was in response to the performance issues from the 2011transmission. The 2011 powertrain design was comprised of the standard Brigg's & Stratton engine, a P90 Polaris CVT and a custom gearbox. The new powertrain system design proposed is an infinitely variable transmission (IVT).

Unlike a gear style of transmission where only finite ratios can be achieved, the IVT system allows for a wide range of ratio outputs. The full range of output ratios extends from full speed in the forward direction, through neutral, to a full output speed in the reverse direction. The IVT system delivers better performance because it allows the engine to operate at its maximum power output at all times. The IVT offers a top theoretical forward speed of 85 [km/hr] and a reverse speed of 1.2 [km/hr]. Another attractive feature of the IVT system is that the overall system output ratio can be altered with one minor modification, allowing different differentials or CVTs to be integrated into future designs.

The IVT designed, meets or surpasses all the requirements requested from the UMSAE Baja team. The powertrain system was given a budget of $5,000. The IVT powertrain will cost the UMSAE Baja team $1,854.34 CAD and is therefore under budget. The new IVT powertrain system was designed with the UMSAE Baja team in mind so that every part of the system will be within the manufacturing capabilities of the Baja Team. The IVT system is a rugged design that will withstand the demands of the UMSAE Baja competition and allow the UMSAE Baja team to be stronger competitors.

4 Bibliography

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APPENDIX A.- ALTERNATIVE CONCEPTS

Multiple designs were considered, and the final design was chosen based on the screening and scoring charts shown below.

Screening Matrix

Table 1 below was used to choose four designs to be considered for a final design.

TABLE 1 DESIGN OPTIONS

Design Options

Need	1/2	3	4/5	6	7	8	9	10	11	12	13
1	+	+	+	+	+	+	-	+	-	+	+
2	+	0	+	+	-	-	-	0	-	+	-
3	+	+	0	+	+	0	-	-	0	+	0
4	+	0	-	+	0	0	-	+	-	+	+
5	0	0	+	-	0	+	0	0	-	-	+
6	+	+	+	+	+	+	0	+	-	+	+
7	+	0	+	+	+	+	-	+	-	+	+
8	+	-	+	0	-	+	-	0	-	+	-
9	0	0	+	-	0	0	0	+	-	-	+
10	0	0	-	+	0	0	-	+	-	-	0
11	+	-	+	+	0	0	0	+	-	-	+
+'s	8	3	9	8	4	5	0	7	0	7	7
0's	3	6	1	1	5	5	4	3	1	0	2
-'s	0	2	2	1	2	1	7	1	10	4	2
TOTAL	8	1	7	7	2	4	-7	6	-10	3	5

Needs

1 - must transfer power from the engine to the wheels

2 - must be optimized for each dynamic event

3 - must be durable

4 - provide different gear ratios

5 - must be easily manufactured

6 - must be able to operate in a variety of terrains

7 - must be packaged to keep the center of mass as low as possible

8 - minimal power losses

9 - cost effective

10 - relatively small

11 - relatively light

Designs

1/2 - multiple planetary gears or planetary gears with a CVT

3 - hydraulic system powered by engine

4/5 - chain drive or belt drive

6 – dual CVT directly from the engine to the rear wheels

7 - electric motor(s) powered by generator which is connected to the engine

8 - pneumatic system gets power from air tank connected to compressor connected to engine

9 - fan boat propeller powered by engine

10 - bicycle-style sprockets

11 - rocket powered

12 - cone-style CVT

13 - friction wheels

Scoring Matrix

A sample of the concept scoring process is shown below. This particular scoring matrix is for a powertrain system comprised entirely of sprockets and chains, similar to a bicycle.

TABLE 2-SAMPLE SCORING MATRIX WITH A BICYCLE SPROCKET POWERTRAIN

CRITERIA	Units	Target Value	Weighting	Specs	Rating	Score	Pass/Fail
Weight	Lbs.	80	20	50	1.60	32.00	
Size	In^3	1000	10	1000	1.00	10.00	
Min Gear Ratio	times	6.00	20	4.7	1.28	25.53	
Max Gear Ratio	ratio	40.00	20	23	0.58	11.50	
Range Gear Ratio	ratio	36.00	10	27.7	0.69	6.93	
Efficiency	%	60%	10	98%	1.63	16.33	
Manufacturability	Easy =3/Medium =2/Difficult=1	2	5	2	1.00	5.00	
Cost	CAD $	$5,000	2	$685.07	7.30	14.60	
FOS Max Torque		2	10	1.2	0.60	6.00	
Rotating Mass	kg	60	5	50	1.20	6.00	
Running life	Km /hours	5,000 km/ 10,000 hours	Pass/Fail	15000	N/A	N/A	Pass
Input RPM range	RPM	1800-3800	Pass/Fail	3800	N/A	N/A	Pass
Reverse	Pass/Fail	Pass	Pass/Fail	Pass	N/A	N/A	Pass
		Total:	112		Total:	133.89	Pass

APPENDIX B.- TECHNICAL ANALYSIS & SIMULATION

Derived Ratio of the Output for IVT System

All of the terms used to solve the ratio delivered from the IVT system is given in TABLE III. It should be noted that the angular displacement of the sun gear(As) is equivalent to the output of the engine.

To determine the ratios for the IVT system the problem was first simplified. Starting with the planetary system two situations were combined by superposition. The two situations are; when the ring gear is locked in place (sun gear input, planet carrier output) and when the sun gear is locked in place (ring gear input, planetary carryout output). The equations for these two situations are as follows:

TABLE 3 VARIABLES USE TO DETERMINE THE RATIO OF IVT OUTPUT

Variable	Description
Ns	# of teeth on sun gear
Nr	# of teeth on ring gear
Ar	Angular displacement of ring gear
As/Ae	Angular displacement of sun gear/engine
Acr	Angular displacement of planet carrier with ring gear free to spin and sun gear locked
Acs	Angular displacement of planet carrier with sun gear free to spin and ring gear locked
Ac	Overall angular displacement of the planet carrier
Rcvt	Ratio delivered from the CVT
Rsp	Ratio delivered from the sprockets
Rg	Ratio delivered from the gear and pinion
Rd	Ratio delivered from the differential
Rf	Overall angular displacement of the engine to the rear axle

$$Acr = Ar\frac{1}{(1+\frac{Ds}{Dr})}$$

$$Acs = As\frac{1}{(1+\frac{Dr}{Ds})}$$

The input from the ring gear and sun gear will have a cancelling effect on the output of the planet carrier. The rotation of the ring gear can be related to the rotation of the sun gear through the CVT, the sprockets and the gears. The differential changes the overall final output of the system in a linear fashion. Using this information the following equations can be stated:

$$Ac = (Acr - Acs)$$

$$Ar = As * Rcvt * Rsp * Rg$$

$$Rf = Ac * Rd$$

By rearrange these equations the overall ratio of the powertrain system can be determined. Also it will be possible to use the equation to manipulate the overall ratios by changing the internal rations between the components. The equation for the overall ratio of the IVT system is as follows.

$$Rf = As * Rd\left\{\frac{Rcvt * Rsp * Rg}{1+\frac{Ns}{Nr}} - \frac{1}{1+\frac{Nr}{Ns}}\right\}$$

Gear Calculations [5]

Power (P) = 10hp

Ratio = 0.9:1

Driving gear diameter (D_P) = 5 in

Number of driving gear teeth (N_P) = 20

Minimum driving gear speed (n_p) = 997 RPM

Driven gear diameter (D_g) = 4.5 in

Number of driven gear teeth (N_g) = 18

Minimum driven gear speed (n_g) = 1108 RPM

Diametral Pitch (P_d) = $N_g/D_g = N_p/D_p = 20/5 = 4\ in^{-1}$

Tangential Force (W_t) = $126050*(P/(n_p*D_p))$ = 252.859 lb

Torque in driving gear (T_p) = $5252*(P/n_p)$ = 52.678 lb-ft

Torque in driven gear (T_g) = $5252*(P/n_g)$ = 47.4102 lb-ft

Pitch line velocity (v) = $(\pi*n_p*D_p)/12$ = 1305.07 fpm

Geometry Factor (J) = 0.3 (for a 20 degree)

Overload Factor (K_O) = 1.75

Size Factor (K_S) = 1.05

Load Distribution Factor (K_M) = 1.05

Rim Thickness Factor (K_B) = 1.00

Dynamic Factor (K_V) = 1.20

Maximum allowable bending stress number for flame-hardened steel ($s_{t,max}$) = 45 ksi (Table 9-3)

Bending Stress number $\boldsymbol{s_t = \frac{W_t P_d}{FJ} K_O K_S K_M K_B K_V = 26.0\ ksi}$

Modulus of Elasticity for steel (E) = $3*10^7$ psi (pg 400)

Poisson's Ratio for steel (ν) = 0.3 (pg 400)

Elastic coefficient (C_p) = 2290.6 (pg 400)

Pitting geometry factor (I) = 0.075 (pg. 402 for 20 degree…)

Maximum allowable bending stress number for flame-hardened steel ($s_{C,max}$) = 170 ksi (Table 9-3)

Bending Stress number $\boldsymbol{s_C = C_p \sqrt{\frac{W_t K_O K_S K_M K_V}{F D_p I}} = 165.2\ ksi}$

The values for s_t and s_C were obtained by varying the face width until the stress numbers were below the acceptable values. The final minimum face width is:

Minimum face width (F) = 0.3 in

Sprockets and Chains Calculation

Based on Manufactures specification DID 520 ATV X-Ring chain has a pitch of 5/8 inches [**3**].

Since the best sprockets ratio is determined to be 1:1, therefore both sprockets will have 15 teeth.

On ratios of less than 3:1, wrap will always be at least 120° in a two sprocket system. The minimum center distance to avoid interference between the two sprockets can be calculated as: [**6**]

$$C = \frac{N + n + 1}{6} = \left(\frac{31}{6}\right) \approx 5.17\ pitches \approx 3.23\ inches$$

Where:

C = Center distance between sprockets

N = Number of teeth on driven sprocket

n = Number of teeth on driver sprocket

For the purpose of our design the actual center distance between sprockets will be used as 6.25 inches which is equivalent to 10 pitches.

The diameter for both sprockets equal:

$$D = \frac{p}{\sin\left(\frac{180°}{N_1}\right)} = \frac{0.625}{\sin\left(\frac{180°}{15}\right)} \approx 3.01\ inches$$

Since the ratio is 1:1, then the angle of wrap for each sprocket would be the same and can be determined as:

$$\theta = 180° - 2sin^{-1}[(D_2 - D_1)/2C] = 180° - 0 = 180°$$

Chain length can be calculated as:

$$L = 2C + \frac{N+n}{2} + k = (2 * 10) + 15 = 35\, pitches = 22\, inches$$

Where:

L=Length of the Chain

C= Center distance between sprockets (pitches)

$$K = 0.0258 * \frac{(N-n)^2}{C} = 0.0258 * \frac{(N-n)^2}{C} = 0$$

APPENDIX C.- COST ANALYSIS

Detailed Cost Analysis

The cost of the IVT powertrain system was broken down into three sections. The three sections are the normal cost, sponsored cost and current cost. The normal cost is the full price without any sponsorship or in-kind donations. The sponsored cost is the amount the IVT system would cost the UMSAE Baja team from sponsors. The current cost of the system takes into account not only the sponsorship discounts and in-kind donation, but also the parts and material the Baja team already has. An example of this is the Polaris P90 CVT. Polaris is a sponsor and therefore the Baja team received a discount on the part, but the Baja team already has a P90 CVT in their possession that could be used for the IVT system. Therefore, the current cost of the P90 CVT is free to the Baja team.

Major components for the IVT system that are listed as a current cost of $0.00 are either in-kind donations from the Baja sponsors or the Baja team already has these components from previous years. The material costs are estimated from the current cost of materials from AED motor sports. AED motor sport offers a discount for all the metals that will be used for the IVT system. Hardware such as bearings and fasteners are donated to the Baja team from NSK Inc. and Fastenal.

The detailed breakdown and summary of the cost from the IVT system are outlined in table 4 .

TABLE 4 SUMMARY OF COST ANALYSIS FOR THE IVT POWERTRAIN SYSTEM

	PART	DETAIL/COMPANY	NORMAL COST	SPONSORED COST	CURRENT COST
Major Components	10 hp Engine 1450 Series	Brigg's & Stratton	$469.99	$200.00	$0.00
	P90 CVT	Polaris	$463.16	$186.00	$0.00
	Gear 1	Martin Sprocket	$38.52	$0.00	$0.00
	Gear 2	Martin Sprocket	$41.98	$0.00	$0.00
	520 Steel Front Sprocket x2	Kawasaki	$39.90	$39.90	$39.90
	DID 520 ATV X-Ring Chain	DID Chain	$104.29	$104.29	$104.29
	Linear Actuator	Firgelliauto	$205.15	$205.15	$205.15
	Planetary system	Anaheim Automation	$1,135.00	$1,135.00	$1,135.00
	Ranger rear differential	Polaris	$949.38	$380.43	$0.00
Material	Case	plate - Al 6160	$425.00	$215.00	$215.00
	Planetary carrier	5" dia - round rod - AL 7075	$55.00	$30.00	$30.00
	Round Shafts	4340 round rod	$180.00	$90.00	$90.00
	Splined Shafts	4340 Spline shafts	$85.00	$35.00	$35.00
	Bearings	NSK Inc.	$320.00	$0.00	$0.00
	Fasteners	Fastenal	$200.00	$0.00	$0.00
Total			$4,712.37	$2,620.77	$1,854.34